The Higgs mechanism:

the origin of mass of elementary particles

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- **The Standard Model of particle physics**
- **The Higgs mechanism**
- **Constraints on the Higgs boson mass**
- **Production and tests at the LHC**
- **Extensions of the SM Higgs sector**

1. The Standard Model

The SM of the electromagnetic, weak and strong interactions

- is relativistic quantum field theory
- based on a local gauge symmetry: invariance under symmetry group
- more or less a carbon–copy of QED, the theory of electromagnetism

QED: invariance under the local transformations of the abelian group U(1)

– transformation of electron field: $\Psi(x) \rightarrow \Psi'(x) = e^{ie\alpha(x)}\Psi(x)$

– transformation of photon field: $A_\mu(x) \rightarrow A'_\mu(x) = A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x)$

The Lagrangian density is invariant under above field transformations

$$\mathcal{L}_{\rm QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\, D_\mu \gamma^\mu \Psi \; - m_e \bar{\Psi}\Psi$$

with field strength $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and cov. derivative $D_\mu = \partial_\mu - ieA$

Very simple and successful theory:

– minimal coupling: the interactions/couplings uniquely determined

– renormalisable, perturbative, unitary (predictive), very well tested..

1. The Standard Model: brief introduction

The SM is based on the local gauge symmetry group

$$\mathrm{G_{SM} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y}$$

- **The group $\mathrm{SU(3)_C}$ describes the strong force:**

– interaction between quarks which are SU(3) triplets: q, q , q

– mediated by 8 gluons, $\mathbf{G^a_\mu}$ corresponding to 8 generators of $\mathbf{SU(3)_C}$

Gell-Man 3×3 matrices: $\mathbf{[T^a, T^b] = if^{abc} T_c}$ with $\mathrm{Tr}[\mathbf{T^a T^b}] = \frac{1}{2}\delta_{\mathbf{ab}}$

– asymptotic freedom: interaction "weak" at high energy, $\alpha_\mathbf{s} = \frac{\mathbf{g_s^2}}{4\pi} \ll 1$

The Lagrangian of the theory is given by:

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4}\mathbf{G^a_{\mu\nu} G^{\mu\nu}_a} + \mathbf{i}\sum_\mathbf{i} \mathbf{\bar{q}_i}(\partial_\mu - \mathbf{i g_s T_a G^a_\mu})\gamma^\mu \mathbf{q_i} \;\; (-\sum_\mathbf{i} \mathbf{m_i \bar{q}_i q_i})$$

with $\mathbf{G^a_{\mu\nu}} = \partial_\mu \mathbf{G^a_\nu} - \partial_\nu \mathbf{G^a_\mu} + \mathbf{g_s\, f^{abc} G^b_\mu G^c_\nu}$

The interactions/couplings are then uniquely determined:

– fermion gauge boson couplings : $-g_i \overline{\psi} V_\mu \gamma^\mu \psi$

– gluon self-couplings : $i g_i\, \mathrm{Tr}(\partial_\nu V_\mu - \partial_\mu V_\nu)[V_\mu, V_\nu] + \frac{1}{2} g_i^2\, \mathrm{Tr}[V_\mu, V_\nu]^2$

1. The SM: brief introduction

• $\mathrm{SU(2)_L \times U(1)_Y}$ **describes the electroweak interaction:**

– **between the three families of quarks and leptons:** $\mathbf{f_{L/R} = \frac{1}{2}(1 \mp \gamma_5)f}$

$$\mathbf{I_f^{3L,3R} = \pm\frac{1}{2}, 0 \quad \Rightarrow L = \left(\begin{array}{c} \nu_e \\ e^- \end{array} \right)_L,\ R = e_R^-,\ Q = \left(\begin{array}{c} u \\ d \end{array} \right)_L,\ u_R,\ d_R}$$

$$\mathbf{Y_f = 2Q_f - 2I_f^3 \Rightarrow Y_L = -1, Y_R = -2, Y_Q = \frac{1}{3}, Y_{u_R} = \frac{4}{3}, Y_{d_R} = -\frac{2}{3}}$$

Same holds for the two other generations: $\mathbf{\mu, \nu_\mu, c, s;\ \tau, \nu_\tau, t, b}$.

There is no ν_R **(and neutrinos are and stay exactly massless)**

– **mediated by the** $\mathrm{W_\mu^i}$ **(isospin) and** $\mathrm{B_\mu}$ **(hypercharge) gauge bosons**

the gauge bosons, corresp. to generators, are exactly massless

$$\mathbf{T^a = \frac{1}{2}\tau^a\,; \quad [T^a, T^b] = i\epsilon^{abc}T_c \ \text{ and } \ [Y, Y] = 0}$$

Lagrangian simple: with fields strengths and covariant derivatives

$$\mathbf{W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g_2 \epsilon^{abc} W_\mu^b W_\nu^c,\ B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu}$$

$$\mathbf{D_\mu \psi = \left(\partial_\mu - igT_a W_\mu^a - ig'\frac{Y}{2}B_\mu\right)\psi\ ,\ \ T^a = \frac{1}{2}\tau^a}$$

$$\mathcal{L}_\mathrm{SM} = \mathbf{-\frac{1}{4}W_{\mu\nu}^a W_a^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{F}_{Li}\, iD_\mu\gamma^\mu\, F_{Li} + \bar{f}_{Ri}\, iD_\mu\gamma^\mu\, f_{R_i}}$$

1. The SM: brief introduction

But if gauge boson and fermion masses are put by hand in $\mathcal{L}_{\rm SM}$

$\frac{1}{2}{\rm M_V^2 V^\mu V_\mu}$ **and/or** ${\rm m_f \bar{f} f}$ **terms: breaking of gauge symmetry.**

This statement can be visualized by taking the example of QED where the photon is massless because of the local ${\rm U(1)_Q}$ **local symmetry:**

$$\mathbf{\Psi(x) \to \Psi'(x) = e^{ie\alpha(x)}\Psi(x)\ ,\ A_\mu(x) \to A'_\mu(x) = A_\mu(x) - \frac{1}{e}\partial_\mu\alpha(x)}$$

- **For the photon (or B field for instance) mass we would have:**

$$\mathbf{\frac{1}{2}M_A^2 A_\mu A^\mu \to \frac{1}{2}M_A^2 (A_\mu - \frac{1}{e}\partial_\mu\alpha)(A^\mu - \frac{1}{e}\partial^\mu\alpha) \neq \frac{1}{2}M_A^2 A_\mu A^\mu}$$

and thus, gauge invariance is violated with a photon mass.

- **For the fermion masses, we would have (e.g. for the electron):**

$$\mathbf{m_e \bar{e} e = -m_e \bar{e}\left(\frac{1}{2}(1-\gamma_5) + \frac{1}{2}(1+\gamma_5)\right) e = -m_e(\bar{e}_R e_L + \bar{e}_L e_R)}$$

manifestly non–invariant under SU(2) isospin symmetry transformations

$\Rightarrow$ **We need a less "brutal" way to generate particle masses in the SM.**

2. The Higgs mechanism

In the SM, for the mechanism of spontaneous EW symmetry breaking,

$\Rightarrow$ **introduce a doublet of complex scalar fields**

$$\mathbf{\Phi} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \text{with} \quad \mathbf{Y_\Phi = +1}$$

with a Lagrangian that is invariant under $\mathrm{SU(2)_L \times U(1)_Y}$

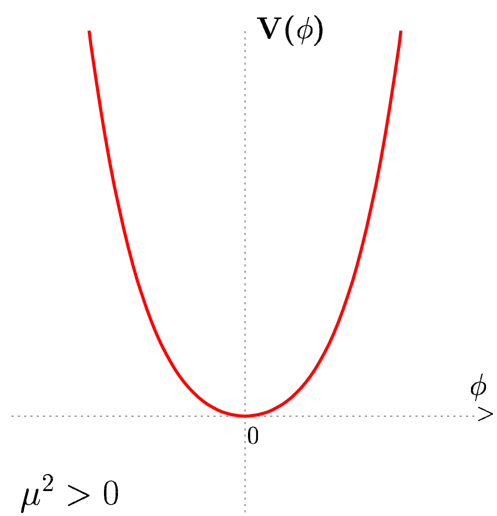
$$\mathcal{L}_\mathbf{S} = (\mathbf{D}^\mu \mathbf{\Phi})^\dagger (\mathbf{D}_\mu \mathbf{\Phi}) - \mu^2 \mathbf{\Phi}^\dagger \mathbf{\Phi} - \lambda (\mathbf{\Phi}^\dagger \mathbf{\Phi})^2$$

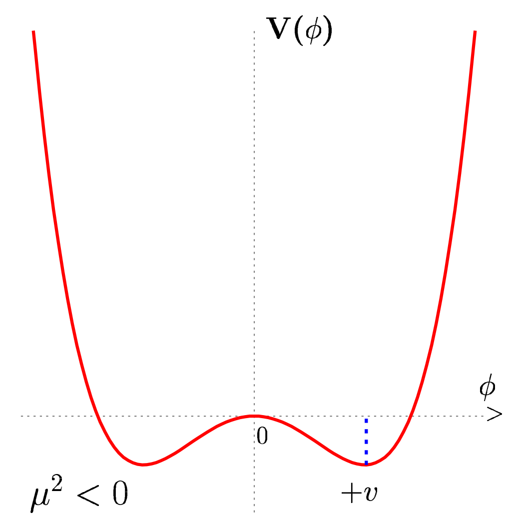
$\mu^2 > 0$: **4 scalar particles.**

$\mu^2 < 0$: Φ **develops a vev:**

$$\langle \mathbf{0} | \mathbf{\Phi} | \mathbf{0} \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$\mathbf{v} = \left(-\frac{\mu^2}{\lambda}\right)^{\frac{1}{2}}$$





2. The Higgs mechanism in the SM

To obtain the physical states, write $\mathcal{L}_S$ with the true vacuum:

- **Write Φ in terms of four fields $\theta_{1,2,3}(x)$ and H(x) at 1st order:**

$$\Phi(x) = e^{i\theta_a(x)\tau^a(x)/v} \frac{1}{\sqrt{2}}\binom{0}{v+H(x)} \simeq \frac{1}{\sqrt{2}}\binom{\theta_2+i\theta_1}{v+H-i\theta_3}$$

- **Make a gauge transformation on Φ to go to the unitary gauge:**

$$\Phi(x) \to e^{-i\theta_a(x)\tau^a(x)}\,\Phi(x) = \frac{1}{\sqrt{2}}\binom{0}{v+H(x)}$$

- **Then fully develop the term $|D_\mu \Phi)|^2$ of the Lagrangian $\mathcal{L}_S$:**

$$|D_\mu\Phi)|^2 = \left|\left(\partial_\mu - ig_1\frac{\tau_a}{2}W_\mu^a - i\frac{g_2}{2}B_\mu\right)\Phi\right|^2$$

$$= \frac{1}{2}\left|\begin{pmatrix} \partial_\mu - \frac{i}{2}(g_2 W_\mu^3 + g_1 B_\mu) & -\frac{ig_2}{2}(W_\mu^1 - iW_\mu^2) \\ -\frac{ig_2}{2}(W_\mu^1 + iW_\mu^2) & \partial_\mu + \frac{i}{2}(g_2 W_\mu^3 - g_1 B_\mu) \end{pmatrix} \binom{0}{v+H}\right|^2$$

$$= \frac{1}{2}(\partial_\mu H)^2 + \frac{1}{8}g_2^2(v+H)^2|W_\mu^1 + iW_\mu^2|^2 + \frac{1}{8}(v+H)^2|g_2 W_\mu^3 - g_1 B_\mu|^2$$

- **Define the new fields $W_\mu^\pm$ and Z_μ [A_μ is the orthogonal of Z_μ]:**

$$W^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp W_\mu^2)\,,\; Z_\mu = \frac{g_2 W_\mu^3 - g_1 B_\mu}{\sqrt{g_2^2+g_1^2}}\,,\; A_\mu = \frac{g_2 W_\mu^3 + g_1 B_\mu}{\sqrt{g_2^2+g_1^2}}$$

$$\sin^2\theta_W \equiv g_2/\sqrt{g_2^2+g_1^2} = e/g_2$$

2. The Higgs mechanism in the SM

- **And pick up the terms which are bilinear in the fields $W^{\pm}, Z, A$:**

$$M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu + \frac{1}{2} M_A^2 A_\mu A^\mu$$

$\Rightarrow$ 3 degrees of freedom for $W_L^{\pm}, Z_L$ and thus $M_{W^\pm}, M_Z$:

$$M_W = \frac{1}{2} v g_2 \, , \; M_Z = \frac{1}{2} v \sqrt{g_2^2 + g_1^2} \, , \; M_A = 0 \, ,$$

with the value of the vev given by: $v = 1/(\sqrt{2} G_F)^{1/2} \sim 246 \, \mathrm{GeV}$.

$\Rightarrow$ The photon stays massless, $U(1)_{\rm QED}$ is preserved.

- **For fermion masses, use <u>same</u> doublet field Φ and its <u>conjugate</u> field $\tilde{\Phi} = i\tau_2 \Phi^*$ and introduce $\mathcal{L}_{\rm Yuk}$ which is invariant under SU(2)xU(1):**

$$\mathcal{L}_{\rm Yuk} = -f_e (\bar{e}, \bar{\nu})_L \Phi e_R - f_d (\bar{u}, \bar{d})_L \Phi d_R - f_u (\bar{u}, \bar{d})_L \tilde{\Phi} u_R + \cdots$$

$$= -\frac{1}{\sqrt{2}} f_e (\bar{\nu}_e, \bar{e}_L) \binom{0}{v+H} e_R \cdots = -\frac{1}{\sqrt{2}} (v + H) \bar{e}_L e_R \cdots$$

$$\Rightarrow m_e = \frac{f_e \, v}{\sqrt{2}} \; , \; m_u = \frac{f_u \, v}{\sqrt{2}} \; , \; m_d = \frac{f_d \, v}{\sqrt{2}}$$

With same Φ, we have generated gauge boson and fermion masses, while preserving SU(2)xU(1) gauge symmetry (which is now hidden)!

What about the residual degree of freedom?

2. The Higgs mechanism in the SM

It will correspond to the physical spin–zero scalar Higgs particle, H.

The kinetic part of H field, $\frac{1}{2}(\partial_\mu \mathrm{H})^2$, comes from $|\mathrm{D}_\mu \Phi)|^2$ term.

Mass and self-interaction part from $\mathrm{V}(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$:

$$\mathrm{V} = \frac{\mu^2}{2}(0, \mathrm{v}+\mathrm{H})\binom{0}{\mathrm{v}+\mathrm{H}} + \frac{\lambda}{2}\left|(0, \mathrm{v}+\mathrm{H})\binom{0}{\mathrm{v}+\mathrm{H}}\right|^2$$

Doing the exercise you find that the Lagrangian containing H is,

$$\mathcal{L}_\mathrm{H} = \frac{1}{2}(\partial_\mu \mathrm{H})(\partial^\mu \mathrm{H}) - \mathrm{V} = \frac{1}{2}(\partial^\mu \mathrm{H})^2 - \lambda \mathrm{v}^2\, \mathrm{H}^2 - \lambda \mathrm{v}\, \mathrm{H}^3 - \frac{\lambda}{4}\, \mathrm{H}^4$$

The Higgs boson mass is given by: $\mathrm{M}_\mathrm{H}^2 = 2\lambda \mathrm{v}^2 = -2\mu^2$.

The Higgs triple and quartic self–interaction vertices are:

$$g_{\mathrm{H}^3} = 3\mathrm{i}\, \mathrm{M}_\mathrm{H}^2/\mathrm{v}\,,\ g_{\mathrm{H}^4} = 3\mathrm{i}\mathrm{M}_\mathrm{H}^2/\mathrm{v}^2$$

What about the Higgs boson couplings to gauge bosons and fermions?

They were almost derived previously, when we calculated the masses:

$$\mathcal{L}_{\mathrm{M_V}} \sim \mathrm{M}_\mathrm{V}^2(1+\mathrm{H}/\mathrm{v})^2\ ,\ \mathcal{L}_{\mathrm{m_f}} \sim -\mathrm{m_f}(1+\mathrm{H}/\mathrm{v})$$

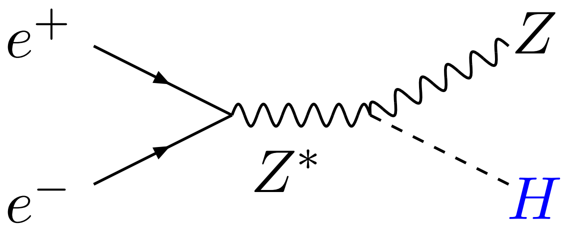
$$\Rightarrow g_{\mathrm{Hff}} = \mathrm{i}\mathrm{m_f}/\mathrm{v}\,,\ g_{\mathrm{HVV}} = -2\mathrm{i}\mathrm{M}_\mathrm{V}^2/\mathrm{v}\,,\ g_{\mathrm{HHVV}} = -2\mathrm{i}\mathrm{M}_\mathrm{V}^2/\mathrm{v}^2$$

Since v is known, the only free parameter in the SM is M_H or λ.

3. Constraints on M_H

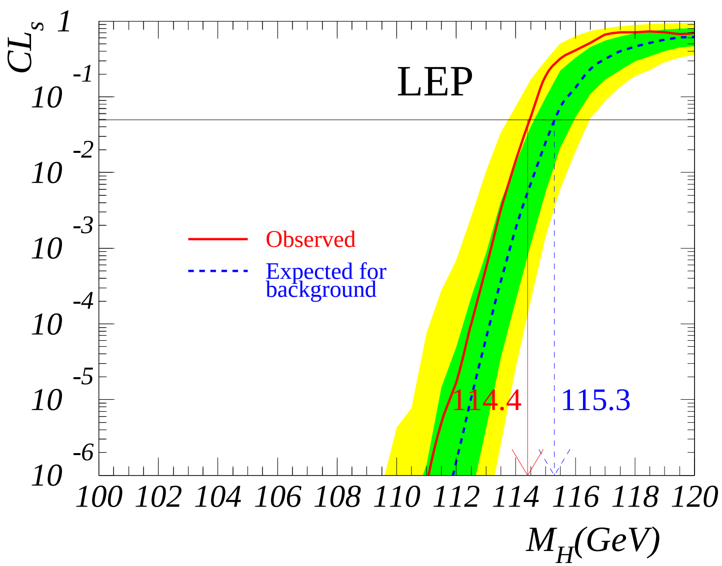
Direct searches at LEP:

H looked for in $\mathrm{e^+e^- \to ZH}$



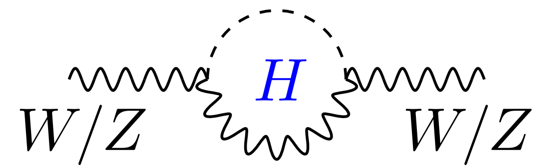
We have a limit at 95% CL:

$\mathrm{M_H > 114.4}$ **GeV**



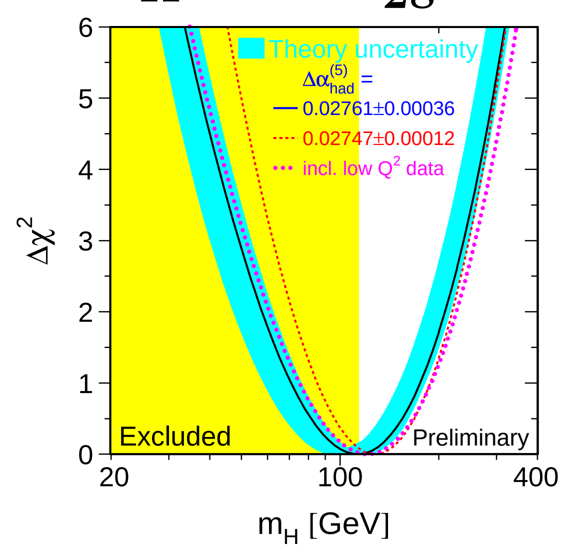
Indirect searches:

H contributes to RC to W/Z masses:



Fit the EW precision measurements:

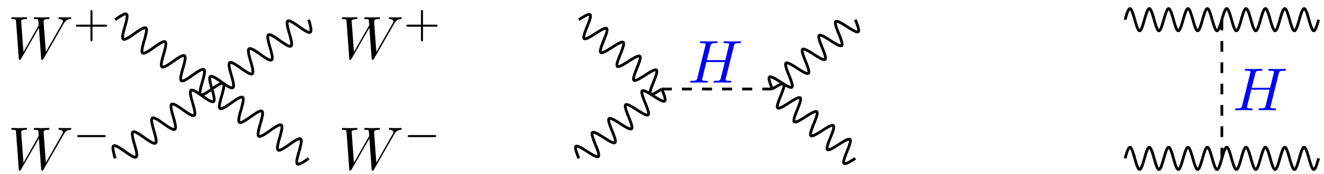
we obtain $\mathrm{M_H = 85^{+39}_{-28}}$ GeV, or



$\mathrm{M_H \lesssim 180}$ **GeV at 95% CL**

3. Constraints on M_H: perturbative unitarity

Scattering of massive gauge bosons $V_L V_L \to V_L V_L$ at high-energy



Because w interactions increase with energy (q^μ terms in V propagator),

$s \gg M_W^2 \Rightarrow \sigma(w^+w^- \to w^+w^-) \propto s$: $\Rightarrow$ unitarity violation possible!

Decomposition into partial waves and choose J=0 for $s \gg M_W^2$:

$$a_0 = -\frac{M_H^2}{8\pi v^2}\left[1 + \frac{M_H^2}{s - M_H^2} + \frac{M_H^2}{s}\log\left(1 + \frac{s}{M_H^2}\right)\right]$$

For unitarity to be fullfiled, we need the condition $|\mathrm{Re}(a_0)| < 1/2$.

At high energies, $s \gg M_H, M_W$, we have: $a_0 \xrightarrow{s \gg M_H^2} -\frac{M_H^2}{8\pi v^2}$

$$\text{unitarity} \Rightarrow M_H \lesssim 870\ \text{GeV} \ \ (M_H \lesssim 710\ \text{GeV})$$

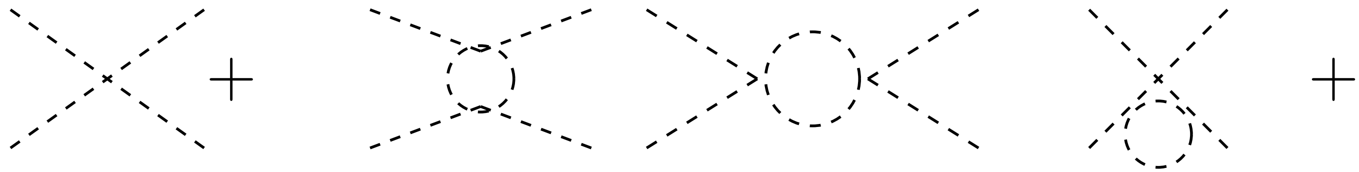
For a very heavy or no Higgs boson, we have: $a_0 \xrightarrow{s \ll M_H^2} -\frac{s}{32\pi v^2}$

$$\text{unitarity} \Rightarrow \sqrt{s} \lesssim 1.7\ \text{TeV} \ \ (\sqrt{s} \lesssim 1.2\ \text{TeV})$$

Otherwise (strong?) New Physics should appear to restore unitarity.

3. Constraints on M_H: triviality

The quartic coupling of the Higgs boson λ ($\propto M_H^2$) increases with energy.



The RGE evolution of λ with Q^2 and its solution are given by:

$$\frac{\mathrm{d}\lambda(Q^2)}{\mathrm{d}Q^2} = \frac{3}{4\pi^2}\,\lambda^2(Q^2) \Rightarrow \lambda(Q^2) = \lambda(v^2)\left[1 - \frac{3}{4\pi^2}\,\lambda(v^2)\log\frac{Q^2}{v^2}\right]^{-1}$$

- If $Q^2 \ll v^2$, $\lambda(Q^2) \to 0_+$: **the theory is said to be trivial (no int.).**
- If $Q^2 \gg v^2$, $\lambda(Q^2) \to \infty$: **Landau pole at** $Q = v\exp\left(\frac{4\pi^2 v^2}{M_H^2}\right)$.

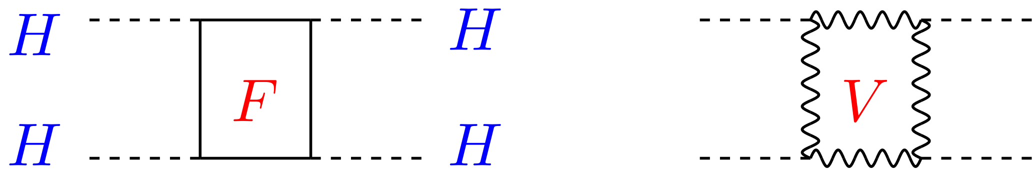
The SM is valid only at scales before λ becomes infinite:

If $\Lambda_C = M_H$, $\lambda \lesssim 4\pi \Rightarrow M_H \lesssim 650$ **GeV**

(comparable to results obtained with simulations on the lattice!)

3. Constraints on M_H: vacuum stability

The top quark and gauge bosons also contribute to the evolution of λ.



The RGE evolution of the coupling at one–loop is given by

$$\lambda(Q^2) = \lambda(v^2) + \frac{1}{16\pi^2}\left[-12\frac{m_t^4}{v^4} + \frac{3}{16}\left(2g_2^4 + (g_2^2+g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

If λ is small (H is light), top loops might lead to $\lambda(0) < \lambda(v)$:

v is not the minimum of the potential and the EW vacuum is instable.

$\Rightarrow$ **Impose that the coupling λ stays always positive:**

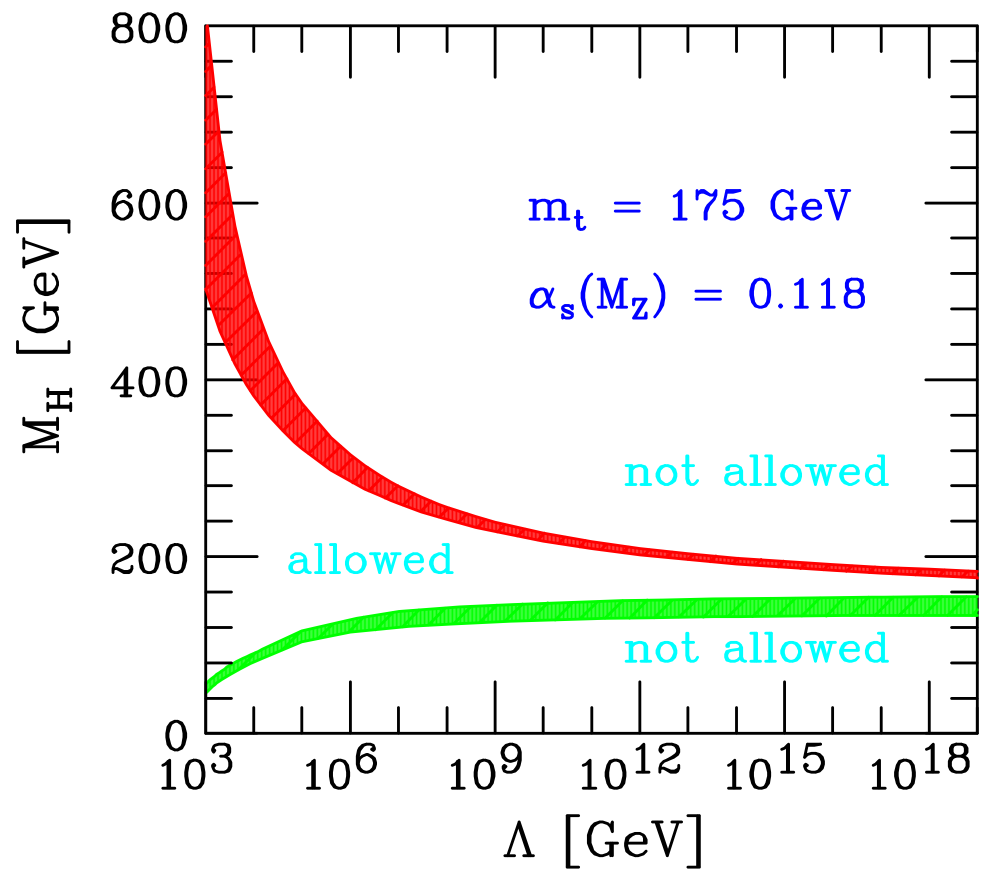
$$\lambda(Q^2) > 0 \Rightarrow M_H^2 > \frac{v^2}{8\pi^2}\left[-12\frac{m_t^4}{v^4} + \frac{3}{16}\left(2g_2^4 + (g_2^2+g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

Very strong constraint: $Q = \Lambda_C \sim 1$ TeV $\Rightarrow M_H \gtrsim 70$ GeV

3. Constraints on M_H: triviality+stability

Combine the two constraints and include all possible effects:

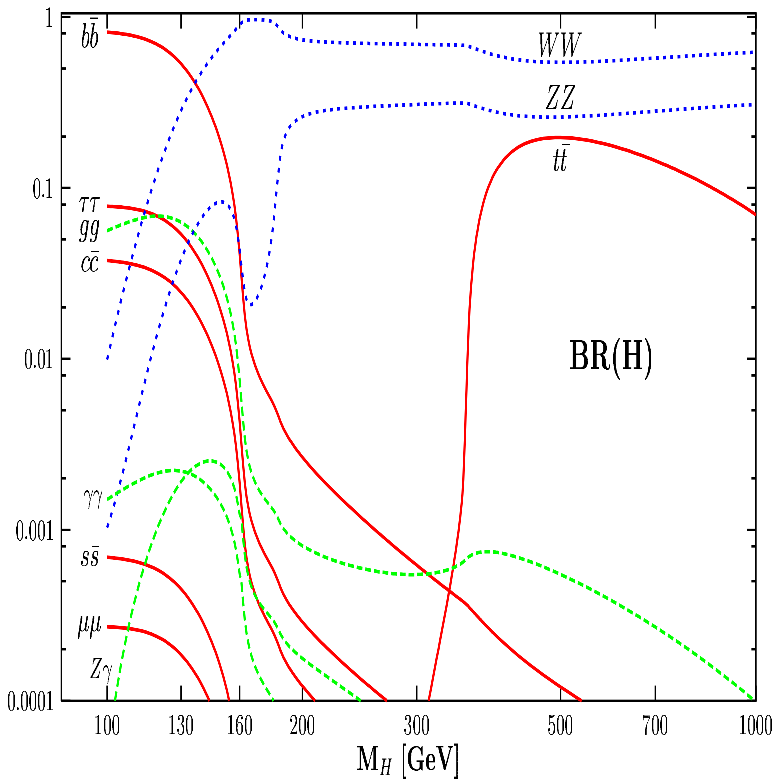
- **– corrections at two loops**
- **– theoretical errors**
- **– experimental errors**
- **– other refinements $\cdots$**

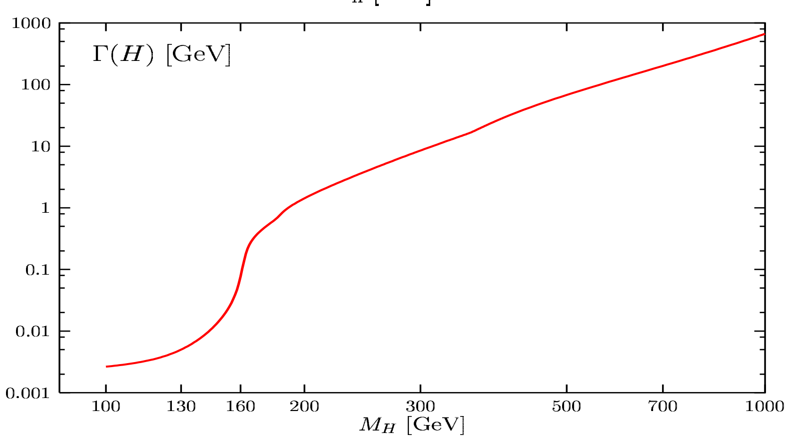


$$\Lambda_C \sim 10^3 \text{ GeV} \quad \Rightarrow \quad 70 \text{ GeV} \lesssim M_H \lesssim 700 \text{ GeV}$$

$$\Lambda_C \sim 10^{16} \text{ GeV} \quad \Rightarrow \quad 130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$$

4. Higgs at the LHC: decay modes



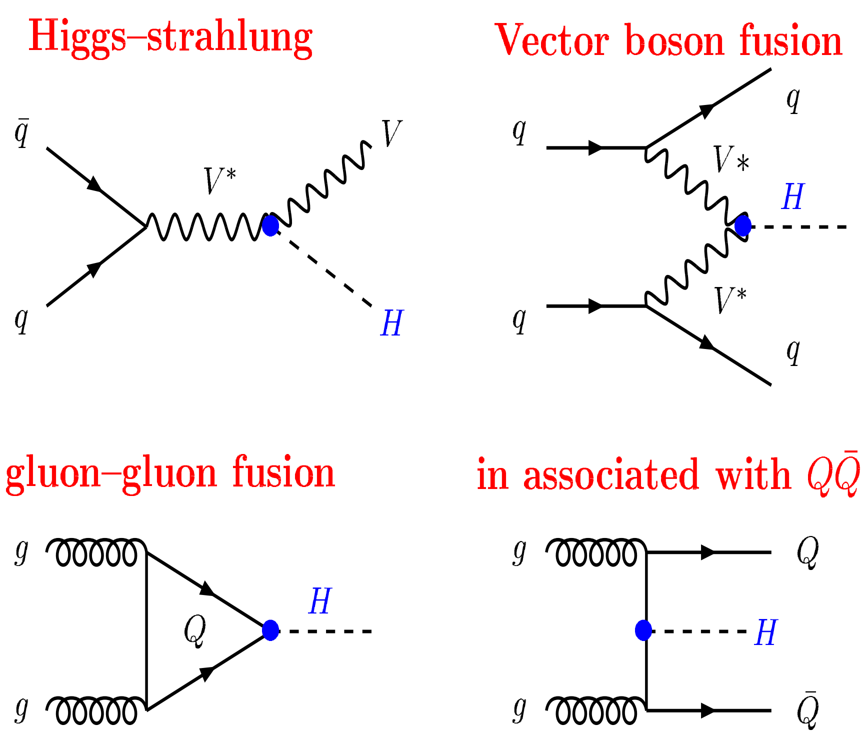


Higgs decays in the SM:

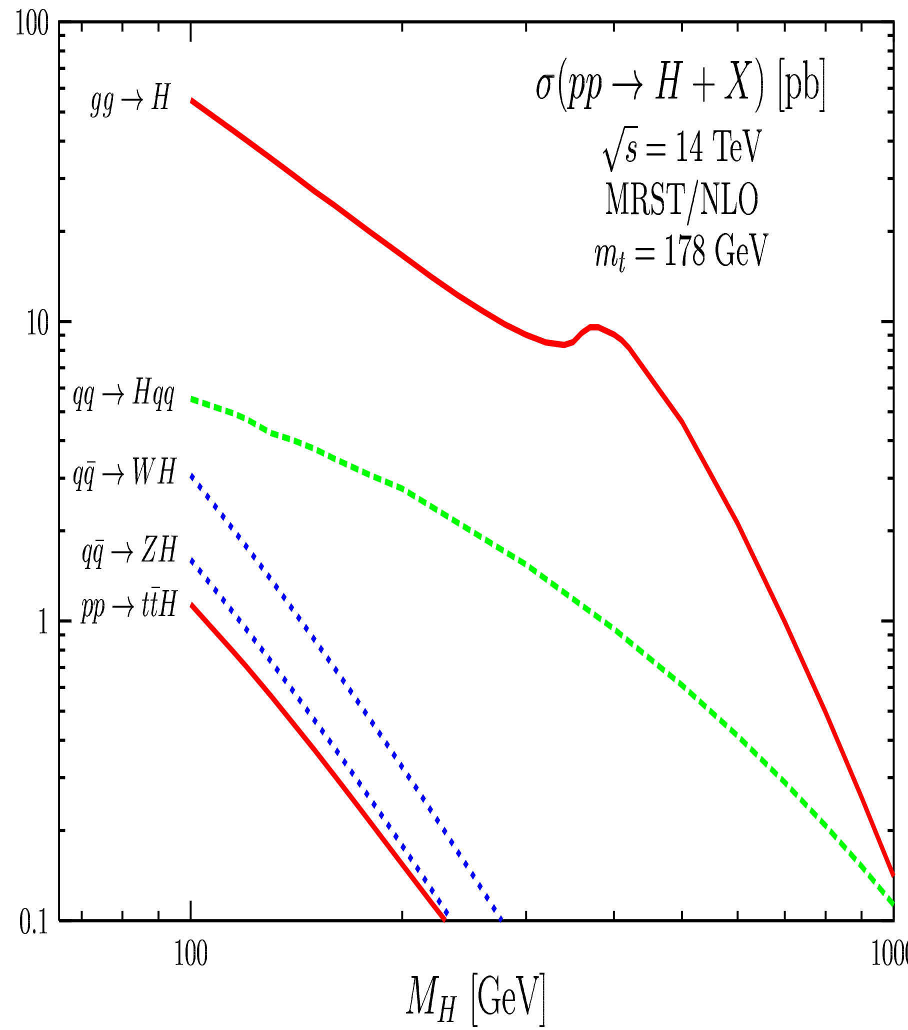
- **H decays into the heaviest particle available by phase space: $\mathbf{g \propto m}$.**
- $\mathbf{M_H \lesssim 130\ GeV}$, $\mathbf{H \to b\bar{b}}$
- – $\mathbf{H \to cc, \tau^+\tau^-, gg = \mathcal{O}(few\ \%)}$
- – $\mathbf{H \to \gamma\gamma = \mathcal{O}(0.1\%)}$
- $\mathbf{M_H \gtrsim 130\ GeV}$, $\mathbf{H \to WW, ZZ}$
- – **below threshold decays possible**
- – **decays into $\mathbf{t\bar{t}}$ for heavy Higgs.**
- **Total Higgs decay width:**
- – **very small for a light Higgs**
- **- comparable to mass for heavy Higgs**

4. Higgs at the LHC: production

SM production mechanisms



Cross sections at the LHC



There are also subleading processes, $gg \to HH$, etc...

4. Higgs at LHC: backgrounds

LHC: pp collider

$\sqrt{s}=7+7=14$ TeV $\Rightarrow \sqrt{s}_{\rm eff} \sim \sqrt{s}/3 \sim 5$ TeV
$\mathcal{L} \sim 10\,{\rm fb}^{-1}$ first years and 100 ${\rm fb}^{-1}$ later

- Huge cross sections for QCD processes.
- Small cross sections for EW Higgs signal.

  S/B $\gtrsim 10^{10} \Rightarrow$ a needle in a haystack!
- Need some strong selection criteria:

Trigger: get rid of uninteresting events...

Select clean channels: $\mathrm{H} \to \gamma\gamma, \mathrm{VV} \to \ell$

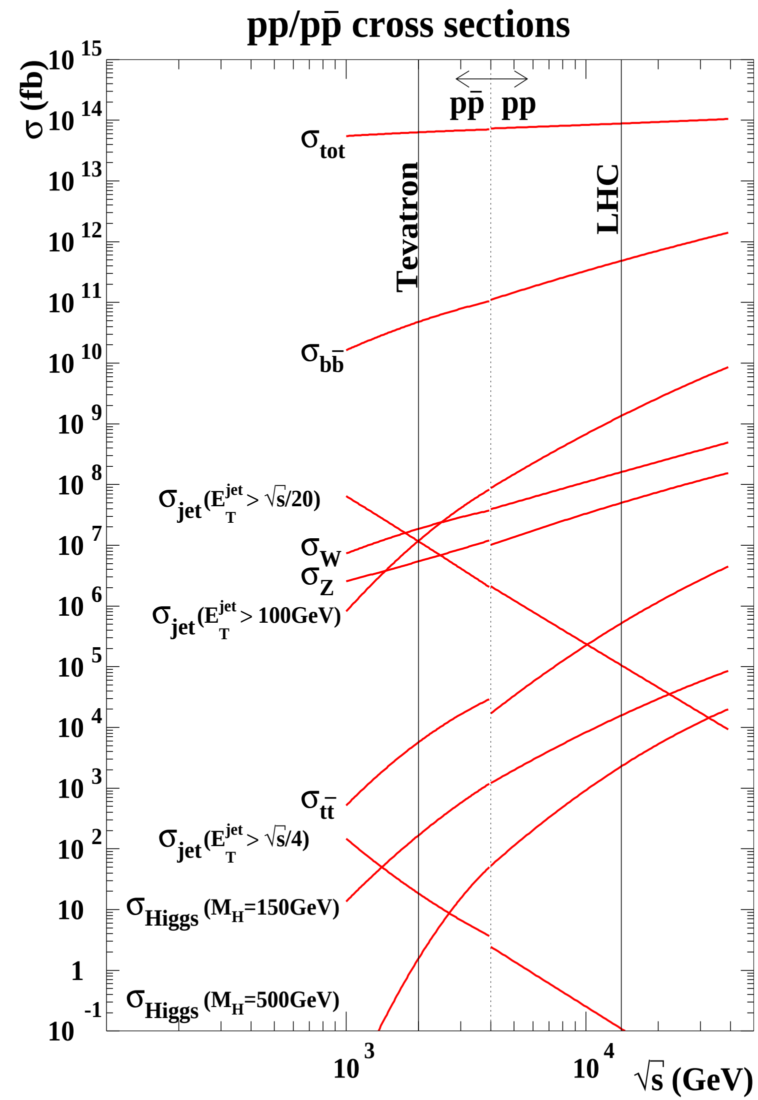
Use different kinematic features for Higgs

Combine different decay/production channels

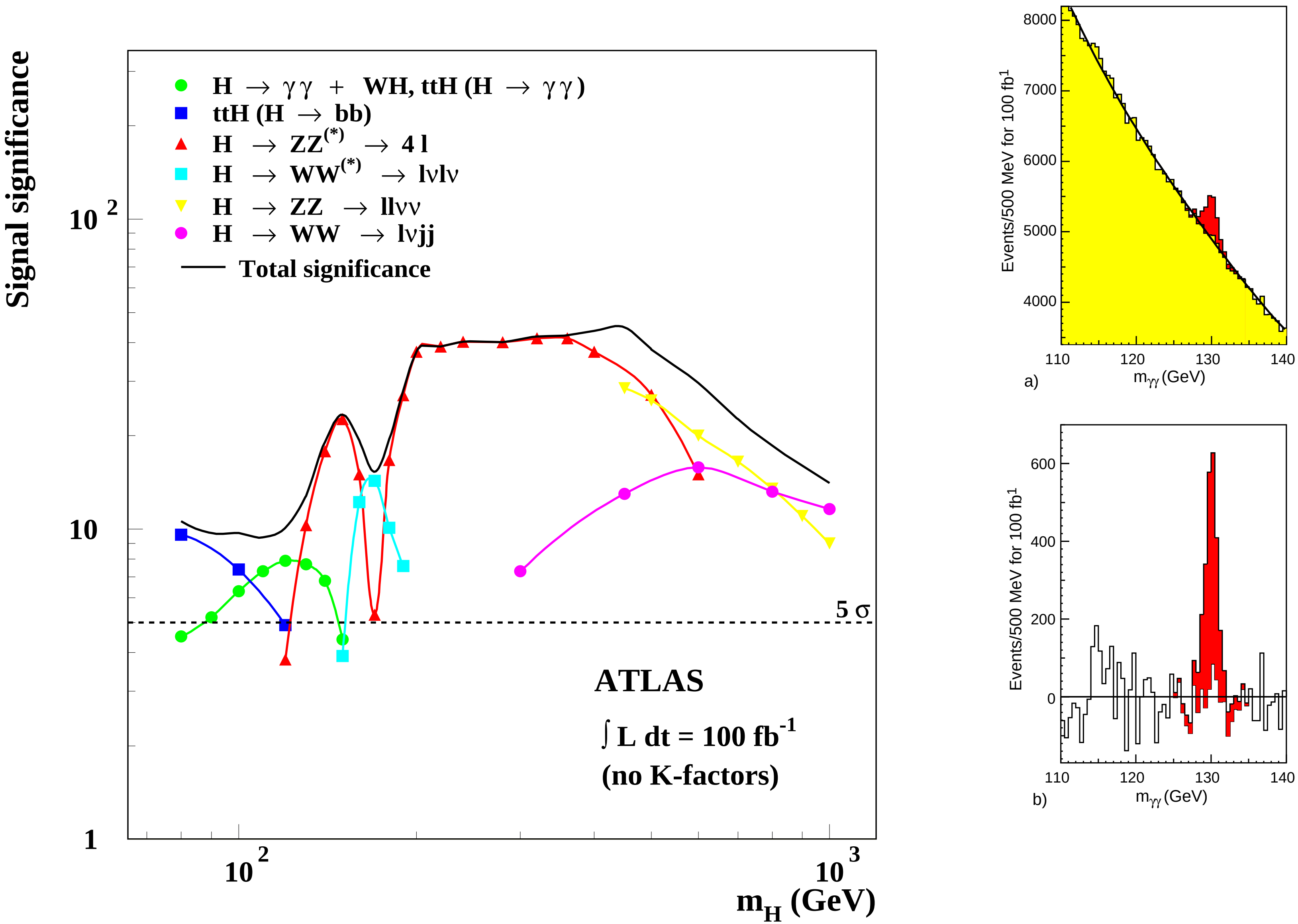
Have a precise knowledge of S and B rates.

(note: higher orders can be factor of 2!)

- Gigantic experimental (+theoretical) efforts!



4. Higgs at the LHC: detection



4. Higgs at the LHC: measurements

In 2-3 years we will find the Higgs:

would particle physics be "closed"?

No! Need to check that H is indeed

responsible of spontaneous EWSB!

Measure its fundamental properties:

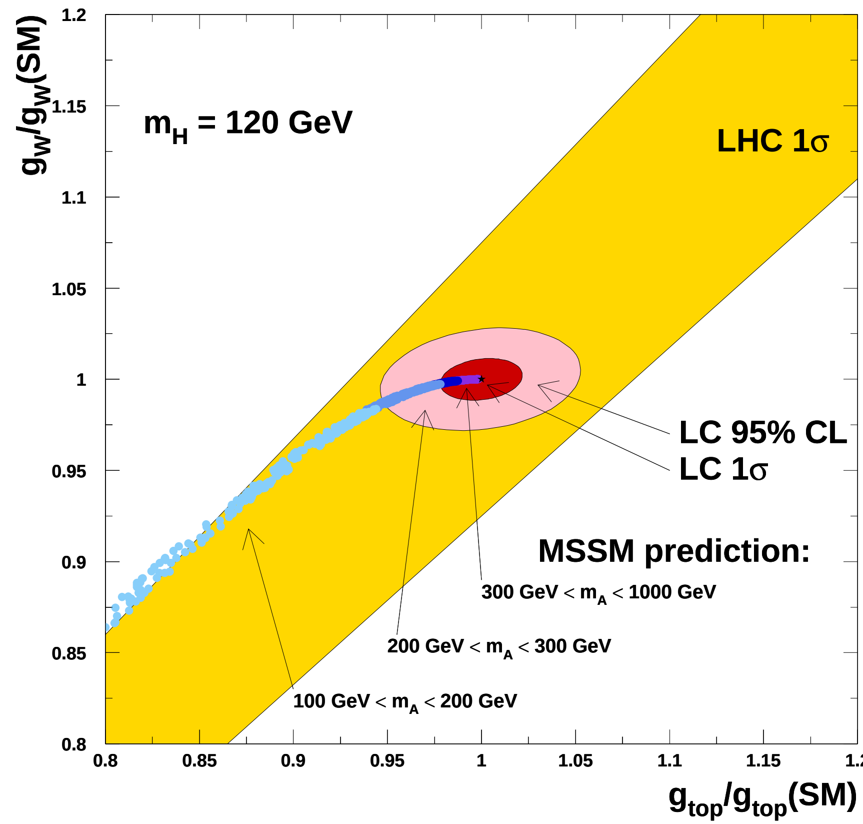
- **mass, width , check spin/parity**
- **couplings to other particles**
- **self–couplings to reconstruct V_H**

A very challenging program indeed:

more difficult than Higgs discovery...

LHC surely will not be sufficient,

we need the ILC for more precision!



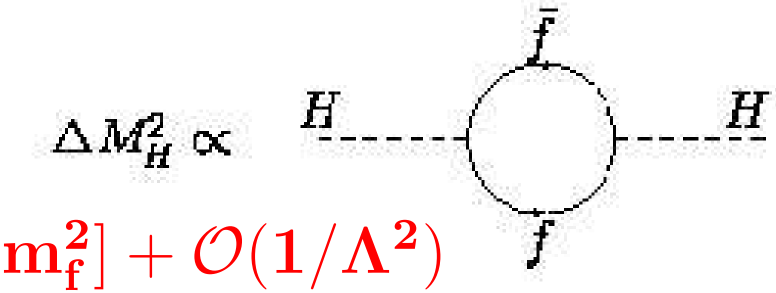
ILC will be even more necessary in extensions of the Standard Model!

5. The Higgs beyond the SM

A severe problem in the SM: the hierarchy/naturalness problem

Radiative corrections to M_H^2 in SM

with a cut–off $\Lambda = M_{NP} = M_{GUT}$



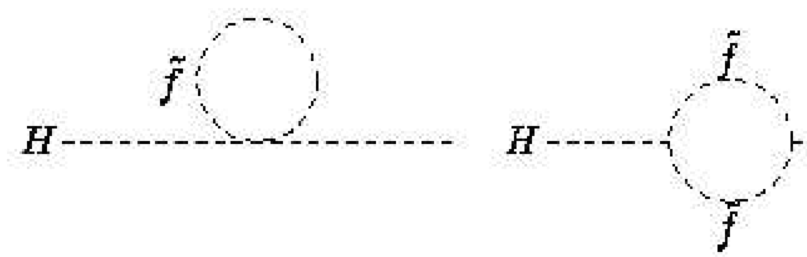
$$\Delta M_H^2 = N_f \frac{\lambda_f^2}{8\pi^2}\left[-\Lambda^2 + 6 m_f^2 \log\frac{\Lambda}{m_f} - 2 m_f^2\right] + \mathcal{O}(1/\Lambda^2)$$

M_H **prefers to be close to the high scale than to the EWSB scale.**

Low energy Supersymmetry provides the most natural solution

add super-partner contribution:

$N_S = N_f, \lambda_f^2 = -\lambda_S, m_1 = m_2 = m_S$



$$\Delta M_H^2\big|^{\rm tot} = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3 m_f^2 \log\left(\frac{m_S}{m_f}\right)\right]$$

Symmetry fermions–scalars $\Rightarrow$ no divergence in Λ^2

But if $M_S \gg 1$ TeV the problem is back again $\Rightarrow$ low energy SUSY.

NB: solution to the gauge coupling unification and dark matter problems

Focus on Minimal Supersymmetric Standard Model (MSSM).

5. The MSSM Higgs sector

In MSSM with two Higgs doublets: $\mathrm{H_1} = \begin{pmatrix} \mathbf{H_1^0} \\ \mathbf{H_1^-} \end{pmatrix}$ **and** $\mathrm{H_2} = \begin{pmatrix} \mathbf{H_2^+} \\ \mathbf{H_2^0} \end{pmatrix}$**,**

- **to cancel the chiral anomalies introduced by the new $\tilde{\mathrm{h}}$ field,**
- **give separately masses to d and u fermions in SUSY invariant way.**

After EWSB (which can be made radiative: more elegant than in SM):

Three dof to make $\mathbf{W_L^\pm}, \mathbf{Z_L} \Rightarrow$ 5 physical states left out: $\mathrm{h}, \mathrm{H}, \mathrm{A}, \mathrm{H^\pm}$

Only two free parameters at the tree level: $\tan\beta, \mathrm{M_A}$; others are:

$$\mathrm{M^2_{h,H}} = \frac{1}{2}\left[\mathrm{M_A^2} + \mathrm{M_Z^2} \mp \sqrt{(\mathrm{M_A^2}+\mathrm{M_Z^2})^2 - 4\mathrm{M_A^2}\mathrm{M_Z^2}\cos^2 2\beta}\right]$$

$$\mathrm{M^2_{H^\pm}} = \mathrm{M_A^2} + \mathrm{M_W^2}$$

$$\tan 2\alpha = \tan 2\beta \, (\mathrm{M_A^2}+\mathrm{M_Z^2})/(\mathrm{M_A^2}-\mathrm{M_Z^2})$$

We have important constraint on the MSSM Higgs boson masses:

$$\mathrm{M_h} \leq \min(\mathrm{M_A}, \mathrm{M_Z}) \cdot |\cos 2\beta| \leq \mathrm{M_Z}, \ \mathrm{M_{H^\pm}} > \mathrm{M_W}, \mathrm{M_H} > \mathrm{M_A} \ldots$$

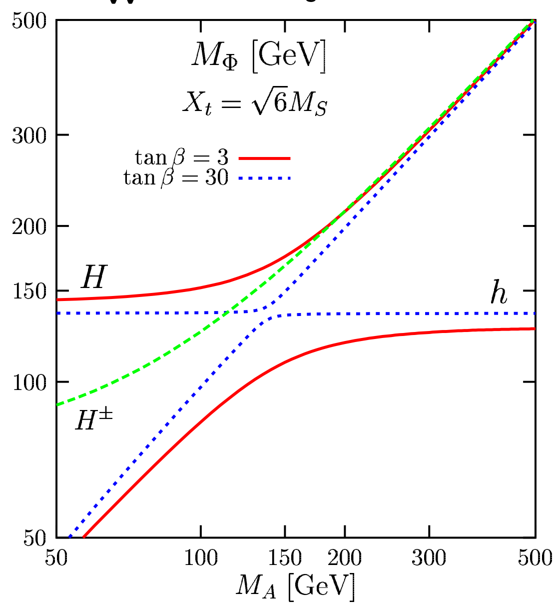
$\mathrm{M_A} \gg \mathrm{M_Z}$**: decoupling regime, all Higgses heavy except for h.**

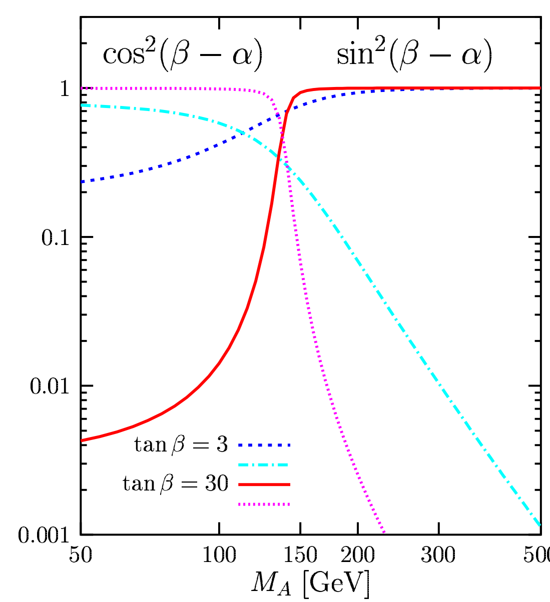
$$\mathrm{M_h} \sim \mathrm{M_Z}|\cos 2\beta| \leq \mathrm{M_Z}!\ , \ \mathrm{M_H} \sim \mathrm{M_{H^\pm}} \sim \mathrm{M_A}\ , \ \alpha \sim \frac{\pi}{2} - \beta$$

5. The MSSM Higgs sector

Radiative corrections important in MSSM Higgs sector; dominant one:

$$\Delta M_h^2 = \frac{3g^2}{2\pi^2}\frac{m_t^4}{M_W^2}\log\frac{m_{\tilde{t}}^2}{m_t^2} \text{ large: } \overrightarrow{M_h^{max}\to M_Z+40\,\text{GeV}} \gtrsim 115\ \text{GeV}$$





Couplings in terms of H_{SM} and their values in decoupling limit:

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

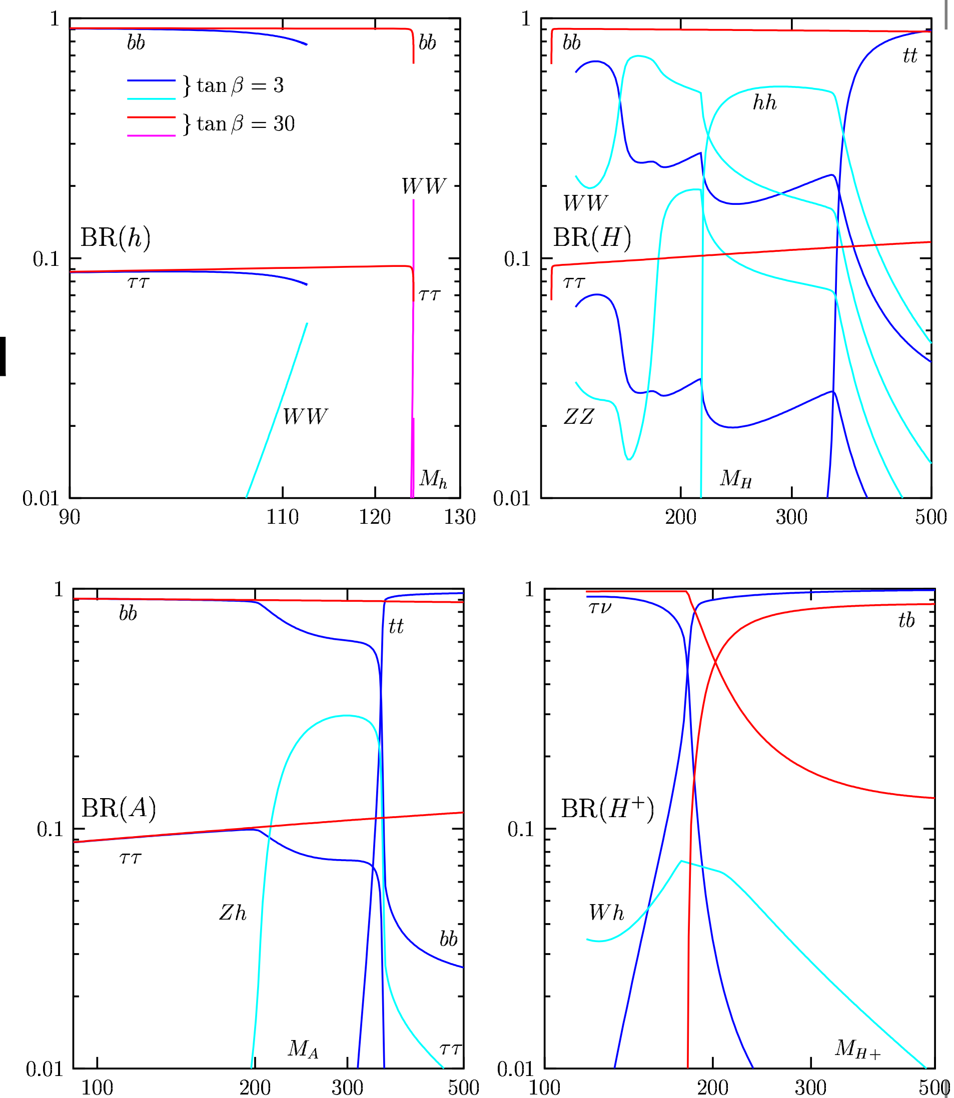
5. The MSSM Higgs sector

Higgs decays in the MSSM:

General features:

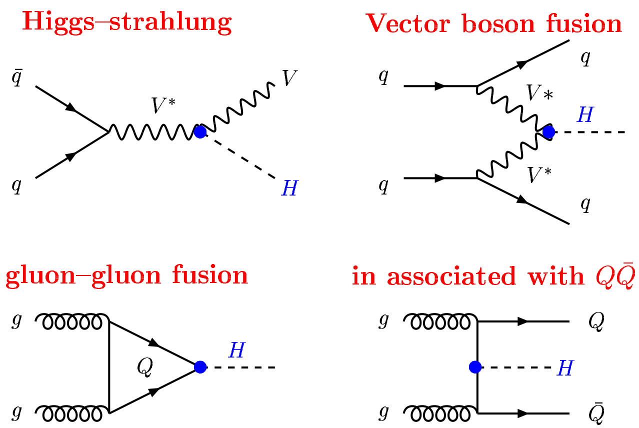
- h: **same as** $\mathrm{H_{SM}}$ **in general**
  (in particular in decoupling limit)
  $\mathrm{h \to b\bar{b}}$ **and** $\tau^+\tau^-$ **same or enhanced**
- A: **only** $\mathrm{b\bar{b}}, \tau^+\tau^-$ **and** $\mathrm{t\bar{t}}$ **decays**
  (no VV decays, hZ **suppressed).**
- H: **same as** A **in general**
  $\mathrm{(WW, ZZ, hh}$ **decays suppressed).**
- $\mathrm{H^\pm}$: $\tau\nu$ **and** tb **decays**
  (depending if $\mathrm{M_{H^\pm}} <$ **or** $> \mathrm{m_t}$**).**

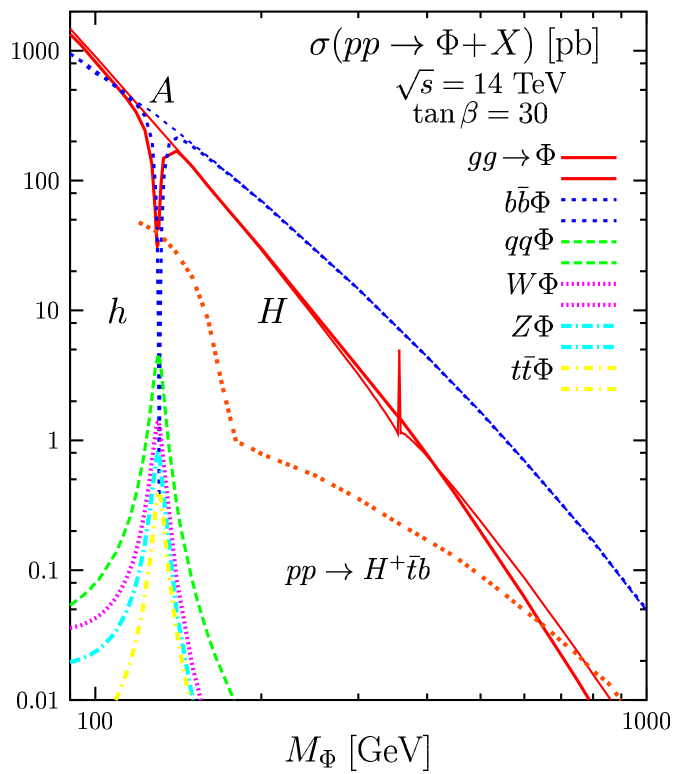
Possible new effects from SUSY



5. The MSSM Higgs sector

SM production mechanisms





What is different in MSSM

- **All work for CP–even h,H bosons.**

– in ΦV, $qq\Phi$ h/H complementary

– $\sigma(\mathrm{h}) + \sigma(\mathrm{H}) = \sigma(\mathrm{H_{SM}})$

– aditionnal mechanism: qq $\to$ A+h/H

- **For $\mathrm{gg} \to \Phi$ and $\mathrm{pp} \to \mathrm{tt}\Phi$**

– include the contr. of b–quarks

– dominant contr. at high tanβ!

- **For pseudoscalar A boson:**

– CP: no $\Phi\mathrm{A}$ and qqA processes

– $\mathrm{gg} \to \mathrm{A}$ and $\mathrm{pp} \to \mathrm{bbA}$ dominant.

- **For charged Higgs boson:**

– $\mathrm{M_H} \lesssim \mathrm{m_t}$: $\mathrm{pp} \to \mathrm{t\bar{t}}$ with $\mathrm{t} \to \mathrm{H^+b}$

– $\mathrm{M_H} \gtrsim \mathrm{m_t}$: continuum $\mathrm{pp} \to \mathrm{t\bar{b}H^-}$

5. The MSSM Higgs sector

Higgs detection in the MSSM at the LHC