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The status of the Standard Model and Physics beyond it

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our wisdom: q = the building blocks of Nature:

theory: $q - l$ interactions $\Rightarrow$ SM, SUSY...

exp: always hadrons h = bound states of q:

$$p = (uud),\ n = (ddu),\ \pi^{\pm} = (u\bar{d}),\ K^{\pm} = (s\bar{u})...$$

exp. $\Leftrightarrow$ theory: 2 basic quantities needed $q \Leftrightarrow h$:

- the parton distribution functions (PDFs): $N \Rightarrow q : q(x)$

$$p_{\mu} \simeq x\, P_{\mu}, \quad \overrightarrow{N} \Rightarrow \overrightarrow{q} : \Delta q(x)$$

- fragmentation functions (FFs): $q \Rightarrow h$: $D_q^h(z)$

$$P_{\mu}^h \simeq z\, p_{\mu}, \quad q(p) \Rightarrow h(P^h)$$

EXP: $\Rightarrow$ PDFs & FFs

PDFs & FFs = SM picture; QCD: energy evolution $Q_0^2 \to Q^2$

the correct info about $q - l$ ints. depends on our knowledge of PDF and FF

at low energies – wave functions
at high energies – almost free quarks $\longrightarrow$ PDFs and FFs

How to determine PDFs and FFs ?

PDFs – quite well known, but FFs – quite new objects!

3 topics:

- **FFs – the problems**
- **SM - it's status**
- **SUSY**

$$D_q^h(z) = ?$$

FFs are universal: $\Rightarrow$ FFs are the same in all processes
$\Rightarrow$ determined in a suitable process – can be used in any other process, at any other energy scale.

Which are the processes for FFs?

- e^+e^- annihilation:

$$e^+ + e^- \to h + X, \quad h = \pi^\pm, K^\pm, p/\bar{p}...$$

$$d\sigma^h = \sum_q e_q^2 \otimes D_{q+\bar{q}}^h$$

$\Rightarrow$ the "cleanest" process, but determines only

$$D_{u+\bar{u}}^h, \quad D_{d+\bar{d}}^h, \quad D_{s+\bar{s}}^h, \quad D_g^h$$

q and $\bar{q}$ are not distinguished

- semi-inclusive DIS:

$$l + N \to l' + h + X, \qquad h = \pi^{\pm}, K^{\pm}, p/\bar{p}...$$

$$d\sigma_N^h = \sum_q e_q^2 \left[q \otimes D_q^h + \bar{q} \otimes D_{\bar{q}}^h \right]$$

- hadron production in pp collisions:

$$p + p \to h + X, \quad h = \pi^{\pm},\ K^{\pm},\ p/\bar{p}..$$

$$d\sigma_{pp}^h = \sum_{a,b,c} q_a \otimes q_b \otimes \hat{\sigma}_{ab}^c \otimes D_c^h$$

D_q^h & $D_{\bar{q}}^h$ determined separately but PDFs involved

- e^+e^-, SIDIS and pp are used to determine D_q^h

too many unknowns: always relats. among the FFs assumed

$\Rightarrow$ TH uncertainties introduced

What are the assumptions on FFs?

fav. FFs = the constituent quarks fragment into h

unfav. FFs = the other quarks fragment into h

different assumptions used by different groups!

$$\underline{\underline{\pi^+ = (u\bar{d})}}$$

I) all fav. FFs and all unfav. FFs are equal ⇒ 2 FFs:

$$\begin{aligned} D_u^{\pi^+} &= D_{\bar{d}}^{\pi^+} \\ D_d^{\pi^+} &= D_{\bar{u}}^{\pi^+} = D_s^{\pi^+} = D_{\bar{s}}^{\pi^+} \end{aligned}$$

II) all fav. FFs are equal and 2 unfav. FFs ⇒ 3 FFs

$$\begin{aligned} D_u^{\pi^+} &= D_{\bar{d}}^{\pi^+} \Leftarrow SU(2) \\ D_d^{\pi^+} &= D_{\bar{u}}^{\pi^+} \Leftarrow SU(2) \\ D_s^{\pi^+} &= D_{\bar{s}}^{\pi^+} \Leftarrow SU(2) \end{aligned}$$

III) fav. & unfav. FFs are proportional

$$3FFs + \mathcal{N} + \mathcal{N}' : \qquad \begin{aligned} D_u^{\pi^+} &= \mathcal{N} D_{\bar{d}}^{\pi^+} \Leftarrow \mathcal{N} = 1.10 \\ D_{\bar{u}}^{\pi^+} &= D_d^{\pi^+} \Leftarrow SU(2) \\ D_s^{\pi^+} &= \mathcal{N}' D_{\bar{u}}^{\pi^+} \Leftarrow \mathcal{N}' = 0.82 \end{aligned}$$

IV) all FFs are proportional

$$1\,FF : \quad D_u^{\pi^+} = D_{\bar{d}}^{\pi^+},\ D_s^{\pi^+} = D_{\bar{s}}^{\pi^+} = D_d^{\pi^+} = (1-z) D_u^{\pi^+}$$

$K^+ = (u\bar{s}), \quad K^- = (s\bar{u})$

I) all fav. FFs and all unfav. FFs are equal ⇒ 2 FFs

$$
\begin{aligned}
D_u^{K^+} &= D_{\bar{s}}^{K^+} \\
D_{\bar{u}}^{K^+} &= D_s^{K^+} = D_d^{K^+} = D_{\bar{d}}^{K^+}
\end{aligned}
$$

II) fav. FFs are not equal, all unfav. FFs equal ⇒ 3 FFs (DSS)

$$
\begin{aligned}
D_u^{K^+}, \qquad & D_{\bar{s}}^{K^+} \quad \Leftarrow \quad m_s >> m_{u,d} \\
D_{\bar{u}}^{K^+} = \; & D_s^{K^+} = D_d^{K^+} = D_{\bar{d}}^{K^+}
\end{aligned}
$$

III) fav. FFs and unfav. FFs are proportional (Kre):

$$
\begin{aligned}
& D_u^{K^+}, \qquad D_{\bar{s}}^{K^+} \quad \Leftarrow \quad m_s >> m_{u,d} \\
& D_u^{K^+} = (1-z) D_{\bar{s}}^{K^+}, \qquad D_d^{K^+} = D_{\bar{d}}^{K^+} = (1-z)^2 D_{\bar{s}}^{K^+}
\end{aligned}
$$

IV) fav. FFs are not equal and unfav. FFs are not equal ⇒ 5 FFs (AKK)

$$
\begin{aligned}
D_u^{K^+}, \qquad & D_{\bar{s}}^{K^+} \\
D_{\bar{u}}^{K^+}, \qquad & D_s^{K^+} \\
D_d^{K^+} = \; & D_{\bar{d}}^{K^+}
\end{aligned}
$$

Different parametrizations for FFs exist

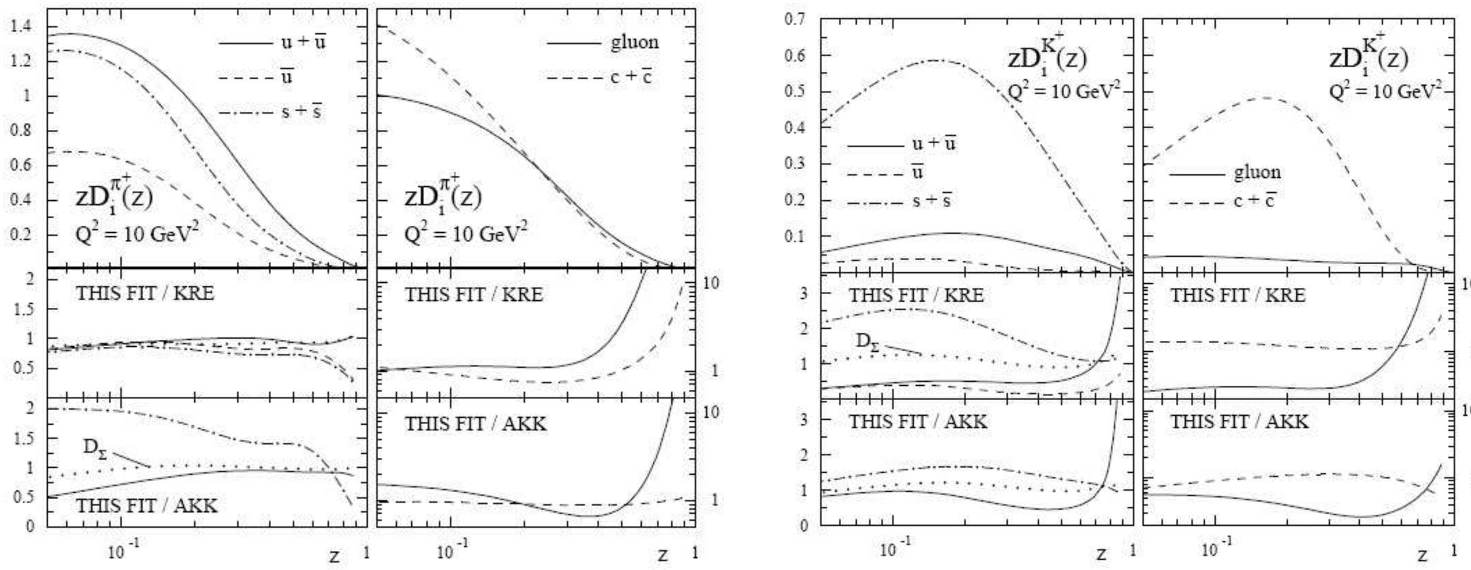
1) B. Kniehl et al, KKP (2000) ⇒ e^+e^-
2) S. Kretzer (2000) ⇒ e^+e^-
3) EMC (1989) ⇒ SIDIS
4) Kretzer et al, (2001) ⇒ e^+e^- & SIDIS
5) M. Hirai et al, HKNS (2007) ⇒ e^+e^-
6) S. Albino et al, AKK (2008) ⇒ e^+e^- & pp
7) De Florian et al, DSS (2007) ⇒ e^+e^-, SIDIS & pp

2 general features about them:

1) different assumptions used

2) they don't agree among themselves

The existing parametrizations



The parametrizations at Q^2=10 GeV [*De Florian etc. (DSS)*]

if fact. theorem: the difference is only in the assumptions

One should be always aware of these uncertainties!

How to check the assumptions?

Model independent approach

Suggested: the difference cross section between h^+ and h^-:

$$\sigma^{h^+},\ \sigma^{h^-}\ \Rightarrow\ \sigma^{h^+-h^-}=\sigma^{h^+}-\sigma^{h^-}$$

$$e+N\ \longrightarrow\ e+h^{\pm}+X:\qquad (\sigma_N^{h^+}-\sigma_N^{h^-})/\sigma^{DIS}$$

$$p+p\ \longrightarrow\ h^{\pm}+X:\qquad \sigma_{pp}^{h^+}-\sigma_{pp}^{h^-}$$

Shown: they determine only

$$u_V\,(D_u^h-D_{\bar u}^h),\quad d_V\,(D_d^h-D_{\bar d}^h),\quad s_V\,(D_s^h-D_{\bar s}^h)$$

Obtained 2 independent measurements for D_q^h & $D_{\bar q}^h$:

$$e^+e^-\longrightarrow h+X:\quad D_q^h+D_{\bar q}^h,\qquad q=u,d,s$$

$$\sigma^h-\sigma^{\bar h}:\qquad D_q^h-D_{\bar q}^h,\quad q=u,d$$

the info on D_q depends on $h=\pi^{\pm},K^{\pm}\ldots$ and the process

1) model independent – only QCD + C-inv!

2) with no assumptions about FFs

3) with no assumptions about PDFs

4) correct in any QCD order

5) only u_V & d_V enter – the best known PDFs $\simeq 2-3\%$

The difference cross sections for $K^{\pm}$ and K_s^0

$\sigma^K \quad \Rightarrow \quad \sigma^{\mathcal{K}} = \sigma^{K^+} + \sigma^{K^-} - 2\sigma^{K_s^0}$ $\qquad K_s^0 = (K^0 + \bar{K}^0)/\sqrt{2}$

in the processes $[K = K^{\pm}, K_s^0]$:

- $e^+e^- \to K + X$: $\quad \sigma^{\mathcal{K}}_{e^+e^-} = \sigma^{K^+}_{e^+e^-} + \sigma^{K^-}_{e^+e^-} - 2\sigma^{K_s^0}_{e^+e^-}$

- $eN \to e + K + X$: $\quad \sigma^{\mathcal{K}}_{N} = \sigma^{K^+}_{N} + \sigma^{K^-}_{N} - 2\sigma^{K_s^0}_{N}$

- $pp \to K + X$: $\quad \sigma^{\mathcal{K}}_{pp} = \sigma^{K^+}_{pp} + \sigma^{K^-}_{pp} - 2\sigma^{K_s^0}_{pp}$

The cross sections for $\sigma^{\mathcal{K}}$:

$$\bullet\, d\sigma^{\mathcal{K}}_{e^+e^-} \simeq 6\sigma_0(\hat{e}_u^2 - \hat{e}_d^2)(1 + \alpha_s\, C_q \otimes)\, \mathrm{D}^{\mathrm{K}^+ + \mathrm{K}^-}_{\mathrm{u-d}}$$

$$\bullet\, d\sigma^{\mathcal{K}}_{p} \simeq [(4u + d) \otimes (1 + \alpha_s\, C_{qq} \otimes) + \alpha_s\, g \otimes C_{gq} \otimes]\, \mathrm{D}^{\mathrm{K}^+ + \mathrm{K}^-}_{\mathrm{u-d}}$$

$$\bullet\, d\sigma^{\mathcal{K}}_{d} \simeq [(u + d) \otimes (1 + \alpha_s\, C_{qq} \otimes) + \alpha_s\, g \otimes C_{gq} \otimes]\, \mathrm{D}^{\mathrm{K}^+ + \mathrm{K}^-}_{\mathrm{u-d}}$$

$$\bullet\, d\sigma^{\mathcal{K}}_{pp} \simeq \sum_{ab} f_a \otimes f_b \otimes \hat{\Sigma}_{ab} \otimes \mathrm{D}^{\mathrm{K}^+ + \mathrm{K}^-}_{\mathrm{u-d}}$$

$$\hat{\Sigma}_{ab} = \hat{\sigma}^{uX}_{ab} + \hat{\sigma}^{\bar{u}X}_{ab} - \hat{\sigma}^{dX}_{ab} - \hat{\sigma}^{\bar{d}X}_{ab}, \quad D^{K^+ + K^-}_{u-d} \equiv (D_u - D_d)^{K^+ + K^-}$$

COMPASS at CERN, SPS fixed target experiment with μ beam:

$$\mu + N \to \mu + h + X, \quad h = \pi, K, p$$

target and beam polarized

the goal: $\Delta G = ? \Delta q = ?$

FFs=?

The SM = our present understanding of Nature
Glashow-Weinberg-Salam, Nobel price 1979

$$G = SU_c(3) \times SU_L(2) \times U(1) \Rightarrow SU_c(3) \times SU_{em}(1)$$

Three types of fields:

1) matter fields, $s = \frac{1}{2}$

$$\begin{pmatrix} u' \\ d' \end{pmatrix}_L, \quad u'_R, \quad d'_R, \qquad \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \quad e_R$$

$\sum e_q = 0 \Rightarrow$ gauge anomalies cancel

3 generations – gauge anomalies cancel in each generation

2) gauge fields, $s = 1$

$$g^a, \quad W^\pm, \quad Z, \quad A$$

3) Higgs fields, $s = 0$

$$\phi = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}_L$$

SSB: $\phi \rightarrow v + H$

$$G \rightarrow SU_c(3) \times U_{em}(1), \quad m_f, m_{W,Z} \neq 0$$

all properties of H fixed, only m_H = free parameter

3 types of tests of the SM

1. Precision tests of EW radiative corrections

2. Unitarity triangle

3. Flavour changing neutral currents

1. Precision tests of EW radiative corrections

combined analysis of data at LEP & SLD (SLAC, USA), CDF & D0 (FNAL) $\Rightarrow$ SM=OK!

$$m_H = 87^{+37}_{-26} GeV, \quad 114 GeV \leq m_H \leq 187 GeV$$
$$m_H \neq 170 - 176\, GeV$$

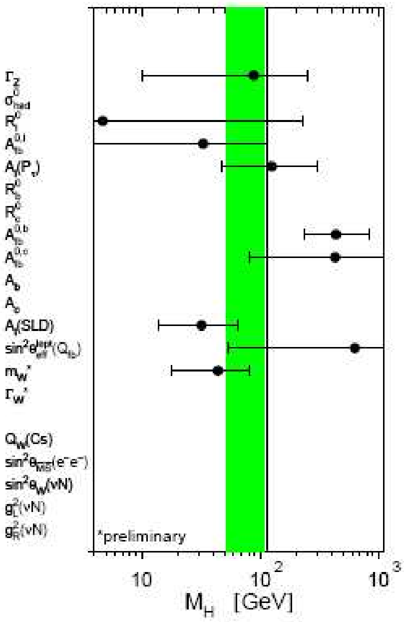


Figure 1. Values of the Higgs mass extracted from different EW observables. The average is shown as a green band [1].

TH: 125 GeV $\leq m_H \leq$ 175 (800) GeV, $\Lambda \simeq 10^{16} - 10^{19}$ (10^3) GeV

However: depends on m_t=178 Gev (EW fits)

or $m_t = 170.9 \pm 1.8$ GeV (CDF/D0)

m_H: 1 loop $\simeq G_F m_W^2 \log m_H^2/m_W^2$, 2 loops $\simeq G_F^2\, m_H^2$

2. The unitarity triangle

In 1999 asymmetric B-factories BaBar (SLAC, USA) & Belle (KEK, Japan) test of CP viol. in SM through unit. triangle

$$\begin{pmatrix} 2/3 \\ -1/3 \end{pmatrix} \qquad \begin{pmatrix} u' \\ d' \end{pmatrix}_L \qquad \begin{pmatrix} c' \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t' \\ b' \end{pmatrix}_L$$

$G = SU(2) \times U(1)$ fixes the gauge ints:

$$\bullet \quad \begin{aligned} \mathcal{L}_{W^\pm} &= \frac{g}{\sqrt{2}} (\bar{u}'_L \gamma^\mu d'_L + \bar{c}'_L \gamma^\mu s'_L + \bar{t}'_L \gamma^\mu b'_L)\, W_\mu \\ \mathcal{L}_{Z^0} &= \frac{g}{\sqrt{2}\, \cos\theta_W} \left(\bar{q}'_L\, I_{3q}\, \gamma^\mu\, q'_L - 2\, e_q\, \sin^2\theta_W\, \bar{q}' \gamma^\mu q' \right) Z_\mu \\ \mathcal{L}_\gamma &= -e_q\, (\bar{q}'\, \gamma^\mu\, q')\, A_\mu \end{aligned}$$

⇒ quark generations do not mix

⇒ universality of generations

• SSB ⇒ q = massive fields, q and q' related by unit. transfs.

$\mathcal{L}_Z$ & $\mathcal{L}_\gamma$ = diagonal, $\mathcal{L}_W$ mixes generations:

$$\mathcal{L}_W = (u_L\, c_L\, t_L)\, \gamma^a\, \mathrm{V}_{\mathrm{u_1 d_1}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\alpha$$

$$\mathrm{V}_{\mathrm{u_1 d_1}} = (V_L^{up})^\dagger V_L^{down}$$

$\mathrm{V}_{\mathrm{u_1 d_1}}$ = the CKM mixing matrix

What is peculiar about V_{ij}?

- $\mathrm{V}_{\mathrm{u_1 d_1}}$ = unitary (3 × 3) matrix:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- CKM ⇒ the only way to mix generations
- CKM ⇒ the only way to generate CP viol.
- exp: V_{ij}
- theory: unitarity

Test of unitarity of CKM is test of the SM → unitarity triangle

Cabibbo, Kobayashi and Maskawa – the CKM matrix

$\underbrace{\textit{Nambu}}_{1/2}$ and $\underbrace{\textit{Kobayashi \& Maskawa}}_{1/2}$ → 2008 Nobel price

History remarks

1963:

the Cabibbo angle $\theta_c \Rightarrow$ mixing of 2 generations:

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \& \quad \begin{pmatrix} c \\ s \end{pmatrix}$$

1963 $\Rightarrow$ only u, d, s quarks are known

1971 $\Rightarrow$ the c-quark is discovered

1964 $\Rightarrow$ CP viol. observed $\Rightarrow$ 3 gens. needed

1973 $\Rightarrow$ Kobayashi & Maskawa predicted 3 gens.

$\Rightarrow$ the CKM matrix – 3 angles + δ_{CP}

1976 $\Rightarrow$ the b-quark, FermiLab

1995 $\Rightarrow$ the t-quark, FermiLab, $m_t = 175$ GeV

Theory predicts only unitarity:

$$VV^\dagger = V^\dagger V = 1$$

2 types of unitary relations:

- test of the number of generations:

$$\sum_{u_1=u,c,t} |V_{u_1 j}|^2 = 1, \qquad \sum_{d_1=d,s,b} |V_{j d_1}|^2 = 1$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- orthogonality of the rows and of the lines:

$$\sum_{u_1=u,c,t} V_{u_1 d} V^*_{u_1 s} = 0, \qquad \sum_{d_1=d,s,b} V_{u d_1} V^*_{c d_1} = 0$$
$$\sum_{u_1=u,c,t} V_{u_1 d} V^*_{u_1 b} = 0, \qquad \sum_{d_1=d,s,b} V_{u d_1} V^*_{t d_1} = 0$$
$$\sum_{u_1=u,c,t} V_{u_1 s} V^*_{u_1 b} = 0, \qquad \sum_{d_1=d,s,b} V_{c d_1} V^*_{t d_1} = 0$$

6 unitarity triangles $\Rightarrow$ test of CP viol.

Why do we need more tests of CP viol?

CP viol. $\Rightarrow$ only in K^0 and B^0

Which triangle?

exp. $\Rightarrow \quad \lambda = 0.22$

$$\begin{pmatrix} V_{ud} & V_{us}(\lambda) & V_{ub}(\lambda^3) \\ V_{cd}(\lambda) & V_{cs} & V_{cb}(\lambda^2) \\ V_{td}(\lambda^3) & V_{ts}(\lambda^2) & V_{tb} \end{pmatrix}$$

1) $\sum_{u_1=u,c,t} V_{u_1 d} V^*_{u_1 s} = 0 \quad \Rightarrow \quad \underbrace{V_{ud}V^*_{us}}_{\lambda} + \underbrace{V_{cd}V^*_{cs}}_{\lambda} + \underbrace{V_{td}V^*_{ts}}_{\lambda^5} = 0$

connects only 1 & 2 families

2) $\sum_{u_1=u,c,t} V_{u_1 s} V^*_{u_1 b} = 0 \quad \Rightarrow \quad \underbrace{V_{us}V^*_{ub}}_{\lambda^4} + \underbrace{V_{cs}V^*_{cb}}_{\lambda^2} + \underbrace{V_{ts}V^*_{tb}}_{\lambda^2} = 0$

connects only 2 & 3 families

3) $\sum_{u_1=u,c,t} V_{u_1 d} V^*_{u_1 b} = 0 \quad \Rightarrow \quad \underbrace{V_{ud}V^*_{ub}}_{\lambda^3} + \underbrace{V_{cd}V^*_{cb}}_{\lambda^3} + \underbrace{V_{td}V^*_{tb}}_{\lambda^3} = 0$

connects all 1, 2 & 3 families

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

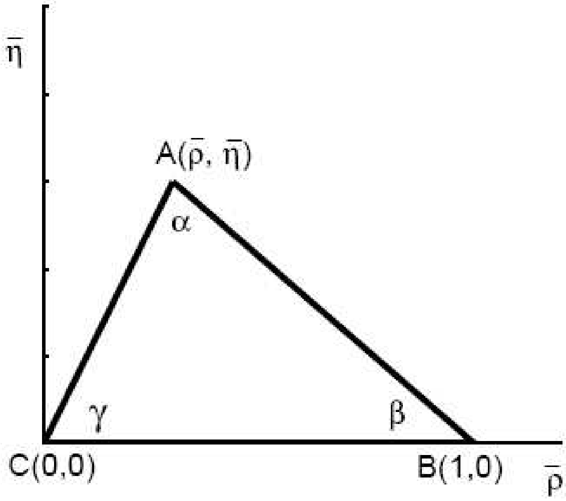
$V_{ud}V^*_{ub},\ V_{cd}V^*_{cb},\ V_{td}V^*_{tb}$ = complex numbers $\simeq A\lambda^3$
= vectors in the complex $\bar{\rho}, \bar{\eta}$ plane

$$\frac{V_{ud}V^*_{ub}}{(-V_{cd}V^*_{cb})} + \frac{V_{td}V^*_{tb}}{(-V_{cd}V^*_{cb})} = 1$$

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = |\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}|e^{i\gamma} = \sqrt{\bar{\rho}^2 + \bar{\eta}^2}e^{i\gamma}$$

$$\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = |\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}|e^{-i\beta} = \sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}e^{-i\beta}$$

CP viol: $\beta, \gamma \neq 0$; 3 families: $\rightarrow$ triangle, D. Bojrken,



1988

- CP viol: $\alpha \neq 0$, $\beta \neq 0$, $\gamma \neq 0$
- 3 families: they form a triangle $\rightarrow \alpha + \beta + \gamma = 180^0$
- different ways of constructing the triangle -....
- test of CP viol. through CP inv. measurements!!
- $S_{\triangle} = \frac{J}{2}$
- is there new Physics?

What do we know about V_{ij}?

theory: 4 parameters $\underbrace{\mathit{3\ angles}}_{\text{the Euler angles in 3 dim. space}} + \underbrace{\mathit{1\ phase}}_{\text{CP viol.}}$

$\longrightarrow$ 3 real and 1 complex pars:

$$\theta_{12}, \quad \theta_{23}, \quad \theta_{13} \quad and \quad \delta$$

exp: $\sin\theta_{12} \sim 2\cdot 10^{-1}$, $\sin\theta_{23} \sim 4\cdot 10^{-2}$, $\sin\theta_{13} \sim 4\cdot 10^{-3}$,

$\Rightarrow$ almost diagonal & a hierarchi of the mixing angles:

$$\sin\theta_{13} << \sin\theta_{23} << \sin\theta_{12} << 1$$

$\Rightarrow$ ν-mixing matrix = the opposite:

$$\sin^2\theta_{12} \sim 0.3, \ \sin^2\theta_{23} \simeq 0.5, \ \sin^2\theta_{13} \leq 0.04$$

- the Wolfenstein parametrization uses the hierarchi $\longrightarrow$ 4 real pars:

$$\lambda, \quad A, \quad \rho, \quad \eta \tag{1}$$

$$\sin\theta_{12} = \lambda, \quad \sin\theta_{23} = A\lambda^2, \quad \sin\theta_{13}e^{-i\delta} = A\lambda^3(\rho - i\eta)$$

$$\lambda = 0.22 = \text{small} \quad \text{parameter}$$

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & A\lambda^2 & 1 \end{pmatrix}$$

$$\bar{\rho} = (1 - \frac{\lambda^2}{2})\rho, \qquad \bar{\eta} = (1 - \frac{\lambda^2}{2})\eta$$

$\Rightarrow$ **fulfills unitarity in all orders of λ**

V_{ij} determined independently in experiments:

1) $d \rightarrow u$ in β decays: $|V_{ud}| = 09728 \pm 0.0030$

2) $s \rightarrow u$ in $K_L(\bar{s}d) \rightarrow \pi^{\pm}(\bar{u}d)l^{\mp}\nu_l$: $|V_{us}| = 0.2257 \pm 0.0021$

3) $b \rightarrow u$ in $B \rightarrow X_u l \nu_l$, $B \rightarrow \pi l \nu$: $|V_{ub}| = (4.31 \pm 0.39)10^{-3}$

- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9992 \pm 0.0005 \pm 0.0009$

4) $c \rightarrow d$: $\nu_\mu + n(ddu) \rightarrow c + \mu^- \rightarrow s + \mu^+ + \nu_\mu + \mu^-$: $|V_{cd}| = 0.213 \pm 0.011$

5) $c \rightarrow s$ in $D \rightarrow K l \nu$: $|V_{cs}| = 0.957 \pm 0.017$

6) $B \rightarrow X_c l \nu$, $B \rightarrow D l \nu$: $|V_{cb}| = (40.9 \pm 1.8)10^{-3}$

- $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.003 \pm 0.027$

7) $\Delta m_d = B_d^0 - \bar{B}_d^0$: $|V_{td}| = (4.7 \pm 0.8)10^{-3}$

- $|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1.001 \pm 0.005$

8) $\Delta m_s = B_s^0 - \bar{B}_s^0 \quad \Rightarrow \quad |V_{ts}| = (40.6 \pm 2.7)10^{-3}$

9) $\frac{\mathcal{B}(t \rightarrow bW)}{\sum_{q=d,s,b} \mathcal{B}(t \rightarrow Wq)} = |V_{tb}|^2 \quad \Rightarrow \quad |V_{tb}| > 0.78$
$t\bar{t}W$-loops in $\Gamma(Z \rightarrow b\bar{b})$: $|V_{tb}| = 0.77^{+0.18}_{-0.24}$

Global fit, UTfit collaboration

input parameters: CP inv. & CP viol.:

$$|\frac{V_{ub}}{V_{cb}}|, \quad \Delta m_d, \quad \frac{\Delta m_d}{\Delta m_s}, \quad \epsilon, \quad \sin 2\beta$$

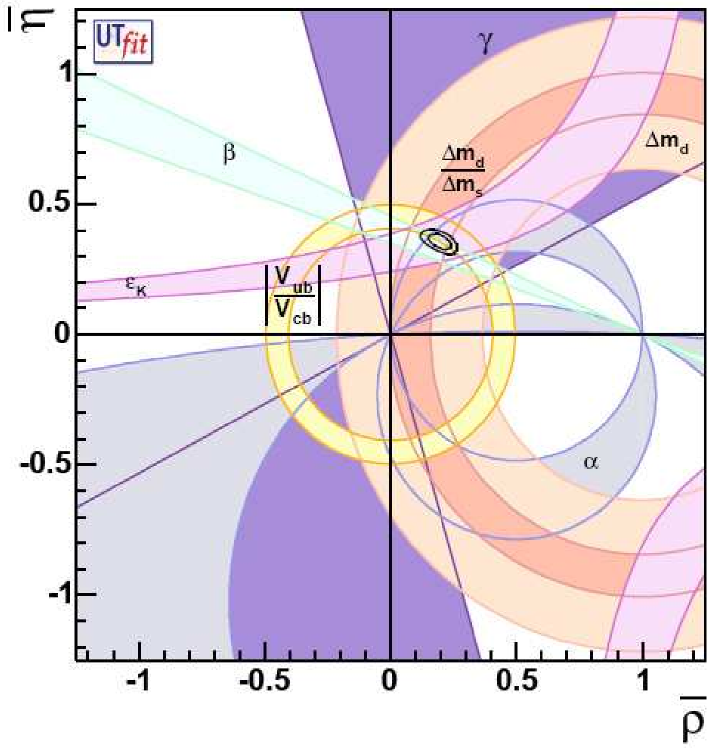
$$\Delta m_d = B_d^0 - \bar{B}_d^0, \qquad \Delta m_s = B_s^0 - \bar{B}_s^0$$

CP viol. quantities:

$$\begin{aligned} \epsilon \quad &\Rightarrow \quad CP\, viol.\ in\ K^0 - \bar{K}^0 \\ \sin 2\beta \quad &\Rightarrow \quad CP\, viol.\ in\ B^0 - \bar{B}^0 \end{aligned}$$

$$\begin{aligned} A_f^{CP}(t) &= \frac{\Gamma(B_d^0(t) \to f) - \Gamma(\bar{B}_d^0(t) \to f)}{\Gamma(B_d^0(t) \to f) + \Gamma(\bar{B}_d^0(t) \to f)} \\ &= \pm \sin 2\beta\, \sin(\Delta m\, t), \quad f = J/\psi + K_{S,L}^0 \end{aligned}$$

the golden mode: hadronization effect cancel=no assumptions!



$$\bar{\rho} = 0.196 \pm 0.045, \quad \bar{\eta} = 0.347 \pm 0.025$$

$$|\frac{V_{ub}}{V_{cb}}|, \quad \Delta m_d, \quad \frac{\Delta m_d}{\Delta m_s} \Rightarrow \sin 2\beta = 0.734 \pm 0.043$$

to be compared to $\sin 2\beta$ from $A^{CP}_{J/\psi,K_S}$ & $A^{CP}_{J/\psi,K_L}$:

$$\sin 2\beta \;=\; 0.710 \pm 0.034 \pm 0.019$$

2006: α and γ measured in B decays:

$$\alpha, \beta, \gamma \;\Rightarrow\; \bar{\rho} = 0.204 \pm 0.055, \qquad \bar{\eta} = 0.317 \pm 0.025$$

$$\alpha + \beta + \gamma = 184^{+20}_{-15}$$

fit to all data:

$$\bar{\rho} = 0.197 \pm 0.031, \qquad \bar{\eta} = 0.315 \pm 0.020$$

3. Flavour Changing Neutral Currents, FCNC

flavour changing = generation mixing

TH:

A) leptons:

⇒ No generation mixing, neither at tree level nor loop induced!

B) quarks:

⇒ FCNC are only loop induced via CKM quark mixing matrix:

$$b \to s\gamma : \qquad b \to [W^+(u,c,t)] \to s\gamma$$

Exp:

Very precise measurements exist:

A) lepton sector – upper bounds

$$BR(\mu \to e\gamma) < 1,2.10^{-11}(10^{-14}?)$$
$$BR(\tau \to e\gamma) < 2,7.10^{-6}$$
$$BR(\tau \to \mu\gamma) < 1,1.10^{-6}$$

B) quark sector – small effects

$$BR(b \to s\gamma) \simeq (1-4).10^{-4}$$
$$K^0 - \bar{K}^0, \quad B^0 - \bar{B}^0, \quad D^0 - \bar{D}^0\, mixings$$

The EDM'a are also FCNC +chiral flip + CP:

$$d_e < 1,5.10^{-27}(10^{-29}?)e\,cm$$
$$d_\mu < 1,5.10^{-18}(10^{-24}?)e\,cm,$$
$$d_\tau < 1,5.10^{-16}e\,cm$$
$$d_n < 7.10^{-26}e\,cm$$

SM is in prefect agreement with exp.!

Summary

- data is in agreement with the SM
- clear bounds on m_H within LHC discovery potential

The problem is not in the discovery of H

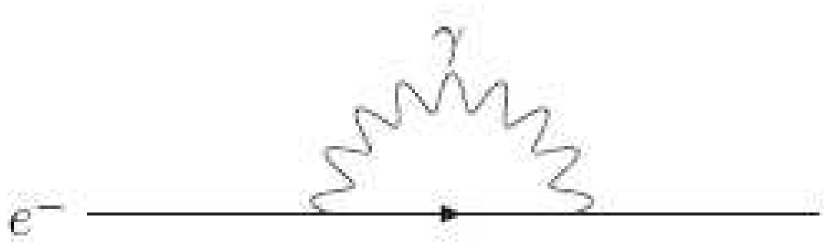
Even when the Higgs is discovered we have problems with the SM.

2 problems of SM

- **hierarchi problem**
  - **quadratic divergencies in the H-sector**
- **quantum gravity cannot be included**

Quadratic divergences in SM

- $s = \frac{1}{2}$



a) $\delta m_e \to 0$, $m_e \to 0$

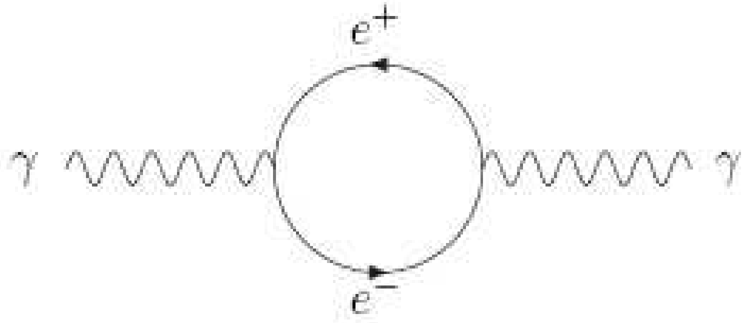
$\delta m_e \simeq \ \alpha_{em}\, m_e \,\log(M_{Pl}/m_e) \simeq 0.24\, m_e$

b) at $m_e = 0$, $\mathcal{L}$ is chiral inv: $\psi \to e^{i\gamma_5 \alpha}\psi$

mass corrs. to $s = \frac{1}{2}$ are kept naturally small by chiral invariance

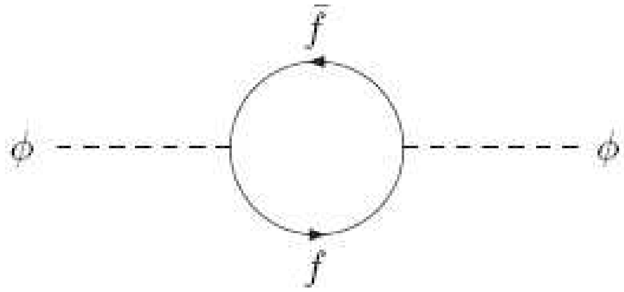
naturally=in all perturbative orders

- $s = 1$



mass corrs. to gauge bosons are kept naturally small by gauge invariance: $\delta m_W < m_W, \ldots$

• $s = 0$



Λ = the renorm. scale above which SM doesn't work:
$\Lambda \simeq 10^{19}$ GeV $\longrightarrow$ Plank scale;
$\Lambda \simeq 10^{16}$ GeV $\longrightarrow$ GUT scale

$$m_h^2 = m_{h^0}^2 + \delta m_h^2 = m_{h^0}^2 + g_F^2 \Lambda^2 + \ldots$$

but TH: $m_h \lesssim 1$ TeV

$$\delta m_h^2 \ll m_h^2 \leq 1\, TeV^2$$

• there is no sym. to protect mass corrs. for $s = 0$ naturally $\Rightarrow m_h \longrightarrow 0$ no help

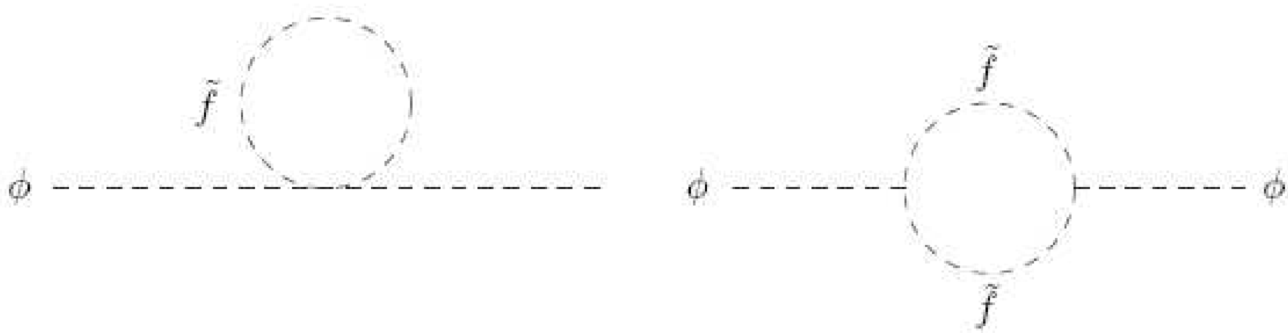
- the fine-tuning problem
- the problem of naturalness
- the hierarchi problem

this doesn't make SM unrenorm, but we need
fine-tuning $\delta m_h^2 \ll m_h^2$ in all perturbative orders – SUSY!

Supersymmetry protects m_h^2 naturally

SUSY

$$\mathcal{L} \sim -g_F\,\bar{f} f\,\phi - g_S^2\,\tilde{f}^* \tilde{f}\,\phi^2$$



$$m_h^2 = m_{h^0}^2 + \frac{g_F^2}{4\pi}(\Lambda^2 + m_F^2) - \frac{g_S^2}{4\pi}(\Lambda^2 + m_S^2) + \ldots$$

- $g_F^2 = g_S^2 \Rightarrow \Lambda^2$ cancels independently of m_F^2 & m_S^2

$$m_h^2 = m_{h^0}^2 + \frac{g_F^2}{4\pi}(m_F^2 - m_S^2)[1 + \log\frac{\Lambda^2}{m_f^2}] + \ldots$$

- $|m_F^2 - m_S^2| \leq m_h^2 \simeq 1$ TeV needed!

In SUSY all divergencies cancel if
1) $g_F = g_S$ and 2) $m_F = m_S$

SUSY is the only sym. that keeps the Higgs as elem. particle

Why do we need scalar bosons?

• the only particles that allow SSB without breaking Lorentz inv: $< H >_0 \neq 0 \Rightarrow m_W, m_Z$
• the only particles that allow Yukawa couplings: $\bar{\psi}\psi H \to m_f$

More motivations

• solves the gauge hierarchi problem

a) hierarchi of the gauge constants: $M_{Pl} \leftrightarrow \Lambda_{EW}, \Lambda_{QCD}$
$\longrightarrow$ SUSY particles at TeV scale required!!

b) hierarchi of the masses: $m_e/m_t \simeq 10^{-6}$ – not solved

• matter and Higgs fields are treated uniquelly
• renormalizable like QED, no quadr. divergencies
• it's a predictive theory = testable
• SM is not enough for GUT $\longrightarrow$ SUSY=OK!
• SM: problems with p-decay
$\longrightarrow$ SUSY – no problems
• more CP-viol. needed than in SM
$\longrightarrow$ SUSY provides it!
• quantum gravity is naturally included
$\Rightarrow$ local SUSY (supergarvity)
• a natural candidate for dark matter

$\rightarrow$ LSP in SUSY

• SUSY is the only non-trivial unification (not as a direct product) of space-time & gauge symms. – the Haag-Lopuszanski-Sohnius theorem

Supersymmetry (SUSY)

SUSY: the most attracticve candidate for Physics beyond the SM

$$|fermion>=\hat{Q}|boson>, \quad |boson>=\hat{Q}|fermion>$$

• the only symmetry

which solves the problem with quadr. divergences keeping H as elementary particle

– generates m_W, m_f through the Higgs mechanism

MSSM ≡ Minimal SUSY extension of SM

= minimal number (N=1) SUSY generatators: $Q, \bar{Q}$

= minimal number (N=2) Higgs doublets: H_1, H_2

• the gauge group:

$$G = SU_c(3) \times SU_L(2) \times U(1)$$

• the superfileds

$$|s = \frac{1}{2}> \longrightarrow \ |s = 0>,$$
$$|s = 1> \longrightarrow \ |s = \frac{1}{2}, Majorana>$$

⇒ 2 types of fields – chiral and vector superfields:

Chiral superfields

$$
\begin{aligned}
\hat{Q} &= (u, d)_L \, (\tilde{u}_L, \tilde{d}_L) \\
\hat{U}^c &= (\bar{u}_R, \tilde{u}^*_R) \\
\hat{D}^c &= (\bar{d}_R, \tilde{d}^*_R) \\
\hat{L} &= (\nu, e)_L (\tilde{\nu}, \tilde{e}_L) \\
\hat{E}^c &= (\bar{e}_R, \tilde{e}^*_R) \\
\hat{H}_1 &= (H_1^0, H_1^-), (\tilde{H}_1^0, \tilde{H}_1^-) \\
\hat{H}_2 &= (H_2^+, H_2^0), (\tilde{H}_2^+, \tilde{H}_2^0)
\end{aligned}
$$

Vector superfields

$$
\begin{aligned}
\hat{G}^a &= (g^a_\mu, \tilde{g}^a), \qquad a = 1, ..8 \\
\hat{W}^i &= (W^i_\mu, \tilde{w}^i), \qquad i = 1, 2, 3 \\
\hat{B} &= (B_\mu, \tilde{b})
\end{aligned}
$$

$$\mathcal{L}_{MSSM} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}}$$

$$\mathcal{L}_{\text{SUSY}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{gauge}} + \mathcal{W}$$

$$
\begin{aligned}
\mathcal{W} &= \left[h_U \hat{Q} \hat{H}_2 \hat{U}^c + h_D \hat{H}_1 \hat{Q} \hat{D}^c + h_E \hat{H}_1 \hat{L} \hat{E}^c \right] + \\
&+ \mu \hat{H}_1 \hat{H}_2
\end{aligned}
$$

$$h_U \simeq \frac{m_u}{m_W \sin\beta}, \quad h_D \simeq \frac{m_d}{m_W \cos\beta}, \quad h_E \simeq \frac{m_l}{m_W \cos\beta}$$

SUSY fixes $\mathcal{L}_{SUSY}$ completely, μ = the only new parm.

2 stages of symmetry breaking

- $m \neq 0 \Rightarrow$ SSB of $G = SU(2) \times U(1)$

$< H_1^0 >= v_1, < H_2^0 >= v_2$

$g^2(v_1^2 + v_2^2) = m_W^2, \tan\beta = v_1/v_2$

- $m \neq \tilde{m} \Rightarrow$ explicit SUSY-breaking $- \mathcal{L}_{\rm soft} =$ superpartners

$$\begin{aligned}\mathcal{L}_{\rm soft} \; = \; & \tfrac{1}{2}M_1\tilde{b}\tilde{b} + \tfrac{1}{2}M_2\tilde{w}\tilde{w} + \tfrac{1}{2}M_3\tilde{g}\tilde{g} \\ & + M_{\tilde{Q}}^2|\tilde{q}_L|^2 + M_{\tilde{U}}^2|\tilde{u}_R^c|^2 + M_{\tilde{D}}^2|\tilde{d}_R^c|^2 \\ & + M_{\tilde{L}}^2|\tilde{l}_L|^2 + M_{\tilde{E}}^2|\tilde{e}_R^c|^2 \\ & + m_{H_1}^2|H_1|^2 + m_{H_2}^2|H_2|^2 + B\mu H_1 H_2 \\ & + \left(A_U H_2\tilde{q}_L\tilde{u}_R^c + A_D H_1\tilde{q}_L\tilde{d}_R^c + A_E H_1\tilde{l}_L\tilde{e}_R^c + \text{h.c.}\right)\end{aligned}$$

~~CP~~ : $\mu = |\mu| e^{i\phi_\mu}$,

$M_1 = |M_1| e^{i\phi_1}, \; M_2 = |M_2| e^{i\phi_2}$

$A_t = |A_t| e^{i\phi_t}, \; A_b = |A_b| e^{i\phi_b}, \; A_\tau = |A_\tau| e^{i\phi_\tau}, \quad A_q \simeq m_q$

exp: $d_n, \; d_n \Rightarrow \phi_\mu \leq 10^{-2}$

The physical states in MSSM

$$\begin{array}{rl} \text{scalar quarks} & q \leftrightarrow \tilde{q} \\ \text{scalar leptons} & l \leftrightarrow \tilde{l} \\ \text{gluino} & g \leftrightarrow \tilde{g}, \\ \text{chargino} & \tilde{\chi}_j^{\pm} = (\tilde{W}^{\pm}, \tilde{H}^{\pm}), \\ \text{neutralino} & \tilde{\chi}_k^0 = (\tilde{\gamma}, \tilde{Z}, \tilde{H}_1^0, \tilde{H}_2^0) \\ \text{Higgs scalars} & h^0,\ H^0,\ A^0,\ H^{\pm} \end{array}$$

th: $m_{h^0} \simeq 130 - 150$ GeV

exp: $81 \leq m_{h^0} \leq 196\,GeV$, best: $m_{h^0} \simeq 88$ GeV

Global R symmetry

R-symm. forbids B and L violation:

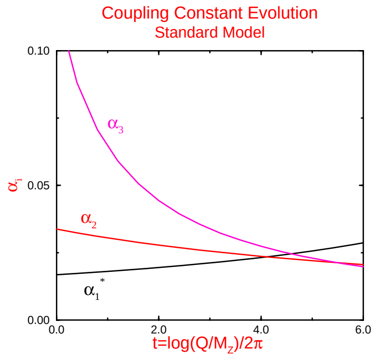
$$\mathcal{W}_{B,L-viol} = \lambda \hat{L}\hat{L}\hat{E}^c + \lambda' \hat{L}\hat{Q}\hat{D}^c + \lambda'' \hat{D}\hat{D}\hat{U} + \mu' \hat{H}\hat{L}$$

R $= +1 \longrightarrow$ ordinary particles
R $= -1 \longrightarrow$ superpartners

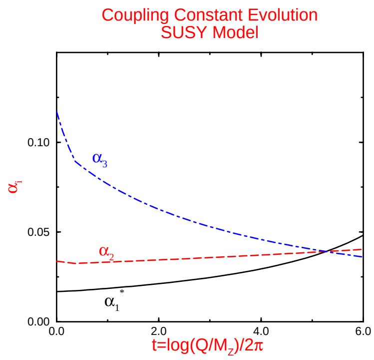
$\Rightarrow$ SUSY particles are produced in pairs
$\Rightarrow$ absolutely stable neutral Lightest SUSY Particle (LSP) exists
$\Rightarrow$ $\tilde{\chi}_1^0$ = a natural candidate for DM

GUT and MSSM

Too many parameters = 50 (124 if FV) $\Rightarrow$ Can we use GUT?



SM: $M_{GUT} \simeq 10^{14}$ GeV if meet ($m_H =?$)
$\tau(p \to e^+\pi) \simeq 10^{30}$ yr $\Leftrightarrow$ exp: $\tau(p \to e^+\pi) \simeq 1.6\ 10^{33}$ yr



MSSM: $M_{GUT} \simeq 10^{16}$ GeV and can meet, $\tau(p \to e^+\pi) \simeq 10^{38}$ years

SUSY is naturally incorporated in GUT

mSugra

GUT + MSSM = mSugra = CMSSM

parms: m_0, $m_{1/2}$, A_0, $\tan\beta$, μ, ϕ_μ, ϕ_A fixed at M_{GUT}

RGE: evolved to low energies

other modifications of MSSM:

mSugra: $(A_{U,D,L})_{ij} = A_0 \Rightarrow$ flavour blind
$(A_{U,D,L})_{ij} = (A_{U,D,L})\,\delta_{ij} \Rightarrow$ no generation mixing
$(A_{U,D,L})_{ij} \neq (A_{U,D,L})\,\delta_{ij} \Rightarrow$ generation mixing
Split SUSY: $\tilde{m}_f$ split from $\tilde{m}_s$

The only problem – it's not discovered yet

LHC to decide!