Introduction to
the Standard Model of ElectroWeak interactions

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Prelude: the four fundamental interactions

- Electromagnetic:
  - governs atomic physics (and beyond)
  - long range, $V(r) \sim 1/r$
  - carried by massless bosons (photons)
  - described as gauge theory (QED)
- Weak:
  - governs radioactive decays of nucleons
  - short range, $V(r) \sim e^{-mr}/r$
  - carried by massive bosons ($W^{\pm}$, Z)
  - described as effective 4-fermion theory
- Strong:
  - governs interactions within nucleons
  - confined, $V(r) \sim r$ (at large r)
  - carried by massless bosons (gluons)
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- Gravity:
  - interactions between massive bodies
  - long range, $V(r) \sim 1/r$, but *very* weak
  - described as geometry of space-time

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ElectroWeak interaction: unified description as spontaneously broken gauge theory

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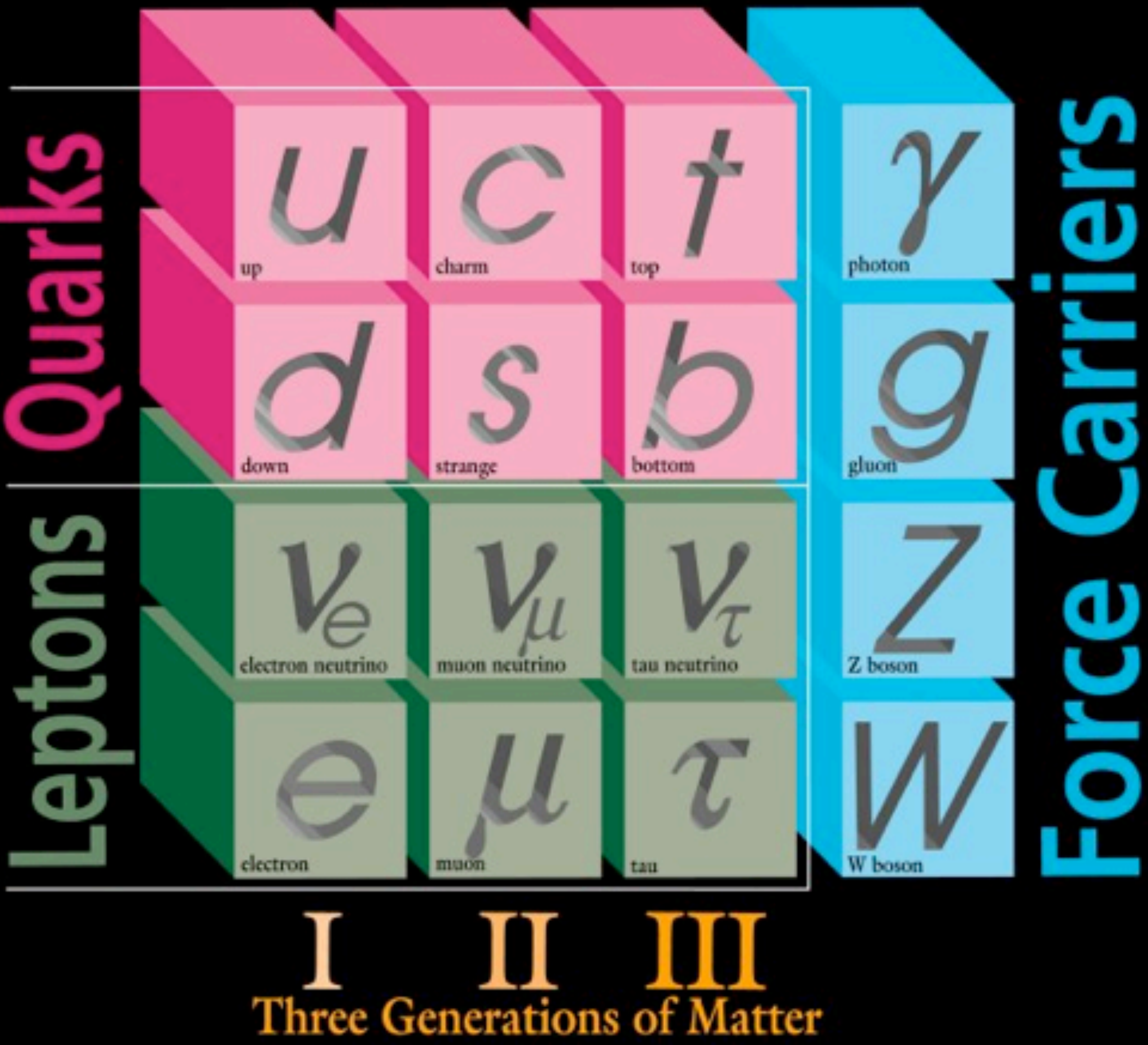
ELEMENTARY PARTICLES



Quarks	u up	c charm	t top	γ photon
	d down	s strange	b bottom	g gluon
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
	e electron	μ muon	τ tau	W W boson
	I	II	III	

Force Carriers

Three Generations of Matter

Fermilab 1995

Outline of the lectures

1) The origin of particle masses in the SM

2) The hunt for the Higgs boson

3) Beyond the Standard Model [?]

I) The origin of particle masses in the SM

Local gauge invariance

e.g., for a fermion field: $\psi(x) \to U(x)\,\psi(x)\,, \qquad U(x) = \exp\left[\,i\alpha^a(x)\,T^a\right]$

Alone, the kinetic term is not invariant: $\bar{\psi}\,\gamma^\mu\,\partial_\mu\,\psi \to \bar{\psi}\,U^\dagger\,\gamma^\mu\partial_\mu\,(U\,\psi)$

We must build a *covariant derivative* such that $D_\mu\,(U\,\psi) \;=\; U\,(D_\mu\,\psi)$

$$D_\mu \;\equiv\; \partial_\mu - i\,g\,V_\mu^a\,T^a$$

If the vector field transforms as $V_\mu^a(x)\,T^a \;\to\; U(x)\left(V_\mu^a(x)\,T^a + \frac{i}{g}\,\partial_\mu\right)U^\dagger(x)$

then the kinetic term is invariant: $\bar{\psi}(x)\,\gamma^\mu\,D_\mu\,\psi \;\to\; \bar{\psi}(x)\,U^\dagger\,U\,\gamma^\mu\,(D_\mu\,\psi)$

Defining the *field strength tensor* as: $F_{\mu\nu}^a \;=\; \partial_\mu V_\nu^a - \partial_\nu V_\mu^a + g\,f_{abc}\,V_\mu^b V_\nu^c$

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$$\left[T^a, T^b\right] \;=\; i\,f^{abc}\,T^c$$

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The gauge sector of the Standard Model

The Standard Model is based on local gauge invariance w.r.t. the group

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

Each subgroup is characterized by its own coupling constant and vector bosons

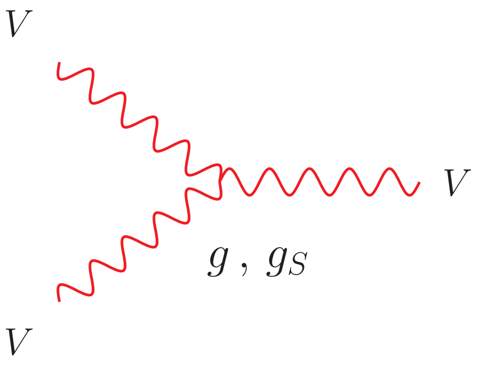
Group	charge	coupling	boson	
$SU(3)_C$	color	g_S	G_μ^a	$(a = 1 \ldots 8)$
$SU(2)_L$	weak isospin	g	W_μ^i	$(i = 1 \ldots 3)$
$U(1)_Y$	hypercharge	g'	B_μ	

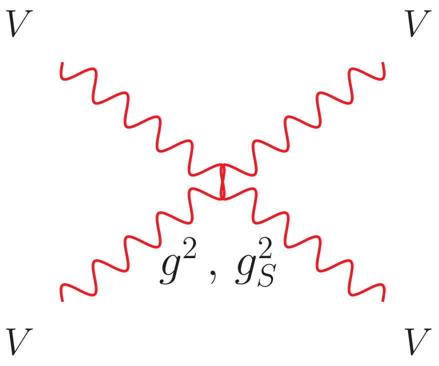
Gauge invariance fixes the Yang-Mills part of the SM Lagrangian

$$\mathcal{L}_{\rm YM} \;=\; -\frac{1}{4}\,G^{\mu\nu\,a}G^a_{\mu\nu}\;-\frac{1}{4}\,W^{\mu\nu\,i}W^i_{\mu\nu}\;-\frac{1}{4}\,B^{\mu\nu}B_{\mu\nu}$$

$$\begin{aligned}
G^a_{\mu\nu} &= \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_S\, f_{abc}\, G^b_\mu G^c_\nu \\
W^i_{\mu\nu} &= \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g\, f_{ijk}\, W^j_\mu W^k_\nu \\
B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu
\end{aligned}$$

This determines the kinetic terms and the self-interactions of the gauge bosons





The fermions come in three generations and belong to different representations of $G_{\rm SM}$

$$q_L^i \equiv \begin{pmatrix} u_L^i \\ \\ d_L^i \end{pmatrix} \sim (3,2,+1/6)\,, \qquad \ell_L^i \equiv \begin{pmatrix} \nu_L^i \\ \\ e_L^i \end{pmatrix} \sim (1,2,-1/2)\,,$$

$$(i = 1 \ldots 3)$$

$$u_R^i \sim (3,1,+2/3)\,, \qquad d_R^i \sim (3,1,-1/3)\,, \qquad e_R^i \sim (1,1,-1)$$

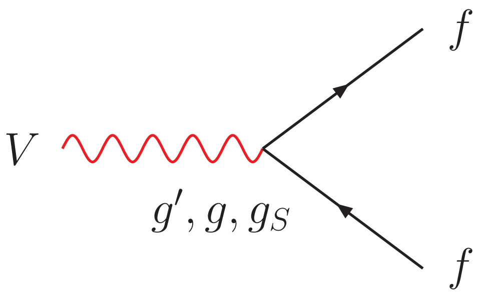
The *flavors* of quarks and leptons are:

$$u^i = \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \quad d^i = \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \quad e^i = \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}, \quad \nu^i = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Gauge invariance also fixes the interaction of the fermions with the gauge bosons

$$\mathcal{L}_{\rm F} = i\, \bar\Psi\, \gamma^\mu\, D_\mu\, \Psi$$

$$D_\mu = \partial_\mu - i\, g_S\, G_\mu^a\, \lambda^a - i\, g\, W_\mu^i\, T^i - i\, g'\, B_\mu\, Y$$



The electromagnetic group $U(1)_{\rm em}$ is contained in $SU(2)_L \times U(1)_Y$

Rotate the neutral gauge fields:

$$\begin{aligned} B^\mu &= A_\mu \cos\theta_W - Z_\mu \sin\theta_W \\ W^3_\mu &= A_\mu \sin\theta_W + Z_\mu \cos\theta_W \end{aligned}$$

$$\begin{aligned} \mathcal{L} &\supset \bar\Psi\,\gamma^\mu \left(g \sin\theta_W\, T^3 + g' \cos\theta_W\, Y\right) \Psi\, A_\mu \\ &+ \bar\Psi\,\gamma^\mu \left(g \cos\theta_W\, T^3 - g' \sin\theta_W\, Y\right) \Psi\, Z_\mu \end{aligned}$$

The first term corresponds to the electromagnetic interaction $e\,\bar\Psi\,\gamma^\mu\, Q\,\Psi\, A_\mu$ if:

$$Q = T^3 + Y\ , \qquad g \sin\theta_W = g' \cos\theta_W = e$$

A is the photon; the weak gauge bosons are Z and $W^\pm = \dfrac{1}{\sqrt{2}}\left(W^1 \mp W^2\right)$

Long before the weak bosons were found, the strength of the interactions they mediate (e.g. muon decay) suggested that they must have masses of the order of 100 GeV

Also, quark and leptons have masses ranging from ~ MeV to 170 GeV

The problem with particle masses

Mass terms for fermions and vector bosons break the gauge symmetry of the Lagrangian

$$\mathcal{L}_{\rm mass} \;=\; -\,m_\psi\,\bar\psi\psi \;+\; \frac{1}{2}\,m_V^2\,V^{\mu a}V^a_\mu$$

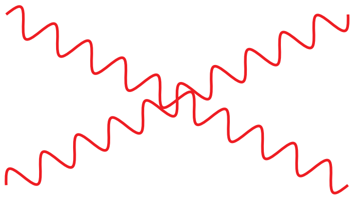
$$m_\psi\,\bar\psi\psi \;=\; m_\psi\left(\bar\psi_L\psi_R + \bar\psi_R\psi_L\right)\,, \qquad\qquad \psi_{L,R} = P_{L,R}\,\psi = \frac{1\mp\gamma_5}{2}\,\psi$$

ψ_L and ψ_R belong to different representations of the gauge group (*chiral fermions)*

Also, mass terms for the vector bosons make the theory non-renormalizable...

$$\Delta^{\mu\nu} \;=\; \frac{i}{k^2-m_V^2}\left(-g^{\mu\nu}+\frac{k^\mu\,k^\nu}{m_V^2}\right) \;\xrightarrow[k\,\to\,\infty]{}\; \text{const}$$

...and they violate the unitarity of the scattering matrix. E.g., consider $V\,V$ scattering:



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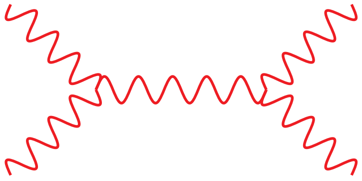


$$+\;\cdots \qquad \mathcal{M}\;\propto\;\frac{s}{m_V^2} \quad \text{for} \quad s \gg m_V^2$$

The Higgs mechanism

The Brout-Englert-Higgs (BEH) mechanism

The Anderson-Higgs mechanism

The LGABEHGHKMPWS’tH mechanism

The Higgs mechanism

The Higgs mechanism and the Higgs boson

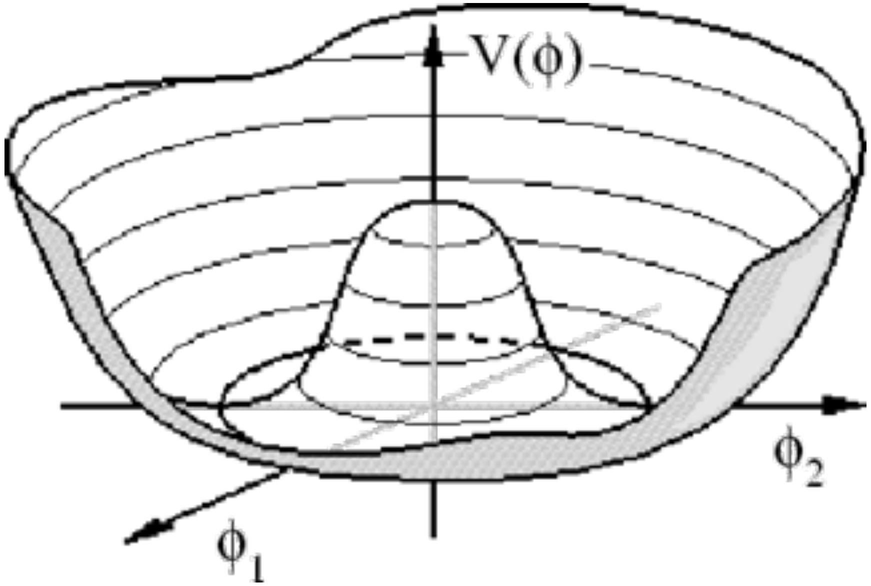
Spontaneous symmetry breaking

The Lagrangian of the theory respects a symmetry, but the vacuum state breaks it

Consider a single complex scalar with a “mexican hat” potential *(Goldstone model)*

$$\phi \equiv \frac{1}{\sqrt{2}}\,(\phi_1 + i\,\phi_2)\,, \qquad \mathcal{L} \;=\; \partial^\mu \phi^*\,\partial_\mu \phi - V(\phi)\,, \qquad V(\phi) \;=\; m^2\,|\phi|^2 \,+\, \lambda\,|\phi|^4$$

$$m^2 < 0\;, \quad \lambda > 0$$



The potential has an infinite number of equivalent minima for $|\phi|^2 \;=\; -\dfrac{m^2}{2\,\lambda}$

The system will choose one specific minimum, breaking the global rotational symmetry

E.g., we can expand the scalar field around a *real* vacuum expectation value (vev)

$$\phi \equiv \frac{1}{\sqrt{2}}\,[v + H(x) + i\,G(x)]\ , \qquad v = \sqrt{-\frac{m^2}{\lambda}}$$

At the minimum of the scalar potential (= the vacuum state) we have $\langle\phi\rangle = \frac{v}{\sqrt{2}}$

Up to an irrelevant constant, the scalar potential becomes

$$\begin{aligned} V \quad = \quad & (m^2 v + \lambda v^3)\,H + \frac{1}{2}\,(m^2 + 3\lambda v^2)\,H^2 + \frac{1}{2}\,(m^2 + \lambda v^2)\,G^2 \\ & + \lambda v\, H(H^2 + G^2) + \frac{\lambda}{4}\,(H^2 + G^2)^2 \end{aligned}$$

Inserting the value of v the linear term vanishes, and the masses of the scalars become

$$m_H^2 = -2\,m^2 = 2\,\lambda\,v^2\,, \qquad m_G^2 = 0$$

G is the *Goldstone boson* associated with the
spontaneous breaking of a continuous global symmetry

The Higgs mechanism: spontaneous breaking of a local symmetry

Consider a U(1) gauge theory with a complex scalar field *(scalar QED)*

$$\mathcal{L} \;=\; -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \;+\; (D_\mu\phi)^* D^\mu\phi \;-\; m^2\,|\phi|^2 \;-\; \lambda\,|\phi|^4 \qquad\qquad (D_\mu \;=\; \partial_\mu - i\,e\,A_\mu)$$

Parameterize the complex scalar as modulus and phase: $\phi \;=\; \rho\, e^{i\,\theta}$

$$\mathcal{L} \;=\; -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \;+\; \rho^2\,(\partial_\mu\theta - e\,A_\mu)^2 \;+\; \partial_\mu\rho\,\partial^\mu\rho \;-\; m^2\,\rho^2 \;-\; \lambda\,\rho^4$$

$B_\mu \equiv A_\mu - \frac{1}{e}\,\partial_\mu\theta$ is gauge invariant, and $F_{\mu\nu} \;=\; \partial_\mu A_\nu - \partial_\nu A_\mu \;=\; \partial_\mu B_\nu - \partial_\nu B_\mu$

Again, for $m^2 < 0$ and $\lambda > 0$ the symmetry is broken and the scalar gets a vev $\qquad \rho \;=\; \frac{1}{\sqrt{2}}\,(v + H)$

$$\mathcal{L} \;=\; -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \;+\; \frac{1}{2}\,e^2\,v^2\,B_\mu B^\mu \;+\; e^2\,v\,H B_\mu B^\mu \;+\; \frac{1}{2}\,e^2\,H^2 B_\mu B^\mu \;+\; \frac{1}{2}\partial_\mu H\partial^\mu H \;-\; V(H)$$

In this “unitary gauge”, the massless field A_μ “eats” the phase and becomes the *massive* field B_μ

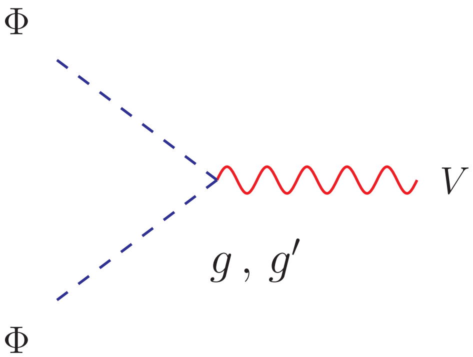
The remaining scalar H is also massive, and interacts with the gauge field

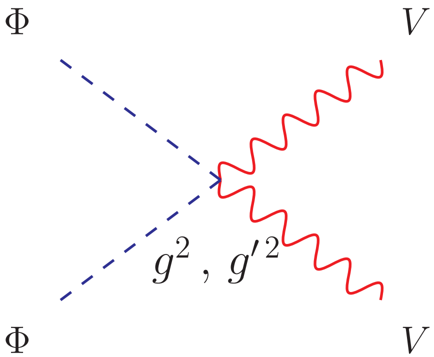
Spontaneous breaking of the SU(2)xU(1) gauge symmetry

Introduce a SU(2) doublet of complex scalars: $\Phi \equiv \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \sim (1, 2, +1/2)$

$$\mathcal{L}_S = (D_\mu \Phi)^\dagger (D^\mu \Phi) - m^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 \qquad \left(D_\mu = \partial_\mu - i \frac{g}{2} W_\mu^i \tau^i - i \frac{g'}{2} B_\mu \right)$$

The kinetic term determines the interactions between scalars and gauge bosons:





If $m^2 < 0$ and $\lambda > 0$ the mexican-hat potential induces a vev v for the doublet

We can parameterize the complex doublet as:

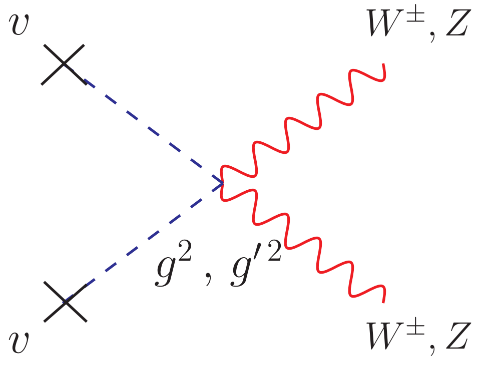
$$\Phi \;=\; \frac{1}{\sqrt{2}}\, e^{i\,\tau^i\,\theta^i(x)} \left(\begin{array}{c} 0 \\ v + H(x) \end{array} \right)$$

Gauge symmetry allows us to rotate away the θ^i via a SU(2) transformation (*unitary gauge*)

$$V \;=\; \frac{1}{2}(2\lambda v^2)H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

The kinetic term for the doublet contains mass and interaction terms for the weak gauge bosons

$$(D_\mu\Phi)^\dagger\,(D^\mu\Phi) \;=\; \frac{1}{2}\partial^\mu H \partial_\mu H + \left[\frac{1}{4}\,g^2\,W^{\mu\,+}W^-_\mu + \frac{1}{8}(g^2 + g'^2) Z^\mu Z_\mu\right]\,(v+H)^2$$



(the photon remains massless)

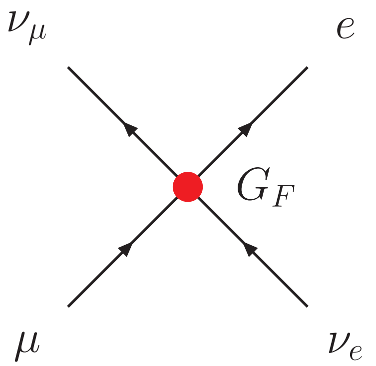
$$m_W^2 \;=\; \frac{1}{4}\,g^2\,v^2 \qquad m_Z^2 \;=\; \frac{1}{4}(g^2 + g'^2)\,v^2$$

Note: $$\frac{m_W^2}{m_Z^2\,\cos^2\theta_W} \;=\; 1$$

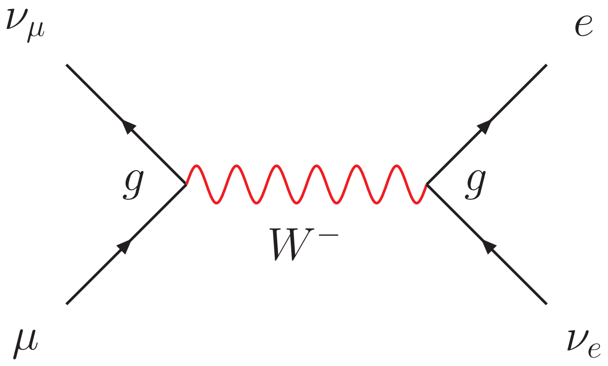
The value of v can be related to the constant G_F in the low-energy effective Lagrangian (four-fermion interaction) that describes the muon decay process $\mu^- \longrightarrow e^- \nu_\mu \overline{\nu}_e$

$$\mathcal{L}_{\text{eff}} \supset -\frac{G_F}{\sqrt{2}} \overline{\nu_\mu} \gamma^\alpha (1-\gamma_5) \mu \, \overline{e} \gamma^\alpha (1-\gamma_5) \nu_e$$

$$\mathcal{A} = -\frac{4\,G_F}{\sqrt{2}}, \qquad \Gamma = \frac{G_F^2 \, m_\mu^5}{192\,\pi^3} + \mathcal{O}(m_e^2/m_\mu^2)$$



In the Standard Model the muon decay is mediated by the exchange of a W boson



$$\mathcal{A} \simeq -\frac{g^2}{2\,m_W^2}$$

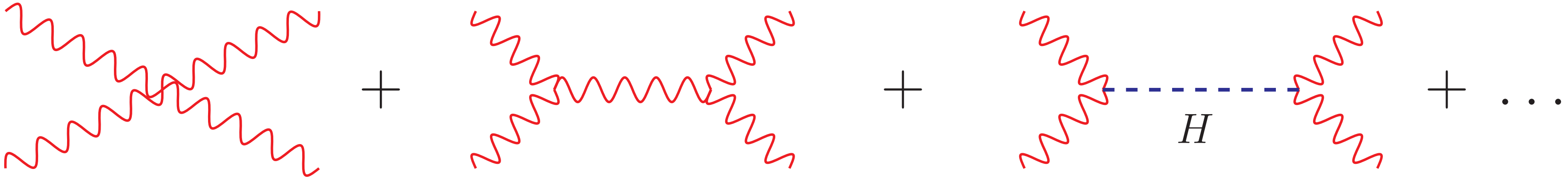
Equating the amplitudes and inserting $m_W = \frac{g\,v}{2}$ we get: $v = (\sqrt{2}\,G_F)^{-1/2} \simeq 246\,\text{GeV}$

This also allows us to derive another relation among measurable quantities:

$$m_W^2\,(1 - m_W^2/m_Z^2) = \frac{\pi\,\alpha}{\sqrt{2}G_F}$$

The inclusion of diagrams with exchange of a scalar *H* restores the unitarity of *V V* scattering at high energy:

$$\mathcal{M} \propto \frac{m_H^2}{v^2}$$



The scalar mass cuts off the divergence. But unitarity is again at risk if m_H is too large

Unitarity conditions on the partial-wave decomposition of the amplitude:

$$\mathcal{M} = 16\pi \sum_{\ell=0}^{\infty} (2\ell+1)\, P_\ell(\cos\theta)\, a_\ell$$

$$|\mathrm{Re}(a_\ell)| < \frac{1}{2}$$

For $m_W^2 \ll m_H^2 \ll s$

$$a_0(W_L W_L \longrightarrow W_L W_L) \approx -\frac{m_H^2}{8\pi\, v^2}$$

Thus, $m_H <$ 870 GeV (even stronger bounds by considering several processes at once)

Counting the bosonic degrees of freedom in the unbroken and broken phases:

unbroken symmetry:

- A complex doublet (Φ)
- Four massless vector bosons $(B\,,\,W^i)$

4+(4x2) = 12 d.o.f.

broken symmetry:

- One real scalar (H): the *Higgs boson*
- Three massive vector bosons $(Z\,,\,W^+,W^-)$
- One massless vector boson (γ)

1+(3x3)+2 = 12 d.o.f.

The degrees of freedom corresponding to the three *would-be-Goldstone bosons* have been absorbed in the longitudinal components of the massive vector fields

The renormalizability of the theory is still hidden in this *unitary* gauge, but it becomes manifest with different gauge choices (‘t Hooft, 1971)

The propagator of the massive vector boson depends on the choice of gauge:

Unitary gauge:

(no would-be-Goldstone boson)

$$\Delta^{\mu\nu} = \frac{i}{k^2 - m_V^2} \left(-g^{\mu\nu} + \frac{k^\mu \, k^\nu}{m_V^2} \right)$$

Renormalizable gauge:

$$\Delta^{\mu\nu} = \frac{i}{k^2 - m_V^2} \left(-g^{\mu\nu} + (1-\xi) \, \frac{k^\mu \, k^\nu}{k^2 - \xi m_V^2} \right)$$

$$\Delta^{G} = \frac{i}{k^2 - \xi m_V^2}$$

The contributions of the unphysical would-be-Goldstone boson combine with those of the gauge boson, and we find the same results as in the unitary gauge

(also, predictions for physical observables must not depend on the arbitrary parameter ξ)

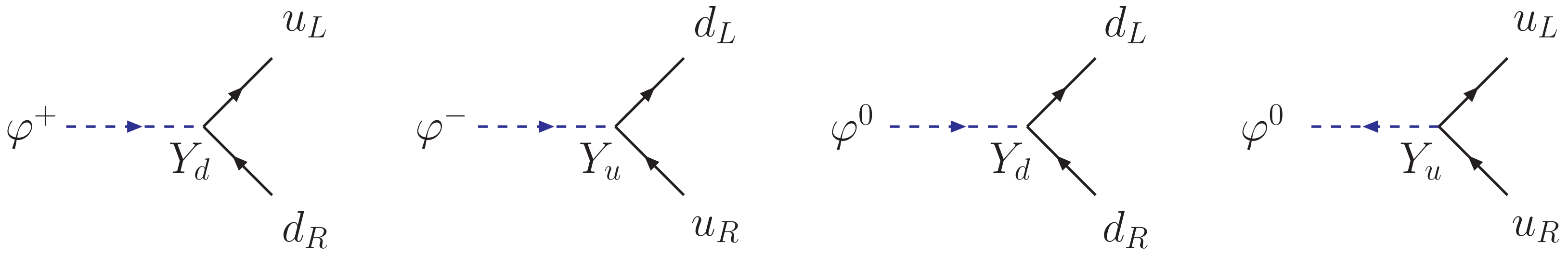
Fermion masses and flavor mixing

We can generate the quark masses by building gauge-invariant interactions with the Higgs

$$q_L^i \equiv \begin{pmatrix} u_L^i \\ \\ d_L^i \end{pmatrix} \sim (3,2,+1/6)\,, \qquad u_R^i \sim (3,1,+2/3)\,, \qquad d_R^i \sim (3,1,-1/3)$$

$$\Phi \sim (1,2,+1/2)\;, \qquad \widetilde{\Phi} \equiv \epsilon\,\Phi^* = \begin{pmatrix} \varphi^{0\,*} \\ -\varphi^- \end{pmatrix} \sim (1,2,-1/2)$$

$$\mathcal{L}_Y = -(Y_D)_{ij}\,\overline{q_L^i}\,\Phi\,d_R^j - (Y_U)_{ij}\,\overline{q_L^i}\,\widetilde{\Phi}\,u_R^j + \text{h.c.}$$



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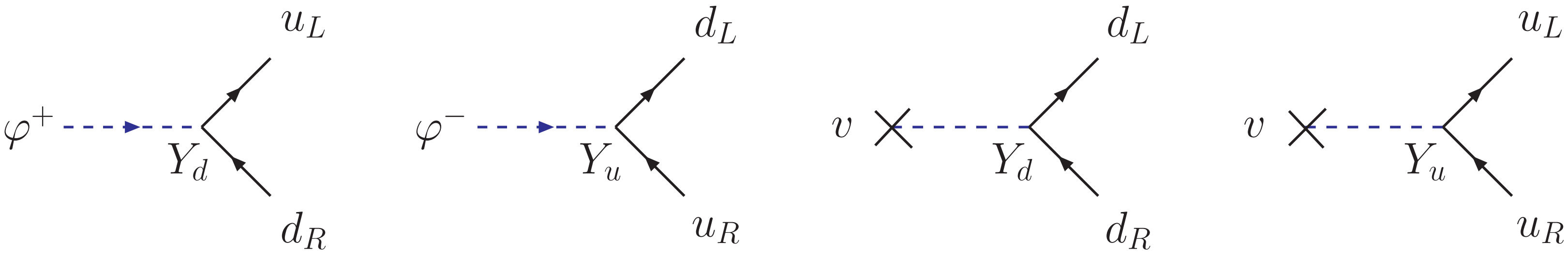
We can generate the quark masses by building gauge-invariant interactions with the Higgs

$$q_L^i \equiv \begin{pmatrix} u_L^i \\ \\ d_L^i \end{pmatrix} \sim (3, 2, +1/6)\,, \qquad u_R^i \sim (3, 1, +2/3)\,, \qquad d_R^i \sim (3, 1, -1/3)$$

$$\Phi \sim (1, 2, +1/2)\;, \qquad \widetilde{\Phi} \equiv \epsilon\, \Phi^* = \begin{pmatrix} \varphi^{0\,*} \\ -\varphi^- \end{pmatrix} \sim (1, 2, -1/2)$$

$$\mathcal{L}_Y = -\,(Y_D)_{ij}\, \overline{q_L^i}\, \Phi\, d_R^j - (Y_U)_{ij}\, \overline{q_L^i}\, \widetilde{\Phi}\, u_R^j \; + \; \text{h.c.}$$



The matrices of Yukawa couplings can be diagonalized by bi-unitary transformations

$$\mathrm{diag}(Y_u, Y_c, Y_t) \;=\; V_u^\dagger \, Y_U \, U_u \;, \qquad \mathrm{diag}(Y_d, Y_s, Y_b) \;=\; V_d^\dagger \, Y_D \, U_d$$

Applying the same rotations to the quark fields:

$$u_L \longrightarrow V_u \, u_L \;, \quad u_R \longrightarrow U_u \, u_R \;,$$

$$d_L \longrightarrow V_d \, d_L \;, \quad d_R \longrightarrow U_d \, d_R$$

the Yukawa interaction Lagrangian becomes (in the unitary gauge):

$$\mathcal{L}_Y \;=\; -\frac{1}{\sqrt{2}} (v + H) \; \left(Y_u \, \bar{u}u + Y_c \, \bar{c}c + Y_t \, \bar{t}t + Y_d \, \bar{d}d + Y_s \, \bar{s}s + Y_b \, \bar{b}b \right)$$

Therefore the masses of the quarks are: $m_q \;=\; \dfrac{Y_q \, v}{\sqrt{2}}$

The *neutral current* couplings of the quarks to photon and Z are not affected by the rotation

$$\mathcal{L} \supset \sum_{q_i} e_i \left(\overline{q_L^i}\, \gamma^\mu\, q_L^i + \overline{q_R^i}\, \gamma^\mu\, q_R^i \right) A_\mu \;+\; \sum_{q_i} \left(g_L^i\, \overline{q_L^i}\, \gamma^\mu\, q_L^i + g_R^i\, \overline{q_R^i}\, \gamma^\mu\, q_R^i \right) Z_\mu$$

e.g. $\overline{u}_L\, \gamma^\mu\, u_L \;\longrightarrow\; \overline{u}_L\, V_u^\dagger\, \gamma^\mu\, V_u\, u_L \;=\; \overline{u}_L\, \gamma^\mu\, u_L$ (and so on)

On the other hand, the *charged current* couplings of the quarks to the W boson are affected:

$$\mathcal{L} \supset \sum_{i} \frac{g}{\sqrt{2}}\, \overline{u_L^i}\, \gamma^\mu\, d_L^i\, W_\mu^+ \;+\; \text{h.c.} \;\longrightarrow\; \sum_{i,j} \frac{g}{\sqrt{2}}\, \overline{u_L^i}\, \gamma^\mu\, V_{ij}^{\rm CKM}\, d_L^j\, W_\mu^+ \;+\; \text{h.c.}$$

Therefore, charged interactions mix quarks of different flavor (neutral interactions don’t)

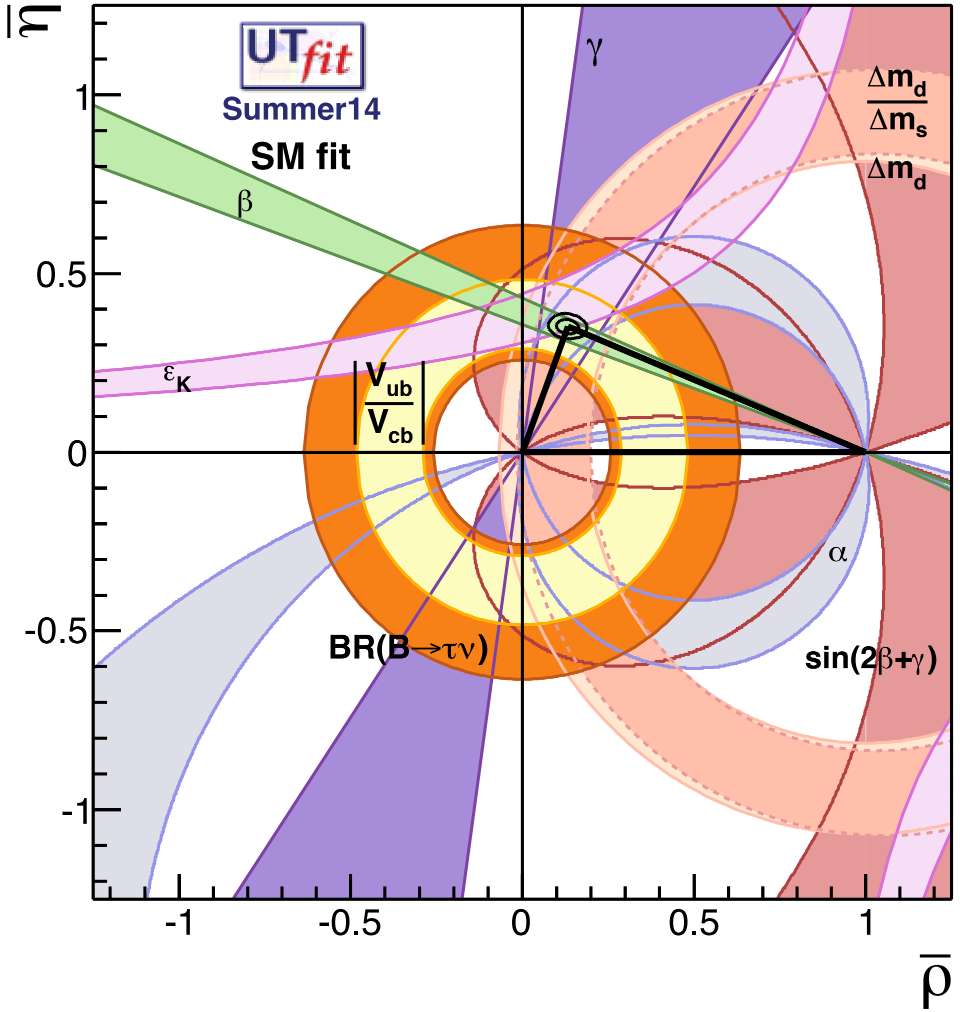
$V_{ij}^{\rm CKM} \;\equiv\; V_u^\dagger V_d$ is the so-called *Cabibbo-Kobayashi-Maskawa* matrix

The CKM matrix can be represented in terms of four independent parameters
(e.g., three independent rotation angles and one complex phase)

An alternative representation of the CKM matrix is the so-called “Wolfenstein parametrization”:

$$V^{\,\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

A large number of flavor-violating processes allow for the determination of the Wolfenstein parameters $\bar{\rho}$, $\bar{\eta}$



The good agreement between many different measurements provides a consistency check of the CKM picture

(plot from UTfit collaboration)

Among the SM leptons, there are no ν_R^i :

$$l_L^i \equiv \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix} \sim (1, 2, -1/2)\,,$$

$$e_R^i \sim (1, 1, -1)$$

The only gauge-invariant Yukawa interaction that we can build gives a mass term for charged leptons:

$$\mathcal{L}_Y = -(Y_E)_{ij}\, \overline{l_L^i}\, \Phi\, e_R^j \;+\; \mathrm{h.c.}$$

Again, we can diagonalize the Yukawa matrix with a bi-unitary transformation

$$\mathrm{diag}(Y_e, Y_\mu, Y_\tau) = V_e^\dagger\, Y_E\, U_e\;, \qquad m_l = \frac{Y_l\, v}{\sqrt{2}}$$

but now we are free to rotate the ν_L parallel to the e_L :

$$\nu_L \to V_e\, \nu_L\;,$$

$$e_L \to V_e\, e_L\;, \quad e_R \to U_e\, e_R$$

Therefore, the charged interaction does not mix leptons of different flavors:

$$\mathcal{L} \supset \sum_i \frac{g}{\sqrt{2}}\, \overline{\nu_L^i}\, \gamma^\mu\, e_L^i\, W_\mu^+ \;+\; \mathrm{h.c.} \;\longrightarrow\;$$ itself

Flavor oscillations in solar, atmospheric, and accelerator-produced neutrinos provide evidence of flavor mixing and (tiny) masses *(the first clear sign of Beyond-the-SM physics!!!)*

This can be fixed by introducing "sterile" right-handed neutrinos: $N_R^i \sim (1,1,0)$

Then, gauge symmetry allows for both a Yukawa interaction and a "Majorana" mass term:

$$\mathcal{L}_Y = -\left[(Y_E)_{ij}\, \overline{l_L^i}\, \Phi\, e_R^j + (Y_N)_{ij}\, \overline{l_L^i}\, \widetilde{\Phi}\, N_R^j + \text{h.c.}\right] - \frac{1}{2} M_{ij}\, \overline{N_R^i}\, N_R^j$$

After EWSB, the mass matrix for the neutrinos becomes (schematically):

$$\mathcal{L} \supset -\left(\overline{\nu_L} \;\; \overline{N_R}\right) \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

with $m_D = \dfrac{Y_N\, v}{\sqrt{2}}$

For $M >> m_D$, this gives both light, almost-left neutrinos and heavy, almost-right neutrinos:

$$m_\nu \approx \frac{m_D^2}{M}, \qquad m_N \approx M$$

(seesaw mechanism)

Introducing heavy sterile neutrinos does not affect SM phenomenology at the weak scale

Flavor oscillations in solar, atmospheric, and accelerator-produced neutrinos provide evidence of flavor mixing and (tiny) masses *(the first clear sign of Beyond-the-SM physics!!!)*

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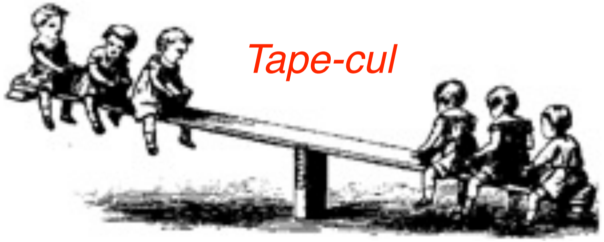

Introducing heavy sterile neutrinos does not affect SM phenomenology at the weak scale

Constraints on non-minimal Higgs sectors

A single SU(2) doublet is the minimal option. Several scalars could contribute to EWSB

However, constraints from precision observables, e.g.:

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \approx 1$$

The contribution to the rho parameter from a given Higgs field depends on its SU(2) properties:

$$\mathcal{L} \supset \frac{1}{2} m_W^2 \left(W^{1\mu} W_\mu^1 + W^{2\mu} W_\mu^2 \right) + \frac{1}{2} \left(W_3^\mu \; B^\mu \right) \begin{bmatrix} M^2 & M'^2 \\ M'^2 & M''^2 \end{bmatrix} \begin{pmatrix} W_{3\mu} \\ B_\mu \end{pmatrix}$$

$$m_\gamma = 0 \quad \longrightarrow \quad \tan\theta_W = \frac{M''}{M} \, , \quad m_Z^2 = M^2 + M''^2 \quad \longrightarrow \quad \rho = \frac{m_W^2}{M^2}$$

For a set of Higgs fields Φ_i :

$$\rho = \frac{\sum_i v_i^2 \left[I_i \left(I_i + 1 \right) - (I_{3i})^2 \right]}{2 \sum_i v_i^2 \, (I_{3i})^2}$$

Doublets are OK. Other SU(2) representations would change rho (*then v_i must be small!*)

The simplest non-minimal case: two-Higgs-doublet model

$$
\begin{aligned}
V \;=\;& m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 \;+\; \text{h.c.}\right] \\
&+\frac{\lambda_1}{2}\,(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}\,(\Phi_2^\dagger\Phi_2)^2 + \lambda_3\,(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4\,(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
&+\left\{\frac{\lambda_5}{2}\,(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6\,(\Phi_1^\dagger\Phi_1) + \lambda_7\,(\Phi_2^\dagger\Phi_2)\right]\,(\Phi_1^\dagger\Phi_2) \;+\; \text{h.c.}\right\}
\end{aligned}
$$

Two complex SU(2) doublets
=> 8 degrees of freedom:

$$\Phi_i = \begin{pmatrix} \varphi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \varphi_i^R + i\,\varphi_i^I) \end{pmatrix}$$

After EWSB:

5 physical states (3 neutral, 2 charged $H^\pm$)
and 3 would-be-Goldstone bosons ($G^0\,,G^\pm$)

If the potential does not break CP, the neutral states
are one pseudoscalar A and two scalars ($h\,,H$)

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \varphi_1^R \\ \varphi_2^R \end{pmatrix}$$

Generating particle masses in many-Higgs-doublet models

The gauge-boson masses receive a contribution from each Higgs vev

$$m_W^2 \;=\; \frac{g^2}{4}\sum_i v_i^2\,, \qquad\qquad m_Z^2 \;=\; \frac{g^2+g'^{\,2}}{4}\sum_i v_i^2$$

Also, each Higgs doublet has its own set of matrices for the couplings to the fermions:

$$-\mathcal{L}_Y \;=\; \sum_i \bar{q}_L\,\widetilde{\Phi}_i\,y_i^U u_R \;+\; \sum_i \bar{q}_L\,\Phi_i\,y_i^D d_R\;, \qquad M^{U,D} = \sum_i y_i^{U,D}\,v_i$$

Rotating the fields to a basis where one Higgs ($\Phi_{\rm SM}$) gets the vev and the others (Φ_i) don't

$$-\mathcal{L}_Y \;=\; \bar{q}_L\,\widetilde{\Phi}_{\rm SM}\,Y^U u_R \;+\; \bar{q}_L\,\Phi_{\rm SM}\,Y^D d_R \;+\; \sum_i \bar{q}_L\,\widetilde{\Phi}_i\,y_i^U u_R \;+\; \sum_i \bar{q}_L\,\Phi_i\,y_i^D d_R$$

In general, the matrices $y_i^{U,D}$ are not diagonal in the basis where $Y^{U,D}$ are diagonal

→ The non-SM doublets mediate Flavor-Changing Neutral Currents!!!

Natural Flavor Conservation:

FCNC in Higgs-quark interactions are *absent* when only one doublet couples to each species of quarks

e.g., in THDMs:

$$-\mathcal{L}_Y = \bar{q}_L \, \widetilde{\Phi}_1 \, Y^U u_R + \bar{q}_L \, \Phi_1 \, Y^D d_R \qquad \text{(Type I)}$$

$$-\mathcal{L}_Y = \bar{q}_L \, \widetilde{\Phi}_2 \, Y^U u_R + \bar{q}_L \, \Phi_1 \, Y^D d_R \qquad \text{(Type II)}$$

Minimal Flavor Violation:

FCNC can be *suppressed* if the matrices of non-SM Higgs couplings are made up of combinations of Y^U and Y^D

$$y_i^U = A_u^i \left(1 + \epsilon_u \, Y^U Y^{U\,\dagger} + \ldots\right) Y^U \,, \qquad y_i^D = A_d^i \left(1 + \epsilon_d \, Y^U Y^{U\,\dagger} + \ldots\right) Y^D$$

Only *two* sets of *SU(3)xSU(2)xU(1)* quantum numbers are allowed for an additional scalar whose Yukawa couplings transform like Y^U and Y^D under rotations in flavor space

(1,2)$_{1/2}$ The usual THDMs

(8,2)$_{1/2}$ The additional scalar is a color octet *(Manohar & Wise, hep-ph/0606172)*

So far, no additional Higgs bosons did show up at colliders

(nor did they manifest through contributions to flavor or EW observables)

Natural Flavor Conservation: FCNC in Higgs-quark interactions are *absent* when only one doublet couples to each species of quarks

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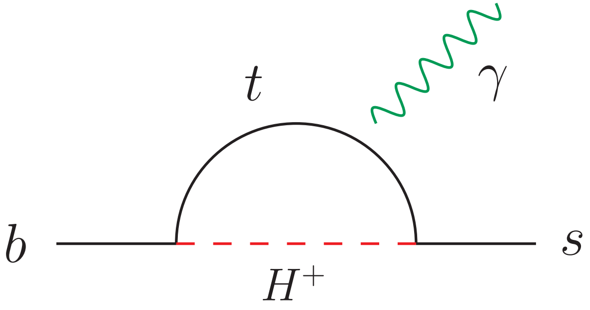
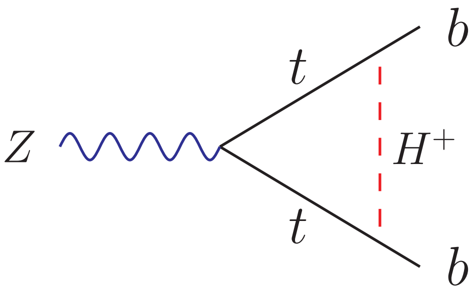
$$-\mathcal{L}_Y \;=\; \bar{q}_L\,\widetilde{\Phi}_1\,Y^U u_R \;+\; \bar{q}_L\,\Phi_1\,Y^D d_R \qquad \text{(Type I)}$$

$$-\mathcal{L}_Y \;=\; \bar{q}_L\,\widetilde{\Phi}_2\,Y^U u_R \;+\; \bar{q}_L\,\Phi_1\,Y^D d_R \qquad \text{(Type II)}$$

Minimal Flavor Violation: FCNC can be *suppressed* if the matrices of non-SM Higgs couplings are made up of combinations of Y^U and Y^D

$$y_i^U = A_u^i\,\left(1+\epsilon_u\,Y^U Y^{U\,\dagger}+\ldots\right)\,Y^U\;, \qquad y_i^D = A_d^i\,\left(1+\epsilon_d\,Y^U Y^{U\,\dagger}+\ldots\right)\,Y^D$$



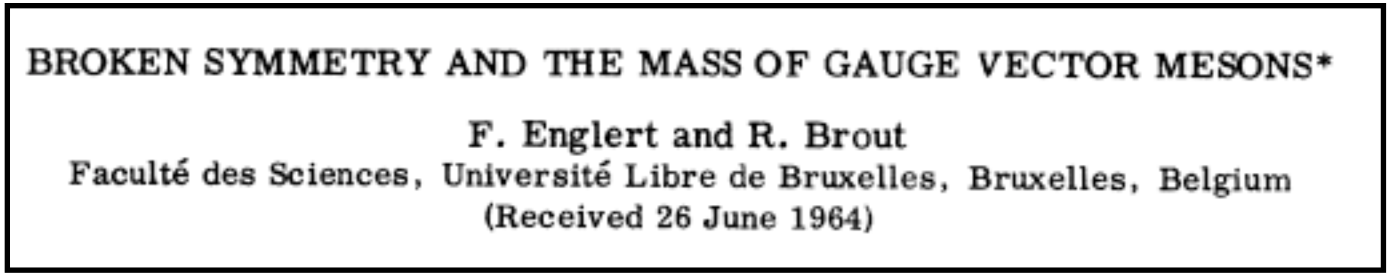


So far, no additional Higgs bosons did show up at colliders

(nor did they manifest through contributions to flavor or EW observables)

Interlude: who ordered this particle?

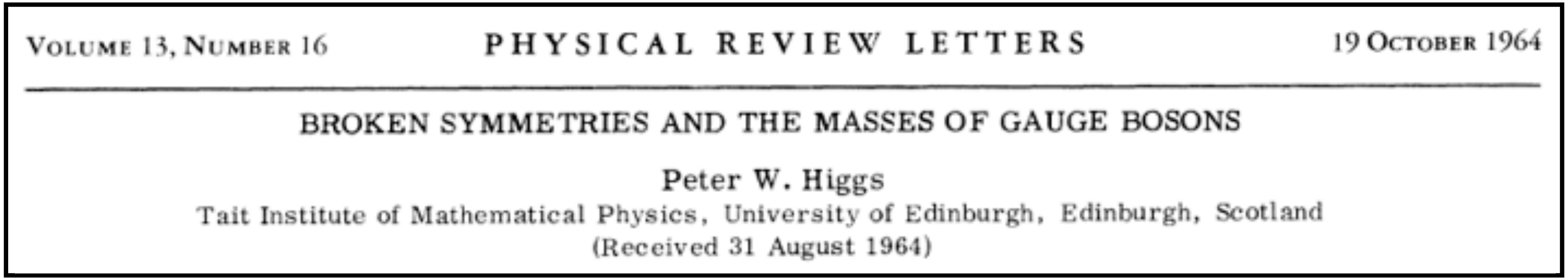
Three PRL papers in 1964 described the mechanism that gives mass to gauge bosons:



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

(does not mention
a physical scalar)

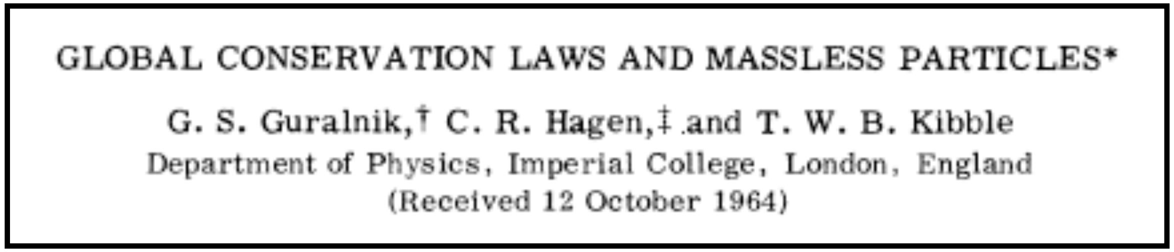


VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

(cites BE , mentions a massive scalar as an essential feature of the mechanism)



GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

(cites BE and H, mentions a scalar
which is *massless and decoupled*)

Then Weinberg (1967) and Salam (1968) incorporated the mechanism in the EW theory and ‘t Hooft (1971) proved that spontaneously broken gauge theories are renormalizable

"Nobelitis"

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comments on this story

Stories by subject

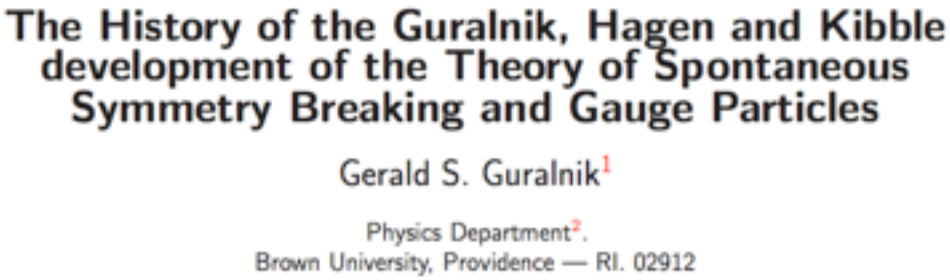
- Physics
- Lab life

Published online 4 August 2010 | Nature | doi:10.1038/news.2010.390

News

Physicists get political over Higgs

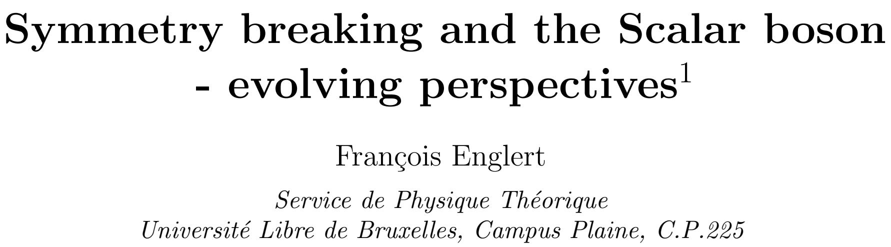
A storm is brewing round the scientists in line to win the Nobel prize for predicting the elusive particle.



The History of the Guralnik, Hagen and Kibble development of the Theory of Spontaneous Symmetry Breaking and Gauge Particles

Gerald S. Guralnik[1]

Physics Department[2],
Brown University, Providence — RI. 02912



Symmetry breaking and the Scalar boson - evolving perspectives[1]

François Englert

Service de Physique Théorique
Université Libre de Bruxelles, Campus Plaine, C.P.225

Rencontres de Moriond EW 2012

chaired by Lydia Iconomidou-Fayard (LAL), Jean Marie Frere (ULB Brussels)

from dimanche 4 mars 2012 at **08:30** to samedi 10 mars 2012 at **12:00** (Europe/Paris)

09:00 **The Search for the BroutEnglertHiggs Boson New Results from the DØ Experiment** *20'*

Speaker: Joseph Haley (Princeton University)

Material: Slides

09:25 **The Search For The BroutEnglertHiggs Boson With Up To 10/fb With CDF** *15'*

Speaker: Dr. Homer Wolfe (The Ohio State University)

Material: Slides

09:45 **Seeking the BroutEnglertHiggs Boson New Results from Tevatron Experiments** *15'*

Speaker: Wade Fisher

Material: Slides

Five authors alive,
only three Nobel slots...

The ending was unexciting...

The Nobel Prize in Physics 2013

Photo: A. Mahmoud

François Englert

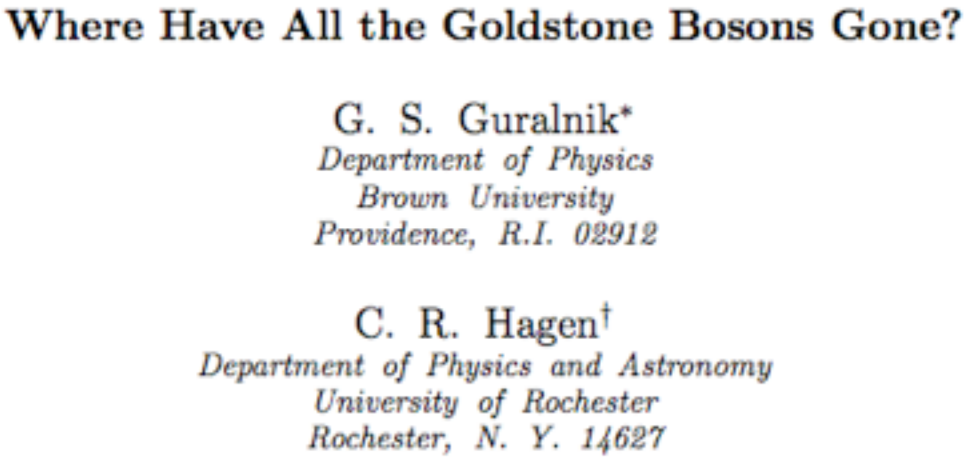
Prize share: 1/2

Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

...but some people just wouldn't let go:



Where Have All the Goldstone Bosons Gone?

G. S. Guralnik*
Department of Physics
Brown University
Providence, R.I. 02912

C. R. Hagen†
Department of Physics and Astronomy
University of Rochester
Rochester, N. Y. 14627

[arXiv:1401.6924]

"(...) the Nobel Committee [5] stated 'The Goldstone theorem holds in the sense that that Nambu-Goldstone mode is there but it gets absorbed into the third component of a massive vector field.' (...) It is shown in what follows that that is not a valid view and that a massless gauge particle necessarily remains in the theory."

II) The hunt for the Higgs boson

The main contenders:

- Large Electron-Positron Collider (LEP) at CERN (1989-2000):

  circular e^+e^- collider, center-of-mass energy up to 209 GeV;

- Tevatron at Fermilab (1983-2012):

  circular $p\bar{p}$ collider, c.o.m. energy up to 2 TeV;

- Large Hadron Collider (LHC) at CERN (2011-2012, 2015-?):

  circular pp collider, c.o.m. energy up to 8 TeV (designed for 14 TeV).

Higgs boson couplings to the other SM particles

The interaction Lagrangian contains *(v + H)*, thus *HPP* couplings are controlled by *m*

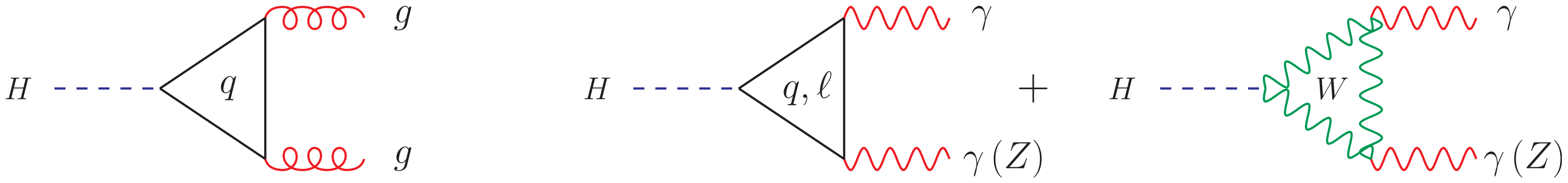
Feynman rules:

$$H\,\bar{f}f\;:\;i\,\frac{m_f}{v}\,,\qquad H\,W_\mu^+W_\nu^-\;:\;2\,i\,\frac{m_W^2}{v}\,g^{\mu\nu}\,,\qquad H\,Z_\mu Z_\nu\;:\;2\,i\,\frac{m_Z^2}{v}\,g^{\mu\nu}\,,$$

$$H\,H\,W_\mu^+W_\nu^-\;:\;2\,i\,\frac{m_W^2}{v^2}\,g^{\mu\nu}\,,\qquad H\,H\,Z_\mu Z_\nu\;:\;2\,i\,\frac{m_Z^2}{v^2}\,g^{\mu\nu}$$

(among fermions, only top, bottom and tau have sizable couplings to the Higgs)

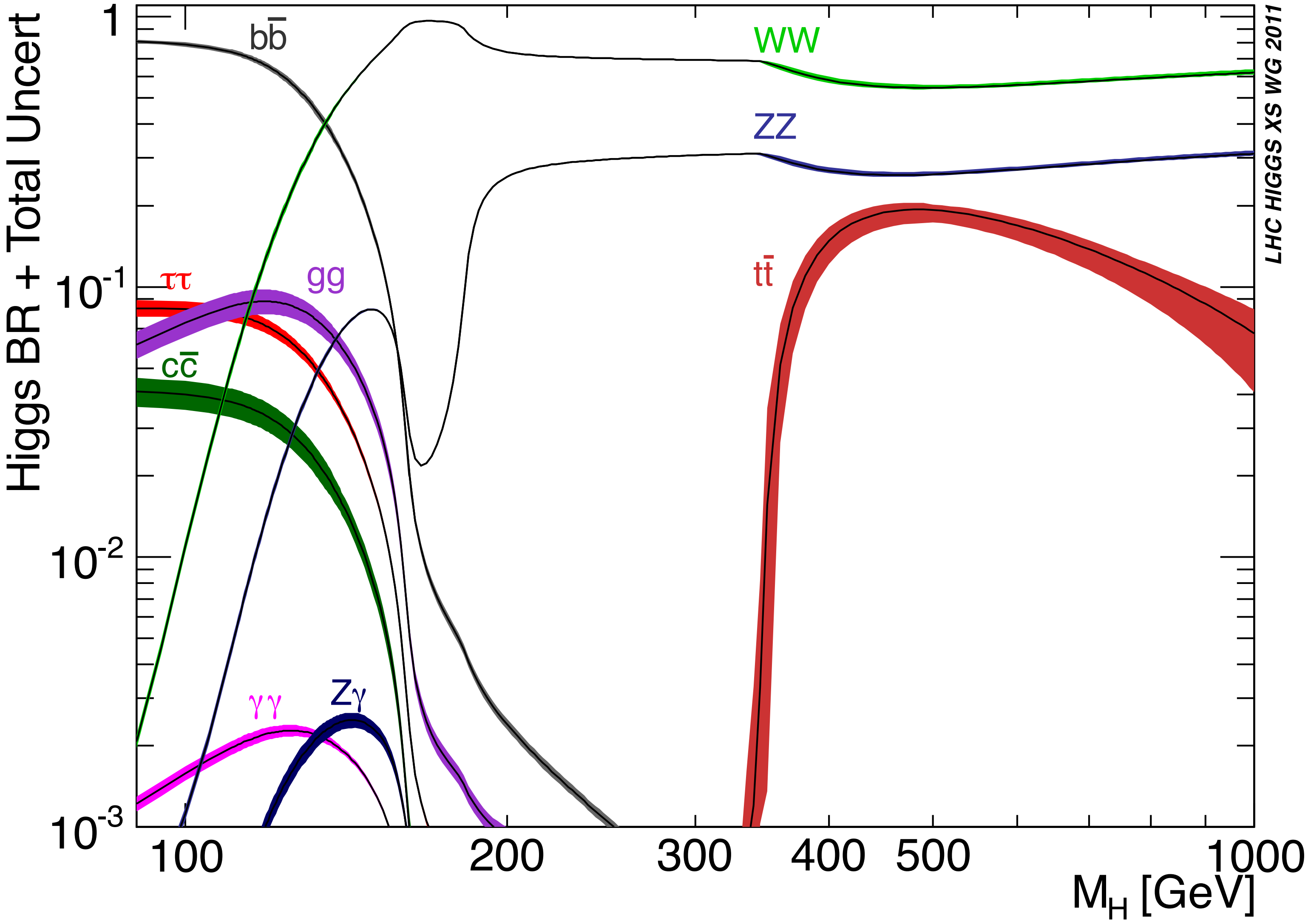
Loops of charged particles also induce Higgs-boson couplings to gluons and photons:



$$\mathcal{L}\;\supset\;-\;C_g\,\frac{\alpha_s}{8\,\pi\,v}\,H\,G^{a\,\mu\nu}G^a_{\mu\nu}\;-\;C_\gamma\,\frac{\alpha}{8\,\pi\,v}\,H\,A^{\mu\nu}A_{\mu\nu}\;-\;C_{\gamma Z}\,\frac{\alpha}{8\,\pi\,v}\,H\,A^{\mu\nu}Z_{\mu\nu}$$

(in practice, only the top, bottom and *W* contributions to the loops are relevant)

The decay rates of the Higgs boson depend only on its mass (the couplings are all fixed)



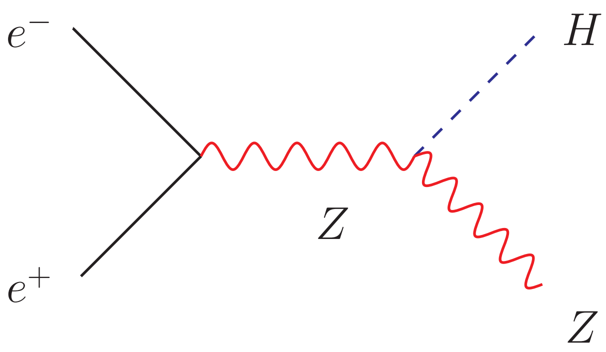
Decays to bottom quarks dominate at low mass, then *WW* (and *ZZ*) for $m_H > 140$ GeV

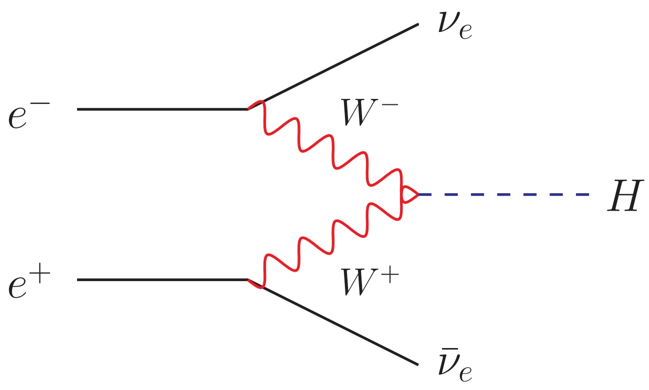
Decays to two photons are loop-suppressed but easy to detect

LEP & Tevatron corner it

Higgs boson production at e^+e^- colliders

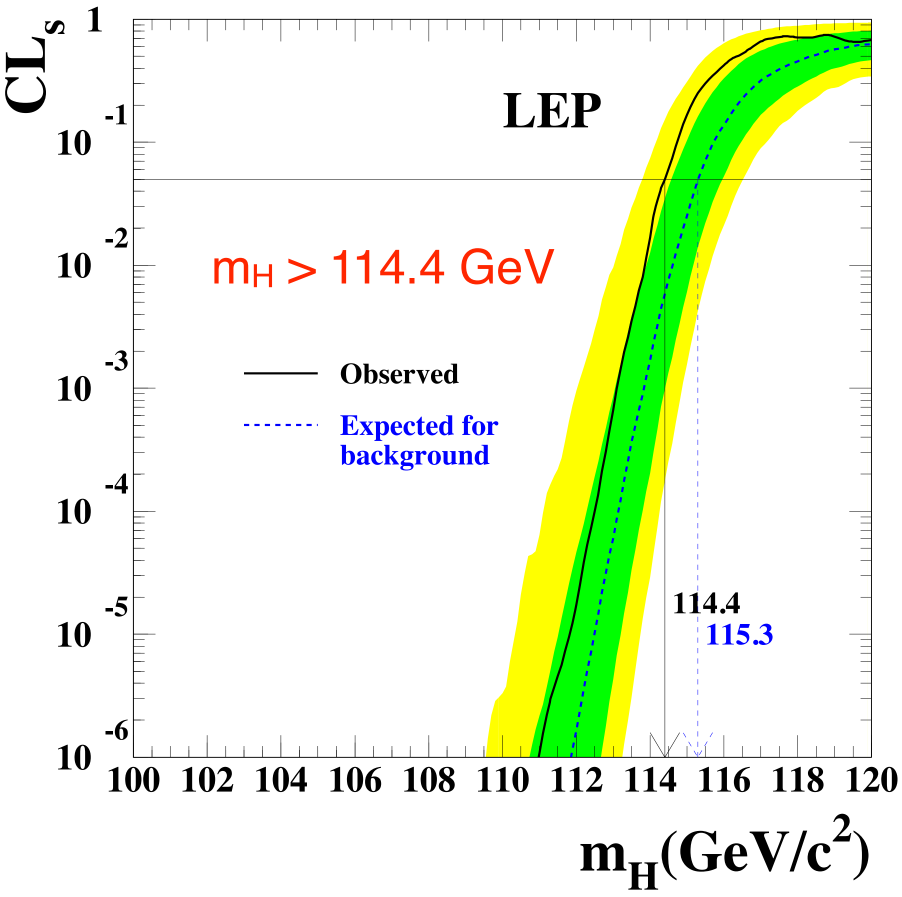
The dominant processes are Higgs-strahlung and *WW* fusion:



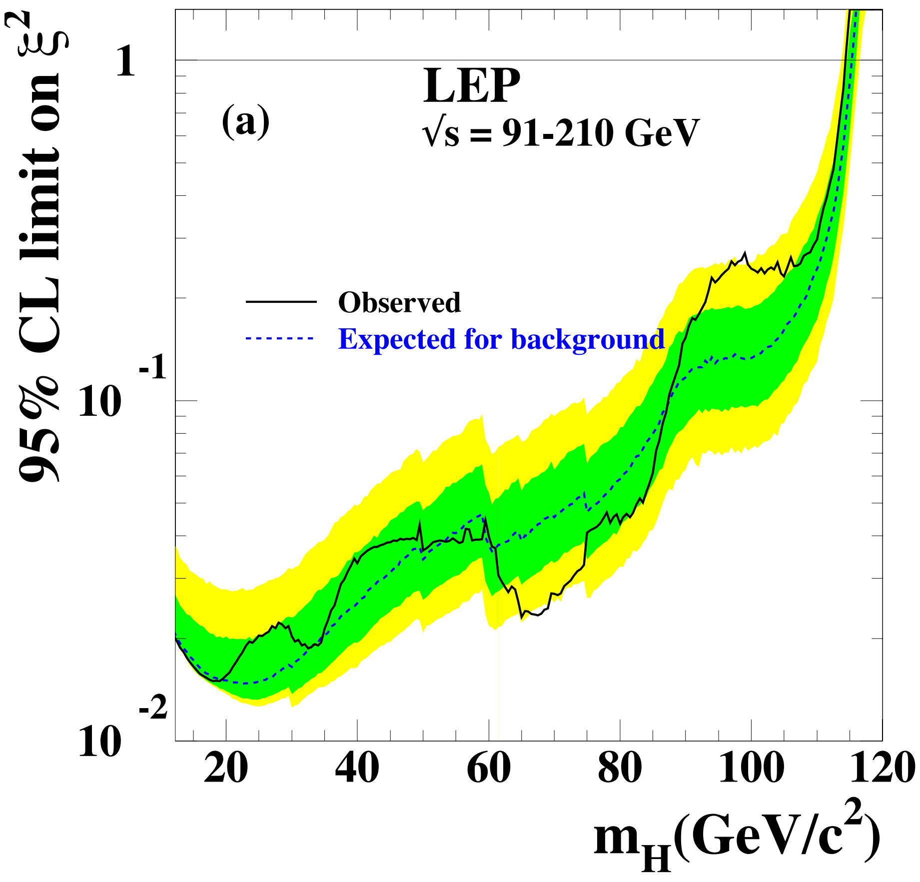


- ✓ Well-defined energy and momentum in the initial state
- ✓ “Clean” experimental environment (no QCD background)
- ✓ Allows for precision studies of the Higgs boson properties (couplings, spin, parity...)
- – The cross section is small and it decreases with energy, high luminosity required
- – Synchrotron radiation makes circular machines unpractical above LEP2 energy
- ✦ The International Linear Collider (~500 GeV) could be the next Higgs factory

At LEP, the dominant channel was Higgs-strahlung followed by decay in bottom or tau pairs

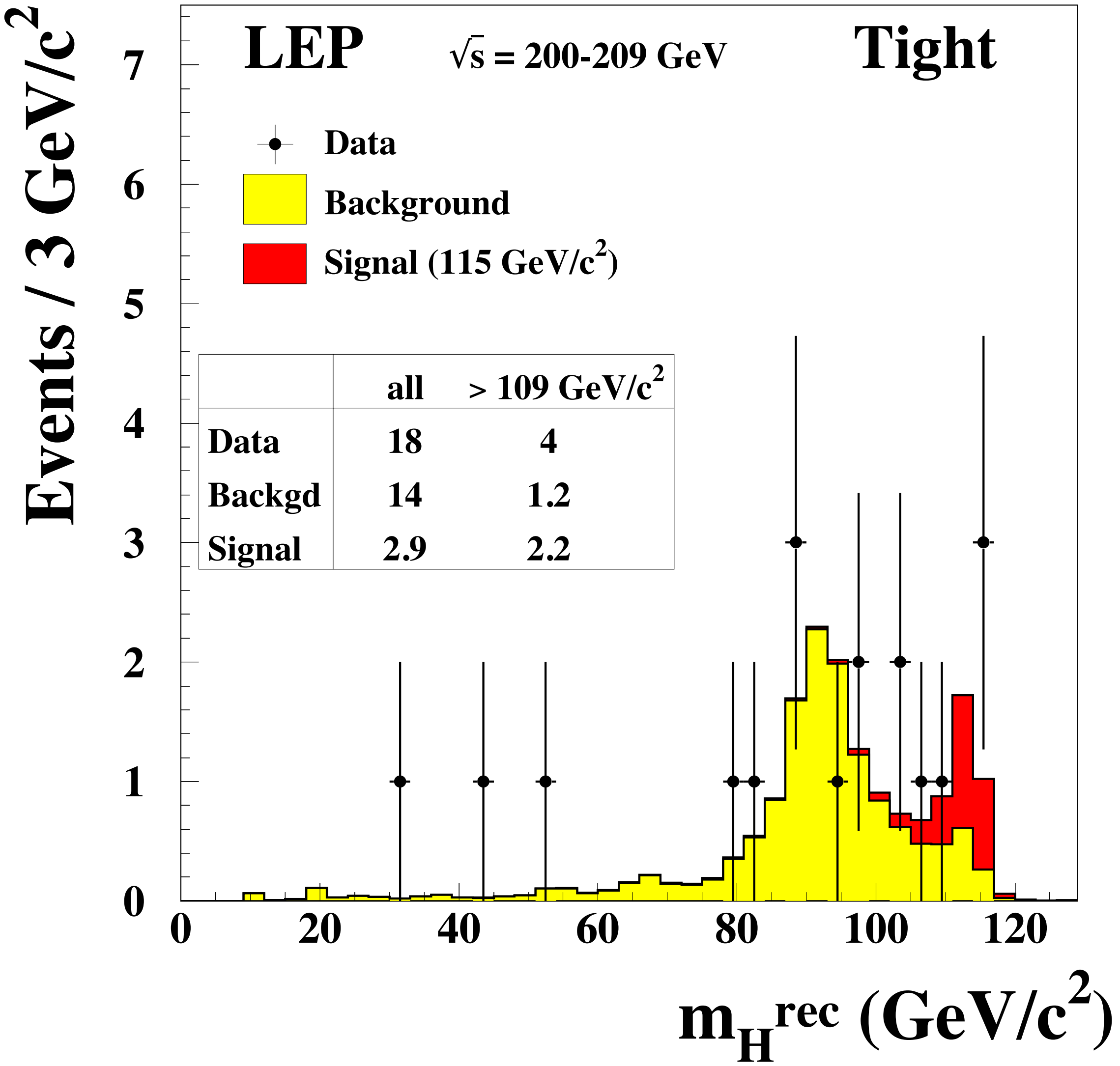


($CL_s = CL_{s+b} / CL_b$)



$\xi^2 = (g_{HZZ}/g_{HZZ}^{SM})^2$

LEP's parting shot: $\sim 1.7\sigma$ excess for $m_H \approx 115$ GeV

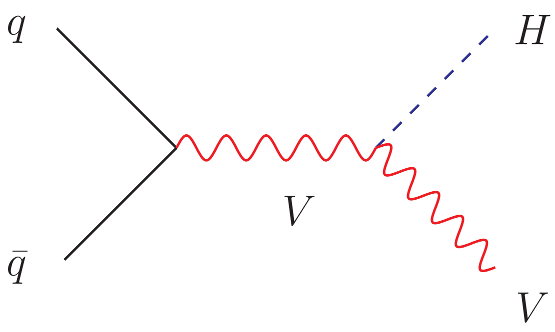


	all	> 109 GeV/c^2
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

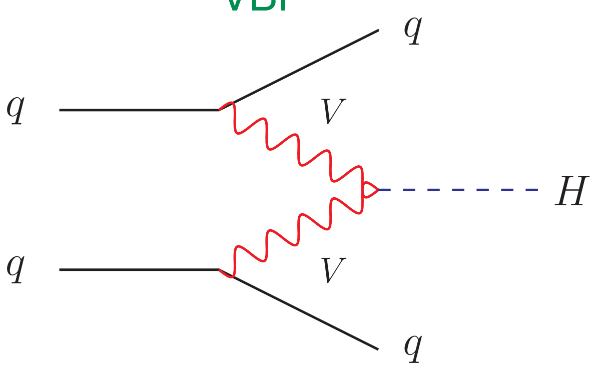
Was it the real thing? People kept arguing about it until the start of the LHC...

Higgs boson production at hadron colliders

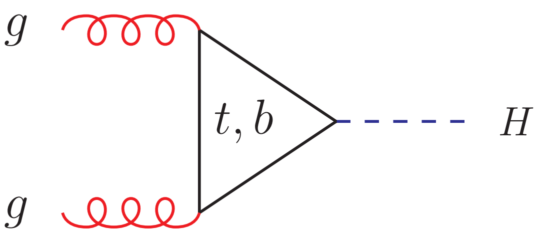
Higgs-strahlung



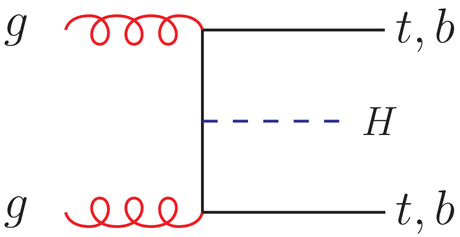
VBF



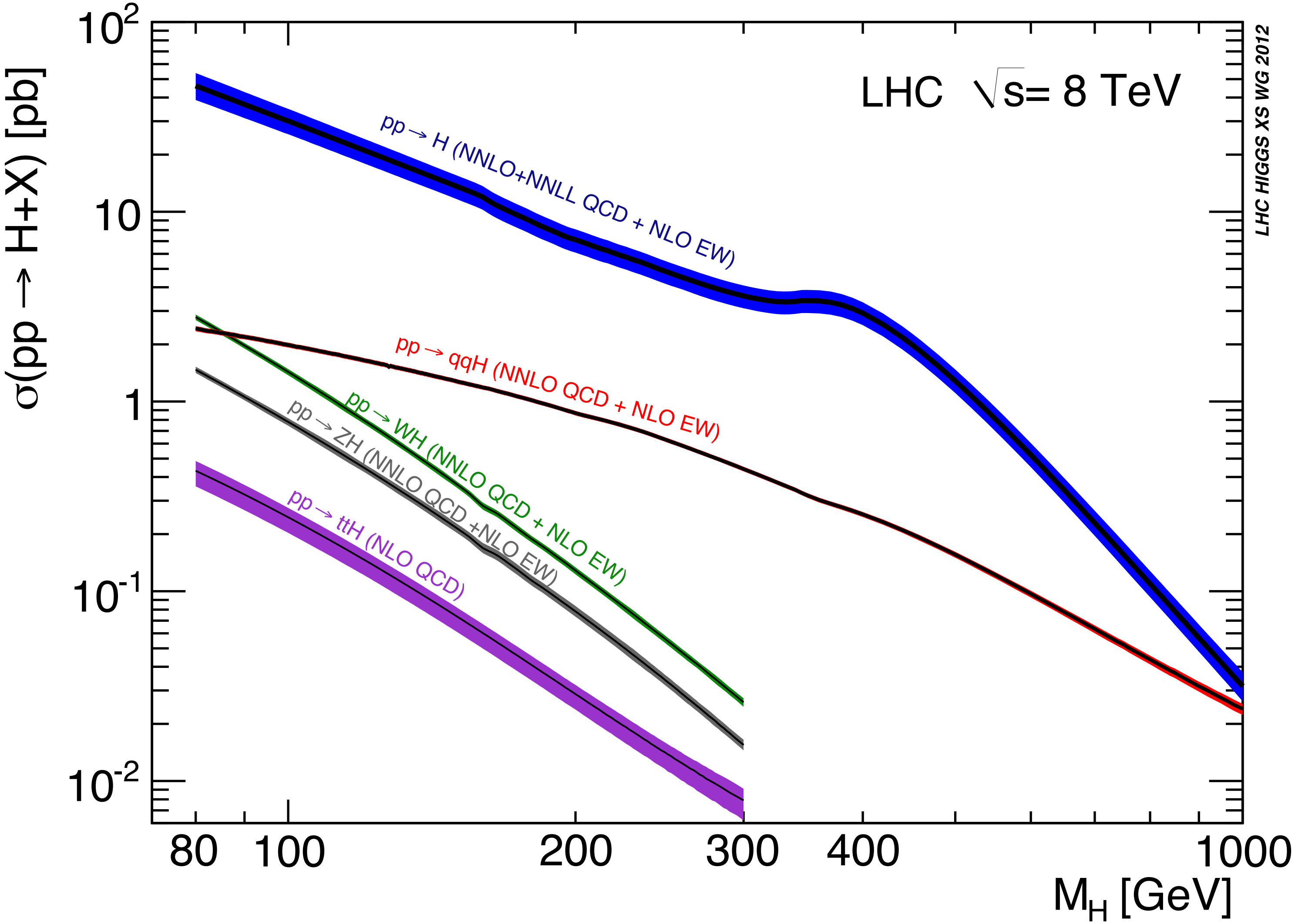
gluon fusion



associated prod. with top/bottom

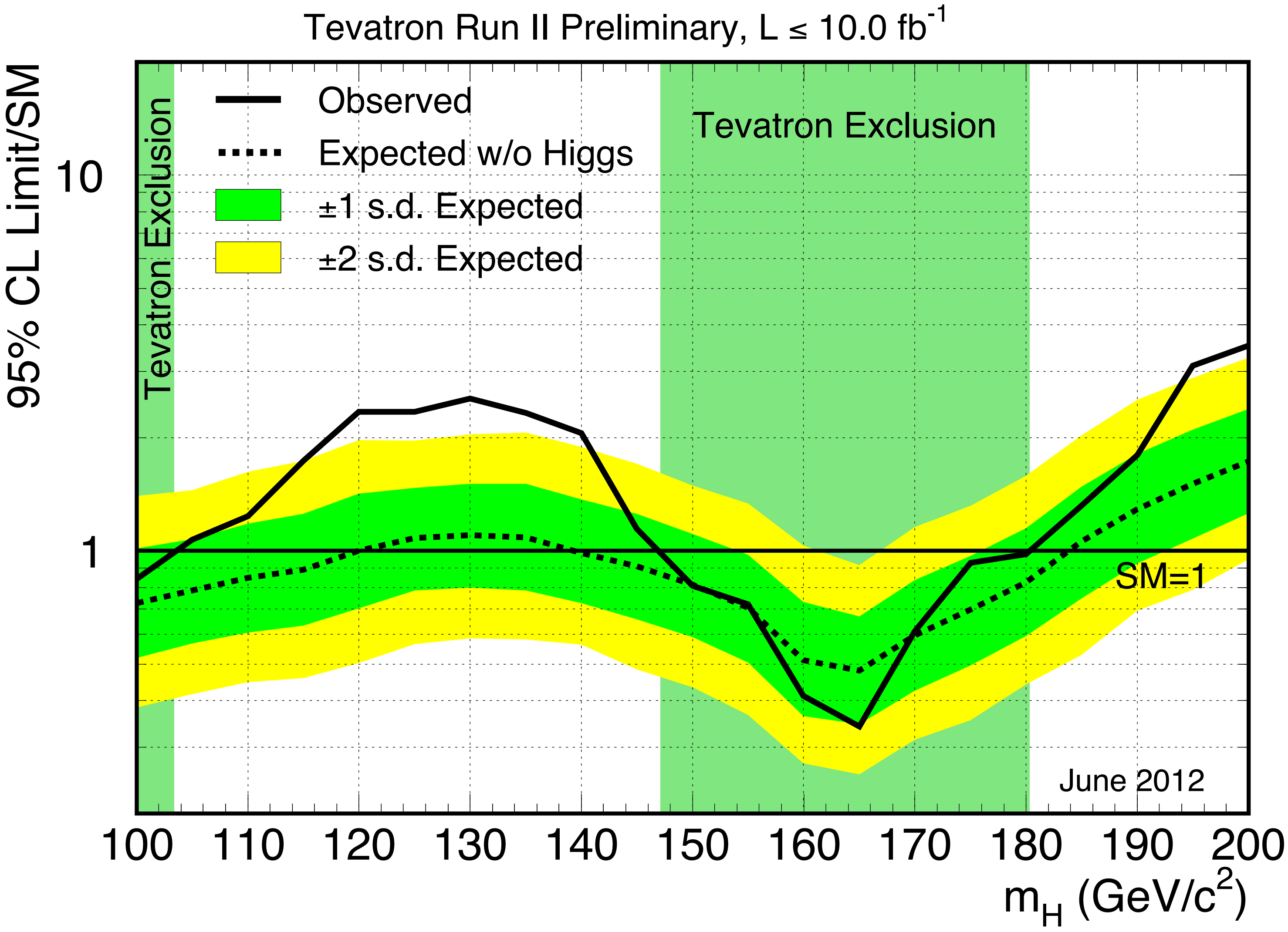


- ✓ Synchrotron radiation negligible: high energies viable with circular machines
- ✓ Colored particles in initial state: large cross section due to the strong interaction
- – Energy and momentum of the initial-state partons not known event-by-event (PDFs)
- – Large QCD backgrounds, “messy” experimental environment



- Gluon fusion is the dominant production mechanism both at the Tevatron and the LHC
- VBF is the second-largest mechanism and can be easily separated from the background
- Higgs-strahlung is the main channel for light Higgs at the Tevatron
- Associated Higgs production with a top pair is rare and has difficult backgrounds

Tevatron experiments did their best, but it wasn't enough



Excluded at 95% CL: 147 GeV < m_H < 180 GeV

Broad excess (mostly from bb) for 115 GeV < m_H < 140 GeV

Constraints on the Higgs mass from EW precision observables

An exercise: let’s start from a set of well-measured electroweak *(pseudo)*-observables

- fine-structure constant (from Thomson scattering)	$\alpha = 1/137.03599911(46)$
- Fermi coupling constant (from muon decay)	$G_F = 1.16637(1) \times 10^{-5}\,\mathrm{GeV}^{-2}$
- Z-boson mass (from LEP data)	$m_Z = 91.1876(21)\ \mathrm{GeV}$
- leptonic width of the Z (from LEP data)	$\Gamma_{\ell^+\ell^-} = 83.984(86)\ \mathrm{MeV}$
- W-boson mass (from LEP+Tevatron data)	$m_W = 80.385(15)\ \mathrm{GeV}$
- effective leptonic Weinberg angle (from LEP+SLC data)	$s^2_{\mathrm{eff}} = 0.23153(16)$

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \equiv \frac{(1/2 - s^2_{\mathrm{eff}})^2 - s^4_{\mathrm{eff}}}{(1/2 - s^2_{\mathrm{eff}})^2 + s^4_{\mathrm{eff}}}$$

At tree level, all of the observables can be expressed in terms of *three* parameters of the SM Lagrangian: $v,\ g,\ g'$ or, equivalently, $v,\ e,\ s \equiv \sin\theta_W$ (also $c \equiv \cos\theta_W$)

$$\alpha = \frac{e^2}{4\pi}, \qquad G_F = \frac{1}{2\sqrt{2}v^2}, \qquad m_Z = \frac{e\,v}{\sqrt{2}sc}, \qquad m_W = \frac{e\,v}{\sqrt{2}s}, \qquad s^2_{\rm eff} = s^2,$$

$$\Gamma_{\ell^+\ell^-} = \frac{v}{48\sqrt{2}\pi}\,\frac{e^3}{s^3c^3}\left[\left(-\frac{1}{2}+2\,s^2\right)^2+\frac{1}{4}\right]$$

Is this consistent with the experimental data? To check, we compute the three Lagrangian parameters in terms of the best-measured observables $\alpha,\ G_F,\ m_Z$

$$e^2 = 4\pi\alpha\,, \qquad v^2 = \frac{1}{2\sqrt{2}G_F}\,, \qquad s^2 = \frac{1}{2} - \frac{1}{2}\sqrt{1-\frac{2\sqrt{2}\pi\alpha}{G_F m_Z^2}}$$

and we plug the resulting values of $v,\ e,\ s$ in the expressions for $m_W,\ s^2_{\rm eff},\ \Gamma_{\ell^+\ell^-}$

	tree-level predictions	*experimental values*
m_W	$= 80.939$ GeV	80.385 ± 0.015 GeV
$s^2_{\rm eff}$	$= 0.21215$	0.23153 ± 0.00016
$\Gamma_{\ell^+\ell^-}$	$= 80.842$ MeV	83.984 ± 0.086 MeV

Off by many standard deviations!!!

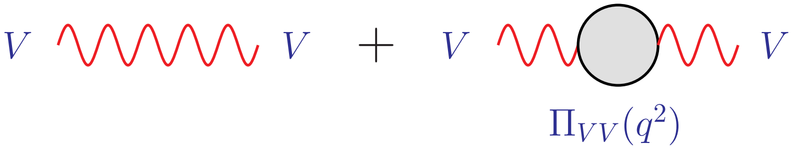
What happened? We tried to use the SM relations at tree level to predict some observables in terms of other observables, and we failed badly

→ Obviously the tree level is not good enough!

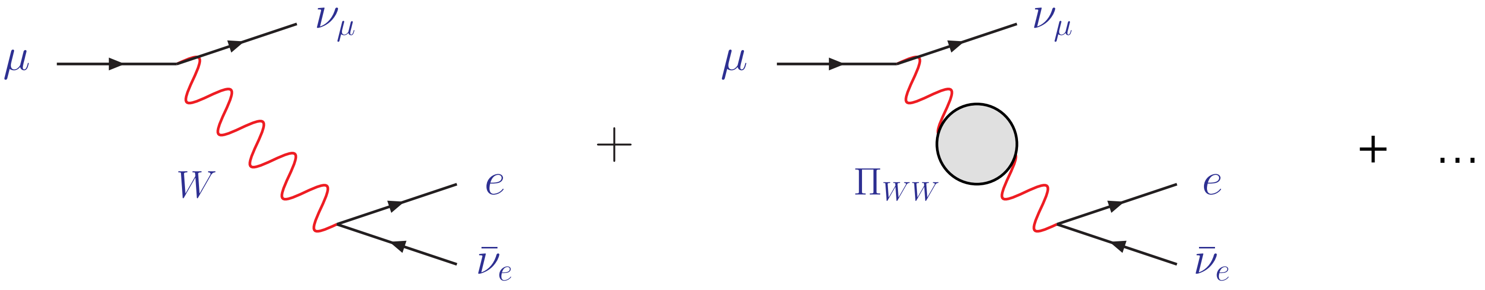
Radiative corrections to the relations between physical observables and Lagrangian params:

$$m_Z^2 = \frac{e^2 v^2}{2\, s^2 c^2} + \Pi_{ZZ}(m_Z^2)$$

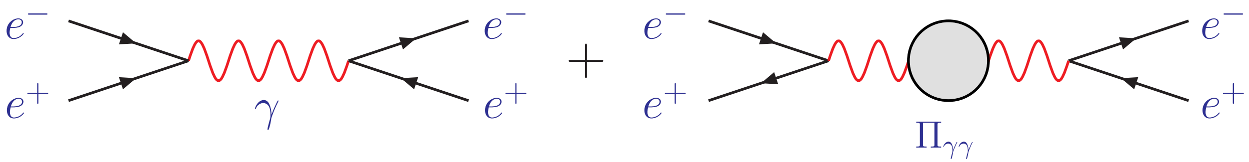
$$m_W^2 = \frac{e^2 v^2}{2\, s^2} + \Pi_{WW}(m_W^2)$$



$$G_F = \frac{1}{2\sqrt{2} v^2}\left[1 - \frac{\Pi_{WW}(0)}{m_W^2} + \delta_{\rm VB}\right]$$



$$\alpha = \frac{e^2}{4\,\pi}\left[1 + \lim_{q^2->0}\frac{\Pi_{\gamma\gamma}(q^2)}{q^2}\right]$$



this one is tricky: the hadronic contribution to $\Pi'_{\gamma\gamma}(0)$ cannot be computed perturbatively

We can however trade it for another experimental observable: $R_{\text{had}}(q^2) = \dfrac{\sigma_{\text{had}}(q^2)}{\sigma_{\ell^+\ell^-}(q^2)}$

$$\alpha(m_Z) = \frac{e^2}{4\pi}\left[1 + \frac{\Pi_{\gamma\gamma}(m_Z)}{m_Z}\right] = \frac{\alpha}{1 - \Delta\alpha(m_Z)}$$

$$\Delta\alpha(m_Z) = \underbrace{\Delta\alpha_\ell(m_Z) + \Delta\alpha_{\text{top}}(m_Z)}_{\text{calculable}} + \Delta\alpha^{(5)}_{\text{had}}(m_Z)$$

$$\Delta\alpha^{(5)}_{\text{had}}(m_Z) = -\frac{m_Z^2}{3\pi}\int_{4m_\pi^2}^{\infty}\frac{R_{\text{had}}(q^2)\text{d}q^2}{q^2\,(q^2 - m_Z^2)} \;=\; 0.02758 \pm 0.00035$$

(This hadronic contribution is one of the biggest sources of uncertainty in EW studies)

All these corrections can be combined into relations among physical observables, e.g.:

$$m_W^2 = m_Z^2 \left[\frac{1}{2} + \frac{1}{2} \sqrt{1 - \frac{2\sqrt{2}\,\pi\alpha}{G_F\, m_Z^2}\ (1 + \Delta r)} \right]$$

Δr can be parameterized in terms of two universal corrections and a remainder:

$$\Delta r \ = \ \Delta\alpha(m_Z) \ - \ \frac{c^2}{s^2}\,\Delta\rho \ + \ \Delta r_{\rm rem}$$

The leading corrections depend quadratically on m_t but only logarithmically on m_H :

$$\Delta\rho \ = \ \frac{\Pi_{ZZ}(0)}{m_Z^2} - \frac{\Pi_{WW}(0)}{m_W^2} \ \approx \ \frac{3\,\alpha}{16\pi c^2} \left(\frac{m_t^2}{s^2 m_Z^2} \ + \ \log\frac{m_H^2}{m_W^2} \ + \ \ldots \right)$$

$$\frac{\delta m_W^2}{m_W^2} \ \approx \ \frac{c^2}{c^2 - s^2}\,\Delta\rho \ , \qquad \delta\,\sin^2\theta_{\rm eff} \ \approx \ - \frac{c^2\,s^2}{c^2 - s^2}\,\Delta\,\rho$$

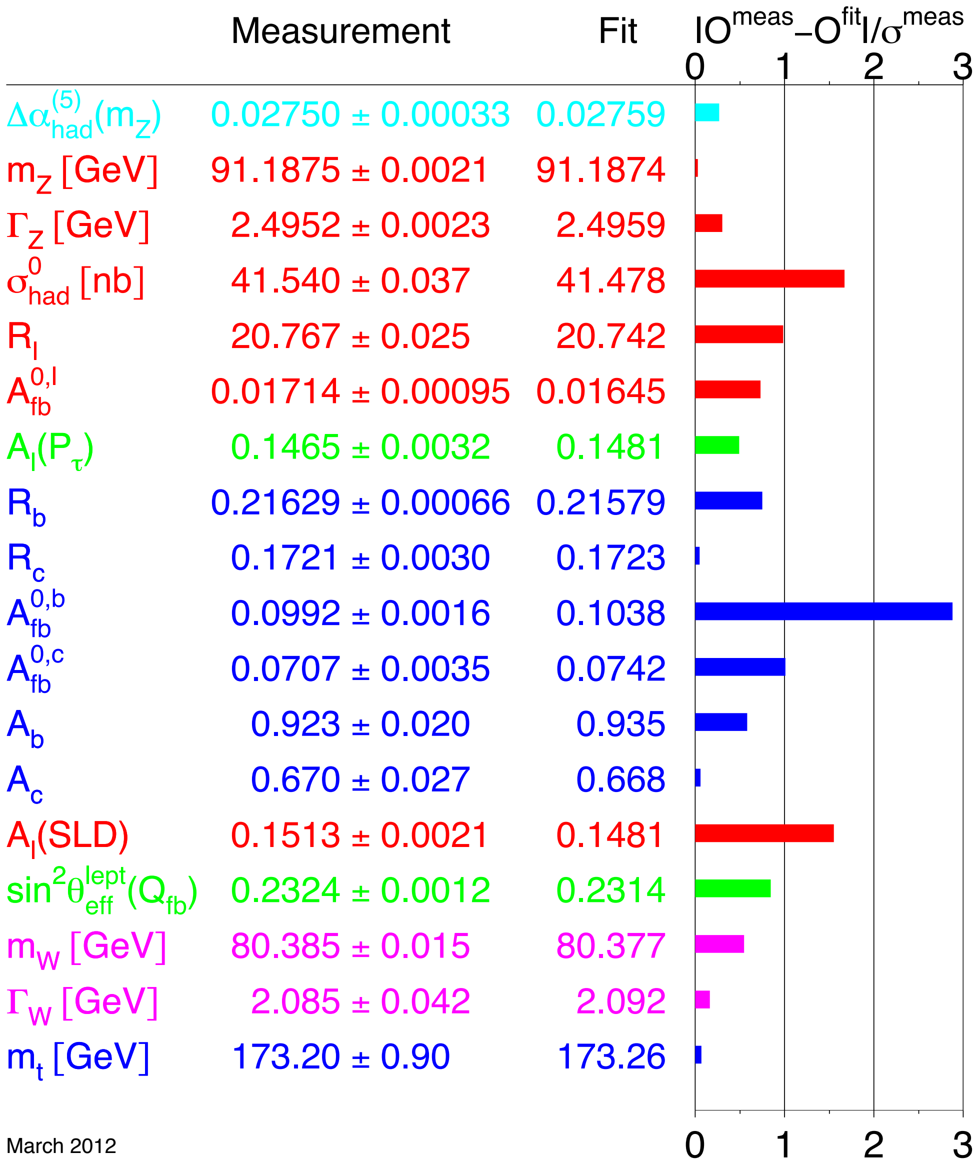
In the SM the predictions for m_W and $\sin^2\theta_{\rm eff}$ have been fully computed at the two-loop order, plus some leading (top/strong) corrections at three and four loops

The radiative corrections bring along a dependence of the experimental observables on all the parameters of the SM Lagrangian

It is no longer possible to invert analytically the relations between observables and Lagrangian parameters. But we can still perform a statistical analysis:

- compute radiative corrections to all of the SM observables
- fit the experimental data and determine the most likely set of Lagrangian parameters
- compute predictions for all the observables in terms of the "best fit" Lagrangian
- compare the predictions with the experimental data and see if they are all consistent

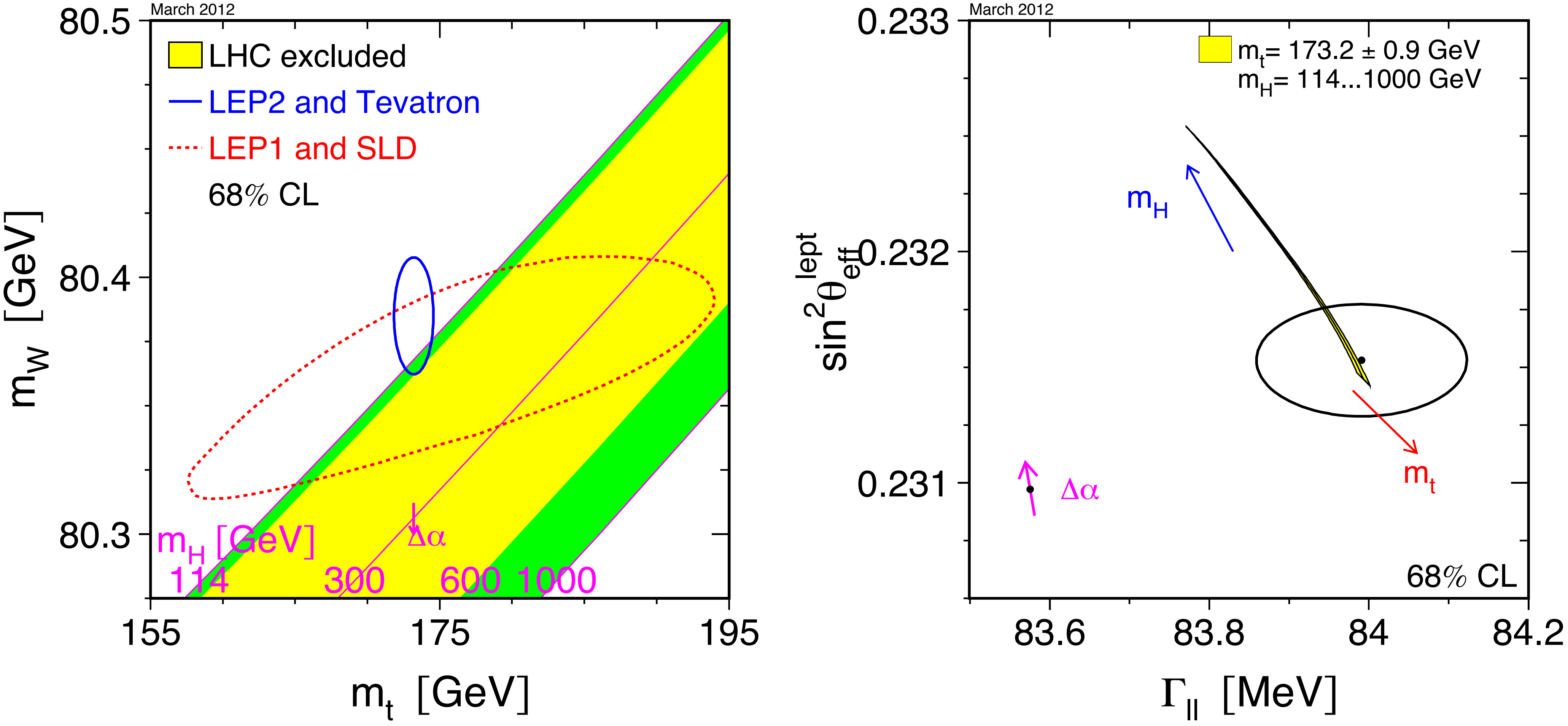
(LEP/TEV EWWG, 2012)



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

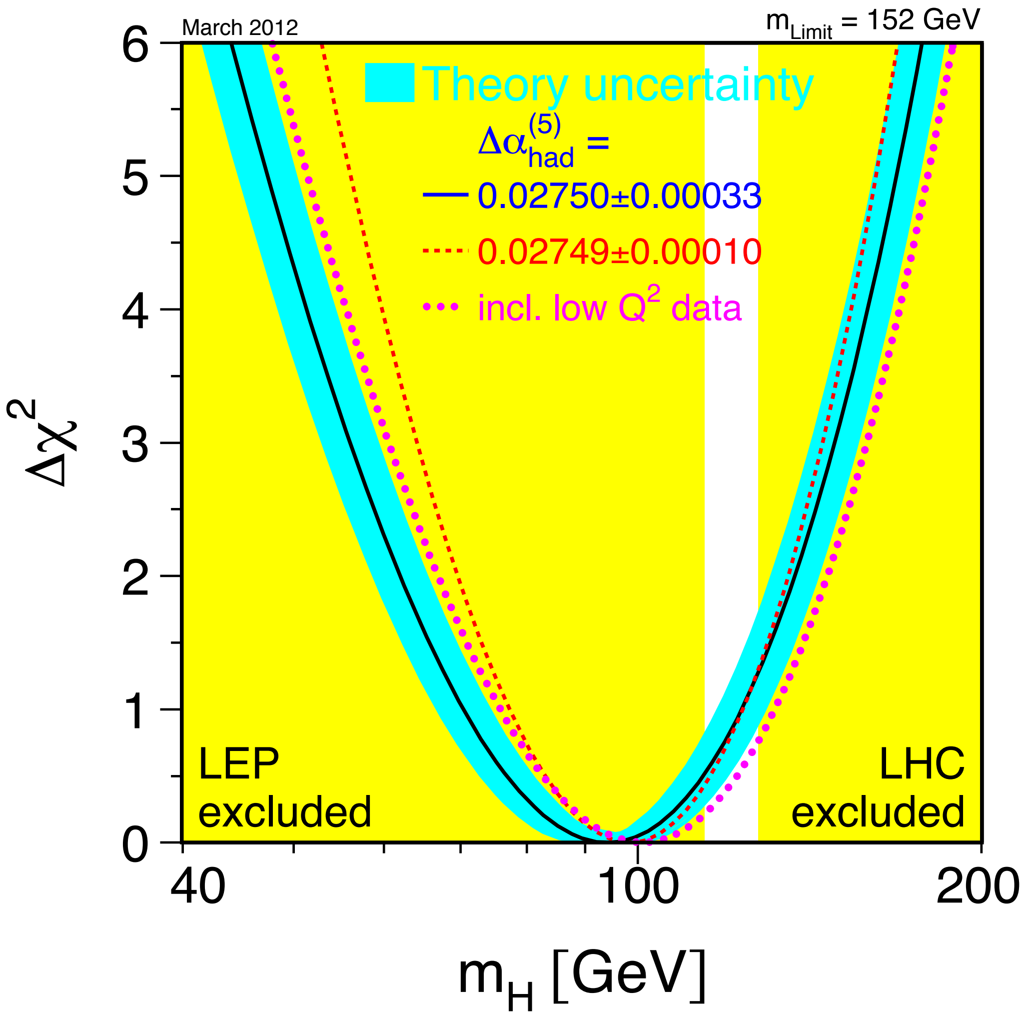
March 2012

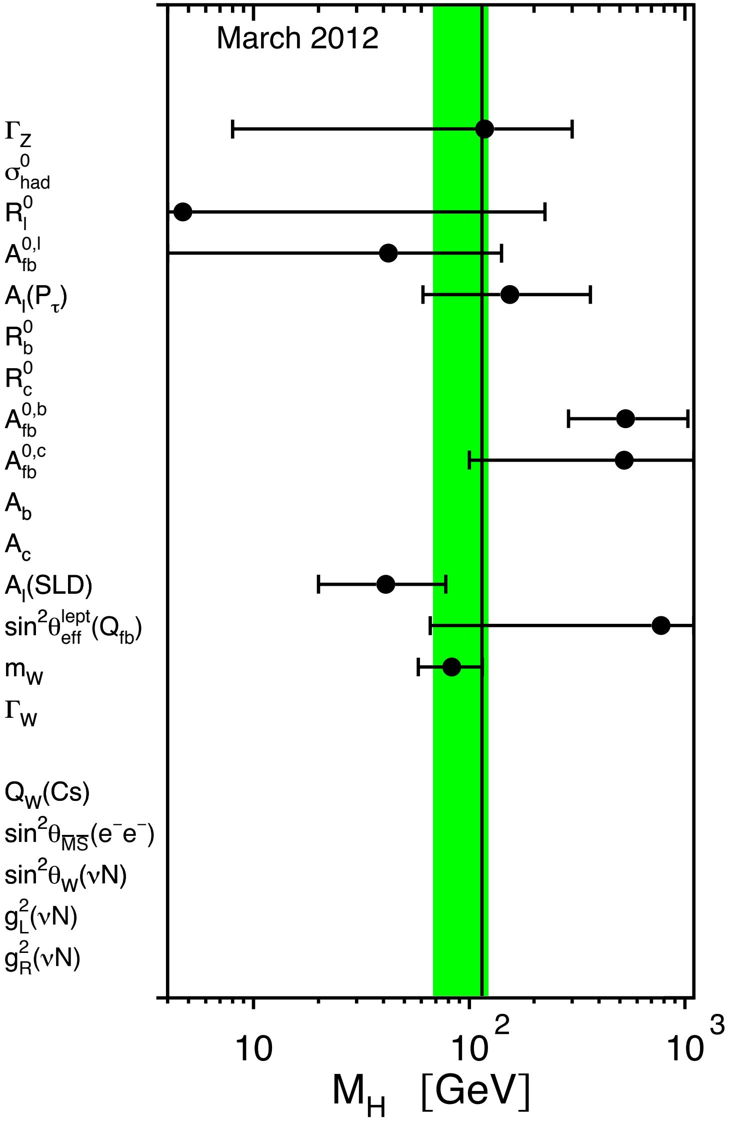
Comparing predictions and experiment (LEP/TEV EWWG 2012)



(the LEP/Tevatron results favor a light Higgs boson)

Constraining the SM Higgs mass (LEP/TEV EWWG 2012)

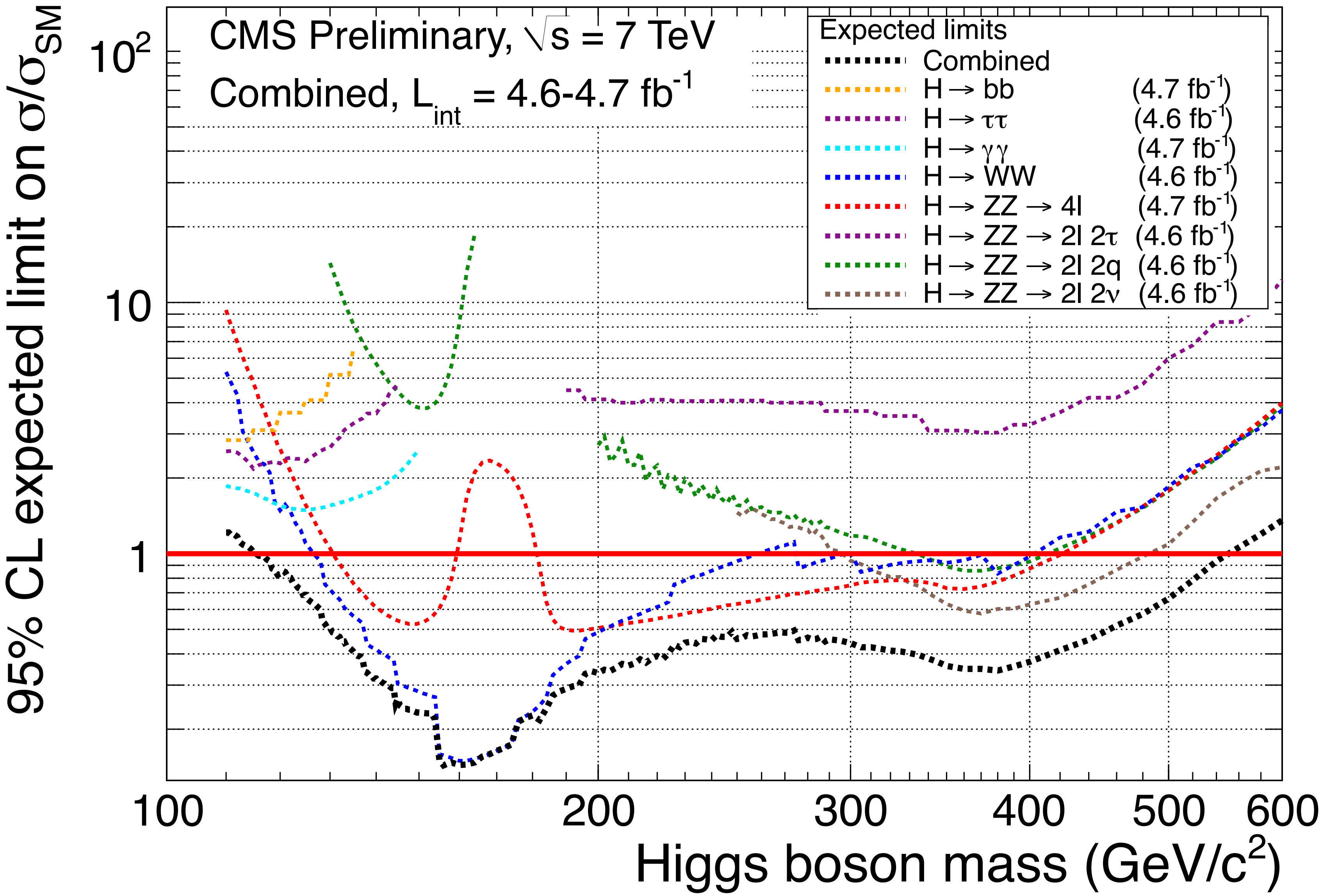




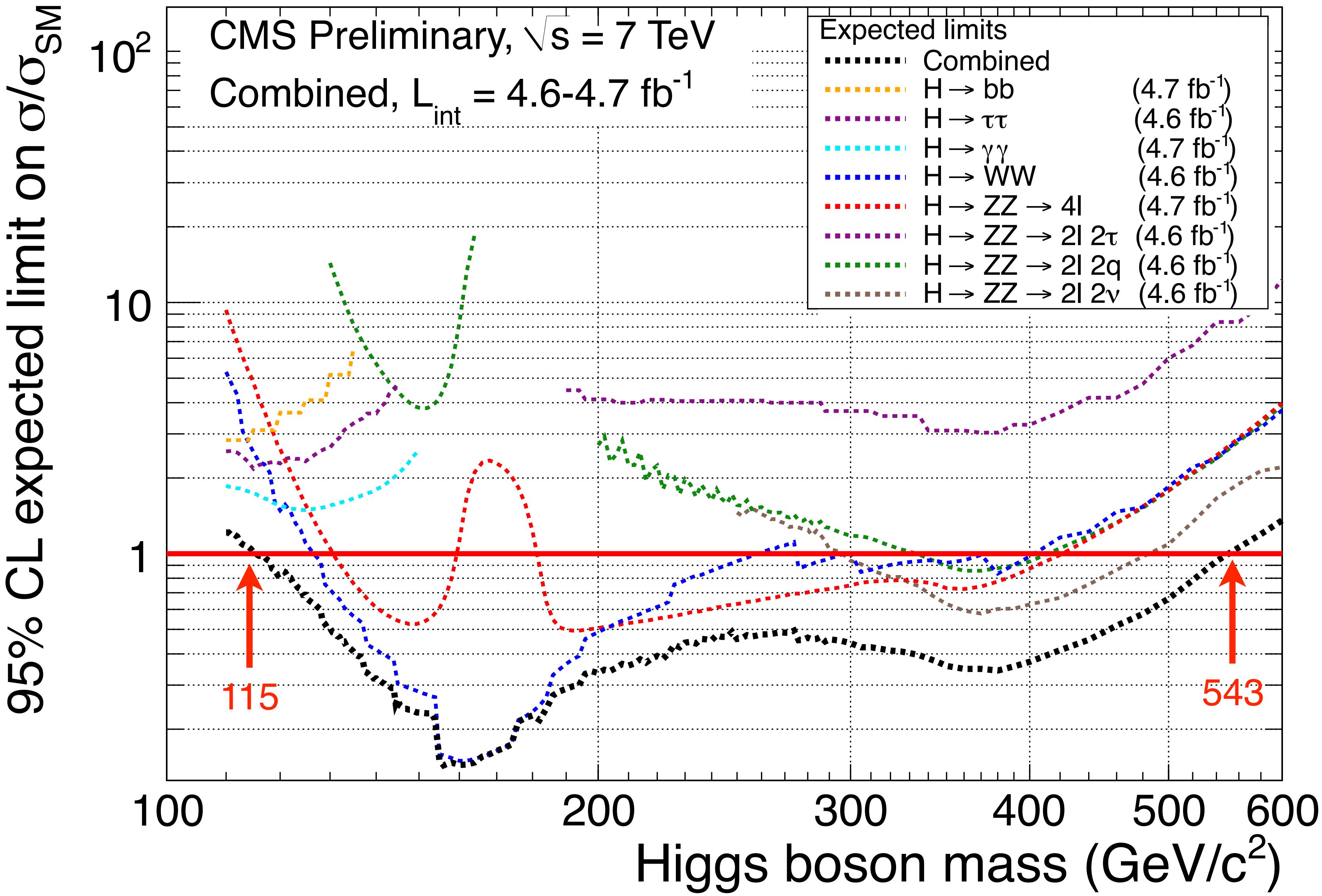
In March 2012, consistency of the SM required $m_H < 152$ GeV at 95% C.L.

The LHC nails it

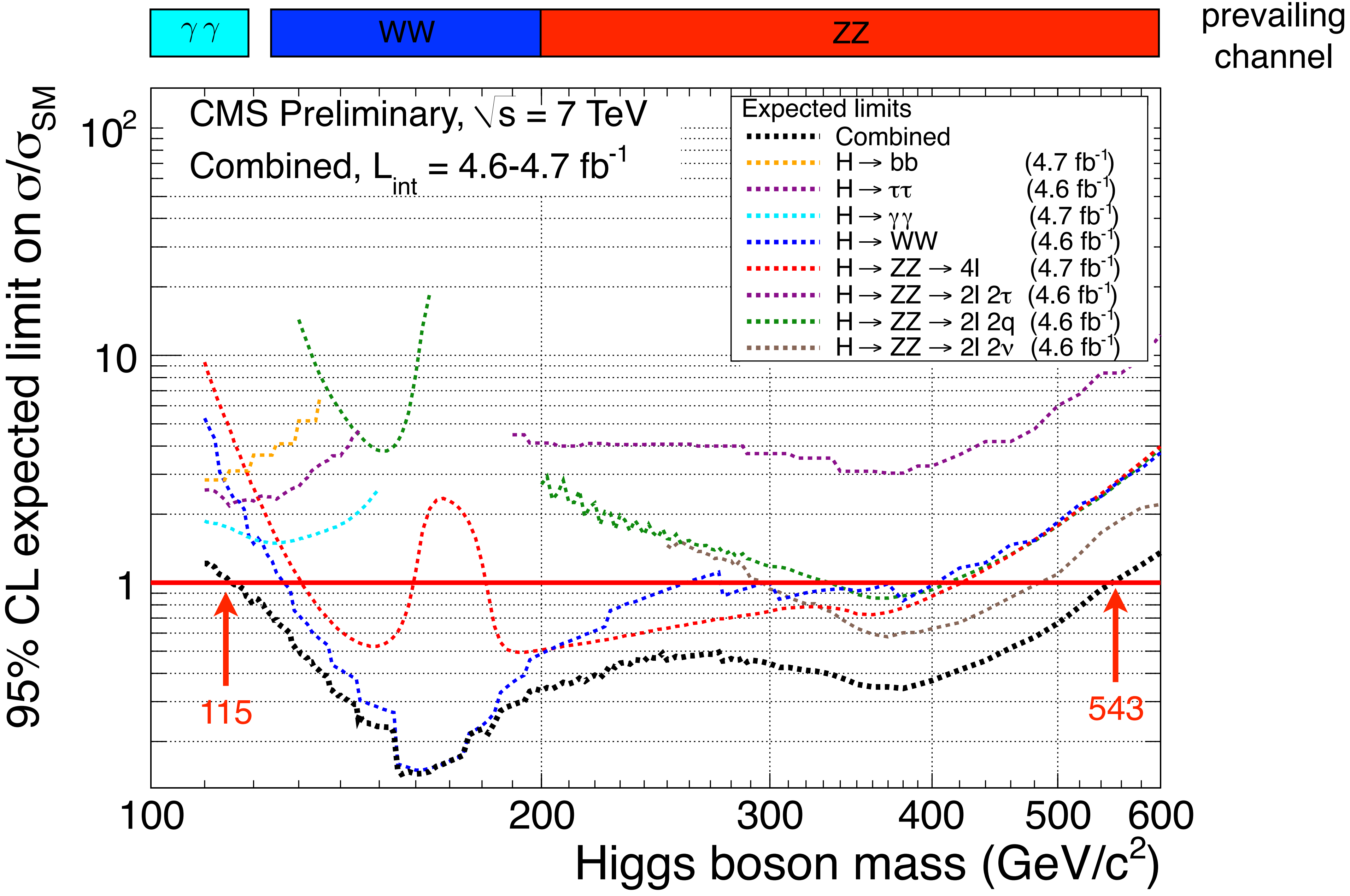
Sensitivity to individual search channels in the 2011 LHC data



Sensitivity to individual search channels in the 2011 LHC data



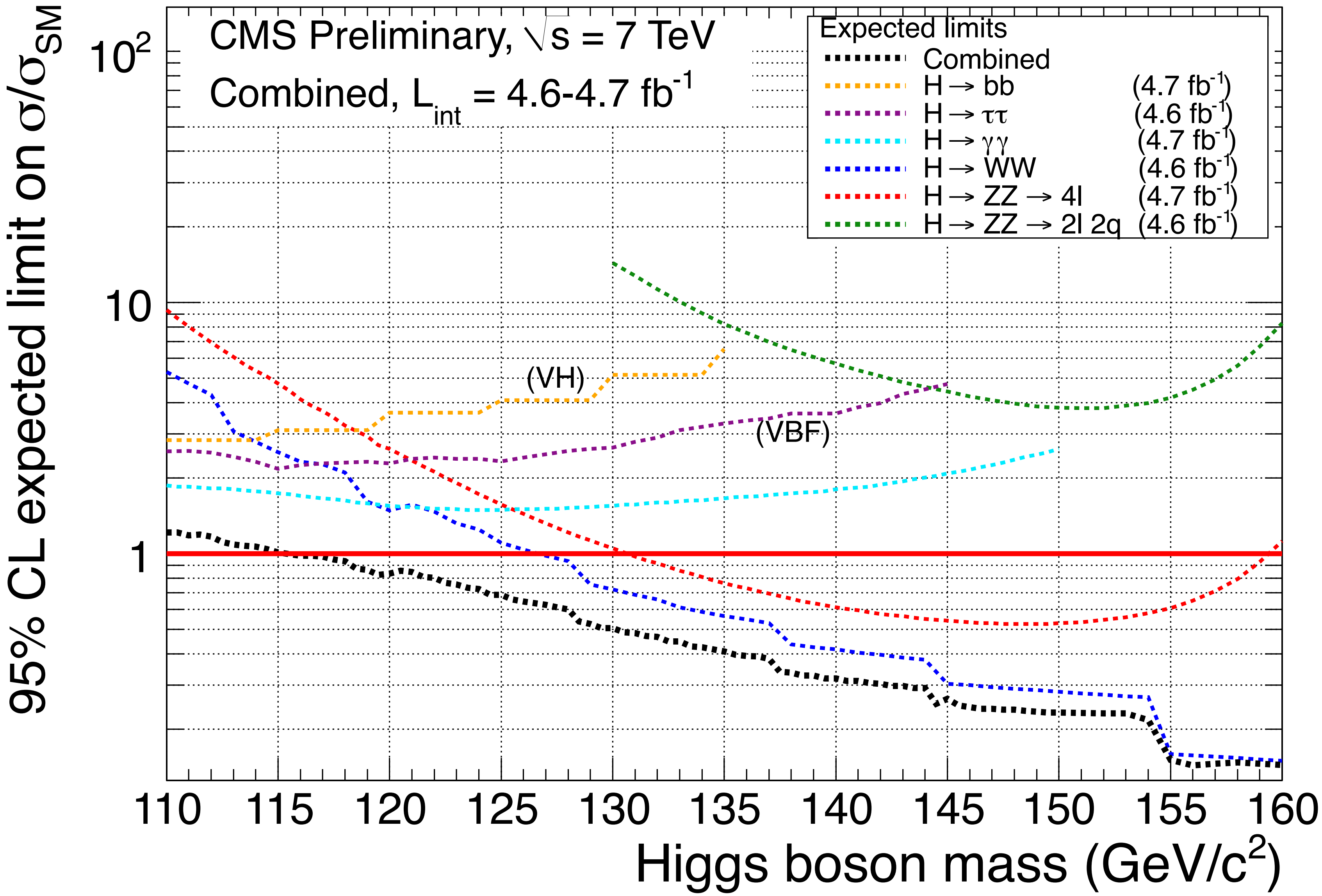
Sensitivity to individual search channels in the 2011 LHC data



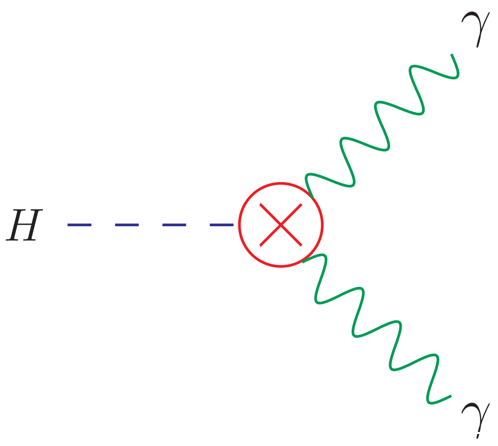
Note how large rates for production and/or decay are not the end of the story:

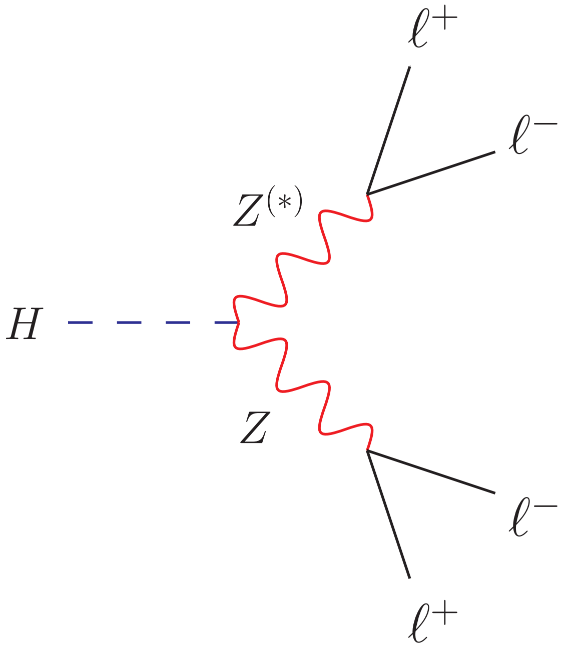
$gg \longrightarrow H \longrightarrow b\,\bar{b}$ dominant for light Higgs, but swamped by QCD background

Needs leptons in the final state: $q\bar{q}' \longrightarrow VH \longrightarrow \ell\,\ell'\,b\,\bar{b}$



The high-resolution channels: two photons and four leptons





Both suppressed!!!

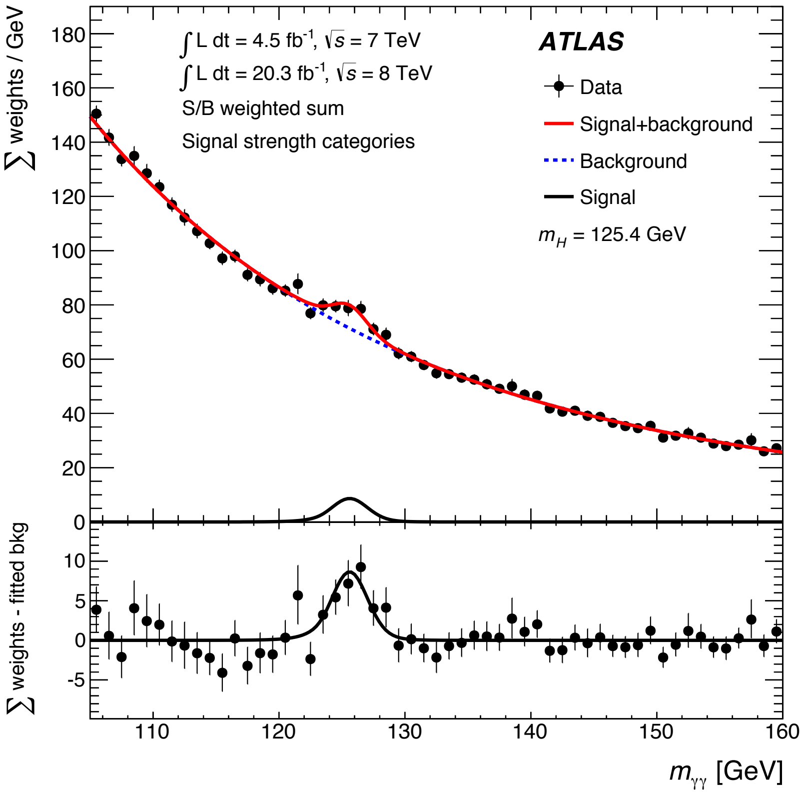
(respectively by a loop factor and, for m_H< 180 GeV, by the virtuality of the Z)

However, the precise reconstruction of the momenta of the particles in the final state produces a narrow peak around m_H in the invariant-mass distribution

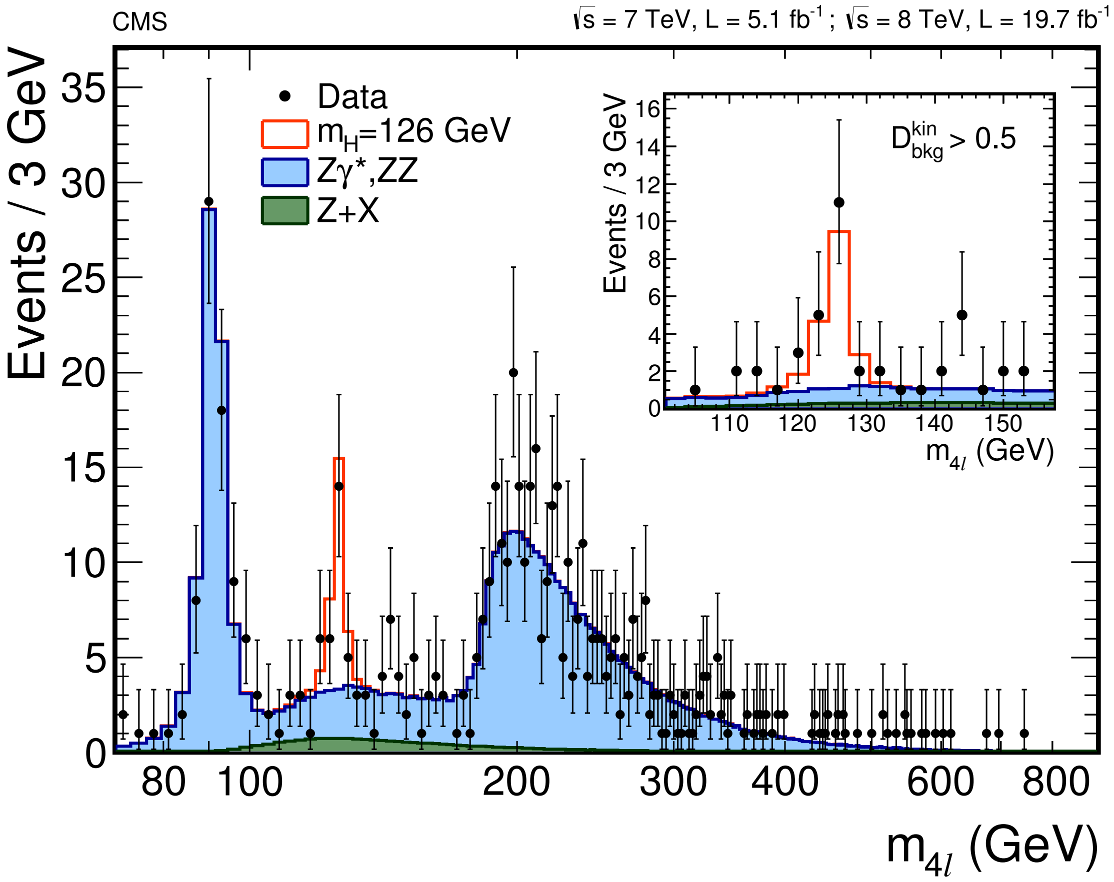
“I think we have it”

[Rolf Heuer at CERN, 04/07/2012]

$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ \rightarrow 4\ell$



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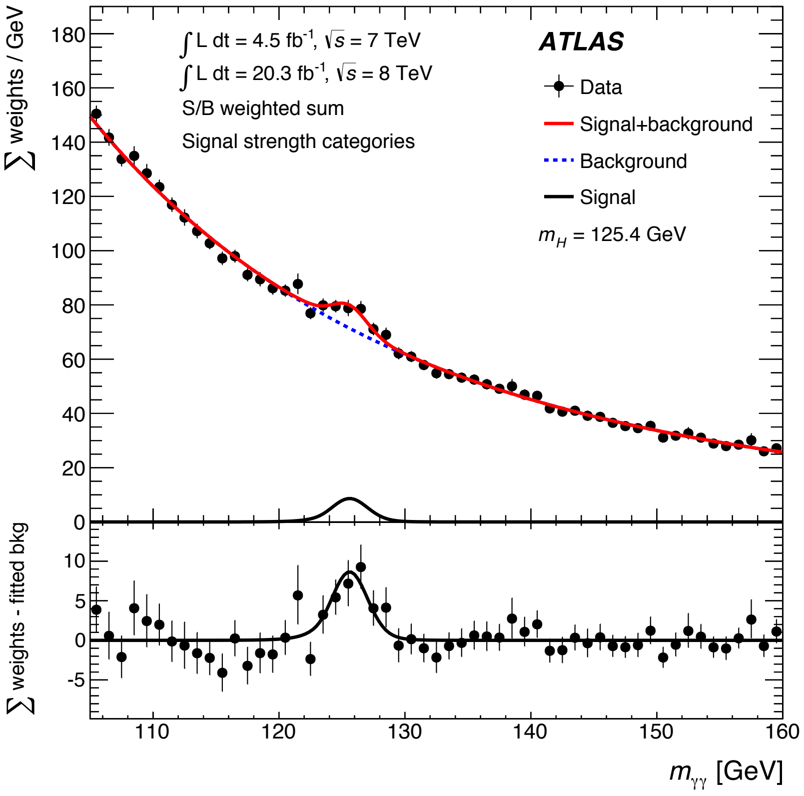

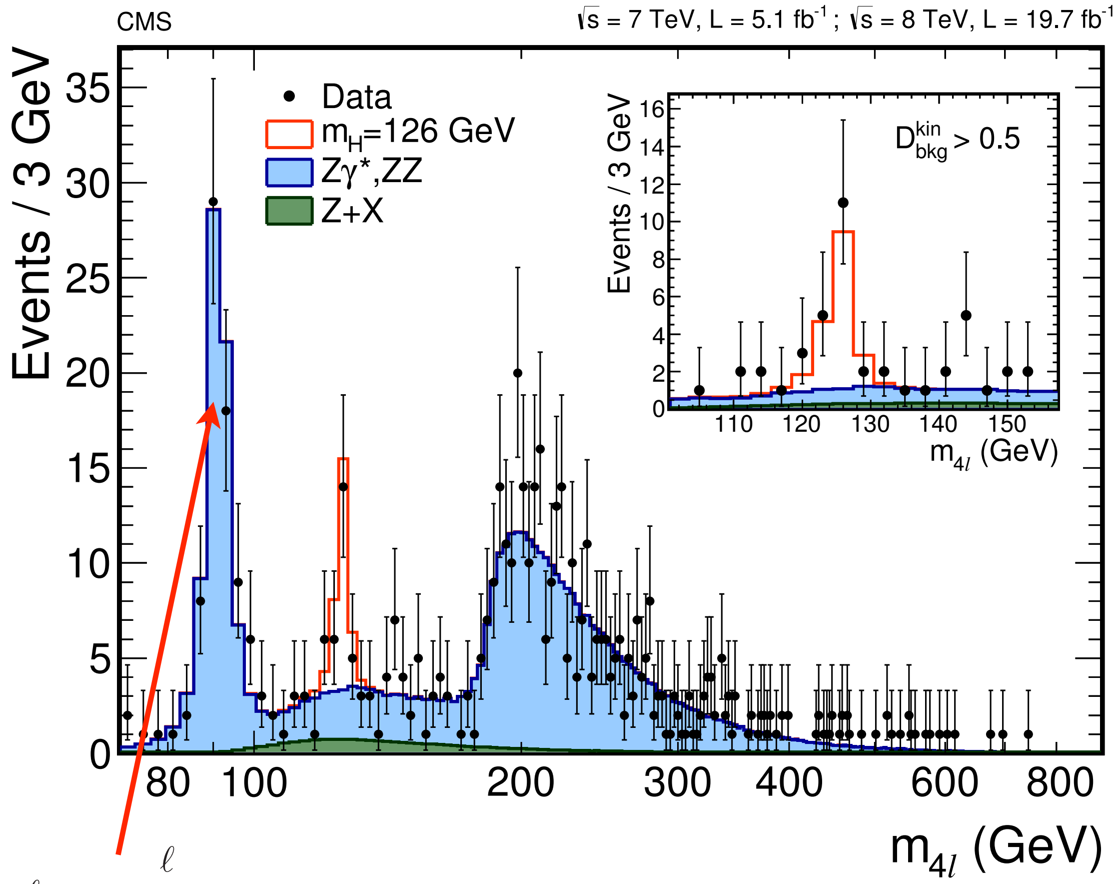

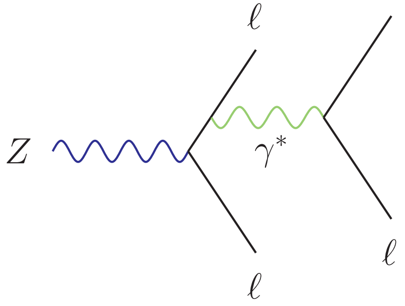

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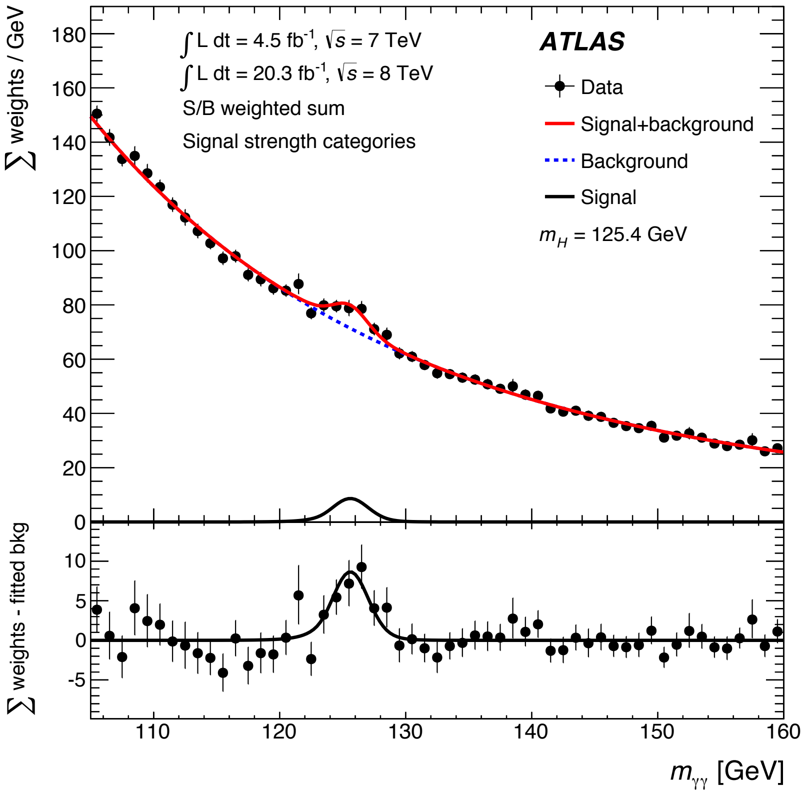

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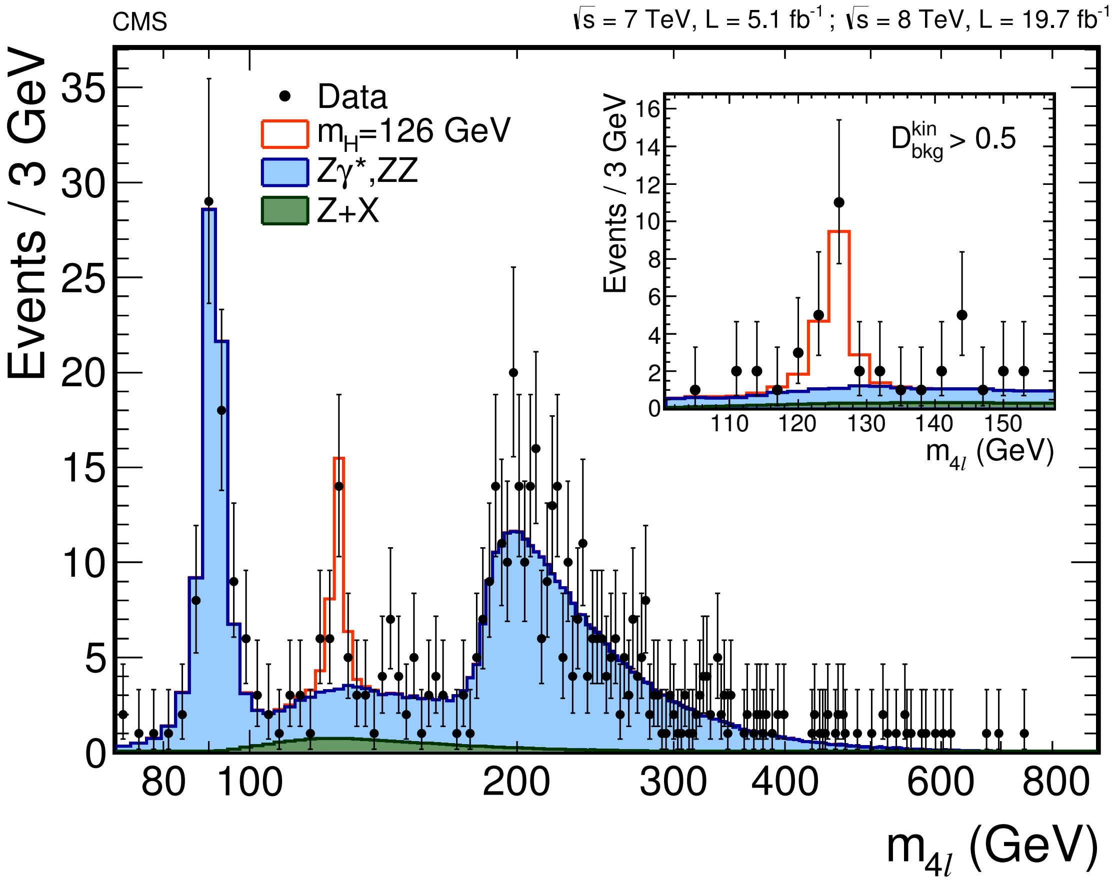
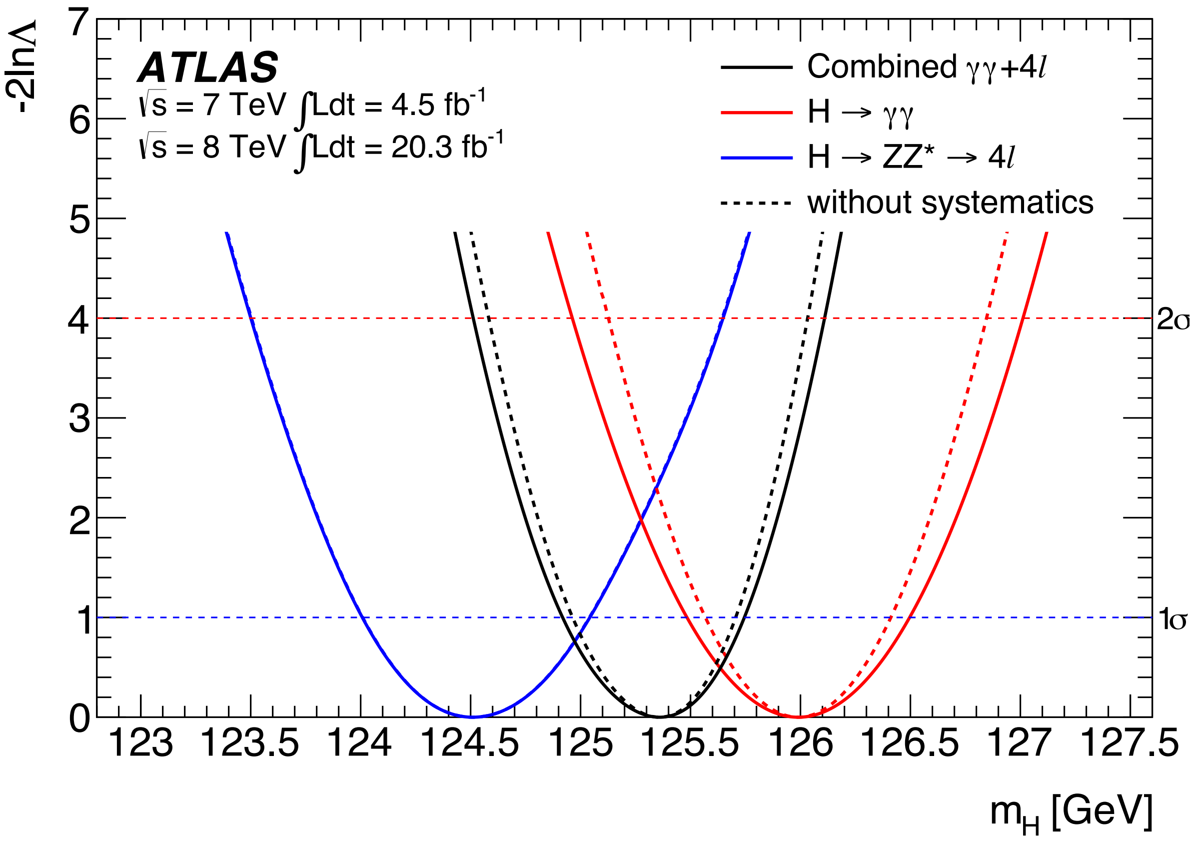
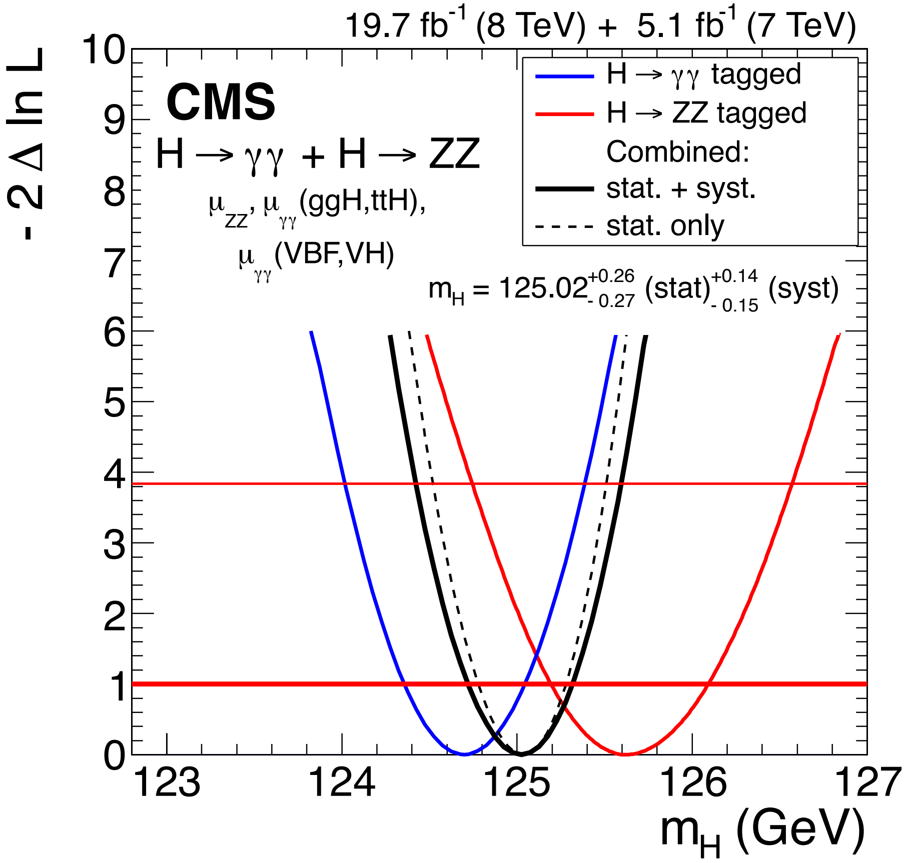


Determination of the Higgs mass by ATLAS and CMS



$m_H = 125.4 \pm 0.4 \pm 0.2$ GeV

[ATLAS, 1406.3827]



$m_H = 125.0 \pm 0.27 \pm 0.15$ GeV

[CMS, 1412.8662]

Profile of a 125-GeV Higgs boson at the LHC with 8 TeV

Theory predictions from the LHC Higgs cross-section Working Group, arXiv:1307.1347

$$\sigma(pp \to H) \;=\; 19.3\,^{+7\%+8\%}_{-8\%-7\%}\ \mathrm{pb}\ , \qquad \sigma(pp \to jjH) \;=\; 1.6\,^{+0.2\%+2.6\%}_{-0.2\%-2.4\%}\ \mathrm{pb}$$

$$\sigma(pp \to WH) \;=\; 0.70\,^{+1\%+2.3\%}_{-1\%-2.3\%}\ \mathrm{pb}\ , \qquad \sigma(pp \to ZH) \;=\; 0.42\,^{+3.1\%+2.5\%}_{-3.1\%-2.5\%}\ \mathrm{pb}$$

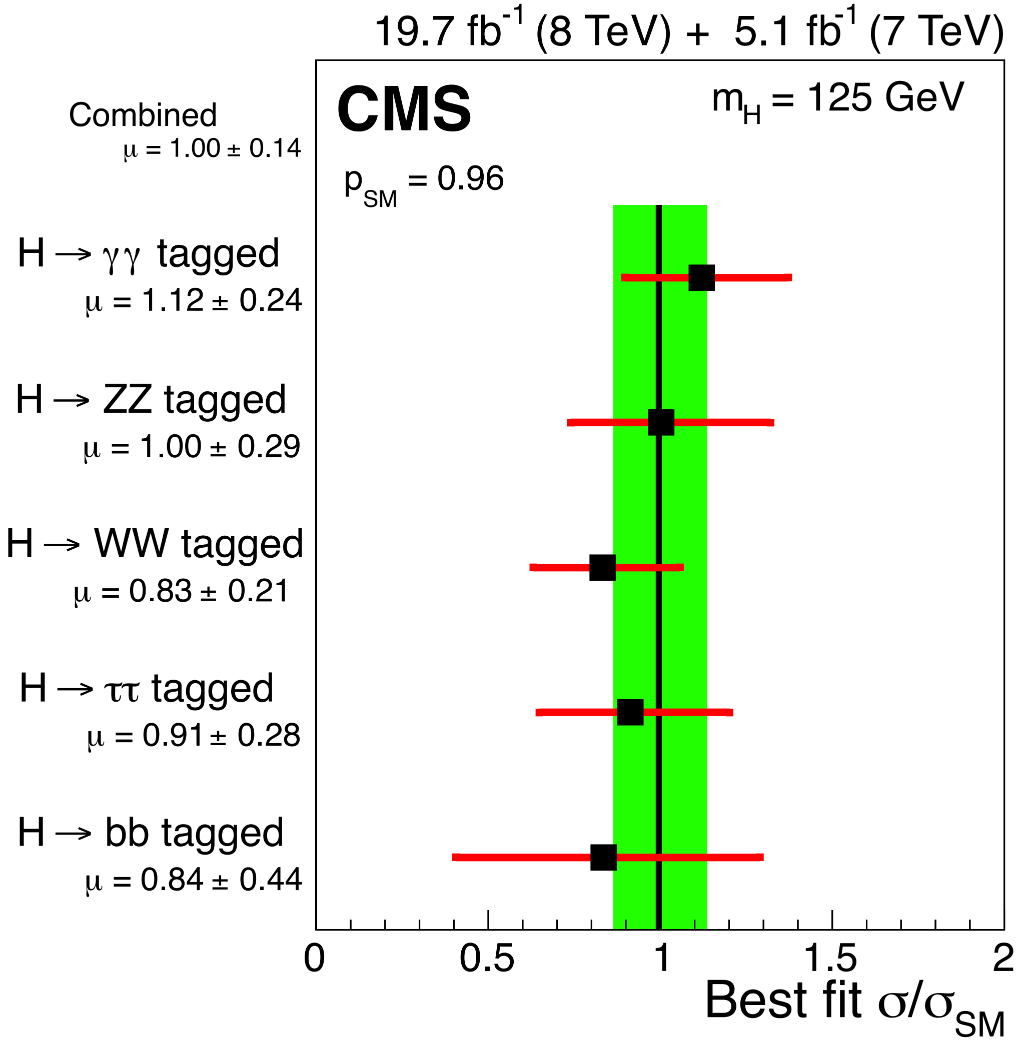
$$\sigma(pp \to ttH) \;=\; 0.13\,^{+3.8\%+8.1\%}_{-9.3\%-8.1\%}\ \mathrm{pb}$$

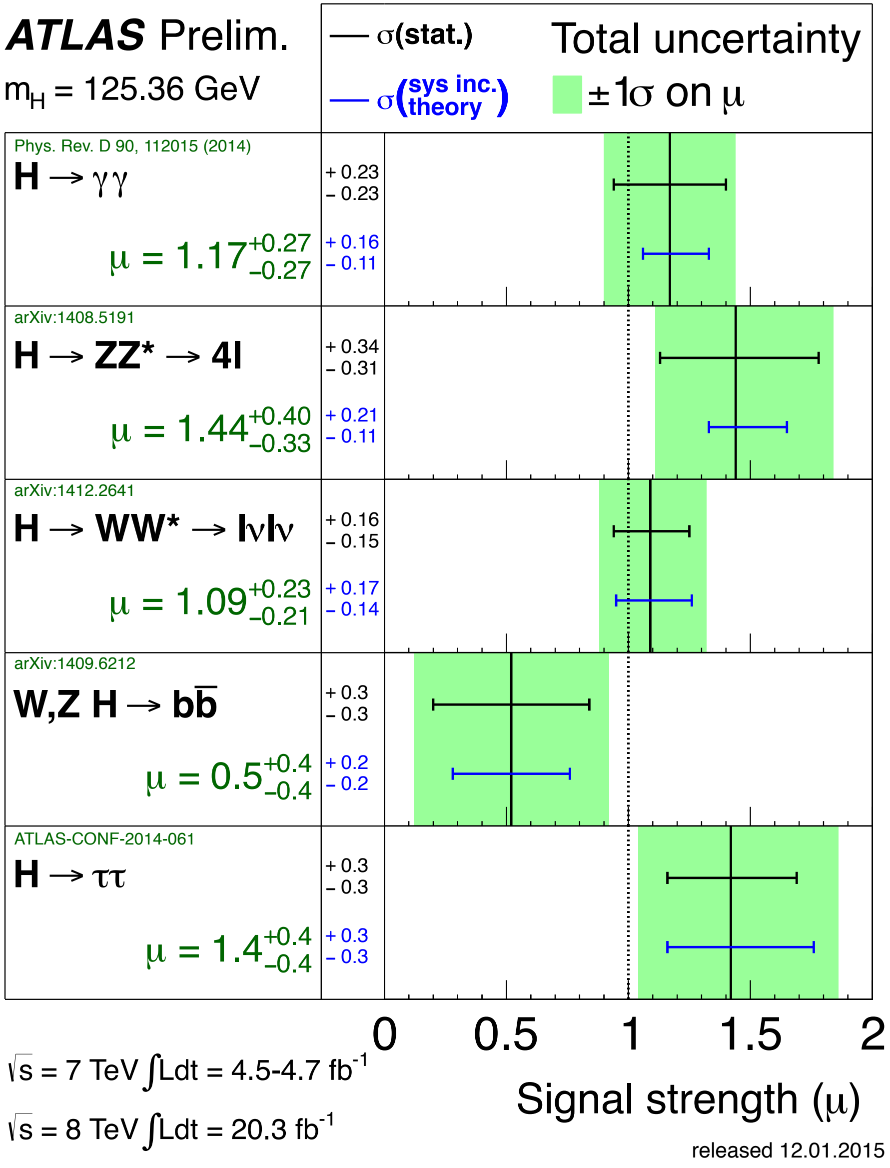
$$\mathrm{BR}(H \to b\bar{b}) \;=\; 57.7\%\,, \quad \mathrm{BR}(H \to WW^*) \;=\; 21.5\%\,, \quad \mathrm{BR}(H \to ZZ^*) \;=\; 2.6\%\,,$$

$$\mathrm{BR}(H \to \tau^+\tau^-) \;=\; 6.3\%\,, \quad \mathrm{BR}(H \to gg) \;=\; 8.6\%\,, \quad \mathrm{BR}(H \to \gamma\gamma) \;=\; 0.23\%$$

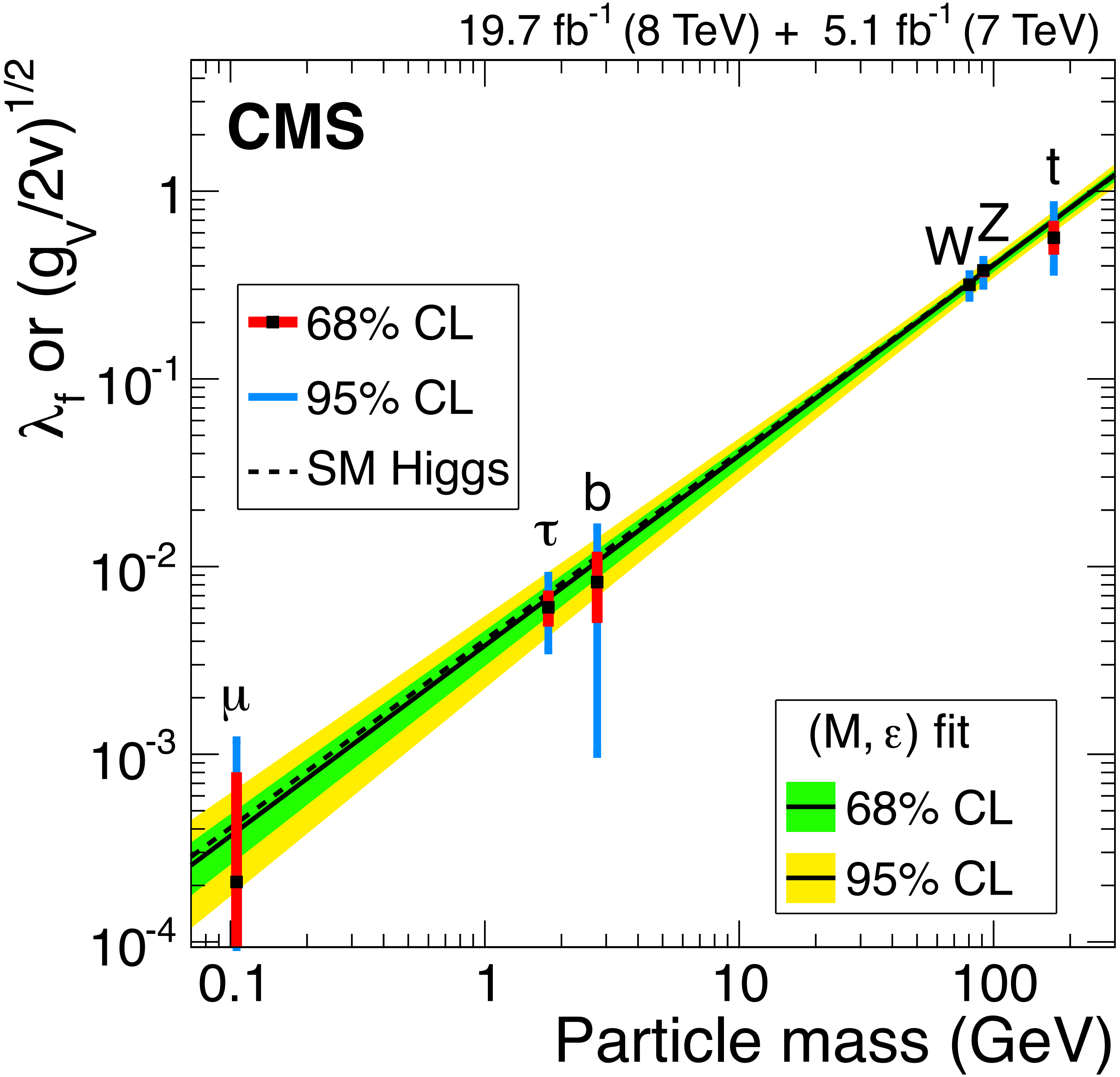
(*relative* errors on the BRs range from 3% for *bb* to 10% for *gg*)

125 GeV is a lucky mass, several decays accessible

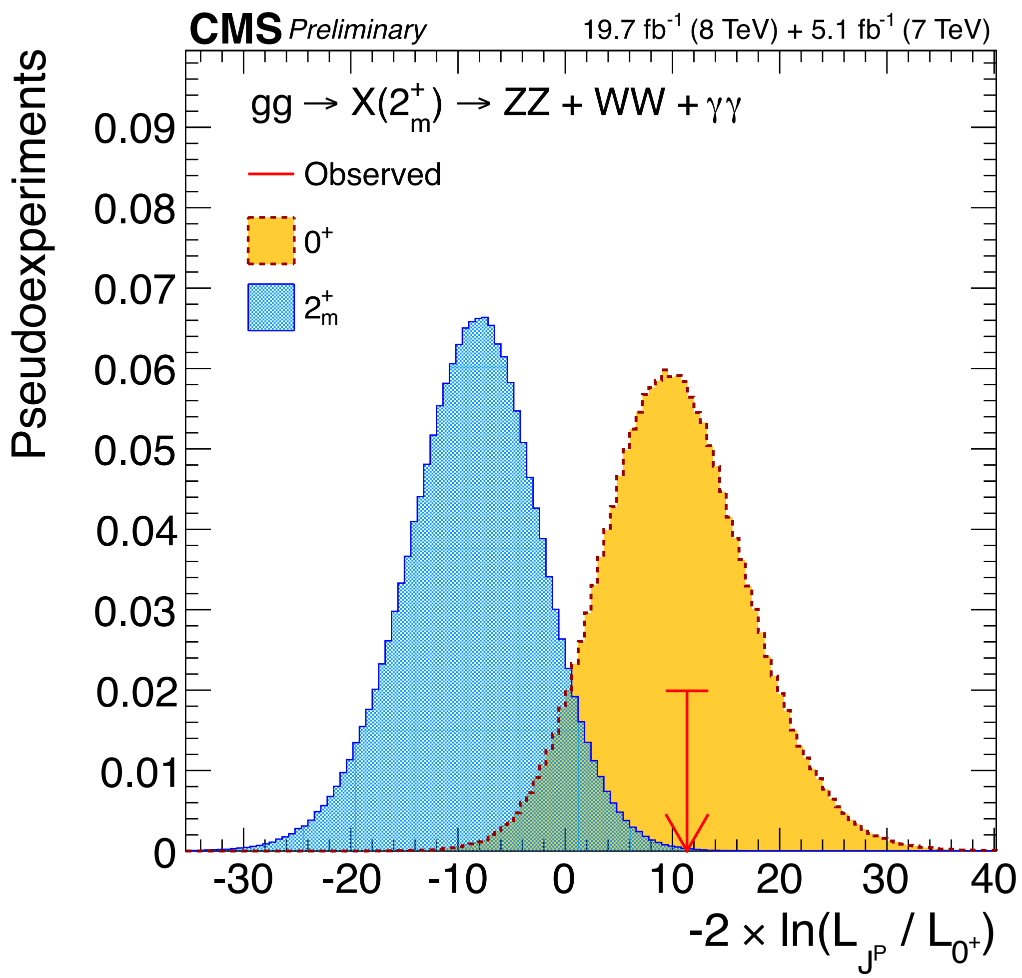




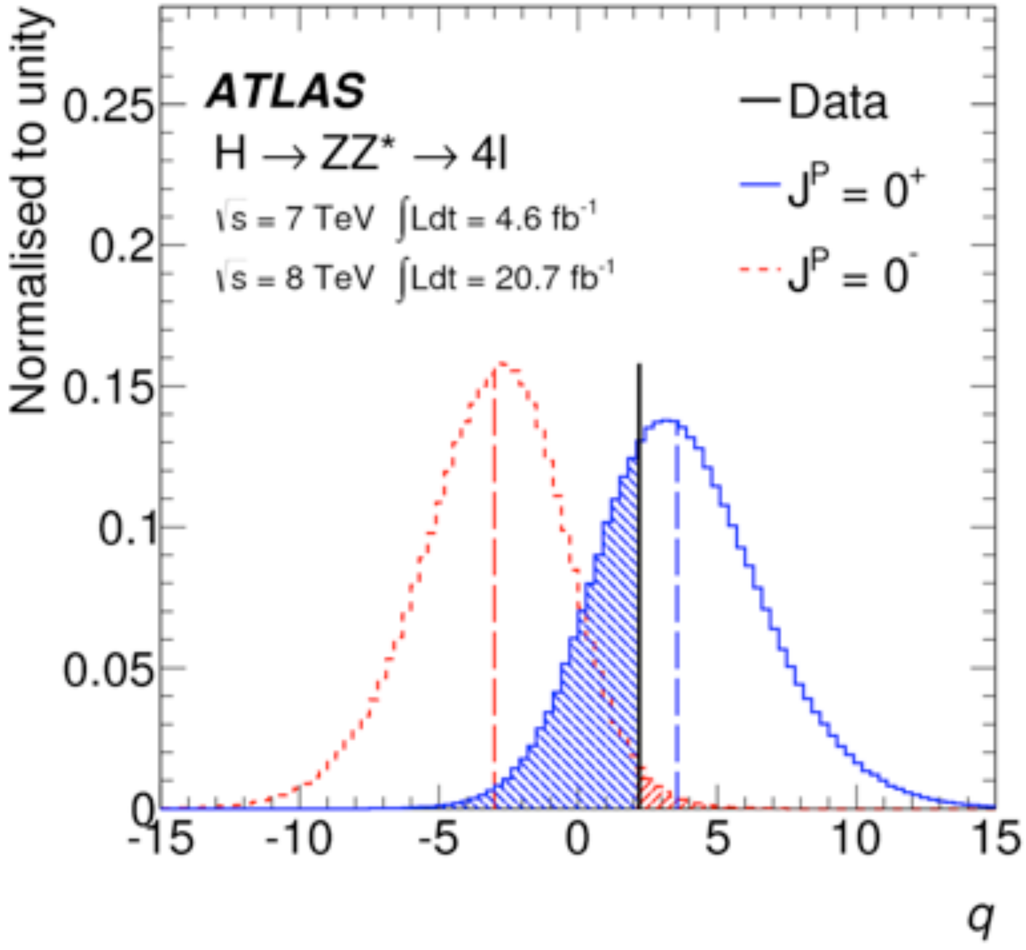
The Higgs couplings to the other SM particles are proportional to their masses:



The angular distribution of the decay products allows to test spin and parity:



(spin 2 disfavored)



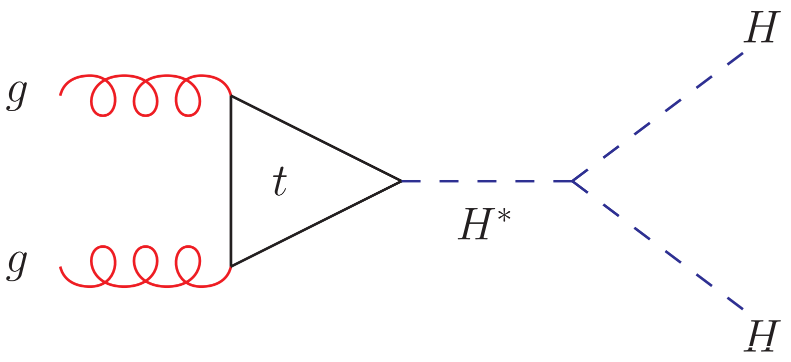
(pseudoscalar disfavored)

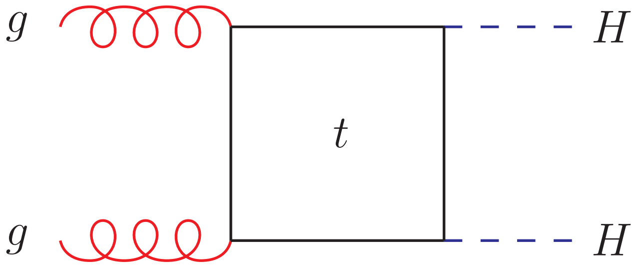
The ultimate test of the Higgs mechanism: self-couplings

The Higgs potential includes trilinear and quartic self-couplings:

$$V = \frac{1}{2}(2\lambda v^2)H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

The three-Higgs coupling can be extracted from Higgs pair production. However, suppressed by phase space and diluted by other topologies. E.g.,

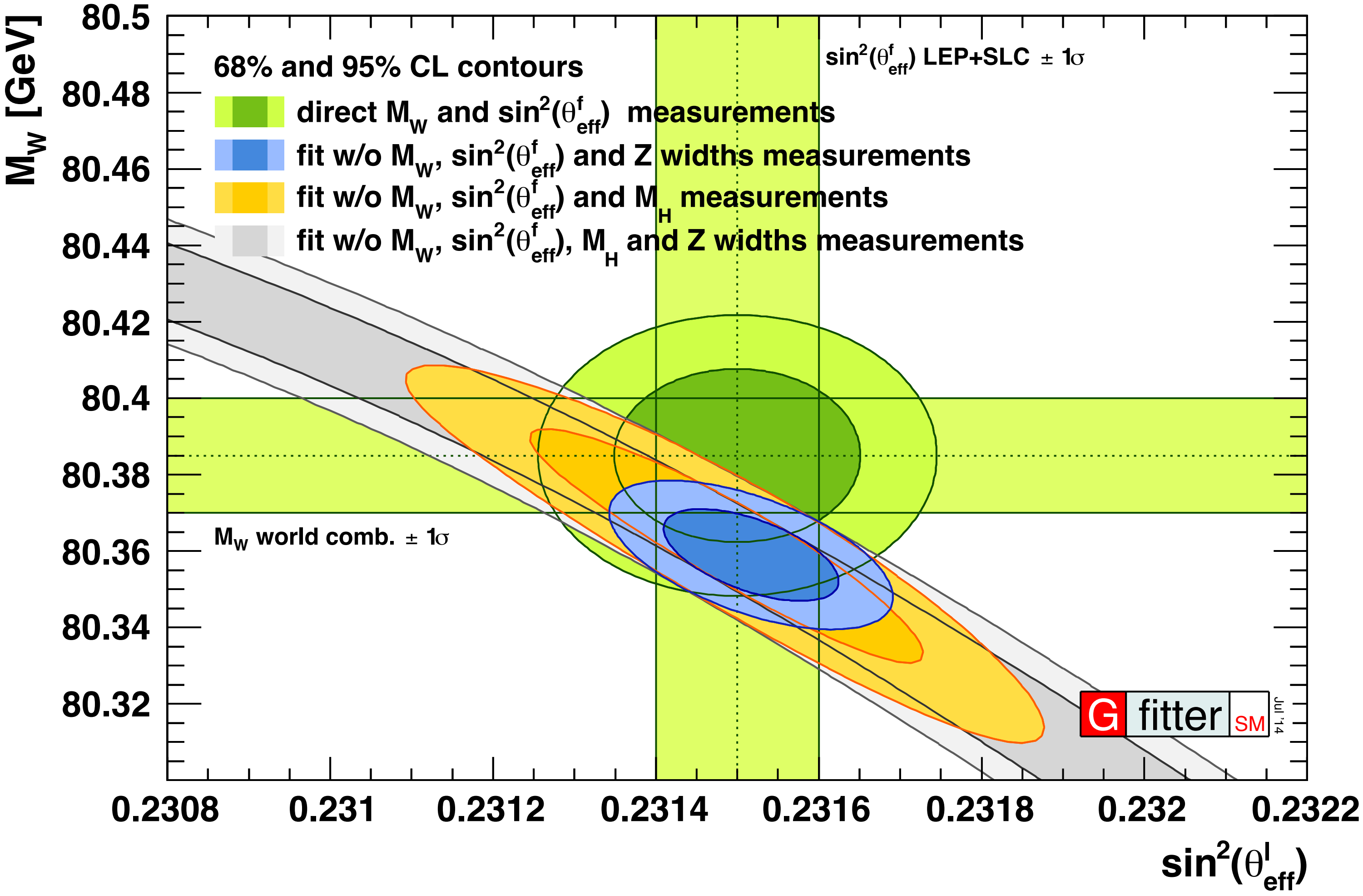




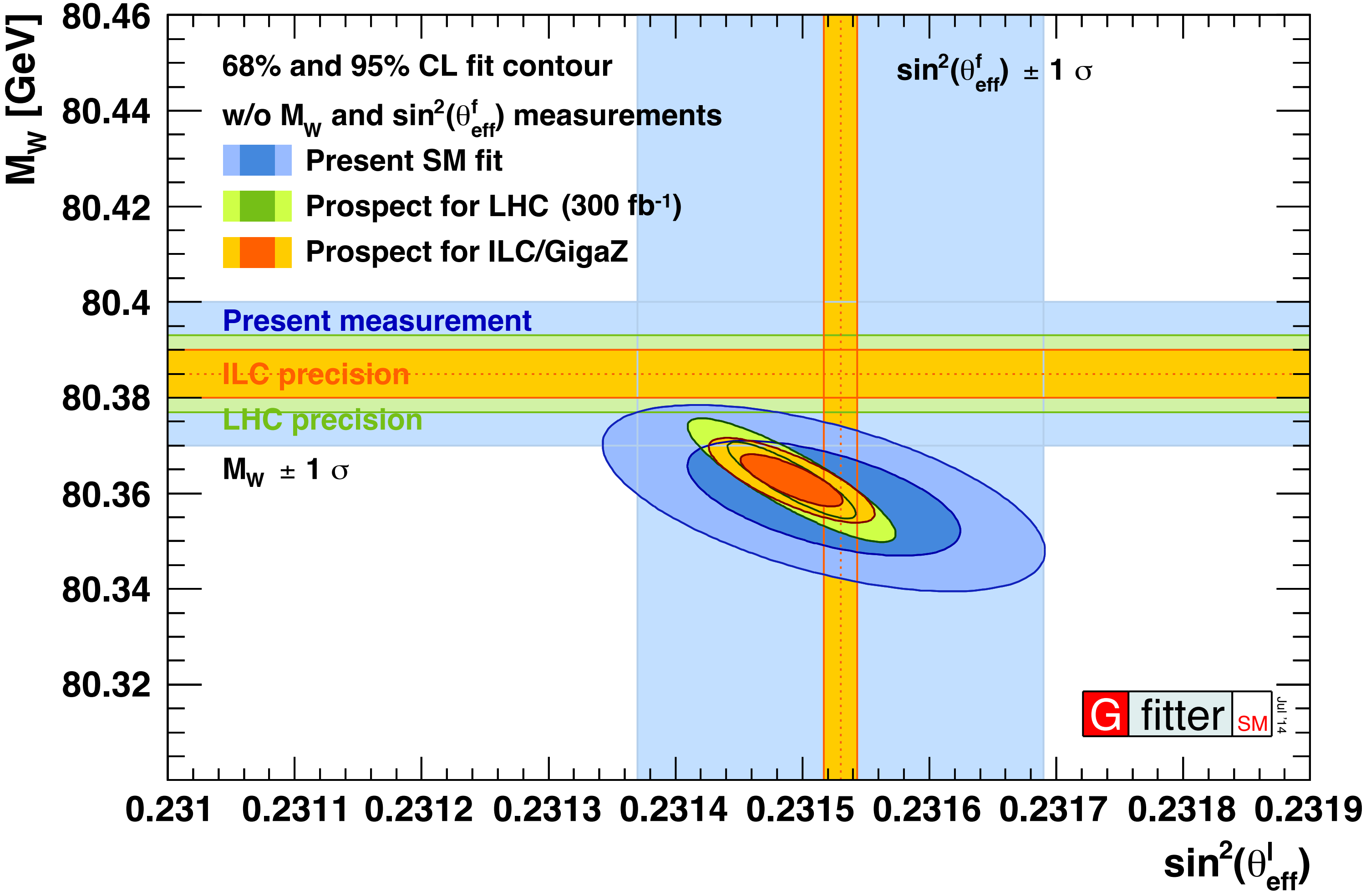
The coupling could be measured with ~50% accuracy in a high-luminosity LHC run and with 10%-20% accuracy at the ILC with 1 TeV

No hope to measure directly the four-Higgs coupling via three-Higgs production

Status of the EW fit after the Higgs discovery
(Gfitter collaboration, 2014)



Status of the EW fit after the Higgs discovery (Gfitter collaboration, 2014)

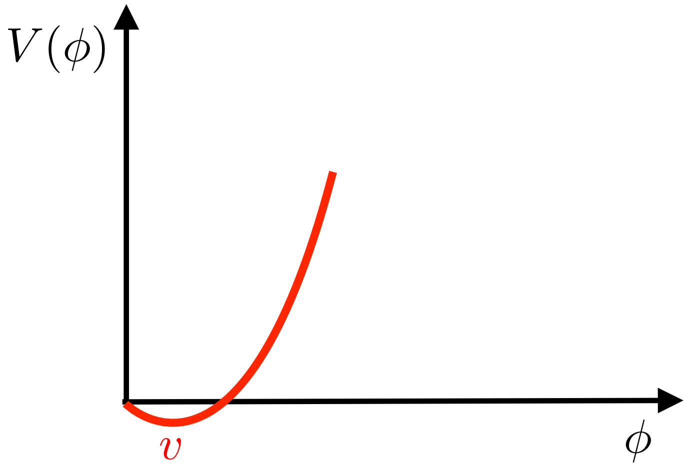


The fate of the SM: stability of the electroweak vacuum

The fate of the SM: stability of the electroweak vacuum

Tree-level scalar potential:

$$V_0(\phi) \;=\; m^2\,|\phi|^2 + \lambda\,|\phi|^4\;, \qquad v = \sqrt{\frac{-m^2}{\lambda}}$$



The fate of the SM: stability of the electroweak vacuum

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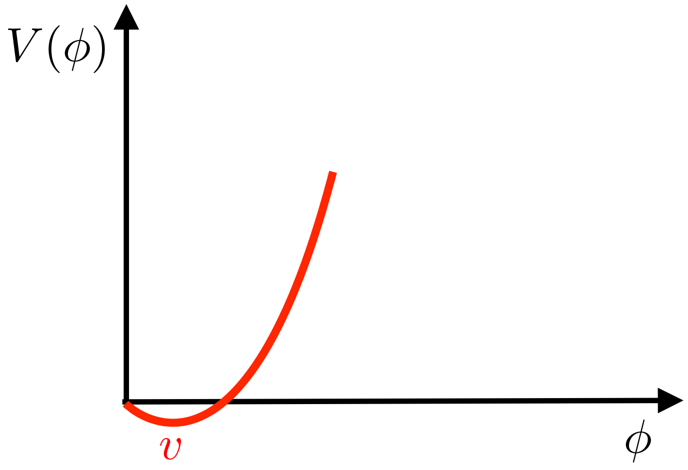
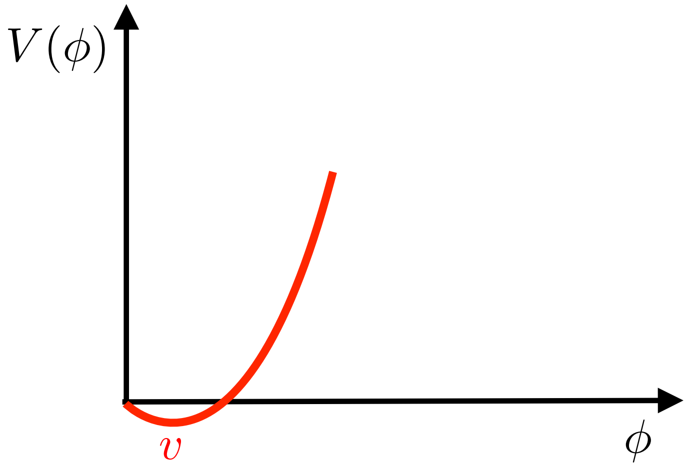


Including quantum corrections:

$$V(\phi) \;=\; m^2(\mu)\,|\phi(\mu)|^2 \,+\, \lambda(\mu)\,|\phi(\mu)|^4 \,+\, \Delta V^{\rm loop}$$

The fate of the SM: stability of the electroweak vacuum



Tree-level scalar potential:

$$V_0(\phi) \; = \; m^2\,|\phi|^2 \,+\, \lambda\,|\phi|^4\,, \qquad v = \sqrt{\frac{-m^2}{\lambda}}$$

Including quantum corrections:

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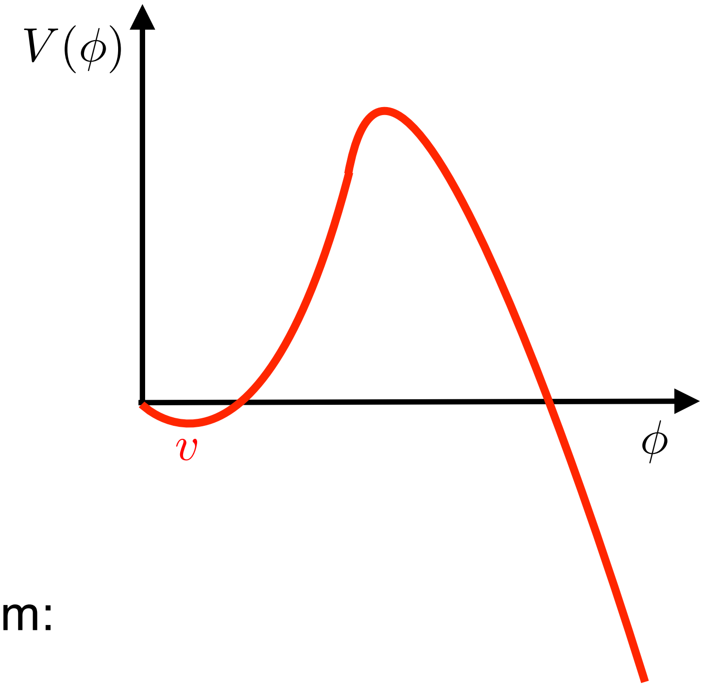

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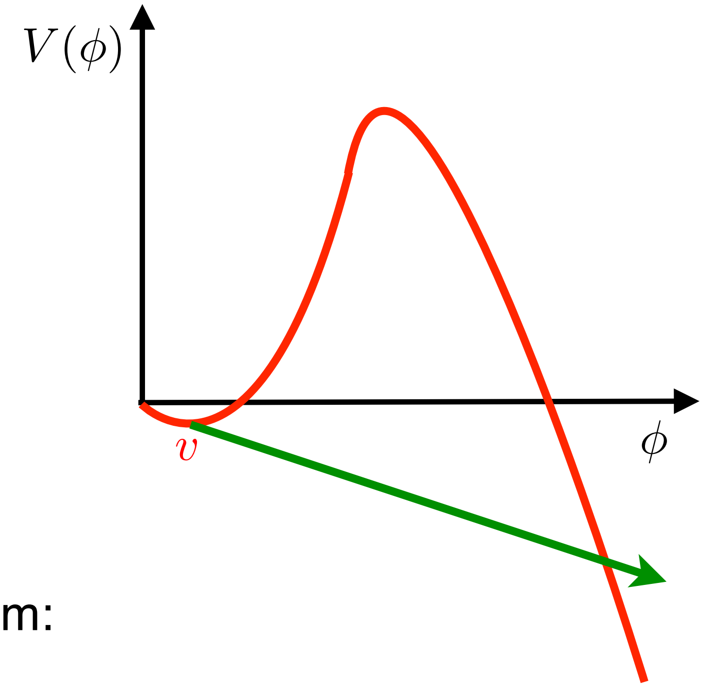

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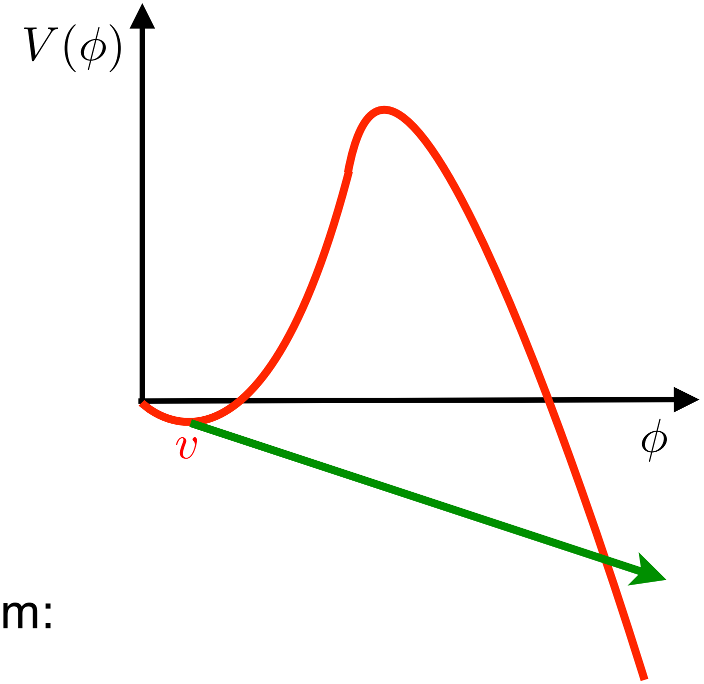

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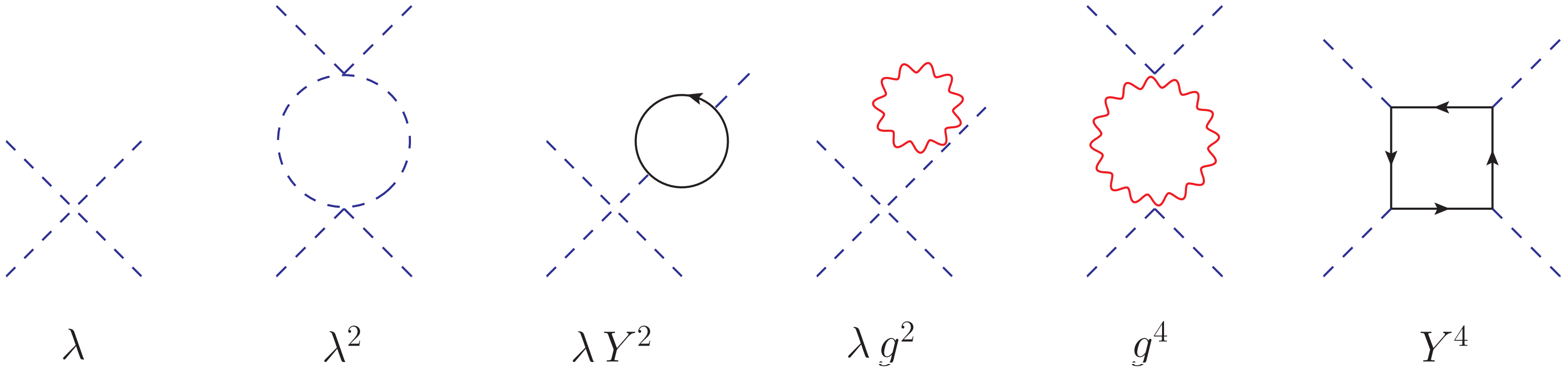
The Higgs field can tunnel to a much larger value, destroying the EW vacuum

The lifetime of the EW vacuum must be longer than the age of the Universe *(metastability)*

We can extract the weak-scale value of λ from $m_H^2 = 2\lambda v^2$ + higher orders

Loops of SM particles determine the dependence of λ on the renormalization scale μ



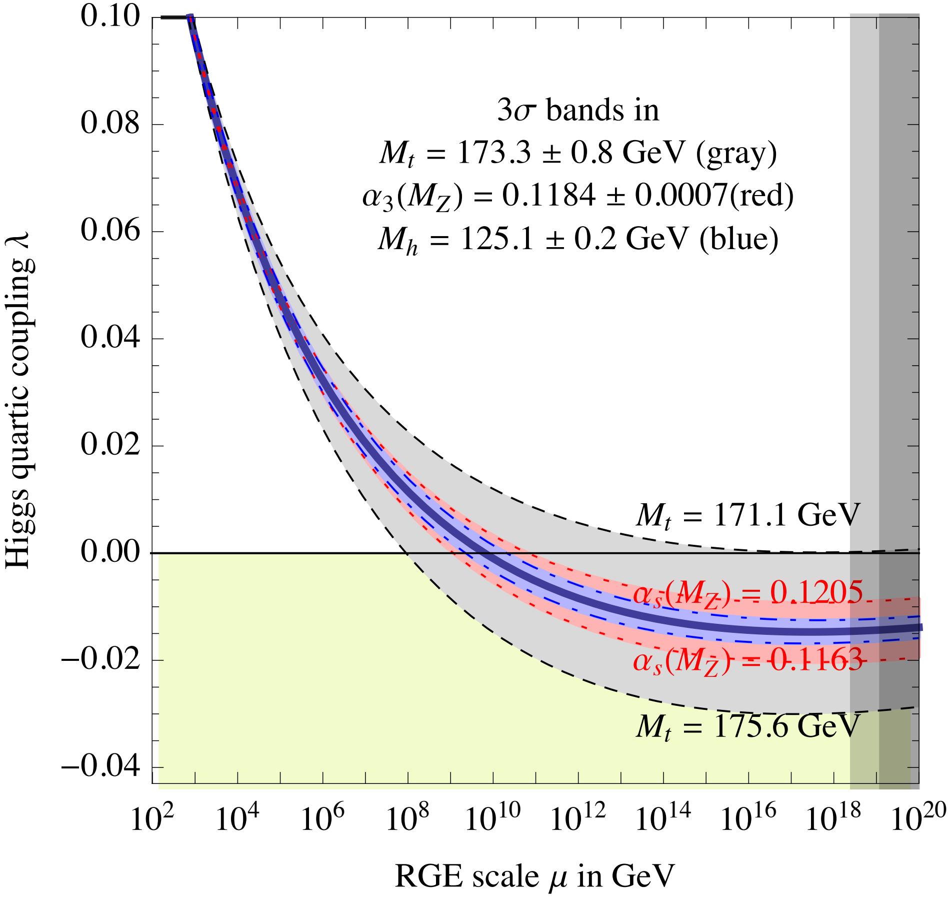
$$\frac{d\lambda}{d\log\mu} = \frac{1}{16\pi^2}\left\{24\,\lambda^2 + \lambda\,\left[12\,Y_t^2 + 12\,Y_b^2 + 4\,Y_\tau^2 - 9\,g^2 - 3g'^{\,2}\right]\right.$$
$$\left. + \frac{9}{8}\,g^4 + \frac{3}{8}g'^{\,4} + \frac{3}{4}\,g^2\,g'^{\,2} - 6\,Y_t^4 - 6\,Y_b^4 - 2\,Y_\tau^4\right\}$$ + higher orders

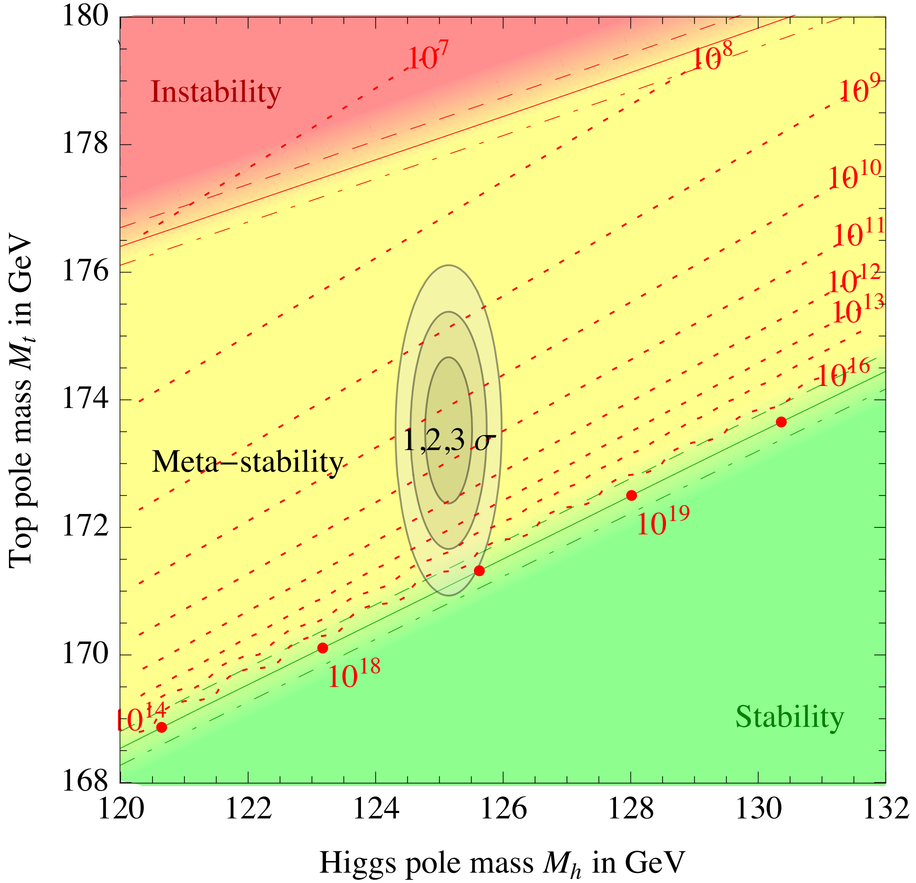
Large m_H: λ^2 prevails, λ grows with μ until it blows up at some scale Λ (Landau pole)

Small m_H: $-Y_t^4$ prevails, λ decreases with μ until it turns negative at Λ (vacuum instability)

Λ is the scale at which new physics must rescue the SM (anyway, $\Lambda \leq \Lambda_{\rm Planck}$)

$m_H \approx 125$ GeV is right at the edge between the stability and metastability regions





Plots from 1307.3536v4

IF the SM is valid up to the Planck scale, the vacuum is most likely metastable

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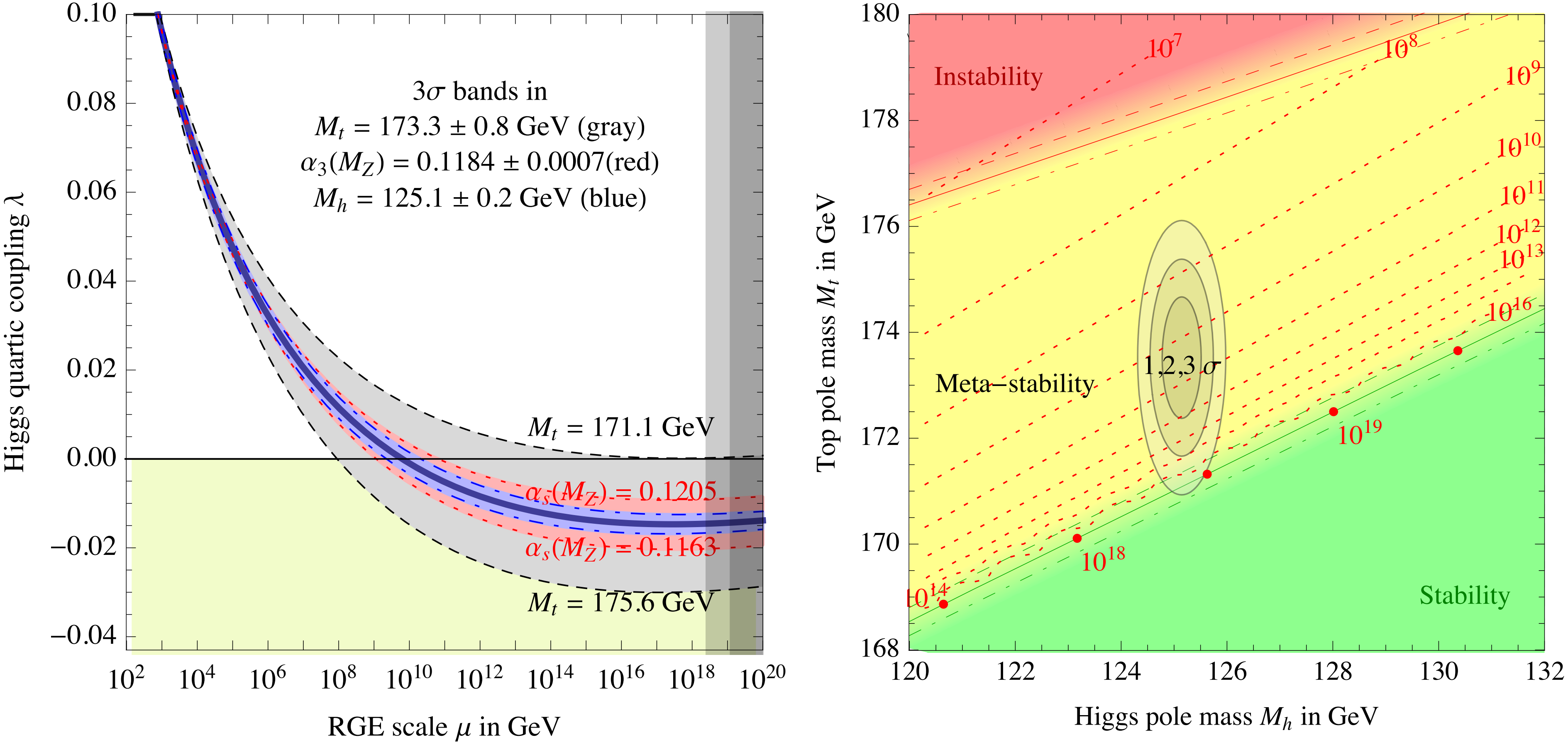


Plots from 1307.3536v4

IF the SM is valid up to the Planck scale, the vacuum is most likely metastable

But should we really buy that “IF”?

III) Beyond the Standard Model

The Standard Model does an excellent job in describing physics at the weak scale.
Still, it is unlikely that it is valid all the way up to the scale of quantum gravity

Observational arguments for BSM physics

- The SM does not account for neutrino oscillations (this, however, can easily be fixed by adding heavy and sterile right-handed neutrinos to the theory)

- The SM does not include a suitable candidate for Dark Matter, and cannot justify the matter-antimatter asymmetry in the Universe

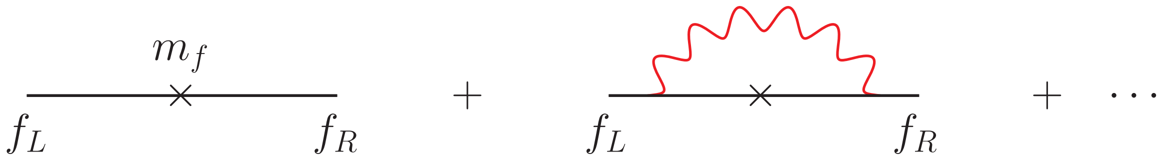
Theoretical arguments for BSM physics

- The SM has many (>20) arbitrary parameters, and a rather complicated structure (“odd” gauge group, generation mixing, large mass hierarchies among fermions). It would be nice to embed it in a simpler and more predictive theory (e.g., a GUT).

- Quantum corrections destabilize the Higgs mass inducing a quadratic dependence on the cutoff scale that regularizes the loop integrals *(the hierarchy problem)*

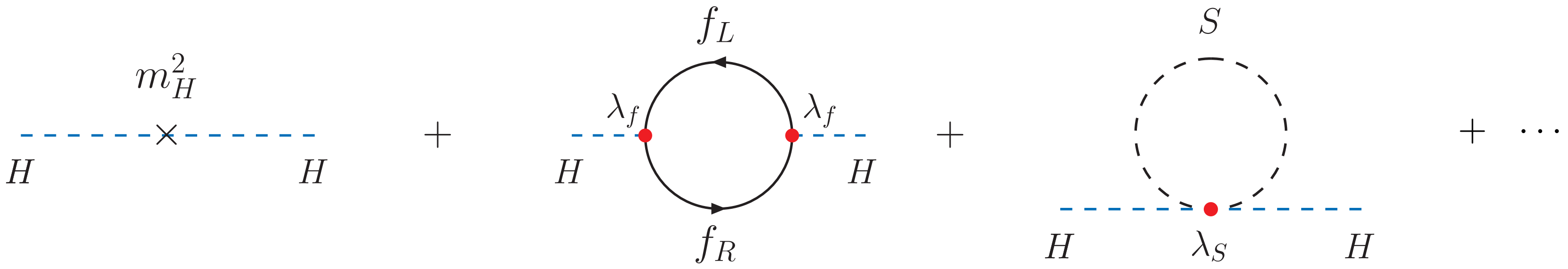
The *hierarchy problem* of the Standard Model

The SM fermion masses are protected by chiral symmetry:



$\delta m_f \propto m_f$, thus if m_f is small it stays so even after including quantum corrections

There is no analogous mechanism to protect the scalar mass term:



The radiative corrections depend quadratically on the cutoff scale where New Physics kicks in:

$$\Delta m_H^2 \supset \frac{3\, G_F\, \Lambda^2}{4\sqrt{2}\pi^2}\left(2\, m_W^2 + m_Z^2 + m_H^2 - 4\, m_t^2\right)$$

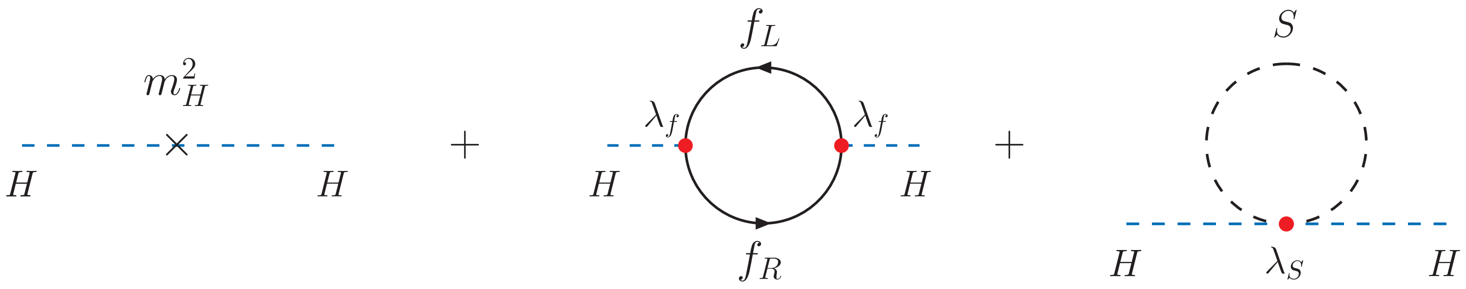
If the validity of the SM extends up to the Planck scale (or the GUT scale) we need an extremely fine-tuned cancellation between the tree-level mass and the radiative corrections

Different approaches are possible:

- New physics intervenes at the TeV scale (supersymmetry, composite Higgs models, ...)
- The scale of quantum gravity is itself at the TeV (models with large extra dimensions)
- Tough luck, live with fine tuning (SM up to high scales: “nightmare” scenario for LHC?)

Supersymmetry and the MSSM

Fermions and bosons enter the quantum corrections to the Higgs mass with opposite sign



In a supersymmetric theory, each fermion has a bosonic partner with the same mass and internal quantum numbers (their couplings to the Higgs are related, $\lambda_S = \lambda_f^2$). Their quadratically divergent contributions to the Higgs mass cancel each other

In the Minimal Supersymmetric Standard Model (MSSM) every SM particle is promoted to a *supermultiplet* (however, two Higgs supermultiplets are required)

The superpartners must be heavier than the ordinary SM particles → SUSY must be *broken* by explicit mass terms for the new particles

These SUSY-breaking masses M_S are *soft*, i.e. they do not reintroduce quadratic divergences:

$$\Delta m_H^2 \propto \frac{\lambda^2}{16\pi^2} M_S^2$$

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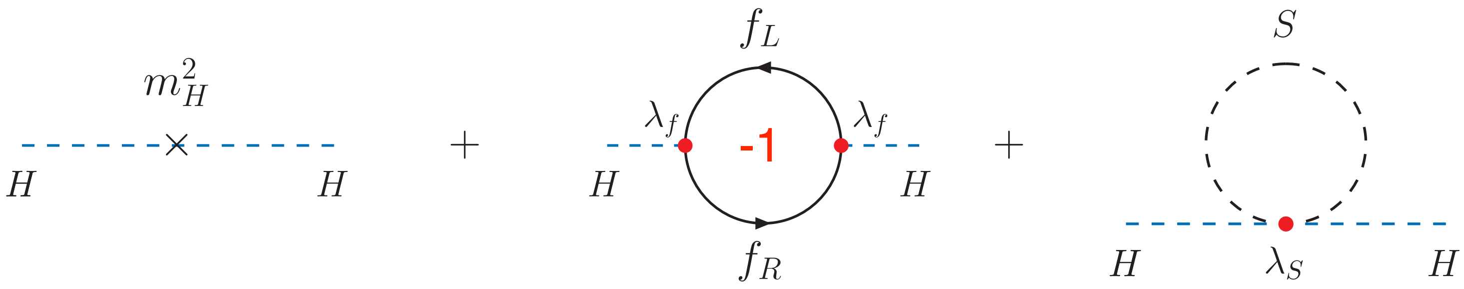

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Composite Higgs models

The hierarchy problem originates from the fact that the SM Higgs is an *elementary* scalar (therefore its mass cannot be protected by chiral or gauge symmetries)

The classical alternative to the SM Higgs mechanism, i.e. dynamical symmetry breaking such as in Technicolor models, is disfavoured by flavour and electroweak precision tests

An intermediate approach is possible:

There *is* a light Higgs scalar (to satisfy the electroweak precision observables) but it is *composite*, the light remnant of a new strong dynamics responsible for EWSB

To preserve EW observables, the particles of the strong sector should be above the TeV scale

The composite Higgs can be lighter than the rest if it is a pseudo-Goldstone boson of a global symmetry of the strong sector *(e.g. Little Higgs, Holographic Higgs, ...)*

Even if the new states are heavy, the composite nature of the Higgs should appear at the LHC:

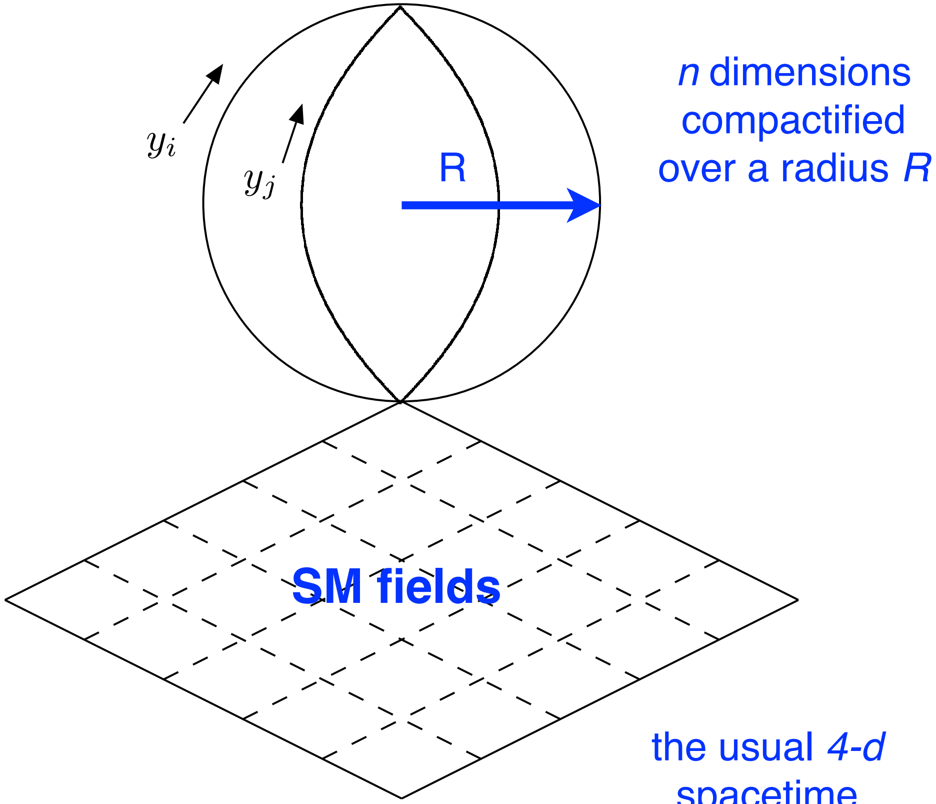
- high-energy growth of the $V\,V \longrightarrow V\,V$ cross sections
- modified couplings of the Higgs to SM particles

Models with Large Extra Dimensions

Supersymmetry helps the Higgs boson cross the *"desert"* between M_{EW} and M_{Planck}

An alternative paradigm: there is no desert, and $M_{Planck} \sim M_{EW}$!!!

The simplest scenario:
Arkani-Hamed *et al.*, hep-ph/9803315



The SM fields live on a 4-d *"brane"*
but gravity propagates in the *"bulk"*

The "true" scale of quantum gravity can be lower than the apparent 4-dim Planck scale:

$$M_{\rm Pl}^2 \;=\; M_*^{n+2}\,(2\pi R)^n$$

$$n \;=\; 1, \quad M_* \;=\; 10\ {\rm TeV} \;\longrightarrow\; R \;\approx\; 10^{10}\ {\rm m}$$

$$n \;=\; 2, \quad M_* \;=\; 10\ {\rm TeV} \;\longrightarrow\; R \;\approx\; 0.1\ {\rm mm}$$

Gravity is untested below 0.1 mm.
For *n* = 2 the scale of quantum gravity
could be as low as 10 TeV
(and even lower for larger *n* !!!)

From a 4d perspective, fields that live in the (4+*n*)d bulk look like a *tower* of “Kaluza-Klein” states

E.g., a massless scalar living in 5 dimensions can be Fourier-decomposed along the compact dimension:

$$\mathbf{\Phi}(x_\mu, Z) \;=\; \mathbf{\Phi}(x_\mu, Z + 2\pi R)$$

$$\mathbf{\Phi}(x_\mu, Z) \;=\; \sum_{k=0,\pm 1\,\ldots} \phi_k(x_\mu)\, e^{ikZ/R}$$

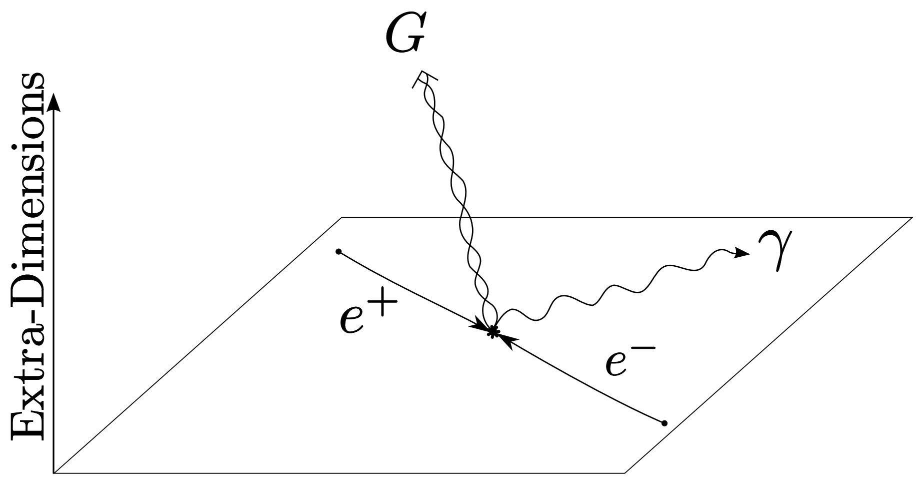
$$\Box_5\, \mathbf{\Phi}(x_\mu, Z) \;=\; 0 \;\longrightarrow\; \left(\Box_4 + \frac{k^2}{R^2}\right) \phi_k(x_\mu) \;=\; 0$$

The zero mode remains massless, the other modes have increasing masses $m_k \;=\; \frac{|k|}{R}$

A typical signature of extra-dim models is the production of gravitons that escape in the bulk

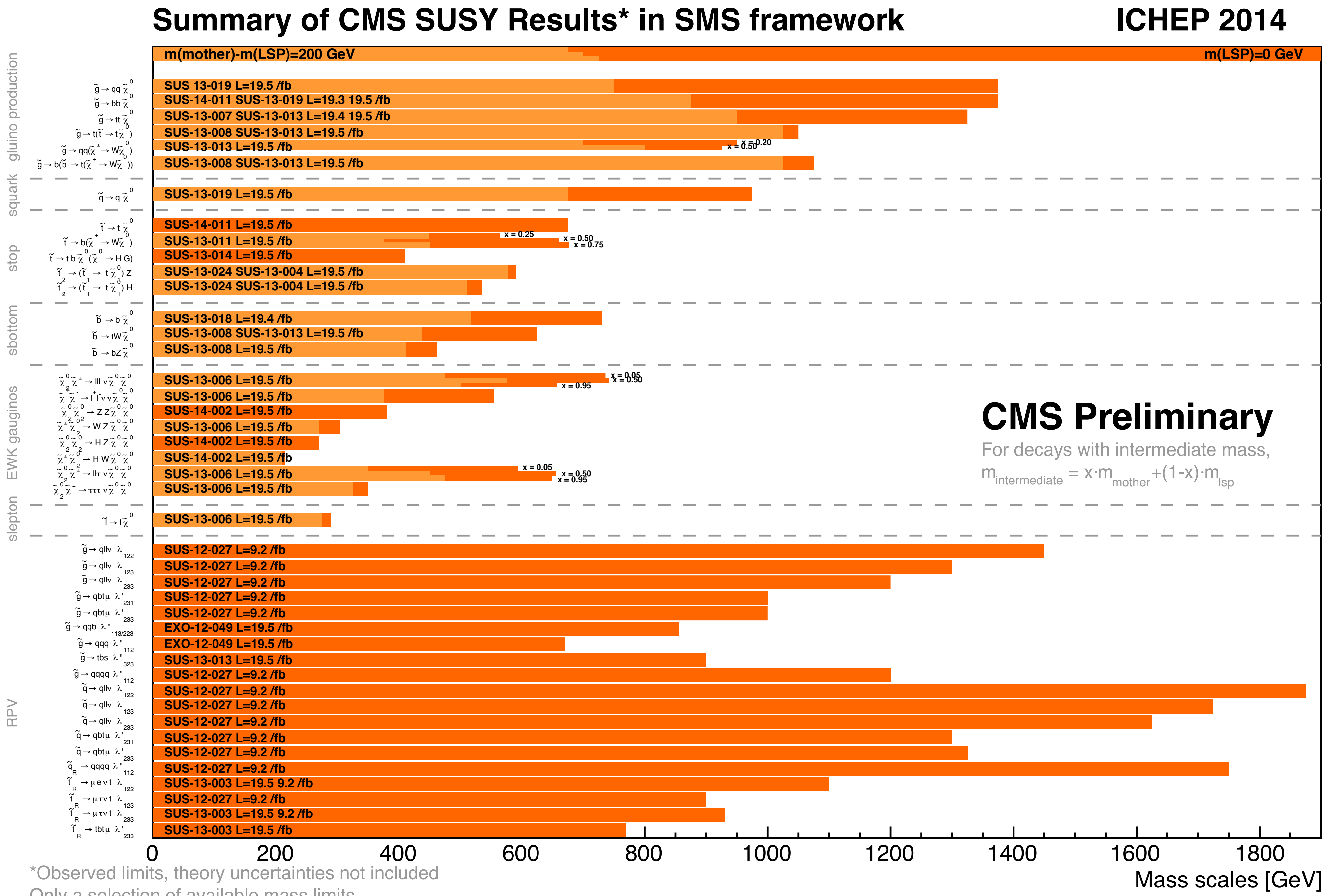
Each KK graviton couples to SM matter like $1/M_{Pl}$, but the sum over the whole tower goes like $1/M_*$.

The collider signature is a photon (or a jet) plus missing energy



Depending on the specific model, other particles may live in the bulk and have KK excitations

After the first two-year run of the LHC with c.o.m. energy of 7-8 TeV,
all we got from BSM searches is bounds on the new-particle masses



*Observed limits, theory uncertainties not included

Only a selection of available mass limits

Probe *up to* the quoted mass limit

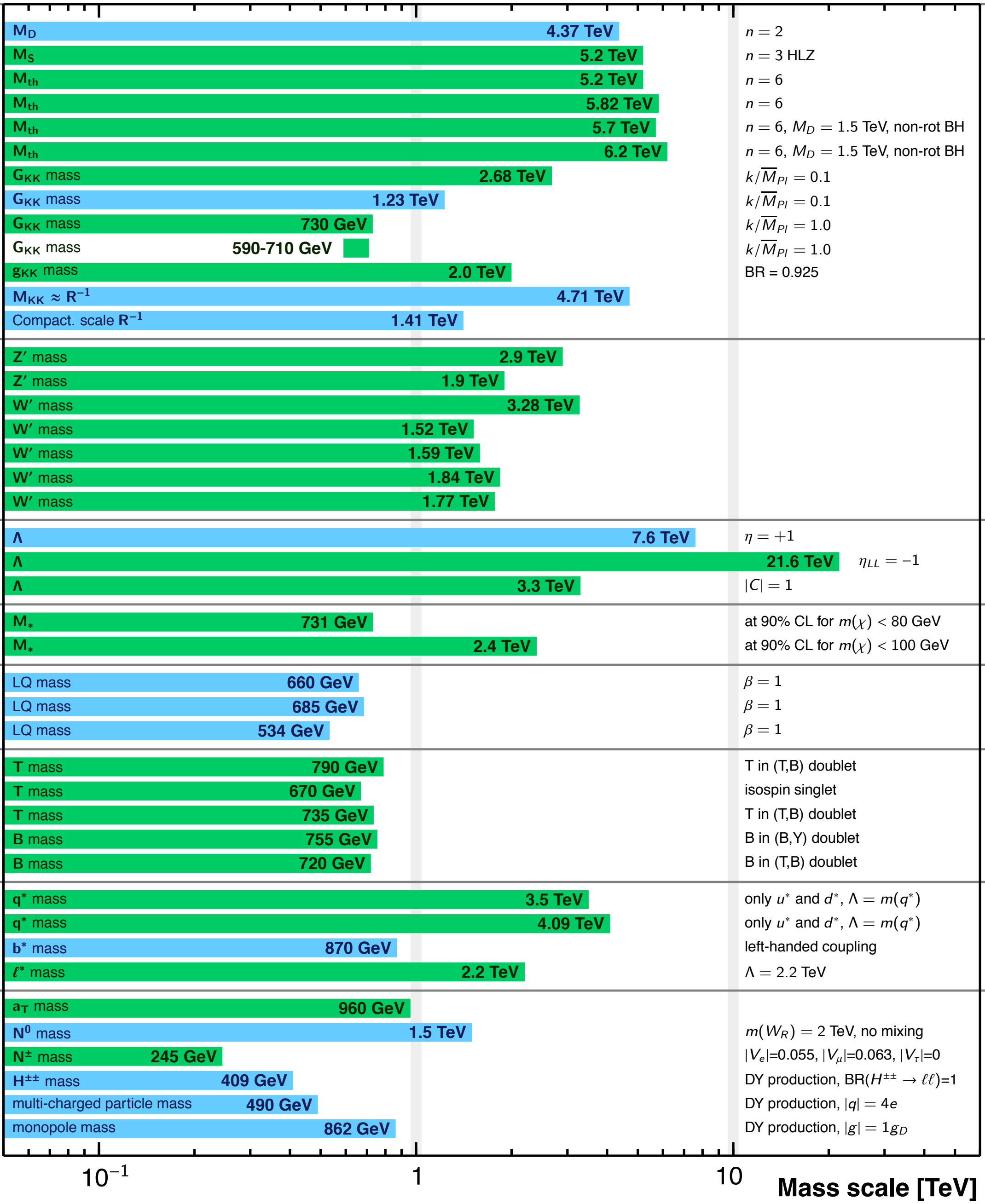
ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	🟦 M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	🟩 M_S 5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	🟩 M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	🟩 M_{th} 5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	🟩 M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	🟩 M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	🟩 G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	🟦 G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	$2\ e, \mu$	2 j / 1 J	–	20.3	🟩 G_{KK} mass 730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	🟩 G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, $\geq$ 1J/2j	Yes	14.3	🟩 g_{KK} mass 2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	🟦 $M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	🟦 Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	🟩 Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	🟩 Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	🟩 W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	🟩 W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2\ e, \mu$	2 j / 1 J	–	20.3	🟩 W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	14.3	🟩 W' mass 1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	🟦 Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	20.3	🟩 Λ 21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	🟩 Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	$0\ e, \mu$	1-2 j	Yes	10.5	🟩 M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	20.3	🟩 M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	🟦 LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	🟦 LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\ e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	🟦 LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	🟩 T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	🟩 T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	🟩 T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	🟩 B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	🟩 B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	🟩 q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	🟩 q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	🟩 b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu, 1\ \gamma$	–	–	13.0	🟩 ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	$1\ e, \mu, 1\ \gamma$	–	Yes	20.3	🟩 a_T mass 960 GeV		to be submitted to PLB
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	2.1	🟦 N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e, \mu$	–	–	5.8	🟩 $N^\pm$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	4.7	🟦 $H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	🟦 multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	🟦 monopole mass 862 GeV	DY production, $\lvert g \rvert = 1 g_D$	1207.6411



🟦 $\sqrt{s}$ = 7 TeV 🟩 $\sqrt{s}$ = 8 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

After a two-year shutdown, the LHC is about to restart at 13-14 TeV.
Let’s hope for new exciting discoveries...

Thank you!!!