Searching for Supersymmetry at the LHC

Jeffrey D. Richman (UC Santa Barbara)
LHC ring: 2 separate magnetic “highways”

- CMS Experiment, (Cessy, France)
- LHCb Experiment
- ATLAS Experiment Meyrin, Switzerland
- Alice Experiment
- Proton beam

- 9300 magnets, including 1232 15-meter dipoles.
- Radio-frequency EM cavity devices to accelerate beams (8/beam; 40 MHz)
Outline

• Basics of supersymmetry
• The Higgs, SUSY, and “naturalness”
• Overview of SUSY search strategies.
• Examples: Searching for gluinos, EWKinos, scalar quarks, dark matter,...
• Prospects for Run 2
• Conclusions

Most results use 19.5 fb⁻¹ (\( \sqrt{s} = 8 \) TeV).
Supersymmetry transformations

• SUSY xf’s map fermionic and bosonic degrees of freedom onto each other.

• $Q = \text{generator of SUSY transformation}$

\[ Q \left| s \right\rangle = \left| f \right\rangle \]

Q must be fermionic in character!

boson (J=0 or J=1)  fermion (J=1/2)

• The charges (interaction couplings) are unchanged.

• Doubles the numbers of degrees of freedom in the particle spectrum (but CPT did that too!)

• Unlike CPT, don’t see SUSY partners with same masses as SM $\rightarrow$ if SUSY exists, it must be broken.
Particle content of the SM

Quarks: spin-1/2

- $u$ (up)
- $c$ (charm)
- $t$ (top)
- $d$ (down)
- $s$ (strange)
- $b$ (bottom)

Leptons: spin-1/2

- $e^-$ (electron)
- $\mu^-$ (muon)
- $\tau^-$ (tau)
- $\nu_e$ (electron neutrino)
- $\nu_\mu$ (muon neutrino)
- $\nu_\tau$ (tau neutrino)

Gauge bosons: spin-1

- $g$ (gluon (8))
- $\gamma$ (photon)
- $Z^0$ (Z boson)
- $W^+$ (W bosons)
- $W^-$ (W bosons)

Higgs boson: spin-0

- $H$ (Higgs boson)

Gauge bosons:
- Strong force: $g$
- EM force: $\gamma$
- Weak force: $Z^0$, $W^+$, $W^-$

Higgs boson:
- Spin-0
- and field vacuum expectation value
Simple (naïve) SUSY spectrum

squarks: spin-0

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

 scalar quark

down squark

charm squark

top squark

up squark

strange squark

bottom squark

Gauginos: spin-1/2 

\[ \tilde{\gamma}, \tilde{\gamma}_e, \tilde{\gamma}_\mu, \tilde{\gamma}_\tau \]

scalar lepton

electron sneutrino

muon sneutrino

tau sneutrino

Higgsino: spin-1/2

\[ \tilde{H} \]

gluino (8)

photino

Zino

Wino

Strong force

EM force

Weak force
Scalar SUSY particles and chiral multiplets

- The SM is a chiral theory: the L and R chiral projections of the fermion fields have different EW interaction quantum numbers.
  - L projections are SU(2)$_L$ doublets $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$, $u_R$, $d_R$
  - R projections are SU(2)$_L$ singlets

- Each chiral projection of a SM fermion has SUSY scalar partner (preserving degrees of freedom).

\[ e^- \leftrightarrow \tilde{e}_L \]
\[ e^- \leftrightarrow \tilde{e}_R \]
\[ t \leftrightarrow \tilde{t}_L \]
\[ t \leftrightarrow \tilde{t}_R \]

partner of the R-handed $e^-$; has $J=0$
### SUSY spectrum in EW sector (MSSM)

<table>
<thead>
<tr>
<th>Particle</th>
<th>$J$</th>
<th>Degrees of freedom</th>
<th>Particle</th>
<th>$J$</th>
<th>Degrees of freedom</th>
<th>Particle</th>
<th>$J$</th>
<th>Degrees of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+$</td>
<td>1</td>
<td>3</td>
<td>$\tilde{W}^+$</td>
<td>1/2</td>
<td>2</td>
<td>$\tilde{\chi}_1^+$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\tilde{W}^-$</td>
<td>1</td>
<td>3</td>
<td>$\tilde{W}^-$</td>
<td>1/2</td>
<td>2</td>
<td>$\tilde{\chi}_1^-$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$Z$</td>
<td>1</td>
<td>3</td>
<td>$\tilde{Z}$</td>
<td>1/2</td>
<td>2</td>
<td>$\tilde{\chi}_2^+$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>1</td>
<td>2</td>
<td>$\tilde{\gamma}$</td>
<td>1/2</td>
<td>2</td>
<td>$\tilde{\chi}_2^-$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$H$</td>
<td>0</td>
<td>1</td>
<td>$\tilde{H}$</td>
<td>1/2</td>
<td>2</td>
<td>$\tilde{\chi}_1^0$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$h$</td>
<td>0</td>
<td>1</td>
<td>$\tilde{h}$</td>
<td>1/2</td>
<td>2</td>
<td>$\tilde{\chi}_2^0$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$H^+$</td>
<td>0</td>
<td>1</td>
<td>$\tilde{H}^+$</td>
<td>1/2</td>
<td>2</td>
<td>$\tilde{\chi}_3^0$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$H^-$</td>
<td>0</td>
<td>1</td>
<td>$\tilde{H}^-$</td>
<td>1/2</td>
<td>2</td>
<td>$\tilde{\chi}_4^0$</td>
<td>1/2</td>
<td>2</td>
</tr>
<tr>
<td>$A$</td>
<td>0</td>
<td>1</td>
<td>Total</td>
<td></td>
<td>16</td>
<td>Total</td>
<td></td>
<td>16</td>
</tr>
</tbody>
</table>

**Mixing**

The gluino ($\tilde{g}$) is special: because of color, it cannot mix with any other particles.

Gauginos = SUSY partners of SM gauge bosons  
Higgsinos = SUSY partners of higgs bosons  
Neutralinos = mix of neutral gauginos and higgsinos  
Charginos = mix of charged gauginos and higgsinos  
EWKinos = term that denotes neutralinos or charginos

If lightest neutralino is LSP, then can be dark matter candidate.
Why are we still looking for SUSY?

<table>
<thead>
<tr>
<th>Hierarchy problem</th>
<th>Unification of couplings</th>
<th>Dark matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>~$10^{18}$ GeV</td>
<td>SM (no SUSY)</td>
<td>Dark matter (24%)</td>
</tr>
<tr>
<td>Planck scale</td>
<td></td>
<td>Atoms: 4.6%</td>
</tr>
<tr>
<td>(quantum gravity)</td>
<td></td>
<td>Dark energy: 71.4%</td>
</tr>
<tr>
<td>Separation of scales</td>
<td>Minimal SUSY</td>
<td>SUSY provides dark matter candidate particle (Lightest Supersymmetric Particle); in MSSM this is neutralino.</td>
</tr>
<tr>
<td>is stabilized by SUSY.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~$10^2$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electroweak scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(unstable in SM)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Higgs and the Gauge Hierarchy Problem

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

• Assuming that it is an *elementary scalar* particle, the Higgs mass is subject to enormous shifts due to short distance quantum corrections.

• These corrections pull the Higgs mass up to a high physical scale, e.g., the Planck scale!

\[ \begin{align*}
  f &= \text{SM fermion, e.g., top quark} \\
  S &= \text{SUSY scalar partner, e.g., top squark}
\end{align*} \]

SUSY amplitudes tame the quantum corrections!
Scalar particles and fine tuning

- Fundamental scalar fields have the problem of quadratic divergences to the scalar mass squared. These arise from loop-corrections to the mass, which are generically for spin 0:

\[
\delta m^2 = \lambda \int \frac{d^4 k}{(2\pi)^4} \frac{1}{k^2} \sim \frac{\lambda}{16\pi^2} \int dk^2
\]

\[
m^2 = m_0^2 + \alpha \lambda \frac{\Lambda^2}{16\pi^2}
\]

In the Standard Model:

\[
\delta m_h^2 = \frac{3\Lambda^2}{8\pi^2 v^2} \left[ (4m_t^2 - 2M_W^2 - M_Z^2 - m_h^2) + O\left( \log \frac{\Lambda}{\mu} \right) \right]
\]

**Note**:Dominant at low \( m_t \)

\[\lambda \sim \frac{m_h^2}{v^2}\]
“Natural SUSY endures”: the current fashion

Only part of the SUSY spectrum can be constrained by naturalness considerations.

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

\[ \tilde{g} \]

\[ \tilde{t}_L \quad \tilde{b}_L \quad \tilde{t}_R \]

\[ \tilde{H} \]

natural SUSY

\[ \tilde{B} \quad \tilde{W} \]

\[ \tilde{L}_i, \tilde{e}_i \]

\[ \tilde{Q}_{1,2}, \tilde{u}_{1,2}, \tilde{d}_{1,2} \]

\[ \tilde{b}_R \]

decoupled SUSY
“Natural SUSY endures”: the current fashion

Only part of the SUSY spectrum can be constrained by naturalness considerations.

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

Focus of SUSY searches

\[ \tilde{g}, \tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R, \tilde{H}, \tilde{L}_i, \tilde{e}_i, \tilde{Q}_{1,2}, \tilde{u}_{1,2}, \tilde{d}_{1,2} \]

natural SUSY

decoupled SUSY
SUSY breaking

• SUSY, if it exists, is clearly a broken symmetry because partners with masses equal to the SM particles would already have been found.

• SUSY breaking is an complex subject with various scenarios; occurs in “hidden sector”; transmitted to MSSM particles via...
  – gravity mediation $\rightarrow$ heavy gravitino ($\tilde{G}$), couplings $\approx$ gravity
  – gauge mediation $\rightarrow$ very light gravitino (eV range); is LSP!

• Whatever the breaking mechanism, SUSY particles still have the same SM gauge couplings as their ordinary SM partners. Key point when thinking about decay modes. Your intuition for the SUSY Particle Date Book is good!
Installing muon readout electronics

Superconducting solenoid: B-field parallel to beam axis

Spring – summer 2014
• Parton momentum transverse to the beam is negligible.
• Parton momentum along the beam direction (z) is large and unknown, except on a statistical basis.

\[
\sum_{i=\text{colliding partons}} p_x^i \approx 0 \\
\sum_{i=\text{colliding partons}} p_y^i \approx 0 \\
\sum_{i=\text{colliding partons}} p_z^i \neq 0
\]
Higgs boson mass peaks

- Discovery was based on searches for narrow peaks at a consistent mass in multiple search channels.
- The determination of the event yield is greatly simplified.
- The masses are Lorentz-invariant quantities. Any reference frame is OK!
An example of a “natural” SUSY model ("NM3")
An example of a “natural” SUSY model ("NM3")

$m_h = 125$ GeV

$H^0, A^0, H^\pm$
An example of a “natural” SUSY model (“NM3”)

Strongly interacting sector:
- Particles with color (QCD) charge.
- Large production cross section if mass is not too high.
An example of a “natural” SUSY model (“NM3”)

Electroweak sector:
- EM/weak interactions
- Major impact on decays of colored particles
- Generally low production cross sections, but may have lower masses.
- LSP lives here!

Lightest Supersymmetric Particle (LSP)
Big themes: production and decays

LHC SUSY Cross Section Working Group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections
Big themes: production and decays

LHC SUSY Cross Section Working Group

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections

arXiv:1206.2897
Measurements of SM processes in CMS

February 2014

CMS Preliminary

Production Cross Section, $\sigma$ [pb]

$W^+$ $n$-jets
$Z^+$ $n$-jets
$W^+$ $\gamma$

Di-boson production

Top-quark production

Higgs production

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

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

$0.1$ pb = 100 fb

Th. $\Delta\alpha$, $\Delta\sigma$
Gluino decay

- SUSY preserves the gauge symmetries, so the SUSY partners of the gluons must also transform according to the 8-dimensional representation of SU(3)$_C$.
- Fundamental vertex for $g \rightarrow \tilde{q}_{L,R} + \bar{q}$ has same coupling strength as that for $g \rightarrow q + \bar{q}$.
Gluino pair production and decay to stop

Signature: 4 top quarks + $p_T^{\text{miss}}$
LSPs are unobserved: cannot reconstruct mass peaks!
Direct pair production of top squarks

Example: direct stop production with decay to neutralinos or charginos.

Sensitivity of the searches will depend strongly on the neutralino mass.

The channel with $\tilde{t} \rightarrow b \tilde{\chi}_1^+$ has sensitivity to lower stop mass.
Anatomy of a background: ttbar

Extremely common background in NP searches.
- looks like low-mass SUSY!
- large real MET from neutrinos in leptonic decays.
- high jet multiplicity, including b jets.

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

2. PRODUCTION
- pT distributions of t and tbar (affected by parton distribution functions, QCD renorm & factorization scales)
- Effect of initial-state radiation
- Spin correlations of t and tbar

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

Each 2-body system shown in 2-body rest frame.
Most “SUSY-like” process in SM: $pp \rightarrow t\bar{t}$

Candidate event for process $pp \rightarrow t\bar{t}$

- $t \rightarrow bW^+$; $W^+ \rightarrow e^+\nu_e$
- $\bar{t} \rightarrow \bar{b}W^-$; $W^- \rightarrow q_1\bar{q}_2$

Missing momentum vector from neutrino
Data analysis for SUSY searches

SIGNAL: Characterize kinematic distributions using simulated (MC) samples.

BACKGROUND: Characterize kinematic distributions using simulated (MC) samples; validate simulation using control samples in data.

DEFINE SIGNAL REGIONS
(without looking at this neighborhood of the event sample).
Use SIGNAL MC to determine SELECTION EFFICIENCY.

PREDICT BACKGROUND contribution in SIGNAL regions, ideally using CONTROL REGIONS. Extrapolation factors from MC, with uncertainties determined from agreement in other control regions.

What could possibly go wrong?
SUSY Search Challenges

1. Presence of LSP in each SUSY decay chain (R-parity conserving models) → no observable mass peak for parent particle.

2. Looking for excess yields in the tails of distributions of kinematic variables, such as missing transverse momentum.

3. The background determination is much more complicated, since one cannot simply use mass sidebands.

4. Many potential problems. Robust and complementary approaches to background determinations are extremely valuable.
What can possibly go wrong?

- Yield in signal region can be biased by tuning selection cuts on the data.
- People often stop looking for mistakes when they obtain a “desirable” result.
- Background shape or normalization can be estimated incorrectly.
- Understanding the background in one kinematic region does not necessarily mean that you understand it in another region.
- Shapes used in fit may not adequate to describe the data. (Especially worrisome in multidimensional fits!)
- Trigger efficiencies may not be accounted for & can bias sig. or backgrounds.
- Systematic errors may be underestimated or incomplete. Assumptions may be wrong!
- Correlations may not taken into account.
- Backgrounds peaking under signal may not correctly determined.
- Signal significance may not be estimated correctly.
- Signal can created artificially as “reflection” of another peaking process.
- Changes in experimental conditions may not fully taken into account.
- Average of many bad measurements might not give a good measurement.
- Bugs in the program!
- Advisor in a hurry. Need to finish thesis! No time to look for more problems.
- A superposition of several of the above effects!
The penta-quark phenomenon: 2002-2005

Slide courtesy of R. Schumacher

<table>
<thead>
<tr>
<th>Photoproduction on Deuteron ( Q^+ )</th>
<th>LEPS-C</th>
<th>CLAS-d1</th>
<th>LEPS-d</th>
<th>LEPS-d2</th>
<th>CLAS-d2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoproduction on Proton ( pK_s^0 )</td>
<td>SAPHIR</td>
<td>CLAS-p</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photoproduction on Proton ( nK^-p^+ )</td>
<td>DIANA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exclusive ( K^+ (N) \rightarrow pK_s^0 )</td>
<td>Hermès</td>
<td>ZEUS</td>
<td>nBC</td>
<td>SPHINX</td>
<td>HyperCP</td>
</tr>
<tr>
<td>Inclusive lepton + D, A ( \rightarrow p K_s^0 )</td>
<td>SVD2</td>
<td>JINR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p + A \rightarrow pK_s^0 + X )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p + p \rightarrow pK_s^0 + S^+ )</td>
<td>COSY-TOF</td>
<td>HERA-B</td>
<td>BELLE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other ( Q^+ ) Upper Limits</td>
<td>BES J,Y</td>
<td>CDF</td>
<td>ALEPH, Z</td>
<td>FOCUS</td>
<td>WA89</td>
</tr>
<tr>
<td>( p + p (or A) \rightarrow X^{--} + X )</td>
<td>NA49/CERN</td>
<td>WA89</td>
<td>HERA-B</td>
<td>ALEPH</td>
<td>ZEUS</td>
</tr>
<tr>
<td>Inclusive ( Q^{++} \rightarrow p K^+ )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclusive ( Q^{0c} \rightarrow D^{(*)-} p )</td>
<td>H1/HERA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Particles and Nuclei International Conference, Santa Fe, 2005
SUSY Search Strategies

1. Large missing momentum transverse to the beam axis.
2. High mass scales (but difficult to isolate decay products of a specific SUSY parent particle)
3. Long decay chains $\rightarrow$ large number of jets and isolated leptons. But mass splittings are unknown, so don’t know energy distributions of these objects.
4. Natural SUSY $\rightarrow$ 3rd generation quarks (t, b) $\rightarrow$ b-jet tagging is extremely important.
5. In models with Gauge Mediated SUSY breaking, can have high pT photons.
6. In some scenarios, can have Higgs bosons produced in the decay chains.
**CMS SUSY Results (ICHEP 2014)**

**Summary of CMS SUSY Results** in SMS framework

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probes "up to" the quoted mass limit

For decays with intermediate mass, $m_{\text{intermediate}} = x m_{\text{mother}} + (1-x) m_{\text{top}}$

**CMS Preliminary**

- Gluino pair production
- Squark pair production
- Top squark pair production
- Bottom squark pair production
- Neutralino/Chargino pair production
- R-parity violating SUSY
Generic hadronic SUSY search using MHT

• Signature: Jets + MHT; events with leptons are vetoed
  – Jets: ≥3 jets with $p_T > 50$ GeV, no b-tagging.
  – Veto event if MHT vector is ≈aligned with any of 3 leading jets.

• Bin data in
  – HT
  – missing HT (MHT)
  – Jet multiplicity (3—5, 6—7, ≥8 jets)

• Background estimation: largely data driven.

\[
H_T = \sum_{j=\text{jets}} |\vec{p}_T^j|
\]

\[
\mathcal{H}_T = \left| \vec{H}_T \right| = -\sum_{j=\text{jets}} \vec{p}_T^j
\]

- ttbar with $W \rightarrow l \nu$
- $W \rightarrow l \nu$ + jets
- ttbar with $W \rightarrow \tau \ (\rightarrow h) \ \nu$
- $W \rightarrow \tau \ (\rightarrow h) \ \nu$ + jets
- $Z \rightarrow \nu\nu$ + jets

Control samples: Single-lepton + jets + MHT

- QCD multijet events
  MHT ~ aligned with high $p_T$ jet.

Control sample:
Multijets with re-balance and smear procedure

Control samples:
$\gamma + $ jets, $Z(\mu\mu)$+jets

SUS-13-012
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13012
Distribution in bins of N(jets), $H_T$, and $H_T$
• Consider the bin with
  – N(observed) = 9 events
  – N(background) = 0.8 ± 1.7 events

• First, let’s ignore the uncertainty on the background. What is the probability for a Poisson with μ=0.8 to fluctuate to at least 9 events?
  – Prob( n≥9 | μ =0.8 ) = 1.8 × 10^{-7}

  Have we discovered new physics?

• NO! The uncertainty is crucial!
  – Prob( n≥9 | μ = 0.8 ± 1.7) ≈ 0.15

• This example highlights the importance of quantifying the uncertainties on the SM backgrounds.
Search for generic jets and MET: results

- Simplified model exclusion plots

1. Compute excluded cross section for each model in param space
2. Compare to reference cross section to see if model excluded
   - Assume 100% branching fraction for stated process!
Search for generic jets and MET: results

- Simplified model exclusion plots

  1. Compute excluded cross section for each model in param space
  2. Compare to reference cross section to see if model excluded
     - Assume 100% branching fraction for stated process!

---

As before, weak limit with reduced number of squarks!
Lepton spectrum method: for leptons produced in W decay, the lepton spectrum can be used to measure the $\nu$ spectrum.

Makes use of W helicity fractions in $t\rightarrow bW$

...and W helicity fractions in W+jets
### MSSM parameter count

<table>
<thead>
<tr>
<th>Sector of MSSM</th>
<th>Number of parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Model parameters</td>
<td>18</td>
</tr>
<tr>
<td>1 Higgs parameter, analogous to Higgs mass in SM</td>
<td>1</td>
</tr>
<tr>
<td>Gaugino/higgsino sector</td>
<td>5</td>
</tr>
<tr>
<td>Gaugino/higgsino sector – CP violating phases</td>
<td>3</td>
</tr>
<tr>
<td>Squark and slepton masses</td>
<td>21</td>
</tr>
<tr>
<td>Mixing angles to define squark and slepton mass eigenstates</td>
<td>36</td>
</tr>
<tr>
<td>CP violating phases</td>
<td>40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>124</strong></td>
</tr>
</tbody>
</table>

In cMSSM, SUSY is described by just 4 continuous real params + 1 sign.
Formulating SUSY – a short history

$\tan(\beta) = 10$

$A_0 = 0 \text{ GeV}$

$\mu > 0$

$m_t = 173.2 \text{ GeV}$

$\mathcal{L}_{\text{int}} = 4.98 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV}$

$\tan(\beta) = 0$

$A_0 = 0 \text{ GeV}$

$\mu = 0$

$m_t = 173.2 \text{ GeV}$

$\mathcal{L}_{\text{int}} = 4.98 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV}$
Gluino pair production and decay to stop

Signature: 4 top quarks + $p_T^{\text{miss}}$
LSPs are unobserved: cannot reconstruct mass peaks!
Results for gluino pair production with $\tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0$

$M(\tilde{\chi}_1^0)$
Mass of LSP

Maximum gluino mass limit at minimum LSP mass.

$M(\tilde{g})$
Mass of pair-produced particle

$\sqrt{s} = 8$ TeV
ICHEP 2014

Increasing mass splitting $\rightarrow$ increasing MET

Decreasing cross section
The famous neutralino dilepton cascade

The $\tilde{\chi}^0_2$ can be produced in any process, not just direct EW production.

$$m_{\ell^+\ell^-}(\text{max}) = \sqrt{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}^0_1})} / m_{\tilde{\ell}}$$
Search for SUSY in opposite sign dileptons

$m_{\ell^+\ell^-} > 20$ GeV, $N(\text{jets}) \geq 2$ ($p_T > 40$ GeV)

**Signal Sample**
- Opposite sign, same flavor leptons ($e\mu$)

**Control Sample**
- Opposite sign, opposite flavor leptons ($\mu\mu$)

**CMS Preliminary**
- 19.4 fb$^{-1}$ (8 TeV)

$E_T^{\text{miss}} > 150$ GeV

$R_{\text{SF/OF}} = 1.00 \pm 0.04$ (central)
$R_{\text{SF/OF}} = 1.11 \pm 0.07$ (forward)

** Prelude sample**
- Dominate by $t\bar{t}$ production

**Data/MC**
- Normalized to data
Search for SUSY in opposite sign dileptons

Fit opposite sign dilepton mass distribution to shapes from (1) Flavor Symmetric (FS) background, Drell Yan, and signal.

CMS Preliminary 19.4 fb⁻¹ (8 TeV)

SIGNAL SAMPLE (e⁺e⁻, μ⁺μ⁻ events)

CONTROL SAMPLE (eμ events)

Signal contribution (2.4σ local significance).
Search for SUSY in opposite-sign dileptons

**Central leptons**

| $|\eta_{lep}|<1.4$ |

**Forward leptons**

$\geq1$ forward lepton $1.6<|\eta_{lep}|<2.4$

2.6$\sigma$ excess (not significant)
Search for SUSY in opposite sign dileptons

$\chi_0 \sim m_\chi \sim m_{\tilde{b}}$
“Direct” pair production of light stops

Example: direct stop production with decay to neutralinos or charginos.

Sensitivity of the searches will depend strongly on the neutralino mass. The channel with $\tilde{t} \rightarrow b\tilde{\chi}_1^+$ has sensitivity to lower stop mass.
Search for direct stop production: $pp \rightarrow \tilde{t}_1 \tilde{t}_1$

$\Delta m = m(\tilde{t}) - m(\tilde{\chi}_1^0)$

$m(\tilde{t}_1) < m(\tilde{\chi}_1^0)$
violates assumed spectrum

$m(\tilde{t}) \geq m(t) + m(\tilde{\chi}_1^0)$

$m(\tilde{t}) < m(W)$
4-body

$m(W) < \Delta m < m(t)$
3-body

$\Delta m > m(t)$
2-body

$\tilde{t} \rightarrow bW^* \tilde{\chi}_1^0$
(off-shell W)

$\tilde{t} \rightarrow bW \tilde{\chi}_1^0$
(on-shell top)

$\tilde{t} \rightarrow t \tilde{\chi}_1^0$

has extra mass parameter

$\tilde{t} \rightarrow c \tilde{\chi}_1^0$

$\tilde{t} \rightarrow b \tilde{\chi}_1^+ \rightarrow bW^* \tilde{\chi}_1^0$
Search for direct stop production: \( pp \rightarrow \tilde{t}_1 \tilde{t}_1 \)

\[
m(t) < m(\tilde{t}_1) < m(\tilde{\chi}_1^0) \Rightarrow \tilde{t} \rightarrow bW^* \tilde{\chi}_1^0
\]

\[
m(\tilde{t}) < m(\tilde{\chi}_1^0) \Rightarrow \tilde{t} \rightarrow c\tilde{\chi}_1^0
\]

\[
m(\tilde{\chi}_1^0) \Rightarrow \tilde{\chi}_1^0 \rightarrow bW^* \tilde{\chi}_1^0
\]

Same final state but different kinematics!
Search for direct stop production: $pp \rightarrow \tilde{t}_1 \tilde{t}_1$

Use BDTs for separate modes & regions.

CMS Simulation \( \sqrt{s} = 8 \text{ TeV}, \int L dt = 19.5 \text{fb}^{-1} \)

Preselection +
\[ M_T > 120 \text{ GeV} \]
\[ \text{MET} > 100 \text{ GeV} \]
\[ \tilde{t} \rightarrow t\tilde{\chi}^0_1 \times 100 \]

Use BDTs for separate modes & regions.

CMS Simulation \( \sqrt{s} = 8 \text{ TeV}, \int L dt = 19.5 \text{fb}^{-1} \)

Preselection +
\[ M_T > 120 \text{ GeV} \]
\[ \text{MET} > 100 \text{ GeV} \]
\[ \tilde{t} \rightarrow b\tilde{\chi}^+_1 \times 100 \]

Use BDTs for separate modes & regions.
Results from searches for top squarks

\[ m_{\tilde{t}} \text{ production, } \tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0 \]

\[ \sqrt{s} = 8 \text{ TeV} \]

ICHEP 2014

CMS Preliminary

- Observed
- Expected

SUS-13-011 1-lep (MVA) 19.5 fb⁻¹
SUS-14-011 0-lep + 1-lep + 2-lep (Razor) 19.3 fb⁻¹
SUS-14-011 0-lep (Razor) + 1-lep (MVA) 19.3 fb⁻¹
SUS-13-009 (monojet stop) 19.7 fb⁻¹ (\( \tilde{t} \rightarrow c \tilde{\chi}_1^0 \))
SUS-13-015 (hadronic stop) 19.4 fb⁻¹
Search for dark matter at the LHC

- Above: direct dark matter detection processes: doesn’t have to be SUSY!
- Use crossing to get $q + \bar{q} \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0$
- How to see $q + \bar{q} \rightarrow$ invisible?
**Signature for dark matter at the LHC**

**Signature:** Jet or photon from initial-state radiation (ISR) + large missing transverse momentum

**Dominant background:** $Z(\rightarrow \nu\nu) +$ jets

...don’t want to rely on MC modeling of initial-state radiation
There are lots of monojet events in the data!

$p_T^{\text{miss}} = 914 \text{ GeV}$
We can predict the contribution from $Z + 1$ jet

\[ \sum_{i=e, \mu, \tau} B(Z \rightarrow \nu_i \bar{\nu}_i) \approx 6 \]

\[ \frac{B(Z \rightarrow \mu^+ \mu^-)}{B(Z \rightarrow \mu^+ \mu^-)} \approx 6 \]
Searching for dark matter: monojet search results

- MET > 250 GeV
- 1 central jet, pT>110 GeV.
- 2nd softer jet allowed, not back-to-back.
- Remarkable that QCD is so well controlled.
- Veto events with leptons
- Z→νν is dominant background; predict from Z→μμ control sample.
Searching for dark matter: monojet search results

\[ \sigma_{\chi-Nucleon} \, [\text{cm}^2] \]

\[ \chi M_\chi [\text{GeV}] \]

CMS, 90% CL, 7 TeV, 5.0 fb\(^{-1}\)
CMS, 90% CL, 8 TeV, 19.7 fb\(^{-1}\)
CMS, 90% CL, 7 TeV, 5.0 fb\(^{-1}\)
CMS, 90% CL, 8 TeV, 19.7 fb\(^{-1}\)

COUPP 2012
ICECUBE W+W
Super-K W+W

\[ \sigma_{\chi-Nucleon} \, [\text{cm}^2] \]

\[ \chi M_\chi [\text{GeV}] \]

CMS, 90% CL, 7 TeV, 5.0 fb\(^{-1}\)
CMS, 90% CL, 8 TeV, 19.7 fb\(^{-1}\)

\[ \frac{\langle \gamma \gamma \chi \rangle}{\Lambda^2} \]

Spin Dependent

\[ \frac{\langle \gamma \gamma \chi \rangle}{\Lambda^2} \]

Axial-vector operator

\[ \frac{\langle \gamma \gamma \chi \rangle}{\Lambda^2} \]

Scalar
Spin Independent
Relative parton luminosities: 13 TeV vs. 8 TeV

- 1350 GeV gluinos: x30
- 1000 GeV gluinos: x20
- 750 GeV squarks: x9
- 350 GeV X⁺⁻X⁰: x3
- Top pairs: x4

Graph showing the ratios of LHC parton luminosities: 13 TeV / 8 TeV with various processes:
- $gg \rightarrow X$
- $qg \rightarrow X$
- $\sum q_i\bar{q}_i \rightarrow X$
Sensitivity projections for selected searches

Summary of CMS SUSY Projections with SMS

Preliminary

- $\tilde{\chi}_1 \tilde{\chi}_2 \rightarrow WZ \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- $\tilde{\chi}_1 \tilde{\chi}_2 \rightarrow WH \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- $\tilde{g} \tilde{g} \rightarrow tttt \tilde{\chi}_1 \tilde{\chi}_1$
- $\tilde{g} \tilde{g} \rightarrow qqqq \tilde{\chi}_1 \tilde{\chi}_1$

5σ discovery: 14 TeV, 3000 fb⁻¹
5σ discovery: 14 TeV, 300 fb⁻¹
95% CL limits: 8 TeV

Probe *up to* the quoted mass

Mass scales [GeV]
“Once you have a collider, every problem starts to look like a particle.”