Physics Motivations

- Experimental
- Theoretical

New particles searches

- Standard Model Higgs Boson
- Higgs Particles of Supersymmetric Extensions to the SM
- Supersymmetric Particles

Other Scenarios

- Large Extra Dimensions

Summary
ATLAS and the LHC

Large Hadron Collider: proton proton collisions at $\sqrt{s} = 14$ TeV

$L_{\text{peak}} = 10^{33}$ cm$^{-2}$s$^{-1}$  2005-2008  “Low luminosity running”

$L_{\text{peak}} = 10^{34}$ cm$^{-2}$s$^{-1}$  2009- ?  “High luminosity running”

20 minimum bias events per crossing at high luminosity

Some physics quantities (e.g. b-tagging efficiency) degraded at high luminosity

P.Krieger      CAP Congress, York University,
June 2000
The Standard Model

The SM healthy at energies $\leq 200$ GeV

Direct measurements of $M_w$ and $M_{\text{top}}$ agree well with indirect constraints from LEP1

Predict low mass Higgs

Higgs boson remains experimentally unobserved

Direct limit from LEP2

$M_H > 107.7$ GeV @ 95% CL

Upper limit from LEP combined electroweak fit

$M_H < 188$ GeV @ 95% CL
Beyond the Standard Model

Hierarchy problem (2 fundamental energy scales)

\[ \frac{M_{\text{EW}}}{M_{\text{planck}}} \approx 10^{-17} \]

Naturalness problem radiative corrections to Higgs mass squared \( \propto \Lambda^2 \) where \( \Lambda \) is the energy scale to which the theory remains valid \( \rightarrow \) fine tuning problem with Higgs mass: can be resolved by

New physics at the TeV scale \( \Lambda \approx 1 \text{TeV} \)

OR

A symmetry protecting the Higgs mass against large radiative corrections (Supersymmetry)

If Higgs not discovered with mass < 800 GeV expect the dynamics of WW, ZZ scattering to reveal new structure energies \( \approx 1 \text{ TeV} \)

Must see something new at energies \( \leq 1 \text{TeV} \)
**Supersymmetry (SUSY)**

For each SM fermion (boson) there is a bosonic (fermionic) supersymmetric partner with identical mass and couplings

<table>
<thead>
<tr>
<th>spin 0</th>
<th>spin ½</th>
<th>spin 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>sleptons</td>
<td>(\tilde{l})</td>
<td>leptons (l)</td>
</tr>
<tr>
<td>squarks</td>
<td>(\tilde{q})</td>
<td>quarks (q)</td>
</tr>
<tr>
<td>gauginos</td>
<td>(\tilde{\gamma}, \tilde{W}, \tilde{Z})</td>
<td>gauge bosons (\gamma, W, Z)</td>
</tr>
<tr>
<td>gluoninos</td>
<td>(\tilde{g})</td>
<td>gluons (g)</td>
</tr>
<tr>
<td>Higgs bosons (5)</td>
<td>Higgsinos (5)</td>
<td></td>
</tr>
</tbody>
</table>

**Charged (neutral) gauginos and Higgsinos mix to form charginos (neutralinos)**

\[
\tilde{\chi}_i^{\pm}, \quad \tilde{\chi}_j^0, \quad i=1,2, \quad j=1,2,3,4
\]

ordered by mass

**R-parity quantum number distinguishes SM and SUSY particles**

Conventional to assume R-parity conservation

- SUSY particles must be produced in pairs
- Must be a lightest SUSY particle (LSP) which cannot decay
- Usually the lightest neutralino \(\tilde{\chi}_1^0\) \(\Rightarrow\) good CDM candidate

**Experimental signature: large missing transverse energy** \(E_T\)

P.Krieger

CAP Congress, York University,

June 2000
Supersymmetry must be a broken symmetry
there is no \( \tilde{e} \) with \( M_{\tilde{e}} = M_e \)
many model parameters (105 extra for MSSM)

SUSY solves the naturalness problem if \( M_{\text{susy}} < 1 \) TeV
Allows for gauge coupling unification if \( M_{\text{susy}} < 1 \) TeV
SUSY with \( M_{\text{SUSY}} < 1 \) TeV is called Weak-Scale SUSY

SUSY can provide dynamical EW symmetry breaking
SUSY may allow unification with gravity (all string theories are inherently supersymmetric)
MSSM Higgs Sector

Two Higgs doublets $\rightarrow$ 5 physical Higgs bosons

$$h^0, H^0, A^0, H^\pm$$

Assume $M_{\text{SUSY}} \sim 1$ TeV so Higgs $\rightarrow$ SUSY kinematically forbidden

All masses and couplings then given as $f(\tan \beta, M_A)$

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**$h^0$**

Lightest MSSM Higgs

$$M_{h^0} < M_Z$$ at tree level

$$M_{h^0} < 140 \text{ GeV}$$ after loop corrections

In limit of large $M_A$ and/or $\tan \beta$, $h^0$ behaves like $H^0_{\text{SM}}$

**$H^0 A^0$**

Heavy neutral CP-even, CP-odd Higgs respectively

Decays to $\tau^+ \tau^-$, $\mu^+ \mu^-$ enhanced for high $\tan \beta$

**$H^\pm$**

Heavy charged Higgs

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NB: for moderate $(M_A, \tan \beta)$ or $M_A > 500$ GeV
only $h^0$ is observable
Higgs Discovery at Tevatron RUN II

\[ pp \rightarrow WH \rightarrow l\nu b\bar{b} \]
\[ pp \rightarrow ZH \rightarrow l^+l^- b\bar{b} \]
\[ pp \rightarrow ZH \rightarrow \nu\nu b\bar{b} \]

Combined Results (WH+ZH)

Int. luminosity target for Run II
15-20 fb\(^{-1}\) / expt. Prior to start of LHC

5 year running \(\Rightarrow 3-5 \sigma\) for \(M_H \leq 130\) GeV
Large QCD backgrounds: look for final states with high-\(p_T\) leptons and photons

Important channels:

- **low mass**
  - \(H \rightarrow \gamma\gamma\)
  - \(H \rightarrow b\bar{b}\)

- **intermediate mass**
  - \(H \rightarrow ZZ^{(*)} \rightarrow l^+l^-l^+l^-\)
  - \(H \rightarrow WW^{(*)} \rightarrow l^+\nu l^-\nu\)

- **high mass**
  - \(H \rightarrow ZZ \rightarrow l^+l^-\nu\nu\)
  - \(H \rightarrow WW \rightarrow l\nu\) jet jet
Production cross-sections at the LHC

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$</th>
<th>Events/sec</th>
<th>Event/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>15 nb</td>
<td>15</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>1.5 nb</td>
<td>1.5</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>800 pb</td>
<td>0.8</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>500 $\mu$b</td>
<td>$10^5$</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>$g\bar{g}$ ($M_g = 1$ TeV)</td>
<td>1 pb</td>
<td>$10^{-3}$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$H_{\text{SM}}$ ($M = 0.8$ TeV)</td>
<td>1 pb</td>
<td>$10^{-3}$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>QCDjets $p_T &gt; 200$ GeV</td>
<td>100 nb</td>
<td>$10^2$</td>
<td>$10^9$</td>
</tr>
</tbody>
</table>

**Direct Higgs production**

$gg$ fusion or vector boson fusion:

Need high $p_T$ leptons or photons from Higgs decay

Huge QCD background for channels with jets

**Associated Higgs production**

High $p_T$ leptons from top decays used for triggering

Top reconstruction used for QCD background suppression
low luminosity running: use direct production (utilize high p_T photons) \(\rightarrow\) large signal, low S/B

high luminosity running: add contributions from associated production, WH, ZH, t\bar{t}H (utilize reconstruction of associated particle(s)) \(\rightarrow\) small signal, good S/B

Backgrounds

\(\gamma\gamma\) (irreducible) \(\sigma_{\gamma\gamma} \sim 3\, \text{pb}\) \(\rightarrow\) need \(\sigma_{M_H} \sim 1\%\)

\(j + jj\) (reducible) \(\sigma_j \sim 10^6 \sigma_{\gamma\gamma}\) \(\rightarrow\) need \(R_j > 10^3\)

\[\ H \rightarrow \gamma\gamma\]

Useful for \(M_H < 140\, \text{GeV}\)

Sets severe requirements of the performance of the ATLAS electromagnetic calorimetry

\[\ M_H = 120\, \text{GeV}\]

\[\ 100\, \text{fb}^{-1}\]

\[\ \sigma_{\text{xBR}} \approx 50\, \text{fb}\]
ATLAS

$H \rightarrow \gamma \gamma \ (m_H=100 \text{ GeV}, \ L=10^{34})$
Largest BR for low mass Higgs, but huge QCD background

Use associated production with full reconstruction of both top quarks (allows triggering and background suppression)

Backgrounds from $ttZ$, $Wjjjjjj$ $ttjj$ etc., (see below)

**Both top quarks reconstructed**

$$H \to bb \quad \epsilon \approx 1\%$$

$$t \to bjj$$

$$\bar{t} \to \bar{b}l\nu$$

**ATLAS 30 fb$^{-1}$**

<table>
<thead>
<tr>
<th>Higgs mass (GeV)</th>
<th>80</th>
<th>100</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal $S$</td>
<td>81</td>
<td>61</td>
<td>40</td>
</tr>
<tr>
<td>$\tilde{t}\tilde{t}Z$</td>
<td>7</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>$Wjjjjjj$</td>
<td>17</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>$ttjj$</td>
<td>121</td>
<td>130</td>
<td>120</td>
</tr>
<tr>
<td>Total background $B$</td>
<td>145</td>
<td>150</td>
<td>127</td>
</tr>
<tr>
<td>$S/B$</td>
<td>0.56</td>
<td>0.41</td>
<td>0.32</td>
</tr>
<tr>
<td>$S/\sqrt{B}$</td>
<td>6.7</td>
<td>5.0</td>
<td>3.6</td>
</tr>
<tr>
<td>$S_{H \to b\bar{b}}/S_{\text{total}}$</td>
<td>0.67</td>
<td>0.64</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Sets stringent requirements on b-tagging performance at high luminosity
SM Higgs Sensitivity 30 fb$^{-1}$

3 years of running at low luminosity

No single channel discovery for $M_H=100-130$ GeV

Full coverage of mass region with significance $> 5 \sigma$

Needs combined channels for discovery at low $M_H$

Multiple discovery channels for $M_H > 300$ GeV
SM Higgs Sensitivity 100 fb\(^{-1}\)

1 year running at high luminosity

Multiple discovery channels for all \( M_H \)

\[
\int L \, dt = 100 \text{ fb}^{-1}
\]

(no K-factors)

N.B. \( H \rightarrow \gamma \gamma \) now includes associated production channels
Search for MSSM Higgs Bosons

$h \to \gamma\gamma$ and $t\bar{t}h, h \to b\bar{b}$ very important in search for lightest MSSM Higgs (as they are for $H_{SM}$)

$h \to \gamma\gamma$

$M_{SUSY} \sim 1$ TeV

Higgs properties are function of $(M_A, \tan \beta)$ only

Almost excluded by LEP

Contributions to exclusion regions from $H/A$ are small

$t\bar{t}h, h \to b\bar{b}$
MSSM Higgs Sensitivity 30fb$^{-1}$

Three years of running at low luminosity

Combined ATLAS/LEP2 exclusion for most of the ($M_A$, $\tan \beta$) plane

Region with moderate ($M_A$, $\tan \beta$) remains unexcluded

N.B. LEP2 exclusion for 200 pb$^{-1}$/expt at 200 GeV so should be conservative
MSSM Higgs Sensitivity 300 fb$^{-1}$

Three years running at high luminosity

Full coverage of the $(M_A, \tan \beta)$ plane

Multiple channel coverage for most the plane

Most important channels $h \rightarrow \gamma \gamma$ and $t\bar{t}h, h \rightarrow b\bar{b}$
Supersymmetric Particle Searches

Reduce number of SUSY free parameters

Assume SUSY broken in some hidden sector at high energy
SUSY breaking “mediated” to visible sector via some interaction

Two popular scenarios with different phenomenologies:

Gravity-mediated
Phenomenology dictated LSP

Gravitino \( \tilde{G} \) very heavy, phenomenologically unimportant

MSUGRA: 5 parameter model, assumes parameter unifications at GUT scale

- \( m_0 \) Common scalar mass at unification scale
- \( m_{1/2} \) Common gaugino mass at unification scale
- \( \tan \beta \) Ratio of Higgs vevs
- \( A_0 \)
- \( \text{sign}(\mu) \)

Gauge-mediated
Phenomenology dictated NLSP

Gravitino is the LSP! \( M_{\tilde{G}} < 1 \text{ MeV} \)

NLSP can have short or long decay length

Minimal model studied by ATLAS has 6 parameters
Supersymmetric Particle Searches

**Signature channels**

<table>
<thead>
<tr>
<th>0 l</th>
<th>Jets + missing $E_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 l</td>
<td>1 lepton + jets + missing $E_T$</td>
</tr>
<tr>
<td>2 l</td>
<td>2 leptons + jets + missing energy SS, OS</td>
</tr>
<tr>
<td>3 l</td>
<td>3 leptons + jets + missing energy</td>
</tr>
<tr>
<td>2 (3)</td>
<td>2 or 3 leptons with jet veto + missing $E_T$</td>
</tr>
</tbody>
</table>

Search channels for direct gaugino or slepton production

\[ \sigma(\text{pp}) \text{ collisions at } E_{cm} = 14 \text{ TeV} \]

$M_\tilde{q} = 2M_{\tilde{g}}$

$M_{\tilde{q}} = M_{\tilde{g}}$

$\sum(\tilde{q}\tilde{q} + \tilde{q}\tilde{g} + \tilde{g}\tilde{g})$

$\tilde{\chi}_1^+ \tilde{\chi}_1^-$

$1^+ 1^- \text{ jet jet + missing } E_T \text{ final state}$
Supersymmetric Particle Searches

SUGRA

5 points in MSUGRA parameter space chosen for study

Mass points shown in red

Coverage shown for various lepton and/or jet + missing energy signals

P.Krieger

CAP Congress, York University,

June 2000
LHC studies choose 5 representative points in parameter space
Two shown here in red

Mass reach defined by $\geq 10$ signal events with $S/\sqrt{B} > 5$

For jets + missing energy, mass reach for squarks and gluinos extends to $> 2$ TeV

In multilepton channels reach extends to $> 1$ TeV

Weak scale SUSY easily discovered. Dominant background to a given process is from other SUSY processes
Most significant difference phenomenologically is $\sim$ massless LSP

Phenomenology dictated by:

$\tilde{\chi}^0_1 \rightarrow G\gamma$ or $\tilde{\chi}^{\pm} \rightarrow G\tilde{l}^{\pm}$

Scale of SUSY breaking (one of model parameters) dictates the gravitino mass and the NLSP lifetime

<table>
<thead>
<tr>
<th>NLSP</th>
<th>short</th>
<th>intermediate</th>
<th>long</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}^0_1$</td>
<td>photons + $E_T$</td>
<td>non-pointing photons + $E_T$</td>
<td>As in SUGRA</td>
</tr>
<tr>
<td>$\tilde{l}$</td>
<td>leptons + $E_T$</td>
<td>kinked charged tracks + $E_T$</td>
<td>Long lived heavy charged particles</td>
</tr>
</tbody>
</table>

Unusual signatures in case of intermediate $\tau_{NLSP}$

Scenarios have especially low standard model backgrounds

Discovery generally straightforward

Parameter determination trickier (as for SUGRA)
Estimate of $M_{SUSY}$ in jets + missing energy channel

$$M_{\text{eff}} = E_T^{\text{miss}} + p_T^1 + p_T^2 + p_T^3 + p_T^4$$
Heavy Higgs

$H_{SM}$ coupling to gauge bosons increases with increasing mass

- Resonance wider
- interaction stronger $\Rightarrow$ eventual violation of unitarity limit

No fundamental scalar?

- Need new physics to EW symmetry breaking, regularization of vector boson couplings and fermion mass generation

Study $V_L V_L \rightarrow V_L V_L$ scattering (longitudinal gauge bosons are goldstone bosons of symmetry breaking process)

Forward-jet tagging important

Sensitivity to WZ resonance shown for $M_{WZ} = 1.2, 1.5$ TeV for $300$ fb$^{-1}$

Non-resonant $V_L V_L$ searches more challenging
Many Other Searches

• Technicolour
• Additional gauge bosons
• Compositeness, leptoquarks, excited quarks
• Monopoles
• R-parity violating SUSY (baryon, lepton number violating decays)
Large Compact Extra Dimensions

Recall hierarchy problem \( \frac{M_{\text{EW}}}{M_{\text{planck}}} \sim 10^{-17} \)

Postulate \( M_{\text{planck}} \) effective energy scale, not fundamental

Assume existence of \( n \) compact spatial dimensions of (compactified) radius \( R \)

\[
V(r) = \frac{m_1 m_2}{M_{\text{pl}}^{2+n}} \cdot \frac{1}{r^{n+1}} \quad (r << R) \quad V(r) = \left\{ \frac{m_1 m_2}{M_{\text{pl}}^{n+2}} \cdot \frac{1}{R^n} \right\} \frac{1}{r} \quad (r >> R)
\]

Effective 4-dim planck \( M_{\text{planck}} \) is then given by \( M_{\text{planck}}^2 = M_{\text{pl}}^{n+2} R^n \)

Requiring \( M_{\text{pl}}^{4+n} \sim M_{\text{EW}} \rightarrow R \sim 10^{\frac{30}{n}-17} \) cm

Various constraints on models with compactification

\( n = 1 \rightarrow R = 10^{13} \) cm (cosmologically excluded)

\( n = 2 \rightarrow R \sim 0.1 - 1.0 \) mm (unexcluded by tests of \( 1/r^2 \) nature of gravitation, but excluded by SN1987)

 Collider limits from missing energy searches (next slide)
Large Compact Extra Dimensions

Model of Arkani-Hamed, Dimopoulos and Dvali:
only gravitons propagate freely in the “bulk”

Massless gravitons in 4+n dim $\rightarrow$ massive KK gravitons $G_M$ in 4D $\rightarrow$ Missing energy signature

Possible signatures at LHC

$$ pp \rightarrow G_M + \text{jet} \quad \text{monojet} $$

$$ pp \rightarrow G_M + \gamma $$

$$ pp \rightarrow G_M + Z $$

Non-kinematic high $p_T$ cutoff

Other particles localized within $1/M_{EW}$ in the extra n dimensions

In sufficiently hard collisions $E_{esc} > M_{EW}$ particles can acquire momentum in the extra dimensions and disappear from the 4D world $\rightarrow$ upper limit for $p_T$ distributions at

$$ p_T = E_{esc} $$

Such particles may or may not periodically return to and deposit energy in the 4D world
Randall and Sundrum: can derive the same relationship between a higher dimensional planck mass and the one of our 4-dim world WITHOUT compactification. Evades some astrophysical constraints on compactified models.
Summary

Exciting times ahead!

LEP provided

Promise of precision tests of the SM
Hope for new physics discoveries

LHC will provide

Promise of discovery
Initial parameter determination

→ precision tests will be done at NLC

Provided they exist, we will observe

SM Higgs or MSSM Higgs ($h^0$)
Weak Scale Supersymmetry

Sensitivity also to other anticipated new physics
not discussed here

Possibly (or even probably ?) we may
discover something entirely unexpected