The Search for Supersymmetry at CDF

David Toback
Texas A&M University
For the CDF collaboration
Why Search for Supersymmetry?

There are some theories that are so compelling that it's worth doing a comprehensive and systematically deep set of searches to see if they are realized in nature.

→ Supersymmetry is such a theory

First things First: What is Supersymmetry and why do we care?
A Quirky Introduction

Typical Introduction:
1. Lay out the theoretical issues
2. Describe how the introduction of SUSY particles solves the problems
3. Touch on other problems that SUSY can solve

My introduction:
• Just touch on the important theoretical issues, focus instead on the “other” experimental results that constrain which versions of SUSY we look for
• The rest of the talk is how we will search for SUSY at the Tevatron
What is Supersymmetry?

Supersymmetry (SUSY) is a theory that postulates a symmetry between fermions and bosons:

\[ Q|\text{Boson}\rangle = |\text{Fermion}\rangle \]
\[ Q|\text{Fermion}\rangle = |\text{Boson}\rangle \]

Minimal Supersymmetric Standard Model (MSSM)

Standard particles

Quarks → Squarks

Gauge Bosons → Gauginos

Leptons → Sleepers

The gaugino states mix → Refer to them as Charginos and Neutralinos
The hierarchy problem and how SUSY helps

Corrections to Higgs boson mass not only finite, but in fact divergent

$$\delta m_{H_1}^2 \approx \Lambda^2 \gg m_{H_1}^2$$

Fermion and Boson contributions to the Higgs cancel nearly exactly in supersymmetry (finite)

$$\delta m_{H_1}^2 \approx O(\frac{\alpha}{\pi}) \times (m_B^2 - m_F^2)$$

The one loop divergences will cancel, provided that the SUSY particles have masses below the Fermi scale

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SUSY and the Coupling Constants

Another issue is that adding extra particles provide a “natural” way for the running of the coupling constants to unify at the GUT Scale.

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Advantages and Disadvantages of SUSY

• There is no unique explanation of the origin of the sparticle masses or couplings
• With all these new couplings and particles it’s possible we could have our known SM particles decaying through loops
  - Any version that predicts/allows a quick proton decay is clearly wrong
  - Any version that has the same mass for the particles and the sparticles must be wrong
    - $m_{\text{positron}} = m_{\text{electron}} \neq m_{\text{selectron}}$

Haven’t observed any bosonic electrons in nature
  → SUSY is broken somehow
Different Ways to Proceed

- There is no unique explanation of the symmetry breaking → need to make some assumptions
- Can put in masses and couplings by hand
  - General SUSY has over 100 new parameters
- Use experimental constraints and theoretical prejudices to further restrict the parameter space
  - To protect the proton lifetime can define R-parity = \((-1)^{3(B-L)+2s}\) and assert that it's conserved
    → R = 1 for SM particles
    → R = -1 for MSSM partners
- R-Parity violating terms would also have to be small for lepton number violation and still allow neutrino mixing
SUSY can provide a Dark Matter Candidate

If R-Parity is conserved
then the lightest SUSY
Particle can’t decay and,
if neutral

Provides an excellent
dark matter candidate

Worth saying a few
words on why we
believe in Dark
Matter and it’s impact
on cosmology

• Rotations of
galaxies
• Bullet galaxies
• Others…

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Astronomy: Galaxy Rotation

Simulation without Dark Matter

Simulation with lots of Dark Matter particles in the galaxy

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Dark Matter?

Data well explained by lots of "Dark Matter" we can't see

Mostly clumped at the center due to gravity

Lots of it in a "halo" around the entire galaxy

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Evidence for Dark Matter From Colliding Galaxies

Blue is the Dark Matter

Red is the baryonic matter (Stars and Hydrogen gas)

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Particle Physics solution to an Astronomy problem?

- **Good:** Predict massive stable particles that can collect in the galaxy and have an impact on the way it rotates.
- **Better:** Provide both a model of particle physics and cosmology that gets the Early Universe Physics correct and correctly predicts the Dark Matter Relic Density.
Entering the Era of Precision Cosmology

WMAP data currently measures the Dark Matter density to be $0.94 < \Omega_{DM} h^2 < 1.29$. 

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Dark Matter = Supersymmetric Particles?

Supersymmetric Particles?

SUSY provides a full calculation of $\Omega_{\text{SUSY DM}}$

Not good enough to simply provide a candidate, need to describe early Universe physics and correctly predict the Dark Matter relic density
Cosmology and Particle Physics?

**Minimal Solution with Cold Dark Matter**
- Minimal Solution \(\rightarrow\) A particle produced in the early Universe is stable and weakly interacting \(\rightarrow\) still here today
- CDM favored by most Cosmological models
- Lots of Supersymmetry models have a lightest particle that fits this description
- The minimal SUSY model that incorporates supergravity grand unification is known as mSUGRA \(\rightarrow\) our baseline Cold Dark Matter search model

**Non-Minimal Solution with Cold Dark Matter**
- Many non-Minimal solutions to the Dark Matter we observe today
- Example: Long-lived Charged particles (CHAMPS) that decay to the Dark Matter

**Example:** CHAMP

\[ \tilde{\tau} \rightarrow \tau \tilde{\chi} \]

Stable on the timescale of inflation

Stable on the timescale of the Universe

**Non-Minimal Solution with Warm Dark Matter**
- Warm Dark Matter also consistent with Astronomical data and inflation models
- Example: Gauge Mediated SUSY with Dark Matter is more complicated or has nothing to do with SUSY
  - Axions?
  - Look for the most general models including R-Parity violating scenarios
Outline of the Searches

- The Tevatron and the CDF Detector
- mSUGRA Searches
  - Squarks & Gluinos
  - Gaugino Pair Production
  - Indirect Searches
- Gauge Mediated Searches
- Other models
  - CHAMPS
  - R-Parity Violation
- Conclusions

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The Fermilab Tevatron

Protons and anti-protons collide with $\sqrt{s} = 1.96\text{TeV}$

• The Tevatron is the high Energy Frontier until LHC turn-on

• Rumours of running until 2012 to be complementary to LHC

Data coming in very nicely and getting better all the time

Delivered: $\sim 4.5 \text{ fb}^{-1}$
Acquired: $\sim 3.7 \text{ fb}^{-1}$
Analyzed: $\sim 3.0 \text{ fb}^{-1}$
(depending on the analysis)

CDF
DØ
Main Injector & Recycler

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The CDF Detector

Muon chambers
Central HAD Calorimeter
Central EM Calorimeter
Central Outer Tracker
Silicon Tracker

Powerful multi-purpose detector
High quality identification for electrons, muons, taus, jets, Missing Energy, photons, b's etc.

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Aside before we begin...

Most analyses will look like they were easy

Noto Bene: It’s 2008 and we’re 7 years into running

This is a lot harder than it looks and it takes a lot longer than it should

I’ll try to comment periodically on lessons for LHC

“It’s a lot of work to make it look this easy”

- Joe DiMaggio

“Yogi Berra”

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mSUGRA

Minimal Supergravity: breaking is mediated by the gravity sector
At the unification scale:
- scalars have mass $m_0$
- gauginos have mass $m_{1/2}$

mSUGRA or Constrained MSSM used as benchmark

5 free parameters (at $M_{GUT}$) determine the sparticle masses
- $m_0$: common scalar mass at $M_{GUT}$
- $m_{1/2}$: common gaugino mass at $M_{GUT}$
- $\tan\beta$: Ratio of the Higgs VEV
- $A_0$: common trilinear coupling at $M_{GUT}$
- $\text{sign}(\mu)$: $\mu$ is the Higgsino mass parameter

We'll come back to this one
The Sparticle Masses

In a typical mSUGRA scenario

- Squarks and gluinos are heavy
- 1st and 2nd generation squarks are mass degenerate
- The lightest neutralino is the LSP
  - Dark Matter candidate

For large values of \( \tan \beta \) Stop, Sbottom and Stau can get much lighter

\[ \rightarrow \] Can also have a significant effect on the branching ratios

Need complementary searches for low \( \tan \beta \) and high \( \tan \beta \)
Golden Search Channels

Three main ways to look for minimal models with Cold Dark Matter Models (mSUGRA-type models)

• Direct production of Squarks and Gluinos
  - Heavy, but strong production cross sections

• Direct production of the Gauginos
  - Lighter, but EWK production cross sections, also leptonic final states have smaller backgrounds

• Indirect search via sparticles in loops
  - Affect branching ratios

Start with low tan\(\beta\), then move to searches with high tan\(\beta\)
Squark and Gluino Searches in Multijet + Met

Three main production diagrams

Final states are mass dependent

$M_{	ilde{g}} \gg M_{\tilde{q}}$

$M_{\tilde{g}} \sim M_{\tilde{q}}$

$M_{\tilde{g}} \ll M_{\tilde{q}}$

2 jets + MET

3 jets + MET

4 jets + MET

3 separate final states + Unified Analysis \(\rightarrow\) best coverage

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Start from difficult backgrounds

Note: Despite the huge production cross sections only about 25% of the final background is QCD.
The rest is ttbar and other EWK processes.

<table>
<thead>
<tr>
<th>Selections</th>
<th>2 jets</th>
<th>3 jets</th>
<th>4 jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>H_{T}&gt;330, E_{T}&gt;180 GeV/c²</td>
<td>H_{T}&gt;330, E_{T}&gt;120 GeV/c²</td>
<td>H_{T}&gt;280, E_{T}&gt;90 GeV/c²</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>18</td>
<td>38</td>
<td>45</td>
</tr>
<tr>
<td>Expected SM</td>
<td>16±5</td>
<td>37±12</td>
<td>48±17</td>
</tr>
</tbody>
</table>
Unified Squark/Gluino Search

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More limits...

You see Hobbs, I can Transmogrify the cross section results into limits on the Sparticle Masses and mSUGRA parameter space.

$M_g < 280$ GeV always excluded

$M > 392$ GeV when $M_g = M_q$

Limit improved beyond LEP in the region

$75 < M_0 < 250$ and $130 < M_{1/2} < 170$ GeV

PRL Submitted
arXiv:0811.2512

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SUSY Searches:
David Toback, Texas
Gaugino Pair Production in Multilepton + Met

Chargino-Neutralino gives three low $p_T$ leptons in the final state

Dominates the production cross section

5 separate final states + Unified Analysis $\rightarrow$ best coverage

- $\text{eee, eem, emm, mmm, eet, emt, & mmt}$

**Supersymmetric Trilepton Event**

- 2 Tight leptons + 1 track + MET
- 1 Tight lepton + 1 Loose lepton + 1 track + MET
- 3 Tight Leptons + MET
- 2 Tight leptons + 1 Loose lepton + MET
- 1 Tight lepton + 2 Loose leptons + MET

*Tracks can be e's or $\mu$'s or $\tau$'s*

Tight (= high purity) and Loose (=not as high purity, but better efficiency) leptons are e's or $\mu$'s

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SUSY Searches at CDF

David Toback, Texas A&M University
Unified Gaugino Pair Production Analysis

<table>
<thead>
<tr>
<th>Channel</th>
<th>Background</th>
<th>Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Tight</td>
<td>0.49±0.04±0.08</td>
<td>1</td>
</tr>
<tr>
<td>2 Tight + 1 Loose</td>
<td>0.25±0.03±0.03</td>
<td>0</td>
</tr>
<tr>
<td>1 Tight + 2 Loose</td>
<td>0.14±0.02±0.02</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total Trilepton</strong></td>
<td><strong>0.88±0.05±0.13</strong></td>
<td><strong>1</strong></td>
</tr>
<tr>
<td>2 Tight + 1 Track</td>
<td>3.22±0.48±0.53</td>
<td>4</td>
</tr>
<tr>
<td>1 Tight + 1 Loose + 1 Track</td>
<td>2.28±0.47±0.42</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total Dilepton + Track</strong></td>
<td><strong>5.5±0.7±0.9</strong></td>
<td><strong>6</strong></td>
</tr>
</tbody>
</table>

CDF Run II Preliminary, L_{int} = 2.0 fb^{-1}
Trileptons in mSUGRA

New study of the details of the full decay chains of the gauginos

Gauginos Decay dominantly via on-shell sleptons

Gauginos Decay dominantly via off-shell W/Z

Look at the lines of constant $M_0$

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Cross Section limits vs. chargino mass

$M_0 = 60$ GeV

Gauginos Decay dominantly via on-shell sleptons

$M_0 = 100$ GeV

Gauginos Decay dominantly via off-shell W/Z

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SUSY Searches

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mSUGRA Exclusion Region

Excluded Region in mSUGRA

CDF Run II Preliminary \( \int Ldt = 2.0 \text{ fb}^{-1} \)

- mSUGRA \( \tan(\beta) = 3, A_0 = 0, \mu > 0 \)
- \( m(\tilde{e}_R), m(\tilde{\mu}_R) > m(\tilde{\tau}_1) \)
- \( m(\tilde{\chi}^0_2) \approx m(\tilde{\tau}_1) \)

Search for \( \chi_1 \chi_2 \)

- Excluded at 95% C. L.
- LEP direct limit

Decay dominantly via on-shell sleptons

Decay dominantly via off-shell W/Z

LEP direct limit

Accepted by PRL
arXiv: 0808.2446

SUSY Searches at CDF

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High Tan$\beta$

- Likelihood fits including Higgs mass limits, $g-2$, and other experimental data to the MSSM in the plane of $m_{1/2}$ and tan$\beta$
  - Prefers high tan$\beta$
- Stop and Sbottom masses can be very different than the other squark masses
- Gaugino branching fractions to $\tau$'s can rise to 100% as the stau gets light...

The Tevatron has moved towards having a full suite of high tan$\beta$ targeted searches
Indirect Search: $B_s \rightarrow \mu \mu$

The search for $B_s \rightarrow \mu \mu$ is perhaps the most sensitive to SUSY since sparticles show up in loops.

Especially sensitive at high $\tan\beta$ ($\text{Br} \propto \tan^6\beta$)

In the Standard Model, the FCNC decay of $B_S \rightarrow \mu^+\mu^-$ is heavily suppressed.

$$\text{BR}_{SM}(B_s \rightarrow \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

Looking at the Data

Heavily optimized search using Neural Net Techniques

The backgrounds are combinatorial and estimated and checked from data using sideband techniques.

Can’t predict the backgrounds from MC → Makes predictions for sensitivity at the LHC precarious.

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Limits on Branching Ratios and mSUGRA

95% CL Limits on $\mathcal{B}(B_s \rightarrow \mu\mu)$

- CDF
- CDF Expected
- D0
- Tevatron

Preliminary Combined CDF/DØ
$BR(B_s \rightarrow \mu\mu) < 4.5 \times 10^{-8}$

CDF, PRL 100, 101802 (2008)

Factor of 10 above SM predictions

mSUGRA at $\tan\beta = 50$
Arnowitt, Dutta, et al., PLB 538 (2002) 121

A_0 = 0, \mu > 0
$\tan\beta = 50$

A factor of 10 above SM predictions

$\mathcal{B}(B_s \rightarrow \mu\mu) \times 4.5 \times 10^{-8}$
Sbottom Searches

Search for Sbottoms in b-jets+Met from gluino production

Use b-tagging and Neural Net techniques

CDF Run II Preliminary

N-Events

-1.5 -1 -0.5 0 0.5 1 1.5

NN Output

Two inclusive b-tags

Signal M(\tilde{g})=335, M(\tilde{t})=315

CDF Data

EWK BOSONS

TOP

Mistags

Inclusive Multijets
Limits on Sparticle Production

Backgrounds are roughly half QCD, half EWK

Most sensitive to large sbottom masses

Complementary to direct Sbottom searches which are gluino mass independent
Dilepton+Jets+Met sample is a fairly pure sample of top-pair production.

However, some of the dilepton events in Run I didn’t “look” like tops.

Do a systematic fit of the kinematics for any evidence of light stops.

Sample made of tops and stops?

Final state particles are the same as in top-pair production.

$M_{\text{Stop}} = 155 \text{ GeV}$

$M_{\text{top}} = 175 \text{ GeV}$

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Can set limits on Stop Admixture

\[ \tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm \rightarrow b \tilde{\chi}_1^0 l\nu \]

Branching Ratio limits are mass dependent...

Small chargino mass Large Chargino mass

**Observed 95% CL**

- CDF Run II Preliminary (1.9 fb⁻¹)
  - \( M(\tilde{\chi}_1^\pm) = 105.8 \text{ GeV/}c^2 \)
  - \( \text{BR}(\tilde{t}_1 \rightarrow \tilde{\chi}_1^\pm b) = 1 \)

- \( \text{BR}(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \nu l) = 1.0 \)
- \( \text{BR}(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \nu l) = 0.50 \)
- \( \text{BR}(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \nu l) = 0.25 \)

**Observed 95% CL**

- CDF Run II Preliminary (2.7 fb⁻¹)
  - \( M(\tilde{\chi}_1^\pm) = 125.8 \text{ GeV/}c^2 \)
  - \( \text{BR}(\tilde{t}_1 \rightarrow \tilde{\chi}_1^\pm b) = 1 \)

- \( \text{BR}(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \nu l) = 0.50 \)
- \( \text{BR}(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \nu l) = 0.25 \)

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Gauge-Mediated SUSY Breaking Models

$\tilde{\chi}^0_1 \rightarrow \gamma \tilde{G}$ models provide a warm dark matter candidate consistent with Astronomical observations and models of inflation.

More natural solution for FCNC problems than mSUGRA

Early Universe

Later Universe

Nanosecond lifetimes

CDF Run I ee$\gamma\gamma$+Met candidate event

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SUSY Searches at CDF

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Three Separate Searches

The lifetime and associated particle production dictate different final states:

- $\gamma\gamma + \text{Met}$ for small lifetime
- Delayed Photon + Met for large lifetime

Use new Photon Timing system

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SUSY Search
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All Neutralino Lifetime Searches

Warm dark matter models of GMSB with $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ favor keV $\tilde{G}$ masses and nanosecond $\tilde{\chi}_1^0$ lifetimes

Measure the time of arrival of photons in $\gamma + \text{Met} + \text{Jet}$ events

Just starting to enter the Cosmology Favored Region

CDF, PRL 99, 121801 (2007)
CDF, PRD 78, 0321015 (2008)

SUSY Searches
Berkeley Seminar  December 11, 2008  David Toback, Texas
$\gamma\gamma + \text{Met}$

New model independent search in $\gamma\gamma + \text{Met}$

New tool: Sophisticated mechanism to measure the significance of the Met measurement

Can straightforwardly separate QCD backgrounds with no intrinsic Met from EWK that does

<table>
<thead>
<tr>
<th></th>
<th>MetSig&gt;3.0</th>
<th>MetSig&gt;4.0</th>
<th>MetSig&gt;5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-collision</td>
<td>0.89 ± 0.32</td>
<td>0.84 ± 0.30</td>
<td>0.77 ± 0.27</td>
</tr>
<tr>
<td>Fake Met</td>
<td>28.1 ± 6.8</td>
<td>3.6 ± 1.8</td>
<td>0.60 ± 0.83</td>
</tr>
<tr>
<td>&quot;No $\gamma\gamma$ Vertex&quot;</td>
<td>4.4 ± 2.0</td>
<td>2.5 ± 1.0</td>
<td>1.5 ± 0.7</td>
</tr>
<tr>
<td>$\gamma\gamma$ (lost $\gamma$)</td>
<td>2.9 ± 1.0</td>
<td>2.2 ± 1.0</td>
<td>1.6 ± 1.0</td>
</tr>
<tr>
<td>EWK real MET</td>
<td>31.6 ± 2.0</td>
<td>26.7 ± 1.9</td>
<td>22.8 ± 1.7</td>
</tr>
<tr>
<td>Total</td>
<td>67.9 ± 7.5</td>
<td>35.8 ± 3.0</td>
<td>27.3 ± 2.3</td>
</tr>
<tr>
<td>Observed</td>
<td>82</td>
<td>31</td>
<td>23</td>
</tr>
</tbody>
</table>

No evidence for new physics
Gauge Mediated Supersymmetry

Optimize the $\gamma\gamma$+Met analysis for 0 ns lifetime:
Significant Met and Large $H_T$
Complement to the Delayed Photon Analysis

Also approaching the Cosmology Favored Region

Set limits for zero and Non-zero lifetimes

CDF Run II Preliminary, 2 $fb^{-1}$

Events per 10 GeV

$H_T$ (GeV) vs. $\chi^0_1$ mass (GeV/c^2)

Data
QCD with fake $\chi^0_1$
SM with real $\chi^0_1$
Non-collision
GMSB signal
$\chi^0_1$ mass=140 GeV, lifetime=0 ns

Expected exclusion region with $\gamma\gamma+\chi_1$ analysis with 2 $fb^{-1}$
Observed exclusion region with $\gamma\gamma+\chi_1$ analysis with 2 $fb^{-1}$
Observed exclusion region with $\gamma+\chi_1$+Jet analysis with 570 $pb^{-1}$
ALEPH exclusion limit
Cosmology favored region with $1.0 < \tilde{G}$ mass $< 1.5$ keV/c^2
Lots of other possibilities

Two worth mentioning here:

1. CHAMPS
   - Charged Massive quasi-stable particles
   - Like GMSB in that the lightest abundant sparticle in the early universe is different than it is today

2. R-parity Violating SUSY
   - Perhaps Supersymmetry is correct but has nothing to do with the Dark Matter problem (Axions?)
   - Still worth looking for, just harder to know where to look
Long-Lived Charged Sparticles (Champs)

- New emphasis in the theory community about the role of long-lived sparticles in the Early Universe and today as Dark Matter
- Use timing techniques
  - Heavy particles arrive later
  - Can measure the “mass” of weakly interacting charged particles (muon-like)

100 ps Time-of-Flight detector

CDF University

Muon CHAMP
**CHAMP Search**

- Dominated by measurement resolution
- Can set limits on stop, staus and charginos
  - Small differences between each
R-Parity Violating SUSY

- One advantage of RPV SUSY is that single-sparticle production is allowed
- Decays also depend on the couplings
- Powerful new tau-ID tools

\[ \text{sneutrino} \rightarrow e\mu, \tau\mu, e\tau \]
sneutrino $\rightarrow e\mu, \tau\mu, e\tau$

Backgrounds dominated by EWK and W+jet with misidentified leptons

Set limits by extrapolating from low mass region

$\sigma \cdot \text{BR}$ excluded at 95% C.L in the $10^{-2}:10^{-1}$ pb range

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Conclusions

• The Tevatron has performed a broad and deep set of searches for Supersymmetry in \( \sim 3 \text{ fb}^{-1} \)
  - Unfortunately, no sign of new physics

• The Tevatron is still running beautifully and the detectors are collecting data at unprecedented levels

• For the time being we are still leading the search for Supersymmetry

"Don’t look back — something might be gaining on you"
- Satchel Paige