Standard Model and Beyond (except supersymmetry)

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Outline

- The Standard Model: reminders and notations
- Model-independent, bottom-up approach to physics BSM
- The gauge sector: Grand Unification
- The EW sector: Composite Higgs and extra-dimensions

The SM
as a renormalizable theory

The (ren) Standard Model lagrangian

$$\mathcal{L}_{\rm SM}^{\rm ren} = \begin{array}{lll} \bar{\Psi}_i i\gamma^\mu D_\mu \Psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} & \text{gauge} & \text{few ‰} \\ +\lambda_{ij}\Psi_i\Psi_j H + \text{h.c.} & \text{flavor} & \text{few \%} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} & \text{? (indirect)} \end{array}$$

- An extremely successful synthesis of particle physics
- in compact notations
- i = 1,2,3: family index
- + neutrinos mass operator: LLHH

The SM fermions

- e,μ,τ, ν_e,ν_μ,ν_τ, d,s,b, u,c,t (Dirac spinors)

  (notation: $e_i \leftrightarrow$ e,μ,τ, $\nu_{ei} \leftrightarrow \nu_e,\nu_\mu,\nu_\tau$, $d_i \leftrightarrow$ d,s,b, $u_i \leftrightarrow$ u,c,t)

- A 4-component Dirac spinor Ψ has two 2-components with definite chirality (γ_5): $\Psi_{L,R} = \dfrac{1 \mp \gamma_5}{2}\Psi$

- A gauge symmetry can mix fields with same Lorentz quantum numbers (in particular it can act differently on Ψ_L, Ψ_R):

$$\Psi + \overline{\Psi} \to \Psi_L, \Psi_R + (\overline{\Psi})_L, (\overline{\Psi})_R \to \Psi_L, (\overline{\Psi})_L + \Psi_R, (\overline{\Psi})_R$$
$$= \underbrace{\Psi_L,\ \overline{\Psi_R}}_{\text{left}} + \underbrace{\Psi_R,\ \overline{\Psi_L}}_{\text{right}}$$

- $e_{iL}, \nu_{e_i L}, d_{iL}, u_{iL}, \overline{e_{iR}}, \overline{\nu_{e_i R}}, \overline{d_{iR}}, \overline{u_{iR}},$

(or)

$$\Psi = \begin{pmatrix} \epsilon\,\psi_c^* \\ \psi \end{pmatrix} \qquad \begin{array}{c} \psi^c \to L\psi_c \\ \psi \to L\psi \end{array} \qquad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\Psi_L = \begin{pmatrix} 0 \\ \psi \end{pmatrix}, \overline{\Psi_R} = \begin{pmatrix} 0 \\ \epsilon\,\psi_c \end{pmatrix} \qquad (\epsilon\psi^c) \to L^{T-1}(\epsilon\psi_c)$$

$$\underbrace{\Psi_L, \overline{\Psi}_R}_{\text{left}} + \underbrace{\overline{\Psi}_L, \Psi_R}_{\text{right}} \leftrightarrow \underbrace{\psi, \psi_c}_{\text{left}} + \underbrace{\psi^*, \psi_c^*}_{\text{right}}$$

- Vocabulary

$$\Psi_1 = \begin{pmatrix} \epsilon\, \psi_1^{c*} \\ \psi_1 \end{pmatrix} \qquad \Psi_2 = \begin{pmatrix} \epsilon\, \psi_2^{c*} \\ \psi_2 \end{pmatrix}$$

$$\overline{\Psi_1}\Psi_2 = \psi_1^c \psi_2 + (\psi_1 \psi_2^c)^* \quad \overline{\Psi_1}\gamma^\mu \Psi_2 = \psi_1^\dagger \sigma^\mu \psi_2 - (\psi_2^c)^\dagger \sigma^\mu \psi_1^c$$

$$\Psi_L = \Psi|_{\psi_c=0} \qquad \Psi_R = \Psi|_{\psi=0}$$

$$(\psi_1\psi_2 = \psi_2\psi_1 = \psi_1^\alpha \epsilon_{\alpha\beta} \psi_2^\beta)$$

- Example: most general mass term with $\psi_1,\ldots,\psi_n$

$$\frac{m_{ij}}{2}\psi_i\psi_j + \text{h.c.} \quad \text{(gauge invariant)}$$

- Note: every theory written in terms of Dirac spinors can be written in terms of Weyl spinors, but not viceversa (e.g. if the number of Weyl spinors is odd)

- Theorem: a gauge theory written in terms of Weyl spinors can be written in terms of Dirac spinors (without L and R projections) if it is Parity invariant and there is no fermion in a real representation of the gauge group

- QED and QCD are parity invariant (Dirac spinors are an historical accident)

The gauge sector

$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

$$q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}$$

$$l_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}$$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
l_i	1	2	-1/2
$e^c{}_i$	1	1	1
q_i	3	2	1/6
$u^c{}_i$	3^*	1	-2/3
$d^c{}_i$	3^*	1	1/3

Y

L-handed
2-component
spinors

i = 1,2,3

A nice property

- The fermion content is chiral
- I.e. no explicit (G_{SM} symmetric) fermion mass term is allowed
- A puzzle or what expected?
- Extra heavy fermions should be vectorlike
(unless they get mass through EWSB)

Another nice property

- Anomaly cancellation
- Is $T_{ijk} \equiv \mathrm{Tr}\,(\tau_i\,\{\tau_j, \tau_k\}) = 0$? $\tau_i = T_A, T_a, Y$

$SU(3)^3$	vectorlike
$SU(3)^2 \times SU(2)$	$\mathrm{Tr}(\sigma_a) = 0$
$SU(3)^2 \times U(1)$	$2\,Y_q + Y_{u^c} + Y_{d^c} = 0$
$SU(3) \times (\text{not } SU(3))^2$	$\mathrm{Tr}(\lambda_A) = 0$
$SU(2)^2 \times U(1)$	$Y_l + 3Y_q$
$U(1)^3$	$2Y_l^3 + 6Y_q^3 + 3Y_{u^c}^3 + 3Y_{d^c}^3 + Y_{e^c}^3 = 0$
grav. anomaly	$2Y_l + 6Y_q + 3Y_{u^c} + 3Y_{d^c} + Y_{e^c} = 0$

(nice, but why??)

SM gauge interactions

From

$$D_\mu = \partial_\mu + i\frac{g}{\sqrt{2}}W_\mu^+ T_+ + i\frac{g}{\sqrt{2}}W_\mu^- T_- + ieQA_\mu + i\frac{g}{c_W}(T_3 - s_W^2 Q)Z_\mu + ig_s g_\mu^A T^A$$

$$e = gs_W = g' c_W = \frac{gg'}{\sqrt{g^2 + g'^2}} \qquad T^\pm = T_1 \pm iT_2$$

Tree level tests of the gauge sector

- Fermion gauge interactions:

$$\overline{\Psi} i \hat{D} \Psi = \overline{\Psi} i \hat{\partial} \Psi - \left(\frac{g}{\sqrt{2}} j_c^\mu W_\mu^+ + \mathrm{h.c.} \right) - \frac{g}{c_W} j_n^\mu Z_\mu - e j_{\mathrm{em}}^\mu A_\mu - g_s j_s^{\mu A} g_\mu^A$$

$$j_c^\mu = \overline{\nu_{iL}} \gamma^\mu e_{iL} + \overline{u_{iL}} \gamma^\mu d_{iL}, \quad j_n^\mu = \sum \overline{f_X} \gamma^\mu (T^3 - s_W^2 Q) f_X$$

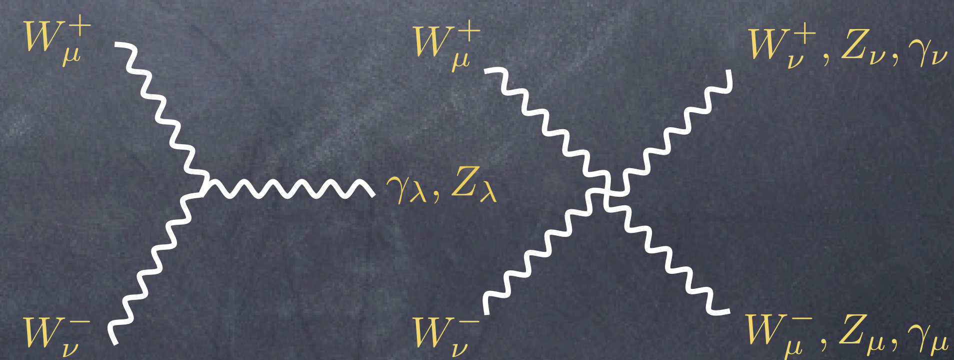
$$(f = \nu_i, e_i, u_i, d_i, \; X = L, R)$$

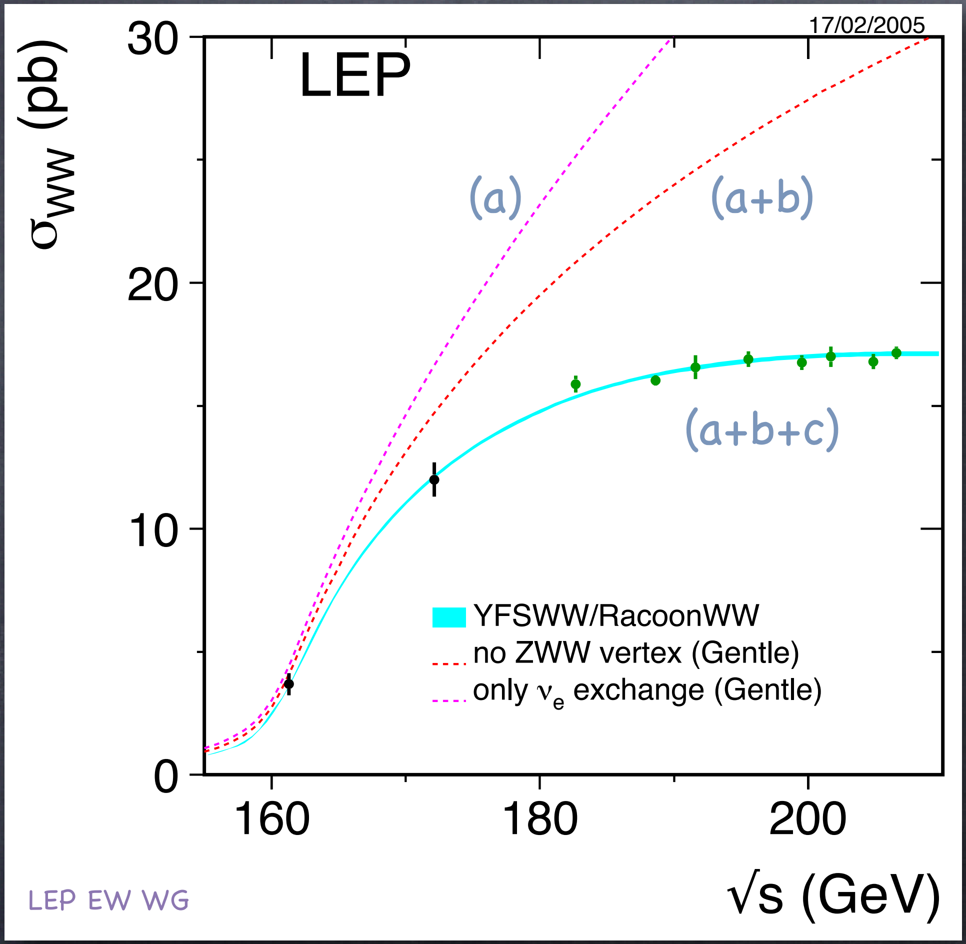
- Gauge boson self-interactions: from $-\frac{1}{4} W_{\mu\nu}^a W^{\mu\nu a} - \frac{1}{4} G_{\mu\nu}^A G^{\mu\nu A}$

$$W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a - g \epsilon_{abc} W_\mu^b W_\nu^c$$

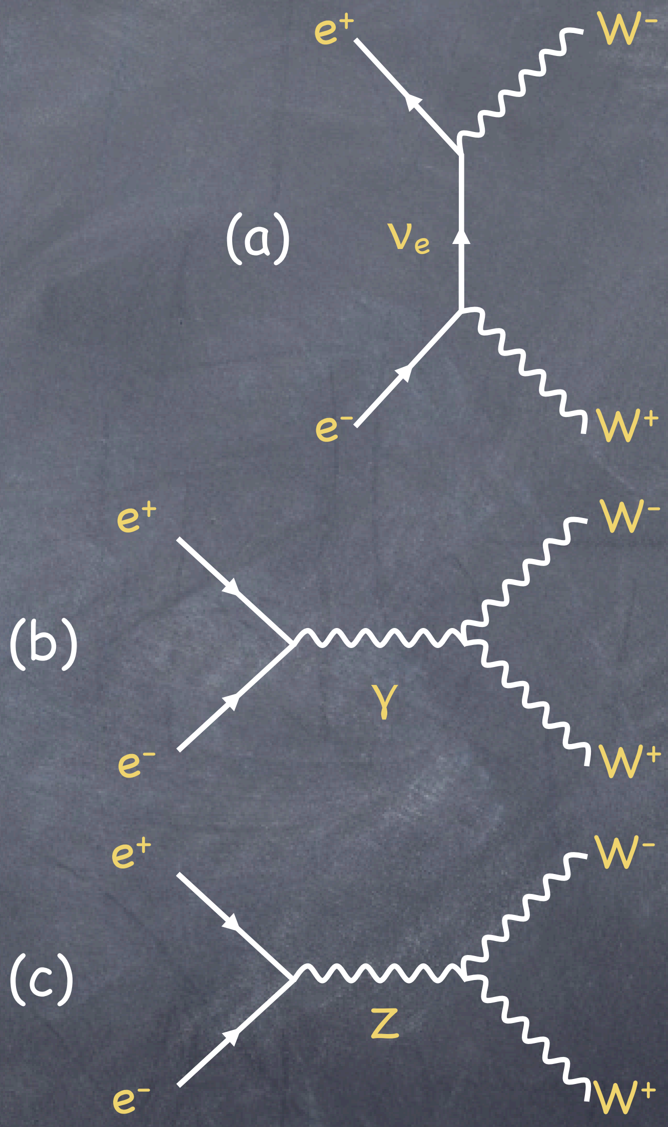
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

in terms of mass eigenstates:





17/02/2005
LEP
σ_{WW} (pb)
30
20
10
0
160
180
200
√s (GeV)
(a)
(a+b)
(a+b+c)
YFSWW/RacoonWW
no ZWW vertex (Gentle)
only ν_e exchange (Gentle)
LEP EW WG



(a)
e^+
W^-
ν_e
e^-
W^+
(b)
e^+
W^-
γ
e^-
W^+
(c)
e^+
W^-
Z
e^-
W^+

The flavour sector

$\mathcal{L}_{\rm SM}^{\rm ren} =$	$\bar\Psi_i i\gamma^\mu D_\mu \Psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$	gauge
	$+\lambda_{ij}\Psi_i\Psi_j H + \text{h.c.}$	flavor
	$+\lvert D_\mu H\rvert^2 - V(H)$	symmetry breaking

family number (horizontal) not understood

	1	2	3
l	l_1	l_2	l_3
e^c	$(e^c)_1$	$(e^c)_2$	$(e^c)_3$
q	q_1	q_2	q_3
u^c	$(u^c)_1$	$(u^c)_2$	$(u^c)_3$
d^c	$(d^c)_1$	$(d^c)_2$	$(d^c)_3$

gauge irreps (vertical) well understood

The flavour sector allows to tell the three families: gauge interactions are $U(3)^5$ symmetric

U(3)^5

$$\mathcal{L}_{\text{SM}}^{\text{ren}} = \begin{array}{lr} \bar{\Psi}_i i\gamma^\mu D_\mu \Psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} & \text{gauge} \\ +\lambda_{ij} \Psi_i \Psi_j H + \text{h.c.} & \text{flavor} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \end{array}$$

Family replication ↔ the gauge lagrangian cannot tell families ↔ is U(3)^5 invariant:

$$U(3)^5 : \begin{array}{l} L_i \to U^L_{ij} L_j \\ e^c_i \to U^{e^c}_{ij} e^c_j \\ Q_i \to U^Q_{ij} Q_j \\ u^c_i \to U^{u^c}_{ij} u^c_j \\ d^c_i \to U^{d^c}_{ij} d^c_j \end{array} \Rightarrow \mathcal{L}_{\text{SM}}^{\text{gauge}} \to \mathcal{L}_{\text{SM}}^{\text{gauge}}$$

(U(3)^5 → U(3) in SO(10) gauge-unified models)

$$\mathcal{L}_{\rm SM}^{\rm flavor} = \lambda_{ij}^{E} e_i^c l_j H^\dagger + \lambda_{ij}^{D} d_i^c q_j H^\dagger + \lambda_{ij}^{U} u_i^c q_j H + \text{h.c.}$$

U(3)^5

$$\mathcal{L}_{\rm SM}^{\rm ren} = \begin{array}{ll} \bar{\Psi}_i i\gamma^\mu D_\mu \Psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} & \text{gauge} \\ +\lambda_{ij}\Psi_i\Psi_j H + \text{h.c.} & \text{flavor} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \end{array}$$

The flavour (Yukawa) lagrangian is is not U(3)^5 invariant (unless λ_{ij}=0)

$$U(3)^5: \begin{array}{l} l_i \to U^l_{ij} l_j \\ e^c_i \to U^{e^c}_{ij} e^c_j \\ q_i \to U^q_{ij} q_j \\ u^c_i \to U^{u^c}_{ij} u^c_j \\ d^c_i \to U^{d^c}_{ij} d^c_j \end{array} \Rightarrow \begin{array}{l} \lambda_E \to U^T_{e^c}\lambda_E U_L \\ \lambda_D \to U^T_{d^c}\lambda_D U_Q \\ \lambda_U \to U^T_{u^c}\lambda_U U_Q \end{array} \quad \begin{array}{c} \mathcal{L}_{\rm SM}^{\rm gauge} \to \mathcal{L}_{\rm SM}^{\rm gauge} \\ \mathcal{L}_{\rm SM}^{\rm SB} \to \mathcal{L}_{\rm SM}^{\rm SB} \\ \langle h \rangle \to \langle h \rangle \end{array}$$

$$\mathcal{L}_{\rm SM}^{\rm flavor} = \lambda^E_{ij} e^c_i l_j H^\dagger + \lambda^D_{ij} d^c_i q_j H^\dagger + \lambda^U_{ij} u^c_i q_j H + \text{h.c.}$$

Accidental symmetries (ren lagrangian)

- The flavour lagrangian breaks $U(3)^5 \times U(1)_H$ to $U(1)_e \times U(1)_\mu \times U(1)_\tau \times U(1)_B \times U(1)_Y$
- In an appropriate flavour basis (i.e. through $U(5)^5$ transformation)

$$\begin{aligned} \lambda^E_{ij} e^c_i L_j H^\dagger &\to \lambda_{e_i} e^{c\prime}_i L'_i H^\dagger \\ \lambda^D_{ij} d^c_i Q_j H^\dagger &\to \lambda_{d_i} d^{c\prime}_i Q'_i H^\dagger \\ \lambda^U_{ij} u^c_i Q_j H &\to \lambda_{u_i} V_{ij} u^{c\prime}_i Q'_i H \end{aligned}$$

- L_e L_μ L_τ: individual lepton numbers
- $L = L_e + L_\mu + L_\tau$: (total) lepton number - arises automatically! (at ren level)
- B: Baryon number - arises automatically! (at ren level)
- (neutrino masses and mixing are a source of LFV; here they are likely to be associated to the NR part of the lagrangian)

No tree level FCNC

- Fermion masses: $H = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix}$ (unitarity gauge)

$$\begin{aligned}\mathcal{L}_{\rm SM}^{\rm flavor} &= \lambda_{ij}^E e_i^c L_j H^\dagger + \lambda_{ij}^D d_i^c Q_j H^\dagger + \lambda_{ij}^U u_i^c Q_j H + \text{h.c.} \\ &= m_{ij}^E e_i^c e_j \quad + m_{ij}^D d_i^c d_j \quad + m_{ij}^U u_i^c u_j \quad + \text{h.c.} + \dots\end{aligned}$$

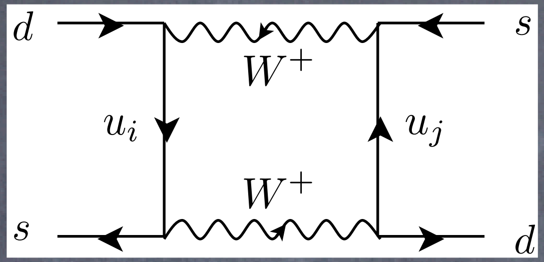
- In terms of mass eigenstates:

$$\begin{aligned} j^\mu_{\rm c,had} &= \overline{u}_i \sigma^\mu d_i = V_{ij} \overline{u}'_i \sigma^\mu d'_j \\ j^\mu_{\rm n,had} &= (j^\mu_{\rm n,had})' \\ j^\mu_{\rm em,had} &= (j^\mu_{\rm em,had})' \end{aligned}$$

$\boxed{V = U_u U_d^\dagger}$ Cabibbo Kobayashi Maskawa (CKM) matrix

Anomalously small loop-induced FCNC

- Expect:



$$\sim \quad \frac{1}{M_W^2} \times \frac{g^4}{(4\pi)^2}$$

K^0 - $\overline{\mathrm{K}}^0$ oscillations

- Instead: 10^6 smaller

- Because of peculiar flavour structure of the SM, or approximate $U(2)^5$ symmetry of SM lagrangian

- Challenge for new physics at TeV scale

Experimental values

- In an appropriate basis

$$\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda_{33} \end{pmatrix} + \text{small} \quad (U,\, D,\, E)$$

(the top Yukawa coupling is O(1); the bottom and tau Yukawas are also small but can be large in the MSSM)

- In particular,
  - $\lambda_{1,2} \ll \lambda_3$
  - $V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \text{small}$

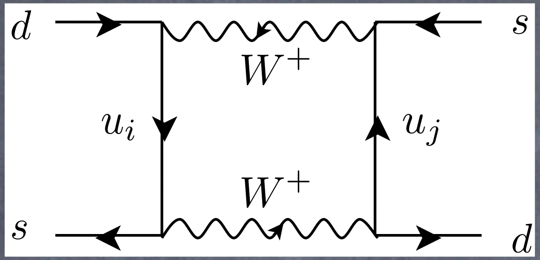
Approximate flavour symmetry

- The flavour lagrangian is approximately $U(2)^5$ flavour symmetric (exactly symmetric in the limit $\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda_{33} \end{pmatrix}$ which also implies $V = 1_3$)

- This (or equivalently the smallness of $\lambda_{1,2}$ and V_{ij} $i \neq j$) is the origin of the anomalously small FCNC processes in the SM (and the origin of the flavour problem)

Anomalously small loop-induced FCNC

- Because of the approximate U(2)^5 (GIM)



K^0 - $\overline{K}^0$ oscillations

$$\sim \quad \frac{1}{M_W^2} \times \frac{g^4}{(4\pi)^2} \times \epsilon$$

$$\epsilon = 0 \quad \text{in the U}(2)^5 \text{ limit}$$

$$\epsilon \sim 10^{-6} \quad \text{experiment}$$

- $\left(\epsilon = (V^\dagger_{su_i} V_{u_i d})(V^\dagger_{su_j} V_{u_j d}) f\left(\frac{m^2_{u_i}}{M_W^2}, \frac{m^2_{u_j}}{M_W^2}\right) \right.$

  i = 3: f = O(1), $|V_{td}V_{ts}| \ll 1$

  i = 1,2: $|V_{id}V_{is}|$ = O(1), f $\ll$ 1)

Challenge for new physics at TeV

- Same for CP-violating effects

Electroweak symmetry breaking

- "Observed" fields:
  - Gauge bosons: $g_\mu^A \quad W_\mu^a \quad B_\mu$
  - Femions: $Q_i \quad u_i^c \quad d_i^c \quad L_i \quad e_i^c$
  - "3/4" of the Higgs field: G_a (long. part of massive gauge bosons, Goldstones of the spontanously broken gauge symmetry)
  - SM masses arise from the symmetry breaking scale v = 174 GeV (G_a decay constant)
- Mission #1 of the LHC: what is the mechanism underlying EWSB? Or where do the G_a and v = 174 GeV come from?
- Mission accomplished: SM Higgs doublet

$$\boxed{G_a + h \;\rightarrow\; H = \begin{pmatrix} G^+ \\ v + \dfrac{h + iG^0}{\sqrt{2}} \end{pmatrix}} \approx (1,2,½)$$

at least approximately

The Higgs sector

- Most general gauge invariant ren. lagrangian for H:

$$\mathcal{L}_H = (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)$$
$$V(H^\dagger H) = \mu^2 H^\dagger H + \frac{\lambda_H}{2}(H^\dagger H)^2$$

- $\lambda_H > 0$
- $\mu^2 < 0 \Rightarrow \langle H \rangle \neq 0 \Rightarrow$ electroweak symmetry breaking
- ($\mu^2 > 0 \Rightarrow$ still electroweak symmetry breaking, but at $\Lambda \approx m_\pi$)

QED unbroken

- Fix the Higgs quantum numbers from fermion masses. Then the electric charge is automatically conserved

$$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}, \; v > 0, \; v^2 = \frac{|\mu^2|}{\lambda_H} \approx (174\,\mathrm{GeV})^2 \qquad m_H^2 = 2\,\lambda_H(v^2)\,v^2$$

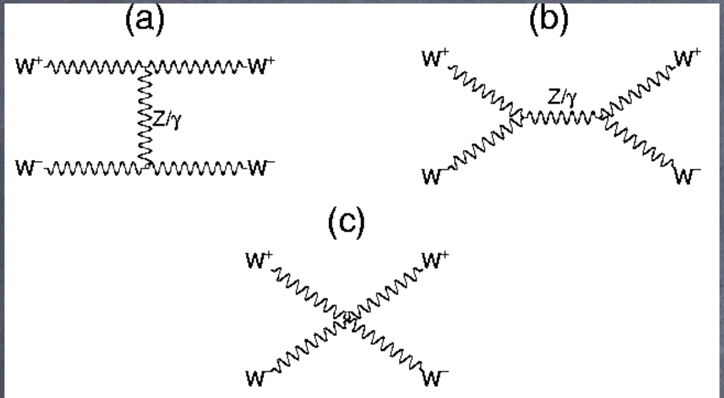
$$T = aY + b_a T_a, \; a, b_a \text{ real}, \; T_a = \frac{\sigma}{2}, \; Y = \frac{\mathbf{1}}{2}$$

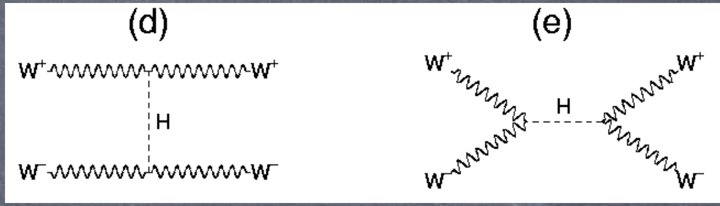
$$0 = T\,\langle H \rangle = \frac{v}{2}\begin{pmatrix} b_1 - ib_2 \\ a - b_3 \end{pmatrix} \Rightarrow T \propto Q$$

- 3 broken generators ↔ 3 massive vectors ↔ 3 unphysical Goldstone bosons ↔ 1 real physical Higgs particle

Constraints on the Higgs mass I
Avoiding the strong coupling regime: $m_H < O(\text{TeV})$

- $A(W_L W_L \to W_L W_L) = \Sigma_l \, a_l \, A_l$, a_l = partial wave amplitude
- Unitarity bound: $|a_0| \leq 1$
- Tree level, no Higgs: $a_0 \sim \dfrac{s}{16\pi v^2}$, $s = (p_1+p_2)^2$, $v \approx 174$ GeV

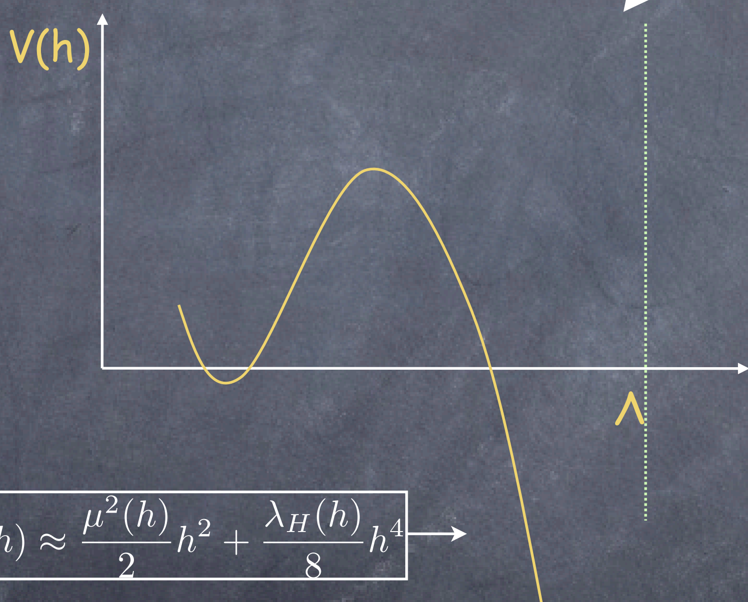




- Unitarity bound saturated at $s \approx (1.2 \text{ TeV})^2$
- Bad behaviour of a_0 due to the longitudinal part of the W propagator ~ $p_\mu p_\nu/(M_W)^2$, cancelled by Higgs exchange

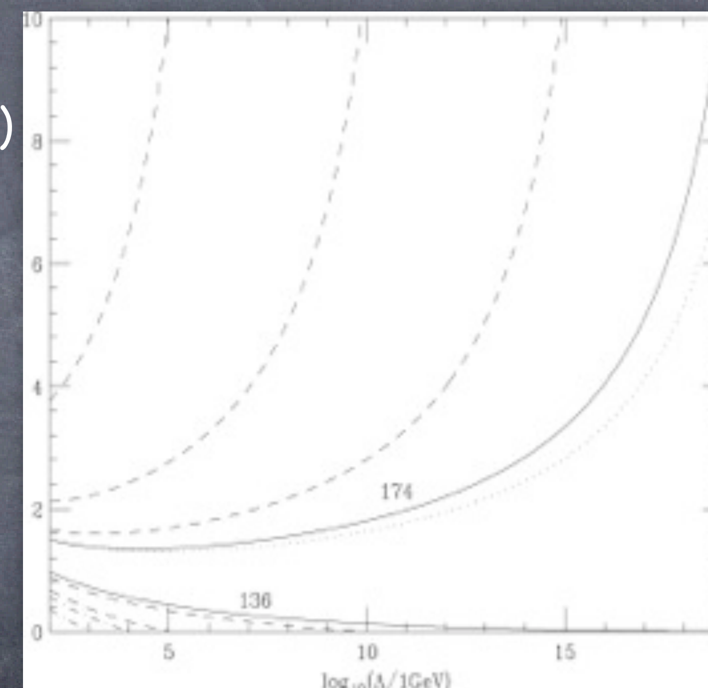
Constraints on the Higgs mass II
Triviality and stability

- Assume that the SM holds up to the scale Λ:
- $\lambda_H(\Lambda)$ finite (perturbative) $\Rightarrow$ upper limit on m_H
- $\lambda_H(\Lambda) > 0$ $\Rightarrow$ lower limit on m_H

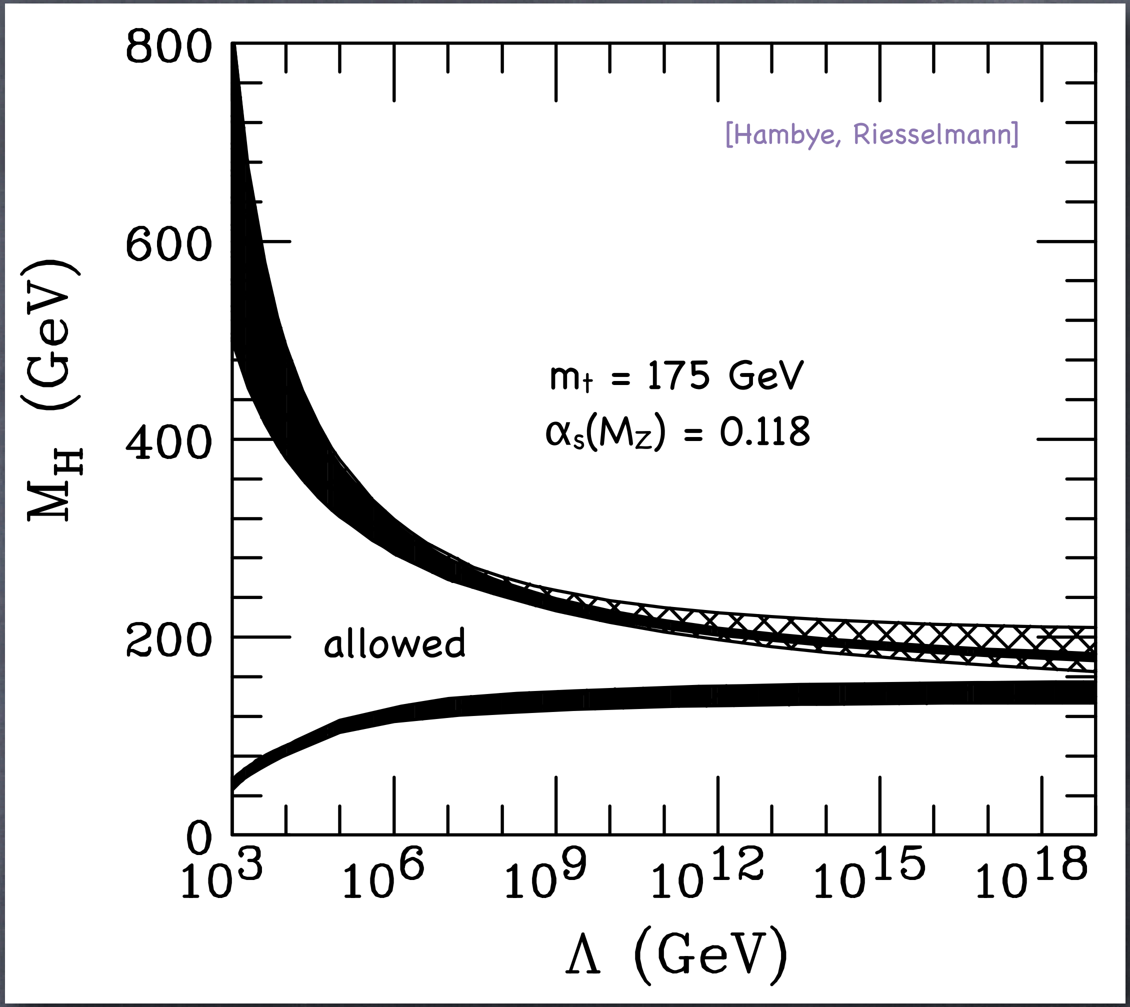


$$V(h) \approx \frac{\mu^2(h)}{2} h^2 + \frac{\lambda_H(h)}{8} h^4$$

$\lambda_H(\Lambda)$



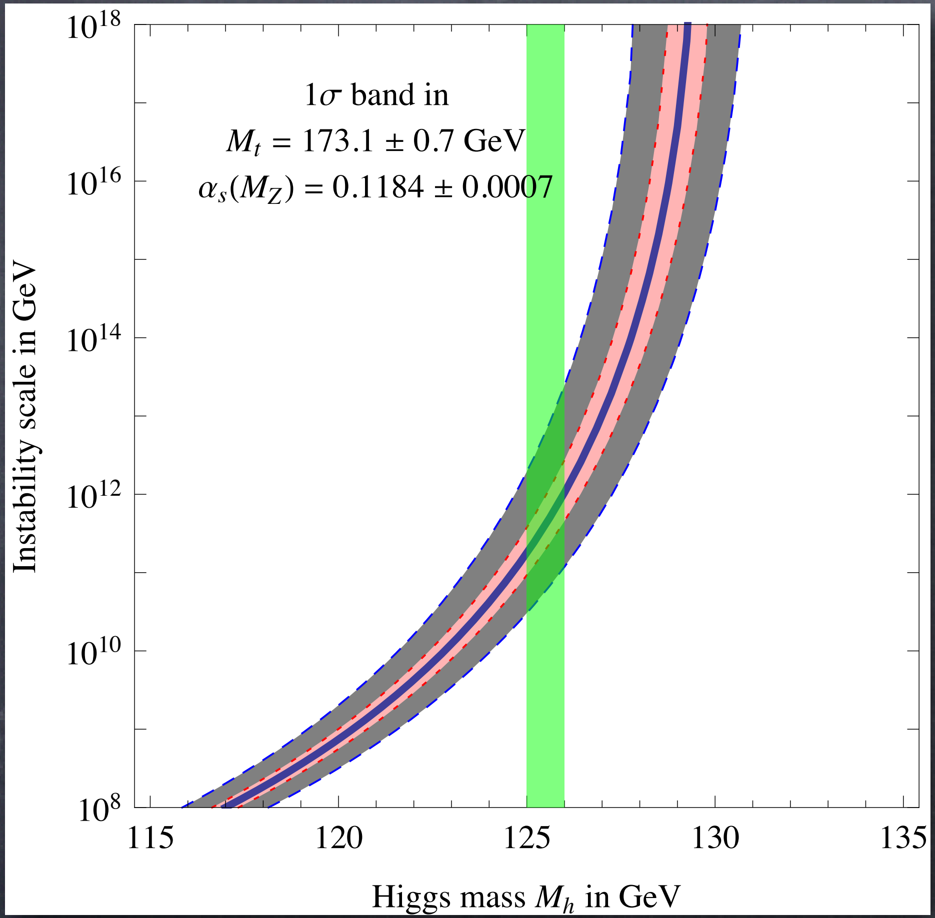
- (if $\lambda_H(\Lambda) < 0$, the absolute minimum of the effective potential resides at or above Λ)

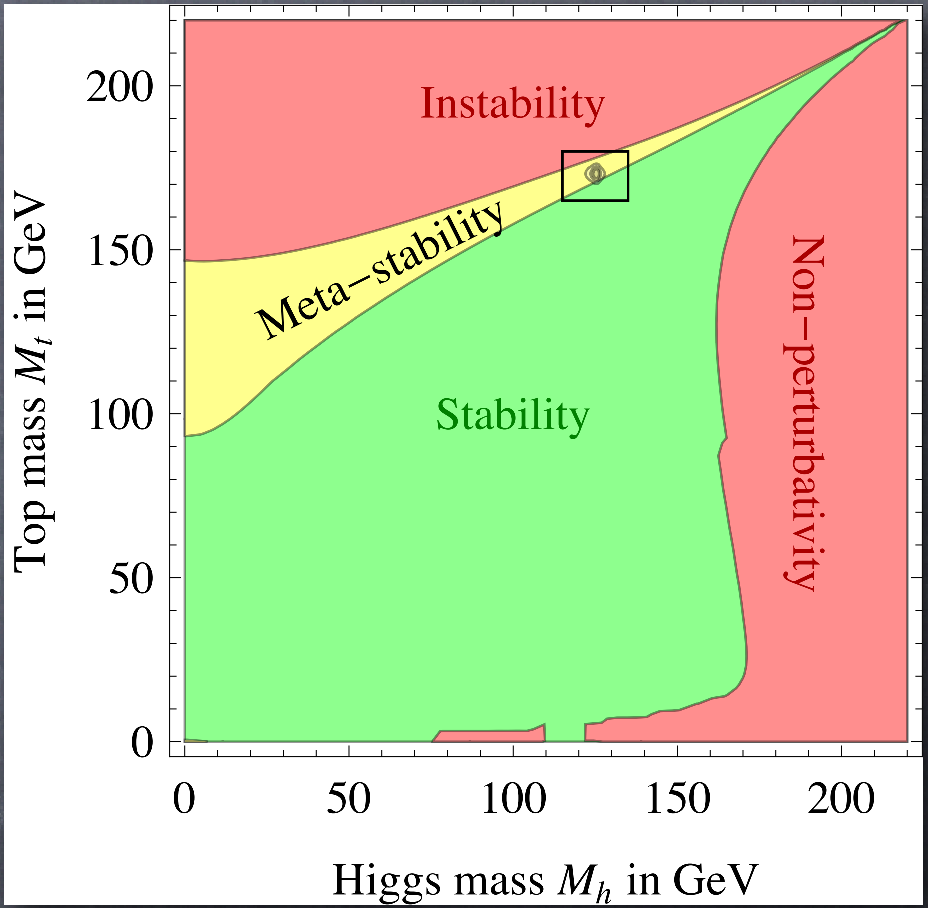


- The lower limit can be relaxed if we live in a metastable vacuum
- $\Lambda \gg v$ introduces a naturalness problem

What the LHC tells us

Degrassi et al





What the LHC tells us

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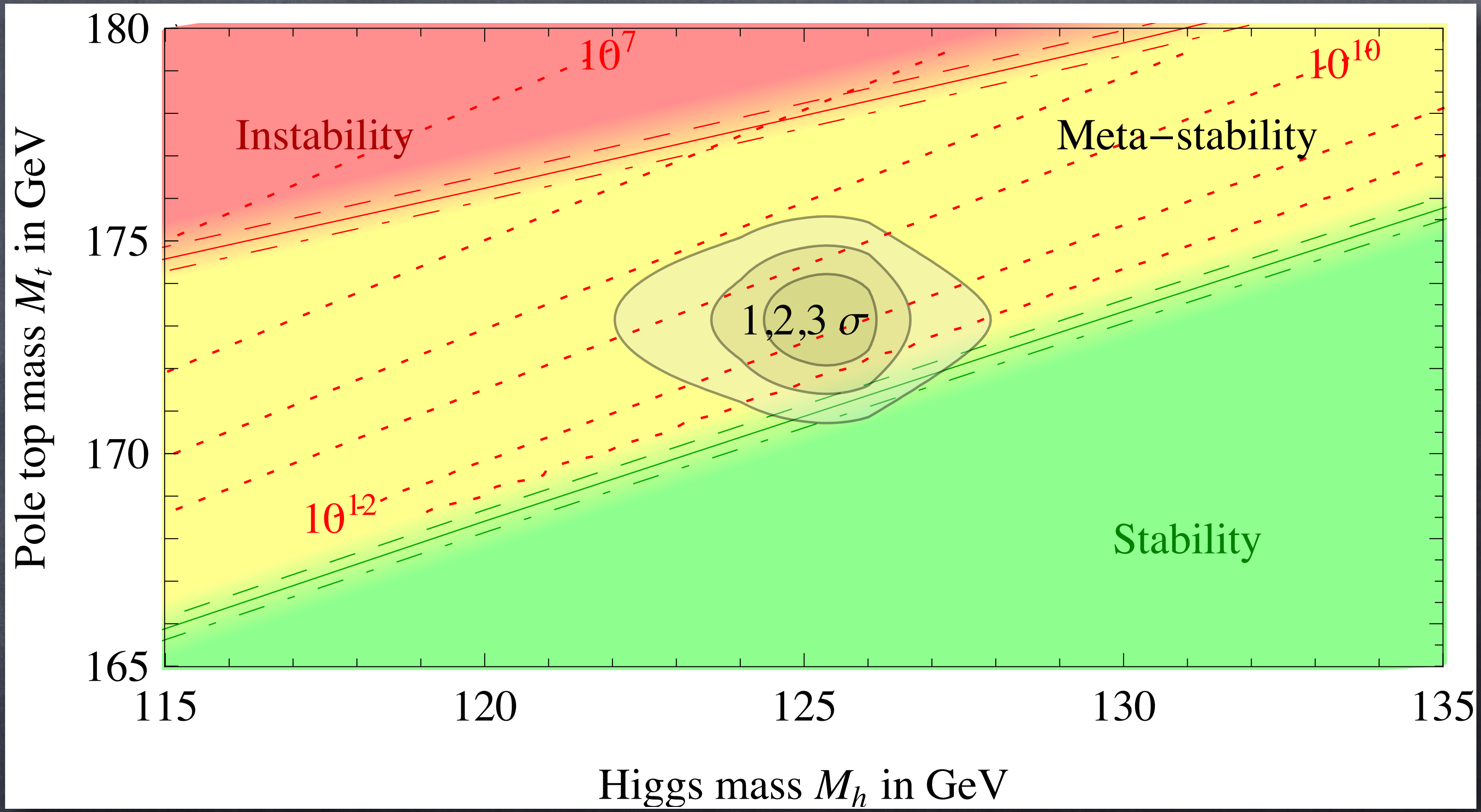
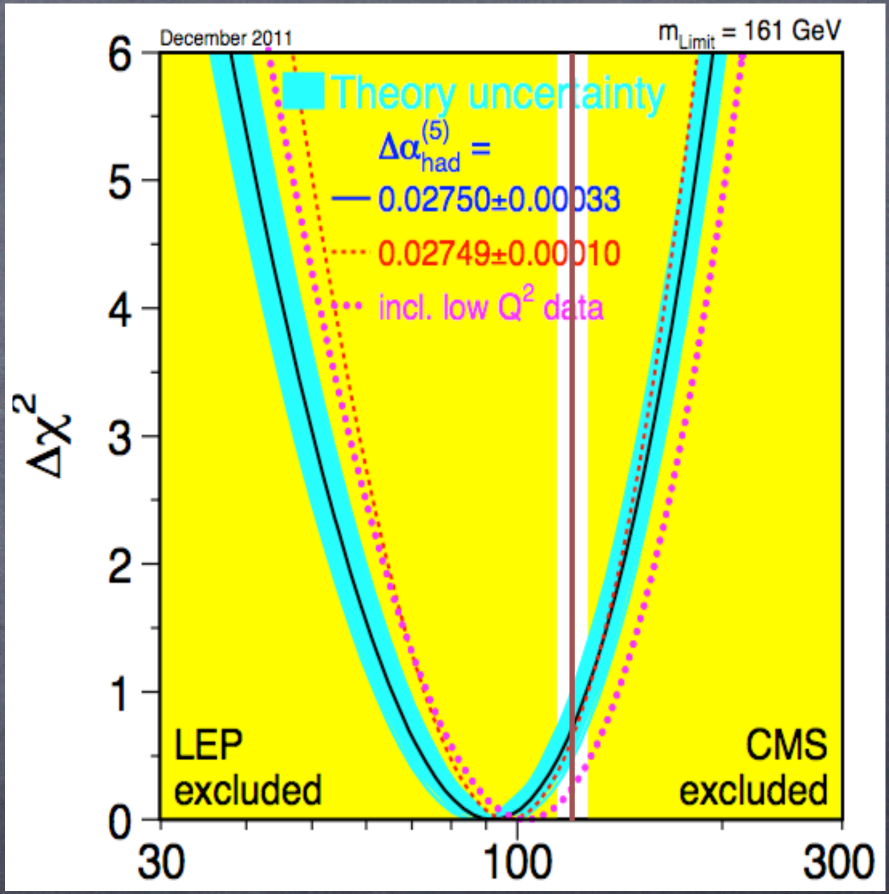


Constraints on the Higgs mass III
Experiment

- Indirect upper limit from EW precision tests (see below):
  161 GeV @ 95% CL (assumes no new physics contributions)

- Direct experimental limit (within SM):
  122 GeV < m_H < 128 GeV @ 99% CL
  or m_H > 600 GeV (trivial combination).
  And actually: m_H = (125.5±0.5) GeV



m_H (GeV)

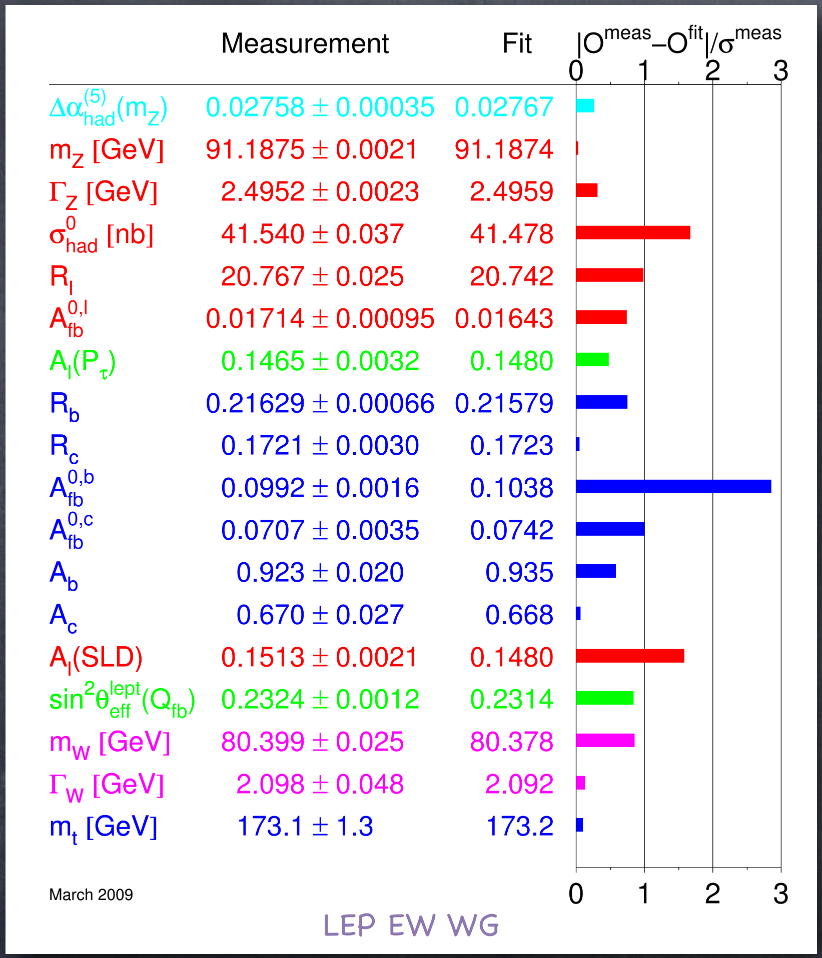
Tests of the gauge (electroweak) sector

- The gauge sector (fermion gauge interactions) is the best tested part of the SM
  - Wide range of predictions:

    $g, g', v \leftrightarrow (\alpha), s_W, v \leftrightarrow$ QED, W&Z masses, their self-interactions and all fermion gauge interactions (tree level)
  - Measurements at the ‰ level: sensitivity to quantum corrections (m_t, m_H)
- Good agreement with the experiment

High energy tests

- At LEP II, LEP I, SLC, Tevatron
- M_Z, Γ_Z,
  - Z resonance in $e+e- \to f\bar{f}$
  - N_ν = 2.9841±0.0083: 3 light neutrinos + anomaly cancellation = 3 families
- M_W, Γ_W from $e^+e^- \to W^+ + W^-$ at LEP II
- $\sigma_{h,l}$
- $WW\gamma$, WWZ couplings $\propto$ e, gc_W
- $$A^f_{LR} = \frac{\Gamma(Z \to f_L \bar{f}_R) - \Gamma(Z \to f_R \bar{f}_L)}{\Gamma(Z \to f_L \bar{f}_R) + \Gamma(Z \to f_R \bar{f}_L)}$$
- A_{FB} ...



- Accuracy in most cases is at the ‰ level → sensitivity to 1-loop corrections, which involve
  - g, g', v
  - m_t, $\alpha_s(M_Z)$, $\Delta\alpha_{had}(M_Z)$
  - m_h
- and bring together
  - the gauge sector: $g^2/(4\pi)^2$, $g'^2/(4\pi)^2$
  - the flavour sector: $\lambda^2/(4\pi)^2$
  - the EW-breaking sector: $g^2/(4\pi)^2 \log(m_h/M_W)$
- The agreement works for relatively low values of m_h

Custodial symmetry

- $\rho \equiv \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 \text{ (tree level)}$
  - Not guaranteed by gauge invariance nor by the breaking pattern
  - Peculiar of EW breaking by a doublet (triplets ruled out)

- Reminder

$$D_\mu = \partial_\mu + igW_\mu^a \frac{\sigma_a}{2} + i\frac{g'}{2}B_\mu$$

$$W_\mu^+ \equiv \frac{W_\mu^1 - iW_\mu^2}{\sqrt{2}}, \; Z_\mu \equiv c_W W_\mu^3 - s_W B_\mu, \; \begin{cases} c_W \equiv \cos\theta_W = g/\sqrt{g^2+g'^2} \\ s_W \equiv \sin\theta_W = g'/\sqrt{g^2+g'^2} \end{cases}$$

θ_W = Weinberg angle

$\rho \approx 1 \leftrightarrow$ (approximate) custodial SU(2)

- $\rho = 1$ if in the $g' = 0$ limit $W^{1,2,3}$ have equal mass

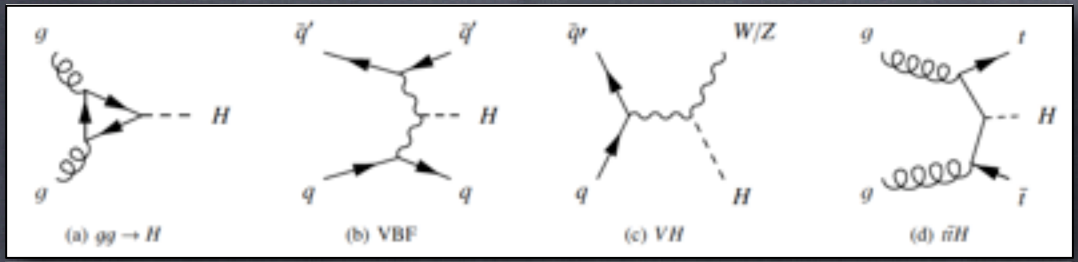
- I.e. if a $SO(3) \approx SU(2)$ symmetry rotates the real fields $W^{1,2,3}$

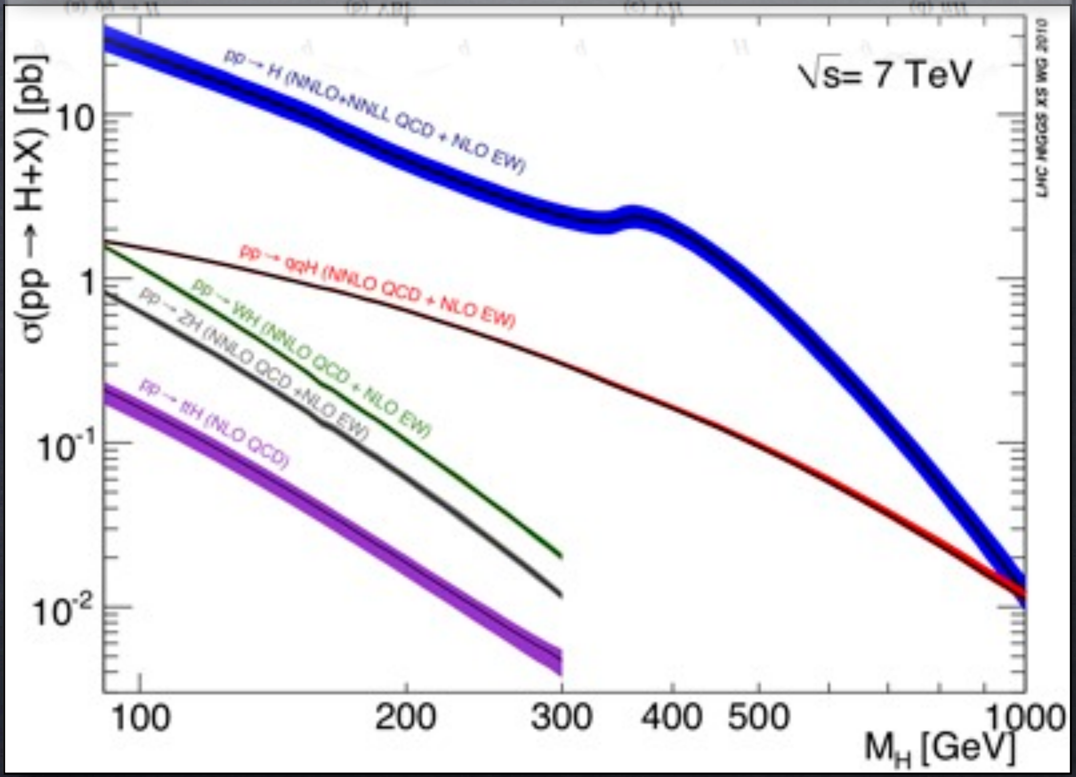
- The custodial symmetry in the Higgs sector: the Higgs lagrangian is SO(4) symmetric, as
$$|H|^2 = h_{1R}^2 + h_{1I}^2 + h_{2R}^2 + h_{2I}^2 \ .$$
SO(4) is spontaneously broken to SO(3) by $\langle h_{2R} \rangle \neq 0$

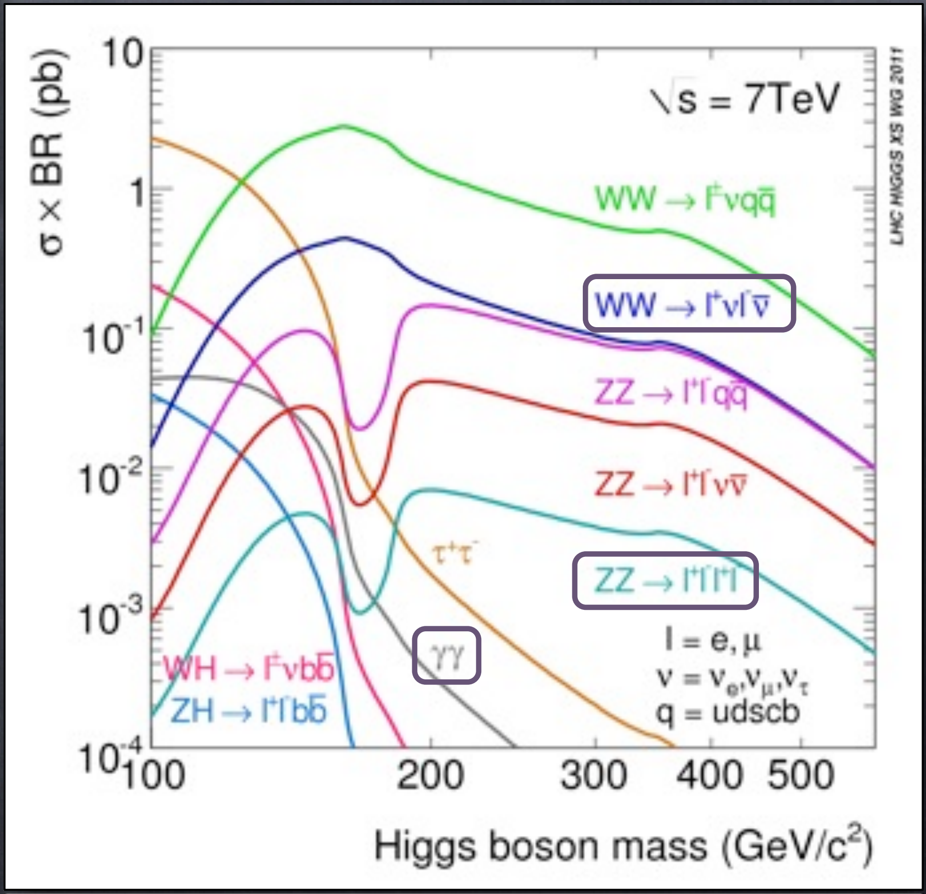
- The custodial symmetry in the fermion sector: $SO(4) \approx SU(2)_L \times SU(2)_R$, where $SU(2)_R$ acts on the right-handed fields

- The symmetry is exact in the limit $g' = 0$, $\lambda_U = \lambda_D \rightarrow$ loop corrections to $\rho = 1$

Direct searches



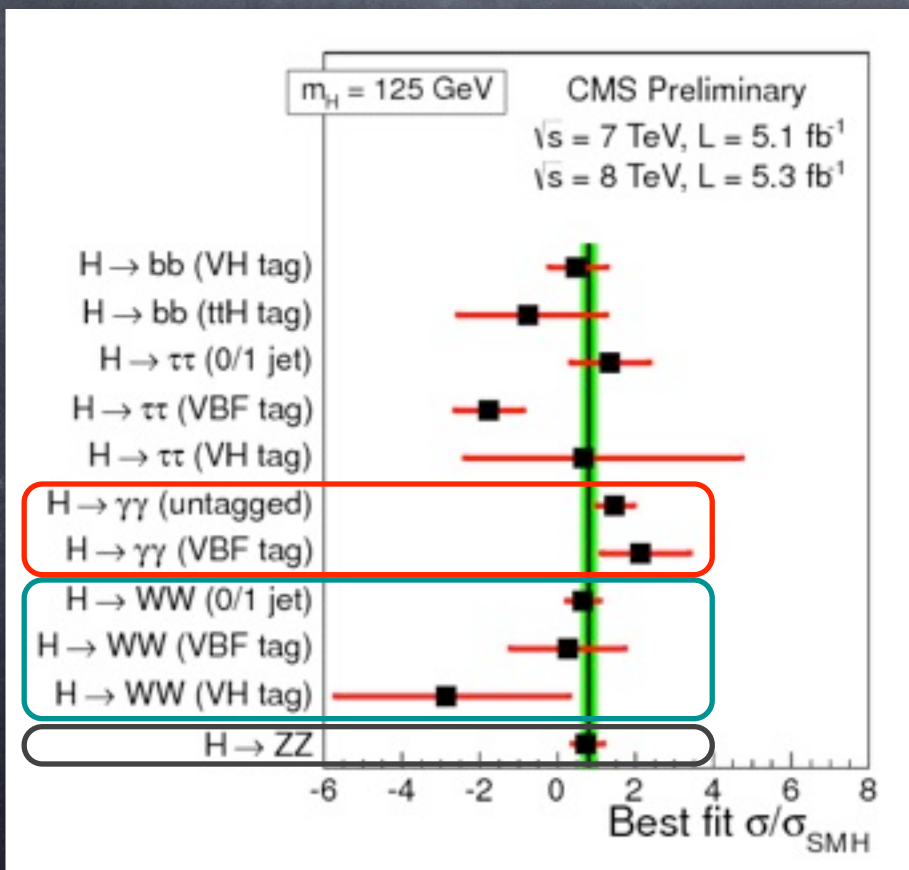


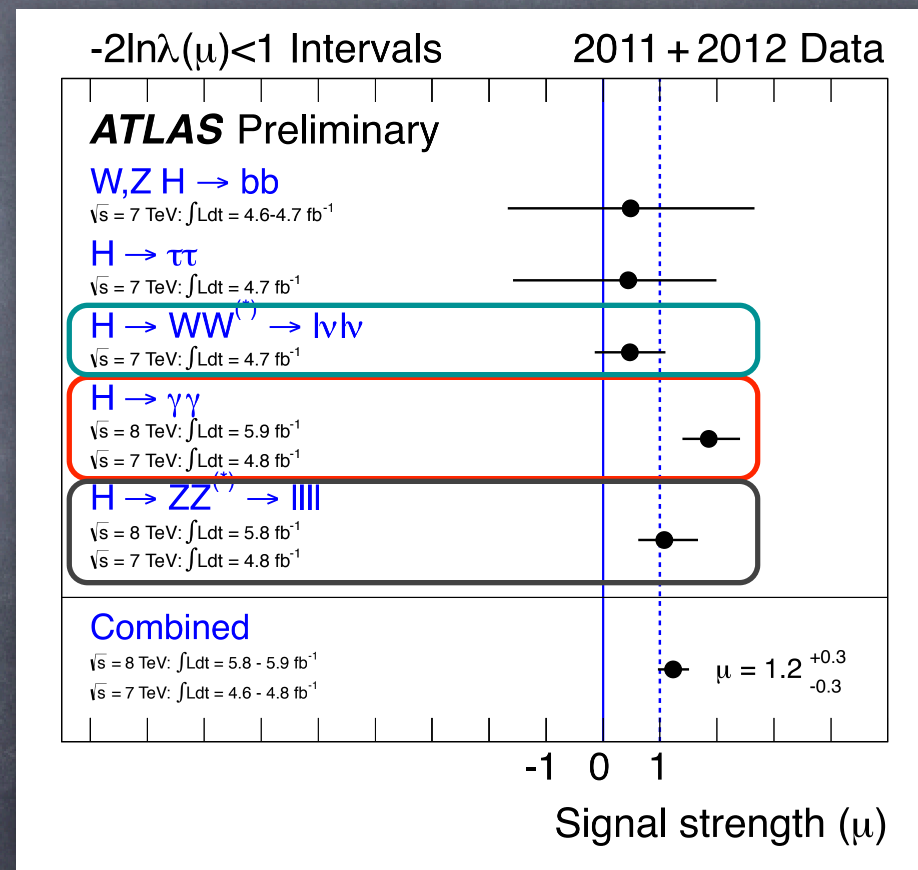


Experimental status

- A new resonance "h" observed
  - CMS: m_H = (125.3±0.6) GeV @ 5σ
  - Atlas: m_H = (126.2±0.7) GeV @ 5σ

and hV → bb (ll,lν,νν) from CDF/D0

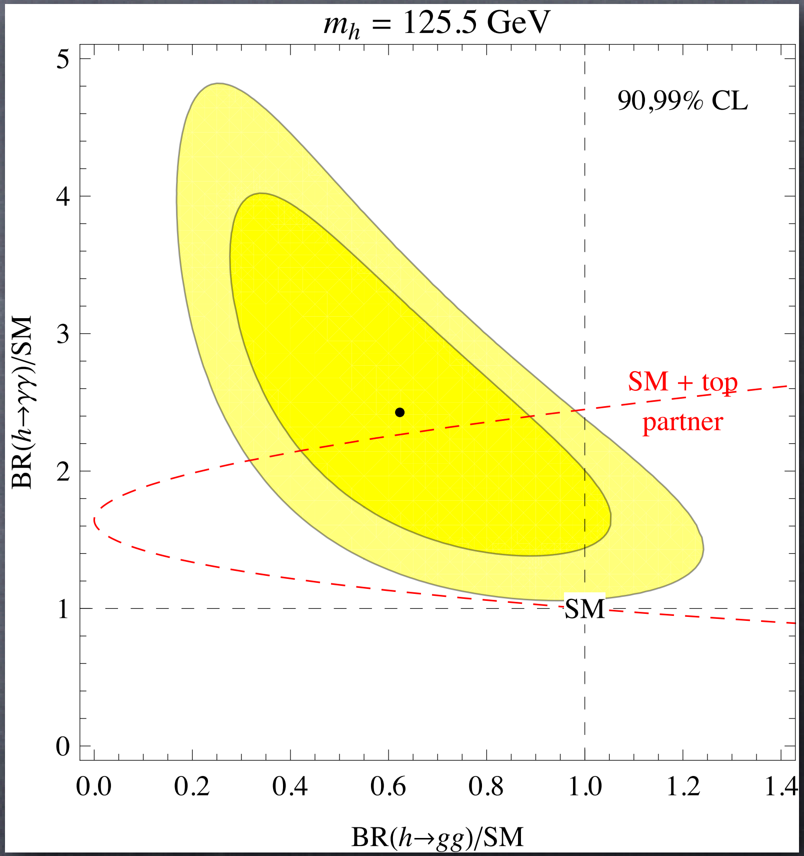




- “h” has S = 0 (or 2)
- “h” is $SU(3)_c \times U(1)_{em}$ neutral
- “h” is a singlet under the custodial symmetry
- “h” compatible with SM Higgs despite some deviations
- deviations from SM not expected to be large given what we knew

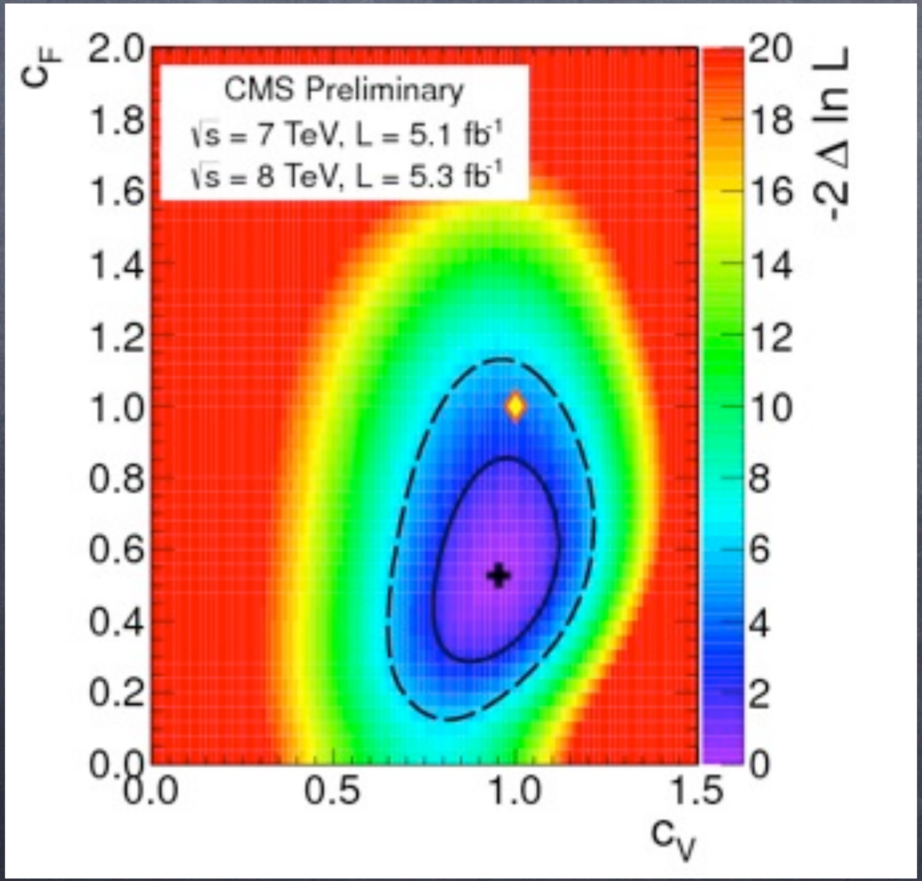
Deviations from SM Higgs? (1)

- All production and decay processes are tree-level except
  - main production process $gg \to h$
  - cleanest decay channel $h \to \gamma\gamma$
- Let those two rates free [Giardino et al, Buckley and Hooper, ...]
- Mild preference for enhanced $\gamma\gamma$, suppressed gg
- SM looks marginal but
  - $\chi^2 \approx 19$ with 16 dofs (expect $n \pm n^{1/2}$)
  - QCD uncertainties [Baglio et al]

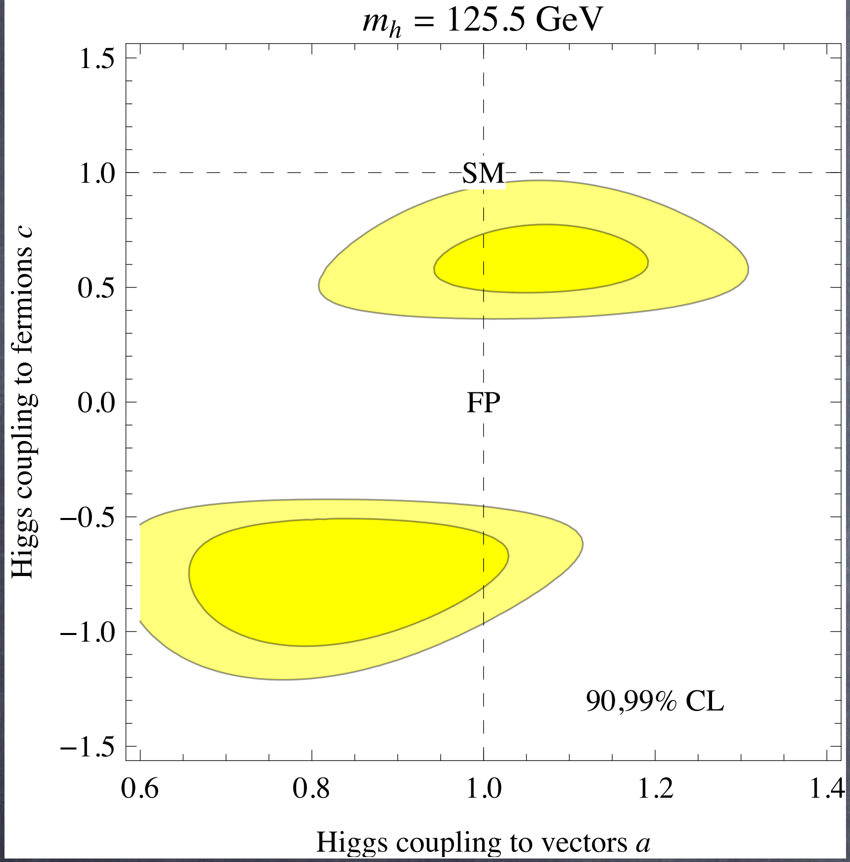


Deviations from SM Higgs? (2)

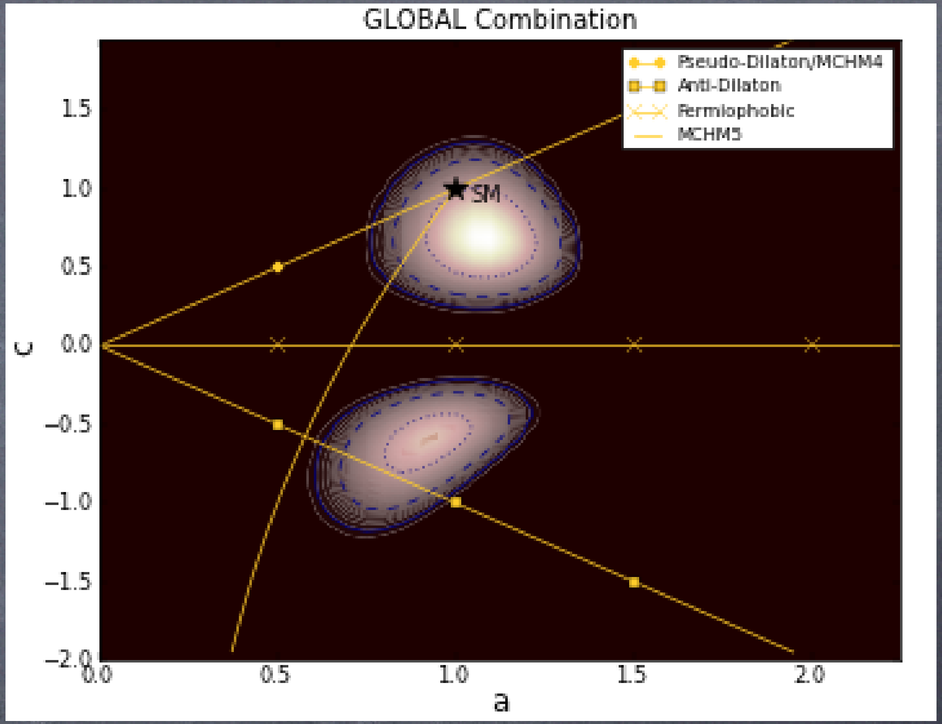
- Fit "h" couplings
- This assumes: SM fermions and gauge bosons + "h" and nothing else
  - contributing to the signal (e.g. heavier H)
  - entering production and decay (same production and detection channels with modified couplings)
- CMS:



(C_F < 0? Atlas?)



m_h = 125.5 GeV
SM
FP
90,99% CL
Higgs coupling to fermions c
Higgs coupling to vectors a



GLOBAL Combination
Pseudo-Dilaton/MCHM4
Anti-Dilaton
Fermiophobic
MCHM5
SM
c
a

$R_t < 1$?