LHC for SUSY Theorists

1. Overview of the LHC Experiments
The natural mass scale for supersymmetric particles is the scale of electroweak symmetry breaking, the mass scale of a few hundred GeV. It was interesting bet that the most recent generation of particle accelerators - SLC, LEP, and the Tevatron - would have enough energy to reach the SUSY scale. But it was not required that this be so.

For LHC, the prospects are very different. We expect that proton beams at the LHC energy will produce SUSY particles in significant numbers.

We should now be planning for the discovery at the LHC of SUSY or another comparable model of electroweak symmetry breaking.
A discovery era in fundamental physics is very different from the era of study and confirmation of a ‘Standard Model’.

The major issues for the SLC, LEP, and Tevatron experiments have been

Can the experimental data be accounted for by known electroweak and strong interaction sources?

What precision can be achieved in the Standard Model parameters when we use QCD and the electroweak theory to model the data?

Which observations of agreement between the Standard Model and the data give the best limits on new physics? Which observations might be most sensitive to the first appearance of new physics?
When our standard theory fails to account for the data, new types of question arise:

In what channels are anomalies observed? Do we understand the standard prediction, in each case, well enough to claim an anomaly. Could the anomaly be an experimental artifact or misinterpretation?

Can we assemble a pattern of anomalies into evidence for a specific new physics model?

What additional anomalies must we observe to confirm this model? What observations claimed by the experiments must be incorrect?

These questions require new and unfamiliar skills. We all need to develop these skills.
In these lectures, I will discuss some topics that I expect will be relevant to these questions:

1. How will the experiments at the LHC be done? What are the difficulties? To what extent do these create opportunities for misinterpretation?

2. Can we understand the Standard Model at a sufficient level to claim that data is inconsistent with its predictions? SUSY predicts complex events. How do we compute the Standard Model backgrounds to these complex event topologies?

3. How can we use LHC observations to constrain the spectrum of SUSY particles in a way that is as model-independent as possible?
1. How will the experiments at the LHC be done? What are the difficulties? To what extent do these create opportunities for misinterpretation?
What considerations drive the design of the LHC experiments?

We are interested in observing cross sections at the level of

$$1 - 10 \text{ pb}$$

for SUSY pair production and Higgs boson production. These must often be multiplied by branching ratios

$$BR(Z^0 \rightarrow \mu^+\mu^-) = 0.034 \quad BR(h^0 \rightarrow \gamma\gamma) \sim 2 \times 10^{-3}$$

So we need luminosities of the order of

$$10 \text{ fb}^{-1}/\text{yr} \quad \text{or} \quad 1 \text{ nb}^{-1}/\text{sec}$$

The LHC design luminosity is 10 times higher. However, the initial LHC running should be at about this level.
The proton bunches collide and interact every 25 nsec.

So,

for a cross section of $1 \text{ nb}$,
  we have $1 \text{ event / second}$

for a cross section of $0.1 \text{ barn}$,
  we have $2.5 \text{ events / bunch crossing}$

for example,

$$\sigma(pp \rightarrow t\bar{t} + X) \sim 0.8 \text{ nb}$$

so we will see almost $1 \text{ } t\bar{t} \text{ pair per second}$, and (hopefully) many SUSY events per hour.
However, there are relevant processes with rates of events/crossing:

the proton-proton total cross section is expected to be 100 mb, or 2.5 events/crossing

the parton-parton hard scattering cross section reaches these rates for \( p_T \sim 10 \text{ GeV} \)

So

We need to be able to observe processes at \( 10^{-10} - 10^{-14} \)

of the rates for these dominant reactions.

Every observed new physics event will be accompanied by additional ‘minimum bias’ events and by additional jets.
Godbole et al, hep-ph/0604214
If events occur at every bunch crossing, we must ask what fraction of these events will be recorded into permanent storage.

The current plan is to record about **200 events/sec**, compared to the bunch crossing rate of \(40 \times 10^6/\text{sec}\).

At about 100 Mb/event, this gives a database of **20 Pb / yr**. The reduced data sets used for scanning and crude analysis are of size **200 Tb / yr**.

**The reduction from 40 MHz to 100 Hz must be done automatically, without direct human intervention.** This is done by the **trigger**, a network of computers and data pipelines. In ATLAS, the trigger has 3 levels. Conceptually,

<table>
<thead>
<tr>
<th>Level</th>
<th>allowed rate</th>
<th>decision time</th>
</tr>
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<tbody>
<tr>
<td>Level 1</td>
<td>1 MHz</td>
<td>100 microsec</td>
</tr>
<tr>
<td>Level 2</td>
<td>10 kHz</td>
<td>10 msec</td>
</tr>
<tr>
<td>Level 3</td>
<td>100 Hz</td>
<td>1 sec</td>
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</tbody>
</table>
more precisely:

N. Ellis, ATLAS
With this background, we can look at the rates of jet production and similar processes.

To understand the jet rates, we should look at the integral $p_T$ spectrum for jet production

$$\int_{p_T}^{\infty} dp_T \frac{d\sigma}{dp_T}$$

as computed from the parton distributions and QCD.

It is acceptable that this quantity becomes larger than the pp total cross section. This only indicates that there are multiple parton scattering events per pp collision.
To deal with the event rate, we must first demand the presence of jets with sufficiently large values of $p_T$. We then need to look for other indicators that the reaction is not simple parton-parton scattering:

- high deposited energy
- central angular distribution
- multiple jets
- missing $p_T$
- isolated or high $p_T$ leptons
- b quarks
- tau leptons
Two of these items deserve special comment.

In pp collisions, much of the particle production occurs at extremely forward angles. A variable more convenient than angle is rapidity \( y \) defined by

\[
E = \mathcal{P}_T \cosh y \quad p^z = \mathcal{P}_T \sinh y \quad \mathcal{P}_T = \sqrt{p_T^2 + m^2}
\]

We then refer to particles or jets by their position in the \((y, \phi, p_T)\) space. The very useful 3-d plot of \( p_T \) over the \((y, \phi)\) plane is called the Lego Plot.

Often we ignore \( m \) and replace polar angle by pseudorapidity \( \eta \)

\[
\cos \theta = \tanh \eta \quad \text{or} \quad \eta = \frac{1}{2} \log \frac{1 + \cos \theta}{1 - \cos \theta}
\]

Boosts are translations in rapidity. Generic particle production and low-\( p_T \) jets result from parton reactions randomly distributed over boosts and are thus approximately uniform in rapidity. High-\( p_T \) collisions occur near \( y = 0 \).
Run 223385 Evt 9802792 Thu Jul 20 17:14:11 2008

ET scale: 10 GeV

DO event
ET scale: 436 GeV
It is difficult to produce leptons without accompanying jets in typical QCD reactions, so **isolated leptons** are important indicators for new physics.

Electrons are detected in the inner detector by the same technologies that are used for jets, but muons are highly penetrating and can be studied outside the region where the hadrons are absorbed. This makes the study of muons a ‘safe’ objective for the LHC experiments, even at high luminosity.

Thus, **the LHC detectors are designed to be precision muon spectrometers**. This is the most important consideration for the large-scale design of ATLAS and CMS.
The LHC cross sections for vector boson production and decay to leptons (e or mu, accepted in $|\eta| < 2.5$) are

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</thead>
<tbody>
<tr>
<td>W+</td>
<td>10</td>
<td>nb</td>
</tr>
<tr>
<td>W-</td>
<td>8</td>
<td>nb</td>
</tr>
<tr>
<td>Z</td>
<td>1.5</td>
<td>nb</td>
</tr>
</tbody>
</table>

So we can in principle write this whole sample to permanent storage. The rates for hadronic W and Z decays are also quite acceptable (~ 50 nb). However, it is not clear how to trigger on general hadronic or tau decays of W, Z without some additional signature.
the Geneva region

with the CERN Large Hadron Collider
Overall view of the LHC experiments.
the ATLAS experiment
arrival of a superconducting muon toroid at CERN

Paula Collins, CERN
A Compact Solenoidal Detector for LHC

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Total Weight</td>
<td>14,500 t.</td>
</tr>
<tr>
<td>Overall diameter</td>
<td>14.60 m</td>
</tr>
<tr>
<td>Overall length</td>
<td>21.60 m</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>4 Tesla</td>
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simulated high-energy event in ATLAS
\[
\sigma\left(\frac{1}{p_T}\right) = \frac{\sigma(p_T)}{p_T^2} = 3.6 \times 10^{-4} \oplus \frac{1.3 \times 10^{-2}}{\sqrt{p_T^2 \sin \theta}} \ (\text{GeV}^{-1})
\]
ATLAS toroidal-field muon spectrometer for the complete muon system

\[
\frac{\sigma(p_T)}{p_T} = \begin{cases} 
2\% & 100 \text{ GeV } \mu \\
10\% & 1 \text{ TeV } \mu 
\end{cases}
\]
ATLAS - Z mass resolution in $Z \rightarrow \mu^+ \mu^-$

$\sigma = 2.5 \text{ GeV}$
ATLAS - muon charge misidentification probability
ATLAS liquid-argon calorimeter
ATLAS liquid Ar calorimeter energy resolution for electrons and photons.

electrons at $\eta = 0.3$:  
$$\frac{\sigma}{E} = \left( \left( \frac{8.5\%}{\sqrt{E}} \right)^2 + (0.5\%)^2 \right)^{1/2}$$
energy resolution of the CMS crystal calorimeter

\[ \sigma(E)/E = 3.6\% \sqrt{E} \oplus 12\%/E \oplus 0.26\% \]
ATLAS - $\pi^0$ rejection in photon detection (50 GeV pions)

ATLAS - rejection factor for jets in photon selection
ATLAS - $\pi^0$ rejection in photon detection (50 GeV pions)

ATLAS - rejection factor for jets in photon selection
ATLAS calorimeter resolution for pions

single pions: \( \frac{\sigma}{E} = \frac{63\%}{\sqrt{E}} \oplus 5.4\% \)

jets: \( \frac{\sigma}{E} = \frac{81\%}{\sqrt{E}} \oplus 1.7\% \oplus \frac{3.9}{E} \)
ATLAS calorimeter electron/pion response
ATLAS: material in front of the ECAL as a function of pseudorapidity

(less than 0.25 is due to the inner detector)
thickness of the ATLAS calorimetry as a function of $\eta$
The geography of the detector becomes an issue in thinking about missing ET. If a part of the detector does not function, you will see missing ET.

More generally, mismeasurement, especially of jets, will produce unbalanced ET.

To control for this, it is necessary to

- calibrate the response of the detector elements using 2-jet events and \( pp \rightarrow \gamma + \text{jet} \)
- look at the geometry of signal event and reject them if they are likely to have been mismeasured.
ATLAS simulation of missing ET in $Z(\rightarrow \mu^+\mu^-) + jet$

$\eta$ of the jet w. the highest ET in events w. ET $> 50$
DO missing ET search - dijet sample
Finally, since we expect that new physics associated with electroweak symmetry breaking can have preferred coupling to the third generation, it is important to understand the tagging of $b$ quarks and $\tau$ leptons.
The principal b tags are

**soft lepton tagging:**

leptons with pT > 1 GeV with respect to a jet are likely to come from b semileptonic decays

**lifetime tagging:**

\[
\begin{align*}
c\tau(B^+) &= 0.49 \text{ mm} , \\
c\tau(B^0) &= 0.46 \text{ mm} \\
c\tau(D^+) &= 0.31 \text{ mm} , \\
c\tau(D^0) &= 0.12 \text{ mm}
\end{align*}
\]

so a precision silicon tracker close to the interaction point should see clusters of tracks displaced from the vertex

Be careful, especially of charm:
impact parameter
vertex
vertex mass
$e^+ e^- \rightarrow Z^0 \rightarrow b \bar{b}$
OPAL

- 1994 data
- Monte Carlo b
- Monte Carlo c
- Monte Carlo uds

tagging variable B
rate

Monte Carlo uds

Monte Carlo c

Monte Carlo b

1994 data
impact parameter significance distribution at DO
ATLAS TDR - background rejection as a function of b jet finding efficiency
To tag taus, look for “tau jets”

low multiplicity:

- 1-prong hadronic decays 50%
- 3-prong hadronic decays 15%

isolated in a narrow cone $R < 0.2$
selection efficiency as a function of cone sizes

tau jets

QCD jets

CMS
Entries 8389

endpoint (fit):
$x_0 = 1.049 \pm 0.003$

smearing factor (fit):
$\sigma = 0.072 \pm 0.003$

Kitano-Ibe
HERWIG + TAOULA + AcerDET
We have now discussed the basic tools for LHC physics. The next step is to discuss the structure of events that resemble new particle production.