Problems of the Standard Model and the 4th generation.

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any problems?

SM successfully describes all known properties of elementary particles.

LHC should help to resolve the problems of SM.

What are the problems?

Great Problems

1. Hierarchy of Planck mass (scale of gravity, 10^{19} GeV) and W mass (scale of weak interactions, 100 GeV) $\longrightarrow$ SUSY; "up-down" approach: we have many particles with masses $\sim M_P$ and nonrenormalizable interactions + (due to symmetries) few massless particles. Gauge - spin 1; local Poincare - spin 2; chirality + gauge - spin 1/2; spin 0 - goldstone (Aleksei Andreevich Anselm).

2. Zoo of SM (why are there 3 generations? where do all constants come from?) Mendeleev table of XXI century: $3*15(16)+12+1+1=59(62)$...

“small” problems

$``2\sigma``$ deviations from CKM predictions for CPV in B-decays:

$$a^s_{sl},\ \beta_s^{J/\psi\phi},\ A_{CP}(K\pi)$$

(If LHC turns $``2\sigma``$ into $``5\sigma``$ any of them will demand New Physics).

4 generation - is it allowed?

Three generations conformism

- Z width: LEP, SLC – 3 neutrinos
- Tevatron – no extra quarks
- Electroweak fits exclude extra generations (PDG08 J. Erler, P. Langacker “An extra generation of ordinary fermions is excluded at the 99.6% CL ...”)
- Electroweak fits require light Higgs

Leptop non-conformism

- LEPTOP – approach to EWRC worked out by Novikov, Okun, Rozanov and Vysotsky in the 90s.
- Phys. Lett. B **476** (2000) 107-115
- Phys. Lett. B **572** (2002) 111-116
- ....

Using LEPTOP it was found that the precision data do not exclude an existence of additional generation of quarks and leptons.

- V.A. Novikov, A.N. Rozanov, M.I. Vysotsky
  Yad.Fiz.**73** (2010) 662-668; arXiv:0904.4570 (hep-ph)

Not excluded yet

Contradictions with New Bible – PDG booklet– claim (2008):

- There is no room for 4th generation of quark and leptons. It is excluded by precision data.
- Precision data prefer a light higgs

$$m_H = 84^{+32}_{-24}\ \mathrm{GeV} \quad .$$

Very soon LHC will fix $N_g = 3$ or $N_g = 4$!

Last chance to give this talk!!

General introduction

Two strategies to look for a New Physics beyond the SM

- Direct -
  LEP and Tevatron search for 4th generation–
  No trace of a New Physics
  L3 $m_E \gtrsim 100.8$ GeV decay to νW;
  CDF, D0 $m_T \gtrsim 335$ GeV, $m_B \gtrsim 338$ Gev (CC decay) ;
  $m_T \gtrsim 220$ GeV, $m_B \gtrsim 190$ Gev (quasi-stable)
- Indirect searches –

  Precision experiment v.s. Precision calculations.
  Sometimes it works!

Radiative corrections in the SM

- Interaction in the SM is mediated by gauge bosons exchange.
- Gauge bosons interact in a universal way with any particles, both the standard ones and the new ones.
- If the new particles do not mix with SM particles there are only “oblique” corrections to SM observables

$$\Downarrow$$

Corrections to the propagation of gauge fields only (to self-energy):

$$\left\{ \begin{array}{c} \text{gauge field} \\ \text{propagator} \end{array} \right\} \equiv G(q^2) = \frac{g_0^2}{q^2 - m_0^2 - \Sigma(q^2)}$$

Decoupling of Heavy d.o.f.

Decoupling of Heavy d.o.f. from Low-Energy Physics

- QED – Berestetsky, Krokhin, Khlebnikov (1956)
- Vector-like theories– Appelquist–Carazzone Theorem (1975)

"Proof" in QED

Let renormalization procedure respect gauge-invariance:

- Photon is massless and propagator has a pole at $q^2 = 0$

$$G(q^2) = \frac{e_0^2}{q^2(1 - \Pi(q^2))}$$

In equation $G(q^2) = g_0^2/(q^2 - m_0^2 - \Sigma(q^2))$ we take

$$m_0^2 = 0, \quad \Sigma(q^2) = q^2\Pi(q^2)$$

and assume that $\Pi(q^2)$ is regular near $q^2 = 0$.

- All particles have one and the same electric charge:

  $$G(q^2) = \frac{e^2}{q^2}$$

  for small q^2 (large distance). It means that $\Pi(0) \equiv 0$ for any particle! Thus

  $$\Pi(q^2) \sim q^2$$

  at $q^2 \sim 0$.

Two step proof of decoupling

The contribution of heavy degrees of freedom to low-energy observables is suppressed by some power if these observables are expressed in terms of renormalized electric charge!

1) First step-dimension argument.

$$[\Pi(q^2)] = (m^2)^0$$

2) Second step-universality of gauge couplings.

$$\Pi(q^2) \sim q^2$$

Thus $\delta\Pi(q^2) \sim q^2/m^2_{\text{heavy}}$ for small q^2.

Heavy d.o.f. decouples from low-energy observables!

g-2 in QED

New particles contribute to anomalous magnetic moment of leptons at the level of two loops :

$$a_l = \frac{1}{2}(g_l - 2) = \frac{\alpha}{2\pi} + O(\alpha^2 \frac{m_l^2}{m_{heavy}^2})..$$

Berestetsky et al. (1956) argued

$$\delta a_e \sim \alpha^2 \left(\frac{m_e^2}{m_{heavy}^2} \right), \quad \delta a_\mu \sim \alpha^2 \left(\frac{m_\mu^2}{m_{heavy}^2} \right).$$

Enhancement factor $(m_\mu^2 / m_e^2) \sim 4 \cdot 10^4$

$(g-2)$ of muon is more suitable for New Physics search.

Current Status of muon (g-2)

Discrepancy with theory

3.2σ if $\alpha(m_\mu)$ is calculated using low-energy e^+e^- data

1.9σ if $\alpha(m_\mu)$ is calculated using data on τ-decay into hadrons

No decoupling in the SM

- An example – the third generation:

$$\begin{pmatrix} t \\ b \end{pmatrix} \quad \text{with} \;\; m_t \gg m_b$$

Thus for low-energy scattering ($E \ll m_t$) we have direct violation of $SU(2) \times U(1)$ symmetry

$$\Downarrow$$

Effective nonrenormalizable theory

$$\Downarrow$$

Power divergencies $\sim \Lambda^2/m_W^2$

Natural cut-off $\Lambda \sim m_t$

Thus EWRC depend on top quark mass as

$$\alpha\left(m_t^2/m_W^2\right)\ ,\ \ \alpha^2\left(m_t^2/m_W^2\right)^2\quad \text{etc.}$$

$$\Downarrow$$

In this way top quark was found.

- Degenerate case

$$\begin{pmatrix} U \\ D \end{pmatrix} \quad \text{with} \;\; m_U \to \infty \; ; \;\; m_D \to \infty \; ; \;\; m_U - m_D = \text{finite}$$

In this case we have finite non-zero contribution to observables.

Main body of the talk

LEPTOP 2009 fit

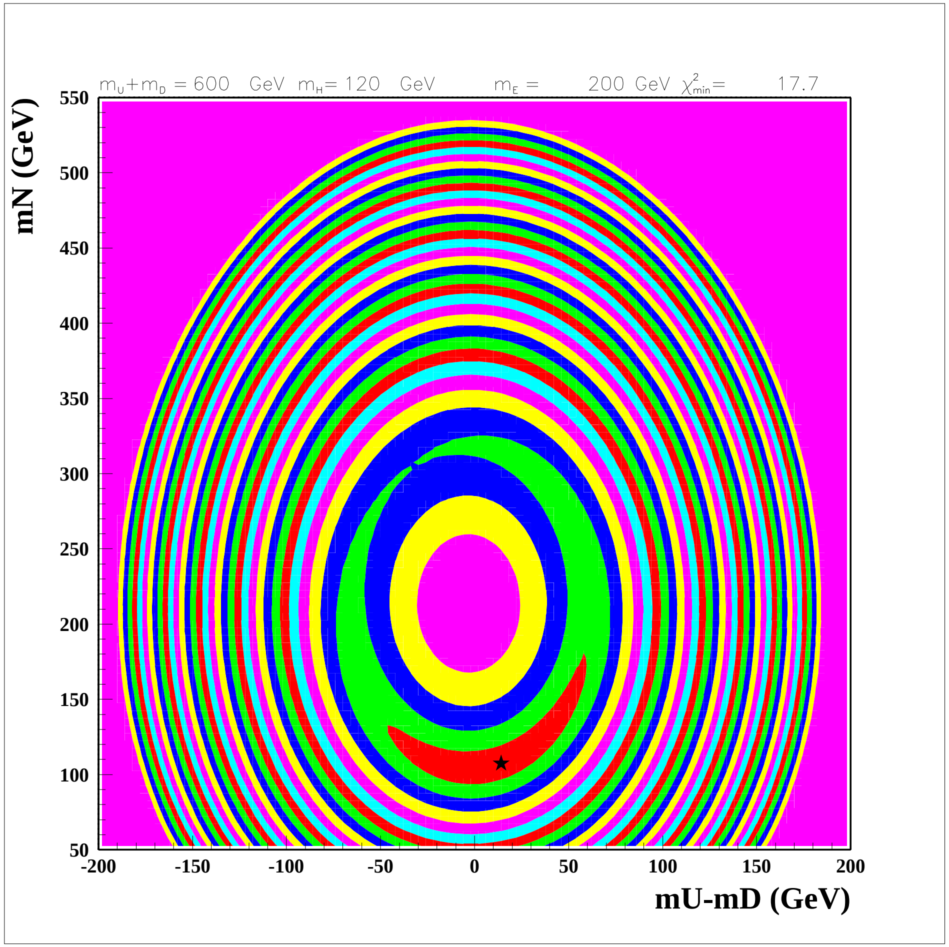
Observable	Exper. data	LEPTOP fit	Pull
Γ_Z, GeV	2.4952(23)	2.4963(15)	-0.5
σ_h, nb	41.540(37)	41.476(14)	1.8
R_l	20.771(25)	20.743(18)	1.1
$A^l_{\rm FB}$	0.0171(10)	0.0164(2)	0.8
A_τ	0.1439(43)	0.1480(11)	-0.9
R_b	0.2163(7)	0.2158(1)	0.7
R_c	0.172(3)	0.1722(1)	-0.0
$A^b_{\rm FB}$	0.0992(16)	0.1037(7)	-2.8
$A^c_{\rm FB}$	0.0707(35)	0.0741(6)	-1.0
s^2_l $(Q_{\rm FB})$	0.2324(12)	0.2314(1)	0.8

Observable	Exper. data	LEPTOP fit	Pull
$A_{\rm LR}$	0.1513(21)	0.1479(11)	1.6
A_b	0.923(20)	0.9349(1)	-0.6
A_c	0.670(27)	0.6682(5)	0.1
m_W, GeV	80.398(25)	80.377(17)	0.9
m_t, GeV	172.6(1.4)	172.7(1.4)	-0.1
$M_{\rm H}$, GeV		84^{+32}_{-24}	
$\hat{\alpha}_s$		0.1184(27)	
$1/\bar{\alpha}$	128.954(48)	128.940(46)	0.3
$\chi^2/n_{\rm d.o.f.}$		18.1/12	

Fits with the fourth generation

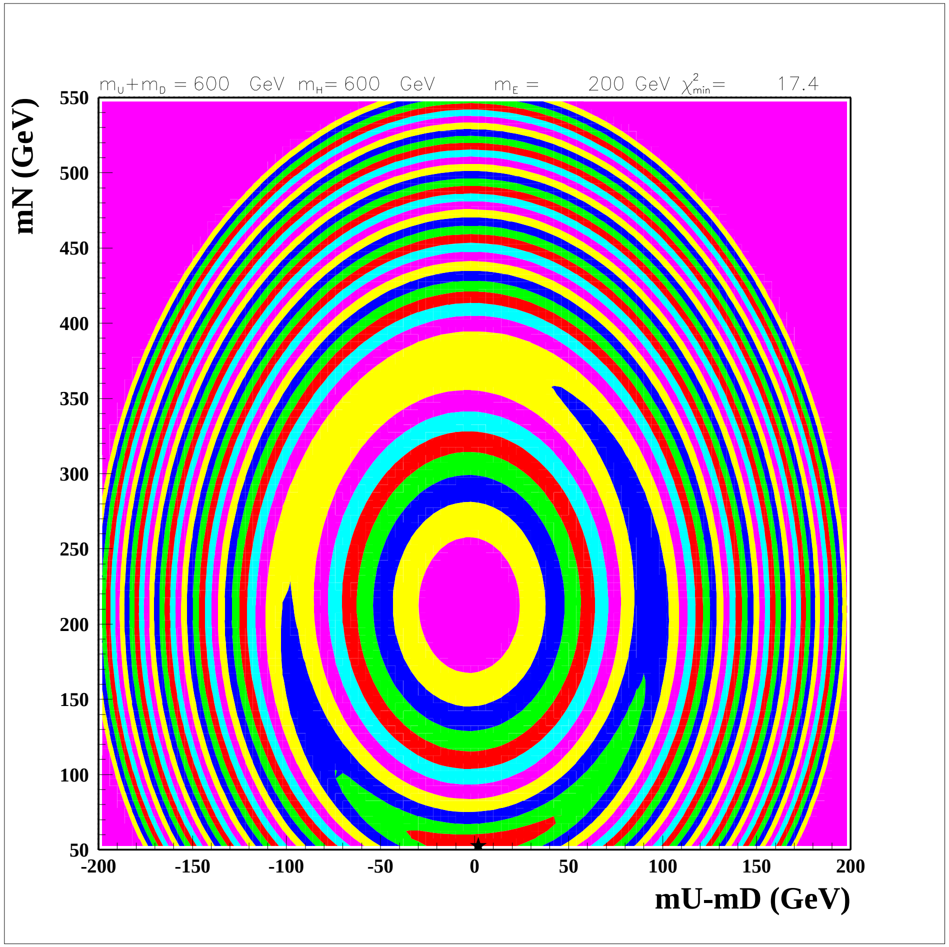
- Suppose that mixing is small.
- Separate steep and flat directions in the dependence of χ^2 on new particle masses (V.A. Novikov et al. (2002))
- Fix $m_U + m_D = 600$ GeV to avoid Tevatron direct search bounds; fix $m_E = 200$ GeV; vary the neutral lepton mass and the difference of Up- and Down-quark masses.

$m_H = 120$ GeV



$$\chi^2/n_{\text{d.o.f.}} = 17.7/11$$

$m_H = 600$ GeV



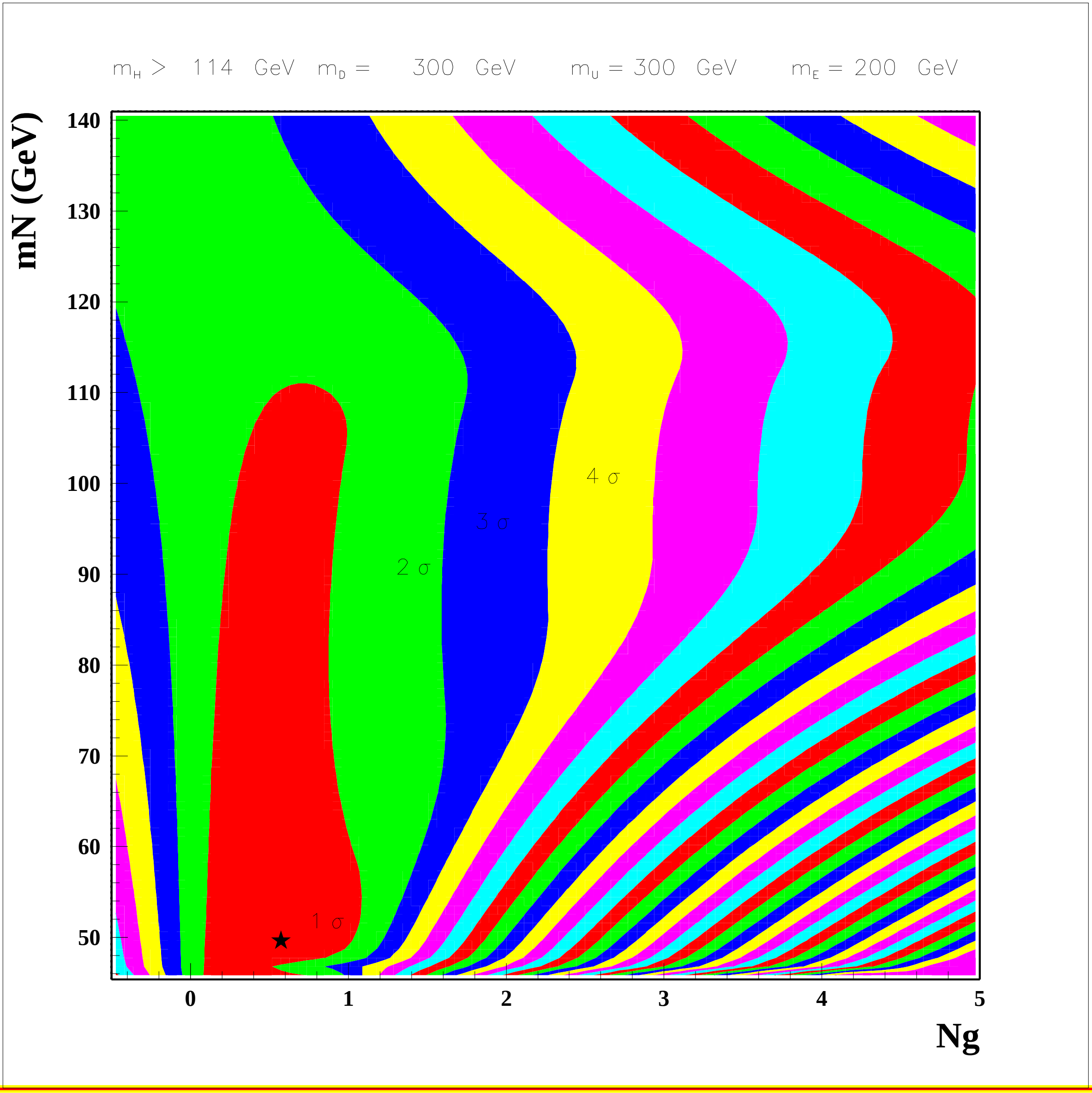
$$\chi^2/n_{\mathrm{d.o.f.}} = 17.4/11$$

- Quality of the fit with extra generation is good and is not worse than the Standard Model fit without additional generation.
- New generation removes upper bound on heavy Higgs

How many extra generations?

- To simplify the analysis we assume degeneracy of new particles with identical quantum numbers: $m_{E_1} = m_{E_2} = ...$, $m_{N_1} = m_{N_2} = ...$, $m_{U_1} = m_{U_2} = ...$, $m_{D_1} = m_{D_2} = ...$
- To study this problem we put $m_E = 200$ GeV, $m_U = m_D = 300$ GeV.
- Take $m_H > 114$ GeV.

The levels of χ^2 are shown in Fig. 4.


$m_H >$ 114 GeV $m_D =$ 300 GeV $m_U =$ 300 GeV $m_E =$ 200 GeV
mN (GeV)
140
130
120
110
100
90
80
70
60
50
0
1
2
3
4
5
Ng
1 σ
2 σ
3 σ
4 σ
★

The value of χ^2 for Standard Model and for $N_g = 1$ are almost the same, while three and more additional generations are strongly excluded.

Tevatron Higgs search

“Combined Tevatron upper limit on $gg->H$ and constraints on the Higgs boson mass in 4th generation fermion models.” arXiv:1005.3216v2 (20 May)

- Cross-section of Higgs production in gluon fusion process is increased by a factor ~ 9
- SM-like Higgs with a mass between 131 Gev and 204 Gev is excluded

LHCb and 4 generation

CKM-4 matrix has additional phases,
so one can easily explain “2σ“ deviations from CKM-3 predictions for CPV in B-decays:

$$a_{sl}^{s},\ \beta_s^{J/\psi\phi},\ A_{CP}(K\pi)$$

But: is there really any effect, or only statistical fluctuations?

Conclusions

- One extra generation with adjusted masses does not contradict to precision data
- New generation remove upper bound on higgs mass
- Strong bounds on higgs mass with 4th generation from Tevatron
- Very soon!! LHC will fix $N_g = 3$ or $N_g = 4$

Global problems with loops

1. Landau pole for Higgs self-coupling, for Yukawa and U(1) coupling

$$\Downarrow$$

Cut-off Λ
for New Physics scale

2. Non-Stable Universe
   Heavy Fermions contribution to V_{higgs}^{eff} is negative and makes Universe unstable.

$$V_{higgs}^{eff}(\Phi) \sim \lambda_{eff}(\Phi)\Phi^4$$

$\lambda(\Phi)$ is negative at large Φ.

Letters B 374 (1996) 127–130

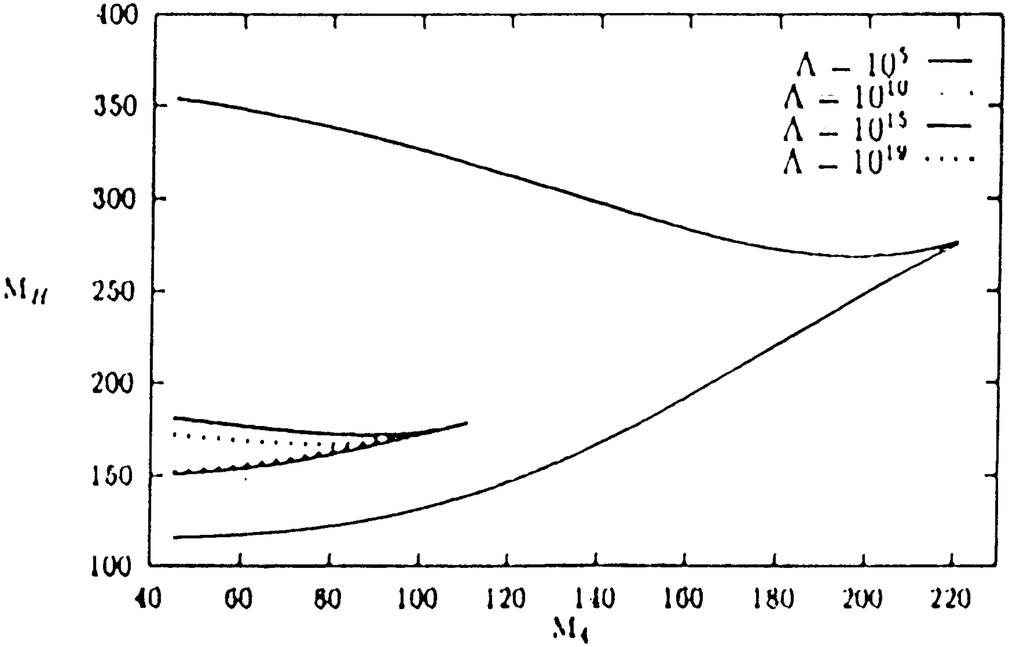


Fig. 1. Allowed values of M_H and M_4 lie between two curves: a. solid for $\Lambda = 10^5$ GeV; b. thin dotted for $\Lambda = 10^{10}$ GeV; c. thick solid for $\Lambda = 10^{15}$ GeV; d. thick dotted for $\Lambda = 10^{19}$ GeV.