The Standard Model and Beyond: The Minimal SUSY extension

Marcela Carena
Academic Lectures
Fermilab

Fermilab–May/June, 2001.

- The SM of electroweak and strong interactions
  - The role of the Higgs field
  - Scale dependence of gauge couplings
  - The Higgs-Yukawa sector
  - SM Higgs boson phenomenology
- Why to go Beyond the SM ?
- Properties of SUSY Theories $\Longrightarrow$ The MSSM
  - Particle–sparticle interactions
  - SUSY breaking scenarios/ parameters
  - Unification of couplings
- The MSSM Higgs Sector
  - Theoretical aspects: radiative correc.; CP violation
  - Prospects at the Tevatron
  - LHC and LC: comments
- SUSY Phenomenology
  - Super-particle masses
  - Decay patterns of SUSY particles
  - Tevatron potential for different SUSY scenarios

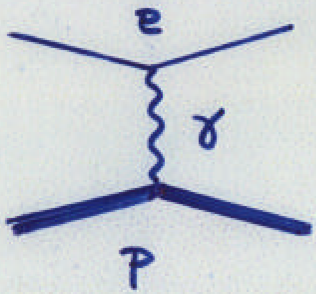
- The SM of electroweak and strong interactions
  - The role of the Higgs field
  - Scale dependence of gauge couplings
  - The Higgs-Yukawa sector
  - SM Higgs boson phenomenology
- Why to go Beyond the SM ?
- Properties of SUSY Theories $\Longrightarrow$ The MSSM
  - Particle–sparticle interactions
  - SUSY breaking scenarios/ parameters
  - Unification of couplings
- The MSSM Higgs Sector
  - Theoretical aspects: radiative correc.; CP violation
  - Prospects at the Tevatron
  - LHC and LC: comments
- SUSY Phenomenology
  - Super-particle masses
  - Decay patterns of SUSY particles
  - Tevatron potential for different SUSY scenarios

Direct observation

→ only electromagnetic and gravitational interaction

- atoms ⟶ protons, nucleons & electrons

- <u>electron</u> ⟶ interacts with protons via em. interac.
mediated by photons (γ) $\quad s_\gamma = 1 \quad m_\gamma = 0$



$\Downarrow$

modeled by a theory based on
a U(1) gauge symmetry

- <u>protons and neutrons</u> ⟶ not fundamental

doing DIS experiments of ep, en ⟶ see structure

$$\left.\begin{array}{l} p \to uud \\ n \to udd \end{array}\right\} \text{formed by quarks: } \begin{array}{ll} u & \text{charge} = 2/3 \\ d & \text{charge} = -1/3 \end{array}$$

- <u>quarks</u> ⟶ bound together by strong interactions
mediated by gluons

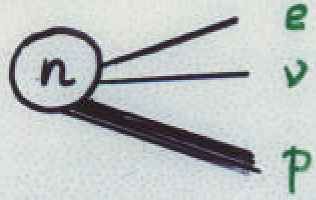
⟨3 colors of quarks & 8 gluons which interchange color

modeled by a theory based on ⟶ $SU(3)_c$ gauge symm

⟨these interactions become very strong at large distance

⟹ confinement ⟶ no free color particles⟩

• Observation of βeta decay:



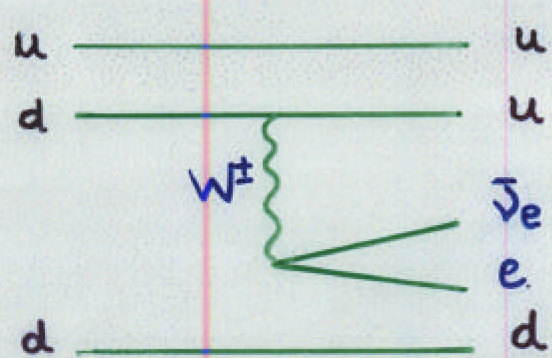
explanation demands a Novel interaction

"Weak" interactions mediated by massive gauge bosons $\longrightarrow$ short range forces
(nuclear range)

modeled by $SU(2)_L$ gauge symm.

$\longrightarrow$ assigns 2 isospin charges $\pm 1/2 \longrightarrow \begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$

n



proton + $\bar{\nu}_e$ + e

• Fermions – quarks & leptons –

can be left-handed or right-handed

$\longleftrightarrow$ dep. on spin direction with respect to propagation,

& transform in different ways $\longrightarrow$ $SU(2)_{Left}$

The Standard Model is based on a gauge field theory with a symmetry group

$$G = SU(3)_c \times SU(2)_L \times U(1)_Y$$

there are 12 fundamental gauge fields

8 gluons, 3 W_μ's and B_μ.

and 3 gauge couplings g_3, g_2, g_1

Matter fields $\longrightarrow$ 3 families of quarks & lepton with the same quantum numbers under gauge groups

$$Q = T_3 + Y/2$$

	$SU(3)_c$ ×	$SU(2)_L$ ×	$U(1)_Y$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$ $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$ $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	(1 ,	2 ,	−1)
$e^c_R = e^+_L$ μ^c_R τ^c_R	(1 ,	1 ,	2)
$\begin{pmatrix} u \\ d \end{pmatrix}_L$ $\begin{pmatrix} c \\ s \end{pmatrix}_L$ $\begin{pmatrix} t \\ b \end{pmatrix}_L$	(3 ,	2 ,	1/3)
u^c_R c^c_R t^c_R	($\bar{3}$,	1 ,	−4/3)
d^c_R s^c_R b^c_R	($\bar{3}$,	1 ,	2/3)

but with different masses

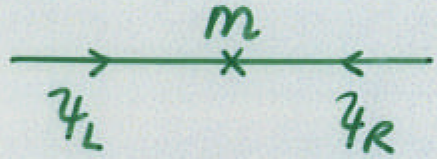
$m_e \simeq 0.5\ 10^{-3}$ GeV $\quad \dfrac{m_e}{m_\mu} \simeq \dfrac{1}{200} \quad \dfrac{m_t}{m_e} > 10^5$

third generation masses :

$m_\tau \simeq 1.78$ GeV $\quad m_b \simeq 5$ GeV $\quad m_t \simeq 175$ GeV

SM $\longrightarrow$ gauge field theory $\longrightarrow$ one can write the interaction Lagrangian, but, due to the chiral nature of the theory,

fermion mass term not invariant under gauge group



$$\mathcal{L} = m\,\bar{\psi}_L \psi_R + h.c.$$

How to give masses to fermions
and to $SU(2)_L$ gauge bosons ?

- introduce a scalar field $\rightarrow$ Higgs with non-trivial quantum numbers under $SU(2)_L \times U(1)_Y$

$$\phi = (1, 2, 1) \qquad \phi = \begin{pmatrix} \phi^+ \\ v + \dfrac{H + i\chi^0}{\sqrt{2}} \end{pmatrix}$$

$v = 174$ GeV

Higgs-fermion interactions ≡ Yukawa int.

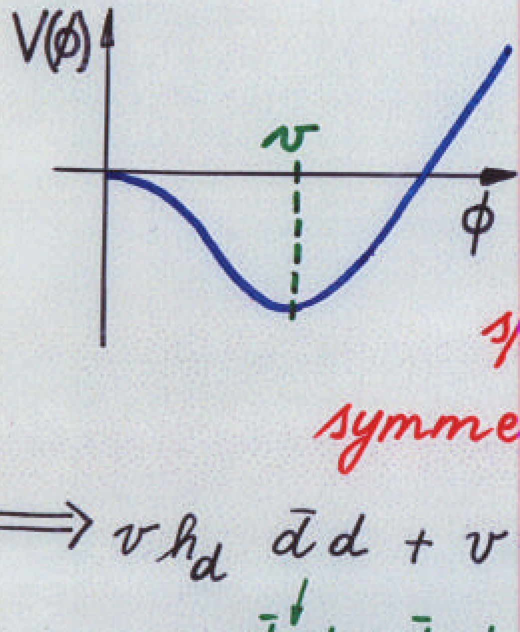
$$h_d \left[(\bar{u}_L \, \bar{d}_L) \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} d_R + h.c. \right]$$

$$h_u \left[(\bar{u}_L \, \bar{d}_L) \begin{pmatrix} \phi_0^* \\ -\phi^- \end{pmatrix} u_R + h.c. \right]$$

⟨similar for leptons → only e_R⟩

Higgs mechanism:

→ when neutral component acquires vacuum expectation value $\langle \phi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$



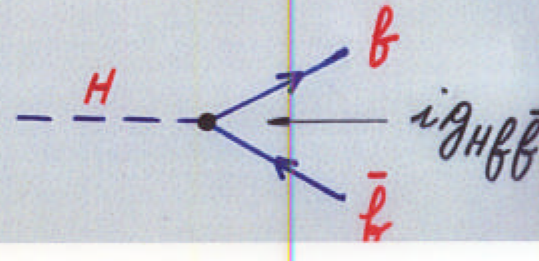
$$V(\phi) = -m^2 \phi^2 + \lambda/_2 \, \phi^4$$

spontaneous breakdown of the symmetry ≡ vacuum becomes a source of E

$$\Longrightarrow v h_d \, \underset{\downarrow \atop \bar{d}_L d_R + \bar{d}_R d_L}{\bar{d} d} + v h_u \, \bar{u} u + v h_\ell \, \bar{\ell} \ell$$

$m_f \equiv v \, h_f$ $\qquad$ h_f → Yukawa couplings

$h_t \simeq \mathcal{O}(1) \qquad h_\ell \ll 1$



Higgs-fermion couplings

$$g_{Hf\bar{f}} = h_f/\sqrt{2} = m_f/_{v\sqrt{2}}$$

Higgs-Vector boson couplings and masses

• Higgs neutral under strong and electromag. interactions ($\Rightarrow$ no coupling)

$$m_g = 0 \qquad m_\gamma = 0$$

Massless Gauge Bosons $\Rightarrow$ Exact symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y \longrightarrow SU(3)_C \times U(1)_{em}$$

$$\mathcal{L}_{SM} \longrightarrow (\mathcal{D}_\mu \phi)^+ \mathcal{D}^\mu \phi$$

with $\mathcal{D}_\mu = \partial_\mu - i g W_\mu^a T_a - i g' \frac{Y}{2} B_\mu$

$\mathcal{D}_\mu$: covariant derivative; T_a: SU(2) generators; $\frac{Y}{2}$: U(1) generator

$$\longrightarrow \phi^+ \left[g_2 W_\mu^a T^a + g_1 B_\mu \frac{Y}{2}\right] \left[g_2 W_b^\mu T^b + g_1 B^\mu \frac{Y}{2}\right] \phi$$

recall $\phi = \begin{pmatrix} \phi^+ \\ v + \frac{H + i\chi^0}{\sqrt{2}} \end{pmatrix}$

and defining

$$Z = (g_2 W_3 - g_1 B) / \sqrt{g_2^2 + g_1^2} \qquad W^\pm = \frac{W_1 \pm i W_2}{\sqrt{2}}$$

$$\gamma = (g_1 W_3 + g_2 B) / \sqrt{g_1^2 + g_2^2}$$

$$\mathcal{L}_{H-W/Z} = \left(v + H/\sqrt{2}\right)^2 \left[\frac{g_2^2}{2} W_\mu^+ W^{-\mu} + \frac{(g_2^2+g_1^2)}{4} Z_\mu Z^\mu\right]$$

setting $H=0$ yields the gauge boson masses

$$M_W^2 = g_2^2 v^2/2 \qquad M_Z^2 = (g_1^2+g_2^2)\, v^2/2$$

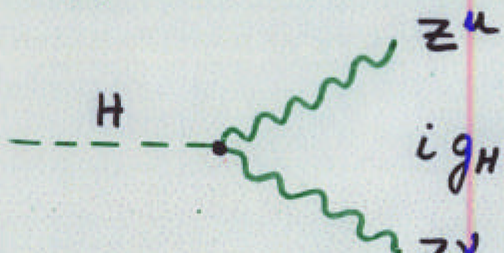
$$\simeq 80.4 \text{ GeV} \qquad \simeq 91.18 \text{ GeV}$$

$$\alpha_i \equiv g_i^2/4\pi$$

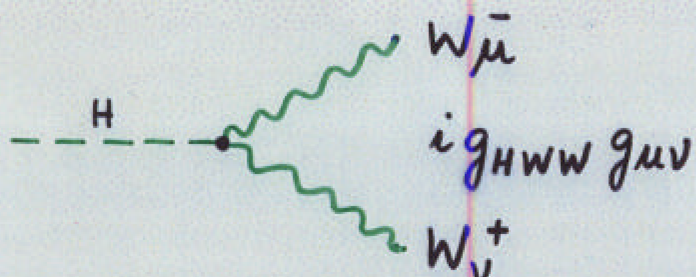
$$\begin{cases} 1/\alpha_{em} = 1/\alpha_1 + 1/\alpha_2 \\ \sin\theta_W = g_1/\sqrt{g_1^2+g_2^2} \end{cases}$$

$$\underline{\underline{\alpha_1, \alpha_2 \longleftrightarrow \alpha_{em}, \sin\theta_W}} \Leftarrow$$

Higgs - Vector Boson couplings



$$g_{HZZ} = \frac{M_Z^2\sqrt{2}}{v} = 2\left(G_F\sqrt{2}\right)^{1/2} M$$



$$g_{WWH} = \frac{M_W^2\sqrt{2}}{v} = 2\left(G_F\sqrt{2}\right)^{1/2} M_W$$

- Also, physical Higgs field remains in the theory

$$m_h^2 = 2\lambda v^2 \qquad \lambda = \text{free param.}$$

At present,

SM $\longrightarrow$ gauge theory based on $G = SU(3)_C \times SU(2)_L \times U(1$

$$\mathcal{L} = \sum_{q_j} \bar{q}\, i \not{D}\, q + \sum_{\ell_j} \bar{\ell}\, i \not{D}\, \ell - \tfrac{1}{4} \mathcal{F}^a_{\mu\nu} \mathcal{F}^{a\mu\nu}$$

$$\left\{ - h_u\, \bar{u}_R\, \varepsilon_{ij}\, \phi^i q^j_L - h_d\, \bar{d}_R \phi^+ q_L - h_\ell\, \bar{\ell}_R \phi^+ \ell_L + h.c. \right.$$

$$+ (\mathcal{D}_\mu \phi)^+ \mathcal{D}_\mu \phi + V(\phi) \qquad q = \begin{pmatrix} q_L \\ q_R \end{pmatrix} \quad q^j_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

- successful description of electroweak & strong int.
- tested to a remarkable degree of accuracy

  ⟨precision measurements confirm its predictions to the level of radiative corrections⟩

- top quark discovery $\longrightarrow$ SM matter sector is essentially complete ✓ (ν_τ ✗, (ν oscill;

but, missing ingredient $\longrightarrow$ Higgs ??

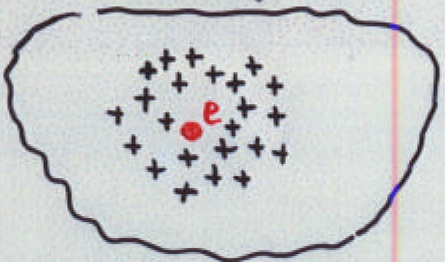
experiments say little about the Higgs and its properties

Higgs search $\Longrightarrow$ may uncover new physics

What is the origin of ~~Electroweak~~ Symmetry (and masses)?

Scale dependence of the gauge couplings

- electric charge e ⟶ polarizes the vacuum



fundamental charge e is screened at long distances

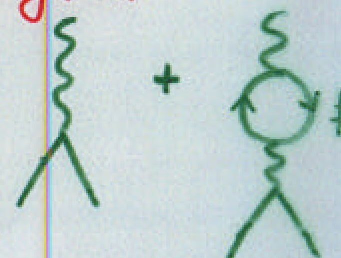
⟹ the effective charge depends on how close one is to the fundamental charge

more energetic photons can go closer to it

⟹ at large Q^2 photon sees a larger charge/coupling

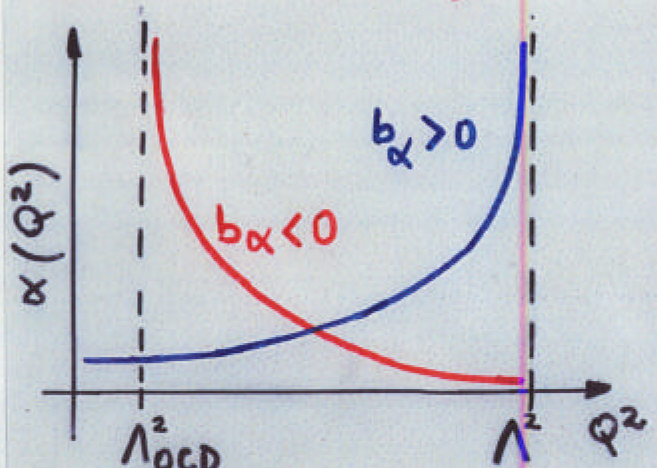
$\alpha_1 = g_1^2/4\pi$

$$Q^2 \frac{d\alpha(Q^2)}{dQ^2} \equiv \beta(\alpha) = \frac{b_\alpha}{2\pi}\alpha^2(Q^2)$$



$$1/\alpha(Q^2) = 1/\alpha(M_X) + \frac{b_\alpha}{2\pi}\ln\left(\frac{M_X^2}{Q^2}\right)$$

Renormalization Group evolution ⟶ allows study of the effective coupling Vs. Q^2



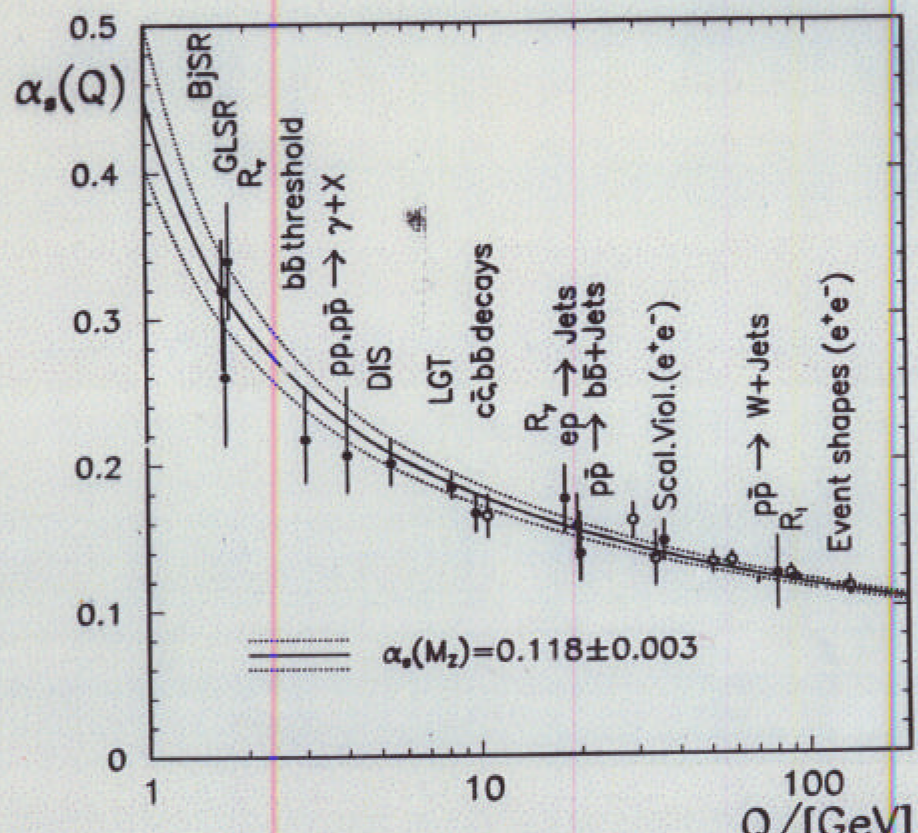
Abelian theories

$b_\alpha > 0$ ⟶ are only consistent as an effective theory up to a cutoff Λ

Non-Abelian th

$b_\alpha < 0$ ⟶ may be asymptotically free at large Q^2 but strongly interacting at small Q^2

Evidence of scale evolution of $\alpha_s(Q)$ coming from many different experiments

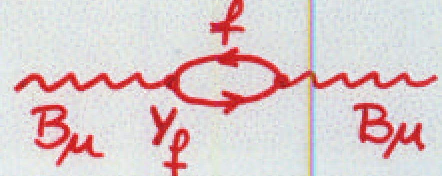


The SM contains many non-asymptotically free couplings g_1, λ, h_t !

these couplings become strong at a finite energy scale $\Longrightarrow$ breakdown of perturbative descriptio[n] or the emergence of a new, fundamental theory

- let's compute Λ_{eff} for g_1:

$$dg_1^2 / d\ln Q^2 = b_1\, g_1^4 / 16\pi^2$$



$$b_1 = 1/6 \sum_f Y_f^2 + 1/12 \sum_s Y_s^2$$

$$= 3 \cdot 1/6 \,(\underset{\downarrow\, \ell_L}{2} + \underset{\downarrow\, \ell_R}{4} + \underset{\downarrow\, q_L}{2/3} + \underset{\downarrow\, u_R}{16/3} + \underset{\downarrow\, d_R}{4/3}) + 1/12 \cdot \underset{\downarrow\, H}{2} = 41/6$$

$$-1/g_1^2(Q^2) + 1/g_1^2(M_Z^2) = 41/6 \; \frac{\ln\left(Q^2/M_Z^2\right)}{16\pi^2}$$

hence, for large $g_1^2(Q^2)$

$$\Lambda_{eff}^2 \equiv Q_{eff}^2 = M_Z^2 \exp\left(\frac{16\pi^2}{41}\,\frac{6}{g_1^2(M_Z^2)}\right)$$

$$\simeq M_Z^2 \exp(100) \gg M_{Pl}^2 \equiv (10^{19}\,\mathrm{Ge}[V]$$

g_1 blows up only at energies above M_{Pl} $\Longrightarrow$

• Gauge sector in the SM is perfectly consistent till energies of $\mathcal{O}(M_{pl})$ where "something" should happen anyway

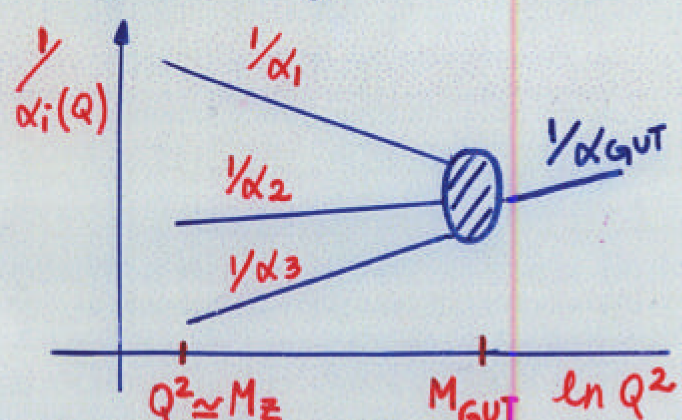
⟨since

SM $\longrightarrow$ no gravitational effects

$\Longrightarrow$ only effective description up to $\Lambda_{eff} \lesssim M_{pl}$ where gravitational interactions become relevant $V(r) \sim G_N \frac{m_1 \cdot m_2}{r}$

with $1/\sqrt{G_N} \sim 10^{19}\,\text{GeV} \equiv M_{pl}$ ⟩

In fact, considering RG evolution of g_3, g_2 $\longrightarrow$ all couplings "tend" to converge at high energies



possible that, 3 couplings come from a single one and the gauge group proceeds from a larger one

$$G \supset SU(3)_c \times SU(2)_L \times U(1)_Y$$

also possible $\longrightarrow$ SM gauge group generators same as G generators

Unification ?

only reasonable possibility if $M_{GUT} < M_{pl}$

$$\frac{d\alpha_1}{d\ln Q^2} = \frac{41}{6} \times \frac{3}{5}\ \alpha_1^2/4\pi$$

$$\frac{d\alpha_{2,3}}{d\ln Q^2} = b_{2,3}\ \alpha_{2,3}^2/4\pi$$

$$b_N = -\frac{11}{3}N + \frac{1}{3}n_f + \frac{1}{6}n_s$$

for $SU(N)$ with

$n_{f,s} \equiv$ fermions, scalars in fundamental rep.

$$b_2 = -22/3 + \frac{1}{3}\overset{3q_L + \ell_L}{3 * 4} + \frac{1}{6}$$

$$b_3 = -11 + \frac{1}{3}\,\underset{u_L, u_R, d_L, d_R}{3.4}$$

$$\Longrightarrow b_2 = -19/6 \qquad b_3 = -7$$

$$1/\alpha_1(M_{pl}) = 1/\alpha_1(M_Z) - \frac{41}{10}\,\frac{\overbrace{\ln(M_{pl}^2/M_Z^2)}^{\sim 6.5}}{4\pi}$$

$$1/\alpha_2(M_{pl}) = 1/\alpha_2(M_Z) + \frac{19}{6}\,\frac{\ln(M_{pl}^2/M_Z^2)}{4\pi}$$

$$1/\alpha_3(M_{pl}) = 1/\alpha_3(M_Z) + 7\,\frac{\ln(M_{pl}^2/M_Z^2)}{4\pi}$$

Given that $1/\alpha_1(M_Z) \simeq 60 \qquad 1/\alpha_2(M_Z) \simeq 30 \qquad 1/\alpha_3(M_Z) \simeq 8.5$

$$\Longrightarrow 1/\alpha_1(M_{pl}) \simeq 32 \qquad 1/\alpha_2(M_{pl}) \simeq 50 \qquad 1/\alpha_3(M_{pl}) \simeq 54$$

hierarchy inverted $\Longrightarrow$ couplings cross at some scale $Q < M_{pl}$, but do they meet at a point?

If G is a simple non-abelian gauge group like SU(N)

$$\mathrm{Tr}\left[T^a\right] = 0$$

in the SM, for one generation

$$\sum_f Y_f = \underset{\substack{\uparrow \\ \ell_L}}{-2} + \underset{\substack{\uparrow \\ \bar{\ell}_R}}{2} + \underset{\substack{\uparrow \\ q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}}}{6} \cdot \tfrac{1}{3} - \underset{\substack{\uparrow \\ u_R^c}}{3} \cdot \tfrac{4}{3} + \underset{\substack{\uparrow \\ d_R^c}}{3} \cdot \tfrac{2}{3} = 0 \, !$$

some logic behind Y_f assignemet

* Consider proper normalization of g_1 to investigate unification condition

$$\mathcal{D}_\mu = \partial_\mu + i g_i T^a A^a_\mu \qquad \mathrm{Tr}\left[T^a T^b\right] = \delta^{ab}/2$$

$$i = 2, 3$$

for hypercharges considered & conventional g_1 values (normaliz.)

$$\mathcal{D}_\mu = \partial_\mu + i g_1^{SM} \frac{Y_f^{SM}}{2} B_\mu$$

Normalization factor N such that

$$\underset{SU(2)\,\text{isospin}}{\mathrm{Tr}\left[T^3 T^3\right]} = N^2 \, \mathrm{Tr}\left[\left(Y_f/2\right)^2\right]$$

$$\underset{3q_L + \ell_L}{4} \times 2 \times \left(1/2\right)^2 = N^2 \, 1/4 \left(\underset{\ell_L}{2} + \underset{\ell_R}{4} + \underset{q_L}{2/3} + \underset{u_R}{16/3} + \underset{d_R}{4/3}\right) \Longrightarrow N = \sqrt{3/5}$$

Hence, $g_1 = g_1^{SM} \sqrt{5/3} \qquad Y_f = \sqrt{3/5}\; Y_f^{SM}$

Given the three RG equations for α_i and assuming they unify at a common value α_{GUT} at the scale M_{GUT}

$$\Rightarrow \; 1/\alpha_3(M_Z) = \left(1 + \frac{b_3 - b_2}{b_2 - b_1}\right)\frac{1}{\alpha_2(M_Z)} - \frac{b_3 - b_2}{b_2 - b_1}\, 1/\alpha_1(M_Z)$$

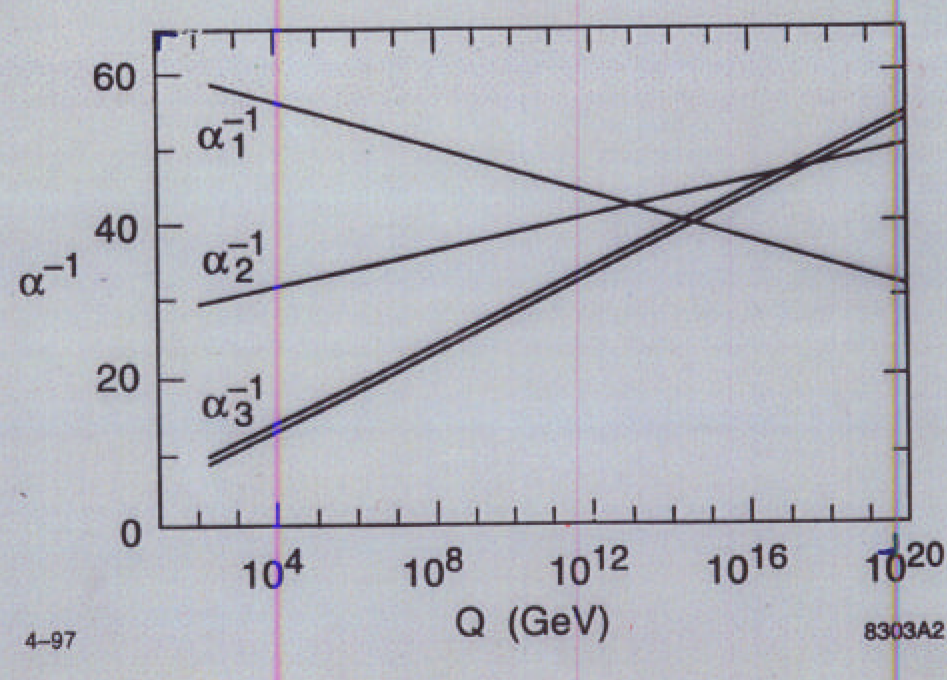
Ex.: derive this expression

using: $1/\alpha_i(M_{GUT}) = 1/\alpha_G = 1/\alpha_i(M_Z) - b_i/4\pi \ln\left(\frac{M_{GUT}^2}{M_Z^2}\right)$

In the SM: $\frac{b_3 - b_2}{b_2 - b_1} = 1/2 + 3/109 \sim 1/2$

$$1/\alpha_3(M_Z) \sim 15 \; ! \qquad \text{but} \quad 1/\alpha_3(M_Z)\Big|_{exp.} \simeq 8.5$$

hence although qualitatively possible Unification of couplings within the SM ⟨simplest scenarios, including SU(5)⟩ ruled out



Higgs - Yukawa Sector

- non-asymptotic behaviour of couplings is related to their large values at high energies

given $m_t \simeq h_t \langle\phi\rangle \simeq 170$ GeV $\quad \langle\phi\rangle = 174$ GeV

$$h_t \sim 1 ! \longrightarrow \text{strong coupling}$$

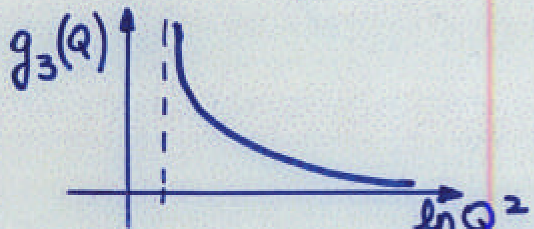
what about its behaviour at large Q^2 ?

$$\frac{d h_t^2}{d \ln Q^2} \simeq h_t^2/16\pi^2 \left[9/2\, h_t^2 - 8 g_3^2 - \mathcal{O}(g_2^2) \right]$$

- two compensating effects:

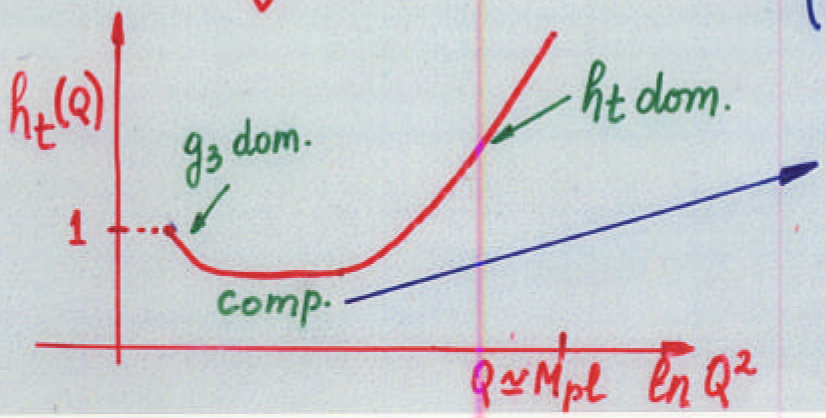
i) $h_t \longrightarrow$ pushes h_t up $\qquad$ ii) $g_3 \longrightarrow$ pushes h_t down

since g_3 is asymptotically free



$\Downarrow$

both effects compensate $\left(dh_t/d\ln Q^2 \simeq 0\right)$ if



$$h_t(Q) = \frac{4}{3}\left(4\pi\alpha_3(Q)\right)^{1/2}$$

If compensation of g_3 & h_t effects in h_t running occured at scales of $\mathcal{O}(m_t)$

$\Longrightarrow$ quasi Infrared fixed point behavior of h_t

$\Rightarrow$ stable predictions for m_t

Indeed, if $h_t(\Lambda)$, with $\Lambda = M_{Pl}$ or $M_{GUT} \simeq 10^{16}$ GeV is sufficiently large $h_t^2/_{4\pi}(\Lambda) \gtrsim 0.1$

then, compensation of effects occur at $Q \simeq m_t$ indep. of exact value of $h_t(\Lambda)$ $\Rightarrow$ IRFP behaviour

$$h_t^2(Q)/_{4\pi} \equiv Y_t(Q) = \frac{Y_t(\Lambda)\; E(Q)}{\left(1 + 9/2\, Y_t(\Lambda)\, F(Q)/4\pi\right)}$$

if $Y_t(\Lambda)$ large $\Rightarrow Y_t^{IRFP}(Q) \simeq \frac{8\pi}{9}\frac{E(Q)}{F(Q)} \simeq \frac{16}{9}\alpha_3(Q)$

$Q \sim m_t$, $E, F \rightarrow$ fc of α_i

However, $h_t^{IRFP} \simeq \frac{4}{3}\left(4\pi\,\alpha_3(m_t)\right)^{1/2} \simeq 1.5$

$\Rightarrow m_t = h_t\, v \simeq 250$ GeV (fig.)

$m_t^{exp.} \simeq 175$ GeV hence

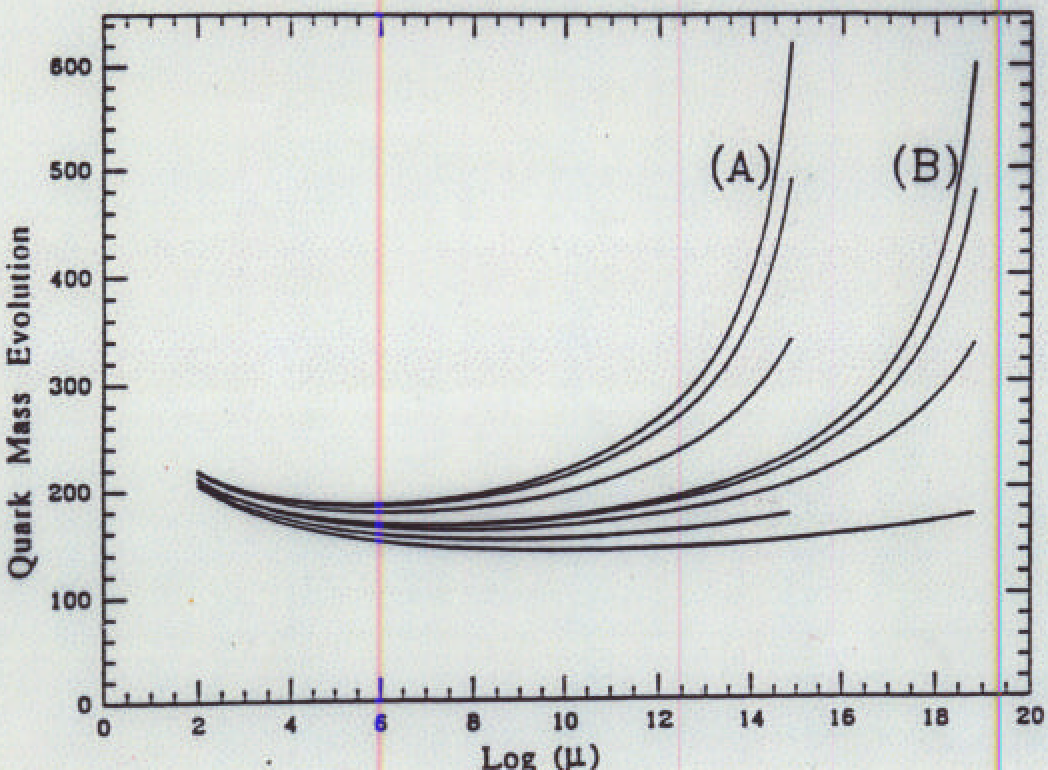
a) IRFP sol. not realized in nature

b) h_t for $m_t = 175$ GeV becomes strong at $\Lambda \gg M_{Pl}$

$\Rightarrow$ no additional info. provided

SM quasi-infrared fixed point of M_t

C. Hill'81, '90



RG trajectories as a function of scale μ

→ for $h_t^2(\mu=\Lambda)/4\pi \gtrsim 0.1$ and consistent with perturbative treatment

M_t^{IR} [GeV] = 218 229 248

if

Λ [GeV] = 10^{19} 10^{15} 10^{11}

Higgs Sector

$$V(\phi) = -m^2 \phi^+\phi + \lambda(\phi)/_2 \, (\phi^+\phi)^2$$

the quartic coupling determines the Higgs boson mass

$$m_H^2 = 2\lambda v^2 \qquad v \equiv \langle\phi\rangle = 174 \text{ GeV}$$

and is not asymptotically free

$$\frac{d\lambda}{d\ln Q^2} = {}^6/_{16\pi^2}\Big(\underbrace{\lambda^2 + \lambda h_t^2}\; - h_t^4\Big) + \text{elw. correc}$$

there is the usual situation of non-asymptotic freedom for sufficiently large Q^2

↓

λ becomes too large

(strongly interacting/ close to Landau pole)

↓

from requiring perturbative validity of the model up to scale Λ (or M_{pl})

$$\lambda^{MAX}(\Lambda)/_{4\pi} = 1$$

$$\Rightarrow m_H^{MAX} = \sqrt{2\,\lambda^{MAX}}\, v$$

the part of β_λ indep. of λ can drive $\lambda(Q)$ to negative values

↓

destabilizing the elw. minimum

↓

lower bound on $\lambda(m_H)$ from stability requirement

↓

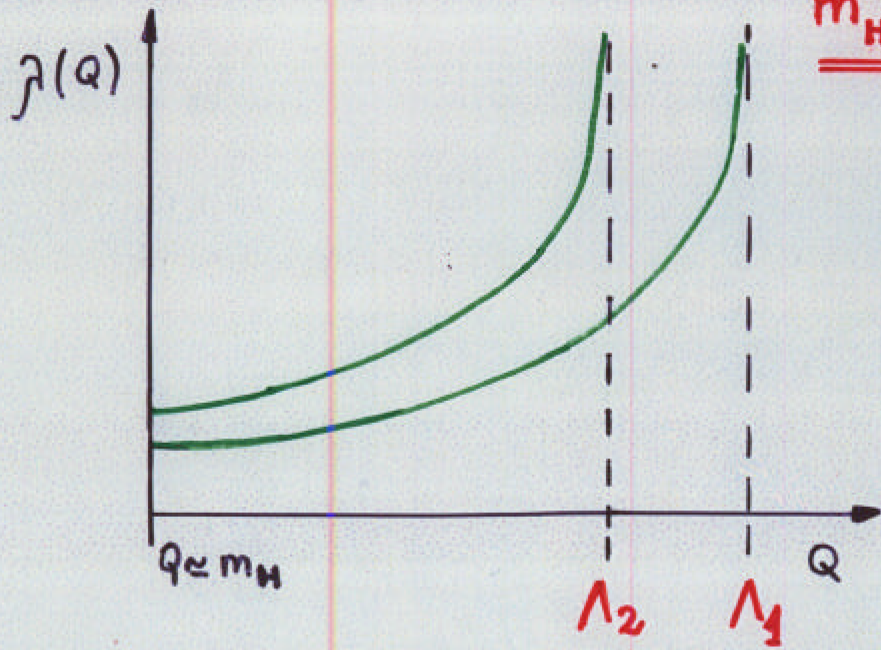
m_H^{min}

strongly dep. on m_t (h_t)

- $\lambda(Q)$ becomes strongly interacting ($\simeq$ has a Landau pole) at $Q = \Lambda$

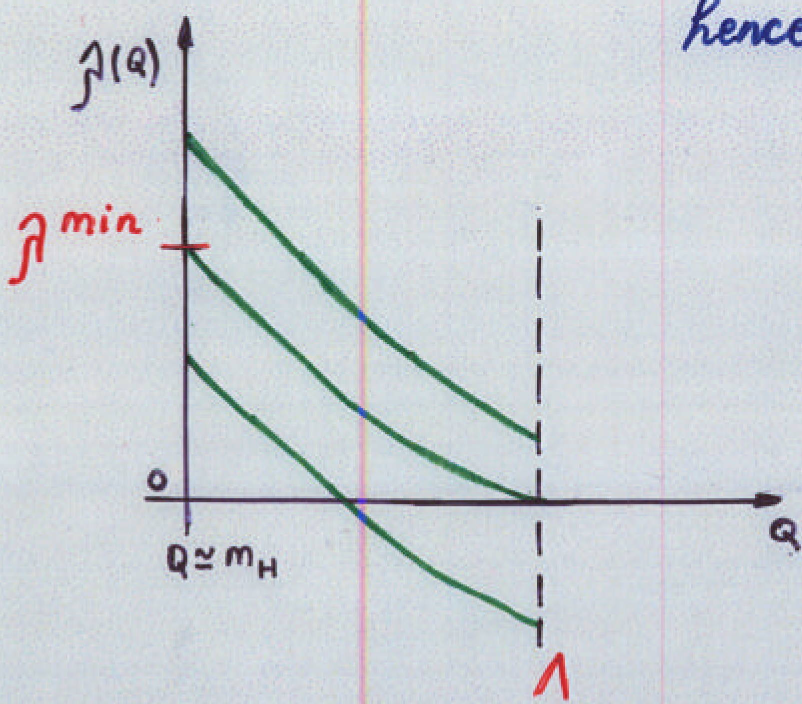
$\Longrightarrow$ determines $\lambda^{MAX.}(Q \simeq m_H)$ $\Rightarrow$ hence

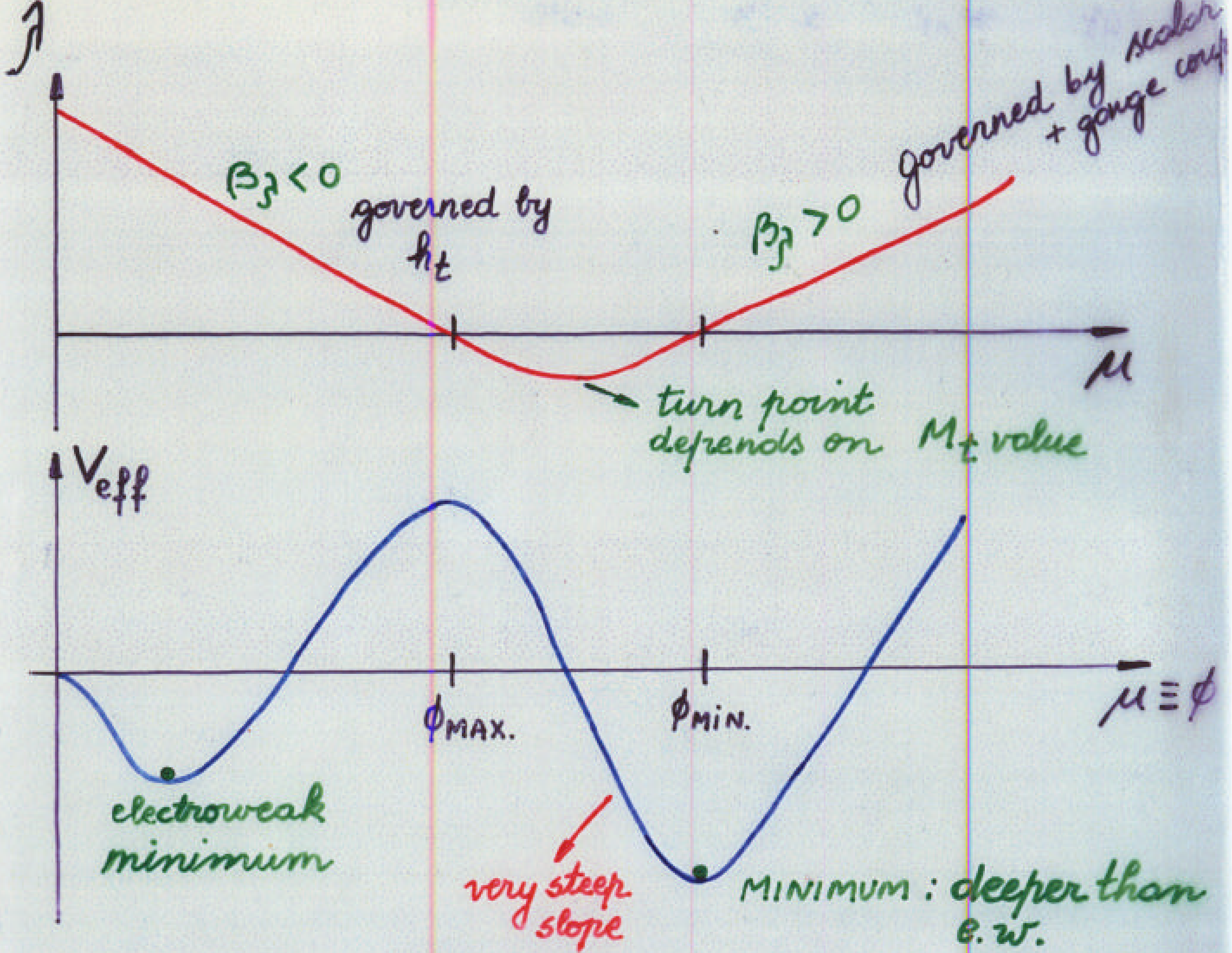
$$\underline{\underline{m_H^{MAX.} = \sqrt{2\lambda^{MAX.}}\, v}}$$



- $\lambda(Q) = 0$ for $Q = \Lambda$ $\Rightarrow$ determines $\lambda^{min.}(Q \simeq m_H)$

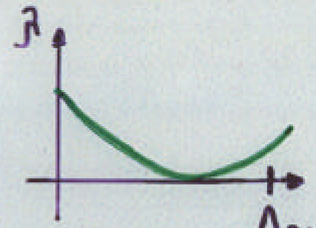
hence $\underline{\underline{m_H^{min} = \sqrt{2\lambda^{min}}\, v}}$



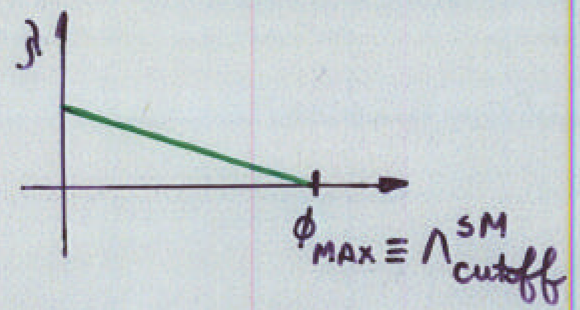


the stability m_H lower bound comes from defining for a given M_t the lower m_H for which

$\Longrightarrow$ no MAXIMUM for $\phi < \Lambda^{SM}_{cutoff}$ $(\equiv \lambda(\phi) \geq 0$ for $\phi < \Lambda^{SM}_{cutoff}$



no ϕ_{MAX} for any Λ



Standard Model Higgs Boson

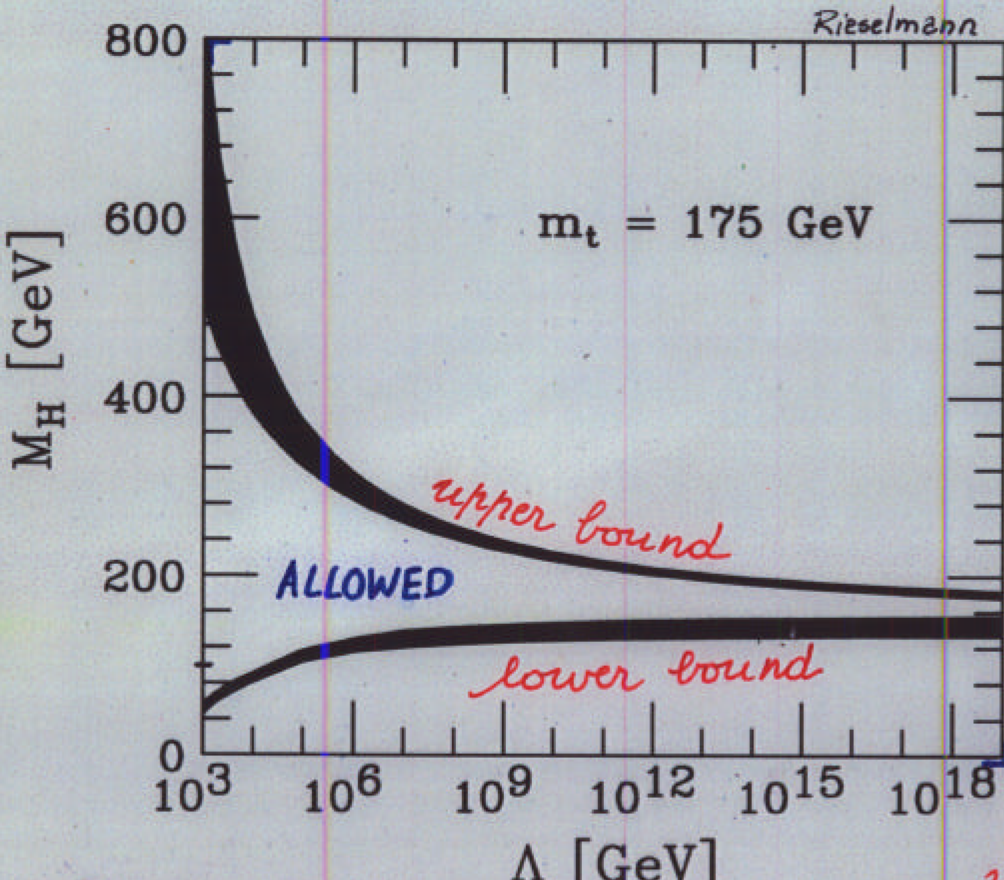
→ Upper, Perturbative and Lower, Stability Bounds

- if SM description valid up to $\Lambda \simeq 10^{13} - 10^{19}$ GeV

  $130 \lesssim m_H\,[\text{GeV}] \lesssim 200$

- if Higgs boson is light → $m_H \lesssim 130$ GeV

$\Longrightarrow$ New Physics beyond the SM should appear at $\Lambda \ll M_{pl}$ ($\Lambda \simeq 10^4 - 10^{11}$ GeV)



$\left.\begin{matrix}180 \text{ GeV} \\ 135 \text{ GeV}\end{matrix}\right\}$

$\Downarrow$

SM may be valid up to M_{pl}.

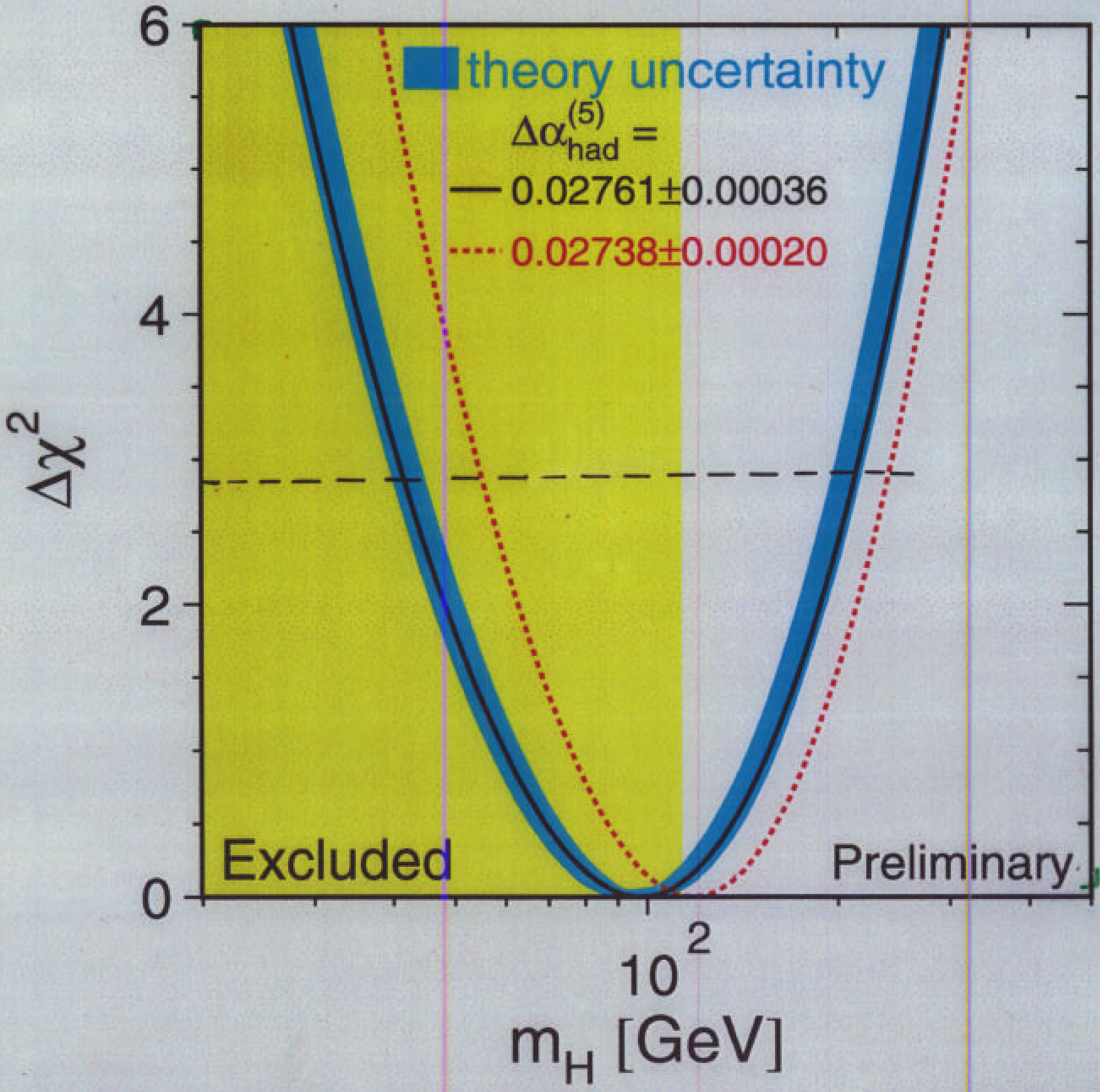
Electroweak data:

loop correc. to electroweak observables dep. on $\mathcal{O}(m_t^2)$ but only log on m_H

Still some information available

$m_H = 98^{+58}_{-38}$ GeV or

$m_H < 212$ GeV @ 95% C.L.



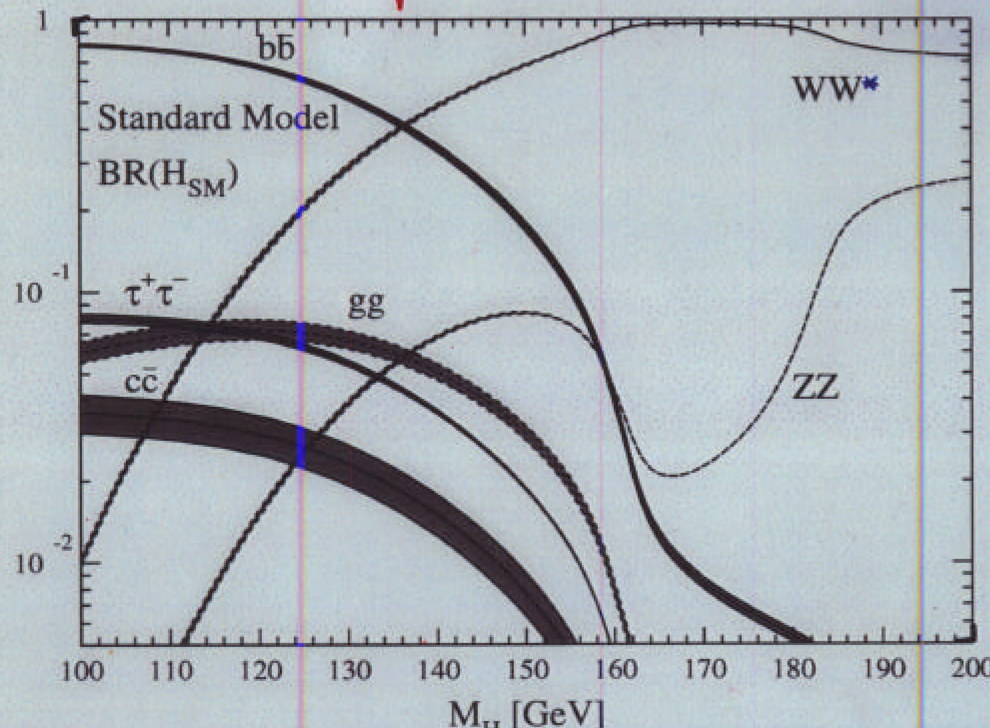
ELWWG, Moriond '01

Dominant Decay modes of the SM Higgs Boson with $m_H \lesssim 200$ GeV

$$BR(H_{SM} \to X) = \frac{\Gamma(H_{SM} \to X)}{\Gamma_{tot}}$$

Djouadi, Spira, Zerwas
Gross, Kniehl, Wolf

BR(H_{SM})



Spira

Uncertainties

$\alpha_s(M_Z) = 0.118 \pm 0.006$

$M_b = (4.62 \pm 0.05)$ GeV; $M_c = (1.42 \pm 0.04)$ GeV; $M_t = (176 \pm 11)$ GeV

Important: expected hierarchy of Higgs decays holds

$BR_{\tau^+\tau^-} \lesssim 10^{-1} BR_{b\bar{b}} \xrightarrow[1]{} \mathcal{O}(m_b^2/m_\tau^2) * 3 \to$ color

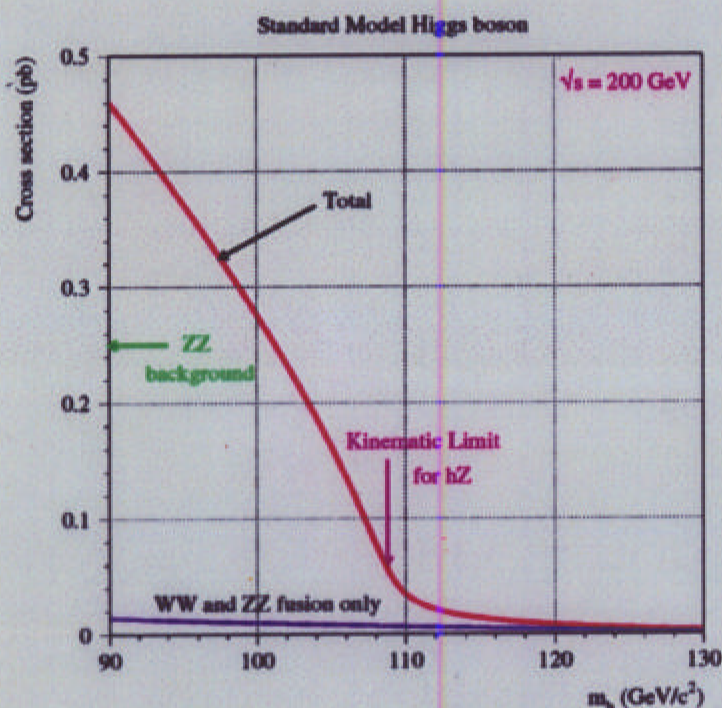
$BR_{c\bar{c}} < BR_{\tau^+\tau^-} \longrightarrow$ due to smallnes of $m_c(m_H)$

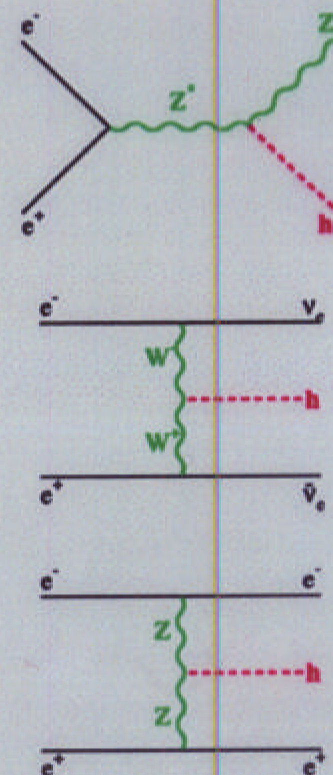
SM Higgs Searches at LEP

Main production channel:

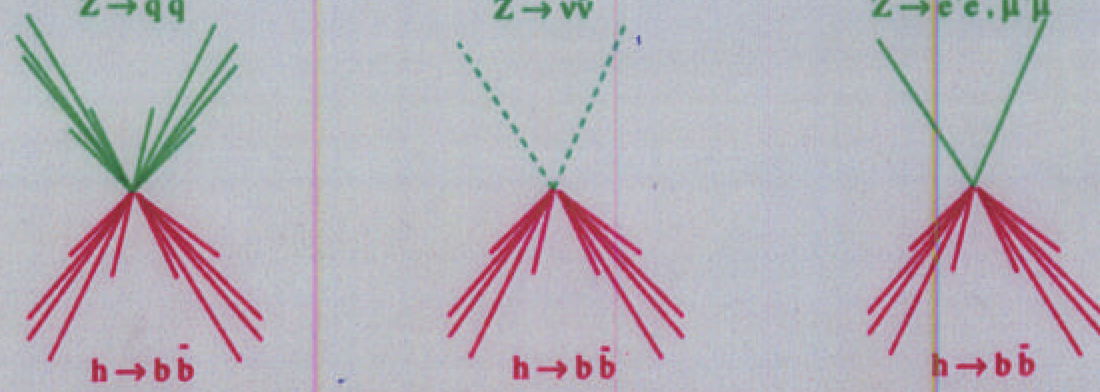
$$e^+e^- \xrightarrow{Z^*} Z\,H \longrightarrow b\bar{b},\ \tau^+\tau^-$$

$$Z \longrightarrow q\bar{q},\ \nu\bar{\nu},\ e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-$$





- small contrib. from vector-boson fusion
  $\longrightarrow$ relevant only near HZ threshold



- LEP "almost" final results

$$m_H^{SM} > 113.5 \text{ GeV} \quad @\ 95\%\ \text{c.l.}$$

- interesting hint of

$m_H \simeq 115$ GeV → compatible with SM cross section

?

- Estimate from precision data

$$m_H^{SM} \lesssim 200 \text{ GeV} \qquad (@\ 95\%\ \text{c.l.})$$

- Upgraded Tevatron → good sensitivity precisely in this mass range

↓

next chance to reveal mechanism of electroweak symmetry breaking

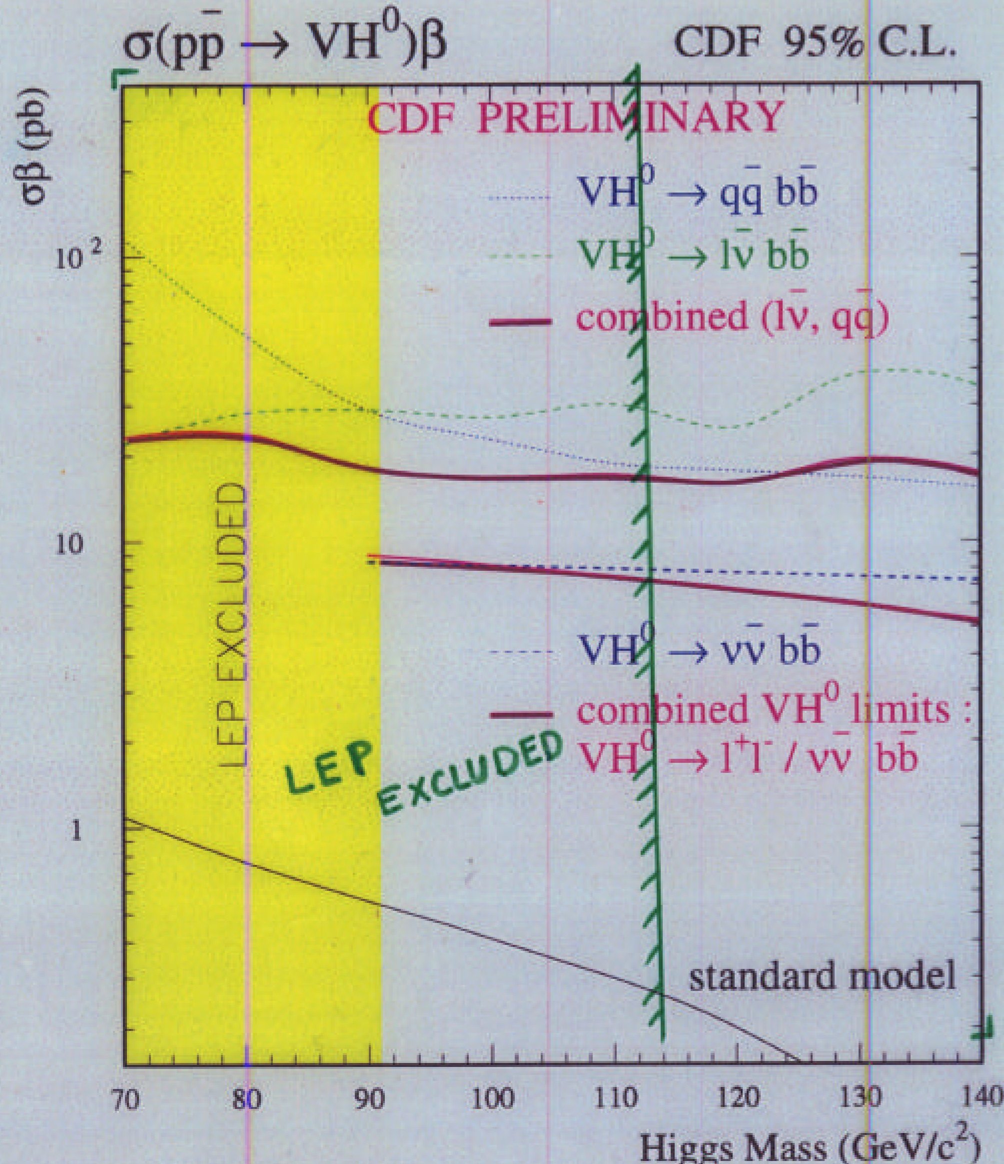
SM Higgs Searches at Tevatron RUN I

$$q\bar{q} \xrightarrow{Z} ZH \to \ell^+\ell^-/\nu\bar{\nu}/q\bar{q} + b\bar{b}$$

$$q\bar{q}' \xrightarrow{W} WH \to q\bar{q}'/\ell\nu + b\bar{b}$$

CDF Run 1 Higgs limits

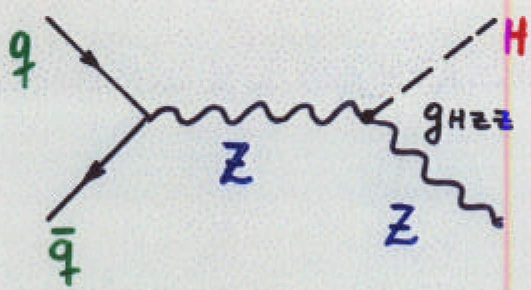
$\sqrt{s} = 1.8$ TeV; $\int \mathcal{L}\,dt \sim 100\,\mathrm{pb}$

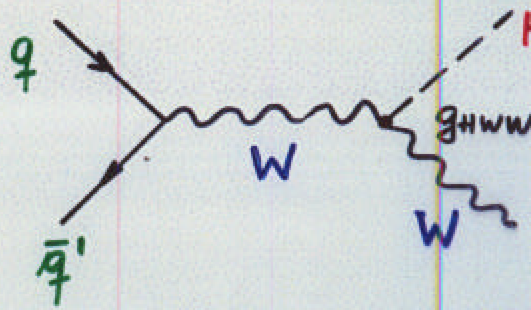


no sensitivity with present data : exp. limits are $\gtrsim$ 1 order of magnitude away from predicted σ_{SM}

Production of the SM Higgs Boson at the Tevatron

- main production mechanism: Glashow, Nanopoulos, Yildi





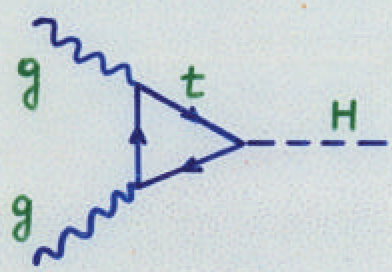
- associated production with a Z or W boson

with $g_{HVV} = 2(G_F\sqrt{2})^{1/2} m_V^2$

- leptonic decay of Z/W provides trigger for the event

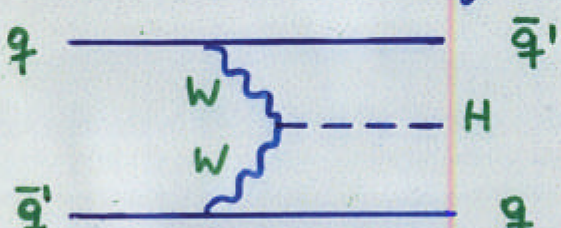
- other processes:

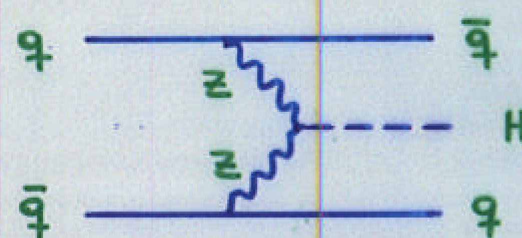
- gluon fusion via virtual top quark loop Georgi, Glashow Machacek, Nanopoulo



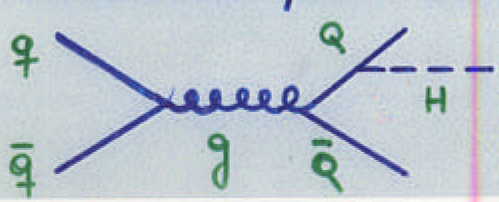
largest cross section but down by backgrounds

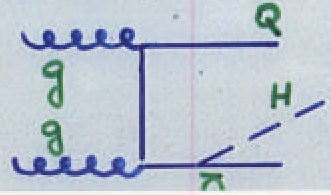
- weak-vector boson fusion Cahn, Dawson/Kane, Repko, Rolnick

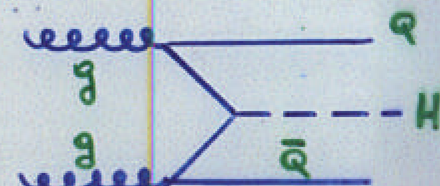




- associated prod. with $b\bar{b}$ or $t\bar{t}$ Dicus, Willenbrock/Ng, Zakarauskas/Kunsz

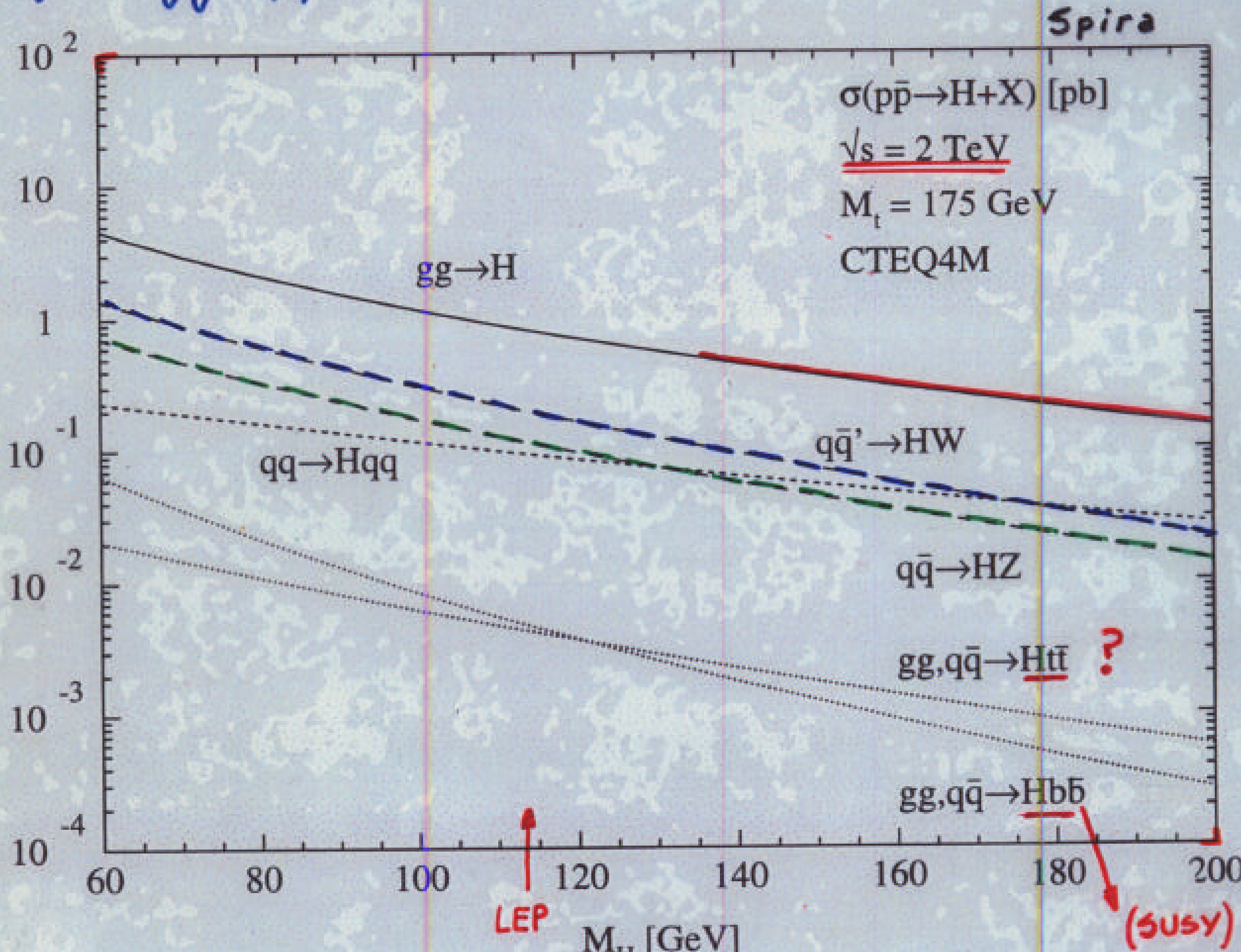






Cross Sections as a function of m_H for SM Higgs production mechanisms at the Tevatron $\sqrt{s} = 2$ TeV

QCD corrections included for all processes but for $gg, q\bar{q} \rightarrow Ht\bar{t}, Hb\bar{b}$



http://home.cern.ch/~spira/proglist.html

⇓

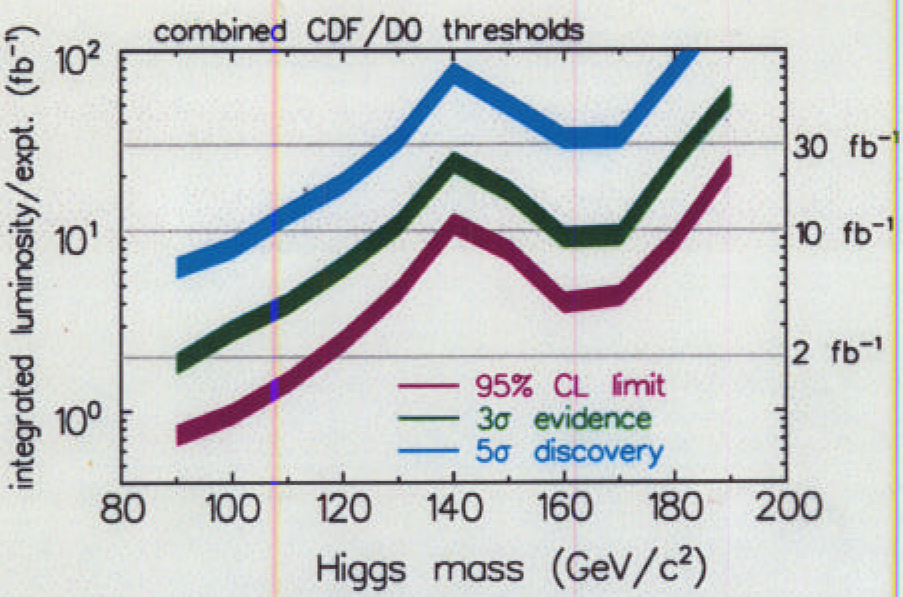
public codes with "all" known radiative correc. available from M. Spira

SM Higgs Prospects at the Tevatron

Higgs/SUSY Workshop & Higgs WG Report results

- $M_H \leq 130\text{GeV} \Longrightarrow p\bar{p} \to VH \to Vb\bar{b}$ (V = W,Z)
- $M_H \geq 130\text{GeV} \Longrightarrow p\bar{p} \to VH \to VWW^*$

$\Longrightarrow p\bar{p} \to H \to WW^*$



- $M_H \leq 180$ GeV $\Longrightarrow$ 95 % C.L. excl. $\to 10\ \text{fb}^{-1}/exp.$

3σ evidence $\to 20\ \text{fb}^{-1}/exp.$ 5σ discovery $\to \approx 60\ \text{fb}^{-1}/exp.$

- $M_H \leq 130$ GeV $\Longrightarrow 5\sigma$ with $30\ \text{fb}^{-1}/exp.$

- $M_H \approx 115$ GeV (LEP Hint?) $\Longrightarrow 3\sigma$ with $\approx 5\ \text{fb}^{-1}/exp.$

$\Longrightarrow 5\sigma$ with $\approx 15\ \text{fb}^{-1}/exp.$

Other Channels: $H \to \tau\tau$ to be explored

$t\bar{t}H \to t\bar{t}b\bar{b}$ prelim. studies very encouraging