New Horizons in Particle Physics
- From the Higgs boson to Dark Matter at the LHC -

• Introduction
  Where do we stand today?
• The open questions
• What answers can we expect from the Large Hadron Collider (LHC) ?
• Dark Matter at the LHC ?
The Standard Model of Particle Physics

(i) Building blocks of matter: Quarks and Leptons

\[
\begin{align*}
    m(e) &= 0.000511 \text{ GeV/c}^2 \\
m(\tau) &= 1.8 \text{ GeV/c}^2 \\
m(u) &= 0.005 \text{ GeV/c}^2 \\
m(t) &= 172.5 \text{ GeV/c}^2 \\
\text{In comparison: } m(p) &= 0.938 \text{ GeV/c}^2
\end{align*}
\]
(ii) **Forces / Interactions:**
mediated via the exchange of field quanta / bosons

\[ m_\gamma = 0, \quad m_g = 0 \]

\[ m_W = 80.398 \pm 0.025 \text{ GeV} / c^2 \]
\[ m_Z = 91.1875 \pm 0.0021 \text{ GeV} / c^2 \]

(iii) **Higgs sector**
New (scalar) field is introduced; Needed to break (hide) the electroweak symmetry

⇒ **Higgs particle**
Theoretical arguments: \( m_H < \sim 1000 \text{ GeV}/c^2 \)

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**Theoretical description:**

**Gauge theories of electroweak and Strong interactions**

(i) **Electroweak theory**

S. Glashow
A. Salam
S. Weinberg

(ii) **Quantum Chromodynamics**

D.J. Gross
H.D. Politzer
F.E. Wilczek

Problem: symmetry requires massless gauge bosons
Where do we stand today?

- The Standard Model is consistent with all experimental data!
- No Physics Beyond the SM observed (except clear evidence for neutrino masses)
- No Higgs seen (yet)

**Direct searches:** (95% CL limits)

- \( m_H > 114.4 \text{ GeV/c}^2 \)
- \( m_H < 160 \text{ GeV/c}^2 \) or \( m_H > 170 \text{ GeV/c}^2 \)

Only unambiguous example of observed Higgs

(P. Higgs, Univ. Edinburgh)
Consistency with the Standard Model

Sensitivity to the Higgs boson and other new particles via quantum corrections:
The Open Questions
Key Questions of Particle Physics

1. **Mass:** What is the origin of mass?
   - How is the electroweak symmetry broken?
   - Does the Higgs boson exist?

2. **Unification:** What is the underlying fundamental theory?
   - Can the interactions be unified at larger energy?
   - How can gravity be incorporated?
   - Is our world supersymmetric?
   - ....

3. **Flavour:** or the generation problem
   - Why are there three families of matter?
   - Neutrino masses and mixing?
   - What is the origin of CP violation?

**Answers to some of these questions are expected on the TeV energy scale**
Problems at a larger scale

We are here

Surrounded by

- Mass (planets, stars, ...., hydrogen gas)
- Dark Matter
- Dark Energy

© Rocky Kolb
The role of the LHC

1. Explore the TeV mass scale

- What is the origin of the electroweak symmetry breaking?
- The search for “low energy” supersymmetry
- Other scenarios beyond the Standard Model
- ……

Look for the “expected”, but we need to be open for surprises

2. Precise tests of the Standard Model

- There is much sensitivity to Physics Beyond the Standard Model in the precision area
The Large Hadron Collider

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>7, 5, 3.5 TeV</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$10^{33} - 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Superconducting dipoles</td>
<td>1232, 15 m, 8.33T</td>
</tr>
<tr>
<td>Stored energy</td>
<td>350 MJ/beam</td>
</tr>
</tbody>
</table>

... became a reality in 2008 after ~15 years of hard work
Proton – proton:

2835 x 2835 bunches
Separation: 7.5 m (25 ns)

$10^{11}$ protons / bunch
Crossing rate of p-bunches: 40 Mio. / s
Luminosity: $L = 10^{34}$ cm$^{-2}$ s$^{-1}$

$\sim 10^9$ pp collisions / s
(superposition of 23 pp-interactions per bunch crossing: pile-up)

$\sim 1600$ charges particles in the detector

⇒ high particle densities
high requirements for the detectors
The ATLAS experiment

- Solenoidal magnetic field (2T) in the central region (momentum measurement)

High resolution silicon detectors:
- 6 Mio. channels (80 µm x 12 cm)
- 100 Mio. channels (50 µm x 400 µm)
  space resolution: ~ 15 µm

- Energy measurement down to 1° to the beam line

- Independent muon spectrometer (supercond. toroid system)

Diameter 25 m
Barrel toroid length 26 m
End-cap end-wall chamber span 46 m
Overall weight 7000 Tons
ATLAS Installation

October 2006

K. Jakobs
Symposium, Graduiertenkolleg, Berlin, Sep. 2009
A historical moment:
Closure of the LHC beam pipe ring on 16th June 2008
ATLAS was ready for data taking in August 2008
CMS Detector closed for 10th Sep. 2008
An excellent start: first beams – September 10, 2008
The very first beam-splash event from the LHC in ATLAS on 10th September 2008, 10:19
Trigger timing with beam splash events

Few days of beam halo and splash events helped enormously to adjust timing of different triggers

1 bunch crossing number = 25 ns
Development of resistive zone in dipole bus bar splice

Incident of September 19th 2008

The 15-m long LHC cryodipole
Diagnose, repair, comeback…..

- A resistive zone developed in an electrical bus bar connection
- Electrical arc → punctured the helium enclosure
- Helium release under high pressure
- Relief discs unable to maintain the pressure rise below 0.15 MPa → large pressure forces

- Lot of repair work ongoing since then
  (14 quadrupole and 39 dipole magnets replaced, electrical interconnections repaired, larger helium pressure release ports installed,…..)

- **Startup plans (2009/10):**
  - Machine will restart in Nov. 2009
  - First collisions at injection energy at 900 GeV
  - Increase energy up to 3.5 TeV (→ 5 TeV)
  - Collect data corresponding to ~200 pb⁻¹
ATLAS Commissioning

with cosmic rays....
ATLAS Commissioning (cont.)

- About 216 Mio. cosmic ray events recorded;
- Efficiencies and noise conditions of all sub-detectors are within specifications, and >99% of channels are working for most systems;
- Detectors have been aligned with high precision, better than expected for day one;
- Valuable experience gained on trigger and reconstruction algorithms....
Towards First Physics Results in 2009/2010
Cross-sections and Production Rates, the first 10 pb$^{-1}$

Events for 10 pb$^{-1}$, $\sqrt{s} = 14$ TeV

<table>
<thead>
<tr>
<th>Process</th>
<th>Events/sec/cm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inelastic pp (minimum bias events)</td>
<td>large (prescaled)</td>
</tr>
<tr>
<td>$W \rightarrow e \nu$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$tt \rightarrow evb qqb$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Higgs (130 GeV)</td>
<td>10</td>
</tr>
<tr>
<td>Gluinos (1 TeV)</td>
<td>1</td>
</tr>
</tbody>
</table>

Physics with 10 – 100 pb$^{-1}$:

- Establish Standard Model signals
- Use them for calibration (tag and probe methods,....)
- Tune Monte Carlos
- Basic SM cross section measurements
- Look for surprises (e.g. high mass di-lepton resonances,...., black holes)
**W/Z and top signals**

Even with early data (10-50 pb\(^{-1}\)) at \(\sqrt{s} = 7\) TeV, high statistics of W/Z and top samples

⇒ Establish performance for leptons, jets, missing transverse energy, ..., b-tagging

\[ Z \rightarrow ee \]

\[ tt \rightarrow ℓνbqqb \]
The Search for

The Higgs boson

The first Higgs at ATLAS
Decays of the Higgs Boson

Decay characteristics are known, as soon as the mass is known:

\[ H \rightarrow W^+ , Z , t , b , c , \tau^+ , \ldots , g , \gamma \]

\[ H \rightarrow W^- , Z , t , b , c , \tau^- , \ldots , g , \gamma \]

Important decays at hadron colliders:

Final states with leptons or photons (via \( H \rightarrow WW, ZZ \) or \( H \rightarrow \gamma\gamma \))

The dominant \( bb \) decays in the low mass region are very difficult to detect (due to the large background from jet production via QCD processes).
A simulated $H \rightarrow ZZ \rightarrow ee \mu\mu$ event
**H → ZZ(*) → ℓℓℓℓ**

**Signal:** Decay via two Z bosons into four leptons

**Background:** Top production: \( tt \rightarrow Wb Wb \rightarrow ℓν cℓν ℓν cℓν \)

Associated Zbb production: \( Z bb \rightarrow ℓℓ cℓν cℓν \)

**Background rejection:** Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: \( \sim 1.5 \) ps)

Dominant background after isolation cuts: ZZ continuum

\[
P_T(1,2) > 20 \text{ GeV} \\
P_T(3,4) > 7 \text{ GeV} \\
|η| < 2.5
\]

Isolated leptons

\[
M(ℓℓ) \sim M_Z \\
M(ℓ'ℓ') \sim < M_Z
\]

Discovery potential in mass range from \( \sim 130 \) to \( \sim 600 \text{ GeV/c}^2 \)
The Search for the Higgs Boson at the LHC

\[ H \rightarrow WW \rightarrow \ell\nu \ell\nu \quad \text{H} \rightarrow \gamma\gamma \]

\[ M_T = \sqrt{(E_T^H + E_T^{\nu\nu})^2 - (p_T^H + p_T^{miss})^2} \]

**ATLAS**

\[ L = 30 \text{ fb}^{-1} \]

**CMS**

\[ L = 1 \text{ fb}^{-1} \]
**H → ττ exploiting the vector boson fusion**

**Experimental challenge:**
- Identification of hadronic taus
- Good $E_T^{\text{miss}}$ resolution
  ($ττ$ mass reconstruction in collinear approximation)
- Control of the $Z → ττ$ background shape in the high mass region

**Diagram:**
- Higgs boson production via $qq → H^0 → ττ → ℓνν$ hadronic channel
- ATLAS and CMS collaboration
- Mass distribution for $M_{ττ}$ in GeV/c$^2$
Important changes w.r.t. previous studies: \( ttH \rightarrow tt bb \) disappeared in both ATLAS and CMS studies from the discovery plot; however, new sensitivity for \( bb \)-decay mode might be present in the associated \( WH \rightarrow \ell \nu bb \) production, with highly boosted Higgs bosons.
Entire mass range, $m_H > 115 \text{ GeV/c}^2$, can be covered (95% CL) by one experiment with data corresponding to an integrated luminosity of $\sim 2 \text{ fb}^{-1}$
The Search for Supersymmetry
Supersymmetry

Extends the Standard Model by predicting a new symmetry
Spin $\frac{1}{2}$ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

New quantum number: R-parity: $R_p = (-1)^{B+L+2S}$

R-parity conservation:
- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable
Why do we like SUSY so much?

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

\[ \Delta m_H = f (m_B^2 - m_f^2) \rightarrow m_{\text{SUSY}} \sim 1 \text{ TeV} \]

(Hierarchy or naturalness problem)

2. Unification of coupling constants of the three interactions seems possible

3. SUSY provides a candidate for dark matter,

The lightest SUSY particle (LSP)

4. A SUSY extension is a small perturbation, consistent with the electroweak precision data
Link to the Dark Matter in the Universe?

Parameters of the SUSY model $\Rightarrow$ predictions for the relic density of dark matter

Interpretation in a simplified model

cMSSM (constrained Minimal Supersymmetric Standard Model)

Five parameters:
- $m_0, m_{1/2}$: particle masses at the GUT scale
- $A_0$: common coupling term
- $\tan \beta$: ratio of vacuum expectation value of the two Higgs doublets
- $\mu$ (sign $\mu$): Higgs mass term

$\rho_{\chi} \sim m_{\chi} n_{\chi}, \quad n_{\chi} \sim \frac{1}{\sigma_{\text{ann}}(\chi\chi \rightarrow \ldots)}$

Regions of parameter space which are consistent with the measured relic density of dark matter (WMAP,.....)
Search for Supersymmetry at the LHC

⇒ combination of jets, leptons, missing transverse energy \((E_{T}^{\text{miss}})\)

1. Step: search for deviations from the Standard Model

   Relatively easy: squarks and gluinos in TeV mass range are copiously produced (QCD production)

2. Step: can the parameter of the model be determined?
   More difficult!
Squarks and Gluinos

- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and $E_T^{\text{miss}}$

- Typical selection: $N_{\text{jet}} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{\text{miss}} > 100$ GeV

- Define: $M_{\text{eff}} = E_T^{\text{miss}} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)

LHC reach for Squark- and Gluino masses: ($\sqrt{s} = 14$ TeV)

- $0.1$ fb$^{-1}$ $\Rightarrow$ $M \sim 750$ GeV
- $1$ fb$^{-1}$ $\Rightarrow$ $M \sim 1350$ GeV
- $10$ fb$^{-1}$ $\Rightarrow$ $M \sim 1800$ GeV

Deviations from the Standard Model due to SUSY at the TeV scale can be detected fast!

example: mSUGRA, point SU3

$m_0 = 100$ GeV, $m_{1/2} = 300$ GeV
$tan \beta = 6, A_0 = -300, \mu > 0$
LHC reach in the $m_0 - m_{1/2}$ mSUGRA plane:

Multijet + $E_T^{miss}$ signature

Expect multiple signatures for TeV-scale SUSY
How can the underlying theoretical model be identified?

- Not easy!!
- Other possible scenarios for Physics Beyond the Standard Model could lead to similar final state signatures e.g. search for direct graviton production in extra dimension models

\[ gg \rightarrow gG , \quad qg \rightarrow qG , \quad q \bar{q} \rightarrow Gg \]
\[ q \bar{q} \rightarrow G \gamma \]
How can the underlying theoretical model be identified?

Measurement of the SUSY spectrum → Parameter of the theory

Test point 01
**LHC Strategy:** End point spectra of cascade decays

Example: \( \tilde{q} \rightarrow q\tilde{\chi}^0_2 \rightarrow q\ell^+\ell^- \rightarrow q\ell^+\ell^-\tilde{\chi}^0_1 \)

\[
M^\text{max}_{\ell^+\ell^-} = \sqrt{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}^0_1})} \quad m_{\tilde{\ell}}
\]

\[
M^\text{max}_{\ell^+\ell^-} = \sqrt{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{q}})(m^2_{\tilde{q}} - m^2_{\tilde{\chi}^0_1})} \quad m_{\tilde{\chi}^0_2}
\]

ATLAS: expected precision for point 01 \((L = 1 \text{ fb}^{-1})\):

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\tilde{\chi}^0_1} )</td>
<td>88 ± 60 ( \mp ) 2</td>
</tr>
<tr>
<td>( m_{\tilde{\chi}^0_2} )</td>
<td>189 ± 60 ( \mp ) 2</td>
</tr>
<tr>
<td>( m_{\tilde{q}} )</td>
<td>614 ± 91 ( \mp ) 11</td>
</tr>
<tr>
<td>( m_{\tilde{\ell}} )</td>
<td>122 ± 61 ( \mp ) 2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} )</td>
<td>100.6 ± 1.9 ( \mp ) 0.0</td>
<td>100.7</td>
</tr>
<tr>
<td>( m_{\tilde{q}} - m_{\tilde{\chi}^0_1} )</td>
<td>526 ± 34 ( \mp ) 13</td>
<td>516.0</td>
</tr>
<tr>
<td>( m_{\tilde{\ell}} - m_{\tilde{\chi}^0_1} )</td>
<td>34.2 ± 3.8 ( \mp ) 0.1</td>
<td>37.6</td>
</tr>
</tbody>
</table>
LHC precision on SUSY model parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SU3 value</th>
<th>fitted value</th>
<th>exp. unc.</th>
<th>theo. + exp. unc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tan \beta$</td>
<td>6</td>
<td>7.4</td>
<td>4.6</td>
<td>$\pm 1$</td>
</tr>
<tr>
<td>$M_0$</td>
<td>100 GeV</td>
<td>98.5 GeV</td>
<td>$\pm 9.3$ GeV</td>
<td>$\pm 9.5$ GeV</td>
</tr>
<tr>
<td>$M_{1/2}$</td>
<td>300 GeV</td>
<td>317.7 GeV</td>
<td>$\pm 6.9$ GeV</td>
<td>$\pm 7.8$ GeV</td>
</tr>
<tr>
<td>$A_0$</td>
<td>$-300$ GeV</td>
<td>445 GeV</td>
<td>$\pm 408$ GeV</td>
<td>$\pm 7.8$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected % precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_0$</td>
<td>$\pm 2%$</td>
</tr>
<tr>
<td>$m_{1/2}$</td>
<td>$\pm 0.6%$</td>
</tr>
<tr>
<td>$\tan(\beta)$</td>
<td>$\pm 9%$</td>
</tr>
<tr>
<td>$A_0$</td>
<td>$\pm 16%$</td>
</tr>
</tbody>
</table>

Complementarity of LHC and ILC in SUSY studies:

LHC: strongly interacting squarks and gluinos
ILC: precise investigation of electroweak SUSY partners
Importance for the interplay between direct and indirect Dark Matter searches

- Following a discovery of New Physics at the LHC (deviation from the Standard Model) the LHC will aim to test the Dark Matter hypothesis.
- Estimation of relic density in a simple model-dependent scenario will be the first goal.
- Less model-dependent scenarios will follow, detailed studies probably require the ILC.
- Conclusive result is only possible in conjunction with astroparticle physics experiments.
- Ultimate goal: observation of LSP at the LHC, confirmed by a signal in a direct dark matter experiment with predicted mass and cross-section.
Summary / Conclusions

• The *Large Hadron Collider* is the largest and most ambitious project realized in particle physics so far (technology, complexity, resources, collaboration, ........)

• With its startup in 2009, Particle Physics is about to enter a new era

• Questions of
  - Existence of Higgs particles,
  - Low energy supersymmetry or
  - many other phenomena beyond the Standard Model at the TeV scale can be answered.

*The answers will most likely modify our understanding of Nature*

.....

*and give guidance to theory and future experiments*
The LHC repairs in detail

1. 14 quadrupole magnets replaced
2. 39 dipole magnets replaced
3. 54 electrical interconnections fully repaired. 150 more needing only partial repairs
4. Over 4 km of vacuum beam tube cleaned
5. A new longitudinal restraining system is being fitted to 50 quadrupole magnets
6. Nearly 900 new helium pressure release ports are being installed around the machine
7. 6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid
ATLAS Collaboration
(Status July 2008)

37 Countries
169 Institutions
2500 Scientific Authors
(1800 with a PhD)

10 vs 14 TeV?

At 10 TeV, more difficult to create high mass objects...

Below about 200 GeV, this suppression is <50% (process dependent)

e.g. \(tt\) ~ factor 2 lower cross-section

Above ~2-3 TeV the effect is more marked

The rest of the talk discusses \(\sqrt{s}=14\) TeV capabilities
LHC data handling, GRID computing

Trigger system selects ~200 “collisions” per sec.

LHC data volume per year: 10-15 Petabytes
\[= 10-15 \cdot 10^{15} \text{ Byte}\]
Early Surprises ??

- as already mentioned, the experiments must be open for surprises / unknowns / unexpected discoveries

- requires unbiased measurements of
  - inclusive lepton spectra
  - dilepton spectra......
  - Missing $E_T$ spectrum.......
  - ......
One example of many….

Z’ → e⁺e⁻ with SM-like couplings (Z_{SSM})

Discovery window above Tevatron limits
m ~ 1 TeV, perhaps even in 2009… (?)
W/Z and top signals

Even with early data (10-50 pb$^{-1}$),
high statistics of W / Z and top samples

⇒ Establish performance for leptons, jets, missing transverse energy, ....

Z $\rightarrow$ ee

K. Jakobs
Symposium, Graduiertenkolleg, Berlin, Sep. 2009
• Complex final states: $H \rightarrow bb$, $t \rightarrow bj$, $t \rightarrow b \ell \nu$
  $t \rightarrow b \ell \nu$, $t \rightarrow b \ell \nu$
  $t \rightarrow bj$, $t \rightarrow bj$

• Main backgrounds:
  - combinatorial background from signal (4b in final state)
  - $ttjj$, $ttbb$, $ttZ$, …
  - $Wjjjjj$, $WWbbjj$, etc. (excellent b-tag performance required)

• Updated ATLAS and CMS studies: matrix element calculations for backgrounds
  → larger backgrounds ($ttjj$ and $ttbb$)

\[ \tt H \rightarrow \tt bb \]

M (bb) after final cuts, 30 fb\(^{-1}\)

estimated uncertainty on the background: $\pm 25\%$ (theory, + exp (b-tagging))

$\Rightarrow$ Normalization from data needed to reduce this (non trivial,...)
New hope for $H \rightarrow bb$ decays at the LHC: $W/Z\ H,\ H \rightarrow bb$

The most important channels at the TEVATRON at low mass!

But: signal to background ratio less favourable at the LHC

Follow idea of J. Butterworth, et al. [PRL 100 (2008) 242001]

Select events ($\approx 5\%$ of cross section), in which $H$ und $W$ bosons have large transverse momenta: $p_T > 200\ GeV$

$\rightarrow b$-quarks in one “fat” Jet

+ Acceptance (more central in detector)
+ Lepton identification, $b$-tagging

$S/\sqrt{B} = 2.1$

$S/B = 1.3\%$

K. Jakobs

Symposium, Graduiertenkolleg, Berlin, Sep. 2009
High $p_T$ W/Z H, $H \rightarrow bb$

Analyze jet structure:

$$L^{int.} = 30 \text{ fb}^{-1} : \frac{S}{\sqrt{B}} = 3.0$$

$M_H = 120 \text{ GeV}$

Combined: \( \frac{S}{\sqrt{B}} = 3.7 \)

(Pileup not yet included)

- S/B much better than for ttH
- Different backgrounds for different channels
- Still good sensitivity including systematics (e.g. $S/\sqrt{B} = 3.0$ for 15% uncertainty on all backgrounds)

ATL-PHYS-PUB-2009-088
Parameter of the SUSY-Model ⇒ Predictions for the relic density of Dark Matter

\[ \rho_\chi \sim m_\chi n_\chi, \quad n_\chi \sim \frac{1}{\sigma_{\text{ann}}(\chi\chi \rightarrow \ldots)} \]

LHC

\( L = 300 \text{ fb}^{-1} \) \( \delta\Omega / \Omega \sim 11\% \)

ILC

\( L = 1000 \text{ fb}^{-1} \) \( \delta\Omega / \Omega \sim 1\% \)

Battaglia et al.
The LHC and the ILC (International Linear Collider, in study/planning phase) are complementary in SUSY searches

Number of observable SUSY particles:

*) Study by J. Ellis et al., hep-ph/0202110