Physics prospects for the LHC

Georg Weiglein

DESY

Abingdon, 09 / 2011

- Introduction
- Physics of electroweak symmetry breaking
- New physics addressing the hierarchy problem
- Conclusions
Introduction
LHC results so far, executive summary:
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Impressive rediscovery of the known ingredients of the Standard Model
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LHC results so far, executive summary:

Impressive rediscovery of the known ingredients of the Standard Model

No evidence for new physics yet
LHC physics: exploring the Terascale

1 TeV \approx 1000 \times m_{\text{proton}} \Leftrightarrow 2 \times 10^{-19} \text{ m}

Temperature / Energy

meV \quad \text{eV} \quad \text{keV} \quad \text{MeV} \quad \text{GeV} \quad \text{TeV}

Atomic physics \quad \text{Nuclear physics} \quad \text{Particle physics}

- Cathode ray tube
- Cyclotron
- LEP, SLC, Tevatron, ILC, LHC
- W, Z, Higgs
- top, SUSY
- Extra Dimensions
- Inflation
- Baryogenesis
- Neutrino Decoupling
- WIMP Decoupling

Time (s)

- $10^{17}$
- $10^{12}$
- $10^{6}$
- 1
- $10^{-6}$
- $10^{-12}$

Physics prospects for the LHC, Georg Weiglein, UK HEP Forum “Physics at the LHC”, Abingdon, 09 / 2011 – p.3
What can we learn from exploring the new territory of TeV-scale physics?
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- How do elementary particles obtain the property of mass: what is the mechanism of electroweak symmetry breaking? Is there a Higgs boson (or more than one)?
- Do all the forces of nature arise from a single fundamental interaction?
- Are there more than three dimensions of space?
- Are space and time embedded into a “superspace”?
- What is dark matter? Can it be produced in the laboratory?
- Are there new sources of $\mathcal{CP}$-violation? Can they explain the asymmetry between matter and anti-matter in the Universe?
Higgs: last missing ingredient of the Standard Model

But: the Standard Model cannot be the ultimate theory
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- The Standard Model does not include gravity
  ⇒ breaks down at the latest at $M_{\text{Planck}} \approx 10^{19}$ GeV
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- “Hierarchy problem”: \[ M_{\text{Planck}}/M_{\text{weak}} \approx 10^{17} \]

How can two so different scales coexist in nature?
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Via quantum effects: physics at $M_{\text{weak}}$ is affected by physics at $M_{\text{Planck}}$

⇒ Instability of $M_{\text{weak}}$

⇒ Would expect that all physics is driven up to the Planck scale
**Higgs: last missing ingredient of the Standard Model**

**But: the Standard Model cannot be the ultimate theory**

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- “Hierarchy problem”: \( M_{\text{Planck}} / M_{\text{weak}} \approx 10^{17} \)

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  \[ \Rightarrow \text{Instability of } M_{\text{weak}} \]

  \[ \Rightarrow \text{Would expect that all physics is driven up to the Planck scale} \]

- Nature has found a way to prevent this

The Standard Model provides no explanation
Hierarchy problem: how can the Planck scale be so much larger than the weak scale?

⇒ Expect new physics to stabilise the hierarchy
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Supersymmetry:
Large corrections cancel out because of symmetry fermions ⇔ bosons
**Hierarchy problem: how can the Planck scale be so much larger than the weak scale?**

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Supersymmetry:
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Extra dimensions of space:
Fundamental Planck scale is $\sim T_eV$ (large extra dimensions), hierarchy of scales is related to a “warp factor” (“Randall–Sundrum” scenarios)
Supersymmetry (SUSY)

Supersymmetry: fermion $\leftrightarrow$ boson symmetry, leads to compensation of large quantum corrections
The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

\[
\begin{align*}
[u,d,c,s,t,b]_{L,R} & \quad [e,\mu,\tau]_{L,R} & \quad [\nu_{e,\mu,\tau}]_{L} \\
[\tilde{u},\tilde{d},\tilde{c},\tilde{s},\tilde{t},\tilde{b}]_{L,R} & \quad [\tilde{e},\tilde{\mu},\tilde{\tau}]_{L,R} & \quad [\tilde{\nu}_{e,\mu,\tau}]_{L} \\
\tilde{g} & \quad \tilde{\chi}_{1,2} & \quad \tilde{\chi}_{1,2,3,4}
\end{align*}
\]

\begin{align*}
\text{Spin } \frac{1}{2} & \\
\text{Spin } 0 & \\
\text{Spin } 1 / \text{Spin } 0 & \\
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Spin $\frac{1}{2}$

\[
\begin{align*}
g &\quad W^\pm, H^\pm \\
\gamma &\quad Z, H_1^0, H_2^0
\end{align*}
\]

Spin 1 / Spin 0

\[
\begin{align*}
\tilde{g} &\quad \tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \\
\tilde{\chi}_3^0, \tilde{\chi}_4^0
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Spin $\frac{1}{2}$

Two Higgs doublets, physical states: $h^0, H^0, A^0, H^\pm$
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\[
g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_{1}^{0}, H_{2}^{0}} \quad \text{Spin } 1 / \text{Spin } 0
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\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \quad \text{Spin } \frac{1}{2}
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Two Higgs doublets, physical states: \(h^{0}, H^{0}, A^{0}, H^{\pm}\)

General parametrisation of possible SUSY-breaking terms \(\Rightarrow\) free parameters, no prediction for SUSY mass scale

Hierarchy problem \(\Rightarrow\) expect observable effects at TeV scale
How does SUSY breaking work?

Exact SUSY $\iff m_e = m_{\tilde{e}}, \ldots$

$\implies$ SUSY can only be realised as a broken symmetry
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MSSM: no particular SUSY breaking mechanism assumed, parameterisation of possible soft SUSY-breaking terms

$\Rightarrow$ relations between dimensionless couplings unchanged

$\Rightarrow$ cancellation of large quantum corrections preserved

Most general case: 105 new parameters
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Most general case: 105 new parameters

Strong phenomenological constraints on flavour off-diagonal and $C\overline{P}$-violating SUSY-breaking terms

$\Rightarrow$ Good phenomenological description for universal SUSY-breaking terms ($\approx$ diagonal in flavour space)
**Simplest ansatz: the Constrained MSSM (CMSSM)**

Assume universality at high energy scale \((M_{\text{GUT}}, M_{\text{Pl}}, \ldots)\) renormalisation group running down to weak scale require correct value of \(M_Z\)

⇒ CMSSM characterised by

\[
m_0^2, \ m_{1/2}, \ A_0, \ \tan \beta, \ \text{sign } \mu
\]

CMSSM has been the “favourite toy” for both theorists and experimentalists so far

CMSSM is in agreement with the experimental constraints from electroweak precision observables (EWPO) + flavour physics + cold dark matter density + . . .
SUSY-breaking scenarios

“Hidden sector”: Visible sector:
SUSY breaking MSSM

“Gravity-mediated”: SUGRA
“Gauge-mediated”: GMSB
“Anomaly-mediated”: AMSB
“Gaugino-mediated”

SUGRA: mediating interactions are gravitational

GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions

AMSB, Gaugino-mediation: SUSY breaking happens on a different brane in a higher-dimensional theory
Models with extra dimensions of space

Hierarchy between $M_{\text{Planck}}$ and $M_{\text{weak}}$ is related to the volume or the geometrical structure of additional dimensions of space

$\Rightarrow$ observable effects at the TeV scale
Gravity in a warped spacetime geometry

[L. Randall, LHC2TSP Workshop ’11]

Natural for gravity to be weak!

- Small probability for graviton to be near the Weakbrane
- If we live anywhere but the Gravitybrane, gravity will seem weak
- Natural consequence of warped geometry

\[ ds^2 = g_{MN} dx^M dx^N = e^{-2\sigma} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2, \]
Phenomenological consequences of extra dimensions

The wave function of a free particle must be $2\pi R$ periodic

$e^{ip \cdot x_5} = e^{ip \cdot (x_5 + 2\pi R)}$

$\Rightarrow$ momentum is quantised

$\Rightarrow$ Looks in 4-dim like a series of new, more massive partners associated with each known particle: “Kaluza–Klein tower”
Phenomenological consequences of extra dimensions

We may be trapped on a \((3 + 1)\)-dimensional brane in a higher-dimensional space-time, while gravity can enter the extra dimensions.

Extra dimensions could be large, even infinite.

- Could explain the apparent weakness of gravity in our 4-dimensional world.

- At the LHC, gravitons could be emitted into the extra dimensions.

- “missing energy” signals

If gravity is strong at the TeV scale, particle collisions at the LHC could form “mini black holes”.
What is the mechanism of electroweak symmetry breaking?

- Standard Model (SM), SUSY, . . . : Higgs mechanism, elementary scalar particle(s)

- Strong electroweak symmetry breaking: a new kind of strong interaction

- Higgsless models in extra dimensions: boundary conditions for SM gauge bosons and fermions on Planck and TeV branes in higher-dimensional space

⇒ New phenomena required at the TeV scale
Standard Model: a single parameter determines the whole Higgs phenomenology: $M_H$

Branching ratios of the SM Higgs:

$\Rightarrow$ dominant BRs:

- $M_H \lesssim 140$ GeV:
  $H \rightarrow b\bar{b}$

- $M_H \gtrsim 140$ GeV:
  $H \rightarrow W^+W^-, ZZ$
Production of a SM-like Higgs at the LHC

SM Higgs production at the LHC:

Dominant production processes:

gluon fusion: $gg \rightarrow H$, weak boson fusion (WBF): $q\bar{q} \rightarrow q'\bar{q}' H$
**Constraints on the SM Higgs from electroweak precision data**

Indirect constraint on $M_{H_{SM}}$, no direct search limits included in the fit

$$\Delta \chi^2$$

July 2011

m_{Limit} = 161 GeV

⇒ Preference for a light Higgs, $M_{H_{SM}} < 161$ GeV, 95% C.L.

[LEPEWWG ’11]
In the SM the same Higgs doublet is used “twice” to give masses both to up-type and down-type fermions

⇒ extensions of the Higgs sector having (at least) two doublets are quite “natural”

⇒ Would result in several Higgs states
**Higgs physics beyond the SM**

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Many extended Higgs theories have over large part of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson

Example: SUSY in the “decoupling limit”
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Many extended Higgs theories have over large part of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson
Example: SUSY in the “decoupling limit”

But there is also the possibility that none of the Higgs bosons is SM-like
Higgs physics in Supersymmetry

“Simplest” extension of the minimal Higgs sector:

Minimal Supersymmetric Standard Model (MSSM)

- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)
- SUSY imposes relations between the parameters
Higgs physics in Supersymmetry

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⇒ Two parameters instead of one: \( \tan \beta \equiv \frac{v_u}{v_d} \), \( M_A \) (or \( M_{H^\pm} \))

⇒ Upper bound on lightest Higgs mass, \( M_h \) (FeynHiggs):

[S. Heinemeyer, W. Hollik, G. W. ’99], [G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. ’02]

\[ M_h \lesssim 130 \text{ GeV} \]

Very rich phenomenology
Indirect prediction for Higgs mass in SM and constrained SUSY models (CMSSM / NUHM1) from precision data

\[ \chi^2 \] fit for \( M_h \), without imposing direct search limits

\[ M_{h, \text{CMSSM}} = 108 \pm 6 \, \text{GeV} \]
\[ M_{h, \text{NUHM1}} = 121^{+2}_{-14} \, \text{GeV} \]

⇒ Accurate indirect prediction; Higgs “just around the corner”?
BSM ⊕ Higgs phenomenology

- Large enhancement / suppression of standard search channels possible
  Example: large enhancement of $H\bar{b}b$ coupling
  $\Rightarrow$ large suppression of $\text{BR}(h \to \gamma\gamma)$, $\text{BR}(h \to WW^*)$, . . .

- New channels, different phenomenology:
  - Experimental evidence for dark matter
    $\Rightarrow$ if dark matter particle is lighter than $M_H/2$
    $\Rightarrow$ large branching fraction into invisible particles
    $\Rightarrow$ large suppression of all other BRs
  - Higgs production in decays of BSM particles
    $h_i \to h_j h_j$ decays
  - Higgs–radion mixing, . . .
  - Higgses with nearly degenerate masses: large interference effects, resonance-type behaviour possible

MSSM with complex parameters:

*a very light SUSY Higgs?*

MSSM with $\mathcal{CP}$-violating phases (CPX scenario):
Light Higgs, $h_1$: strongly suppressed $h_1VV$ couplings
Second-lightest Higgs, $h_2$, possibly within LEP reach (with reduced $VVh_2$ coupling), $h_3$ beyond LEP reach

Large $\text{BR}(h_2 \rightarrow h_1h_1) \Rightarrow$ difficult final state

$\Rightarrow$ Light SUSY Higgs not ruled out!

[LEP Higgs WG ’06]
**A light Higgs in SUSY cascades**

Example: NMSSM scenario, light $\mathcal{C}\mathcal{P}$-even Higgs, 
$20 \text{ GeV} < M_{h_1} < 110 \text{ GeV}$, in agreement with all search limits 
(large singlet component)

$\mu_{\text{eff}} = -200 \text{ GeV}$, $M_1 = 300 \text{ GeV}$, $M_2 = 600 \text{ GeV}$

$M_{\text{SUSY}} = 750 \text{ GeV}$, $m_{\tilde{g}} = 1 \text{ TeV}$

⇒ Higgs production in chargino and neutralino decays 
in SUSY cascades

\[ \tilde{q} \rightarrow q\tilde{\chi}_i^0 \rightarrow q\tilde{\chi}_1^0 h_k \rightarrow q\tilde{\chi}_1^0 b\bar{b} \]

\[ \tilde{g} \rightarrow g\tilde{q} \rightarrow gq\tilde{\chi}_i^0 \rightarrow gq\tilde{\chi}_1^0 h_k \rightarrow gq\tilde{\chi}_1^0 b\bar{b} \]

\[ \ldots \]
Results for $b\bar{b}$ jet invariant mass distribution:

**SUSY signal, SUSY background, SM $t\bar{t}$ background (grey)**

$$\int \mathcal{L} = 5 \text{ fb}^{-1}, \; M_{h_1} \approx 40 \text{ GeV}$$

$\sqrt{s} = 7$ TeV

$\Rightarrow$ Signal over background ratio looks encouraging

$h_1$ peak and $Z$ peak visible

$\Rightarrow$ We could get a signal for SUSY + Higgs at once
How to infer the underlying physics from the experimental signatures?

- A Higgs or not a Higgs?
- Fundamental or composite?
- SM, MSSM or beyond?
- Is there other new physics; what is it?
- How does the observed new physics fit into the global picture (ew precision observables, flavour physics, ...)?
- ...

⇒ Intense effort will be needed to identify the nature of electroweak symmetry breaking
**Higgs searches: what did we learn so far?**

ATLAS SM Higgs search: combined upper limit normalised to the SM expectation (left) and observed result vs. expectation for a SM Higgs signal (right)

[ATLAS Collaboration ’11]

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**Physics prospects for the LHC, Georg Weiglein, UK HEP Forum “Physics at the LHC”, Abingdon, 09 / 2011 – p.28**
Combined confidence limit vs. expectation for a SM Higgs signal

CMS Preliminary, $\sqrt{s} = 7$ TeV
Combined, L$_{int} = 1.1$-1.7 fb$^{-1}$
LHC excludes (at least at 90% C.L.) the range of
\[ 145 \text{ GeV} \lesssim M_{H_{\text{SM}}} \lesssim 460 \text{ GeV} \]
**SM Higgs searches, high-mass region**

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  \[ 145 \text{ GeV} \lesssim M_{H_{SM}} \lesssim 460 \text{ GeV} \]

\[\Rightarrow\] Results from direct searches are in agreement with indirect constraints from electroweak precision data
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  ATLAS sees an excess beyond $M_{H_{SM}} = 460 \text{ GeV} \ldots$
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- A high mass Higgs?

  ATLAS sees an excess beyond $M_{\text{HSM}} = 460 \text{ GeV}$ . . .

  However: a heavy SM-like Higgs appears to be theoretically questionable
Prospects for SM Higgs searches in the high mass region

[W. Murray, LHC2TSP Workshop’11]

ATLAS & CMS best channel for $m_H > 300$
High mass almost background free

H → ZZ → 2l 2υ (l = e, μ)

Scaling faster than $1/\sqrt{s}$
Should extend to 550+ by end of 2011

⇒ Large increase in coverage expected

Physics prospects for the LHC, Georg Weiglein, UK HEP Forum “Physics at the LHC”, Abingdon, 09 / 2011 – p.31
SM Higgs search: ATLAS and CMS results in the low mass region

Combined upper limit normalised to the SM expectation, low mass region

[ATLAS Collaboration ’11]

[CMS Collaboration ’11]

⇒ Broad excess in low mass region
CMS results for SM Higgs searches: local $p$ value and observed best-fit signal strength

With LEE: probability to see an excess at least as large as the one observed in the data is $\approx 0.4$

Best compatibility with a SM Higgs for $M_{H_{SM}} \lesssim 125$ GeV
ATLAS results for SM Higgs searches: local p value vs. expectation for a SM Higgs signal

⇒ Best compatibility with a SM Higgs for $M_{H_{SM}} \lesssim 130$ GeV

Slight deficit w.r.t. SM expectation
**SM Higgs search: Tevatron results, CDF + D0**

CDF + D0 combined upper limit normalised to the SM expectation

![Graph showing Tevatron Run II Preliminary, L ≤ 8.6 fb⁻¹](image)

- LEP Exclusion
- Tevatron Exclusion

⇒ Broad excess in low mass region

*CDF and D0 Collaborations ’11*

Implications of SM Higgs searches
Search for SM Higgs has narrowed down to
\[ 114 \text{ GeV} \lesssim M_{\text{HSM}} \lesssim 135 \text{ GeV} \] ( + high mass region)
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- Broad excess in low mass region observed by ATLAS, CMS and the Tevatron
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- What about a Higgs with $M_H \approx 145 \text{ GeV}$ with somewhat reduced $\sigma \times \text{BR}(H \rightarrow WW^*)$ compared to SM case?
Implications of SM Higgs searches

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- What about a Higgs with $M_H \approx 145 \text{ GeV}$ with somewhat reduced $\sigma \times \text{BR}(H \rightarrow WW^*)$ compared to SM case?
  
  Difficult to get sufficiently large $\text{BR}(H \rightarrow WW^*)$ in the MSSM, can better be accomodated in the NMSSM
CMS excess in $H \rightarrow \gamma\gamma$ search

[W. Murray, LHC2TSP Workshop ’11]

⇒ 1.6σ excess at $M_H \approx 140$ GeV after taking into account LEE

Searches in categories
- Detector resolution,
- $P_T$ – CMS only
- Not yet using $\cos \theta^*$, $n_{jets}$, explicit $n_{Higgs}$
- Resolution is key work area for both experiments
Search for the heavy SUSY Higgs bosons $H, A$: limits in the $M_A - \tan \beta$ plane

$\Rightarrow$ Large coverage in $M_A - \tan \beta$ plane
LHC + LEP start to close the region of very low $M_A$
Search for the heavy SUSY Higgs bosons $H, A$:

cross section limit from CMS

⇒ Excess for $M_A \gtrsim 200$ GeV
However: has the acceptance for $gg \rightarrow H, A$ be overestimated?

- Remark on $gg\rightarrow\phi$ generation
  - CMS used PYTHIA, ATLAS used POWHEG
  - both generators do not include b-quark in the loop:
    - acceptance for $gg\rightarrow\phi$ is overestimated; how much?

Top-loop vs b-loop in $gg\rightarrow h$:
Different Higgs $p_T$!
Fundamental or composite Higgs?

Renewed interest in composite Higgs models, mostly from extra dimensions

[N. Arkani-Hamed, A. Cohen, H. Georgi ’01]
[K. Agashe, R. Contino, A. Pomarol ’05], . . .

Composite Higgs: light remnant of a strong force
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Relation extra dimensions ⇔ new strong forces?

Correspondence (AdS/CFT):

Warped gravity model ⇔ Technicolour-like theory in 4D
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Signatures at LHC: new resonances, $W', Z', t'$, KK excitations

Under pressure from electroweak precision tests
Effective field-theory description of a composite Higgs

Agreement with electroweak precision data can be improved if there is a strongly interacting light Higgs, e.g.

**Little Higgs** [N. Arkani-Hamed, A. Cohen, E. Katz, A. Nelson ’02]

**Holographic Higgs** [R. Contino, Y. Nomura, A. Pomarol ’03], [K. Agashe, R. Contino, A. Pomarol ’05], . . .

Effective Lagrangian formalism for model-independent analysis of effects of a Strongly-Interacting Light Higgs (SILH) [G. Giudice, C. Grojean, A. Pomarol, R. Rataazzi ’07]

⇒ Specific pattern of modified Higgs couplings

Strong $WW$ scattering at high energies despite light Higgs

⇒ Need precision measurement of Higgs couplings

+ test of longitudinal gauge-boson scattering
Strongly-Interacting Light Higgs: deviation of $\sigma \times BR$ from the case of a SM Higgs

$[G. \ Giudice, \ C. \ Grojean, \ A. \ Pomarol, \ R. \ Ratazzi \ '07]$
Further prospects

Prospects for searches for a 114 GeV SM-like Higgs:

⇒ 2011 data, when combined between ATLAS + CMS, should provide $2\sigma$ sensitivity down to $M_H = 114$ GeV
Prospects for the signal significance

⇒ With 2012 data, ATLAS + CMS combined: expect sensitivity of at least $3.5\sigma$
New physics addressing the hierarchy problem

SUSY production cross sections at the LHC with 7 TeV:

⇒ Highest cross section for gluino and squarks of the first two generations

Squark and gluino couplings $\sim \alpha_S$; cross sections mainly determined by $m_{\tilde{q}, \tilde{g}}$, small residual model dependence
SUSY searches at the LHC

Dominated by production of coloured particles: gluino, squarks (mainly first two generations)

Very large mass reach in the searches for jets + missing energy

⇒ gluino, squarks accessible up to 2–3 TeV at LHC (14 TeV)

Coloured particles are usually heavier than the colour-neutral ones

⇒ long decay chains possible; complicated final states

\[ \tilde{g} \rightarrow \bar{q}q \rightarrow \bar{q}q\tilde{\chi}^0_2 \rightarrow \bar{q}q\tau\tau \rightarrow \bar{q}q\tau\tau\tilde{\chi}^0_1 \]

Many states produced at once, difficult to disentangle
**Pre-LHC: Fit results for the CMSSM from precision data**

Comparison: preferred region in the $m_0-m_{1/2}$ plane vs. prospective CMS 95% C.L. reach for 0.1, 1 fb$^{-1}$ at 7 TeV


$\tan\beta = 10$, $A_0 = 0$, $\mu > 0$

CMS preliminary
$\sqrt{s} = 7$ TeV
Hadronic search, 95% C.L. curves

$L = 1000/pb$
$L = 100/pb$

$\Rightarrow$ Best fit point was within the 95% C.L. reach with 1 fb$^{-1}$
SUSY search results for the CMSSM

⇒ High sensitivity from search for jets + missing energy
Previous best-fit point is excluded
CMSSM starts to get under pressure
"Simplified model": squarks of first two generations, gluino + massless neutralino (LSP), all other SUSY particles heavy

[ATLAS Collaboration '11]
Limits for gluinos and squarks in simplified models, LSP mass varied between 0 and 200 GeV

Ranges of exclusion limits for gluinos and squarks, varying $m(\tilde{\chi}^0_1)$

CMS preliminary

For limits on $m(\tilde{g})$, $m(\tilde{q}) >> m(\tilde{g})$ (and vice versa), $\sigma^{\text{prod}} = \sigma^{\text{NLO-QCD}}$.

$m(\tilde{g})$, $m(\tilde{q}) = \frac{m(\tilde{g}) + m(\tilde{q})}{2}$.

$m(\tilde{\chi}^0_1)$ is varied from 0 GeV/c^2 (dark blue) to m(\tilde{g})-200 GeV/c^2 (light blue).

⇒ Large dependence on LSP mass

[CMS Collaboration ’11]
Stop production in gluino decays

[ATLAS Collaboration ’11]

⇒ Observed limit decreased with 30 × more luminosity

1.2 σ excess in both electron and muon channels

Physics prospects for the LHC, Georg Weiglein, UK HEP Forum “Physics at the LHC”, Abingdon, 09 / 2011 – p.52
Global fit in the CMSSM including 2011 LHC data $(1 \text{ fb}^{-1})$ and XENON100 results

68% and 95% CL contours, pre- and post-LHC


⇒ Preferred region “opens up”, overall $\chi^2$ worsened
Shift towards higher mass scales, higher values of $\tan \beta$

Comparison: GMSB yields much larger splitting between coloured and colour-neutral part of the spectrum
Status of SUSY searches

- Search for jets (+ leptons) + missing energy
  ⇒ Bounds on gluino and squarks of first two generations of $\mathcal{O}(\text{TeV})$
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  \[ \Rightarrow \text{The constrained scenario CMSSM starts to get under some tension: direct search limits vs. } (g - 2)_\mu \]

- Reduced sensitivity to compressed spectra

- Limited sensitivity to 3rd generation squarks
  Hardly any direct constraints from the LHC on colour neutral SUSY particles up to now
SUSY searches: what next?

Assuming colored particles (1\textsuperscript{st} and 2\textsuperscript{nd} generation squarks and gluinos) are beyond the LHC range:

a) Need dedicated exclusive studies to constrain stops and sbottoms
   - With and without the cross section help from the colored particles
   - See also M. Papucci’s EPS-2011 talk
   - [http://indico.in2p3.fr/contributionDisplay.py?contribId=904&sessionId=6&confId=5116](http://indico.in2p3.fr/contributionDisplay.py?contribId=904&sessionId=6&confId=5116)

b) Need dedicated activity on EWK inos
   - Current limits on Chargino/neutralinos are low
   - Explore LHC reach for the electroweak sector
     (See also Shufang Su SUSY-11 talk)
Search for heavy resonance: dileptons

<table>
<thead>
<tr>
<th>Model/Coupling</th>
<th>RS Graviton</th>
<th>E6 Z’ Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass limit [TeV]</td>
<td>0.01 0.03 0.05 0.1</td>
<td>Z’_w Z’_N Z’_1 Z’_S Z’_X</td>
</tr>
<tr>
<td></td>
<td>0.71 1.03 1.33 1.63</td>
<td>1.49 1.52 1.54 1.56 1.60 1.64</td>
</tr>
</tbody>
</table>

RS graviton (k/M_{Pl} = 0.1):
\( m(G_{kk}) > 1.63 \text{ TeV} @ 95\% \text{ C.L.} \)

Sequential SM:
\( m(Z’_{SSM}) > 1.83 \text{ TeV} @ 95\% \text{ C.L.} \)

As expected with current data
Search for dilepton resonances: CMS

Limits with dimuons, dieelectrons

EXO-11-019

$Z'_{SSM}$: 1940 GeV
$Z'_{\psi}$: 1620 GeV
$KK$: 1450 GeV ($\frac{k}{M}=0.05$)
$KK$: 1780 GeV ($\frac{k}{M}=0.1$)

Exclusion limits for SSM, superstring-inspired, RS KK (1.5-2 TeV, as well as ADD models for several parameters (2-3 TeV)

EXO-11-039
Search for dijet resonances: ATLAS

Search for Heavy Resonance: dijet

\[ m(\text{jet-jet}) = 4.0 \text{ TeV} \quad \text{Missing } E_T = 100 \text{ GeV} \]
Search for dijet resonances: CMS

Resonances: limits with dijets

Derived limits for several models, with excluded masses up to 4 TeV

<table>
<thead>
<tr>
<th>Model</th>
<th>Excluded Mass (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>String Resonances</td>
<td>4.00</td>
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<tr>
<td>$E_6$ Diquarks</td>
<td>3.52</td>
</tr>
<tr>
<td>Excited Quarks</td>
<td>2.49</td>
</tr>
<tr>
<td>Axigluons/Colorons</td>
<td>2.47</td>
</tr>
<tr>
<td>$W'$ Bosons</td>
<td>1.51</td>
</tr>
</tbody>
</table>

arXiv.1107.4771
(submitted to PLB)
EXO-11-015
Search for the rare decay $B_s \rightarrow \mu^+ \mu^-$

B physics rare decay par excellence:

$$BR(B_s \rightarrow \mu \mu)_{SM} = (3.2 \pm 0.2) \times 10^{-9}$$


Precise prediction (which will improve)!

Very high sensitivity to NP, eg. MSSM:

One example [O. Buchmuller et al, arXiv:0907.5568]: NUHM (= generalised version of CMSSM)

$$BR^{MSSM}(Bq \rightarrow l^+ l^-) \propto \frac{m_b^2 m_l^2 \tan^6 \beta}{M_{A_0}^4}$$

BR UL 95% CL as of Spring 2011:

CDF (3.7 fb$^{-1}$): $< 4.3 \times 10^{-8}$

D0 (6.1 fb$^{-1}$): $< 5.1 \times 10^{-8}$

LHCb (37 pb$^{-1}$): $< 5.6 \times 10^{-8}$

Recent exciting hint from CDF (7 fb$^{-1}$):

$$BR = 1.8^{+1.1}_{-0.9} \times 10^{-8}$$

[arXiv:1107.2304]
$\text{BR}(B_s \rightarrow \mu^+\mu^-): \text{combined result from LHCb and CMS}$

- LHCb and CMS have performed a preliminary combined limit
  [LHCb-CONF-2011-043, CMS PAS BPH-11-019]
  - LHCb: $\text{BR}(B_s \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8}$ at 95%(90%) c.l.
  - CMS: $\text{BR}(B_s \rightarrow \mu^+\mu^-) < 1.9 \times 10^{-8}$ at 95%(90%) c.l.

- LHCb+CMS limit: $\text{BR}(B_s \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-8}$ at 95%(90%) c.l.

⇒ Very good agreement with SM expectation (so far)
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There is much more to come — the party has just begun!