The SM and SUSY after the LHC Results

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The main LHC results so far

• A robust exclusion interval for the SM Higgs. Essentially only a narrow window below 600 GeV: 122-128 GeV.

• Some indication for $m_H \sim 125$ GeV

• No evidence of new physics, although a big chunk of new territory has been explored

• Important results on $B$ and $D$ decays from LHCb (also CMS) [e.g. $B_s \rightarrow J/\Psi \phi$, $B_s \rightarrow \mu \mu$, .... CP viol in $D$ decay]
95% exclusion
ATLAS:
110-117.5, 118.5-122.5, 129-539 GeV
CMS:
127.5-600 GeV

All experiments see some excess at ~ 122 - 128 GeV
The indication is that $m_H$ is in this range

The evidence could still evaporate

We need to wait for the 2012 run

**Good:**
- $\gamma\gamma$ excess in ATLAS (2.8$\sigma$ at 126.5) and in CMS (2.9$\sigma$ at 125)
- $ZZ\rightarrow 4l$ in ATLAS (2.1$\sigma$ at $\sim$125: 3 events)
- $bb+WW$ at Tevatron (2.7$\sigma$ in 115-135) are all compatible

**Bad:**
- $ZZ\rightarrow 4l$ in CMS (2.5$\sigma$ at 119.5: 3 events)
- $WW$ in ATLAS less than expected, CMS compatible
- $bb, \tau\tau$ in ATLAS & CMS nothing
What if the evidence evaporates in ‘12?

Can we do without the Higgs?

Suppose we take the gauge symmetric part of the SM and put masses by hand.

What is the fatal problem at the LHC scale?

The most immediate disease that needs a solution is the occurrence of unitarity violations in some amplitudes.

To avoid this either there is one or more Higgs particles or some new states (e.g. new vector bosons).

Thus something must happen at the few TeV scale!!
The SM Higgs is close to be observed or excluded!

Either the SM Higgs is very light (122 - 128 GeV)
or rather heavy (i.e. > 600 GeV)

The range $m_H = 122 - 128$ GeV is in agreement
with precision tests, compatible with the SM and also with
the SUSY extensions of the SM

$m_H \sim 125$ GeV is what you expect from a direct interpretation
of EW precision tests: no fancy conspiracy with new physics
to fake a light Higgs while the real one is heavy

$m_H > 600$ GeV would point to the conspiracy alternative
A light SM Higgs in the 122-128 GeV range is in agreement with EW tests.

Excl. by ATLAS and/or CMS
also $300 < m_H < 600$ GeV is excluded.
Theoretical bounds on the SM Higgs mass

\( \Lambda \): scale of new physics beyond the SM

Upper limit: No Landau pole up to \( \Lambda \)
Lower limit: Vacuum (meta)stability

If the SM would be valid up to \( M_{\text{GUT}}, M_{\text{Pl}} \) with a stable vacuum then \( m_H \) would be limited in a small range

\[ 130 \text{ GeV} < m_H < 180 \text{ GeV} \]

Isn’t \( m_H = 125 \text{ GeV} \) a bit too light?

\( \alpha_s \) depends on \( m_t \) and \( \alpha_s \)
But metastability (with sufficiently long lifetime) is enough!

\[ V[\phi] = -\mu^2 \phi^2 + \lambda \phi^4 \]

we are here

\[
\begin{array}{cc}
\text{V} & \text{\lambda negative} \\
\text{true vacuum} & \phi
\end{array}
\]

(something is assumed to stabilize \( V \) at \( \sim M_{Pl} \))

In the absence of new physics, for \( m_H \sim 125 \text{ GeV} \), the Universe becomes metastable at a scale \( \Lambda \sim 10^{10} \text{ GeV} \)

But the SM remains viable up to \( M_{Pl} \) (Early universe implications)
$m_H > \sim 130$ GeV for stability

The vacuum could be stabilized by a minimum of added new physics like a heavy singlet $S$ with a large VEV below the metastability scale

Elias-Miro et al '12
The Standard Model works very well
So, why not find the Higgs and declare particle physics solved?

Because of both:

Conceptual problems

- Quantum gravity
- The hierarchy problem
- The flavour puzzle

and experimental clues:

- Neutrino masses
- Coupling unification
- Dark matter
- Baryogenesis
- Vacuum energy

- some experimental anomalies: \((g-2)_\mu\), .....
Solutions to the hierarchy problem

• Supersymmetry: boson-fermion symm.
  The most ambitious and widely accepted
  Simplest versions now marginal
  Plenty of viable alternatives

• Strong EWSB: Technicolor
  Strongly disfavoured by LEP. Coming back in new forms

  Composite Higgs
  Higgs as PG Boson, Little Higgs models......

• Extra spacetime dim’s that somehow “bring” $M_{Pl}$ down to $\mathrm{o}(1\text{TeV})$ [large ED, warped ED, ......]. Holographic composite H
  Exciting. Many facets. Rich potentiality. No baseline model emerged so far

• Ignore the problem: invoke the anthropic principle

  Extreme, but not excluded by the data
What do we mean by the “SM”?

An enlarged SM (to include RH ν’s but no new physics at LHC) valid up to a large scale is an (enormously fine tuned) option

A light Higgs

SO(10) non SUSY GUT

SO(10) breaking down to SU(4)xSU(2)LxSU(2)R at an intermediate scale \((10^{11-12})\) [coupling unification, p-decay OK]

Majorana neutrinos and see-saw \((-\rightarrow 0\nu\beta\beta)\)

Axions as dark matter

Baryogenesis thru leptogenesis

(but: \((g-2)_\mu\) and other present deviations from SM in colliders should be disposed of)

\[\text{following the anthropic philosophy}\]
Muon g-2

\( a_\mu \) is a plausible location for a new physics signal!!

eg could be light SUSY (now tension with LHC)

\[ a_\mu \exp - a_\mu^{\text{SM}} = (28.7 \pm 8.0) \times 10^{-10} \]

\[ \Rightarrow 3.6 \text{ "standard deviations" } (e^+e^-) \]

\[ \Rightarrow 2.4 \text{ "standard deviations" } (\tau) \]

\[ \delta a_\mu = 13 \cdot 10^{-10} \left( \frac{100 \text{ GeV}}{M_{\text{SUSY}}} \right)^2 \tan \beta \]

Error dominated by th error from \( \gamma - \gamma \)
SUSY effects could improve the EW fit

“light SUSY” = light s-leptons and charginos; s-quarks >~ 1 TeV

G.A, Caravaglios, Gambino, Giudice, Ridolfi ‘01

The same region as for (g-2)_{\mu}
SUSY: boson fermion symmetry

The hierarchy problem: \[ \delta m_{h|_{top}}^2 = \frac{3G_F}{2\sqrt{2}\pi} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2 \]

In broken SUSY \( \Lambda^2 \) is replaced by \( (m_{\text{stop}}^2 - m_t^2)\log\Lambda \)

\( m_H > 114.4 \) GeV, \( m_{\chi^+} > 100 \) GeV, EW precision tests, success of CKM, absence of FCNC, all together, impose sizable Fine Tuning (FT) particularly on minimal realizations (MSSM, CMSSM…).

Yet SUSY is a completely specified, consistent, computable model, perturbative up to \( M_{\text{Pl}} \) quantitatively in agreement with coupling unification (GUT’s) (unique among NP models) and has a good DM candidate: the neutralino (actually more than one).

Remains the reference model for NP
Beyond the SM SUSY is unique in providing a perturbative theory up to the GUT/Planck scale.

Other BSM models (little Higgs, composite Higgs, Higgsless....) all become strongly interacting and non perturbative at a multi-TeV scale.
The general MSSM has > 100 parameters

Simplified versions with a drastic reduction of parameters are used for practical reasons, e.g.

CMSSM, mSUGRA: universal gaugino and scalar soft terms at GUT scale $m_{1/2}$, $m_0$, $A_0$, $\tan\beta$, sign($\mu$)

NUHM1,2: different than $m_0$ masses for $H_u, H_d$ (1 or 2 masses)

It is only these oversimplified models that are now cornered
A more flexible setup is the MSSM with CP and R conservation and 19 parameters (pMSSM) recently studied in several works

Arbey et al ‘11, ‘12
Jets + missing $E_T$ 

CMSSM (degenerate $s$-quarks)
Impact of $m_H \sim 125$ GeV on SUSY models

Minimal models with gauge mediation are disfavoured (predict $m_H$ too light)

Arbey et al’11; Draper et al, ‘11

some versions, eg gauge mediation with extra vector like matter, could still work

Endo et al ‘11

Anomaly mediation is also generically in trouble

Gravity mediation is better but CMSSM, mSUGRA, NUHM1,2 need squarks heavy, $A_t$ large and lead to tension with g-2 (that wants light SUSY) and $b \rightarrow s \gamma$

Arbey et al’11, Akura et al; Baer et al; Battaglia et al; Buchmuller et al, Kadastik et al; Strege et al; ‘11
\[ m_H = 125 \, \text{GeV} \text{ plus new bounds from negative searches disfavour simplest versions of SUSY} \]
M_H \sim 125 \text{ GeV}
makes CMSSM/mSUGRA marginal
As a comparison, the upper limit on $m_h$ is larger in the pMSSM

$$m_h^2 = m_Z^2 |\cos 2\beta|^2 + \delta m_h^2$$

$$125^2 = 91^2 + 86^2$$

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left( \log \left( \frac{m_t^2}{m_t^2} \right) + \frac{X_t^2}{m_t^2} \left( 1 - \frac{X_t^2}{12 m_t^2} \right) \right)$$

$$X_t = A_t - \mu \cot \beta$$

large $M_S$

large $X_t$ needed
blue: $m_H \sim 125$ GeV
note $A_0$ large and negative
inconsistent with g-2

Baer et al '11

NUHM1,2
add 1 or 2 separate mass parameters for Hu, Hd
Dark Matter in mSUGRA: normally too much is predicted for $m_H = 125$ GeV

$mSUGRA: \mu > 0, m_h = 125 \pm 2$ GeV, $m_\chi = 173.3$ GeV

Baer et al ‘12

blue: $m_0 < 5$ TeV
orange: $5 < m_0 < 20$ TeV
Exp
Extended EW precision tests

- The EW precision tests
- Muon g-2
- Flavour precision observables
- Dark Matter
- Higgs mass constraints and LHC

$m_h$ goes up in CMSSM when $b \rightarrow s \gamma$, $(g-2)_\mu$, $\Omega_{DM}$ are added

Before LHC ‘11

O. Buchmuller et al ’07-’11
with $g-2$ $m_H \sim 119$ GeV
without $g-2$ $m_H \sim 125$ GeV
gluinos and 1-2 gen s-quarks are mostly affected by LHC not EW-inos and stops

Sekmen et al '11

pMSSM

gluino
left squark
right squark

neutralino
chargino
stop
One must go beyond the CMSSM, mSUGRA, NUHM1,2

There is plenty of room for more sophisticated versions of SUSY as a solution to the hierarchy problem

The pMSSM shows that SUSY is alive

Simplest new ingredients

- Heavy first 2 generations
- NMSSM
- $\lambda$ SUSY

\{ an extra Higgs singlet \}
For MSSM to be natural

\[- \frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2\]

\(\mu\) related to lightest Higgsino mass

\[\delta m_{H_u}^2 |_{\text{stop}} = -\frac{3}{8\pi^2} y_t^2 \left( m_{t_1}^2 + m_{t_2}^2 + |A_t|^2 \right) \log \left( \frac{\Lambda}{\text{TeV}} \right) \]

largest radiative corrections involve s-top and gluinos

\[\delta m_{H_u}^2 |_{\text{gluino}} = -\frac{2}{\pi^2} y_t^2 \left( \frac{\alpha_s}{\pi} \right) |M_3|^2 \log^2 \left( \frac{\Lambda}{\text{TeV}} \right)\]

Tree level

\(\sin^2 2\beta \ll 1\)

(no extra singlet in MSSM)

\[m_{\tilde{g}}, m_{\tilde{t}}, m_{\tilde{b}}, m_{\tilde{h}} < \sim 1 \text{ TeV}\]
Beyond the CMSSM, mSugra, NUHM1,2

Heavy 1st, 2nd generations

- Flavour and CP problems improved
  - Dimopoulos, Giudice 1995
  - Pomarol, Tommasini 1995
  - B, Dvali, Hall 1995
  - Cohen, Kaplan, Nelson 1996

- Pioneer papers
- Recent papers, e.g.
  - Papucci et al '11
  - Brust et al '11
  - Larsen et al '12
  - Csaki et al '12
  - ...
For example, may be gluinos decay into 3-gen squarks

e.g.,

\[ \tilde{g} \rightarrow \tilde{t}_1 \ ; \ \tilde{t}_1 \rightarrow b\tilde{\chi}^\pm_1 \]

and \[ \tilde{\chi}_1^\pm \rightarrow W^* \tilde{\chi}_1^0 \]

\[ m(\text{gluino}) > 500 \ \text{GeV at 95\% C.L.} \]

\[ m_{s\text{-top}} > \sim 250 \ \text{GeV} \]
Going beyond the MSSM: an extra singlet Higgs

In a promising class of models a singlet Higgs \( S \) is added and the \( \mu \) term arises from the \( S \) VEV (the \( \mu \) problem is solved)

\[
\lambda \, S H_u H_d
\]

Mixing with \( S \) can modify the Higgs mass and couplings at tree level

**NMSSM:** \( \lambda < \sim 0.7 \) the theory remains perturbative up to \( M_{\text{GUT}} \) (no need of large stop mixing, less fine tuning)

**SUSY:** \( \lambda \sim 1 - 2 \) for \( \lambda > 2 \) theory non pert. at \( \sim 10 \text{ TeV} \)
\[ m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2. \]

Additional term

Less need of loop terms

\[ \rightarrow \text{lighter s-top, less FT} \]

Hall et al '11

\[ \tan \beta \]
It is not excluded that at 125 GeV the heaviest of the two is seen and the lightest escaped detection at LEP.

Ellwanger ‘11

the $\gamma\gamma$ and $\tau\tau$ couplings of the lightest higgs are suppressed while enhanced for the heavier at 125 GeV.
A moderate enhancement of the $\gamma\gamma$ rate may be indicated.
For $\lambda > 0.7$ the full mixing matrix must be considered the $\lambda$ term is too large, but mixing with $S$ pushes $H$ down.

Hall et al '11

No need of loops
Fine tuning can be very small
Summary

• A robust exclusion interval for the SM Higgs.
  A narrow window below 600 GeV: 122.5-127.5 GeV

• An indication for $m_H \sim 125$ GeV (to be checked in ‘12)

• No evidence of new physics, although a big chunk of new territory has been explored

• $m_H \sim 125$ GeV is a bit too light for SM (metastability)

• $m_H \sim 125$ GeV is a bit too heavy for CMSSM, mSUGRA, NUHM...
  OK for pMSSM, NMSSM, $\lambda$-SUSY

• Tension with g-2

• Heavy 1,2 generations of spartners favoured