Search for Supersymmetry with early LHC data
David Stuart, UC, Santa Barbara. May 12, 2010

3 PFlow jets $p_T > 10$ GeV
$p_T$ cut on tracks displayed $> 0.4$ GeV
Outline

What is Supersymmetry & why are we looking for it?

How do we go about searching for it?

When might we find it?
The Standard Model, an incomplete success

Parameters unexplained: masses, mixings, couplings.
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$\Rightarrow$ Search for Higgs at CMS
The Standard Model, an incomplete success

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Parameters unexplained: masses, mixings, couplings. W, Z, fermion masses could be generated by Higgs mechanism. Though values not explained. And $m_H$ should diverge due to corrections. Would cancel if fermion $\leftrightarrow$ boson “super symmetry”.

\[ \begin{aligned}
  &H \quad g \quad g \quad H \\
  &\overline{W} \quad \tilde{W} \quad W
\end{aligned} \quad \begin{aligned}
  &H \quad h \quad h \quad H \\
  &\tilde{f} \quad f
\end{aligned} \]
The Standard Model, an incomplete success

Parameters unexplained: masses, mixings, couplings. W, Z, fermion masses could be generated by Higgs mechanism. Though values not explained. And $m_H$ should diverge due to corrections. Would cancel if fermion $\leftrightarrow$ boson “super symmetry”. Cancel the debt by printing more particles.
The Standard Model, an incomplete success

Parameters unexplained: masses, mixings, couplings. Unification would be nice.
The Standard Model, an incomplete success

Parameters unexplained: masses, mixings, couplings. Unification would be nice, and corrections from the extra “SUSY” particles seem to provide it.
The Standard Model, an incomplete success

The standard model does not explain dark matter.
The Standard Model, an incomplete success

The standard model does not explain dark matter. A conserved SUSY quantum number would. The LSP.
Supersymmetry, an experimentalists dream

Many parameters to measure.
  Doubled mass spectrum, more mixings.

New puzzles to solve.
  Whence the masses and mixings?
  Why is the symmetry broken?
Supersymmetry, an experimentalists dream

Many parameters to measure.
  Doubled mass spectrum, more mixings.

New puzzles to solve.
  Whence the masses and mixings?
  Why is the symmetry broken?

Supersymmetry’s variety of signatures makes it a target representative of many new models.
How to search for SUSY?

Produce super-partners, and detect that we have done so.
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Massive, so need energy => LHC
How to search for SUSY?

Produce super-partners, and detect that we have done so.

Massive, so need energy => LHC

Production via SM like diagrams. For example...
How to search for SUSY?

The same diagram that produces WZ in SM…
How to search for SUSY?

…could produce Winos and Zinos.
How to search for SUSY?

The cross section for weak production is small.

But squarks & gluinos would be strongly produced...
How to search for SUSY?

In pairs if RP conserving.
How to search for SUSY?

Cross-section is calculable given masses.

Example: 400 GeV squark and gluino gives $\sigma \approx 40$ pb at 7 TeV.

$\approx 1/4$ of top quark cross-section.

Could produce thousands this year.
Varied signatures

A CMS mSUGRA benchmark, LM0

Higgs sector

- $H^0, A^0 \rightarrow H^0$
- $\tilde{t}_2$
- $\tilde{b}_1$
- $\tilde{l}_1$
- $\tilde{l}_2$
- $\tilde{t}_L$
- $\tilde{b}_L$
- $\tilde{l}_R$
- $\tilde{b}_R$
- $\tilde{g}$
- $\tilde{q}$

Squarks

- $q$
- $\tilde{q}$
- $\tilde{g}$
- $\tilde{q}$

Gluino

- $\tilde{g}$
- $\tilde{q}$
- $\tilde{g}$
- $\tilde{q}$

Sleptons

- $\tilde{\chi}_1^0$
- $\tilde{\chi}_2^0$
- $\tilde{\chi}_2^\pm$
- $\tilde{\chi}_3^0$
- $\tilde{\chi}_4^\pm$

Charginos/neutralinos

- $\chi_1^0$
- $\chi_2^0$
- $\chi_3^0$
- $\chi_4^0$

LSP

- $\tilde{\chi}_1^0$
- $\tilde{\chi}_2^0$
- $\tilde{\chi}_3^0$
- $\tilde{\chi}_4^0$

$W^{\pm}$

$Z^{0*}$

$\ell^{\pm}$
Varied signatures

A CMS mSUGRA benchmark, LM0

Higgs sector

- $H^0, A^0 \rightarrow H^+$
- $\tilde{b}_1$ (squarks)
- $\tilde{g}$ (gluino)
- $\tilde{q}_L, \tilde{q}_R, \tilde{\tau}_1, \tilde{\tau}_2$
- $\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3$
- $\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_2$
- $h^0$

Sleptons

- $\tilde{\tau}_1, \tilde{\tau}_2$

Charginos/neutralinos

- $\tilde{\chi}^\pm_1$
- $\tilde{\chi}^0_2$
- $\tilde{\chi}^0_3$
- $Z^0, W^\pm$
- $\ell^\pm$

LSP
Varied signatures

A CMS mSUGRA benchmark, LM0

Higgs sector

Higgs bosons: $H^0, A^0$, $H^+$

Squarks

$g_1, q_L, q_R, b_1$

Gluino

$\tilde{g}$

Sleptons

$\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\tau}_L, \tilde{\tau}_R$,

Charginos/neutralinos

$\tilde{\chi}_{1,2}^0, \tilde{\chi}_{1,2}^\pm$, LSP $\tilde{\chi}_1^0$

Varied signatures

Diagrams:

- $g \rightarrow q, \tilde{g} \rightarrow q$
- $q \rightarrow \tilde{q}$
- $\tilde{\chi}_1^0 \rightarrow \chi^0$
- $\tilde{\chi}_2^0 \rightarrow Z^0, \ell^\pm$
- $\tilde{\chi}_1^\pm \rightarrow W^\pm, \ell^\pm$
Many different search modes

Multijets + MET

Lepton + jets + MET

Dileptons + jets + MET

Same sign dileptons + jets + MET

Trileptons + jets + MET
Many different search modes

Each mode has different backgrounds.

Search amounts to predicting these bkgds and looking for an excess above prediction.

Multijets + MET

Lepton + jets + MET

Dileptons + jets + MET

Same sign dileptons + jets + MET

Trileptons + jets + MET
Background cross-sections

\[ \sqrt{s} = 7 \text{ TeV} \]

- \( W + \text{jets} \)
  - \( W \rightarrow \ell \overline{\nu} \)
  - 28000 pb NLO

- \( Z + \text{jets} \)
  - \( Z \rightarrow \ell^+ \ell^- \)
  - 2800 pb NLO

- \( t\bar{t} \)
  - 165 pb NNLO

- \( t + X \)
  - (t-chan)
  - 63 pb NLO

- \( tW \)
  - 10.6 pb

- \( W^+W^- \)
  - 43 pb

- \( t + X \)
  - (s-chan)
  - 4.6 pb

- \( WZ \)
  - 18 pb

- \( ZZ \)
  - 5.9 pb
Background cross-sections

- $tt$: 165 pb NNLO
- $t + X$ (t-channel): 63 pb NLO
- $tW$: 10.6 pb
- $W^+W^-$: 43 pb
- $t + X$ (s-channel): 4.6 pb
- $WZ$: 18 pb
- $ZZ$: 5.9 pb
- Low mass SUSY benchmark points:
  - LM0: 39 pb
  - LM1: 4.9 pb
  - LM3: 3.4 pb
  - LM9: 7.1 pb
Need to predict the Njet and MET tails?

But kinematic tails are hard to calculate: higher orders, pdfs, detector effects…

e.g., Z+jets
How to predict the Njet and MET tails?

Monte Carlo predictions?

Sophisticated, higher order modeling, e.g., ALPGEN.

Elaborate simulation of detector response.
How to predict the Njet and MET tails?

Monte Carlo predictions?

Sophisticated, higher order modeling, e.g., ALPGEN.

Elaborate simulation of detector response.

Both are software...Only trust in so far as validated with data.
How to predict the Njet and MET tails?

Data validation challenges:

Slow.

Fit away signal?
How to predict the Njet and MET tails?

Data validation challenges:
  Slow.
  Fit away signal?

Don’t want to wait…
How to predict the Njet and MET tails?

Would like a quick, data-driven method to predict MET in Z+jet events.

In this case it is fake MET, from mis-measurement.
Missing $E_T$ in Z+jets

The Z is well measured. The MET comes from the detector’s response to the jet system.
For each Z+jet event, find an event w/ a comparable jet system and use its MET as a prediction.

Huge QCD x-section makes such events SUSY free.
For each Z+jet event, use a MET template measured from events with a comparable jet system in $O(1)$ pb$^{-1}$. Templates measured in bins of $N_J$ and $J_T = \Sigma_j E_T$. 
Missing $E_T$ in Z+jets

Example of template parameterization

For each data event...

Data distribution

Background prediction
Missing $E_T$ in Z+jets

Example of template parameterization

For each data event, look up the appropriate template. Sum these, each with unit normalization, to get the full background prediction.
Missing $E_T$ in $Z+\text{jets}$, MC closure test

$Z+\text{jets}$: $N_j = 2$ (50 GeV)
Missing $E_T$ in $Z$+jets, MC closure test

$Z$+jets: $N_j = 3$ (50 GeV)
Missing $E_T$ in Z+jets, MC closure test

$Z$+jets: $N_j \geq 4$ (50 GeV)
"Scaled" includes a low MET normalization, which is important for low $N_j$. 

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The figure shows the measurement of $E_T$ in Z+jets, with different $N_j$ values: 
- $N_j = 2$ 
- $N_j = 2$ (scaled) 
- $N_j = 3$ 
- $N_j \geq 4$
Missing $E_T$ in $\gamma$+jets, MC closure test

$\gamma$+jets: $N_J = 2$ (50 GeV)
Missing $E_T$ in $\gamma$+jets, MC closure test

$\gamma$+jets: $N_J = 3$ (50 GeV)
Missing $E_T$ in $\gamma$+jets, MC closure test

$\gamma$+jets: $N_j \geq 4$ (50 GeV)
“Scaled” includes a low MET normalization, which is important for low $N_j$. 

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**Missing $E_T$ in $\gamma$+jets, MC closure tests**
Missing $E_T$ in $Z/\gamma+$jets, robustness tests

Various detector effects could add MET tails.

Check robustness with MC tests, applied equally to all samples.
Missing $E_T$ in $Z/\gamma$+jets, robustness tests

- $\Delta R=0.8$ hole at $(h,f) = (0,0)$
- Double gaussian smearing
- Randomly add 50-100 GeV “noise jets”
- Vary $n_J$ slope by $\pm 50\%$.
- Jet energy scale sensitivity.

$Z$+jets: $N_J = 3$

- Inefficiencies for non-leading jets
- Increased Gaussian smearing
- Hot cells or noise
- ALPGEN composition
Missing $E_T$ in $Z/\gamma+\text{jets}$, robustness tests

- $\Delta R=0.8$ hole at $(h,f)=(0,0)$
- Double gaussian smearing
- Randomly add 50-100 GeV “noise jets”
- Vary $n_J$ slope by $\pm 50\%$
- Jet energy scale sensitivity.

Now working to validate this with low $E_T\gamma+\text{jets}$ from early data.
Missing $E_T$ in $W(\mu\nu)+\text{jets}$

Can we predict $W+\text{jets}$, and $tt\rightarrow W+\text{jets}$?
Missing $E_T$ in $W(\mu\nu)+jets$

Can we predict $W+jets$, and $tt\rightarrow W+jets$?

Templates can predict the *fake* MET in $W+jet$ events, but we also need to predict the *real* MET, i.e., the $\nu p_T$. 
Missing $E_T$ in $W(\mu \nu)+\text{jets}$

Can we predict $W+\text{jets}$, and $tt\rightarrow W+\text{jets}$?

Templates can predict the fake MET in $W+\text{jet}$ events, but we also need to predict the real MET, i.e., the $\nu p_T$.

But, the $\nu p_T$ spectrum is $\approx$ same as the $\mu p_T$ spectrum, if we ignore V-A or randomize $W$ polarization.
Pretend we could detect $\nu$ and apply templates.
Mismatch due to b-jet dominance.
But, neutrino $p_T$ dominates MET.
Combining template prediction with $\mu p_T$ spectrum gives a prediction for the full MET distribution.
The same approach predicts W shape, if polarization is not extreme.
Comparison with signal

Benchmark points (LM4 and LM1) stand out with 200/pb at 14 TeV.
LM4=(m_0=210,m_{1/2}=285); LM1=(60,250). tan(β)=10.
But we don’t have 14 TeV.
But we don’t have 14 TeV. So it will be a bit harder.

When will we discover SUSY with 7 TeV?
But we don’t have 14 TeV. So it will be a bit harder.

When will we constrain SUSY with 7 TeV?
When?

Expected limits in multijets + MET search

Systematic uncertainty assumed to be 50% overall. Separate tight selections for 100 pb\(^{-1}\) and 1 fb\(^{-1}\).
When?
Similar limits from same-sign dilepton search

CMS Preliminary, $\sqrt{s} = 7$ TeV
- Observe 1 event in 100 pb$^{-1}$
- Observe 4 event in 1 fb$^{-1}$
- CDF Preliminary 3l (3.2 fb$^{-1}$)
- D0 observed limit (2.3 fb$^{-1}$)
- LEP excluded regions

$m_{1/2}$ (GeV/c$^2$)

$m_0$ (GeV/c$^2$)

$m_{1/2}$: tan$\beta = 3$, $A_0 = 0$, ($\mu$) > 0
When?
So far, we only have a few inverse nanobarns. But, that is a few hundred million events…
Detector performance encouraging with first data.
Tracking calibrated with $K_s$, $\Lambda$, $\Xi$, $\Omega$, $J/\psi$, $D$ resonances.
When?
Expect 100 pb⁻¹ by end of this year and 1 fb⁻¹ by end of next year.
Tuning up…
Summary

Potential for quick sensitivity to Supersymmetry

If we can obtain robust, data-driven background predictions

QCD based templating gives an \textit{in situ} prediction of MET distribution.

Charged lepton $p_T$ predicts neutrino $p_T$. 
Acknowledgements

MET prediction method by Victor Pavlunin. PRD81:035005 arXiv:0906.5016

Several slides borrowed from Jeff Richman

Other material from

...and references therein.
Extra slides
Dileptons

\[ m(\ell^+ \ell^-) \]
\[ \tilde{\chi}^0_2 \rightarrow \ell^+ \tilde{\ell}^-; \quad \tilde{\ell}^- \rightarrow \ell^- \tilde{\chi}^0_1 \]

\[ m(e^\pm \mu^\mp) \]
How to search for SUSY?

Leading order cross section, \( \tan \beta = 3, A=0, \mu>0 \)

Rough limit from Tevatron
Typical decay patterns in LM0

\[ \tilde{b}_1 \rightarrow \tilde{\chi}_2^0 b \ (29\%) \]
\[ \rightarrow \tilde{\chi}_1^- t \ (24\%) \]

\[ \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 e^+ e^- \ (3.3\%) \]
\[ \tilde{\chi}_1^0 \mu^+ \mu^- \ (3.3\%) \]

\[ \tilde{b}_1 \rightarrow \tilde{\tau}_1 W^- \ (43\%) \]

\[ \tilde{\tau}_1 \rightarrow \tilde{\chi}_1^+ W^- \ (100\%) \]
Typical decay patterns in LM0

\[ \tilde{g} \rightarrow \tilde{t}_1 \tilde{t} + \text{c.c.} \ (46\%) \]

\[ \tilde{b}_1 \rightarrow \tilde{t}_1 W^- \ (43\%) \]

\[ \tilde{t}_1 \rightarrow \tilde{\chi}_1^+ W^- \ (100\%) \]

\[ \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 u \bar{d}, \tilde{\chi}_1^0 c \bar{s} \ (66\%) \]
Standard Model backgrounds to Z+jets

\[
\begin{align*}
\tilde{q} & \rightarrow e^+ \\
q & \rightarrow \gamma^*/Z^0 \\
q & \rightarrow Z \\
\end{align*}
\]