Introduction to particle physics: Standard Model and beyond

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IFIC
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Lecture 2

CSIC
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ISAPP 2014,Via Mazzini 121/125, Belgirate, Lago Maggiore (Italy)

CC and NC weak interactions

fermion gauge interactions

determined by the fermion covariant derivatives

$$
\begin{aligned}
D_\mu \chi_L &= \partial_\mu \chi_L - igA_\mu \chi_L - i\frac{g'}{2} B_\mu \chi_L \\
D_\mu \chi_R &= \partial_\mu \chi_R \qquad\qquad\qquad - ig' B_\mu \chi_R \\
D_\mu \psi_L &= \partial_\mu \psi_L - igA_\mu \psi_L - i\frac{g'}{6} B_\mu \psi_L \\
D_\mu \psi_{uR} &= \partial_\mu \psi_{uR} \qquad\qquad\qquad + \frac{2ig'}{3} B_\mu \psi_{uR} \\
D_\mu \psi_{dR} &= \partial_\mu \psi_{dR} \qquad\qquad\qquad - \frac{ig'}{3} B_\mu \psi_{dR}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\text{matter}} &= -\sum_A (\bar{\chi}_{AL} \gamma_\mu D_\mu \chi_{AL} + \bar{\chi}_{AR} \gamma_\mu D_\mu \chi_{AR}) \\
&\quad - \sum_A (\bar{\psi}_{AL} \gamma_\mu D_\mu \psi_{AL} + \bar{\psi}_{AR} \gamma_\mu D_\mu \psi_{AR}) + \mathcal{L}_{\text{Yukawa}}
\end{aligned}
$$

CHARGED CURRENT INTERACTIONS & CKM MATRIX

$$\mathcal{L}^q_{CC} = \frac{ig}{\sqrt{2}} W^+_\mu \bar{U}_L \gamma_\mu D_L + \textbf{h.c.}$$

$$\mathcal{L}^q_{CC} = \frac{ig}{\sqrt{2}} W^+_\mu \bar{u}_L \gamma_\mu \underbrace{\Omega^{u\dagger}_L \Omega^d_L}_{V} d_L + \textbf{h.c.}$$

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix}_L \longrightarrow \begin{pmatrix} e^{i\theta_u} & & \\ & e^{i\theta_c} & \\ & & e^{i\theta_t} \end{pmatrix} \begin{pmatrix} u \\ c \\ t \end{pmatrix}_L$$

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \longrightarrow \begin{pmatrix} e^{i\theta_d} & & \\ & e^{i\theta_s} & \\ & & e^{i\theta_b} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

quark phases can be redefi ned keeping mass terms invariant leaving only $n^2 - n - (n-1) = n^2 - 2n + 1 = (n-1)^2$, thus 9-3-2=4 physical parameters in the KM matrix

Symmetrical CKM parametrization

$$V^{\text{CKM}} = \omega_0(\gamma) \prod_{i<j}^{n} \omega_{ij}(\eta_{ij})$$

$$\omega_0(\gamma) = \exp i(\sum_{a=1}^{n} \gamma_a \, , A^a_a)$$

$$\omega_{ab}(\eta_{ab}) = \exp \sum_{a=1}^{n} (\eta_{ab} A^b_a - \eta^*_{ab} A^a_b)$$

$$\eta_{ab} = |\eta_{ab}| \exp i\theta_{ab}$$

Schechter & JV PRD22 (1980) 2227 & PDG

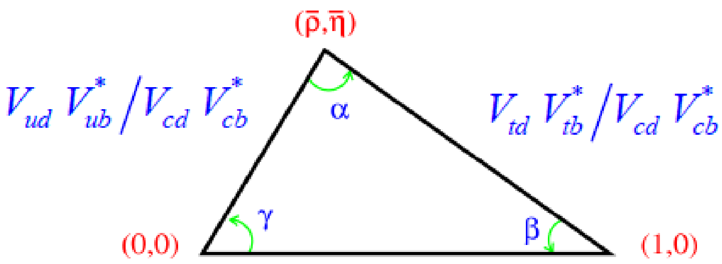
Rodejohann, JV Phys.Rev. D84 (2011) 073011

Wolfenstein useful truncation

$$\mathbf{V} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}(\lambda^4)$$

Unitarity triangles

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Area gives an invariant measure of CP violation in the CKM model

ELECTRO-WEAK NEUTRAL CURRENTS

$$D_\mu = \cdots - igA^3_\mu T_3^\psi \psi + \frac{ig'}{2} B_\mu Y_W^\psi \psi$$

$$= \cdots[-ig(c_W Z_\mu - s_W A_\mu)T_3^\psi + \frac{ig'}{2}(s_W Z_\mu - c_W A_\mu)Y_W^\psi]\psi$$

$$= \cdots[i \underbrace{g s_w}_{e} A_\mu \underbrace{(T_3 + \frac{1}{2}Y_W)_\psi}_{Q_\psi} - \frac{ig'}{2} Z_\mu \underbrace{(T_3 - s_W^2 Q)_\psi}_{\text{neutral current (NC)}}]\psi$$

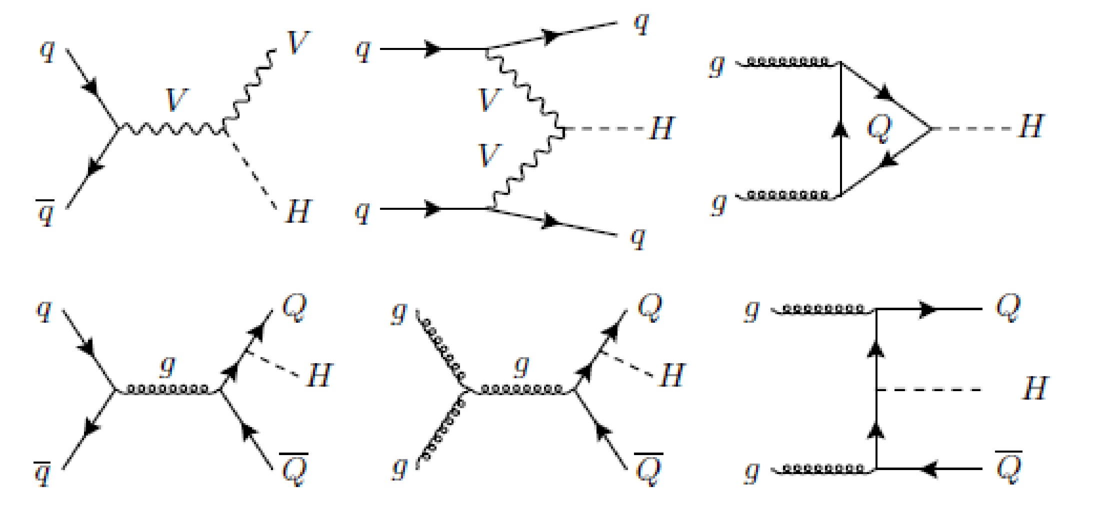
$$J_\mu^{\text{em}} = i \sum_{\text{all}} \bar{\psi}\gamma_\mu Q_\psi \psi$$

$$J_\mu^Z = i \sum_{\text{all}} \bar{\psi}\gamma_\mu (T_3 - xQ)\psi$$

ψ	T_3	Q	$T_3 - xQ$
ν_L	$1/2$	0	$1/2$
e_L	$-1/2$	-1	$-1/2 + x$
u_L	$1/2$	$2/3$	$1/2 - 2/3x$
d_L	$-1/2$	$-1/3$	$-1/2 + 1/3x$
e_R	0	-1	x
u_R	0	$2/3$	$-2/3x$
d_R	0	$-1/3$	$1/3x$

GIM mechanism: *no FCNC*

Higgs production @ hadron colliders



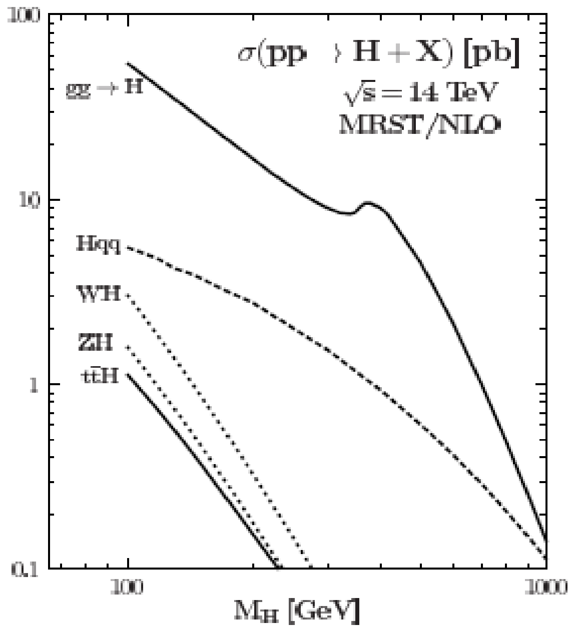
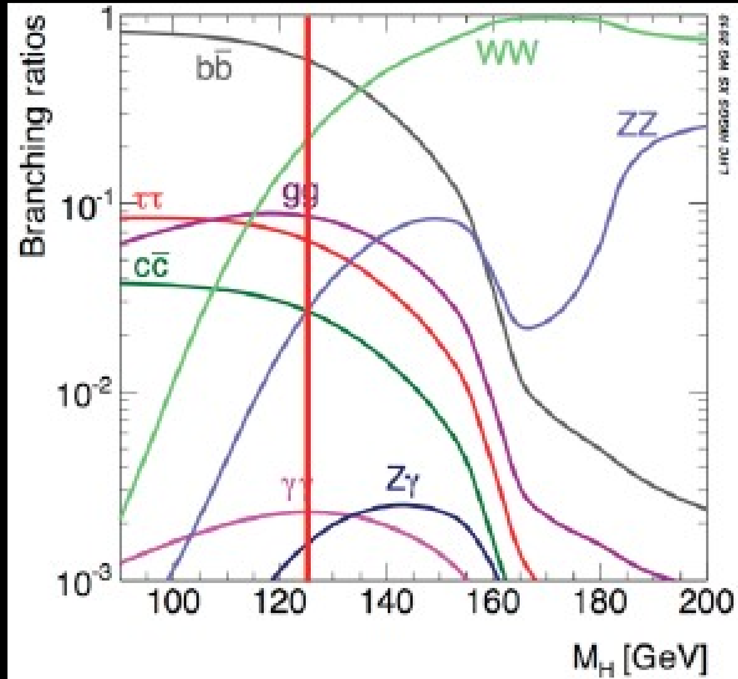
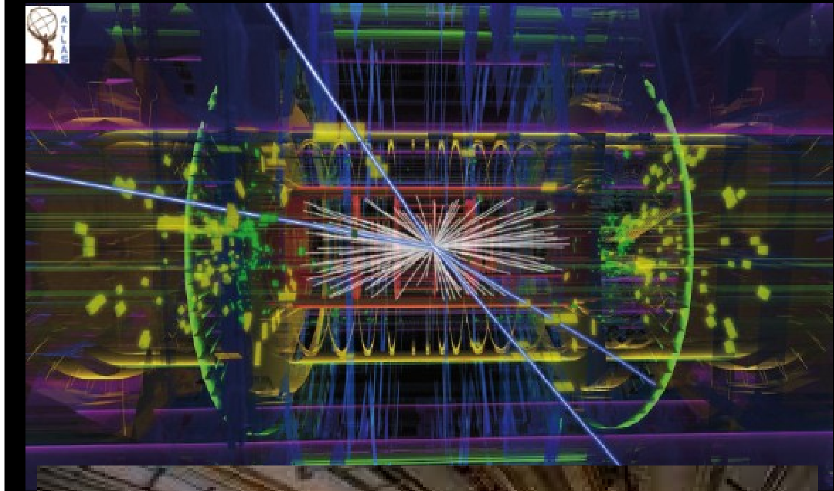
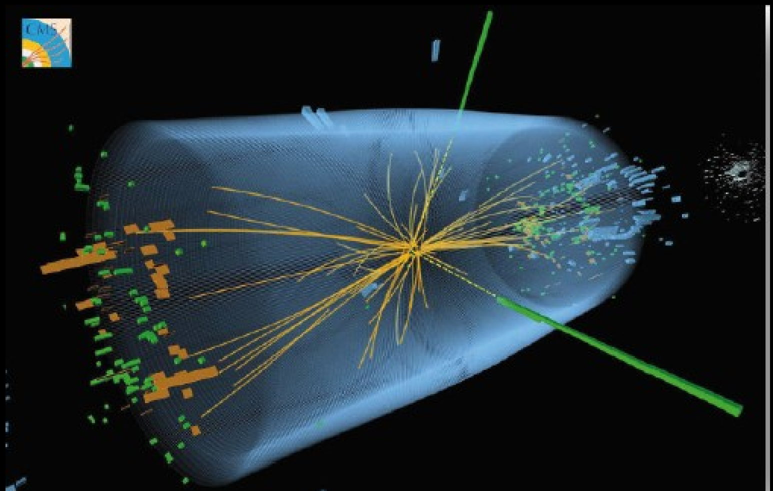


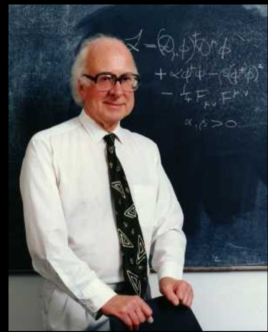
Figure 8.5 Total cross sections for dominant Higgs boson production mechanisms at the LHC, as a function of the Higgs boson mass. Adapted from Ref. [350].



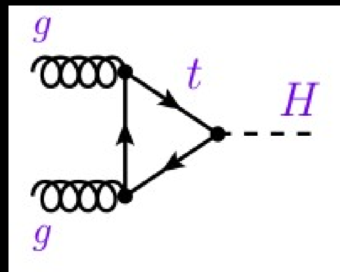


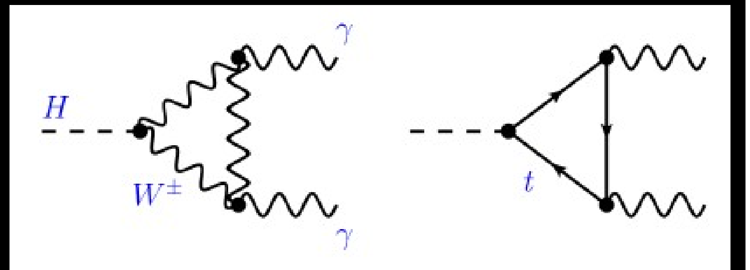


The Higgs discovery



Kibble, Guralnik, Hagen, Englert, and Brout





production

decay

Theory considerations on the Higgs mass

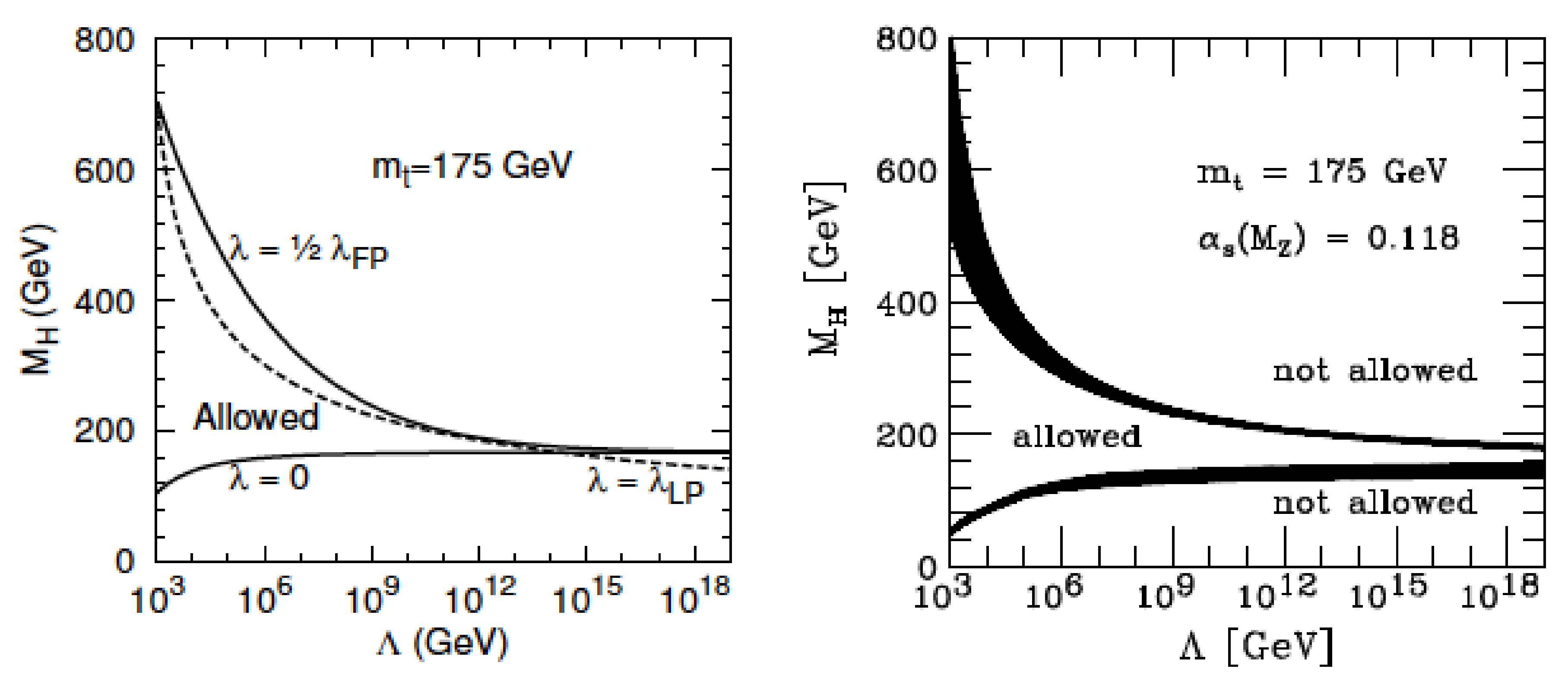


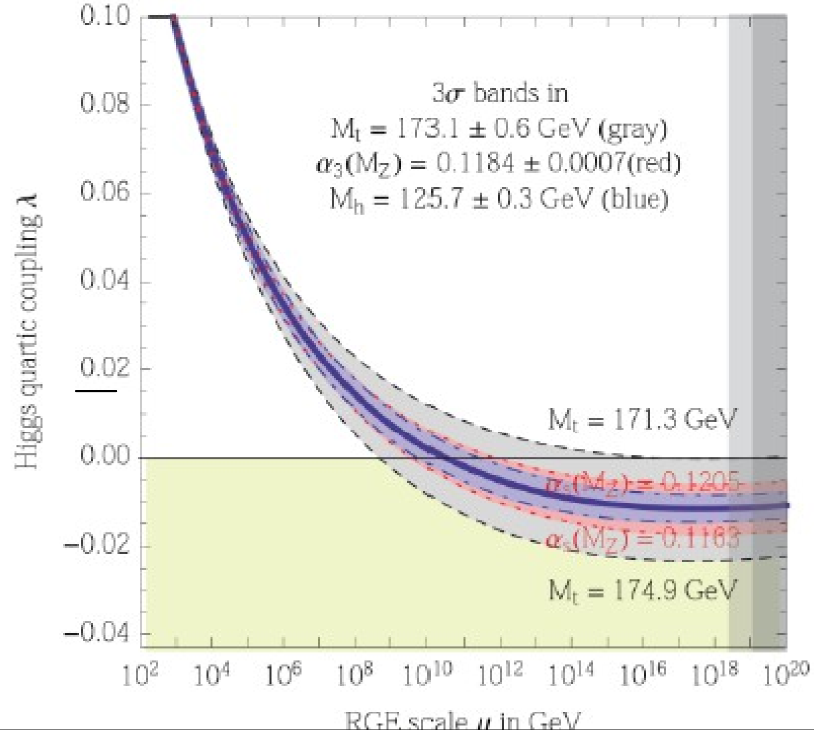
Figure 2.5 Theoretical limits on the Higgs boson mass as a function of the scale of new physics. On the left panel we present the result of our one-loop calculations, see text for details. On the right panel we show the results from a complete two-loop calculation taken from Ref.[161].

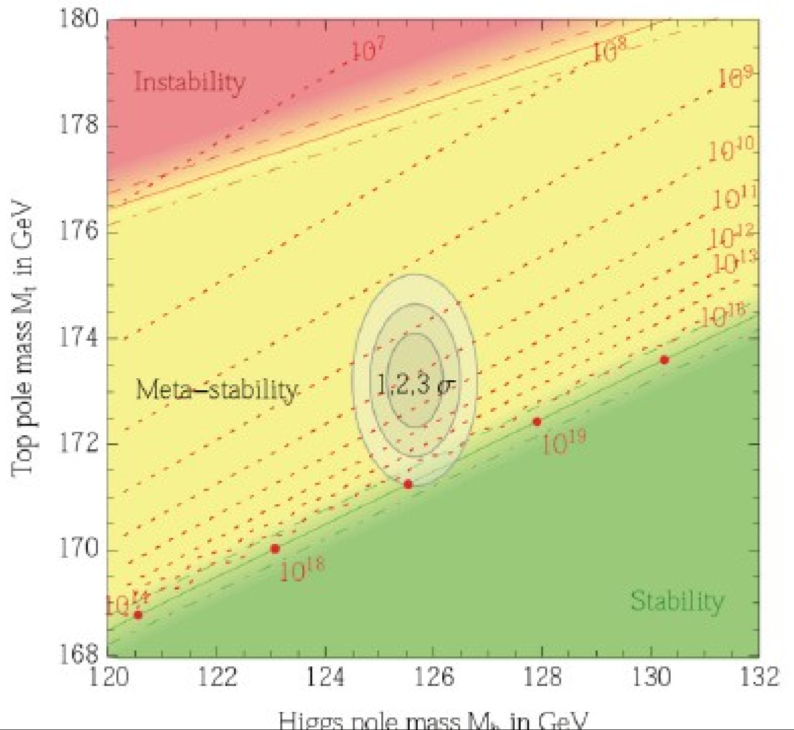
Above upper branch theory becomes non-perturbative

Below lower branch vacuum becomes unstable

Now the important question is how the standard model Higgs boson, with a mass around 125 GeV, recently discovered at CERN [162, 163], fits in this picture. Just by looking at the plot it seems that 125 GeV falls a bit too short of allowing Λ to go all the way up to M_{Planck}. New studies [164] including higher order corrections seem to indicate the need of a new physics scale lying below the Planck scale, although not too far away.

Danger: Living at the edge!





Grogean @ ICHEP

- Is it the SM Higgs?
- Is it an elementary/composite particle?
- Is it unique/solitary?
- Is it temporary?
- Is it natural?

- Is it the first supersymmetric particle ever observed?
- Is it really "responsible" for the masses of all the elementary particles?
- Is it mainly produced by top quarks or by new heavy vector-like quarks?
- Is it a portal to a hidden world?
- Is it at the origin of the matter-antimatter asymmetry?
- Has it driven the inflationary expansion of the Universe?

Experimental tests of the SM

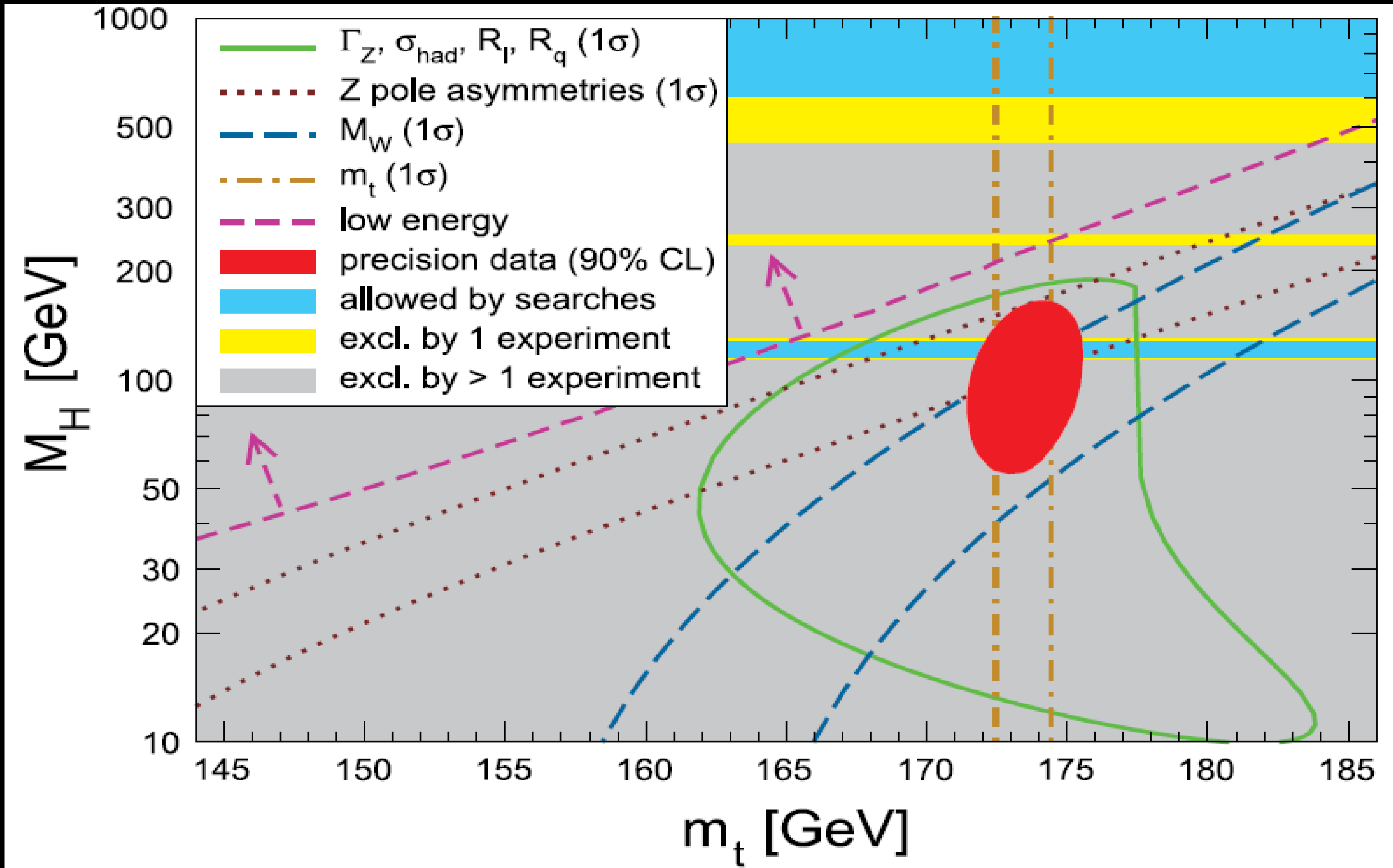


Figure 2.6 One-standard-deviation (39.35%) uncertainties in M_H as a function of m_t for various inputs, and the 90% CL region allowed by all data. The bright (yellow) bands are excluded by one experiment and the remaining (gray) regions are ruled out by more than one experiment (95% CL). Adapted from the PDG handbook [21].

LEPTONIC CC WEAK INTERACTION

$$
\begin{aligned}
D_\mu \chi_L &= \ldots - \frac{ig}{\sqrt{2}} \begin{pmatrix} & W_\mu^+ \\ & \end{pmatrix} \begin{pmatrix} \chi_0 \\ \chi_- \end{pmatrix}_L + \cdots \\
&\rightarrow \frac{-ig}{\sqrt{2}} W_\mu^+ \chi_{-L}
\end{aligned}
$$

thus we have $\quad -\chi_L \gamma_\mu D_\mu \chi_L \rightarrow \mathcal{L}^{\ell}_{\mathrm{CC}} = \frac{ig}{\sqrt{2}} W_\mu^+ \bar{\chi}_{0L} \gamma_\mu \chi_{-L} + \mathrm{h.c.}$

where
$$
\begin{aligned}
\chi_{0L} &= \Omega_L^\nu N_L \\
\chi_{-L} &= \Omega_L^e E_L
\end{aligned}
$$

thus $\quad \mathcal{L}^{\mathrm{lep}}_{\mathrm{CC}} = \frac{ig}{\sqrt{2}} W_\mu^+ \bar{N}_L \gamma_\mu \underbrace{\Omega_L^{\nu\dagger} \Omega_L^e}_{1} E_L + \mathrm{h.c.}$

no mixing & no oscillations

$$
\mathcal{L}_{\mathrm{CC}} = \frac{ig}{\sqrt{2}} W_\mu^+ \bar{N}_L \gamma_\mu E_L + \bar{u} \gamma_\mu V D_L + \mathrm{h.c.}
$$

muon decay width in the SM compared with old Fermi theory : Derive this

$$
\mathrm{amp} = -\mathrm{i} \frac{\mathrm{g}^2}{8\mathrm{M}_\mathrm{W}^2} [\bar{\mathrm{u}}_1 \gamma_\mu (1 + \gamma_5) \mathrm{v}_2][\bar{\mathrm{u}}' \gamma_\alpha (1 + \gamma_5) \mathrm{u}]
$$

$$
\Gamma_{\mu^- \rightarrow e^- \nu_e \nu_\mu} = \frac{1}{192\pi^3} G_F^2 m_\mu^5
$$

$$
\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 m_W^2}
$$

$$
G_F \approx 1.16 \times 10^{-5}\ \mathrm{GeV}^{-2}
$$

DRAWBACKS & CHALENGES OF THE STANDARD MODEL

Hierachy problem: how to estabilize the Higgs mass

Gauge coupling unification

Origin of neutrino mass …

how to unify the weak, em & strong interactions ?

SM particles can be put in multiplets of larger gauge groups

SU5 $\quad \mathbf{1} = \nu^c,\ \mathbf{5} = (d^c, \ell),\ \mathbf{10} = (Q, u^c, \ell)$

SO10 $\quad \mathbf{16} = (Q, u^c, d^c, \ell, e^c, \nu^c)$

How to combine gravity with the SM?

local Supersymmetry (SUGRA) implies gravity

Hierarchy problem

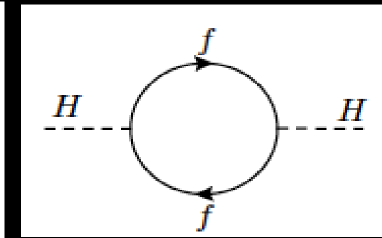
To see how one can solve this problem, consider that we enlarge our model. We take N_f Dirac fermions and N_S complex scalars coupled through the following Lagrangian,

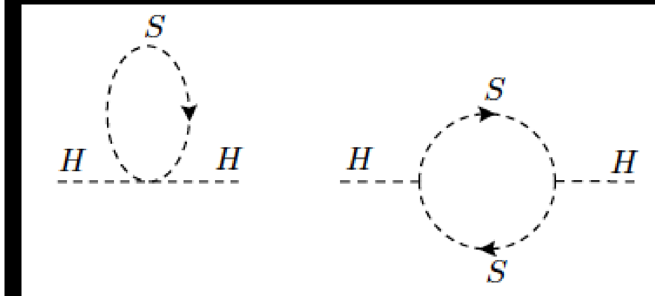
$$\mathcal{L} = -\frac{\lambda_f}{\sqrt{2}} H \bar{f} f - \frac{1}{2}\lambda_S H^2 |S|^2 - v\lambda_S H |S|^2 \,, \tag{2.94}$$

We now calculate the one loop corrections to the Higgs boson mass coming from a fermion f, as shown in Fig 2.7. The contribution to Higgs boson mass coming from this diagram reads,

$$\delta m_H^{2(f)} = \frac{\lambda_f^2}{16\pi^2}\left(-2\Lambda^2 + 12 m_f^2 \ln\frac{\Lambda}{m_f} - 4m_f^2\right), \tag{2.93}$$

where Λ is the ultraviolet momentum cutoff used to regulate the divergence of the integral. It should be interpreted as the energy scale where new physics will enter. In GUTs this should be at least of the order of M_X, hence many orders of magnitude above M_H, signaling the hierarchy problem as we mentioned before.





$$\delta m_H^{2(S)} = \frac{\lambda_S}{16\pi^2}\left[\Lambda^2 - 2m_S^2 \ln\left(\frac{\Lambda}{m_S}\right)\right] - \frac{\lambda_S^2 v^2}{16\pi^2}\left[-1 - 2\ln\left(\frac{\Lambda}{m_S}\right)\right]$$

Martin, S.P. (1997) A supersymmetry primer. hep-ph/9709356.

If we assume that $N_S = 2N_f$ and $\lambda_S = \lambda_f^2 = \frac{2m_f^2}{v}$ we get

$$\delta m_H^2 = \frac{\lambda_f^2 N_f}{16\pi^2}\left[4(m_f^2 - m_S^2)\ln\left(\frac{\Lambda}{m_S}\right) + 12 m_f^2 \ln\frac{m_S}{m_f}\right],$$

SUSY SOLUTION

Gauge coupling unification

gauge couplings as well as the masses *run* with the scale Q. At a certain scale only the particles with masses lighter than the scale contribute to the running. In grand unified theories there is a scale M_X above which the coupling constants should be the same. Below M_X the coupling constants evolve according to the β functions of the gauge group. If we assume that the standard model is valid all the way up to the scale M_X we can compute the β functions in perturbation theory and we can verify if the three coupling constants do indeed join.

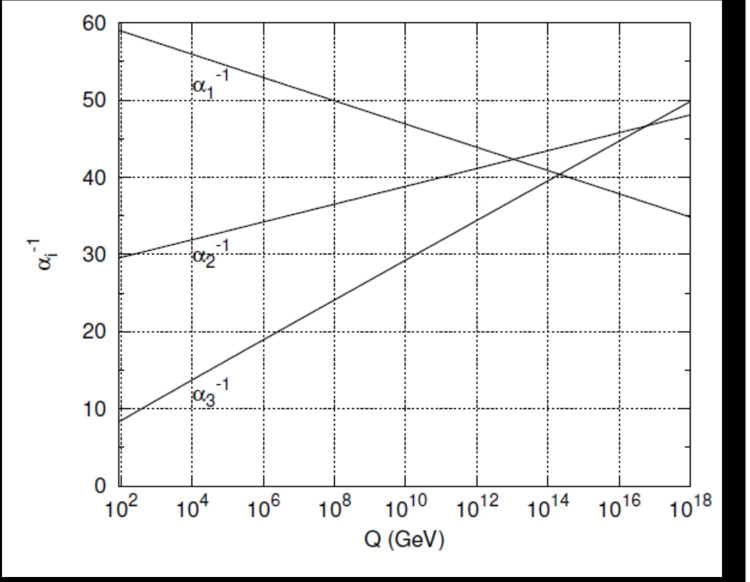
In the two-loop approximation the RGE for the gauge couplings are given by

$$\frac{1}{2\pi}\frac{dg_i}{dt} = \frac{g_i^3}{16\pi^2}\left[b_i + \frac{1}{16\pi^2}\sum_{j=1}^{3} b_{ij} g_i^2 g_j^2\right], \qquad (2.97)$$

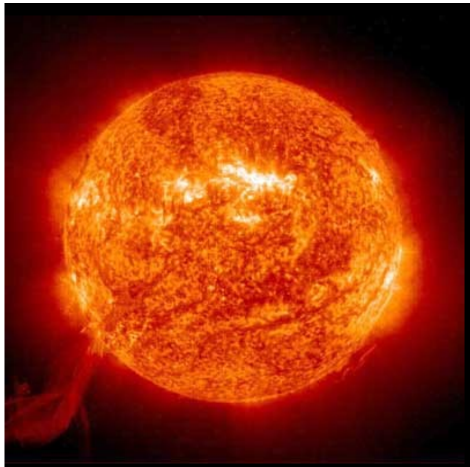
where we have neglected the effect of the running masses. We have denoted by $g_1 = g'\sqrt{5/3}$, $g_2 = g$, and g_3 the coupling constant of the strong interaction and, $t = \frac{1}{4\pi}\ln(\frac{Q^2}{\mu^2})$. In the standard model the b's functions are [169],

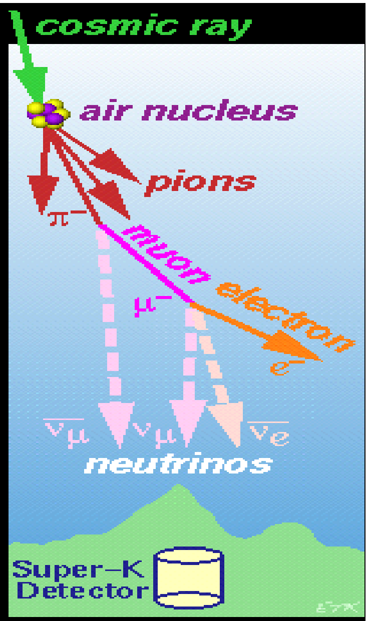
$$b_i = \left[\frac{41}{10}, -\frac{19}{6}, -7\right] \quad , \quad b_{ij} = \begin{bmatrix} \frac{199}{50} & \frac{27}{10} & \frac{44}{5} \\ \frac{9}{10} & \frac{35}{6} & 12 \\ \frac{11}{10} & \frac{9}{2} & -26 \end{bmatrix}. \qquad (2.98)$$

Integrating gives ...

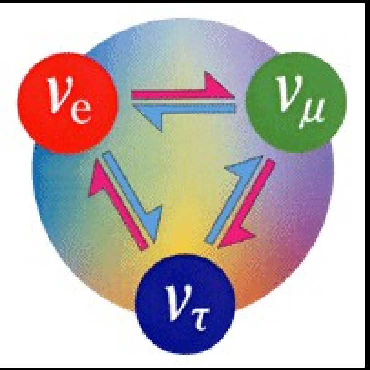


SM does not unify, in contrast SUSY does !!





Neutrinos oscillate



Homestake, SAGE
GALLEX/GNO,
Super-K, SNO
Borexino
KamLAND,D-Chooz,
DayaBay, RENO

not accounted for in the SM

Need neutrino masses

Super-K,
MINOS, T2K
735 Km