Search for gluinos and squarks with Missing Energy plus multijets
CDF (Run Ib) data

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Missing Energy provides the classic R-parity conserving SUSY signature \((R=(-1)^{3B+L+2S})\) but appears in many other phenomenological paradigms

**MET + 3 jets (squarks, gluinos)**, **MET + c-tagged jets (scalar top)**

**MET + b-tagged jets (scalar bottom, Higgs)**, **MET + monojet (gravitino, graviton)**, **MET + photons (gravitino)**
INSTRUMENTAL SOURCES OF MISSING ENERGY

MAIN RING

DETECTOR MALFUNCTIONS/NOISE

COSMICS

These are eliminated with a set of timing and good jet quality requirements.

FNAL W&C
Jets

Jet variables used for “good jetiness” criterion:

* Charge Fraction (CHF)
* EM fraction (EMF)
DATA PRE-SELECTION
## DATA PRE-SELECTION

<table>
<thead>
<tr>
<th>of 2517998 events</th>
<th>Number of events fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathbb{E}_T$</td>
<td>1123734</td>
</tr>
<tr>
<td>Out-Time</td>
<td>506241</td>
</tr>
<tr>
<td>Stage 1 = $\mathbb{E}_T \oplus$ Out-Time</td>
<td>1625603</td>
</tr>
<tr>
<td>Total passing Stage 1</td>
<td>892395</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>of 892394 events</th>
<th>Number of Events Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 central jet</td>
<td>372978</td>
</tr>
<tr>
<td>EEMF</td>
<td>24992</td>
</tr>
<tr>
<td>ECHF</td>
<td>591449</td>
</tr>
<tr>
<td>Total passing Stage 2</td>
<td>300945</td>
</tr>
</tbody>
</table>
MISSING ENERGY + MULTIJET
STANDARD MODEL COMPONENT

\[ Z(\rightarrow \ell\ell) + \text{jets} \]
\[ W(\rightarrow \ell\nu) + \text{jets} \]
\[ t\bar{t}, \text{single top} \]
\[ \text{Di boson} \]
\[ \text{QCD multijet} \]

Note: The missing energy is a QCD sample
Solves the “hierarchy problem”

Apparently Unifies the three gauge couplings

\[ R = (-1)^{3(B-L)+2S} +1 \text{ (SM particles)} -1 \text{ SUSY particles} \]

If R-parity is conserved
- sparticles are produced in pairs and eventually decay to the
  Lightest
  SUSY Particle (LSP)
- the LSP is stable and weakly interacting
  > missing energy signature

LSP is a good candidate for dark matter
<table>
<thead>
<tr>
<th>Name</th>
<th>Spin</th>
<th>$R$</th>
<th>Mass Eigenstates</th>
<th>Gauge Eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>$h^0$ $H^0$ $A^0$ $H^\pm$</td>
<td>$H_u^0$ $H_d^0$ $H_u^+$ $H_d^-$</td>
</tr>
<tr>
<td>squarks</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$</td>
<td>$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{s}_L$ $\tilde{s}_R$ $\tilde{c}_L$ $\tilde{c}_R$</td>
<td>$\tilde{s}_L$ $\tilde{s}_R$ $\tilde{c}_L$ $\tilde{c}_R$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{t}_1$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{b}_2$</td>
<td>$\tilde{t}_L$ $\tilde{t}_R$ $\tilde{b}_L$ $\tilde{b}_R$</td>
</tr>
<tr>
<td>sleptons</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$</td>
<td>$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{\mu}_L$ $\tilde{\mu}<em>R$ $\tilde{\nu}</em>\mu$</td>
<td>$\tilde{\mu}_L$ $\tilde{\mu}<em>R$ $\tilde{\nu}</em>\mu$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{\tau}_1$ $\tilde{\tau}<em>2$ $\tilde{\nu}</em>\tau$</td>
<td>$\tilde{\tau}_L$ $\tilde{\tau}<em>R$ $\tilde{\nu}</em>\tau$</td>
</tr>
<tr>
<td>neutralinos</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$</td>
<td>$\tilde{B}^0$ $\tilde{W}^0$ $\tilde{H}_u^0$ $\tilde{H}_d^0$</td>
</tr>
<tr>
<td>charginos</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{\chi}_1^\pm$ $\tilde{\chi}_2^\pm$ $\tilde{\chi}_3^\pm$</td>
<td>$\tilde{W}^\pm$ $\tilde{H}_u^+$ $\tilde{H}_d^-$</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{g}$</td>
<td>$\tilde{g}$</td>
</tr>
<tr>
<td>gravitino/goldstino</td>
<td>3/2</td>
<td>-1</td>
<td>$\tilde{G}$</td>
<td>$\tilde{G}$</td>
</tr>
</tbody>
</table>
The Super-Models

MSSM

- $m_{\tilde{g}}$: gluino mass
- $\mu$: Higgs mass parameter
- $\tan \beta = \frac{v_2}{v_1}$
- $A$: mass of CP-odd Higgs
- $m_{\tilde{t}}, m_{\tilde{q}}$: slepton and squark masses
- $A_{\tilde{t}}, A_{\tilde{q}}$: trilinear couplings

mSUGRA

- $M_{1/2}$: unified gaugino masses
- $M_0$: unified scalar masses
- $\tan \beta = \frac{v_2}{v_1}$
- $A_0$: unified trilinear couplings
- sign $\mu$
Present Results

FNAL W&C
mSUGRA DØ result

\[ \tan \beta = 2 \]

\[ m_{\text{gluino}} = 300 \text{ GeV/c}^2 \]

\[ m_{\text{squark}} = 250 \text{ GeV/c}^2 \]
Production/Decay Graphs

Production of squarks and gluinos

Decay of gluino to jets

Decay of gluinos to leptons
ANALYSIS DRIVING VARIABLES

The Missing Transverse Energy \( E_T \)

The Number of Jets \( N_{\text{Jet}} \)

\[ E_T(2^{nd\text{jet}}) + E_T(3^{rd\text{jet}}) + E_T \]

The Number of isolated tracks \( N_{\text{iso trk}} \)

FNAL W&C
"The BOX"

(3) \(H_T\) (70,150)

(8) The Blind Box

(6) \(E_T\)

(5) \(H_T\) (70,150)

(1) \(E_T\)

(2) \(N_{\text{tik}}^{\text{iso}=0}\)

(7) \(N_{\text{tik}}^{\text{iso}>0}\)
For this analysis the $Z/W + N$ jet predictions are normalized to the Zee+jets CDF data using:

$$R = \frac{N}{N+1}^{\text{DATA}}$$

(normalize the 3 jet predictions using the 2 jet data)

$$R' = \frac{W^{\text{MC}}}{Z}$$

(normalize the $W$ predictions using the $Z$ data)
Ratios in the normalization:

\[ \frac{Ld \sigma}{dN_{\text{jet}}} \]

CDF \( Z(\rightarrow \text{ee}) + \text{Jets} \quad L_{\text{int}} = 87 \text{ pb}^{-1}, \quad \sqrt{s} = 1.8 \text{ TeV} \)

jet cone 0.7, \( E_\text{t(thres)} = 15 \text{ GeV} \)
\[ N(N+1)^{-1} = 4.93 \pm 0.31 \]
Ratios in the normalization: $\frac{W}{Z}$

CDF PRELIMINARY

Inclusive selected $W(\rightarrow e\nu) + \geq 2j$ over $Z(\rightarrow ee) + \geq 2j$

Raw Ratio $\frac{W}{Z}$: $\frac{MC^*}{Data} = 7.0 \pm 0.23$

$\frac{W}{Z}$ = 6.4 ± 0.4

*VECEOS+HERWIG+CDF DETECTORS SIMULATION, MRS GD1, $D^2 = <P_T>^2 + M^2$
Lepton Universality

CDF Lepton Universality $|Ldt| = 87 \text{ pb}^{-1} \sqrt{s} = 1.8 \text{ TeV}$

CDF PRELIMINARY

$w(v \rightarrow e v) + \frac{\pm 2i}{w(\rightarrow \mu v) + \pm 2i}$

Jet multiplicity, Njet

- □ raw ratio
- ▼ with acceptance x efficiency folded
$Z^+ \geq N_{jets}$ ($N=2, 3$)

SHAPES
$Z^+ \geq N \text{ jets} \ (N=2, 3)$

**SHAPES**
MC samples Luminosity norm using theoretical cross sections

\[ \sigma_{\bar{t}\bar{t}} = 5.06 \text{ pb } \pm 18\% \]
\[ \sigma_{Wg} = 1.7 \text{ pb } \pm 17\% \]
\[ \sigma_{W \to t\bar{b}} = 0.73 \text{ pb } \pm 9\% \]
\[ \sigma_{WW} = 9.5 \text{ pb } \pm 7\% \]
\[ \sigma_{WZ} = 2.6 \text{ pb } \pm 12\% \]
\[ \sigma_{ZZ} = 1.0 \text{ pb } \pm 20\% \]
Simulate 3-jet events for a very low threshold trigger (JET20) and a higher threshold trigger (JET50).

NO Missing Energy required - use the whole Missing Energy spectrum.

Fold in the trigger efficiencies measured in the data.

Merge samples and compare kinematic lineshapes between data and QCD predictions.

Measure the prescale factors and Luminosity of the JET data samples used.
CDF QCD Shapes $\sqrt{s}=1.8$ TeV

CDF PRELIMINARY

- QCD MC*, 2-to-2, N≥3j
- $\nabla$ JET20+JET50 DATA N≥3j

jLdt(JET20)=0.09 pb$^{-1}$, jLdt(JET50)=2.4 pb$^{-1}$
pre-scale(JET20)=1000, pre-scale(JET50)=40

* HERWIG, MRSG, normalized to data
CDF QCD Shapes $\sqrt{s}=1.8$ TeV

CDF PRELIMINARY

- QCD MC*, 2-to-2, $N \geq 3j$
- JET20 + JET50 DATA $N \geq 3j$

$\int L dt(\text{JET20}) = 0.09 \text{ pb}^{-1}$, $\int L dt(\text{JET50}) = 2.4 \text{ pb}^{-1}$

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CDF QCD Shapes $\sqrt{s}=1.8$ TeV

CDF PRELIMINARY

- QCD MC, 2-to-2, N≥3
- HEPET20+JET50 DATA

$|L dt(JET20)|=0.09 \text{ pb}^{-1}$, $|L dt(JET50)|=2.4 \text{ pb}^{-1}$
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CDF QCD Shapes $\sqrt{s}=1.8$ TeV

CDF PRELIMINARY

- QCD MC*, 2-to-2, N≥3j
- ▼ JET20+JET50 DATA

$|\Delta t(JET20)|=0.09$ pb$^{-1}$, $|\Delta t(JET50)|=2.4$ pb$^{-1}$

prescale(JET20)=1000, prescale(JET50)=40

*HERWIG, MRSG, normalized to data
Missing Energy from QCD mismeasurements

FNAL W&C
Missing Energy from QCD mismeasurements
Missing Energy from QCD mismeasurements

HERWIG(2-to-2)+CDF DETECTOR SIMULATION N≥ 3 Jets
JET FIDUCIALITY

If the $\eta_\text{jet}$ of the second jet is consistent with one of the gaps AND its $\phi$ is 0.5 radians or closer to the $\phi$ of the $E_T$, then the event is vetoed.
## Analysis Path

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Number of Events passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Selection and Bad Run veto</td>
<td>286728, (I)</td>
</tr>
<tr>
<td>$N_{jet} \geq 3$ (cone .7,$ E_T \geq 15$ GeV)</td>
<td>107509, (II)</td>
</tr>
<tr>
<td>Fiduciality</td>
<td></td>
</tr>
<tr>
<td>fiducial 2nd, 3rd jet</td>
<td>57011</td>
</tr>
<tr>
<td>2-D $\delta \phi$</td>
<td>23381</td>
</tr>
<tr>
<td>BOX data removed</td>
<td></td>
</tr>
<tr>
<td>$E_T(1) \geq 70$ GeV</td>
<td></td>
</tr>
<tr>
<td>$E_T(2) \geq 30$ GeV</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>EMF(1), EMF(2) $\leq 0.9$</td>
<td>6013</td>
</tr>
<tr>
<td>L2 trigger</td>
<td>4679</td>
</tr>
<tr>
<td>$\delta \phi_{min} \geq 0.3$</td>
<td>2737</td>
</tr>
</tbody>
</table>
CDF PRELIMINARY
\(|L=84 \text{ pb}^{-1} \cdot |s=1.8 \text{ TeV}\)

Data Selection

FNAL W&C
## Comparisons SM predictions—Data around the Blind Box

<table>
<thead>
<tr>
<th>Description</th>
<th>EWK</th>
<th>QCD</th>
<th>All</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T \geq 70, H_T &gt; 150, N_{trk}^{iso} &gt; 0$</td>
<td>13.9</td>
<td>6.26</td>
<td>20.2±4.7</td>
<td>10</td>
</tr>
<tr>
<td>$E_T \geq 70, H_T &lt; 150, N_{trk}^{iso} = 0$</td>
<td>2.3</td>
<td>6.26</td>
<td>8.6±4.5</td>
<td>12</td>
</tr>
<tr>
<td>$35 &lt; E_T &lt; 70, H_T &gt; 150, N_{trk}^{iso} = 0$</td>
<td>1.95</td>
<td>134.6</td>
<td>136.5±27.8</td>
<td>134</td>
</tr>
<tr>
<td>$E_T &gt; 70, H_T &lt; 150, N_{trk}^{iso} &gt; 0$</td>
<td>1.73</td>
<td>0</td>
<td>1.73±0.3</td>
<td>2</td>
</tr>
<tr>
<td>$35 &lt; E_T &lt; 70, H_T &gt; 150, N_{trk}^{iso} &gt; 0$</td>
<td>13.95</td>
<td>9.39</td>
<td>23.34±5.7</td>
<td>24</td>
</tr>
<tr>
<td>$35 &lt; E_T &lt; 70, H_T &lt; 150, N_{trk}^{iso} = 0$</td>
<td>4.9</td>
<td>413.16</td>
<td>418.1±68.8</td>
<td>410</td>
</tr>
<tr>
<td>$35 &lt; E_T &lt; 70, H_T &lt; 150, N_{trk}^{iso} &gt; 0$</td>
<td>3.3</td>
<td>28.17</td>
<td>31.4±10.2</td>
<td>35</td>
</tr>
<tr>
<td>$E_T &gt; 70, H_T &gt; 150, N_{trk}^{iso} = 0$</td>
<td>35.3</td>
<td>40.69</td>
<td>76.02±12.8</td>
<td>?</td>
</tr>
<tr>
<td>$35 &lt; E_T &lt; 70, H_T &lt; 150$</td>
<td>8.2</td>
<td>441.3</td>
<td>449.5±72</td>
<td>445</td>
</tr>
</tbody>
</table>
Comparisons SM predictions—Data around the Blind Box

CDF PRELIMINARY $\int L = 84$ pb$^{-1}$ $\sqrt{s} = 1.8$ TeV

- EWK (W/Z/t/diboson/single t)
- + QCD
- Uncertainty
- Data

Summary of predictions and data around the Blind Box

Events/bin

BIN NUMBER

1 2 3 4 5 6 7 8 9
SHAPES AROUND THE BOX (examples)
CDF PRELIMINARY $\sqrt{s} = 1.8$ TeV

Bin9. SM Prediction = 450, Data = 445

Events/(5 GeV)

Events/bin

Events/(8 GeV)

Events/(20 GeV)

$E_T$ Leading jet (GeV)

$H_T$ (GeV)
OPTIMIZATION IN SUSY SPACE

<table>
<thead>
<tr>
<th>Regions</th>
<th>$E_T, H_T$(GeV)</th>
<th>Standard Model prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/D</td>
<td>90,160</td>
<td>32.7±6.7</td>
</tr>
<tr>
<td>B</td>
<td>110,230</td>
<td>3.7±.5</td>
</tr>
<tr>
<td>C</td>
<td>110,170</td>
<td>10.6±1</td>
</tr>
</tbody>
</table>
"The BOX"

The Box: SM Expected 76(13)

FNAL W&C
"The BOX"

The Box: SM Expected 76(13)

Found in data 74
“The BOX”

CDF PRELIMINARY $\sqrt{s}=1.8$ TeV

BOX. SM Prediction=76, Data=74
“The other BOXes”

A/D SUSY boxes:
SM Expected 33(7)
“The other BOXes”

A/D SUSY boxes:
SM Expected 33(7)

Found in data
31
"The other BOXes"
“The other BOXes”

SUSY box B
SM Expected 3.7(0.5)
"The other BOXes"

SUSY box B
SM Expected 3.7(0.5)

Found in data
5
"The other BOXes"
“The other BOXes”

SUSY box C:
SM Expected 10.6(1)
“The other BOXes”

SUSY box C: SM Expected 10.6(1)

Found in data 14
“The other BOXes”

CDF PRELIMINARY $\sqrt{s}=1.8$ TeV
SUSY-C. SM Prediction=10.6, Data=14
<table>
<thead>
<tr>
<th>Box</th>
<th>MET,HT</th>
<th>Expected</th>
<th>Observed</th>
<th>$N_{95%C.L.}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>90,160</td>
<td>32.7 ± 6.7</td>
<td>31</td>
<td>17.7</td>
</tr>
<tr>
<td>B</td>
<td>110,230</td>
<td>3.7 ± 0.5</td>
<td>5</td>
<td>7.4</td>
</tr>
<tr>
<td>C</td>
<td>110,170</td>
<td>10.6 ± 1</td>
<td>14</td>
<td>11.9</td>
</tr>
<tr>
<td>D</td>
<td>90,160</td>
<td>32.7 ± 6.7</td>
<td>31</td>
<td>17.3</td>
</tr>
</tbody>
</table>
Overall Relative Uncertainty on Signal Acceptance

<table>
<thead>
<tr>
<th>ind</th>
<th>a16</th>
<th>a14</th>
<th>b13</th>
<th>b4</th>
<th>d18</th>
<th>d6</th>
</tr>
</thead>
<tbody>
<tr>
<td>% &lt;PDF8&gt;</td>
<td>6.5</td>
<td>3.5</td>
<td>5.5</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>% max(Radiation)</td>
<td>12.5</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>% max(Q^2)</td>
<td>6.5</td>
<td>6.5</td>
<td>5.5</td>
<td>5.5</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>% &lt;JET&gt;</td>
<td>4.5</td>
<td>3.5</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>% Trigger</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% MC stat.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;0.2</td>
<td></td>
</tr>
</tbody>
</table>
The limit in the squark-gluino mass plane

\[ \tilde{q} = \tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, b \]

\[ \mu < 0 \]

\[ m_{\text{SUGRA}} \]

CDF PRELIMINARY

\[ |Ldt=84 \text{ pb}^{-1} \ \sqrt{s}=1.8 \text{ TeV} \]

ISAJET 7.37 + PROSPINO

\[ \tan \beta = 3 \]

95% C.L.

\[ \tilde{q} = \tilde{u}, \tilde{d}, \tilde{s}, \tilde{c} \]

\[ \mu = 800 \text{ GeV/c}^2 \]

MSSM

CDF 84 pb^{-1}

CDF 19 pb^{-1}

CDF 4.3 pb^{-1}

UA1

UA2

LEP II

LEP I

\[ m_{\tilde{q}} < m_{\chi_1^0} \]
mSUGRA $E_T$+Jets Searches

CDF PRELIMINARY

$\sqrt{s}=1.8$ TeV
$q,g$ only, $\tan\beta=3$, $\mu<0$
ISAJET 7.37 + PROSPINO
q=u,d,s,c,b
95% C.L.
For $m_q \approx m_g$, $m < 300 \ \text{GeV}/c^2$

For $m_q \ll m_g$, $m_g < 570 \ \text{GeV}/c^2$

For $m_q \gg m_g$, $m_g < 195 \ \text{GeV}/c^2$
If the sparticles are too heavy then SUSY requires fine tuning and the hierarchy problem reappears. How much fine tuning is tolerable determines how probable low energy supersymmetry is and how soon it will be discovered.

It has been recently pointed out (Bastero-Gil et al./ Dimopoulos et al.) that the electroweak scale looks more natural if $M_3$ is relatively small.
The required cancellation is easier if the gluino mass is not so big.

\[ M_Z^2 = -1.7\mu^2 + 7.2M_3^2 - 0.24M_2^2 + 0.014M_1^2 + \ldots \]

\[ M_3 \geq 300 \rightarrow \frac{7.2M_3^2}{M_Z^2} \geq 80 \]

With gaugino mass unification \( M_1:M_2:M_3::0.5:1:3.3 \)

The result of this analysis as well as the LEP result on the chargino \( M_2 < 90 \text{ GeV} \) make it interesting to drop gaugino unification and allow lower gluino mass.
If low energy supersymmetry exists and given that the amount of fine tuning depends critically on the gluino mass, this result indicates that RUNII and the missing energy + jets channel (with lepton veto) constitute a very good probe and have discovery potential.

Phenomenological Implications/Discussion
Candidate Event