Higgs boson: what exactly are we looking for?

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Recent news from Tevatron and LHC (Spring & Summer 2011):

- possible indication of Higgs boson with mass 120–140 GeV
- exclusion of supersymmetric particles lighter than 1 TeV –
  – end of supersymmetry?

IS HIGGS NEEDED?

Standard model of particles and interactions

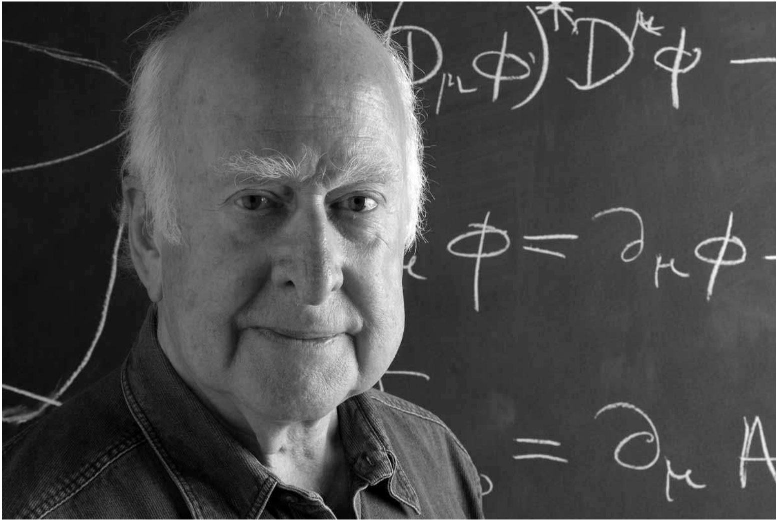
- works extremely well in low energies
- does not explain gravity (should it?)
- relies on many free parameters (ca. 20) taken from experiments
- does not explain: number of generations, symmetry structure, masses, mass hierarchies, number of elementary forces...

In the Glashow–Salam–Weinberg model
particles are **massless**

- Higgs mechanism: at least one additional complex scalar field with non-zero vacuum expectation value
- Higgsless models: technicolor and others

Higgs is...

> *...the toilet of the Standard Model; every house must have one, but no one likes to talk about it.*
>
> /an eminent theorist/



PETER HIGGS

Actually, the people involved in formulating this mechanism, got APS Sakurai Prize in 2010:

- Englert
- Brout
- Higgs
- Guralnik
- Hagen
- Kibble

HIGGS MECHANISM
THE IDEA

A complex scalar field with specific potential

$$\mathcal{L}_H = \partial_\mu \phi \partial^\mu \phi^* - V(\phi, \phi^*) = \partial_\mu \phi \partial^\mu \phi^* - [M^2 \phi \phi^* + h(\phi \phi^*)^2]$$

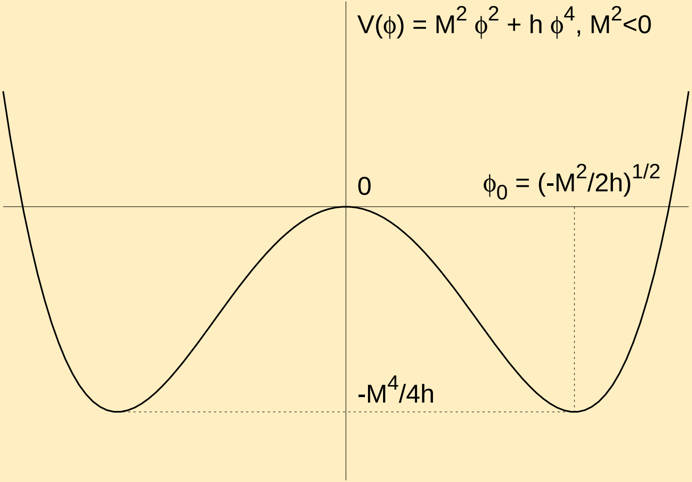
where $h > 0$ (interaction) and $M^2 < 0$ (mass term).
Minimizing the potential leads to Euler–Lagrange equation

$$\frac{\delta \mathcal{L}_H}{\delta \phi^*} = 0 \qquad \Rightarrow \qquad \partial_\mu \partial^\mu \phi + \frac{\delta V}{\delta \phi^*} = 0$$

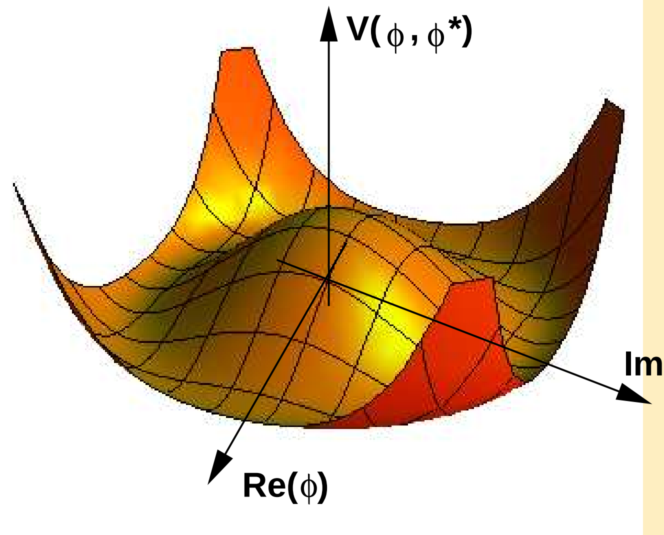
with minimum in

$$|\phi_0|^2 = \frac{-M^2}{2h} \equiv \frac{1}{2} v^2 > 0$$

The ground state (vacuum) is NOT at $\phi = 0$
which allows for spontaneous symmetry breaking



Higgs potential in 2D



Higgs potential in 3D

Observations:

- the ground state

$$\langle 0|\phi|0\rangle = \phi_0 = \frac{v}{\sqrt{2}}\exp(i\beta)$$

  is not invariant under a global gauge symmetry $\phi' = \exp(i\Lambda)\phi$. This is called spontaneous symmetry breaking and leads in SM directly to massive gauge bosons

- the field has imaginary mass ($M^2 < 0$) – not a physical particle. This can be fixed by a simple gauge transformation:

$$\phi \to \phi + \phi_0 \qquad \text{(unitary gauge)}$$

The Higgs field in unitary gauge

$$\phi = \frac{1}{\sqrt{2}}(v + \phi_1 + \mathrm{i}\phi_2)$$

The Euler–Lagrange equations for both real components

$$\begin{cases} \Box\phi_1 - 2M^2\phi_1 = -h \times \text{(interaction terms 1)} \\ \Box\phi_2 \qquad\qquad\quad = -h \times \text{(interaction terms 2)} \end{cases}$$

result in one massive and one massless field

$$\begin{aligned} m_1^2 &= -2M^2 > 0 \\ m_2^2 &= 0 \end{aligned}$$

HIGGS MECHANISM IN STANDARD MODEL

Glashow–Salam–Weinberg model:

- a gauge theory with symmetry $SU(2)_L \times U(1)_Y$
- the generators (gauge bosons B, $W_{1,2,3}$) are massless
- other particles (fermions) are massless too

Missing features:

- the electroweak symmetry needs to be broken to electromagnetism $SU(2)_L \times U(1)_Y \to U(1)_Q$
- massive gauge bosons ($W^{\pm}$, Z^0), except the photon (γ)
- massive fermions

Incorporation of the Higgs mechanism in the SM: a complex scalar $SU(2)$ doublet. For proper electroweak symmetry breaking (EWSB) the choice is

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}[v + \chi(x)] \end{pmatrix}$$

Repeating the minimization procedure for

$$\mathcal{L}_{GSW-H} = (D_\mu \Phi)^\dagger (D_\mu \Phi) - \frac{1}{2} M^2 (v + \chi)^2 - \frac{1}{4} h (v + \chi)^4$$

one gets the masses

$$\begin{aligned} m_\gamma &= 0 \\ m_W &= \frac{gv}{2} \\ m_Z &= \frac{gv}{2\cos\theta} = \frac{m_W}{\cos\theta} \\ m_H &= \sqrt{-2M^2} \end{aligned}$$

Summary: standard model

- A single complex scalar $SU(2)$ doublet added to the model generates mass terms for the gauge bosons
- The same scalar doublet couples through Yukawa-like interactions giving masses to leptons and quarks
- Three out of four degrees of freedom of the Higgs field couple to the gauge bosons: two are massive (W, Z), one massless (γ)
- Fourth massive degree of freedom results in a new scalar particle, the Higgs boson; it is CP-even and its own antiparticle; rough estimates are

  $$60 - 62\ \text{GeV} < m_H < 200 - 250\ \text{GeV}$$

  but lots of more detailed arguments alter these values!
- Absolute upper limit is ~ 710 GeV, above which the SM breaks down as a perturbative theory

Using the expression for the electron–neutrino scattering cross-section one finds that

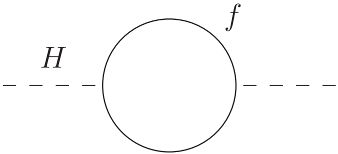
$$v^2 = (\sqrt{2}G_F)^{-1} \Rightarrow v \approx 246 \text{ GeV}$$

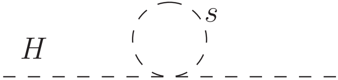
But $v = \sqrt{-M^2/h}$ so we expect $-M^2 \sim (100 \text{ GeV})^2$.

Therefore a light Higgs boson is preferred!

Problems in SM and why supersymmetry:

- m_H receives huge quantum corrections (t quark boosts it 30 orders of magnitude above the desired level!)
- corrections are sensitive to the UV cut-off scale Λ_{UV}
- lowering Λ_{UV} introduces new physics above that scale
- supersymmetry introduces heavy scalar particles, which cancel the quantum corrections and allow for light Higgs





$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \ldots$$

$$\Delta m_H^2 = \frac{\lambda_s^2}{16\pi^2}\Lambda_{UV}^2 + \ldots$$

HIGGS MECHANISM IN MINIMAL SUSY MODELS

Minimal Supersymmetric Standard Model (MSSM) requires two Higgs doublets

- In SM the gauge anomalies *accidentally* (?) cancel

  $$\mathrm{Tr}[(T_3)^2 Y] = \mathrm{Tr}[Y^3] = 0$$

  where T_3 – 3rd isospin component, Y – weak hypercharge, $Q = T_3 + Y$. Traces go over all L-handed Weyl fermions (in SM: leptons and quarks). Adding one Higgs fermionic partner (higgsino) with $Y = +1/2$ or $Y = -1/2$ triggers anomaly. Adding two Higgses with $Y = +1/2$ and $Y = -1/2$ is OK.
- Structure of supersymmetry allows only $Y = +1/2$ Higgs to couple to $Q = +2/3$ up-type quarks, and $Y = -1/2$ Higgs to $Q = -1/3$ down-type quarks and charged leptons.

Chiral superfield	$SU(3)_c \times SU(2)_L \times U(1)_Y$ assignement	Components
H_d	$(1,2,-\frac{1}{2})$	$\begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix}$, $\begin{pmatrix} \tilde{h}_d^0 \\ \tilde{h}_d^- \end{pmatrix}$
H_u	$(1,2,+\frac{1}{2})$	$\begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix}$, $\begin{pmatrix} \tilde{h}_u^+ \\ \tilde{h}_u^0 \end{pmatrix}$

$$W \sim Y_E L H_d \bar{E} + Y_D Q H_d \bar{D} + Y_U Q H_u \bar{U} + \mu H_u H_d + \kappa L H_u$$

So, in principle, **8 real components** of the Higgs bosons are present in the model. Isn't it too much? Not really...

A single Higgs is just dumb. It explains nothing.

/Chris Hill (Fermilab)/
(FermiNews, vol. 21, no. 2, 23.01.1998)

The procedure is standard but far more complicated than in SM

- the neutral scalar potential V_{neutral} must be extracted from the full superpotential
- the Higgs part is mixed with sneutrino contributions, which also develop v.e.v.'s (five v.e.v.'s in total: v_u, v_d, v_1, v_2, v_3)
- minimization conditions are

$$\left.\frac{\partial V_{\text{neutral}}}{\partial \text{Re}(h^0_{u,d})}\right|_{\text{min}} = 0 \qquad \left.\frac{\partial V_{\text{neutral}}}{\partial \text{Re}(\tilde{\nu}_\alpha)}\right|_{\text{min}} = 0$$

  allow to get μ, κ and other couplings from the Higgs sector
- massess emerge from diagonalization of mass (mixing) matrices, constructed from the superpotential in the interaction basis

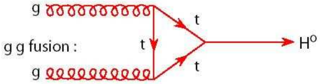
RECENT EXPERIMENTS

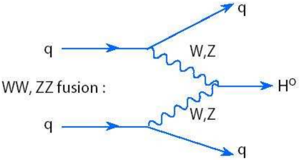
(briefly, no details)

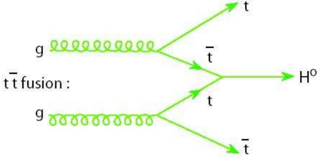
CDF, D0 – Tevatron, ATLAS, CMS – LHC

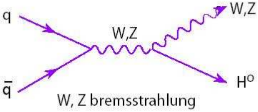
A few words about the experiments:

- Higgs searches: LHC and Tevatron
- Higgs quickly decays – no direct observation
- several decay channels (more if SUSY)
- signatures: jets + missing energy = undetectable particles: neutrinos, sneutrinos,... – impossible to tell apart some channels
- outcome is model dependent
- usual stuff (background, data analysis, channel separation...)







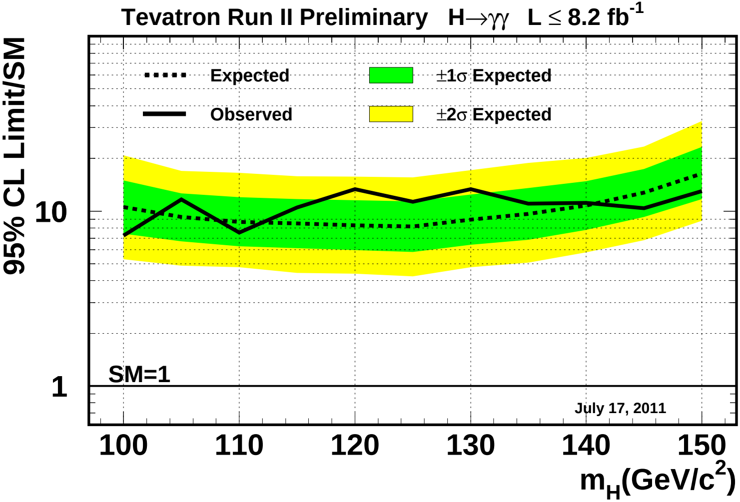


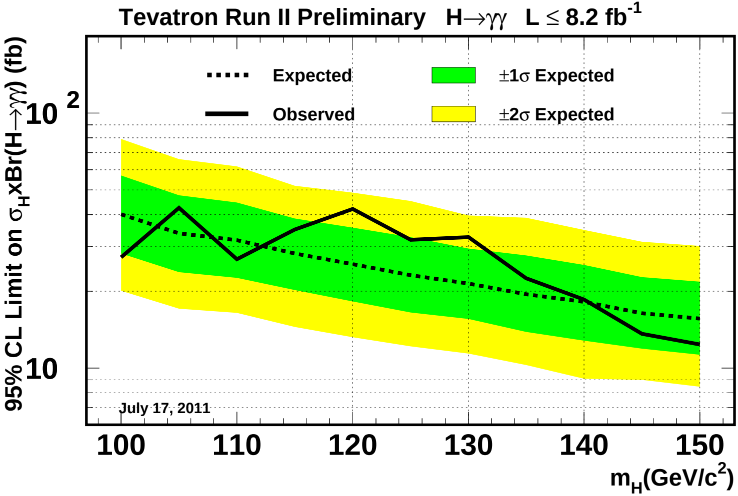
Recent Higgs results
`tevnphwg.fnal.gov`

- newest constraints (Summer 2011) on the SM Higgs particle exclude the region 145–466 GeV; what is left

$$\begin{aligned} \text{(old LEP data)} \rightarrow\ & 115 - 145\ \mathrm{GeV} \\ & 466 - 800\ \mathrm{GeV}\ \leftarrow\ \text{(not likely)} \end{aligned}$$

- CDF and D0 collaborations saw an excess of events
  - a SM Higgs decaying into $b\bar{b}$?
  - a statistical fluctuation?
  - **data compatible with a supersymmetric Higgs of 120–140 GeV with significance 2.5 σ**


Tevatron Run II Preliminary H→γγ L ≤ 8.2 fb^{-1}
Expected
Observed
±1σ Expected
±2σ Expected
95% CL Limit/SM
10
1
SM=1
July 17, 2011
100
110
120
130
140
150
m_H(GeV/c^2)


Tevatron Run II Preliminary H→γγ L ≤ 8.2 fb^{-1}
Expected
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10^2
10
July 17, 2011
100
110
120
130
140
150
m_H(GeV/c^2)
95% CL Limit on σ_HxBr(H→γγ) (fb)

What about SUSY?
(check ATLAS and CMS web pages)

Other data from LHC ruled out supersymmetric extensions of SM in which masses of the supersymmetric particles are smaller than 1 TeV.

- high masses of SUSY particles can be achieved for high values of free parameters, for which the theory almost breaks down
- is SUSY in trouble?
- not really: the data are for very specific (simplest) SUSY model
    - conserved baryon and lepton number (R–parity)
    - stable lightest particle (LSP) must be a neutralino or sneutrino
    - superpartners affected by strong nuclear forces are significantly heavier than other superpartners of known particles

I will loose the lepton number conservation assumption.

LIGHTEST HIGGS MASSES

IN RpV mSUGRA

R–parity broken supersymmetry

- in SM lepton and baryon numbers are conserved *a priori*, because our observations suggest it
- in neutrino oscillations, the generation lepton numbers L_e, L_μ, and L_τ are not conserved
- in general, all possible terms should be present in the lagrangian (superpotential); some of them should be suppressed
- biggest constraint comes from the proton decay
- we don't know what happens at high energies
- we don't know any theoretical mechanism forbidding breaking of L and/or B

Higgs bosons mass eigenstates

1. CP-even neutral Higgs–sneutrino mixing (5 × 5 matrix)

$$\mathrm{Re}(h_u^0), \mathrm{Re}(h_d^0), \mathrm{Re}(\tilde{\nu}_i) \rightarrow \boldsymbol{h^0}, H^0, \tilde{\nu}_i^+$$

2. CP-odd neutral Higgs–sneutrino mixing (5 × 5 matrix)

$$\mathrm{Im}(h_u^0), \mathrm{Im}(h_g^0), \mathrm{Im}(\tilde{\nu}_i) \rightarrow A, \tilde{\nu}_i^-$$

   plus one massless (in unitary gauge) Goldstone boson

3. charged Higgs boson–sleptons mixing (8 × 8 matrix)

$$h_u^- = (h_u^+)^*, h_d^- = (h_d^+)^*, \tilde{e}_{Li}, \tilde{e}_{Ri} \rightarrow G^\pm, H^\pm, \tilde{e}_{i=1\ldots6}$$

Five particles: $\boldsymbol{h^0}, H^0, A^0, H^\pm$ (degenerate)

Free parameters of the model (top-down approach: 105+$\to$5)

- A_0 is the common value for the Yukawa and RpV coupling constants at m_{GUT}

$$A_0 \in (200, 1000) \text{ every } 100$$

- m_0 common mass of the scalars at m_{GUT}

$$m_0 \in (200, 1000) \text{ every } 20 \text{ GeV}$$

- $m_{1/2}$ common mass of the fermions at m_{GUT}

$$m_{1/2} \in (200, 1000) \text{ every } 20 \text{ GeV}$$

- $\tan\beta = v_u/v_d$

$$\tan\beta \in (5, 35) \text{ every } 5$$

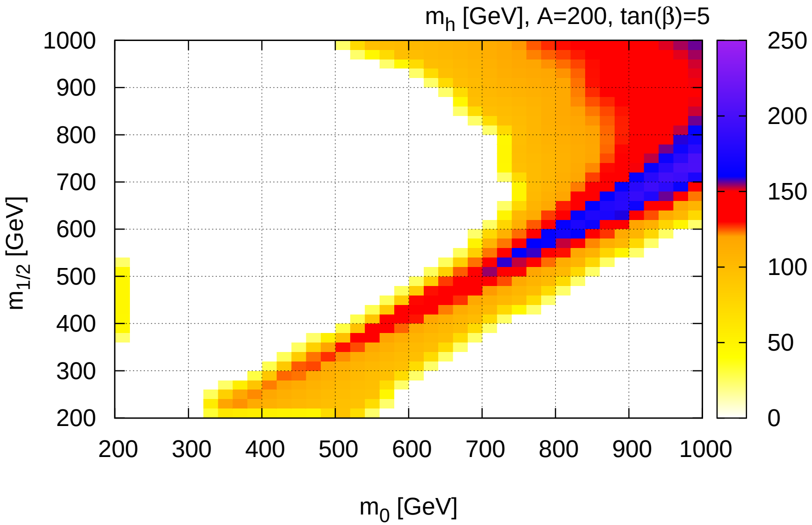
- sgn(μ)=+1

Constraints imposed on the model:

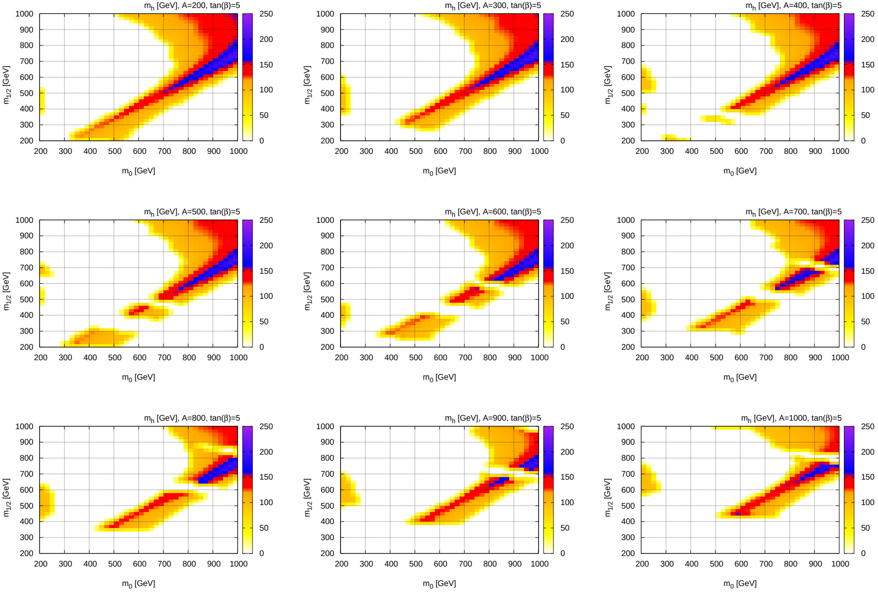
- formally correct (calculable), ie. positive parameters should stay positive etc.
- final mass spectrum in agreement with known experimental bounds K.Nakamura et al. (Particle Data Group) JPG 37 (2010) 075021 http://pdg.lbl.gov

particle		lower bound for mass [GeV]
neutralinos	$\tilde{\chi}^0_{1,2,3,4}$	46, 62, 100, 116
charginos	$\tilde{\chi}^{\pm}_{1,2}$	94
sleptons	$\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$	107, 94, 82
squarks	$\tilde{q}$	379
gluino	$\tilde{g}$	308

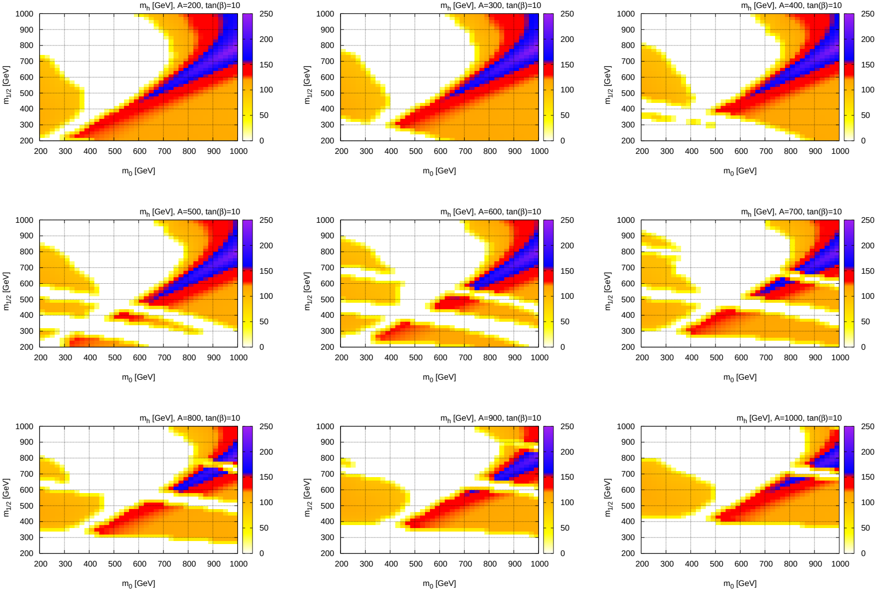
Example of a full mass map



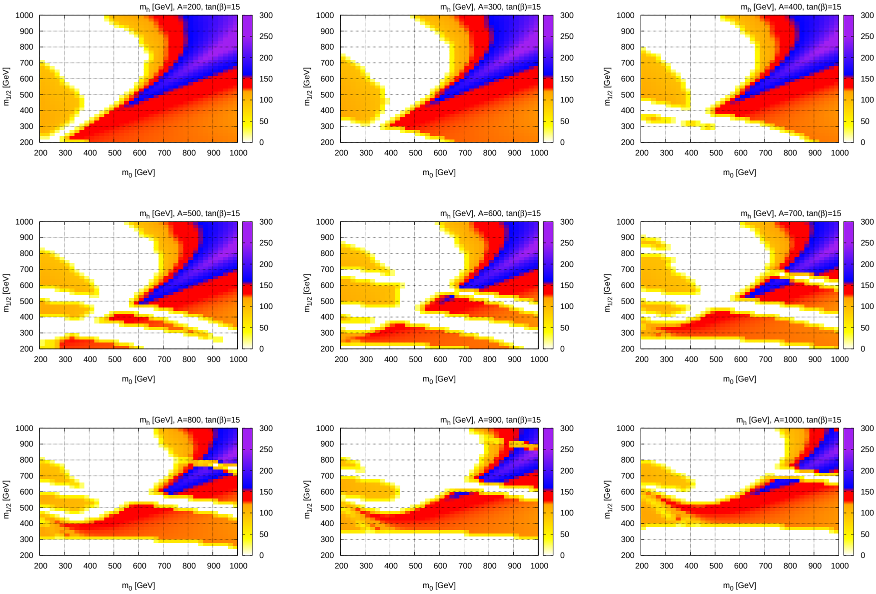
tan = 5, $A_0 = 200 - 1000$



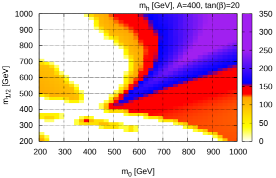
$\tan = 10, A_0 = 200 - 1000$

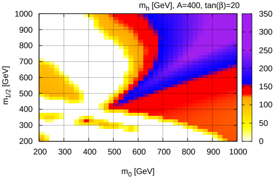


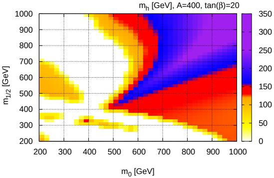
$\tan = 15, A_0 = 200 - 1000$

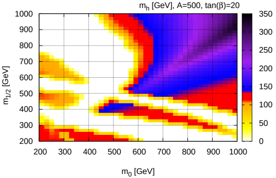


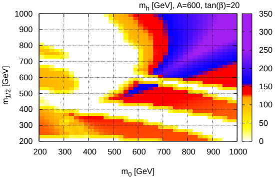
$\tan = 20, A_0 = 200 - 1000$

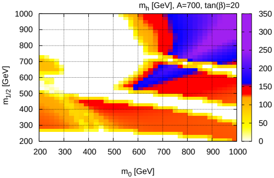


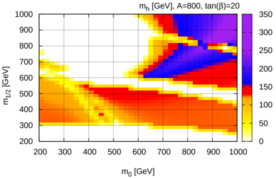


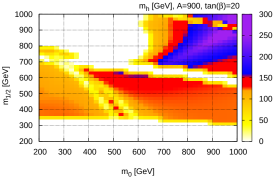


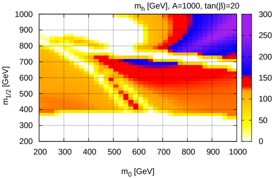












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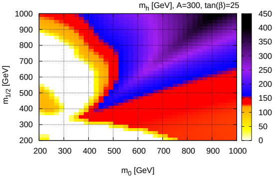

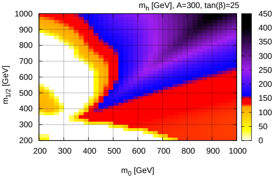

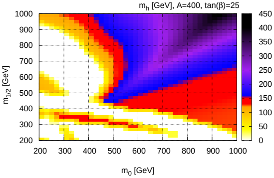

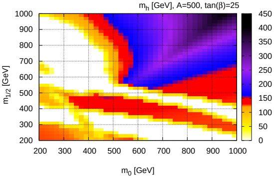

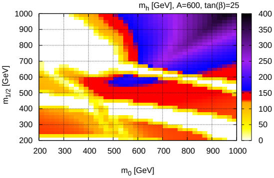

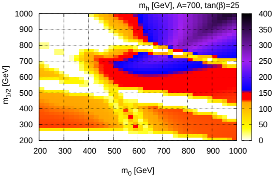

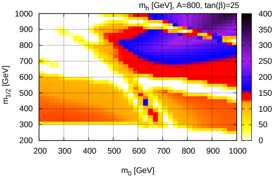

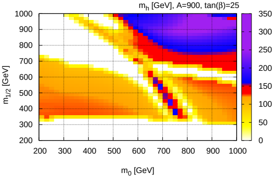

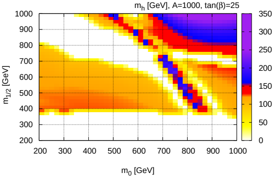

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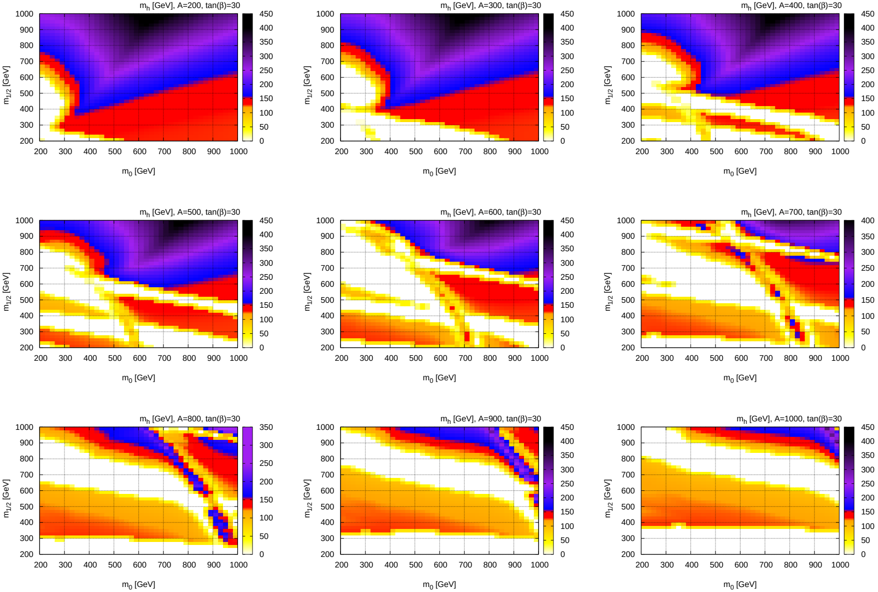

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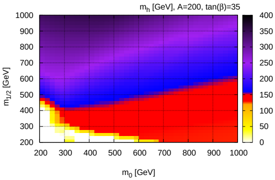
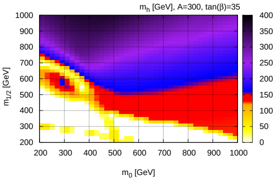
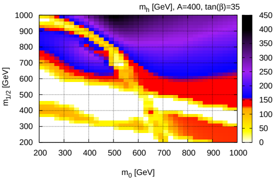
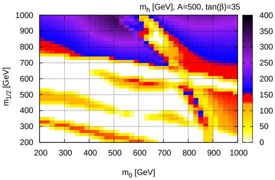
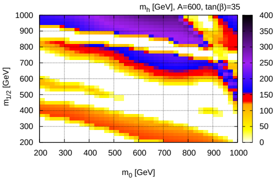
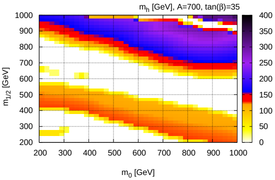


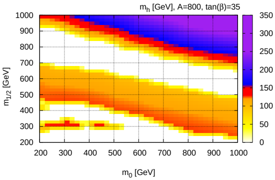


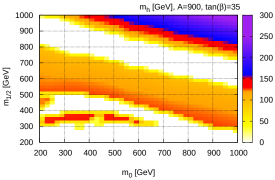


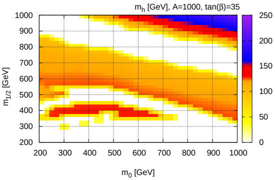




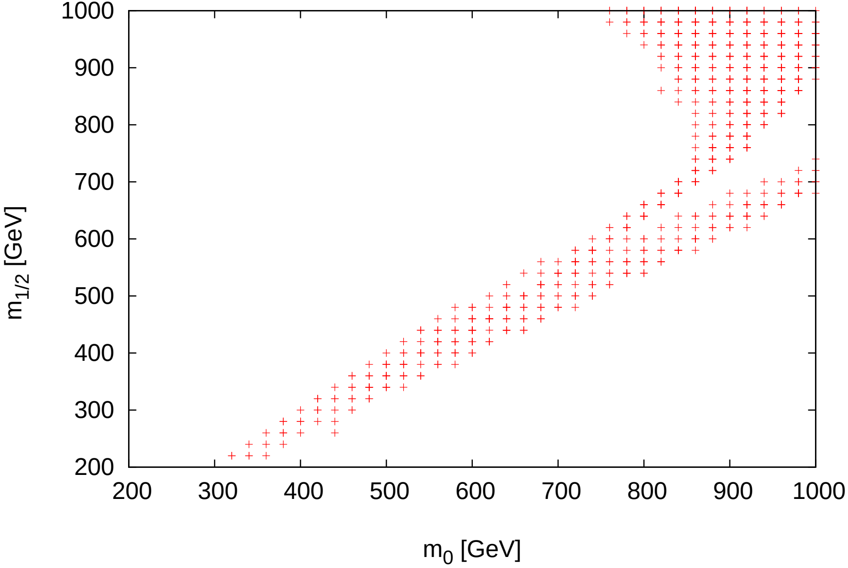




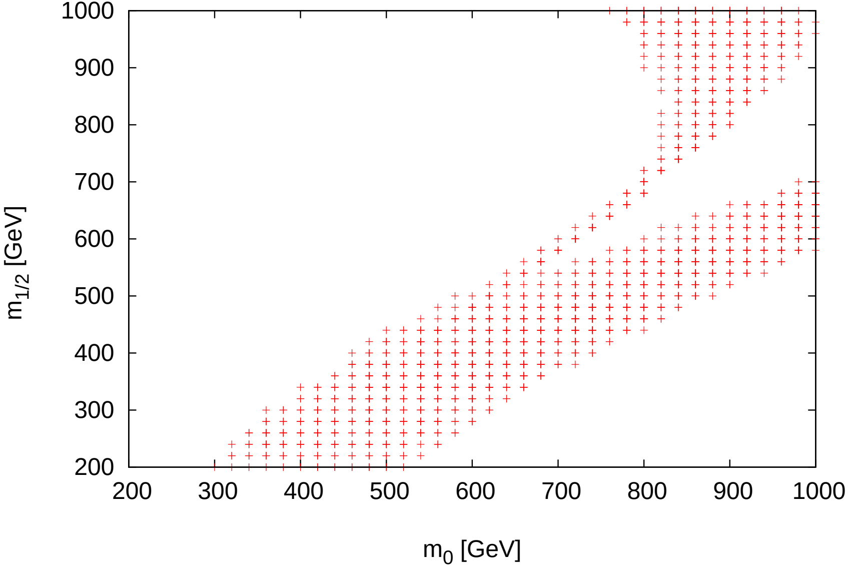




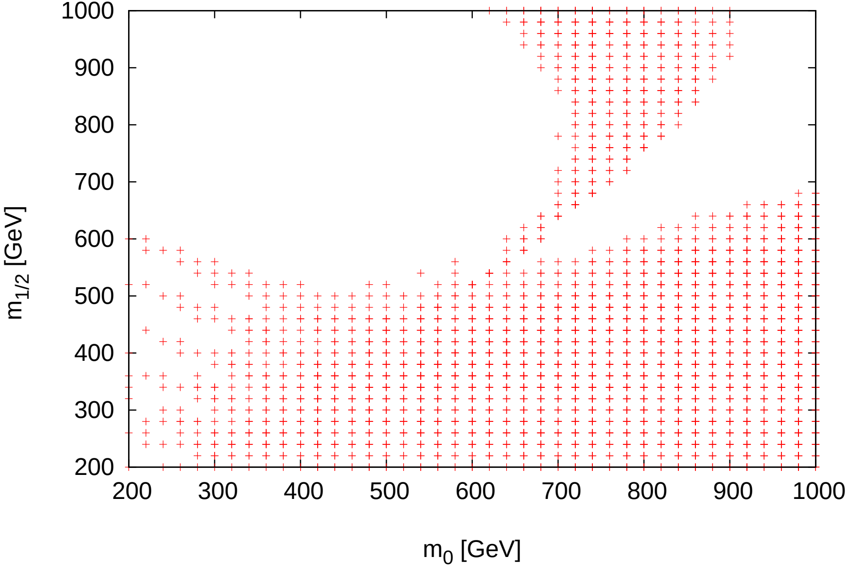
$\tan = 5, A_0 \in (200 - 1000)$



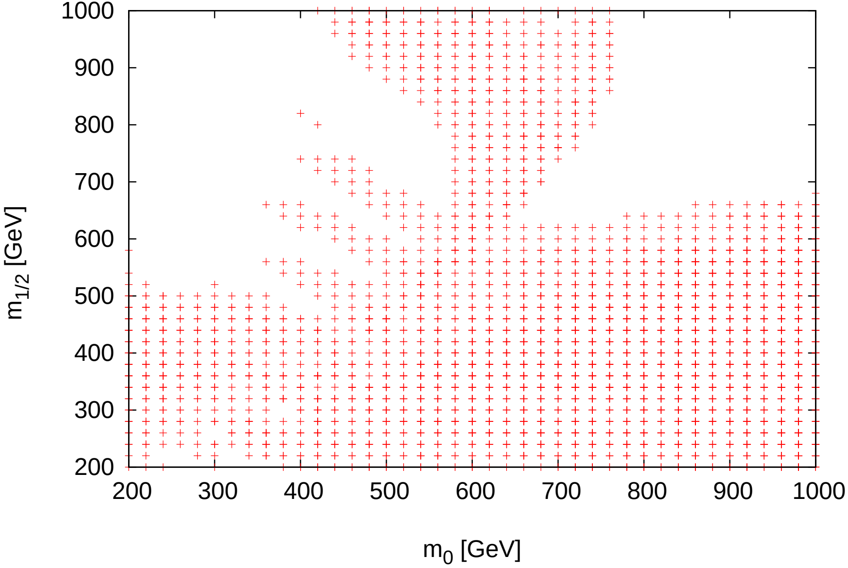
$\tan = 10, A_0 \in (200 - 1000)$



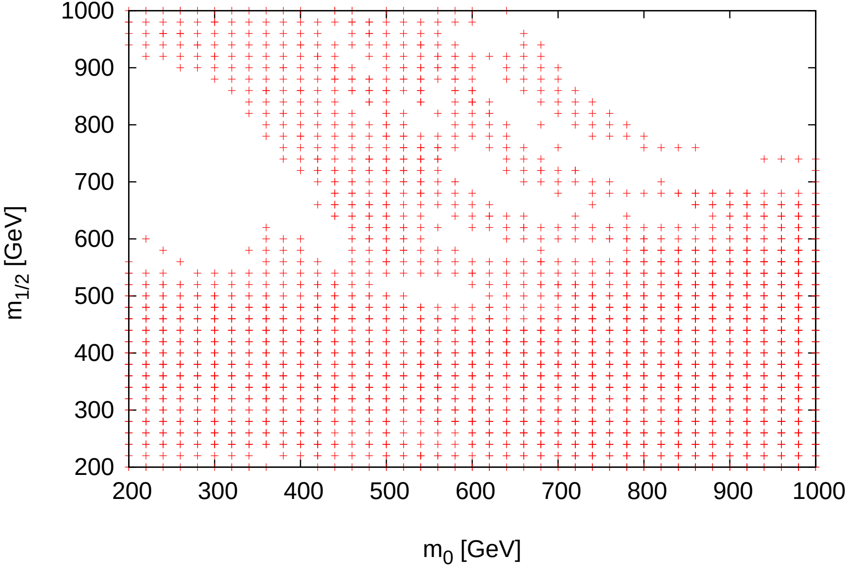
$\tan = 15, A_0 \in (200 - 1000)$



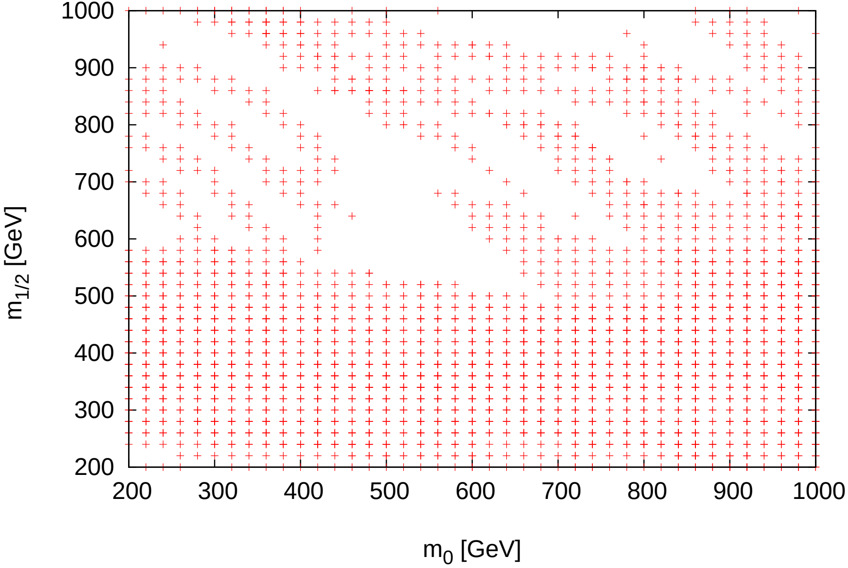
$\tan = 20, A_0 \in (200 - 1000)$



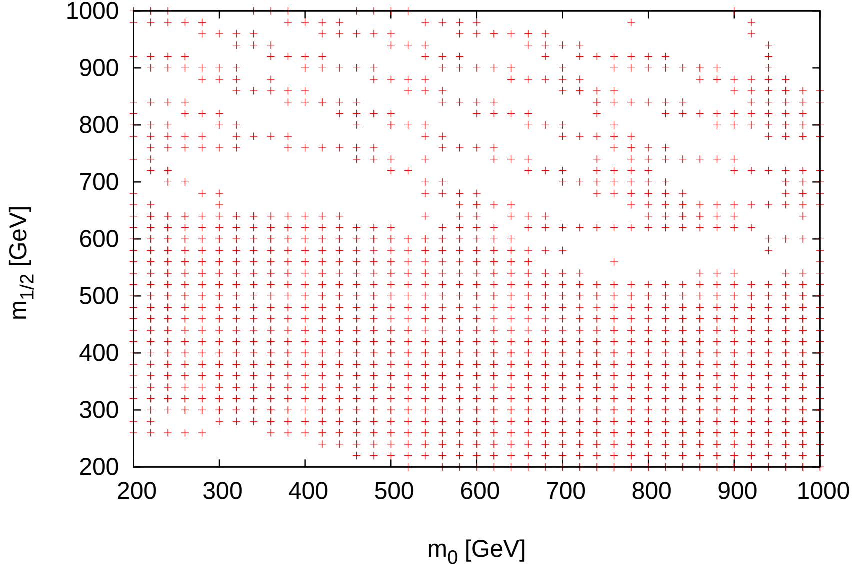
$\tan = 25, A_0 \in (200 - 1000)$



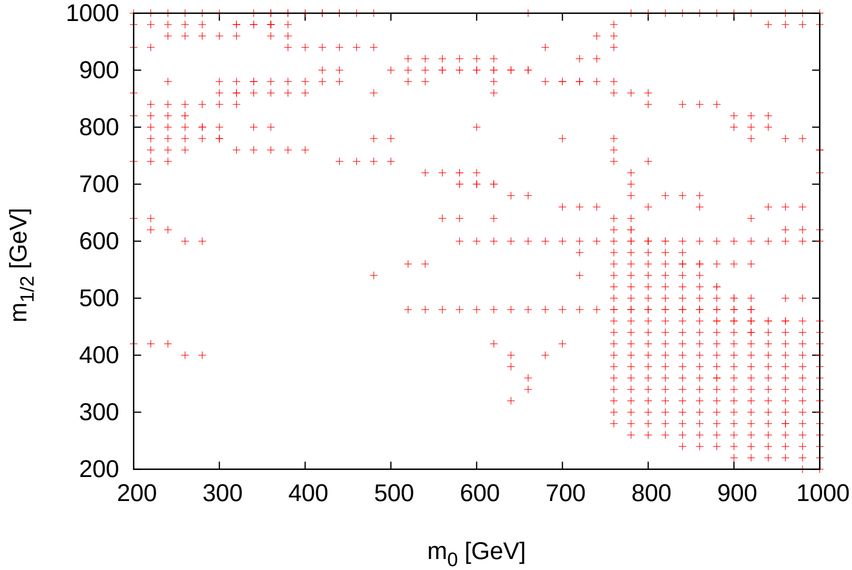
$\tan = 30, A_0 \in (200 - 1000)$



$\tan = 35, A_0 \in (200 - 1000)$



$\tan = 40, A_0 \in (200 - 1000)$



Closing remarks:

- RpV SUSY models are allowed by newest experimental data
- assuming the lightest Higgs in the region 120–140 GeV (agreement with Tevatron and LHC 2.5 σ excess of counts) regions of parameters may be found to fulfill all the constraints

$$\begin{aligned} 5 \leq & \quad \tan\beta & < 40 \\ 200 \leq & \quad A_0 & \leq 1000 \end{aligned}$$

- other data may narrow the allowed regions: calculations are performed right now
- A_0 parameter may be negative
- $\mathrm{sgn}(\mu) = -1$