New Physics Searches at CDF

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For the CDF Collaboration
Motivation

- The **SM Higgs** is yet to be found
- Many hints (Naturalness Problem, neutrino oscillations, ...) that the standard model is incomplete
- New theories (SUSY, Technicolor, ...) predict new, heavy particles to appear at energies which may be now accessible at the Fermilab Tevatron

⇒ Search strategies:
1) Search specifically for a particle predicted by a major model
2) Do a signature-based search where no-one has looked before
**Outline**

- Introduction
- Signature-based searches in $\gamma\gamma + (E_T, \gamma, \mu, \text{or } e)$
- High-Mass searches:
  - Particles decaying into $Z + \text{jets}, Z' \rightarrow ee$
- Searches for heavy, long-lived particles:
  - Charged (CHAMPs) and neutral (GMSB neutralinos)
- SUSY searches in the golden mode:
  - combined result for gaugino final states
- Higgs Searches: MSSM Higgs $\rightarrow \tau\tau$, SM $h \rightarrow WW$
- Conclusion
CDF II at the Tevatron

Initial Luminosity: $\sim 250 \times 10^{30} \text{ cm}^2\text{s}^{-1}$

Most Results shown today:
1-1.2 fb$^{-1}$ up to Sep. 2006

Data recorded at CDF: $\sim 2 \text{ fb}^{-1}$
Signature-Based $\gamma\gamma+ (E_T, \gamma, \mu \text{ or } e)$

... $\tau$ and $b$ coming soon!

Lots of models: SUSY $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$, $\tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0$, Higgs $\rightarrow \gamma\gamma$, CDF $ee\gamma E_T$ candidate event

$E_T > 50$ GeV:

$1.6 \pm 0.3$ exp., 4 obs.

Lepton $E_T > 20$ GeV:

electrons: $6.82 \pm 0.75$ exp., 3 obs.

muons: $0.79 \pm 0.11$ exp., 0 obs.

$3^{rd}$ photon $E_T > 13$ GeV:

$2.2 \pm 0.6$ exp., 4 obs.
High-Mass Decays to $Z$+jets

Could be $b'$, Higgs, sparticles, ...

1. E-pair or $\mu$-pair consistent with the Z-mass
2. $\geq3$ additional jets with $E_T > 30$ GeV
   
   suppress SM $Z$+jets production
3. Parametrize the jet $E_T$-distributions of events with 1 or 2 jets and extrapolate to the blinded signal region at $\geq3$
4. Set limits using $b'$-models with $BR=100\%$:

   $m(b') > 270$ GeV

$\Sigma(jet \ E_T)$ (GeV)

$\sigma \times \left[ 1 - BR(b' \rightarrow bZ^0) \right]^2$ (pb)

$L = 1.1 \ fb^{-1}$

CDF Run II Preliminary, 1.1 fb$^{-1}$

- 95% CL limit
- LO calculation, with $BR(b' \rightarrow bZ^0) = 1$
High Mass $Z' \rightarrow ee$

Could be $Z'$, Randall-Sundrum Graviton...

- Require a high-$E_T$ central electron and a high-$E_T$ central or plug electron
- Blind signal region: $m_{ee} > 150$ GeV
- Scan the mass range in 1 GeV steps using the $Z'$ mass resonance width (10-45 GeV)

No stat. significant excess found $\Rightarrow$ set limits on SM and E6 $Z'$ and RS models

Spin 1

$m(Z') > 923$ GeV

Spin 2
Neutral, Long-Lived Particle Decays to Photons

GMSB $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ with ~nanosecond lifetime, Hidden Valley Models...

$E_T^\gamma > 30 \text{ GeV, } E_T > 30 \text{ GeV}$ and $\geq 1$ jet to reduce non-collision bkg

Use calorimeter timing to separate signal from SM photon background:
signal window $2 \text{ ns} < t^\gamma < 10 \text{ ns}$

$\setminus = 570 \text{ pb}^{-1}$

Set GMSB limits: $m(\tilde{\chi}_1^0) > 101 \text{ GeV}$ at 5 ns lifetime

Model-independent limit: 5.5 events

ALEPH limits

1.3±0.7 exp., 2 obs.
Charged, Massive Particles (CHAMPS)

Search for slow-moving, massive particles with mass > 100 GeV
- Can e.g. occur in SUSY, GMSB with long-lived $\tilde{\tau}$ or $\tilde{\tau}$...
- Look at high-$p_T$ muon or track
- Determine its mass from its velocity and its momentum

$\Rightarrow$ Model-independent limits $\sigma_{95} \cdot A_{\text{kin}} \cdot A_{\text{fid}}$
- strongly interacting CHAMPs: 48 fb
- weakly interacting CHAMPs: 10 fb

Model-dependent limits using SUSY $\tilde{\tau}$:

$L = 1.03 \text{ fb}^{-1}$

$1.5 \pm 0.2 \text{ exp.}, 1 \text{ obs.}$

with $m > 100$ GeV

$m(\tilde{t}) > 255$ GeV
SUSY Multilepton Searches

- mSUGRA is one of the most important SUSY models
- $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production is expected to be a golden mode at the Tevatron:

- Low $\sigma_{\text{prod}}$ (~0.1-0.4 pb), however backgrounds very small
- Perform 14 blind searches that require high $E_T$ and either 2 (like-sign) or 3 isolated leptons (e or $\mu$)
SUSY Multilepton: Combined Results

Largest excess in ee+track: 0.97±0.3 exp., 3 obs.
⇒ Limit-setting with mSUGRA-like MSSM without slepton mixing (same as D0)

M(\tilde{\chi}_1^\pm) > 130 \text{ GeV} obs. limit, sensitive to M(\tilde{\chi}_1^\pm) = 160 \text{ GeV} D0 limit (obs.)

Interesting event in the ee+track search:

- $E_T = 12 \text{ GeV}$, $\eta = -0.2$
- $E_T = 41 \text{ GeV}$, $\eta = 0.4$
- $E_T = 45 \text{ GeV}$

CDF Run II Preliminary: 700–1000 pb$^{-1}$

- $\sigma_{\text{NLO}} \times \text{BR}$
- $\sigma_{\text{NLO}} \times \text{BR}$ Uncertainty
- 95% CL Upper Limit: observed
- 95% CL Upper Limit: expected
- Expected Limit ± 2\sigma
- Expected Limit ± 1\sigma

MSSM: tan$\beta$=3, $\mu$>0, $M(\tilde{\chi}_2^0)$–$M(\tilde{\chi}_1^0)$–2$M(\tilde{\chi}_1^0)$; no slepton mixing

Excluded by LEP
MSSM Higgs $\rightarrow \tau^+\tau^-$

- Dominant production of h,H,A ($\equiv \phi$) at the Tevatron is gg-fusion
- $\phi \rightarrow \tau^+\tau^-$ has BR $\sim 10\%$ (low compared to $b\bar{b}$), but can reduce both $Z/\gamma$ and QCD background by selecting events with $\tau_h^{\tau_e/\mu}$ or $\tau_\tau^{\tau_e/\mu}$
- To have sensitivity to low mass $\phi$ don't reject the major $Z$ bkg.
- Binned likelihood fit to the visible combined $\tau$-mass and scan through Higgs masses

Set limits for MSSM scenarios:

Slight excess (<2$\sigma$) for $m_\phi = 160$ GeV in the $\tau_h^{\tau_e/\mu}$ channel

$\Rightarrow$ observed limits don't extend far
SM Higgs $h^0 \rightarrow WW^*$

- At the Tevatron $gg\rightarrow h^0$ ($\sigma_{\text{prod}} = 0.2$-$1\text{pb}$) dominates, $h^0\rightarrow WW^*$ is the dominant decay mode for $m_h \gtrsim 135$ GeV
- require one $l=e$ or $\mu$ from each leptonic $W$ decay
- Major background (30-70%): SM diboson ($WW$)

Leptons from resonant $WW$ production are correlated $\Rightarrow$ to discriminate signal from bkg use the azimuthal separation of the two leptons, for $m_h = 110 \ldots 200$ GeV

$m_h = 160$ GeV, $e$ and $\mu$ total

At $m=160$ GeV: $\sigma(\text{obs})=3.6\text{pb}$
Limit / SM rate $= 6.0 \ \text{exp, 9.2 obs}$
Lots of results from the recent new physics searches at CDF:

- Signature-based $\gamma\gamma + X$: broad search for exotic photon production
- Heavy objects:
  - Decays to $Z + \text{jets}$: world best mass limits using $b'$
  - High Mass $Z' \rightarrow \text{ee}$: world best mass limits on $Z'$ and RS models
- Charged, massive particles: $\tilde{t}$ mass limit at 255 GeV
- Neutral, long-lived particle-decays to photons: already world best mass-lifetime limits on GMSB $\tilde{\chi}_1^0$

SUSY in the “golden mode”:

- Trileptons combined: most sensitive channel for mSUGRA
- MSSM Higgs $\rightarrow \tau\tau$: slight excess at $\sim 160$ GeV $\rightarrow$ investigate!
- SM Higgs $h^0 \rightarrow WW^*$: sensitive to 4th gen. Higgs, only factor 6.0 away from the SM prediction, small excess

... stay tuned! We already doubled the data...
BACKUP
$B_s \rightarrow \mu \mu$

$B_{SM} = 3.4 \times 10^{-9}$

\[
B_l = B_{l}^{\text{SM}} + B_{l}^{\text{SUSY}} \approx \tan^6 \beta
\]

$M_{\tilde{g}} \sim 1400 \text{ GeV}/c^2$
\[ B_s \rightarrow \mu \mu \]
SUSY: Combined Results I

- Trilepton search results:

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>$ee(CEM) + \ell$</th>
<th>$ee(PLUG) + \ell$</th>
<th>$\mu\mu + \ell$ (high-$p_T$)</th>
<th>$ee + track$</th>
<th>$\mu\mu + \ell$ (low-$p_T$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_T^1, P_T^2, P_T^{3,\text{track}}$ (GeV/c)</td>
<td>1034 pb$^{-1}$</td>
<td>954 pb$^{-1}$</td>
<td>745 pb$^{-1}$</td>
<td>745 pb$^{-1}$</td>
<td>680 pb$^{-1}$</td>
</tr>
<tr>
<td>20,8,5</td>
<td>20,8,5</td>
<td>20,5,5</td>
<td>20,5,5</td>
<td>15,5,4</td>
<td>5,5,5</td>
</tr>
<tr>
<td>Expected number of SM background events</td>
<td>0.44± 0.08</td>
<td>0.34± 0.10</td>
<td>0.28± 0.09</td>
<td>0.64± 0.18</td>
<td>0.42± 0.08</td>
</tr>
<tr>
<td>Number of observed events</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

- LS-dilepton search results:

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>$ee$ LS</th>
<th>$e_{si}e$ LS</th>
<th>$e_{si}e_{si}$ LS</th>
<th>$e_{si}\mu$ LS</th>
<th>$e\mu$ LS</th>
<th>$\mu\mu$ LS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_T^{\ell 1}, P_T^{\ell 2}$ (GeV/c)</td>
<td>993 pb$^{-1}$</td>
<td>993 pb$^{-1}$</td>
<td>993 pb$^{-1}$</td>
<td>971 pb$^{-1}$</td>
<td>971 pb$^{-1}$</td>
<td>1087 pb$^{-1}$</td>
</tr>
<tr>
<td>20,10</td>
<td>20,10</td>
<td>20,10</td>
<td>20,10</td>
<td>20,10</td>
<td>20,10</td>
<td></td>
</tr>
<tr>
<td>Expected number of SM background events</td>
<td>0.10± 0.10</td>
<td>1.50± 0.30</td>
<td>1.30± 0.30</td>
<td>1.70± 0.20</td>
<td>2.30± 0.50</td>
<td>0.90± 0.10</td>
</tr>
<tr>
<td>Number of observed events</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Backgrounds: mainly Drell-Yan, W/Z$\gamma$, dibosons and fake leptons
SUSY: Combined Results

- Each accepted event can only occur in one analysis only.
- Both the requirement optimization in each analysis and the limit-setting are guided by the mSUGRA point:
  \[ M_0 = 100 \text{ GeV}, \ M_{1/2} = 180 \text{ GeV/c}, \ A_0 = 0, \ \tan(\beta) = 3, \ \mu > 0 \]

\[ \Rightarrow M(\chi_1^\pm) \approx M(\chi_2^0) \approx 113 \text{ GeV} \approx 2 \times M(\chi_1^0), \ M(\tilde{q}) \approx 400 \text{ GeV} \]

- Limit-setting with mSUGRA-like MSSM without slepton mixing (same as D0)

\[ M(\chi_1^\pm) > 130 \text{ GeV obs. limit}, \text{ sensitive to } M(\chi_1^\pm) \approx 160 \text{ GeV} \]

![Graph showing the limit on the mass of charginos](image)
**Technicolor: \( \rho_T \to \pi_T + W \)**

At the Tevatron: \( \sigma_{\text{prod}} \sim 1\,\text{3 pb} \)

1) require **exactly** 2 jets, separate into a single (neural network) and a double \( b \)-tag analysis

2) combine results for limit calculation

\( \not{E}_T > 25 \text{ GeV} \) reduces QCD events with fake leptons

**Method:** Look for peaks in dijet and \( Q=m(W+2\text{jet})-m(\text{dijet})-m(W) \) distributions

Fit simultaneously with a 2D binned likelihood

→ Cross section limits at \( \sim 3\,-4\pi \) pb

At \( m(\pi_T)=105 \text{ GeV} \), \( m(\rho_T)=210 \text{ GeV} \): excess with p-value 2.6%!

**BUT:** it's mostly from single \( b \)-tag data

**Plan:** more data, optimize event selection...
SM Higgs $h^0 \rightarrow WW^*$

Tevatron Run II Preliminary

95% CL Limit/SM

$10^3$
$10^2$
$10^1$
$10$
$1$

$110 \rightarrow 190$

$m_H$ (GeV)

CDF+D0 Combined

July 26, 2006

21 P. Wagner
Lake Louise Winter Institute 2007
02/20/07
SM Higgs $h^0 \rightarrow WW^*$
Dielectron Search

Probability of the Background Fluctuating to $N_{obs}$

CDF Run II Preliminary

Expected Range for Min. Obs. Prob.

3 $\sigma$ evidence level

$\int L\,dt = 1.3$ fb$^{-1}$
Dielectron Search

RS Graviton 95% Confidence Limits

CDF Run II Preliminary $\int L dt = 1.1 - 1.3 \text{ fb}^{-1}$

$k/M_{pl} = 0.1$
$k/M_{pl} = 0.07$
$k/M_{pl} = 0.05$
$k/M_{pl} = 0.025$

$\sigma . Br(G \rightarrow l^+ l^-)$ (pb)

obs. $e^+ e^-$ limits
expected $e^+ e^-$ limits
obs. $\gamma \gamma$ limits
expected $\gamma \gamma$ limits
obs. $\gamma \gamma + e^+ e^-$ limits
expected $\gamma \gamma + e^+ e^-$ limits
LO $\sigma . Br \times 1.3$

$M_G$ (GeV/c$^2$)