The Higgs particle in the minimal supersymmetric Standard Model

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2. Standard Model Higgs
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Standard Model

relativistic and causal quantum field theory
described by Lagrangian $\mathcal{L}(\phi_\mu, \psi)$

explains kinematics and interactions of known matter and energy

based on conservation of symmetries

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based on conservation of symmetries:

global symmetries	local (gauge) symmetries
translational invariance	hypercharge, $U(1)_Y$
Lorentz transformations	isospin, $SU(2)_\text{w}$
$\Rightarrow$ Poincaré invariance	color, $SU(3)_\text{c}$

implementation in theory:
Lagrangian (more general: action) must be invariant under applications of symmetry transformations $\mathcal{T}$ to quantum fields

$$\mathcal{L}\left(\phi_\mu, \psi\right) \stackrel{!}{=} \mathcal{L}\left(\mathcal{T}\phi_\mu, \mathcal{T}\psi\right)$$

mass terms

Standard Model particles:

type	origin	name	spin	
gauge bosons	$U(1)_Y$	B_μ	1	
	$SU(2)_\mathrm{w}$	W_μ^a	1	$a \in \{1, 2, 3\}$
	$SU(3)_\mathrm{c}$	G_μ^a	1	$a \in \{1, \ldots, 8\}$
matter		ψ	$\frac{1}{2}$	

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explicit mass terms forbidden by symmetries:

- $m\phi^{\mu\dagger}\phi_\mu$ forbidden by gauge invariance
- $m\bar{\psi}\psi$ forbidden by chirality of $SU(2)_\mathrm{w}$ invariance

$\rightarrow$ particles have no mass

Higgs field

introduce a scalar $SU(2)_{\mathsf{W}}$-doublet $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

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corresponding Lagrangian:

$$\mathcal{L}_{\mathrm{Higgs}} = (D^\mu \phi)^\dagger (D_\mu \phi) + \mu^2 \phi^\dagger \phi - \frac{\lambda}{4} \left(\phi^\dagger \phi \right)^2$$

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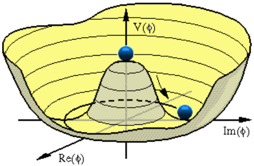
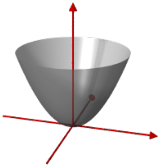
for $\mu > 0$ and $\lambda > 0$ the potential has a non-trivial minimum,

defines stable ground state at $\phi_{min} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$ with $\left(\frac{v}{\sqrt{2}}\right)^2 = \frac{2\mu^2}{\lambda}$



Higgs potential



paraboloid

Higgs boson

consider excitations of ϕ out of the ground state:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} G^+ \\ v + H + \mathrm{i}G^0 \end{pmatrix}$$

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elimination of G^+, G^0 by gauge fixing

$$\Rightarrow \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

H is the Higgs boson

Higgs mechanism

couplings of Higgs field and fermions at ground state:

$$y_d \left(\psi_\mathrm{L} \cdot \phi\right) \psi_\mathrm{R}^d = \frac{1}{2} m_d \psi_\mathrm{L}^d \psi_\mathrm{R}^d$$
$$y_u \left(\psi_\mathrm{L} \cdot \phi^\dagger\right) \psi_\mathrm{R}^u = \frac{1}{2} m_u \psi_\mathrm{L}^u \psi_\mathrm{R}^u$$

$\rightarrow$ mass terms for fermions

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kinetic term of Higgs field at ground state:

$$\left(D^{\mu}\phi\right)^{\dagger}\left(D_{\mu}\phi\right)=\frac{1}{2}M_W^2\left(W^{1\mu}W_{\mu}^{1}+W^{2\mu}W_{\mu}^{2}\right)+\frac{1}{2}M_Z^2Z^{\mu}Z_{\mu}$$

$\rightarrow$ mass terms for gauge bosons
massless photon

SM-Higgs: tree-level mass

from Lagrangian: $m_h^2 = 2\mu^2 = \frac{\lambda v^2}{2}$

no restrictions on λ or μ

$\rightarrow$ Higgs mass is a free parameter from Lagrangian: $m_h^2 = 2\mu^2 = \frac{\lambda v^2}{2}$

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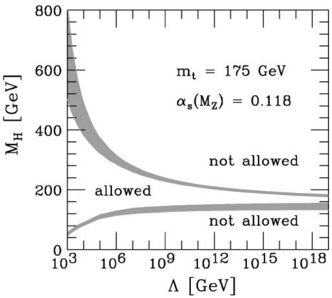
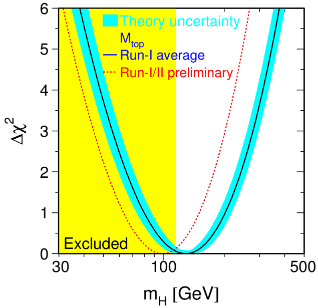
general constraints:



upper bound:
dependence of λ on the cut-off scale Λ

lower bound:
stability of Higgs potential
stability of the vacuum

constraints by direct search from LEP:



lower bound:

$m_h \geq 114.4\text{GeV}$ (95% C. L.)

SM-Higgs: experimental bounds

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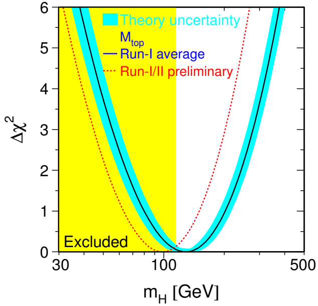

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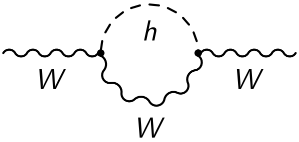
indirect constraints from precision measurement and calculation:

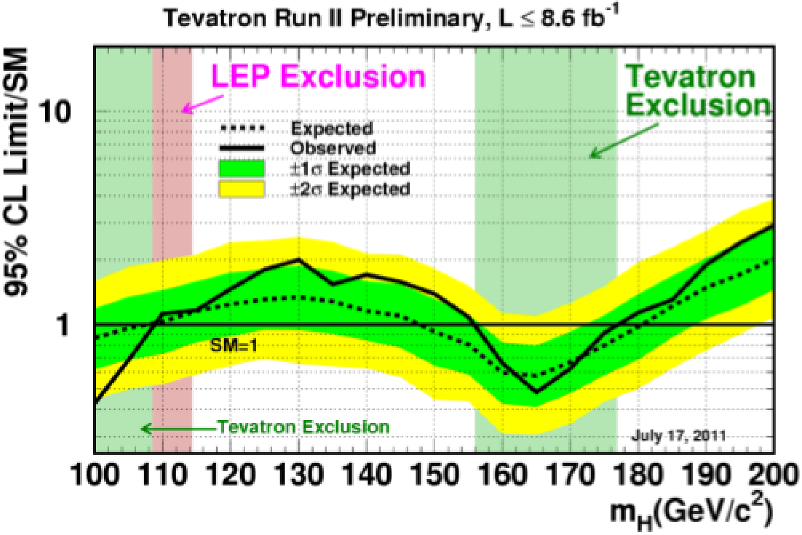


upper bound:

$m_h \leq 186\text{GeV}$ (95% C. L.)

SM-Higgs: experimental bounds

constraints by Tevatron (combined CDF- and DØ-data):



Supersymmetry

another symmetry with relation to spin:

- every fermion has a bosonic superpartner
- every boson has a fermionic superpartner
- symmetry conservation forbids trilinear couplings of fields with hermitian conjugated fields

$\rightarrow y_u \left(\psi_\mathsf{L} \cdot \phi^\dagger\right) \psi_\mathsf{R}^u$ (like in the Standard Model) not allowed

$\rightarrow$ (at least) two Higgs doublets needed

Higgs fields

two Higgs doublets in the MSSM:

$$h_1 = \begin{pmatrix} \frac{1}{\sqrt{2}} \left(v_1 + \phi_1^0 - \mathrm{i}\gamma_1^0 \right) \\ -\phi_1^- \end{pmatrix} \quad \text{and} \quad h_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}} \left(v_2 + \phi_2^0 - \mathrm{i}\gamma_2^0 \right) \end{pmatrix}$$

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mass eigenstates:

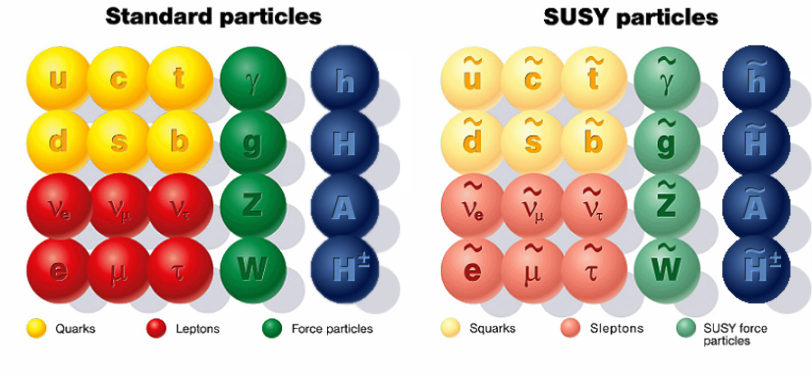
$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \qquad \begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \gamma_1^0 \\ \gamma_2^0 \end{pmatrix},$$

$$\begin{pmatrix} G^- \\ H^- \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^- \\ \phi_2^- \end{pmatrix}, \qquad \begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$

$G^\pm$, G^0 eliminated by gauge fixing
five physical Higgs bosons:

- neutral *CP*-even h^0 and H^0
- neutral *CP*-odd A^0
- charged $H^\pm$

MSSM particles



MSSM-Higgs: tree-level masses

from the Higgs potential

$$m_1^2 h_1^\dagger h_1 + m_2^2 h_2^\dagger h_2 - m_{12}^2 \left(h_1 \cdot h_2 + h_1^\dagger \cdot h_2^\dagger \right) + \frac{1}{8} \left(g_Y^2 + g_w^2 \right) \left(h_2^\dagger h_2 - h_1^\dagger h_1 \right)^2 + \frac{1}{2} g_w^2 h_1^\dagger h_1 h_2^\dagger h_2$$

we get the tree-level masses

$$m_{H,h}^2 = \frac{1}{2} \left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - (2 m_Z m_A \cos 2\beta)^2} \right),$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2,$$

$$\tan \beta = \frac{v_2}{v_1}$$

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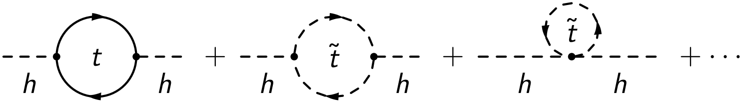
$$m_{H^\pm}^2 = m_A^2 + m_W^2,$$
$$\tan\beta = \frac{v_2}{v_1}$$

two free MSSM parameters: $\tan\beta, m_A$

theoretical upper bound: $m_h^2 \leq \left(m_Z \cos 2\beta\right)^2$

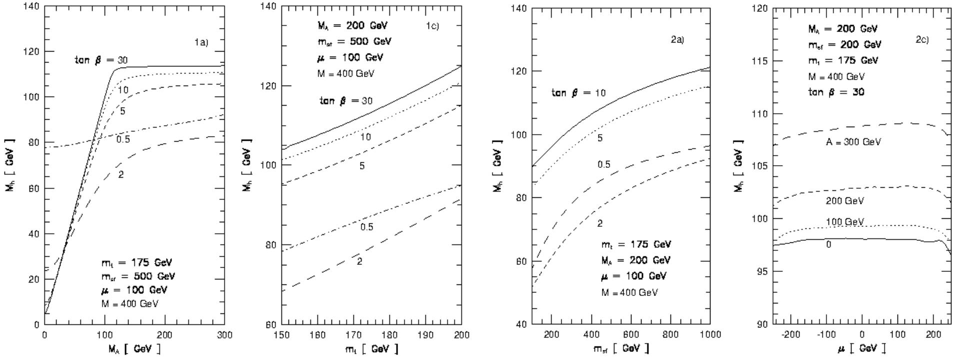
MSSM-Higgs: one-loop contribution

main contributions come from t and $\tilde{t}$ loops; proportional to m_t^4:

$\Sigma_{hh} =$ 

additional parameters: $\mu, m_{\tilde{t}}, m_{\tilde{t}_L}, a_t$
mass contribution: ca. 40%

MSSM-Higgs: one-loop contribution



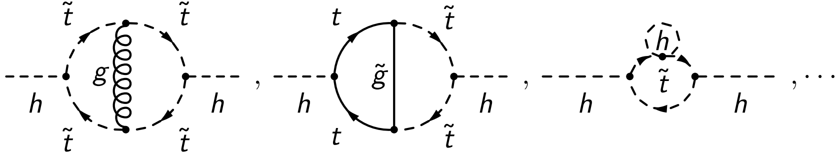
from left to right: M_h-M_A, M_h-m_t, M_h-m_{sf}, M_h-μ

[A. Dabelstein, Zeitschrift für Physik C 67 (1995)]

MSSM-Higgs: two-loop contribution

most important parts:

corrections to m_t-enhanced one-loop contributions, e. g.

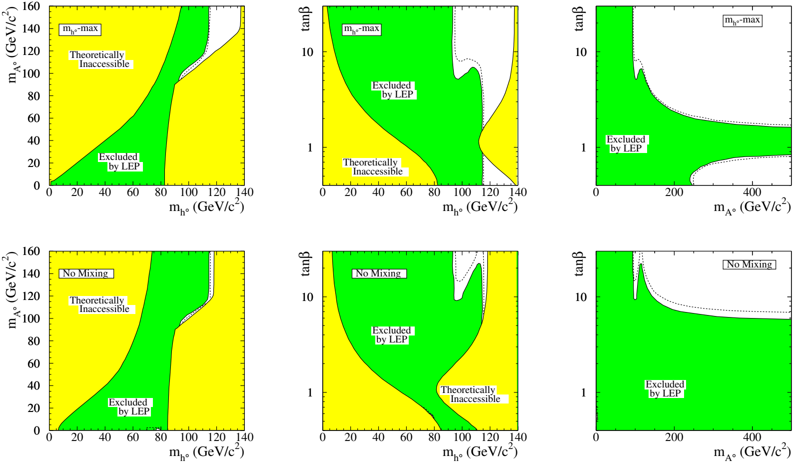


proportional up to m_t^6

further corrections of 1 to 10 GeV

MSSM-Higgs: experimental bounds

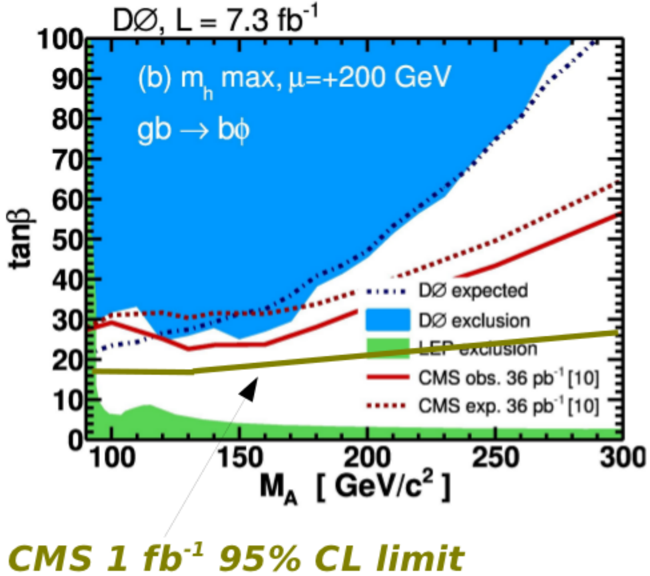
LEP constraints:



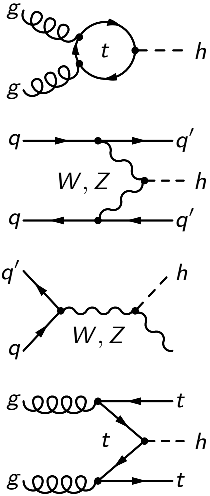
limits in the maximum-mixing and no-mixing scenarios, $m_t = 179.3\text{GeV}$

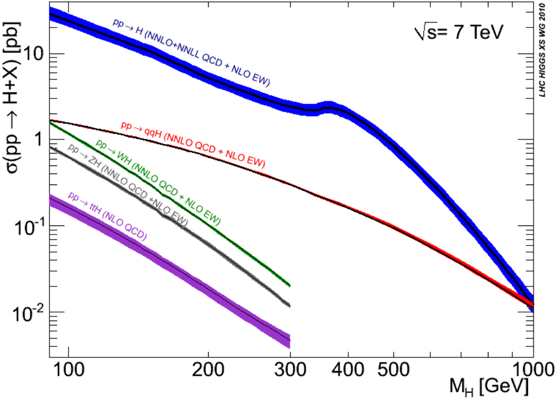
[ALEPH, DELPHI, L3, OPAL Collaborations. The LEP Working Group "for Higgs Boson Searches" (2006)]

Tevatron constraints:

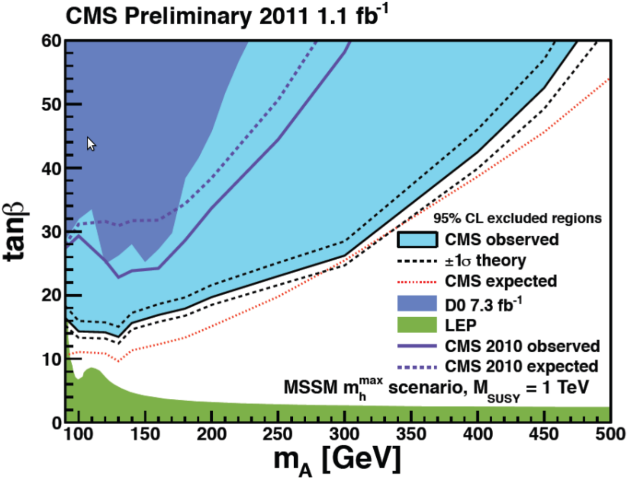


different channels for Higgs search:





recent LHC results



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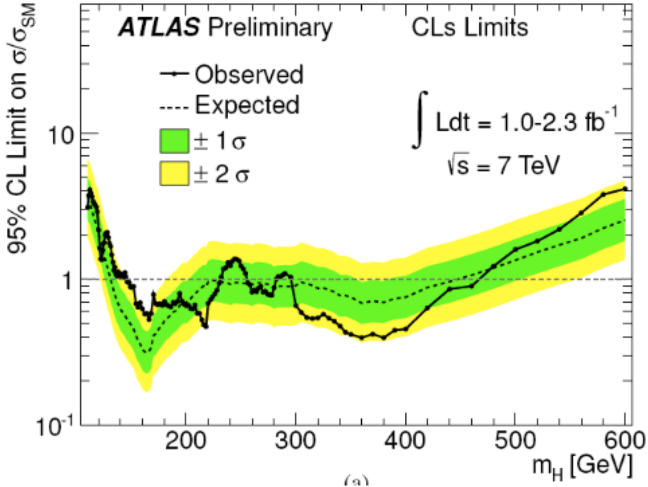

conclusions

- Higgs mechanism is an elegent method
  to generate mass terms for fermions and gauge bosons
- applicable to supersymmetric models
- strong constraint on the lightest Higgs mass in the MSSM,
  exclusion of mass region between 114 GeV and 155 GeV
  would be the doom of the MSSM
- if no signal is found at all up to the TeV scale,
  then we would have to think again

Thanks for your attention!