Supersymmetry in LHC Run 2 and Beyond

Jeffrey D. Richman
CMS Experiment
University of California, Santa Barbara

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Outline

• Introduction: mass scales, symmetries, naturalness and SUSY
• Searching for SUSY: a primer
• An early 13 TeV SUSY search: Jets + 1 lepton + $\not{p}_T$ with $\sim 2$ fb$^{-1}$ (one of many presented at CERN Physics Jamboree and at Moriond)
• A brief look at prospects for SUSY with 300 fb$^{-1}$ (Runs 2-3) and 3000 fb$^{-1}$ (HL-LHC)

Drawing courtesy Sergio Cittolin, CMS
A new era in particle physics

F.A.Q.s
ABOUT THE
HADRON COLLIDER

Q: How does the Hadron Collider work?
A: You didn’t even understand eleventh-grade math, so why are you asking?

Q: How many miles of pipes and whatnot are in it?
A: A bajillion.

Q: How much did it cost?
A: Forty squillion.

Q: What would happen if you, like, put a cat inside it?
A: I don’t know.

Q: What would happen if you, like, put a cat inside it?
A: No.

Q: If I concentrate ultra-hard, will I ever be able to understand it?
A: Don’t touch that.
Mass scales in particle physics and the TeV scale

Generation puzzle (leptons)

Hadronic mass scale

Generation puzzle (quarks)

Electroweak scale

\[ M(e) \approx 0.511 \text{ MeV} \]

\[ M(\mu) \approx 106 \text{ MeV} \]

\[ M(\tau) \approx 1777 \text{ MeV} \]

\[ M(p) \approx 938.3 \text{ MeV} \]

\[ M(n) \approx 939.6 \text{ MeV} \]

\[ M(u) \approx 2.5 \text{ MeV} \]

\[ M(c) \approx 1.27 \text{ GeV} \]

\[ M(t) \approx 172 \text{ GeV} \]

\[ M(W) \approx 80.4 \text{ GeV} \]

\[ M(Z) \approx 91.2 \text{ GeV} \]

\[ M(H) \approx 125 \text{ GeV} \]

\[ M(eV/c^2) \]

Si band gap: \( \approx 1.1 \text{ eV} \)

\[ m(\nu) \sim 0.1 \text{ eV} ? \]

\[ m(\tilde{g}) \sim 2 \text{ TeV} ? \]

\[ M_{\text{Planck}} \approx 10^{18} \text{ GeV} \]
Mass scales in particle physics

**Generation puzzle**

- Hadronic mass scale
  - Generation puzzle (quarks)
  - Electroweak scale

**Particles**

- $e$, $\mu$, $\tau$, $p$, $n$, $c$, $t$, $W$, $Z$, $H$

**Masses**

- $M(e)$, $M(\mu)$, $M(\tau)$, $M(p)$, $M(n)$, $M(u)$, $M(c)$, $M(t)$, $M(W)$, $M(Z)$, $M(H)$

**Si band gap**

- $\approx 1.1$ eV

**Other quantities**

- $m(\nu) \sim 0.1$ eV?
- $m(\tilde{g}) \sim 2$ TeV?
- $M_{\text{Planck}} \approx 10^{18}$ GeV

**Notes**

- SUSY?, Dark matter?
- New gauge bosons?
Perspective from Run 1

- Higgs discovery: strong evidence for our overall picture of EW symmetry breaking. **But the question of how the EW mass scale is stabilized against short-distance quantum corrections is now even more urgent.**

- LHC-b: 2 charmonium-pentaquark states → **Still a lot to learn about the hadronic (≈1 GeV) mass scale, 80 years after the discovery of the pion.**

- A guess: it will take at least as long to understand the physics of the EW scale.
Mapping the standard model: the foundation of searches

CMS Preliminary

Production Cross Section, \( \sigma [pb] \)

- 7 TeV CMS measurement (\( L \leq 5.0 \text{ fb}^{-1} \))
- 8 TeV CMS measurement (\( L \leq 19.6 \text{ fb}^{-1} \))
- 7 TeV Theory prediction
- 8 TeV Theory prediction
- CMS 95%CL limit

Typical SUSY cross sections: ~few fb to hundreds of fb

0.1 pb = 100 fb
If you were wondering about the γγ excess...

- **CMS:** 13 TeV data: local signif.: 2.8 - 2.9σ, Global signif. < 1σ
- **ATLAS:** 13 TeV data: local signif.: 3.9σ, Global signif., 2.0σ (J=0)
- “Today it could be everything, including nothing.” — A. Strumia

<table>
<thead>
<tr>
<th>Hierarchy problem</th>
<th>Unification of couplings</th>
<th>Dark matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sim 10^{18} \text{ GeV} )</td>
<td>Planck scale (quantum gravity)</td>
<td>Atoms: 4.9%</td>
</tr>
<tr>
<td>Separation of scales can be stabilized by SUSY, extra dim's, ...</td>
<td></td>
<td>Dark matter: 26.8%</td>
</tr>
<tr>
<td>( \sim 10^2 - 10^3 \text{ GeV} )</td>
<td>Electroweak scale (unstable in SM)</td>
<td>Dark energy: 68.3%</td>
</tr>
</tbody>
</table>

WIMP Miracle \( \rightarrow \) TeV scale

SUSY provides dark matter candidate particle (Lightest Supersymmetric Particle); in MSSM this is neutralino.

S. Raby, Particle Data Book.
The gauge hierarchy problem and SUSY

- Evidence is very strong that the new particle discovered at \( m \approx 125 \text{ GeV} \) is a/the Higgs boson, with quantum numbers \( J^{PC} = 0^{++} \) (scalar).

- Assuming that it is an elementary scalar particle, the Higgs mass is subject to enormous shifts from short-distance quantum-loop corrections.

- These corrections can in principle pull the Higgs mass and the electroweak scale up to the cutoff scale of the SM, e.g., the Planck scale. Requires extraordinary fine tuning if no NP.

- SUSY can tame these corrections (as can other NP theories).

\[ f = \text{SM fermion, e.g., top quark} \]

\[ S = \text{SUSY scalar partner, e.g., top squark} \]
Supersymmetry basics

• The symmetry operation in SUSY is a mapping between fermionic and bosonic degrees of freedom.

• SUSY preserves the SM couplings (charges) of particles.

• Fermions: the SM is a chiral theory, and the L-handed and R-handed fermions have different EW charges!
  - L-handed fermions are SU(2)_L doublets
  - R-handed fermions are SU(2)_L singlets

• Each chiral projection of an SM fermion has a J = 0 SUSY partner, preserving degrees of freedom.

\[
\begin{bmatrix}
  u_L \\
d_L
\end{bmatrix}
\begin{bmatrix}
u_R \\
d_R
\end{bmatrix}
\]

partner of R-handed electron; has J = 0!
### SUSY partners of gauge and higgs bosons

<table>
<thead>
<tr>
<th>Particle</th>
<th>$J$</th>
<th>Degrees of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+$</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$\tilde{W}^-$</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$Z$</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$H$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$h$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$H^+$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$H^-$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$A$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>16</td>
</tr>
</tbody>
</table>

**Gaugino/Higgino basis**

<table>
<thead>
<tr>
<th>Particle</th>
<th>$J$</th>
<th>Degrees of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{W}^+$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{W}^-$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{Z}$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{\gamma}$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{H}$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{h}$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{H}^+$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{H}^-$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>16</td>
</tr>
</tbody>
</table>

**Chargino/Neutralino basis**

<table>
<thead>
<tr>
<th>Particle</th>
<th>$J$</th>
<th>Degrees of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}^+$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{\chi}^-$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{\chi}^+_1$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{\chi}^-_1$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{\chi}^+_2$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{\chi}^-_2$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{\chi}^+_3$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{\chi}^-_3$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{\chi}^+_4$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{\chi}^-_4$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>16</td>
</tr>
</tbody>
</table>

If lightest neutralino is LSP, then can be dark matter candidate.

**Generic term for all of the above “Electroweakinos” (EWKinos)**
CPT symmetry and the positron

- Dirac relativistic wave equation (1928): extra, “negative-energy” solutions.
- Positron interpretation confirmed by C.D. Anderson (cosmic ray experiment) at Caltech.

\[ a \rightarrow \bar{a} : \quad q_a = -q_{\bar{a}} \quad m_a = m_{\bar{a}} \quad \tau_a = \tau_{\bar{a}} \quad (CPT) \]

The Positive Electron

Carl D. Anderson, California Institute of Technology, Pasadena, California
(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

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On August 2, 1932, during the course of photographing cosmic-ray tracks produced in a vertical Wilson chamber (magnetic field of 15,000 gauss) designed in the summer of 1930 by Professor R. A. Millikan and the writer, the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence in this case of a particle carrying a electrons happened to produce two tracks so placed as to give the impression of a single particle shooting through the lead plate. This assumption was dismissed on a probability basis, since a sharp track of this order of curvature under the experimental conditions prevailing occurred in the chamber only once in some 500 exposures, and since there was practically no
315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE

Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $60 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

In trying to ferret out ever deeper layers of nature's secrets, scientists are being forced to accept a markedly slower pace of discovery in many fields of research, and the consequent rising cost of experiments has prompted public and political criticism.

...ouch.
Stabilizing the EW scale in a “natural” way (without excessive fine tuning) involves only a subset of the SUSY spectrum. Which SUSY partners are constrained?

“Natural SUSY endures”: still the current fashion

M. Papucci, J.T. Ruderman, and A. Weiler http://arxiv.org/abs/1110.6926

Stabilizing the EW scale in a “natural” way (without excessive fine tuning) involves only a subset of the SUSY spectrum. Which SUSY partners are constrained?

Focus of SUSY searches

The natural SUSY spectrum is well-suited to a treatment in the simplified-model framework.

In natural model scenarios, typically assume that some or all these particles are very heavy.

While natural SUSY models are a key focus, we do not restrict ourselves to them.
**SUSY Production Cross Sections**

**LPCC SUSY Cross Section WG**

![Graph showing SUSY production cross sections](image)

- **Strong production**
- **Electroweak production**

- **8 EWKinos:** 4 charginos, 4 neutralinos

- **Electroweak Cross Sections:** $\sigma(pp \rightarrow \tilde{g}\tilde{g}) \sim 1 \text{ fb}$
  - $m(\tilde{g}) = 2 \text{ TeV}$

**SUSY sparticle mass [GeV]**

- $\sqrt{s} = 14 \text{ TeV}$

**Events in 3000 fb$^{-1}$**

*arXiv:1407.5066*

https://twiki.cern.ch/twiki/bin/view/LHCPhysics
Simplified models for interpretation of search results

Strong production of gluinons

Strong production of squarks

Electroweak Production

Avoids the SUSY “curse of many parameters”: in each case, the number of mass parameters is just 2-3.
Simplified models for interpretation of search results

**Strong production of gluinos**

- Initial state: $p\bar{p} \rightarrow \tilde{g}\tilde{g} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- Final state: $q\bar{q} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$

**Strong production of squarks**

- Initial state: $p\bar{p} \rightarrow \tilde{t}\tilde{t} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- Final state: $t\bar{t} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$

**Electroweak Production**

- Initial state: $p\bar{p} \rightarrow \tilde{\chi}_1^\pm W \nu$ or $p\bar{p} \rightarrow \tilde{\chi}_2^0 Z \ell^\nu$

**Signature:** Large $p_T^{miss}$, high jet multiplicity, leptons, b-jets
Simplified models for interpretation of search results

Strong production of gluinos

Strong production of squarks

Electroweak Production

Just a few of the many models being used. Provides decomposition of search results in terms of basic signatures \(\Rightarrow\) applicable in many theoretical scenarios.
SUSY searches at the end of Run 1

\[M(\tilde{g}) > 1.35 \text{ TeV}\]
for \(\tilde{g} \rightarrow \tilde{t} \tilde{\chi}_1^0\); \(B(\tilde{t} \rightarrow t \tilde{\chi}_1^0) = 1\)
and small \(M(\tilde{\chi}_1^0)\)

\[M(\tilde{t}) > 750 \text{ GeV}\]
for \(B(\tilde{t} \rightarrow t \tilde{\chi}_1^0) = 1\)
and small \(M(\tilde{\chi}_1^0)\)

\[M(\tilde{\chi}_1^0) = M(\tilde{\chi}_2^0) > 420 \text{ GeV}\]
\[\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W^\pm \tilde{\chi}_1^0\]

\[M(\tilde{\chi}_1^0) = M(\tilde{\chi}_2^0) > 250 \text{ GeV}\]
\[\tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W^\pm \tilde{\chi}_1^0\]
A full-spectrum SUSY model

higgs  sleptons  EWKinos  Strong

NM3

\[ \tilde{\ell}_L, \tilde{\ell}_R, \tilde{\nu}_L, \tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_\tau, \tilde{q}_L, \tilde{q}_R, \tilde{b}_1, \tilde{b}_2, \tilde{t}_1, \tilde{t}_2, \tilde{g}, \tilde{\chi}_0^1, \tilde{\chi}_0^2, \tilde{\chi}_0^3, \tilde{\chi}_0^4, \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm, \tilde{\chi}_3^0, \tilde{\chi}_4^0 \]

Mass / GeV

1.7 TeV

1.1 TeV

CMS PAS SUS-14-012
From 8 TeV to 13 TeV: 2 fb\(^{-1}\) goes a long way!

- The 13 TeV data sample has only \(~1/10\) the luminosity of the 8 TeV data sample.
- But sensitivity for this search still surpasses that at 8 TeV!
Working on the CMS detector
Working on the CMS detector
A single-lepton SUSY search (CMS SUS-15-007)

- Designed for a high jet multiplicity signal, with 1 isolated lepton, large $p_T^{\text{miss}}$, and at least one b-jet.
- Strong production process already has sensitivity gain from increase in CM energy.
- Probes gluino decay to on-shell or off-shell top squark + top quark.
**SUS-15-007: Baseline event selection**

- **Trigger:** $p_T(e, \mu) > 15$ GeV with v. loose isolation, $H_T > 350$ GeV ($\epsilon_{\text{trig}} = 95\%$ for offline selection, measured with $E_T^{\text{miss}} > 170$ GeV trigger sample).

- **Baseline selection:** exactly 1 isolated $e$ or $\mu$, $p_T(e, \mu) > 20$ GeV, $H_T > 500$ GeV, $E_T^{\text{miss}} > 200$ GeV, $N(\text{jets}) \geq 6$, $N(\text{b-jets}) \geq 1$.

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### Event yields: Selection/MC sample

<table>
<thead>
<tr>
<th>Event yields: Selection/MC sample</th>
<th>DY, VV</th>
<th>QCD incl. tt → had</th>
<th>ttV</th>
<th>Single t</th>
<th>W + jets</th>
<th>ttbar 1 lep</th>
<th>ttbar 2 lep</th>
<th>Total SM</th>
<th>T1tttt 1500, 100 (~14 fb)</th>
<th>T1tttttt 1200,800</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 iso lepton, HT&gt;500</td>
<td>3850</td>
<td>29240</td>
<td>660</td>
<td>2690</td>
<td>29290</td>
<td>25690</td>
<td>3170</td>
<td>94620</td>
<td>11</td>
<td>42</td>
</tr>
<tr>
<td>BASELINE</td>
<td>9</td>
<td>2.4</td>
<td>28</td>
<td>59</td>
<td>61</td>
<td><strong>600</strong></td>
<td><strong>135</strong></td>
<td><strong>890</strong></td>
<td>8.4</td>
<td>17.7</td>
</tr>
<tr>
<td><strong>SUSY benchmarks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>S/B ≈ 1%</strong></td>
<td></td>
</tr>
<tr>
<td>BASELINE + M_j &gt; 250 and M_T &gt; 140</td>
<td>0.7</td>
<td>1.3</td>
<td>3.0</td>
<td>3.5</td>
<td>1.2</td>
<td><strong>5.4</strong></td>
<td><strong>32</strong></td>
<td><strong>47</strong></td>
<td>6.8</td>
<td>9.0</td>
</tr>
</tbody>
</table>

*SUSY benchmarks $m(\tilde{g}), m(\tilde{\chi}_1^0)$*
Beyond the baseline selection: $M_T$ and $M_J$

The cut $m_T > 140$ GeV suppresses most single-lepton $t\bar{t}$ events.

Large-$R$ jets formed by clustering standard AK4 jets; highly robust
Masses of large-R jets, MJ, & initial-state radiation

Starting from standard anti-kT jets ($R = 0.4$), we build large radius, or “fat” jets by further combining these AK4 jets using the anti-kT algorithm with cone size $R = 1.4$.

Define $M_J$ to be the scalar sum of these fat jet masses:

$$M_J = \sum_{\text{large-R jets } J_i} m(J_i)$$
Anatomy of the ttbar → 2 lepton background

ONLY 2 non-ISR/FSR jets in a ttbar dilepton event!

Our analysis requires at least 6 standard jets → rest come from ISR!
Event with 9 jets, 1 isolated electron, $M_J = 1173$ GeV

<table>
<thead>
<tr>
<th>$H_T$ (GeV)</th>
<th>$M_J$ (GeV)</th>
<th>$p_T^{miss}$ (GeV)</th>
<th>$m_T$ (GeV)</th>
<th>$N_{jets}$</th>
<th>$N_b$</th>
<th>lep, $p_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2903</td>
<td>1173</td>
<td>347</td>
<td>91</td>
<td>9</td>
<td>2</td>
<td>e, 172</td>
</tr>
</tbody>
</table>

ISR jet = 1468 GeV

Both tops + more ISR/FSR

e = 172 GeV
Event with 9 jets, 1 isolated electron, $M_J = 1173$ GeV

- $p_T^{\text{miss}} = 347$ GeV
- $e = 172$ GeV
- $b$-tag = 307 GeV
- $b$-tag = 160 GeV

1468 GeV AK4 jet
Event with 9 jets, 1 isolated electron, $M_J = 1173$ GeV

- Fat jet $p_T = 1597$ GeV
  Mostly from 1 ISR jet
  Mass = 254 GeV

- Fat jet $p_T = 146$ GeV
  Contains just 1 AK4 jet
  Mass = 22 GeV

- $p_T^{miss} = 347$ GeV
  Both tops + 2 ISR/FSR jets
  Mass = 897 GeV

- $e = 172$ GeV

- $b$-tag = 160 GeV
  Mass = 1468 GeV AK4 jet

- $b$-tag = 307 GeV
  Mass = 1468 GeV AK4 jet
Beyond the baseline selection: $M_T$ and $M_J$

Nominal signal region: $t\bar{t}$ 2-lep background dominates.

Very small $M_J - m_T$ correlation, but background composition changes from low to high $m_T$!
Background estimation method

- Do we understand the $M_J$ distribution for these backgrounds, given the large role of ISR?
- We will establish an “ABCD method”

To increase sensitivity, perform a similar background estimate for signal regions that are binned in

$$E_T^{\text{miss}} = [200-400, >400 \text{ GeV}], \quad N_{\text{jets}} = [6-8, \geq 9], \quad \text{and } N_b = [1,2, \geq 3]$$
Shape of $M_J$ distributions is very similar. Ratio of high-$m_T$ to low-$m_T$ yields is $\sim$uniform across $M_J$ bins.

Shape of $N(jets)$ distributions is very similar. Ratio of high-$m_T$ to low-$m_T$ yields is $\sim$uniform across $N(jets)$ bins.
Unblinded data: $N_b = 1$ (background dominated)
Unblinded data: $N_b = 2$ (sensitive to signal)
### Predicted and observed event yields

<table>
<thead>
<tr>
<th>Bin</th>
<th>$\kappa$</th>
<th>Sig. NC</th>
<th>Sig. C</th>
<th>Bkg. Pred. (PF)</th>
<th>Bkg. Pred. (GF)</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$200 &lt; \text{MET} \leq 400 \text{ GeV}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4: $6 \leq n_j \leq 8$, $n_b = 1$</td>
<td>$1.12 \pm 0.09 \pm 0.42$</td>
<td>0.2</td>
<td>0.2</td>
<td>$3.4 \pm 1.4$</td>
<td>$3.6 \pm 1.0$</td>
<td>6</td>
</tr>
<tr>
<td>R4: $n_j \geq 9$, $n_b = 1$</td>
<td>$0.91 \pm 0.05 \pm 0.82$</td>
<td>0.1</td>
<td>0.3</td>
<td>$0.3 \pm 0.3$</td>
<td>$0.4 \pm 0.2$</td>
<td>1</td>
</tr>
<tr>
<td>R4: $6 \leq n_j \leq 8$, $n_b = 2$</td>
<td>$1.12 \pm 0.05 \pm 0.42$</td>
<td>0.3</td>
<td>0.3</td>
<td>$3.0 \pm 1.2$</td>
<td>$3.0 \pm 0.8$</td>
<td>2</td>
</tr>
<tr>
<td>R4: $n_j \geq 9$, $n_b = 2$</td>
<td>$1.04 \pm 0.10 \pm 0.94$</td>
<td>0.3</td>
<td>0.6</td>
<td>$0.5 \pm 0.3$</td>
<td>$0.4 \pm 0.2$</td>
<td>0</td>
</tr>
<tr>
<td>R4: $6 \leq n_j \leq 8$, $n_b \geq 3$</td>
<td>$1.25 \pm 0.11 \pm 0.75$</td>
<td>0.3</td>
<td>0.3</td>
<td>$1.0 \pm 0.5$</td>
<td>$0.9 \pm 0.3$</td>
<td>0</td>
</tr>
<tr>
<td>R4: $n_j \geq 9$, $n_b \geq 3$</td>
<td>$1.04 \pm 0.09 \pm 0.96$</td>
<td>0.3</td>
<td>0.7</td>
<td>$0.1 \pm 0.1$</td>
<td>$0.1 \pm 0.1$</td>
<td>0</td>
</tr>
<tr>
<td>$\text{MET} &gt; 400 \text{ GeV}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4: $6 \leq n_j \leq 8$, $n_b = 1$</td>
<td>$1.15 \pm 0.17 \pm 0.44$</td>
<td>0.6</td>
<td>0.2</td>
<td>$2.4 \pm 1.9$</td>
<td>$1.2 \pm 0.7$</td>
<td>0</td>
</tr>
<tr>
<td>R4: $n_j \geq 9$, $n_b = 1$</td>
<td>$1.01 \pm 0.15 \pm 0.92$</td>
<td>0.4</td>
<td>0.3</td>
<td>$0.3 \pm 0.3$</td>
<td>$0.3 \pm 0.3$</td>
<td>1</td>
</tr>
<tr>
<td>R4: $6 \leq n_j \leq 8$, $n_b \geq 2$</td>
<td>$1.28 \pm 0.19 \pm 0.50$</td>
<td>1.8</td>
<td>0.4</td>
<td>$1.0 \pm 0.9$</td>
<td>$0.5 \pm 0.4$</td>
<td>0</td>
</tr>
<tr>
<td>R4: $n_j \geq 9$, $n_b \geq 2$</td>
<td>$0.90 \pm 0.13 \pm 0.81$</td>
<td>1.5</td>
<td>0.9</td>
<td>$0.2 \pm 0.3$</td>
<td>$0.1 \pm 0.1$</td>
<td>0</td>
</tr>
</tbody>
</table>

- Observed yields in data are consistent with predicted background in all bins.
- Interpret results as exclusion limits on cross sections and SUSY particle masses. Incorporate signal systematic uncertainties on efficiencies, luminosity, etc.
Distributions of $M_J$ for $N_b \geq 2$ at low and high $m_T$

**Low $m_T$**

**High $m_T$**
Signal efficiency and expected yields for T1tttt

Signal efficiency vs. $M(\tilde{g})$ and $M(\tilde{\chi}_1^0)$

- Signal efficiency increases moving away from the diagonal, where the spectrum compresses and $E_T^{\text{miss}}$ becomes small.

- Expected signal event yield decreases with increasing $m(\tilde{g})$.
Gluino pair production with off-shell top squarks

Mass limits are based on comparing cross section limits to theory assuming 100% branching fraction to the assumed decay mode. Exclude gluinos up to ~1.6 TeV. Compare to ~1.35 TeV at 8 TeV.
How would intermediate-state, on-shell top squarks in gluino decay affect the limits?

Most difficult case (lowest efficiency) corresponds to the smallest allowed top squark mass for a given LSP mass:

\[ m(\tilde{t}) = m(\tilde{\chi}_1^0) + m(t) = m(\tilde{\chi}_1^0) + 175 \text{ GeV} \]

Very little loss in mass reach!
CMS searches: gluino and stop pair production

Presented either at the CERN physics jamorboo (Dec 2015) or at Moriond 2016,

- The sensitivity of this analysis for T1ttttt is typical of most 0-lepton and 1-lepton searches with the early 13 TeV data.
Long-term LHC schedule

- **2015** to **2018**: Run 2
- **2019**: HL-LHC Civil engineering
- **2020**: LIU installation
- **2022** to **2024**: Run 3
- **2025**: HL-LHC installation
- **2026** to **2028**: Run 4
- **2029** to **2035**: LS 4 to LS 5

**Phases:**
- **Phase 1**: 2015 - 2028
  - 2015 - 2017: ∼25 fb⁻¹
  - 2019 - 2021: ∼300 fb⁻¹

- **Phase 2**: 2029 - 2035
  - 2029 - 2032: ∼3000 fb⁻¹

- **Future Plans**:
  - HL-LHC installation
  - LS 4 to LS 5
Largest increase in discovery sensitivity with HL-LHC is for direct production of electroweak SUSY partners (EWKinos). Small cross section!

Up to 500 GeV increase in discovery reach with HL-LHC for chargino-neutralino pair production (Wh mode).

If strongly interacting SUSY partners are too heavy to be produced, EWKinos may be our best window to SUSY at the HL-LHC. Searches for ~degenerate Higgsinos are extremely difficult but highly motivated by naturalness.

Discovery sensitivity: neutralinos up to ~1 TeV

Discovery sensitivity: gluinos up to ~2.2 TeV

Probe *up to* the quoted mass
Discovery scenarios with full-spectrum models

CMS PAS SUS-14-012

- Studied 5 full-spectrum SUSY models.
- 9 analyses performed in parallel.
- $m_H = 125$ GeV
- NM 1,2,3 =“Natural”
  - Model 1, 2, 3
  - $m(\tilde{g})=1.7$ TeV, $m(\tilde{t})=1.1$ TeV
- STC -Stau co-annihilation
  - $m(\tilde{\tau}_1) \approx m(\tilde{\chi}_1^0) \approx 190$ GeV
- STOC-Stop co-annihilation
  - $m(\tilde{t}_1) \approx m(\tilde{\chi}_1^0) \approx 400$ GeV

The nature of the EWKino sector has a large influence on the decays of the top squark.

<table>
<thead>
<tr>
<th></th>
<th>NM1</th>
<th>NM2</th>
<th>NM3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(\tilde{t} \rightarrow t \tilde{\chi}_1^0)$</td>
<td>0.6%</td>
<td>1.5%</td>
<td>39%</td>
</tr>
</tbody>
</table>
Discovery scenarios with full-spectrum models

Lepton-rich
Dilepton edge signature
\[ \tilde{\chi}_2^0 \rightarrow \ell^\pm \ell'^\mp \rightarrow \ell^\pm \ell'^\mp \tilde{\chi}_1^0 \]

EWKino Wh + MET
\[ B(\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0) = 100\% \]
\[ B(b_1 \rightarrow b \tilde{\chi}_1^0) = 67\% \]

stop co-annihilation
\[ m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 6 \text{ GeV} \]
\[ B(\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0) = 99\% \]

Invisible \( t_1 \)
CMS: lessons from full-spectrum SUSY studies

- Search for all-hadronic jets + MET.
- MT2 can provide valuable information on the kinematics/mass splittings of the signal processes.
- NM1: more leptons $\rightarrow$ few events in hadronic channel.

- Designed as 1-lepton search for top-squark pair production.
- Show stacked contributions from NM1 model. Target process does not dominate the observed yield!
- “Discovery” does not mean you found what you were looking for!
Experimental signature

No mass peaks! Interpretation will be very complex. Is it even SUSY? Different signatures can require very different amounts of data to detect!
• Powerful approach, but in reality, there are an infinite number of possible theories (not 5), so the challenge is very significant.
• Multi-signature fingerprint will require large data samples to acquire.
• Different search channels can produce significant signals at very different times.
• Interpretation of a significant excess is likely to be much slower than for the Higgs discovery.
• “Discovery” could take place with multiple 3-4 σ excesses, rather than a single 5σ excess.
History and a prediction

315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE

Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

Ouch...

8,345 Physicists Report Discovery of Something But Aren’t Exactly Sure What It Is

Eight thousand, three hundred and forty five physicists worked on two gigantic experiments, ATLAS and CMS.

Their apparatus included the Large Hadron Collider, the world’s most powerful particle accelerator, as well as...
Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

In trying to ferret out ever deeper layers of nature's secrets, scientists are being forced to accept a markedly slower pace of discovery in many fields of research, and the consequent rising cost of experiments has prompted public and political criticism.

To some, the elaborate trappings and null result of the latest Fermilab experiment seem to typify both the lofty goals and the staggering difficulties of "Big Science," a term coined in 1961 by Dr. Alvin M. Weinberg of Oak Ridge National Laboratory. Some regard such failures as proof that high-energy physics, one of the biggest avenues of big science, is fast approaching a dead end.

Others call the latest experiment a useful, though inconclusive, step toward gauging the ultimate basis of material existence. The difficulty of science is increasing exponentially as scientists grope toward ultimates, they point out, and particle physicists believe that society must accept the smaller increments and higher costs of progress, if progress is to continue.

The paper reporting results of the latest big experiment appeared Dec. 14 in the prestigious journal Physical Review Letters. The names of the 315 scientists whose work contributed to the paper, arranged in alphabetical order, occupied an entire page -- more than one-fifth the overall length of the report. Following this top-heavy opening, the paper concluded in essence that the scientists had failed to find what they were looking for.

Eight thousand, three hundred and forty five physicists worked on two gigantic experiments, ATLAS and CMS.

Their apparatus included the Large Hadron Collider, the world’s most powerful particle accelerator, as well as…
You can discover something and not know what it is… Columbus did not reach his intended destination, but instead a whole new continent was coming into view…
Summary/Observations

• Early Run 2 searches have already significantly extended the mass reach for strongly produced SUSY particles.
• Expect ~10 X more data in 2016 running → another jump in sensitivity.
• If no significant excess is observed with ~300 fb\(^{-1}\), the strongest discovery possibilities may be associated with EWK processes.
• Evidence or discovery of an excess event yield over the SM with ~300 fb\(^{-1}\) will open the door to an intensive HL-LHC program to illuminate the nature of the excess.
• **A compelling discovery scenario may arise with several 3-4 \(\sigma\) effects, rather than a single 5\(\sigma\) effect.** Life could be quite complicated (e.g., look-elsewhere effects).
• Interpretation of any observed excess will be complex and will require a full fingerprint from multiple searches.
Backup slides
Mass scales in particle physics

Generation puzzle (leptons)

1. Generation puzzle (quarks)

Hadronic mass scale

Electroweak scale

Dark matter?

\[ M(eV/c^2) \]

\[ 1.0 \times 10^{11} \]

\[ 1.0 \times 10^{10} \]

\[ 1.0 \times 10^{9} \]

\[ 1.0 \times 10^{8} \]

\[ 1.0 \times 10^{7} \]

\[ 1.0 \times 10^{6} \]

\[ 1.0 \times 10^{5} \]

\[ 0.511 \]

\[ 106 \]

\[ 1777 \]

\[ 939.6 \]

\[ 2.5 \]

\[ 172 \]

\[ 91.2 \]

\[ 125 \]

\[ M(e) \]

\[ M(mu) \]

\[ M(tau) \]

\[ M(p) \]

\[ M(n) \]

\[ M(u) \]

\[ M(c) \]

\[ M(t) \]

\[ M(W) \]

\[ M(Z) \]

\[ M(H) \]

Si band gap: \( \approx 1.1 \text{ eV} \)  
\[ m(\nu) \sim 0.1 \text{ eV?} \]  
\[ m(\tilde{g}) \sim 2 \text{ TeV?} \]  
\[ M_{\text{Planck}} \approx 10^{18} \text{ GeV} \]
Mass scales in particle physics

- Generation puzzle (quarks)
- Hadronic mass scale
- Electroweak scale

Leptons:
- $M_e$: $0.511 \text{ MeV}$
- $M_{\mu}$: $106 \text{ MeV}$
- $M_{\tau}$: $1777 \text{ MeV}$

Quarks:
- $M_u$: $2.5 \text{ MeV}$
- $M_d$: $938.3 \text{ MeV}$
- $M_s$: $939.6 \text{ MeV}$
- $M_c$: $1.27 \text{ GeV}$
- $M_t$: $172 \text{ GeV}$
- $M_W$: $80.4 \text{ GeV}$
- $M_Z$: $91.2 \text{ GeV}$
- $M_H$: $125 \text{ GeV}$

Si band gap: ≈ $1.1 \text{ eV}$

$M(eV/c^2)$ scales:
- $M_{Planck} ≈ 10^{18} \text{ GeV}$

SUSY?, Dark matter? New gauge bosons?
<table>
<thead>
<tr>
<th><strong>Reconstruction object</strong></th>
<th><strong>Method/criteria</strong></th>
<th><strong>Performance/Comments</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets</td>
<td>$p_T &gt; 30$ GeV, $</td>
<td>\eta</td>
</tr>
<tr>
<td>Large-R jets</td>
<td>Cluster standard jets with anti-kT and</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b - tagged jets</td>
<td>$N(b\text{-tag}) \geq 1$, $p_T &gt; 30$ GeV, $</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electrons</td>
<td>$p_T &gt; 20$ GeV, $</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>muons</td>
<td>$p_T &gt; 20$ GeV, $</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$ and $E_T^{\text{miss}} =</td>
<td>p_T^{\text{miss}}</td>
<td>$</td>
</tr>
</tbody>
</table>
Validation of $M_J$ modeling using data

Before using MJ, we performed an extensive set of studies in data and Monte Carlo.

- By clustering AK4 PF jets ($p_T > 30$ GeV, $|\eta| < 2.4$), we are robust against pile-up effects because standard jets are already corrected for pile-up.

- Simulation of $M_J$ distributions tested in QCD, ttbar, Z+jets, W+jets dominated samples in 8 TeV data.
Anatomy of the $t\bar{t} \rightarrow 2$ lepton background

1. EVENT ENVIRONMENT
- Effects of pileup: isolation, jets, MET, vertices
- Underlying event.

2. PRODUCTION
- $p_T$ distributions of $t$ and $t\bar{t}$ (affected by parton distribution functions, QCD renorm & factorization scales)
- Effect of initial-state radiation
- Spin correlations of $t$ and $t\bar{t}$

3. DECAY CHAIN
- $W$ polarization
- Final-state radiation
- Decay branching fractions

Each 2-body system shown in 2-body rest frame.

ONLY 2 non-ISR jets in a $t\bar{t}$ dilepton event!
Studying the validity of ABCD in simulation

• Standard ABCD method

  Estimated background: \( \mu_{R4} = N_{R2} \times N_{R3}/N_{R1} \)

• Apply correction factor \( \kappa \approx 1 \) from MC: \( \kappa = N_{R4} N_{R1}/N_{R2} N_{R3} \) (MC)

• Perform calculation in 10 signal bins of \( E_T^{\text{miss}}, N_{\text{jets}}, \) and \( N_b \)

Values computed for the full simulated background.

Uncertainties shown are statistical, from MC.

We perform extensive studies in data to establish systematic uncertainties on these correction factors.
Shape of $M_J$ distributions is very similar for all dilepton events reconstructed with 1 lepton, independent of low or high $m_T$.

→ 2-lep ttbar “contamination” at LOW $m_T$ is not a problem.

Shape of $M_J$ distributions is NOT similar for all 1-lepton events, independent of low or high $m_T$.

→ 1-lep ttbar “contamination” at HIGH $m_T$ is a potential problem. But this contamination is very small.
Studying the validity of ABCD in simulation

\[ R_{m_T} = \frac{N(m_T > 140)}{N(m_T \leq 140)} \]

\[ \kappa = \frac{R_{m_T}(M_J > 400)}{R_{m_T}(M_J \leq 400)} \]

\[ R_{m_T} = N(m_T > 140) \]

\[ N(m_T \leq 140) \]

\[ \kappa = \frac{R_{m_T}(M_J > 400)}{R_{m_T}(M_J \leq 400)} \]

\[ \kappa \text{ for each of the 10 signal bins} \]
Predicted and observed event yields

• Perform two types maximum likelihood fits:

- “Predictive fit”: uses yields in R1, R2, and R3 only to predict R4 (convenient way to implement ABCD method while propagate uncertainties). Assumes no signal contamination of R1-R3. Test of null hypothesis.

- “Global fit”: uses yields in R1, R2, R3, and R4 in each of 6 analysis bins. Allows for signal events in all regions, in relative proportion set by signal models.

\[
\begin{align*}
\mu_{R1}^{bkg} &= \mu \\
\mu_{R2}^{bkg} &= \mu \cdot R(M_J) \\
\mu_{R3}^{bkg} &= \mu \cdot R(m_T) \\
\mu_{R4}^{bkg} &= \kappa \cdot \mu \cdot R(M_J) \cdot R(m_T)
\end{align*}
\]

\[
L^{data} = \prod_{i=1}^{4} \prod_{k=1}^{N_{bins}(Ri)} \text{Poisson}(N_{Ri,k}^{data} | \mu_{Ri,k}^{bkg} + r \cdot \mu_{Ri,k}^{MC sig})
\]
Systematic uncertainties on the background

• Incorporated as uncertainty on \( \kappa \).

• Dominant background: 2-lep ttbar → use 2-lep control sample to measure an uncertainty. Replace R3, R4 with corresponding 2-lep control regions D3, D4

<table>
<thead>
<tr>
<th>Region</th>
<th>( \kappa )</th>
<th>Bkg. Pred.</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: ( m_T \leq 140, M_J \leq 400 )</td>
<td>–</td>
<td>330.1 ± 18.2</td>
<td>330</td>
</tr>
<tr>
<td>R2: ( 6 \leq N_{\text{jets}} \leq 8, m_T \leq 140, M_J &gt; 400 )</td>
<td>–</td>
<td>100.9 ± 10.0</td>
<td>101</td>
</tr>
<tr>
<td>R2: ( N_{\text{jets}} \geq 9, m_T \leq 140, M_J &gt; 400 )</td>
<td>–</td>
<td>14.0 ± 3.7</td>
<td>14</td>
</tr>
<tr>
<td>D3: ( M_J \leq 400 )</td>
<td>–</td>
<td>31.0 ± 5.6</td>
<td>31</td>
</tr>
<tr>
<td>D4: ( 5 \leq N_{\text{jets}} \leq 7, M_J &gt; 400 )</td>
<td>1.17 ± 0.03</td>
<td>11.1 ± 2.4</td>
<td>12</td>
</tr>
<tr>
<td>D4: ( N_{\text{jets}} \geq 8, M_J &gt; 400 )</td>
<td>1.08 ± 0.04</td>
<td>1.4 ± 0.5</td>
<td>2</td>
</tr>
</tbody>
</table>

• Additional systematic uncertainties (all < 11%)
  - 1-lep ttbar events at high mT (due to jet energy mismeasurement), effect of jet energy resolution and corrections, ISR and top pT modeling, non-ttbar background
Key kinematic distributions in data and simulation
# CMS full-spectrum SUSY models

<table>
<thead>
<tr>
<th>Sparticle</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NM1</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>1686</td>
</tr>
<tr>
<td>$\tilde{b}_1$</td>
<td>1177</td>
</tr>
<tr>
<td>$\tilde{t}_1$</td>
<td>1092</td>
</tr>
<tr>
<td>$\tilde{t}_2$</td>
<td>1874</td>
</tr>
<tr>
<td>$\tilde{q}$</td>
<td>3025</td>
</tr>
<tr>
<td>$\tilde{\ell}^+ - \tilde{\ell}^-$</td>
<td>432</td>
</tr>
<tr>
<td>$\tilde{\tau}_1$</td>
<td>3000</td>
</tr>
<tr>
<td>$\tilde{\tau}_2$</td>
<td>427</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1$</td>
<td>419</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2$</td>
<td>515</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_3$</td>
<td>603</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_4$</td>
<td>644</td>
</tr>
<tr>
<td>$\tilde{\chi}^+_1$</td>
<td>512</td>
</tr>
<tr>
<td>$\tilde{\chi}^+_2$</td>
<td>642</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NM1</td>
</tr>
<tr>
<td>$\tilde{g} \tilde{g}$</td>
<td>5.4</td>
</tr>
<tr>
<td>$q\bar{q}$</td>
<td>2.0</td>
</tr>
<tr>
<td>$\tilde{q} \tilde{q}, \tilde{q} \tilde{q}^*$</td>
<td>0.14</td>
</tr>
<tr>
<td>$\tilde{b}_1 \tilde{b}_1^*$</td>
<td>2.6</td>
</tr>
<tr>
<td>$\tilde{t}_1 \tilde{t}_1^*$</td>
<td>4.4</td>
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<tr>
<td>$\tilde{\chi}^0_1$</td>
<td>1.1</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2$</td>
<td>29</td>
</tr>
<tr>
<td>$\tilde{\chi}^+_1 \tilde{\chi}^0_1$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\chi}^+_2 \tilde{\chi}^0_2$</td>
<td>15</td>
</tr>
<tr>
<td>$\tilde{\ell}^+ \tilde{\ell}^-$</td>
<td>3.3</td>
</tr>
<tr>
<td>$\tilde{\ell}^+ \tilde{\ell}^<em>, \tilde{\ell}^- \tilde{\ell}^</em>$</td>
<td>12</td>
</tr>
<tr>
<td>$\tilde{\nu} \tilde{\nu}^*$</td>
<td>3.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NM1</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow t_1 \bar{t}_1^*$</td>
<td>59%</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow b_1 b_1$</td>
<td>41%</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow b_2 b_2^*$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow b_2 b_2$</td>
<td>-</td>
</tr>
<tr>
<td>$t_1 \rightarrow b_1^0 \ell^- \nu$</td>
<td>0.6%</td>
</tr>
<tr>
<td>$t_1 \rightarrow t_1^0 \ell^- \nu$</td>
<td>13%</td>
</tr>
<tr>
<td>$t_1 \rightarrow t_1^0 \ell^- \nu$</td>
<td>22%</td>
</tr>
<tr>
<td>$t_1 \rightarrow t_1^0 \ell^- \nu$</td>
<td>30%</td>
</tr>
<tr>
<td>$t_1 \rightarrow b_1 \tilde{\chi}^0_1$</td>
<td>16%</td>
</tr>
<tr>
<td>$t_1 \rightarrow b_1 \tilde{\chi}^0_2$</td>
<td>18%</td>
</tr>
<tr>
<td>$t_1 \rightarrow c_1^0 \tilde{\chi}^0_1$</td>
<td>-</td>
</tr>
<tr>
<td>$b_1 \rightarrow b_1^0 \ell^- \nu$</td>
<td>1.5%</td>
</tr>
<tr>
<td>$b_1 \rightarrow b_1^0 \ell^- \nu$</td>
<td>11%</td>
</tr>
<tr>
<td>$b_1 \rightarrow b_1^0 \ell^- \nu$</td>
<td>0.6%</td>
</tr>
<tr>
<td>$b_1 \rightarrow b_1^0 \ell^- \nu$</td>
<td>4.5%</td>
</tr>
<tr>
<td>$b_1 \rightarrow t_1^0 \ell^- \nu$</td>
<td>32%</td>
</tr>
<tr>
<td>$b_1 \rightarrow t_1^0 \ell^- \nu$</td>
<td>49%</td>
</tr>
<tr>
<td>$b_1 \rightarrow W^{-} t_1$</td>
<td>0.4%</td>
</tr>
<tr>
<td>$b_1 \rightarrow b_2 \tilde{\ell}^+ \tilde{\nu}$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\chi}^+_1 \rightarrow \ell^+ \ell^-$</td>
<td>56%</td>
</tr>
<tr>
<td>$\tilde{\chi}^+_1 \rightarrow \nu \ell^-$</td>
<td>43%</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1 \rightarrow W^- \tilde{\chi}^0_1$</td>
<td>1.8%</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1 \rightarrow q \bar{q} \tilde{\chi}^0_1$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1 \rightarrow \ell^+ \nu \tilde{\chi}^0_1$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1 \rightarrow t \ell$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \rightarrow \ell^+ \ell^- \ell^- \ell^-$</td>
<td>59%</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \rightarrow \nu \bar{\nu} \nu \bar{\nu}$</td>
<td>41%</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \rightarrow Z \tilde{\chi}^0_1$</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \rightarrow H \tilde{\chi}^0_1$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \rightarrow q \bar{q} \tilde{\chi}^0_1$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \rightarrow \ell^+ \ell^- \tilde{\chi}^0_1$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \rightarrow \nu \nu \tilde{\chi}^0_1$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \rightarrow q \bar{q} \tilde{\chi}^0_1$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \rightarrow \ell^+ \nu \tilde{\chi}^0_1, \ell^- \nu \tilde{\chi}^0_1$</td>
<td>-</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \rightarrow t \ell$</td>
<td>-</td>
</tr>
</tbody>
</table>
### Table 15: Overview of the most relevant sparticle masses for the models NM1, NM2, NM3

<table>
<thead>
<tr>
<th>Process</th>
<th>Mass (GeV)</th>
<th>NM1</th>
<th>NM2</th>
<th>NM3</th>
<th>STC</th>
<th>STOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>b₁ b₁̄</td>
<td>2.6</td>
<td>2.6</td>
<td>2.8</td>
<td>8.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>t₁ t₁̄</td>
<td>4.4</td>
<td>4.4</td>
<td>3.1</td>
<td>19</td>
<td>2110</td>
<td>-</td>
</tr>
<tr>
<td>̃χ₁⁺ ̃χ₁⁻</td>
<td>1.1</td>
<td>0.2</td>
<td>520</td>
<td>11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>̃χ₂⁺ ̃χ₂⁻</td>
<td>29</td>
<td>22</td>
<td>460</td>
<td>1104</td>
<td>5.5</td>
<td>-</td>
</tr>
<tr>
<td>̃χ₁⁺ ̃χ₂⁻</td>
<td>-</td>
<td>-</td>
<td>258</td>
<td>0.02</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>̃χ₁⁺ ̃χ₂⁺</td>
<td>15</td>
<td>11</td>
<td>278</td>
<td>553</td>
<td>2.6</td>
<td>-</td>
</tr>
<tr>
<td>t₁ → t₁⁺</td>
<td>0.6%</td>
<td>1.5%</td>
<td>39%</td>
<td>20%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>b₁ → b₁⁺</td>
<td>1.5%</td>
<td>1.0%</td>
<td>1.3%</td>
<td>67%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>b₁ → b₁⁻</td>
<td>11%</td>
<td>10%</td>
<td>1.0%</td>
<td>2.2%</td>
<td>5.7%</td>
<td>-</td>
</tr>
<tr>
<td>b₁ → b₁⁺</td>
<td>0.6%</td>
<td>0.6%</td>
<td>0.4%</td>
<td>8.2%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>b₁ → b₁⁻</td>
<td>4.5%</td>
<td>5.7%</td>
<td>5.7%</td>
<td>7.6%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>b₁ → t₁⁻</td>
<td>32%</td>
<td>34%</td>
<td>80%</td>
<td>3.4%</td>
<td>11%</td>
<td>-</td>
</tr>
<tr>
<td>b₁ → W⁻ t₁</td>
<td>49%</td>
<td>48%</td>
<td>12%</td>
<td>12%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>b₁ → W⁺ t₁</td>
<td>0.4%</td>
<td>0.7%</td>
<td>-</td>
<td>&lt; 0.1%</td>
<td>65%</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 16: Cross sections of main SUSY particle production processes for the models NM1, NM2, NM3

<table>
<thead>
<tr>
<th>Process</th>
<th>NM1</th>
<th>NM2</th>
<th>NM3</th>
<th>STC</th>
<th>STOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>̃g ̃g</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
<td>0.007</td>
<td>0.53</td>
</tr>
<tr>
<td>̃q ̃q</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>0.05</td>
<td>0.30</td>
</tr>
<tr>
<td>̃q̃q̂ ̃q̃q̂⁺</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>̃t₁ t₁</td>
<td>4.4</td>
<td>4.4</td>
<td>3.1</td>
<td>19</td>
<td>2110</td>
</tr>
<tr>
<td>̃χ₁⁺ ̃χ₁⁻</td>
<td>1.1</td>
<td>0.2</td>
<td>520</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>̃χ₂⁺ ̃χ₂⁻</td>
<td>29</td>
<td>22</td>
<td>460</td>
<td>1104</td>
<td>5.5</td>
</tr>
<tr>
<td>̃χ₁⁺ ̃χ₂⁻</td>
<td>-</td>
<td>-</td>
<td>258</td>
<td>0.02</td>
<td>-</td>
</tr>
<tr>
<td>̃χ₁⁺ ̃χ₂⁺</td>
<td>15</td>
<td>11</td>
<td>278</td>
<td>553</td>
<td>2.6</td>
</tr>
<tr>
<td>̃l⁺ ̃l⁻</td>
<td>3.3</td>
<td>-</td>
<td>-</td>
<td>34</td>
<td>-</td>
</tr>
<tr>
<td>̃l⁺ ̃l⁻</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>̃ν̄ν</td>
<td>3.3</td>
<td>-</td>
<td>-</td>
<td>13</td>
<td>-</td>
</tr>
</tbody>
</table>
Search for $Wh(bb) + E_{T}^{\text{miss}}$

1 lepton + $m(bb) + E_{T}^{\text{miss}} + mT$ cut + mCT

Dominant SM background: ttbar production

CMS-PAS-SUS-14-012

Discovery sensitivity: up to $\sim 950$ GeV.

Effect of aged Run 1 detector performance on search for $Wh(bb) + E_{T}^{\text{miss}}$

Study based on full simulation.

- Emulated aged detector with worse $E_{T}^{\text{miss}}$ resolution ($\rightarrow$ impact MT), b-tagging efficiency, e/μ efficiency.
- Discovery sensitivity substantially reduced with aged detector.
Remarks on backgrounds and methods

- Have entered the territory where SUSY cross sections are much less than those of the dominant SM backgrounds.
- Very tight kinematic cuts; operate on extreme tails of SM distributions such as $E_T^{\text{miss}}$. “Weak” signatures (no peaks).
- Most HL-LHC simulations use parametrized MC with background uncertainties either guessed (based on actual measurements with 8 TeV data), or simply assumed.
- Studies generally use simple methods; best to regard the results as *indicative*.
- Compare reach for 300 fb$^{-1}$ & 3000 fb$^{-1}$. 

---

![Graph](graph.png)

• Prospect for a search for direct pair production of a chargino and a neutralino decaying via a W boson and the lightest Higgs boson...with the ATLAS detector, [ATL-PHYS-PUB-2015-032](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies).

• Search for Supersymmetry at the high luminosity LHC with the ATLAS Detector, [ATL-PHYS-PUB-2014-010](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies).


• CMS Upgrade and physics documents Twiki: [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP)


• Supersymmetry discovery potential in future LHC and HL-LHC running with the CMS detector, [CMS-PAS-SUS-14-012](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP).


• Enhanced scope of a Phase 2 CMS detector for the study of exotic physics signatures at the HL-LHC, CMS PAS EXO-14-007.
• **Dijet Resonance Searches with the ATLAS Detector at 14 TeV LHC**, ATLAS Collab., ATL-PHYS-PUB-2015-004.


• **Natural SUSY Endures**, M. Papucci et al., arXiv:1110.6926.


• **Hunting Quasi-Degenerate Higgsinos**, Z. Han et al., arXiv 1401.1235.

• **Constraining Supersymmetry at the LHC with Simplified Models for Squark Production**. L. Edelhauser et al., arXiv:1410.0965.

CMS studies of discovery scenarios

ratios of LHC parton luminosities: 14 TeV / 8 TeV and 33 TeV / 8 TeV

luminosity ratio

M_X (GeV)

WJS2012

MSTW2008NLO