Searching for the Supersymmetry at the Large Hadron Collider and beyond

Alan Barr
The Standard Model

\[
L = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} \\
+ i \bar{\psi} D\psi + h.c. \\
+ \ell_i \bar{\ell}_i Y_{\ell_i} \phi + h.c. \\
+ |\partial_\mu \phi|^2 - V(\phi)
\]
Proton-proton

CM energy
7 -> 8 -> 14 TeV

40 M collisions / second

26.659 km circumference
9300 magnets
Lorentz factor ~7000
Measuring tracks
First beam at the LHC
Pile up (many collisions in one time period)

Excellent vertex finding required
Recent: WW scattering interactions

$3.6 \, \sigma$ evidence for electroweak $W^\pm W^\pm$ scattering

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Strong interactions

Proton structure

Gluon density function with unprecedented accuracy

Perturbative

Multiple consistent measurements of $\alpha_s$
H -> ZZ -> e^+e^- e^+e^- ?
Higgs $\rightarrow \gamma\gamma$?
Many happy people
Properties?

- Mass
- Parity
- Spin
- SM Couplings
- Exotic Couplings?
- Self Couplings?
- Uniqueness?
- Naturalness?
Naturalness of the Standard Model?

\[ \Delta m(h)^2 \sim \Lambda^2 \]

\[ m^2(h) = 149058072860157071229512437042397658961 - 149058072860157071229512437042397643336 = 15625 \text{ GeV}^2 \]
Adding a scalar fixes the (worst of the) loop correction problem.
Extended higgs sector (2 doublets)

<table>
<thead>
<tr>
<th>SM</th>
<th>SUSY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin-1/2</td>
<td></td>
</tr>
<tr>
<td>quarks (L&amp;R)</td>
<td>squarks (L&amp;R)</td>
</tr>
<tr>
<td>leptons (L&amp;R)</td>
<td>sleptons (L&amp;R)</td>
</tr>
<tr>
<td>neutrinos (L&amp;?)</td>
<td>sneutrinos (L&amp;?)</td>
</tr>
<tr>
<td>Spin-1</td>
<td></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Bino</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>Wino</td>
</tr>
<tr>
<td>$W^\pm$</td>
<td>$Wino^\pm$</td>
</tr>
<tr>
<td>gluon</td>
<td>gluino</td>
</tr>
<tr>
<td>Spin-0</td>
<td></td>
</tr>
<tr>
<td>$h^0$</td>
<td>$\tilde{H}^0$</td>
</tr>
<tr>
<td>$H^0$</td>
<td></td>
</tr>
<tr>
<td>$A^0$</td>
<td></td>
</tr>
<tr>
<td>$H^\pm$</td>
<td></td>
</tr>
</tbody>
</table>

After Mixing

4 x neutralino

2 x chargino

Extended higgs sector (2 doublets)
Dark Matter Candidates?

Many candidates exist

Weakly Interacting Massive Particle = Lightest Supersymmetric Particle?
A “natural” spectrum

Mass

~ 1 TeV

~ 200 GeV

Gluino

Stop Squarks

Neutralino (invisible)

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A difficult channel...

\[ \tilde{g} + \tilde{g} \rightarrow (t + \bar{t} + \tilde{X}_1^0) + (t + \bar{t} + \tilde{X}_1^0) \]

• Each top quark can decay to 3 jets
• Want to be sensitive to e.g. \textbf{many jets} + \textbf{P}_T^{\text{miss}}
• \textbf{No way} to make this prediction using current Monte Carlo only
An event with ten jets and missing transverse energy
Standard Model Backgrounds

$Z \rightarrow \nu \bar{\nu} + \text{jets}$
Measure SM process in “control region”
Fake $E_T^{\text{miss}}$: Resolution effects

- QCD backgrounds dominated by FAKE $E_T^{\text{miss}}$
- Resolution (largely) determined by Poisson sampling statistics*

- Expect $\sigma_E \propto \sqrt{E}$

Has almost universal distribution for QCD events
where \( H_T = \sum_j p_T^j \)
≥10 jets + Missing $E_T$
Results summary

<table>
<thead>
<tr>
<th>Signal region</th>
<th>9j50</th>
<th>10j50</th>
</tr>
</thead>
<tbody>
<tr>
<td>b-jets</td>
<td>0</td>
<td>≥ 2</td>
</tr>
<tr>
<td>Observed events</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Total events after fit</td>
<td>3.3 ± 0.7</td>
<td>6.1 ± 1.7</td>
</tr>
</tbody>
</table>

Results in agreement with Standard Model predictions
\[ \tilde{g} \tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0; m(t) \gg m(\tilde{g}) \]

**ATLAS**
\[ \int L \, dt = 20.3 \text{ fb}^{-1} \]
Multijet Combined

- **Expected limit** ($\pm 1 \sigma_{\text{exp}}$)
- **Observed limit** ($\pm 1 \sigma_{\text{SUSY \_theory}}$)

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**NOT ALLOWED**

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**EXCLUDED**

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**NOT YET EXCLUDED**

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32
Interpretation?

“Supersymmetry is not dead, but it is in the hospital”

Perhaps...

• Fine tuning > $10^2$ level
• However one part in $10^2$ seen elsewhere
• Is $10^4$ possible?
Further in the future?
Pillars of a “100 TeV” pp machine

- Boosted objects
- Weak bosons in jets
- Naturalness
- Flavour
- Proton structure
- Physics above the EW phase transition
- Vacuum potential
- Precision top physics
- Precision Higgs tests
- Strongly coupled matter
- Dark Matter
The advantage of higher energy

\[ pp \rightarrow \tilde{g} \tilde{g} \rightarrow t\bar{t}\chi_1^0 t\bar{t}\chi_1^0 \]

5 \sigma discovery

- Green: 100 TeV, 140 PU, 3000 fb\(^{-1}\)
- Red: 33 TeV, 140 PU, 3000 fb\(^{-1}\)
- Blue: 14 TeV, 140 PU, 3000 fb\(^{-1}\)
- Black: 14 TeV, 50 PU, 300 fb\(^{-1}\)
In the case of discovery

• Measure properties of new particles
  – Mass
  – Spin
  – Coupling

• Reconstruct Langrangian of BSM theory
Ideas for a detector...
Magnets...

Herman ten Kate
FCC Workshop @ CERN, 27 May 2014

See also Phil Allport, ICHEP 2014
Rad-hard CMOS could revolutionise tracker technology
Calorimeter...

Tracking ECAL
\[ \Delta E/E \sim 16\%/\sqrt{E} \mp 1.1\% \]

HCAL deep enough to prevent punch-through
\[ \Delta E/E \sim 35-60\%/\sqrt{E} \mp 3\% \]

Clement Helsens, Steinar Stapnes: FCC workshop, CERN, May 2014
...OR...?
CEPC – SPPC proposed layout

LTB : Linac to Booster
BTC : Booster to Collider Ring
Conclusion

• LHC-1 a very successful machine
• LHC-2 starting soon
• Higgs(125) being investigated
• Naturalness and dark matter still mysterious for now
• A higher energy would bring many benefits...
DETAILS
Proof of principal... universal shape

6-jet distribution from 5-jet template
Selection cuts for the analysis

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Multi-jet + flavour stream</th>
<th>Multi-jet + $M_T^2$ stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet $</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>Jet $p_T$</td>
<td>$&gt; 50$ GeV</td>
<td>$&gt; 80$ GeV</td>
</tr>
<tr>
<td>Jet count</td>
<td>$= 8$</td>
<td>$= 9$</td>
</tr>
<tr>
<td>$b$-jets ($p_T &gt; 40$ GeV, $</td>
<td>\eta</td>
<td>&lt; 2.5$)</td>
</tr>
<tr>
<td>$M_T^{N_{\ell}}$ [GeV]</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$E_T^{miss}/\sqrt{H_T}$</td>
<td>$&gt; 4$ GeV(^{1/2})</td>
<td>$&gt; 4$ GeV(^{1/2})</td>
</tr>
</tbody>
</table>

Table 1. Definition of the nineteen signal regions. The jet $|\eta|$, $p_T$ and multiplicity all refer to the $R = 0.4$ jets. Composite jets with the larger radius parameter $R = 1.0$ are used in the multi-jet + $M_T^2$ stream when constructing $M_T^2$. A long dash ‘—’ indicates that no requirement is made.
### Results in full

<table>
<thead>
<tr>
<th>Signal region</th>
<th>$8j50$</th>
<th>$9j50$</th>
<th>$10j50$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$-jets</td>
<td>$0$</td>
<td>$1$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>Observed events</td>
<td>$40$</td>
<td>$44$</td>
<td>$44$</td>
</tr>
<tr>
<td>Total events after fit</td>
<td>$35 \pm 4$</td>
<td>$40 \pm 10$</td>
<td>$50 \pm 10$</td>
</tr>
<tr>
<td>Fitted $t\bar{t}$</td>
<td>$2.7 \pm 0.9$</td>
<td>$11.8 \pm 3.0$</td>
<td>$23.0 \pm 5.0$</td>
</tr>
<tr>
<td>Fitted $W+jets$</td>
<td>$2.0^{+2.6}_{-2.0}$</td>
<td>$0.62^{+0.81}_{-0.62}$</td>
<td>$0.29^{+0.28}_{-0.23}$</td>
</tr>
<tr>
<td>Fitted others</td>
<td>$2.9^{+1.8}_{-1.8}$</td>
<td>$1.7^{+1.5}_{-1.2}$</td>
<td>$2.8^{+2.3}_{-2.0}$</td>
</tr>
<tr>
<td>Total events before fit</td>
<td>$36$</td>
<td>$48$</td>
<td>$59$</td>
</tr>
<tr>
<td>$t\bar{t}$ before fit</td>
<td>$3.5$</td>
<td>$15$</td>
<td>$30$</td>
</tr>
<tr>
<td>$W+jets$ before fit</td>
<td>$2.9$</td>
<td>$1.0$</td>
<td>$0.29$</td>
</tr>
<tr>
<td>Others before fit</td>
<td>$2.4$</td>
<td>$1.8$</td>
<td>$2.8$</td>
</tr>
<tr>
<td>Multi-jets</td>
<td>$27 \pm 3$</td>
<td>$30 \pm 10$</td>
<td>$26 \pm 10$</td>
</tr>
</tbody>
</table>

Table 4. Number of observed and expected (fitted) events for the seven $p_T^{min} = 50$ GeV signal regions of the multi-jet + flavour stream. The category indicated by ‘others’ includes the contributions from $Z+jets$, $t\bar{t}+W$, $t\bar{t}+Z$, and single top. The table also contains for each signal region the probability, $p_0$, that a background-only pseudo-experiment is more signal-like than the observed data; the significance, $\sigma$, of the agreement between data and the Standard Model prediction; the 95% CL upper limit on the number of events, $N_{BSM}$, originating from sources other than the Standard Model; and the corresponding cross section times acceptance times efficiency, $\sigma_{BSM,max} \cdot A \cdot \epsilon$. 

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