Searches for Exotic Physics at CDF

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For the CDF Collaboration

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Introduction

- CDF at the Fermilab Tevatron
- The “Discovery Watch” idea
- Existing discrepancies
  ... and related new search results
  - Resonances
  - Higgs beyond the standard model
  - Global searches
- Conclusions
LINAC
-Accelerates protons to 400 MeV

Booster
-Accelerates protons to 8 GeV

Main Injector
-Accelerates protons to 120 GeV
  - to nickel target to make $\bar{p}$'s
  - to fixed target and $\nu$ expts.
-Accelerates $p$'s and $\bar{p}$'s to 150 GeV for injection into Tev.

Accumulator
- Receives $\bar{p}$'s

Recycler
-Holds (~400mA) and cools $\bar{p}$'s

Tevatron
-Superconducting synchrotron
-Accel. to 980 GeV and collides
-Counter-rotating helical beams

$\sqrt{s} = 1.96$ TeV
Tevatron Performance

Record Instantaneous Luminosity
= $332 \times 10^{30} / \text{cm}^2 / \text{s}$
(November 4, 2008)

- Additional records:
  - Integrated for single store: 11.0 pb$^{-1}$
  - Most $\bar{p}$'s collected in one hour: 27 mA
  - Largest stash of $\bar{p}$'s: 465 mA

- Achievements:
  - Electron cooling of $\bar{p}$ beam
  - Routine operation of two $\bar{p}$ storage rings
Collider Detector at Fermilab

Silicon
- 8 layers
  at r=1.3 cm to 28 cm

Drift Chamber
- 4 axial + 4 stereo
  “super-layers”
- |η| < 1.1

1.4T solenoid
- superconducting

EM calorimeters
- central: |η| < 1.1
- plug: 1.1 < |η| < 3.6

Hadronic calo.
- central and plug

Muon systems
- drift chambers
- 3 systems: |η| < 1.0
CDF Performance

Delivered: 5.23 fb\(^{-1}\)
Acquired: 4.31 fb\(^{-1}\)
Good store efficiency
20 store ave (acquired)
20 store ave (good)
20 store ave (w/silicon)
The “Discovery Watch” Idea

History

- Initially conceived as an internal tool to:
  - Organize effort onto interesting topics
  - Demonstrate, to funding agencies, cases for running Tevatron $\geq$ 2010

But what is it?

- A collection of CDF results that show some discrepancy compared to the standard model prediction. The discrepancy may appear in:
  - Kinematic distribution
  - Observed number of events (and related cross section limit)
  - Measured parameter

- Such discrepancies, appearing in results using up to 3 fb$^{-1}$, are candidates for becoming discoveries with the final full CDF Run II data sample
There is a webpage
- Soon to be made public (all the results are public)

Aren't there limitations to doing this?
- Expect statistical fluctuations
  - ~180 Run II publications so far
  - Only some are searches
  - Searches have many channels and many distributions
  - For 180, expect ~8 deviations of >2σ
- Worse than looking under the lamp post for our keys
  - First we looked only where we had a shot at seeing something, and now we talk about only a subset of those
- You might think of other limitations...
- I am not advocating using this to guide all of CDF's efforts
This talk features the highlights from the current Discovery Watch list, and related new results.

They fall into three categories:

I. Resonances

II. Higgs beyond the standard model

III. Global searches
Resonance Searches

- I will present results of three searches for new resonances

1. Dielectron search, including two forward electrons
2. Dielectron search, including $\geq 1$ central electron
3. Dimuon search

New
Resonances Motivation I

- $e^+e^-$ and $\mu^+\mu^-$ are classic discovery signatures ($J/\psi$, Upsilon, $Z$)
  - Search in leptonic decays instead of hadronic decays:
    - Lower backgrounds, better identification, better momentum measurement; more than make up for lower branching fraction

- Spin-0:
  - Still searching for a fundamental scalar
  - MSSM Higgs could have enhanced production to dileptons
  - SUSY R-parity violation can yield sneutrinos

- New fermion for every boson, and new boson for every fermion

Particles

\begin{align*}
\bar{d} & \quad \bar{c} & \quad \bar{t} & \quad \gamma \\
\bar{d} & \quad \bar{s} & \quad \bar{b} & \quad g \\
\nu_e & \quad \nu_\mu & \quad \nu_\tau & \quad Z \\
e & \quad \mu & \quad \tau & \quad W
\end{align*}

Sparticles

\begin{align*}
\tilde{\nu}_e & \quad \tilde{\nu}_\mu & \quad \tilde{\nu}_\tau & \quad \tilde{Z} \\
\tilde{\nu}_e & \quad \tilde{\nu}_\mu & \quad \tilde{\nu}_\tau & \quad \tilde{W}
\end{align*}

$\lambda = \bar{d}d\tilde{\nu}$ coupling
Resonances Motivation II

- **Spin-1: \( Z' \)**
  - Heavy neutral gauge boson
  - Unification of forces (as in GUTs) through extended gauge groups such as SO(10) or E6
    - Spontaneous symmetry breaking to SM groups
      → Additional U(1) gauge group(s)
      → \( Z' \) bosons
  - Breaking E6 can result in various U(1) symmetries
    - Example: \( SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)' \)
      With \( U(1)' = U(1)_\psi \cos \theta + U(1)_\chi \sin \theta \)
      → \( Z'_{\psi}, Z'_{\chi}, ... \)
  - Coupling to SM fields
    - Determined by specifics of the group theory and by weak charge
  - Long-standing discrepancy (~3.2\( \sigma \)) within precision electroweak fits
    - Mixing between \( Z' \) and SM \( Z \)?
Spin-2: Graviton

- Graviton in Randall-Sundrum model of warped extra dimensions
- Seeks to solve hierarchy problem between Planck scale and electroweak scale
- Exponential warp factor weakens gravity at weak brane compared to gravity brane

Gravity

Gravity Brane

Weak Brane

Extra spacial dimension

- Gravitons propagate everywhere
- Standard model exists within weak (TeV) brane

Excited massive graviton with electroweak scale couplings to SM particles
Forward Electrons

- Central ($|\eta| < 1.1$) and forward ($1.2 < |\eta| < 3.6$) regions
  - $ee$: central+central, central+forward, forward+forward
  - $\mu\mu$: central+central

Results:

<table>
<thead>
<tr>
<th>$m_{\ell\ell}$ (GeV/c$^2$)</th>
<th>Observed</th>
<th>Expected</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 150</td>
<td>205</td>
<td>212.9 ± 99.3</td>
<td>58</td>
<td>55.3 ± 2.5</td>
</tr>
<tr>
<td>&gt; 200</td>
<td>84</td>
<td>78.2 ± 33.4</td>
<td>18</td>
<td>20.9 ± 1.0</td>
</tr>
<tr>
<td>&gt; 300</td>
<td>22</td>
<td>13.6 ± 4.4</td>
<td>6</td>
<td>5.2 ± 0.3</td>
</tr>
<tr>
<td>&gt; 400</td>
<td>5</td>
<td>2.9 ± 0.7</td>
<td>1</td>
<td>2.3 ± 0.2</td>
</tr>
<tr>
<td>&gt; 500</td>
<td>2</td>
<td>0.8 ± 0.1</td>
<td>1</td>
<td>1.2 ± 0.1</td>
</tr>
</tbody>
</table>

- Two $ee$ events observed around 515 GeV/c$^2$
  - SM expectation is $0.8 ± 0.1$ events above 500 GeV/c$^2$
  - Both are forward+forward
  - Such excess has not been observed in central+central or central+forward searches using larger samples

Set limits:
- $m_{\text{sneutrino}} > 725$ GeV/c$^2$ at 95% C.L.
- $m_{\text{SM Z}} > 825$ GeV/c$^2$ at 95% C.L.
- $m_{\text{Graviton}} > 710$ GeV/c$^2$ at 95% C.L.
There is a 3.8σ discrepancy in 228-250 GeV/c^2 window.

Probability to observe a fluctuation at least this large somewhere in analysis range, 150-1000 GeV/c^2, is 0.6%. **Significance is 2.5σ.**
**e^+e^- Resonance Limits**

Submitted to PRL, arXiv:0810.2059v1

- **Spin-1**: SM-like Z' mass limit
  \[ m_{\text{SM } Z'} > 966 \text{ GeV/c}^2 \] at 95% C.L.

- **Spin-2**: Randall-Sundrum graviton limit
  \[ m_G > 850 \text{ GeV/c}^2 \] at 95% C.L.

For \[ \frac{k}{M_{\text{PL}}} = \frac{\text{negative curvature}}{\text{Planck mass}} = 0.1 \]

**CDF Run II Preliminary**

Cross Section Upper Limits (95% C.L., spin-1)

Cross Section Upper Limits (95% C.L., spin-2)
Search for narrow resonance in Dimuon *inverse* mass spectrum

- At high mass, curvature resolution is independent of curvature
- Constant resolution in $1/p_T$ and $1/m$
- $17\%$ $m^{-1}$ resolution at 1 TeV

Two muons, with $p_T > 30$ GeV/c

Backgrounds

- Electroweak: from Monte Carlo, scaled using Z peak region
- In-flight kaon decays and jets faking leptons: from jet data, normalized using like-sign data
- Cosmic rays: from data, normalized using timing information

Data are consistent with SM prediction

- $p$-value = 6.6%

Place limits on the following scenarios

- Spin-0: R-parity violating SUSY
- Spin-1: Massive $Z'$
- Spin-2: Randall-Sundrum graviton

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\textbf{\(\mu^+\mu^-\) Resonance Limit: RPV SUSY 2.3 fb\(^{-1}\)}

- Spin-0: sneutrino in R-parity violating SUSY
- Place limits on \(\sigma \times \text{BR}(\tilde{\nu} \rightarrow \mu^+ \mu^-)\) and on \(m_{\tilde{\nu}}\) for a variety of values of \(\lambda^2 \times \text{BR}\)

\[
\lambda = \text{dd} \tilde{\nu} \text{ coupling}
\]

<table>
<thead>
<tr>
<th>(\lambda^2 \times \text{BR})</th>
<th>(m_{\tilde{\nu}}) limit (GeV/c(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>278</td>
</tr>
<tr>
<td>0.0002</td>
<td>397</td>
</tr>
<tr>
<td>0.0005</td>
<td>457</td>
</tr>
<tr>
<td>0.001</td>
<td>541</td>
</tr>
<tr>
<td>0.002</td>
<td>662</td>
</tr>
<tr>
<td>0.005</td>
<td>751</td>
</tr>
<tr>
<td>0.01</td>
<td>810</td>
</tr>
</tbody>
</table>
**μ⁺μ⁻ Resonance Limit: Z'**

Submitted to PRL, arXiv:0811.0053v1

- Spin-1: Heavy boson (Z')
- Limits on $\sigma \times \text{BR}(Z' \rightarrow \mu^+ \mu^-)$ and on $m_{Z'}$ for a variety of models

Assume no interference between Z' and SM $Z/{\gamma}^*$

### Table of Limit

<table>
<thead>
<tr>
<th>Model</th>
<th>$m_{Z'}$ Limit (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'_I$</td>
<td>789</td>
</tr>
<tr>
<td>$Z'_{sec}$</td>
<td>821</td>
</tr>
<tr>
<td>$Z'_N$</td>
<td>861</td>
</tr>
<tr>
<td>$Z'_{\psi}$</td>
<td>878</td>
</tr>
<tr>
<td>$Z'_{\chi}$</td>
<td>892</td>
</tr>
<tr>
<td>$Z'_{\eta}$</td>
<td>982</td>
</tr>
<tr>
<td>$Z'_{SM}$</td>
<td>1030</td>
</tr>
</tbody>
</table>
Spin-2: Search for first excited Randall-Sundrum graviton

Limits on $\sigma \times \text{BR}(G^* \rightarrow \mu^+\mu^-)$ and on $m_{G^*}$ for a variety $k/M_{\text{PL}}$

<table>
<thead>
<tr>
<th>$k/M_{\text{PL}}$</th>
<th>$m_{G^*}$ limit (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>293</td>
</tr>
<tr>
<td>0.015</td>
<td>409</td>
</tr>
<tr>
<td>0.025</td>
<td>493</td>
</tr>
<tr>
<td>0.035</td>
<td>651</td>
</tr>
<tr>
<td>0.05</td>
<td>746</td>
</tr>
<tr>
<td>0.07</td>
<td>824</td>
</tr>
<tr>
<td>0.1</td>
<td>921</td>
</tr>
</tbody>
</table>
Summary of Resonance Searches

(1) Dielectron search, including two forward electrons

(2) Dielectron search, including \( \geq 1 \) central electron

(3) Dimuon search New

Mass lower limits at 95% C.L. (in GeV/c\(^2\))

<table>
<thead>
<tr>
<th>Search</th>
<th>Lumi</th>
<th>Spin-0 (( \tilde{\psi} )) ( \lambda^2 BR = 0.01 )</th>
<th>Spin-1 (( Z' )) ( Z'_{SM} )</th>
<th>Spin-2 (( G^* )) ( k/M_{PL} = 0.1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) ee and ( \mu \mu )</td>
<td>0.20 fb(^{-1})</td>
<td>725</td>
<td>825</td>
<td>710</td>
</tr>
<tr>
<td>ee</td>
<td>0.45 fb(^{-1})</td>
<td>-</td>
<td>850</td>
<td>-</td>
</tr>
<tr>
<td>ee (and ( \gamma \gamma ))</td>
<td>1.3 fb(^{-1})</td>
<td>-</td>
<td>923</td>
<td>889</td>
</tr>
<tr>
<td>(3) ( \mu \mu )</td>
<td>2.3 fb(^{-1})</td>
<td>810</td>
<td>1030</td>
<td>921</td>
</tr>
<tr>
<td>(2) ee</td>
<td>2.5 fb(^{-1})</td>
<td>-</td>
<td>966</td>
<td>850</td>
</tr>
</tbody>
</table>
Beyond SM Higgs Searches

- Will present results of three searches for Higgs beyond the standard model

1. MSSM Higgs, using $b\bar{b}b$ channel
2. MSSM Higgs, using $\tau\tau$ channel
3. Fermiophobic Higgs, using $\gamma\gamma$ channel  New
MSSM Higgs: \( g g \rightarrow bbH \rightarrow bbbb \)

- Production of neutral scalars h, H, A, in association with \( b\bar{b} \)
  
  \[
  \begin{array}{ccc}
  g & b & b \\
  g & \rightarrow & H \\
  \bar{b} & b \\
  \end{array}
  \]

- For small \( m_A \) (pseudoscalar mass) and large \( \tan \beta \) (d-type / u-type couplings)
  - \( bb\rightarrow H \) production enhanced
  - \( \text{BR}(H\rightarrow bb) \approx 90\% \), \( \text{BR}(H\rightarrow \tau\tau) \approx 10\% \)

- Three b-tagged jets
  - Secondary vertex tagging
  - Three leading jets with \( E_T > 20 \text{ GeV} \)
  - \( |\eta| < 2 \)

- 1 fb!

For \( \text{BR}(H\rightarrow bb) \approx 90\% \), \( \text{BR}(H\rightarrow \tau\tau) \approx 10\% \)

Worse background

Just right

Worse cross section

Dawson, Jackson, Reina, Wackeroth

hep-ph/0603112
**MSSM Higgs: bbb**

![Graph](image1)

- **Data and background template fit**
  - $m_{12} = \text{mass of two leading jets}$
  - Includes hypothetical H
  - shows corresponding excess and deficit

- **Upward fluctuation of observed limit compared to expected limit around $m_H=140 \text{ GeV/c}^2$**

- **Downward fluctuation around $m_H=200 \text{ GeV/c}^2$**
MSSM Higgs: bbb

- Analysis updated with twice the data
- Deviations, small though they were, are even smaller now

$$\tan\beta$$ vs $$m_A$$ limit
- Excludes $$\tan\beta$$ above ~90
MSSM Higgs: $H \rightarrow \tau\tau$

- Two processes contribute

\[
\begin{align*}
g & \xrightarrow{b} H \\
g & \xrightarrow{b} H
\end{align*}
\]

- Best signatures
  - One $\tau$ decays to $e$ or $\mu$, other hadronic (BR=23%+23%)
  - One $\tau$ to $e$ and one $\tau$ to $\mu$ (6%)

- Selection
  - Leptons: $p_T > 10$ GeV/c
  - Hadronic $\tau$: $p_T > 15$ GeV/c, mass < 1.8 GeV/c^2
  - Opposite charge

- Significance of excess is $<2\sigma$ when entire mass range is considered

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MSSM Higgs: $H \rightarrow \tau \tau$

- Update from 1.0 fb$^{-1}$ to 1.8 fb$^{-1}$
- Excess is gone
- $\tan\beta$ excluded above ~40 around $m_A=140$ GeV/c$^2$

Update from 1.0 fb$^{-1}$ to 1.8 fb$^{-1}$

Excess is gone

$\tan\beta$ excluded above ~40 around $m_A=140$ GeV/c$^2$
Beyond SM Higgs: $h_f \rightarrow \gamma\gamma$

- **SM production**
  - **Gluon Fusion**
    - $\sigma \sim 1000 \text{ fb} \ (m_h = 120 \text{ GeV/c}^2)$
  - **Associated Production**
    - $\sigma \sim 225 \text{ fb}$
  - **Vector Boson Fusion**
    - $\sigma \sim 70 \text{ fb}$
Beyond SM Higgs: $h_f \rightarrow \gamma\gamma$

- Fermiophobic Production
- Gluon Fusion

Associated Production
$\sigma \sim 225 \text{ fb}$

Vector Boson Fusion
$\sigma \sim 70 \text{ fb}$

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Beyond SM Higgs: $h_f \rightarrow \gamma\gamma$

- SM decay

$$h \rightarrow bb$$

$$h \rightarrow \gamma\gamma$$

BR < 0.25%

3.0 fb$^{-1}$
Beyond SM Higgs: $h_f \rightarrow \gamma\gamma$

Fermiophobic decay

$h \rightarrow bb$
Suppressed by $m_b^2/m_W^2$

$h \rightarrow \gamma\gamma$
(Enhanced by $>100\times$)
Beyond SM Higgs: $h_f \rightarrow \gamma \gamma$

3.0 fb$^{-1}$

• Do we have sensitivity?
  - Not to the SM version (~20×SM with 4 fb$^{-1}$)
  - Use fermiophobic scenario as benchmark

• Selection:
  - Di-photon trigger and photon $E_T > 15$ GeV
  - Optimize for Associated Production, using expected limit
    \[ p_T(\gamma\gamma) > 75 \text{ GeV/c} \]
  - Keeps ~30% signal, rejects >99.5% bkg

- Background: SM $\gamma\gamma$ and QCD fakes
- Search for narrow peak on smooth bkg
- Background estimated from sidebands

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Beyond SM Higgs: $h_f \rightarrow \gamma \gamma$

- No significant narrow resonance seen in data
  - Fit used for expected sensitivity and for testing signal hypothesis

- Binned likelihood, to set limits
  
  $m_{h_f} > 106$ GeV/c$^2$ at 95\% C.L.
  - Strongest from hadron collider
  - LEP limit: $m > 109.7$ GeV/c$^2$
Beyond SM Higgs: Wrap up

(1) MSSM Higgs, using bbb channel
   - Initial excess has subsided
   - Look for update with 6-8 fb$^{-1}$

(2) MSSM Higgs, using $\tau\tau$ channel
   - Initial excess has subsided
   - Improvement coming: split into b-tagged and untagged samples, switch to multi-variate approach

(3) Fermiophobic Higgs, using $\gamma\gamma$ channel
    - Not sensitive to SM branching ratios, but interesting to prepare for LHC
    - Fermiophobic case (as beyond SM benchmark) gives good limits
CDF Global Searches

- Model-independent global searches for new high-$p_T$ physics
  
  (1) Vista: Examine population and kinematic features of high-$p_T$ data
  
  (2) Bump Hunter: Search for resonances in invariant mass combinations
  
  (3) Sleuth: Look for excesses at high sum-$p_T$
Global Search Overview

- **Capturing data**
  - Results use 2 fb$^{-1}$
  - Events come in on inclusive high-$p_T$ electron, muon, photon, and jet triggers

- **Object identification**
  - $e^\pm$, $\mu^\pm$, $\tau^\pm$, $\gamma$, $j$, $b$, $E_T$
  - $p_T > 17$ GeV/c

- **Selecting events**
  - Offline requirements such as $E_T(e) > 25$ GeV, $p_T(\mu) > 25$ GeV/c, or $E_T(\gamma) > 60$ GeV, etc.

- **Categorization**
  - ~4.3 million events partitioned into 399 exclusive final states
  - New categories created as needed
Global Search Strategy

- Use Monte Carlo event generators such as PYTHIA and MadEvent to mimic Standard Model
- Simulate CDF detector response using GEANT-based CDFSim
- Fit for 43 correction factors to improve SM prediction
  - Global fit to all final states, subject to external constraints
  - Leading order theory cross sections corrected
  - Object reconstruction efficiencies and mis-identification rates corrected
- Iterate until clear case for new physics or all discrepancies have known sources

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Population Results

- Summary of “Vista” final state population comparisons (data to SM bkg.)

<table>
<thead>
<tr>
<th>Final State</th>
<th>Data</th>
<th>Background</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\ell^{\pm}\ell^{\mp}$</td>
<td>690</td>
<td>817.7 ± 9.2</td>
<td>-4.3</td>
</tr>
<tr>
<td>$\gamma^{\pm\pm}$</td>
<td>1371</td>
<td>1217.6 ± 13.3</td>
<td>+4.0</td>
</tr>
<tr>
<td>$\mu^{\pm\mp}$</td>
<td>63</td>
<td>35.2 ± 2.8</td>
<td>+3.7</td>
</tr>
<tr>
<td>$b2j_{p}$ high-$\Sigma p_T$</td>
<td>255</td>
<td>327.2 ± 8.9</td>
<td>-3.7</td>
</tr>
<tr>
<td>$2j_T^{\pm}$ low-$\Sigma p_T$</td>
<td>574</td>
<td>670.3 ± 8.6</td>
<td>-3.6</td>
</tr>
<tr>
<td>$3j_T^{\pm}$ low-$\Sigma p_T$</td>
<td>148</td>
<td>199.8 ± 5.2</td>
<td>-3.5</td>
</tr>
<tr>
<td>$e^{\pm}\rho^{\mp}$</td>
<td>36</td>
<td>17.2 ± 1.7</td>
<td>+3.5</td>
</tr>
<tr>
<td>$2j_T^{\pm\mp}$</td>
<td>33</td>
<td>62.1 ± 4.3</td>
<td>-3.5</td>
</tr>
<tr>
<td>$e^{\pm}j$</td>
<td>741710</td>
<td>764832 ± 6447.2</td>
<td>-3.5</td>
</tr>
<tr>
<td>$j2\ell^{\pm}$</td>
<td>105</td>
<td>150.8 ± 6.3</td>
<td>-3.4</td>
</tr>
</tbody>
</table>

... plus 389 additional, less discrepant, population comparisons

- No population shows a significant discrepancy after accounting for the trials factor (e.g. $-4.3\sigma$ becomes $-2.7\sigma$)
Kinematic Distribution Results

- Summary of “Vista” kinematic shape comparisons (data to SM bkg.)
- Automatically produces and examines 19650 kinematic distributions

Example from 19095 shapes that agree:

- Inspect the 555 shapes with significant (>5σ) discrepancy more closely...
Shape Discrepancies

- Soft jet emission modeling problem
- No claims for new physics based on these
Bump Hunter

- Resonance might show up as bump in invariant mass

- **Strategy:**
  - Form all object mass combinations
  - Compare data to SM backgrounds
  - Use search window of $2\Delta M$ ($\Delta M$ = expected detector mass resolution)
  - Candidate bumps must have:
    - $\geq 5$ data events
    - Side-bands in better agreement than center
  - Use pseudo-experiments to estimate significance of bumps

Example, using $Z'$ events injected into a mix of pseudo-data based on SM backgrounds:

- **Simulated $Z'$ events**

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Bump Hunter Results

- 5036 mass distributions scanned → 2316 have qualifying bumps
- Shift caused by local deficiencies in the SM prediction
- “Discovery” threshold is $5\sigma$, corresponding to $3\sigma$ after trials factor for 5036 distributions

Probability for corresponding bump from pseudo-data to have larger significance than the one found in data

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The only significant bump
- 4 jets and low $\sum p_T$

But it's just due to the jet $\Delta R$
problem seen before

No new physics found by the bump hunter in 2 fb$^{-1}$
High $\Sigma \vec{p}_T$

• “Sleuth” makes three assumptions
  - New physics will show up as excess
  - Excess will be at high $\Sigma \vec{p}_T$
  - Excess will be in one final state

• Search variable
  
  $\Sigma \vec{p}_T \equiv \Sigma |\vec{p}_T| + |\text{unc}| + |\vec{p}_T|$

• For each final state
  - Scan the $\Sigma \vec{p}_T$ distribution
  - Select the one-sided region with most significant excess of data

• Perform pseudo-experiments to evaluate significance
  - $P = \text{fraction of pseudo-experiments that find region at least as discrepant in this final state}$
  - Then account for trials factor of looking at so many final states

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Aron Soha, UC Davis
Sleuth Results

Final state: $e^+ \mu^+ j j \slashed{p}_T$

Significance of region:
$P = 0.0021$ (2.86$\sigma$) before trials factor,
27% probable after trials factor

Significance of region:
$P = 0.00055$ (3.26$\sigma$) before trials factor,
8.5% probable after trials factor

SLAC Seminar, Nov. 2008

SLAC Seminar, Nov. 2008
Sleuth Summary

- Top 5 most discrepant high $\Sigma p_T$ tails:

<table>
<thead>
<tr>
<th>Sleuth Final State</th>
<th>$P$</th>
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<tbody>
<tr>
<td>$e^+ \mu^+$</td>
<td>0.00055</td>
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<tr>
<td>$e^+ \mu^+ j j p_T$</td>
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<td>$e^+ \mu^+ p_T$</td>
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<td>$\ell^+ \ell^- \ell' p_T$</td>
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<td>$\ell^+ \tau^+ p_T$</td>
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</table>

- Last step is to calculate what fraction of CDF-like experiments would find an excess at least as large as the top Sleuth final state:

  Answer = ~8%

- Therefore, no claim for discovery of new physics using Sleuth on 2 fb$^{-1}$

  (but there certainly can still be new physics in the CDF data)
Aside: Dedicated Same Sign Search

- 1 fb⁻¹ search found slight excess (not statistically significant)

\[ \int \mathcal{L} \, dt = 1.0 \text{ fb}^{-1} \]

**Loose selection:** 2 same sign leptons

Expect 33.7 ± 3.5, Observe 44 (7.6% probable)

**Tight selection:** 2 same sign leptons & Z region veto & \( E_T > 15 \text{ GeV} \)

Expect 7.9 ± 1.0, Observe 13 (6.1% probable)

- Now updating to 3 fb⁻¹

- If discrepancy just increases with stats, it becomes \( \sim 2.5\sigma \)  
  (plus gains in acceptance)
Global Search: Wrap up

- Find no indication of new physics in populations, kinematic distributions, invariant mass peaks, or high-$\Sigma p_T$

- Five final states with most discrepant high-$\Sigma p_T$ tails all have same sign leptons

- Provide broad view of high-$p_T$ data samples, and enhance understanding of detectors and standard model simulation

- Happily, they do not rule out new physics
The Discovery Watch has guided our attention to the following results:

I. Resonances
   1. Dielectron search, including two forward electrons
   2. Dielectron search, including ≥1 central electron
   3. Dimuon search

II. Higgs beyond the standard model
   1. MSSM Higgs, using bbb channel
   2. MSSM Higgs, using ττ channel
   3. Fermiophobic Higgs, using γγ channel

III. Global searches
   1. Vista (population and kinematics)
   2. Bump Hunter
   3. Sleuth (high sum-p_T)

List will evolve, with more than factor of two data left to analyze.
Conclusions II

- Run II luminosity projections

![Graph showing luminosity projections with key dates and values]

- More information
  
  http://www-cdf.fnal.gov/physics/exotics/exotic.html
Backup Slides →
Other CDF “Discoveries”

- Observation of $B_s$-mixing
  - $\Delta m_s = 17.77 \pm 0.10$ (stat) $\pm 0.07$ (sys)

- Observation of new baryon states
  - $\Sigma_b$ and $\Xi_b$

- WZ discovery ($6\sigma$)

- ZZ observation ($4.4\sigma$)

- Single top evidence
  - cross section = $2.2^{+0.7}_{-0.6}$ (stat+sys) pb
  - $|V_{tb}| = 0.88^{+0.13}_{-0.12}$ (stat+sys) $\pm 0.07$ (theory)
Vista Correction Factors

- 43 correction factors, with values and errors obtained from global fit
- Only applicable within the Vista correction model

<table>
<thead>
<tr>
<th>Code</th>
<th>Category</th>
<th>Explanation</th>
<th>Value</th>
<th>Error</th>
<th>Error(%)</th>
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<td>( b\bar{c}p )</td>
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<td>2.0</td>
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<td></td>
</tr>
<tr>
<td>( \gamma^* ) ( \rightarrow \eta ) ( \rightarrow \gamma \gamma ) ( \rightarrow \gamma \gamma \gamma ) ( \rightarrow 4\pi )</td>
<td>175</td>
<td>178.6 ± 16.2</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu^+ \mu^- ) ( \rightarrow \eta ) ( \rightarrow \gamma \gamma ) ( \rightarrow \gamma \gamma \gamma ) ( \rightarrow 4\pi )</td>
<td>5037</td>
<td>4968.8 ± 70</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma^* ) ( \rightarrow \eta )</td>
<td>23</td>
<td>28.9 ± 4.7</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu^+ \mu^- ) ( \rightarrow \eta )</td>
<td>82</td>
<td>82.0 ± 6.7</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma^* ) ( \rightarrow \eta )</td>
<td>67</td>
<td>58.6 ± 7.7</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu^+ \mu^- ) ( \rightarrow \eta )</td>
<td>468</td>
<td>513.7 ± 14.2</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma^* ) ( \rightarrow \eta )</td>
<td>128</td>
<td>107.0 ± 6.9</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu^+ \mu^- ) ( \rightarrow \eta )</td>
<td>5358</td>
<td>5502.8 ± 207.5</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma^* ) ( \rightarrow \eta )</td>
<td>190973</td>
<td>196842 ± 784.1</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu^+ \mu^- ) ( \rightarrow \eta )</td>
<td>165956</td>
<td>165330 ± 1581</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma^* ) ( \rightarrow \eta )</td>
<td>220</td>
<td>240.5 ± 3.2</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu^+ \mu^- ) ( \rightarrow \eta )</td>
<td>11</td>
<td>8 ± 2.4</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma^* ) ( \rightarrow \eta )</td>
<td>560</td>
<td>583 ± 15.7</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \mu^+ \mu^- ) ( \rightarrow \eta ) ( \rightarrow \gamma \gamma ) ( \rightarrow \gamma \gamma \gamma ) ( \rightarrow 4\pi )</td>
<td>96</td>
<td>114.6 ± 3.3</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The calculation of \( \epsilon \) accounts for the trials factor.
More Sleuth Results

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Final state: \( \ell^+ \ell^- \ell' \phi_T \)

- \( \ell = e \) or \( \mu \)
- \( \ell' = e \) or \( \mu \), but different from \( \ell \)

Significance of region:

- \( P = 0.0047 \) (2.6\( \sigma \)) before trials factor,
- 50% probable after trials factor

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Significance of region:

- \( P = 0.0042 \) (2.6\( \sigma \)) before trials factor,
- 46% probable after trials factor

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SLAC Seminar, Nov. 2008

Aron Soha, UC Davis