The Theory of the Standard Model Higgs

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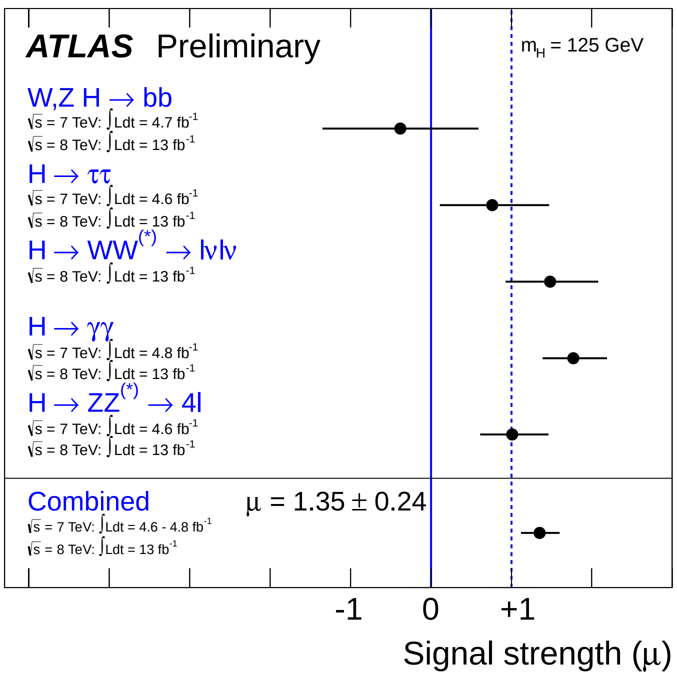
The new boson

ATLAS-CONF-2012-170



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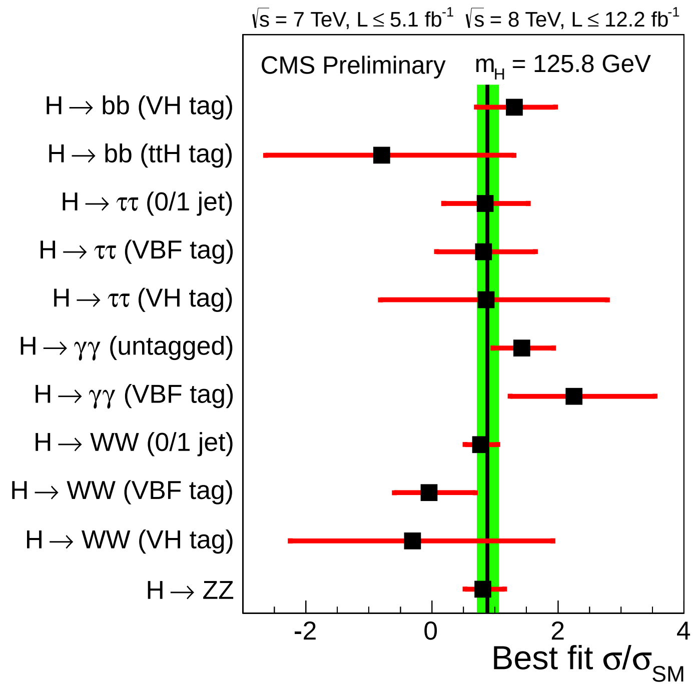

Is it the SM Higgs boson?

- SM couplings ⇔ anomalous couplings
- correct spin
- quantum numbers (CP even/odd)

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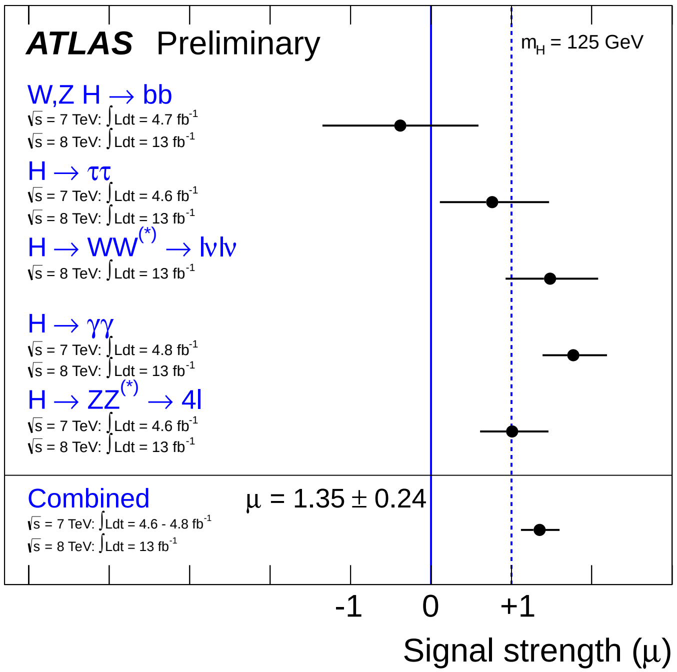

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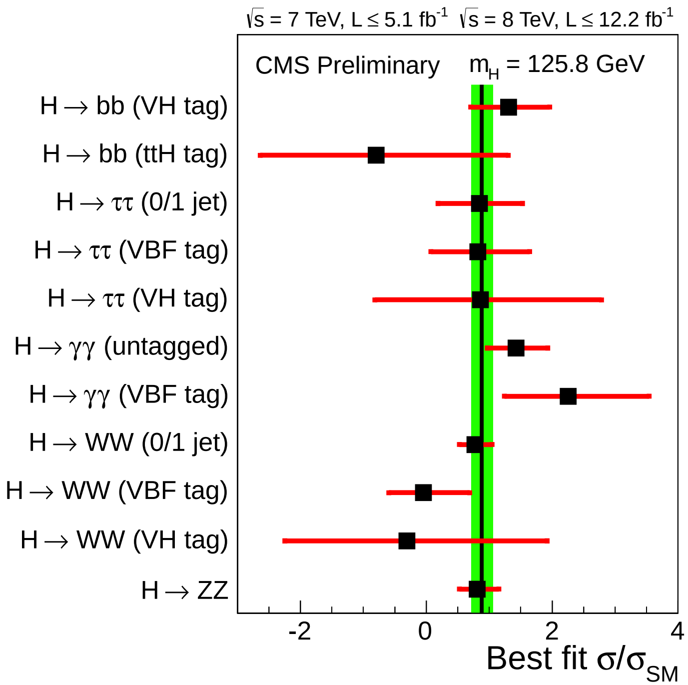

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⇒ let's investigate the SM Higgs

Outline

Today: Standard Model Higgs Theory

- Brief SM introduction
- Symmetry breaking: Masses and Goldstone modes
- The role of the Higgs boson
- The SM Higgs sector

Tomorrow: Higgs Phenomenology at the LHC

- Higgs decays
- Higgs production
- Higgs properties

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The Standard Model

Matter interacting via gauge interactions:

- Gauge structure: $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$

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  - gauge symmetry spontaneously broken
  - 3 more (longitudinal) degrees of freedom
  - masses and couplings related:

$$M_\mathrm{W}/M_\mathrm{Z} = \cos\Theta_\mathrm{W} = g/\sqrt{g^2 + g'^2} \qquad \text{(or } \rho = 1 \text{ at tree-level)}$$

The Standard Model

Matter: Fermions

- defined by quantum numbers w.r.t. gauge groups

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The Standard Model

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- quarks are colour triplets, leptons are colour singlets
- chiral electroweak sector
  - only left-handed quarks Q_{L} and leptons L_{L} form $\mathrm{SU}(2)_{\mathrm{L}}$ doublets
  - different $\mathrm{U}(1)$ hypercharges for left-handed doublets and right-handed singlets u_{R}, d_{R}, l_{R}, and ν_{R}

$\Rightarrow$ chosen for correct electric charges

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- only massless fermions

  $\Leftrightarrow$ mass terms forbidden by gauge invariance

  $\Rightarrow$ fermion masses by symmetry breaking

The Standard Model

Higgs sector:

- needed for electroweak symmetry breaking (EWSB)
- makes gauge bosons and fermions massive

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- at least 3 would-be Goldstone bosons
  - needed for longitudinal $\mathrm{W}^{\pm}$ and Z
  - true for any new physics model as well

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- anything else?

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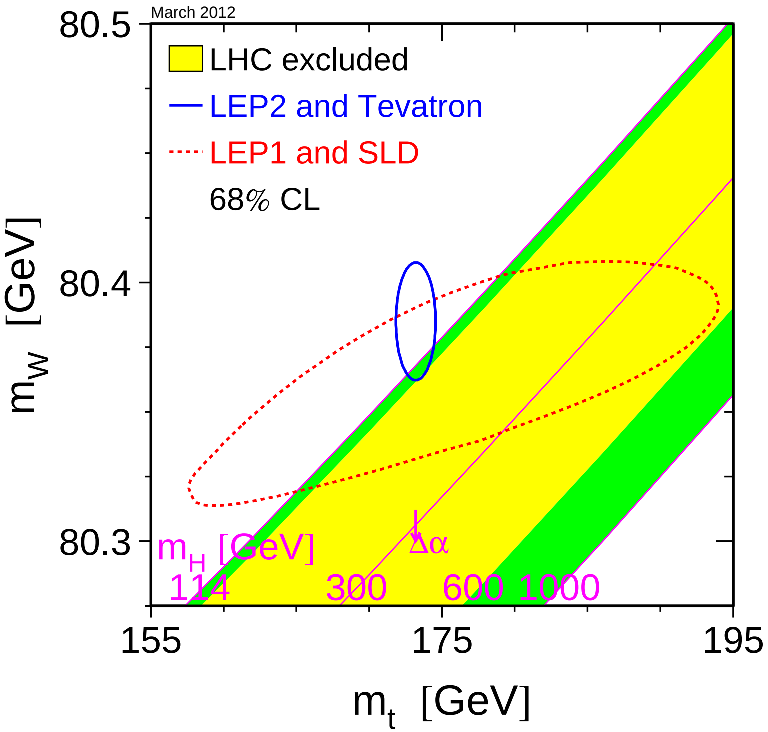
  - true for any new physics model as well
- anything else?
  - something needed at high energies!
  - SM prediction: exactly one scalar $\Rightarrow$ the Higgs
    (new physics: different solutions)

The Standard Model

Indirect hints for the SM Higgs:



$\Rightarrow$ consistent picture with light SM Higgs
from quantum corrections
within the SM

EW symmetry breaking

Let's try to first understand

electroweak symmetry breaking

on general grounds. . .

(see also 1005.4269 by R. Contino)

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EW symmetry breaking

An Abelian model:

- $U(1)$ gauge field A^μ
- charged left-handed fermion Ψ_L
- neutral right-handed fermion Ψ_R

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$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi}_L D_\mu \gamma^\mu \Psi_L + i\bar{\Psi}_R \partial_\mu \gamma^\mu \Psi_R$$

with: $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ (field strength tensor)

$D_\mu = \partial_\mu - igA_\mu$ (covariant derivative)

Gauge transformations:

$$A_\mu \to A_\mu + \partial_\mu \alpha(x)$$
$$\Psi_L \to e^{ig\alpha(x)} \Psi_L$$
$$\Psi_R \to \Psi_R$$

EW symmetry breaking

Gauge invariance:

$\Rightarrow$ no mass terms ($M_A^2\, A^\mu A_\mu/2$ forbidden)
$\Rightarrow$ A_μ has only two degrees of freedom
(no longitudinal gauge bosons)

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- add gauge invariant interaction

$\Rightarrow$ covariant derivative acting on something

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- so introduce $\Sigma = e^{i\phi(x)/v}$ with $\Sigma \to e^{i\,g\,\alpha(x)}\,\Sigma$:

$$\mathcal{L}_{\mathrm{EWSB}} = \frac{v^2}{4}(D_\mu\Sigma)^\dagger\,(D^\mu\Sigma) \supset \frac{v^2 g^2}{4}\Sigma^\dagger\Sigma\,A_\mu A^\mu = \frac{v^2 g^2}{4}\,A_\mu A^\mu$$

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unitary gauge $\Sigma = 1$: $\quad \mathcal{L}_{\text{EWSB}} = \frac{v^2 g^2}{4}\, A_\mu A^\mu$

$\Rightarrow$ only mass term added!

EW symmetry breaking

What happened?

- add only one scalar degree of freedom:

  would-be Goldstone boson ϕ

- spontaneous symmetry breaking implicit:

  vacuum not invariant: $\Sigma = 1$ or v chosen real

- unitary gauge:

  ϕ becomes longitudinal gauge boson

  (Goldstone boson "eaten" by the gauge boson)

  $\Rightarrow$ massive gauge boson with 3 degrees of freedom

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- there is no Higgs
- but Higgs can be introduced:

$$\Sigma = (1 + \frac{h(x)}{v})e^{i\phi(x)/v} \quad \text{or} \quad \Sigma = v + h(x) + i\tilde{\phi}(x)$$

($h(x)$ is another degree of freedom)

- and decoupled again (by $m_{\mathrm{H}} \to \infty$)

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Fermion mass:

- also simply coupled to Σ (with Yukawa coupling λ)

$$\mathcal{L}_{\mathrm{EWSB}} = -\frac{v}{\sqrt{2}}\lambda\bar{\Psi}_L\Sigma\,\Psi_R = -\frac{v}{\sqrt{2}}\lambda\bar{\Psi}_L\,\Psi_R \quad \text{(in unitary gauge)}$$

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EW symmetry breaking

In the SM: (in complete analogy)

- 3 Goldstone bosons χ^a needed (for longitudinal $\mathrm{W}^\pm, \mathrm{Z}$):

$$\mathcal{L}_{\mathrm{EWSB}} = \frac{v^2}{4} \mathrm{Tr}\left((D_\mu \Sigma)^\dagger (D^\mu \Sigma) \right) - \frac{v}{\sqrt{2}} \bar{Q}_L \Sigma \left(\lambda_u u_R, \lambda_d d_R \right)^{\mathrm{T}}$$

with: $\Sigma(x) = \exp(i \frac{\sigma^a}{2} \chi^a(x)/v)$

$$D_\mu \Sigma = \partial_\mu \Sigma - i g \frac{\sigma^a}{2} W_\mu^a \Sigma + i g' \Sigma \frac{\sigma^3}{2} B_\mu$$

- gauge transformation:

$\Sigma(x) \to e^{i g \alpha_L^a(x) \sigma^a/2} \Sigma(x) e^{i g' \alpha_{\mathrm{Y}}(x) \sigma^3/2} \quad \Rightarrow \quad$ unitary gauge: $\Sigma = 1$

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$\Sigma(x) \to e^{ig\alpha_L^a(x)\sigma^a/2}\Sigma(x)\, e^{ig'\alpha_{\mathrm{Y}}(x)\sigma^3/2} \quad \Rightarrow \quad$ unitary gauge: $\Sigma = 1$

- masses for gauge bosons and chiral fermions

but still no Higgs boson. . .

EW symmetry breaking

- Higgs boson not needed for masses

  (only the 3 Goldstone bosons)

- Higgs makes model well behaved at large energies

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EW symmetry breaking

- Higgs boson not needed for masses

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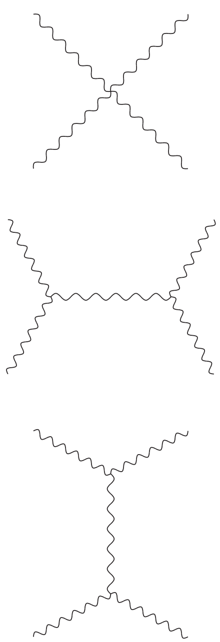
- Let’s look at gauge-boson scattering without a Higgs:



- $\mathrm{W}^+\mathrm{W}^- \to \mathrm{W}^+\mathrm{W}^-$ at high energies dominated by longitudinal W bosons

$$\mathcal{M} = \frac{g^2}{4M_\mathrm{W}^2}(s+t) + \mathcal{O}(M_\mathrm{W}^2/s)$$

- amplitude grows with energy

  (from $\epsilon_\mathrm{L}^\mu = p^\mu/M_\mathrm{W} + \mathcal{O}(M_\mathrm{W}/E)$)
- violates perturbative unitarity
- tightly connected with EWSB

EW symmetry breaking

Goldstone-boson equivalence theorem:

- At high energies longitudinal gauge bosons behave like Goldstone bosons

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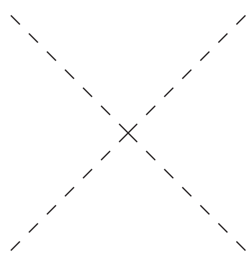

$$\mathcal{M} = \frac{1}{v^2}(s+t)$$

(due to derivative interactions)

$$\left(\frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger\,(D^\mu\Sigma)\right]\right)$$

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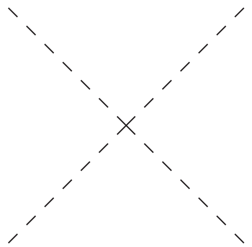

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(due to derivative interactions)

- EWSB is not UV complete yet
- something has to unitarize the model at high energies
- at least one more degree of freedom needed

EW symmetry breaking

add only a scalar and parameterize interactions:

$$\mathcal{L}_{\mathrm{EWSB}} = \mathcal{L}_h + \frac{v^2}{4}\mathrm{Tr}\left((D_\mu \Sigma)^\dagger (D^\mu \Sigma)\right)\left(1 + a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \cdots\right)$$
$$-\frac{v}{\sqrt{2}}\bar{Q}_L \Sigma\,(\lambda_u u_R, \lambda_d d_R)^{\mathrm{T}}\left(1 + c\,\frac{h}{v} + \cdots\right)$$

with: $\mathcal{L}_h = \frac{1}{2}(\partial_\mu h)^2 + V(h)$

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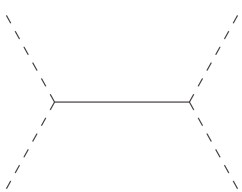

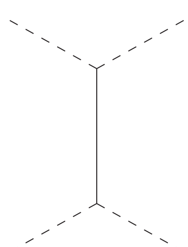

$$\mathcal{M} = \frac{1}{v^2}\left(s - \frac{a^2}{4}\frac{s^2}{s-M_{\rm H}} + t - \frac{a^2}{4}\frac{t^2}{t-M_{\rm H}}\right)$$

- unitarization for $a = 2$ and small $M_{\rm H}$
- other processes: $b = 1$ and $c = 1$

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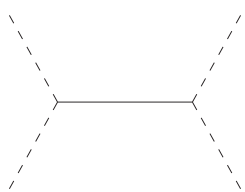

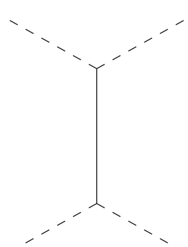

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The most minimal model...

- $a = 2$, $b = 1$, $c = 1$, no higher order terms
- renormalizable $V(h)$

...defines the SM Higgs sector!

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Unitary gauge:

$$\mathcal{L}_{\mathrm{EWSB}} = \frac{v^2}{4}\mathrm{Tr}\left((D_\mu(1+h(x)/v))^\dagger\,(D^\mu(1+h(x)/v))\right) + V(h)$$
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with: $D_\mu = \partial_\mu - ig\frac{\sigma^a}{2}W^a_\mu + ig'\frac{\sigma^3}{2}B_\mu$

$\Rightarrow$ all couplings proportional to mass!

The SM Higgs

Equivalent parameterization: Higgs doublet

$$\Phi(x) = e^{i\frac{\sigma^a}{2}\tilde{\chi}^a/v} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad \text{or} \quad \Phi(x) = \begin{pmatrix} \chi^+(x) \\ (v + h(x) + i\chi^0(x))/\sqrt{2} \end{pmatrix}$$

$\Rightarrow$ unitary gauge: $\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$

Lagrangian:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) + \mathcal{L}_{\text{Yukawa}}$$

with: $D_\mu = \partial_\mu - ig\, T^a W^a_\mu - ig'\, Y\, B_\mu \qquad (T^a = \frac{\sigma^a}{2},\ Y = 1/2)$

renormalizable Higgs potential:

$$V(\Phi) = -\mu^2\, \Phi^\dagger \Phi + \lambda\, (\Phi^\dagger \Phi)^2$$

The SM Higgs

additional features and limitations:

- Electroweak symmetry breaking from $V(\Phi)$:
  - Mexican hat potential for $\mu^2 > 0 \quad \Rightarrow \quad v = (\mu^2/\lambda)^{1/2}$
  - vacuum expectation value $\langle \Phi \rangle$ not gauge invariant
  - EWSB parameterized but not dynamic

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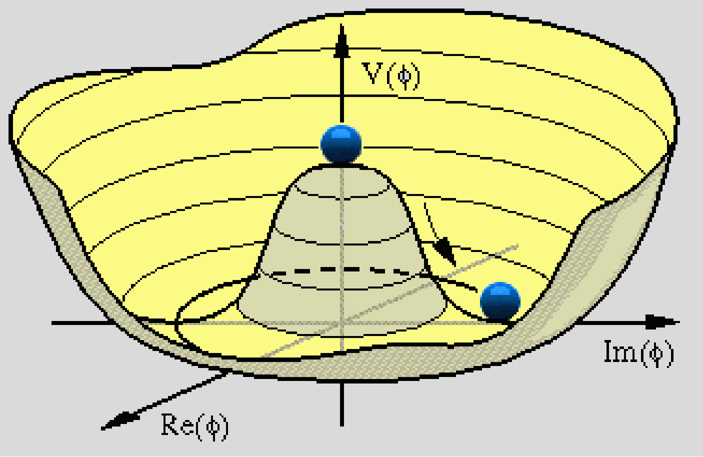

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- only one free parameter: $M_{\mathrm{H}} = \sqrt{2}\,\mu^2 = \sqrt{\lambda}\,v/\sqrt{2}$

  (v fixed by gauge-boson masses)
- given M_{H} SM Higgs sector is completely predictive

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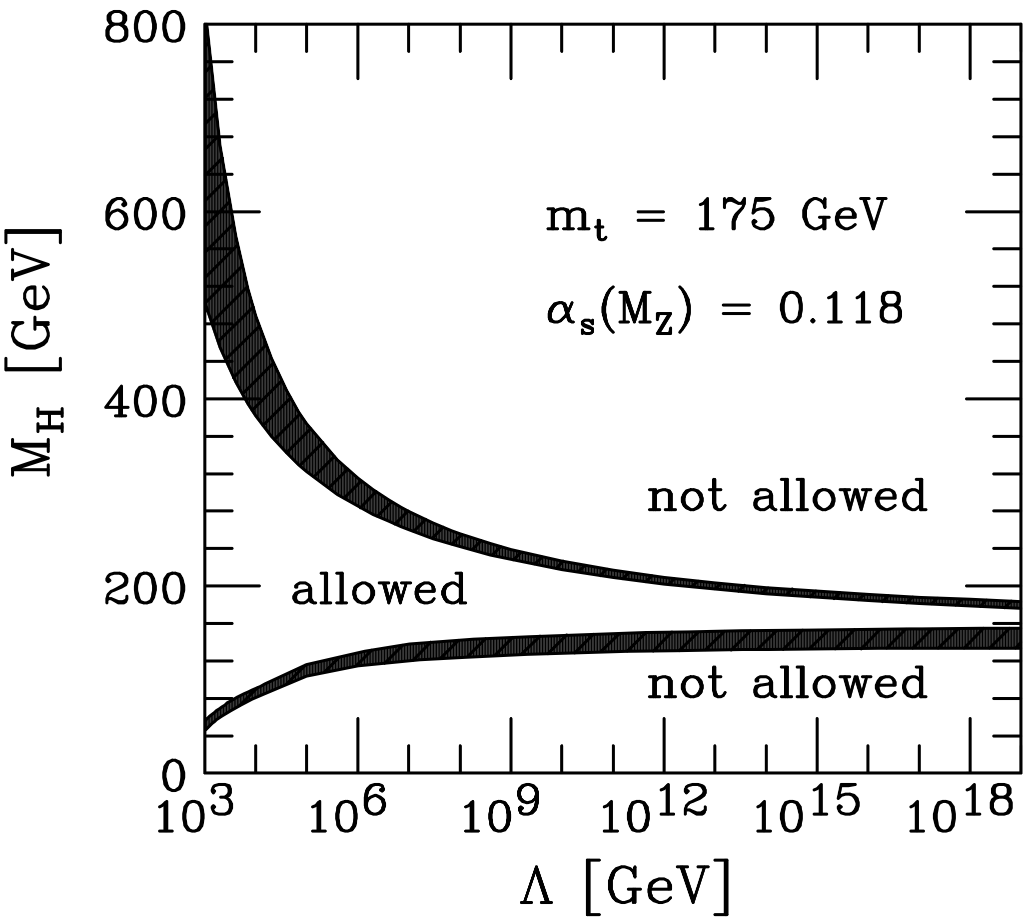
- given M_{H} SM Higgs sector is completely predictive
- hierarchy problem (M_{H} unprotected from radiative corrections)

  $\Leftrightarrow$ expect new physics at the TeV scale

The SM Higgs

extrapolating the SM towords the Planck scale...



Hambye, Riesselmann '97

Landau pole ($\lambda \to \infty$)

stability ($\lambda < 0$)

The SM Higgs

Gauge sector: $\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$

with: $D_\mu = \partial_\mu - ig\, T^a W^a_\mu - ig' Y B_\mu \qquad (T^a = \frac{\sigma^a}{2},\ Y = 1/2)$

- unbroken generator: $T^3 + Y$

  $\Rightarrow$ massless photon: $A_\mu = s_w W^3_\mu + c_w B_\mu$

  (with $s_w = \sin\Theta_w = g'/\sqrt{g^2 + g'^2}$)

- correct mass pattern
  - $M_{\text{W}} = gv/2, \quad M_{\text{Z}} = \sqrt{g^2 + g'^2}\, v/2 \quad \Rightarrow \quad M_{\text{W}}/M_{\text{Z}} = \cos\Theta_{\text{W}}$

    $(W^\pm_\mu = (W^1_\mu \mp i W^2_\mu)/\sqrt{2},\ Z_\mu = c_w W^3_\mu - s_w B_\mu)$

  - guaranteed by custodial SU(2)

    (all SU(2)_{L} generators equally broken)

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN
RWTH

The SM Higgs

Fermion sector:

- mass terms for quarks

$$\mathcal{L}_{\text{mass}} = -\lambda_{d,ij} \left(\bar{Q}_{L,i}\Phi\right) d_{R,j} - \lambda_{u,ij}\, \bar{Q}_{L,i}\, i\sigma^2\, \Phi^*\ u_{R,j} + h.c.$$

(two different SU(2) invariants)

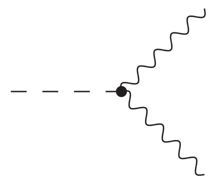
($i, j = 1, 2, 3$ generation indices)

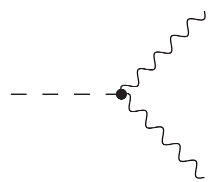
- leptons in analogy (right-handed ν's $\Leftrightarrow$ ν masses?)
- flavour physics parameterized by CKM matrix, but not explained
  - 3 generations
  - fermion mass hierarchy
  - flavour mixing, CP violation

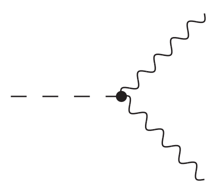
The SM Higgs

Higgs couplings:

- proportinal to mass
- couplings of CP-even scalar
- specific coupling structures: gauge bosons

SM:  $\propto g^{\mu\nu}$ $\mathcal{L} \propto h A^\mu A_\mu$

CP-even alternative:  $\propto g^{\mu\nu} k_1 \cdot k_2 - k_1^\mu k_2^\nu$ $\mathcal{L} \propto h F^{\mu\nu} F_{\mu\nu}$

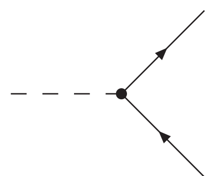
CP-odd alternative:  $\propto \epsilon^{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma}$ $\mathcal{L} \propto \epsilon^{\mu\nu\rho\sigma} h F_{\mu\nu} F_{\rho\sigma}$

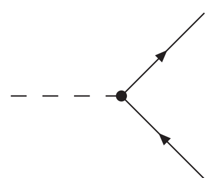
$k_{1,2}$: boson momenta

The SM Higgs

Higgs couplings:

- proportinal to mass
- couplings of CP-even scalar
- specific coupling structures: fermions

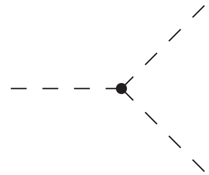
SM:  $\propto 1$ $\mathcal{L} \propto h\,\bar{\Psi}\Psi$

CP-odd alternative:  $\propto \gamma^5$ $\mathcal{L} \propto h\,\bar{\Psi}\gamma^5\Psi$

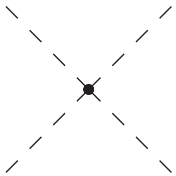
The SM Higgs

Higgs couplings:

- proportinal to mass
- couplings of CP-even scalar
- specific coupling structures: Higgs self-couplings



$$\propto \frac{M_{\rm H}^2}{M_{\rm W}} \qquad \mathcal{L} \propto \lambda\, v\, h^3$$



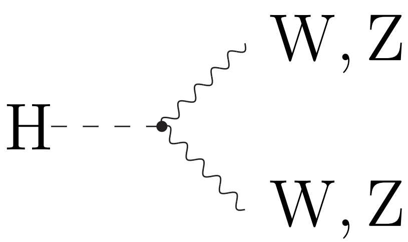
$$\propto \frac{M_{\rm H}^2}{M_{\rm W}^2} \qquad \mathcal{L} \propto \lambda\, h^4$$

$\Leftrightarrow$ measuring the Higgs potential

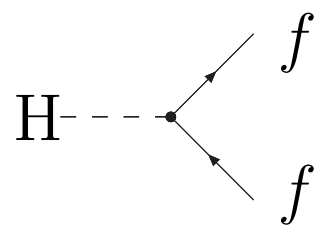
Important Couplings

Tree-level couplings:

- to gauge bosons and fermions



$\propto \frac{M^2_{\mathrm{W,Z}}}{M_{\mathrm{W}}}$



$\propto \frac{m_f}{M_{\mathrm{W}}}$

$\Rightarrow$ all couplings proportional to mass

Important Couplings

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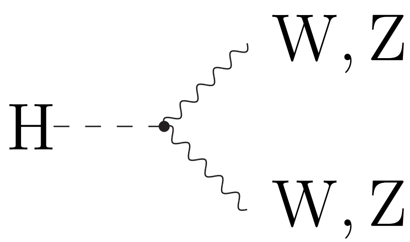
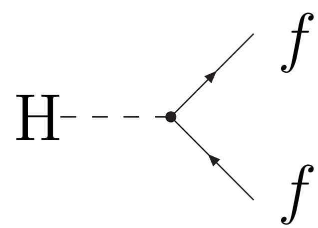


$\propto \frac{M^2_{\mathrm{W,Z}}}{M_{\mathrm{W}}}$

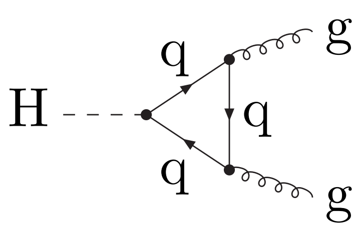


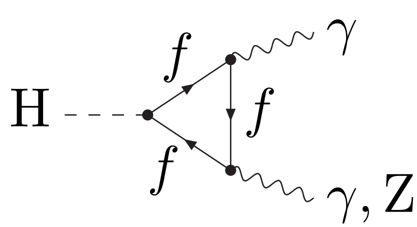
$\propto \frac{m_f}{M_{\mathrm{W}}}$

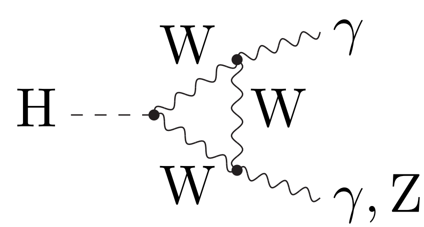
$\Rightarrow$ all couplings proportional to mass

Loop-induced couplings:

- to gluons and photons







from above: $\mathrm{q} = f =$ top most relevant in the SM and extremely important at the LHC

Summary

The SM Higgs sector

- minimal, complete model for EWSB
  - gauge-boson and fermion masses
  - unitarization of gauge-boson scattering by Higgs boson
  - precision tests $\Rightarrow$ light Higgs boson
- last free parameter M_{H} of the SM

  $\Rightarrow M_{\mathrm{H}} = 125$ GeV $\Rightarrow$ all predictions fixed
- to be tested by more and more data
- the hierarchy problem remains