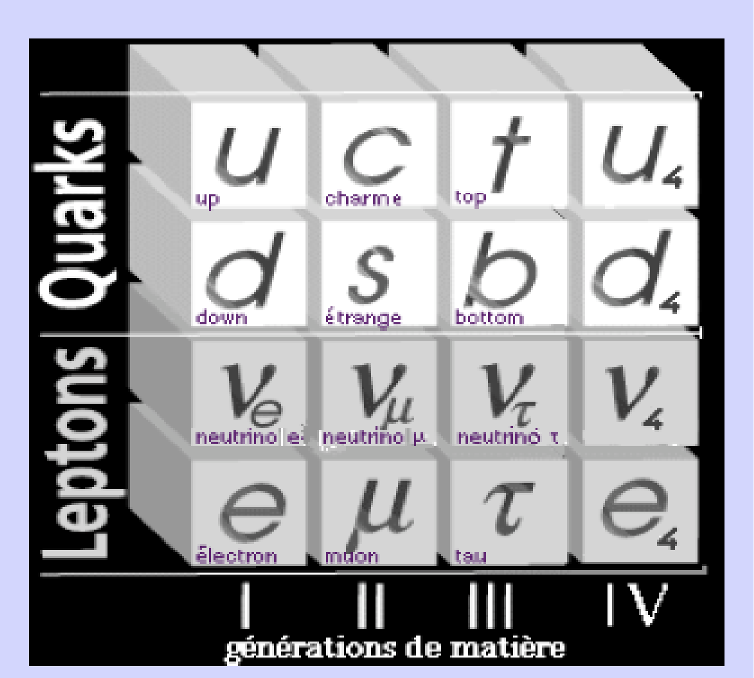
Naturalness of the Fourth SM Family

Saleh SULTANSOY

TOBB University of Economics and Technology, Ankara, Turkey
&
AMEA Institute of Physics, Baku, Azerbaijan

PDG 201?:



After repeating arguments on naturalness of the fourth SM family n'th time (repetition is the base of education!), I will present some results of our studies (see also following presentations by Erkcan and Orhan) since the last 4th family workshop

http://cdsweb.cern.ch/record/1114576

(for **resume** of the workshop, see B. Holdom et al., *Four Statements about the Fourth Generation*, e-Print: **arXiv:0904.4698** [hep-ph])

The second Workshop is beeing planned…

1. Two kinds of New Physics

1. New Physics Beyond the SM (preons, SUSY and so on)

2. New Physics Within the SM structure [#]

Electroweak: massive neutrinos, fourth family (**LHC**)

Strong: small x_g etc (**QCD Explorer**, recently renamed as LHeC)

Hypothesis: QCD – Confinement

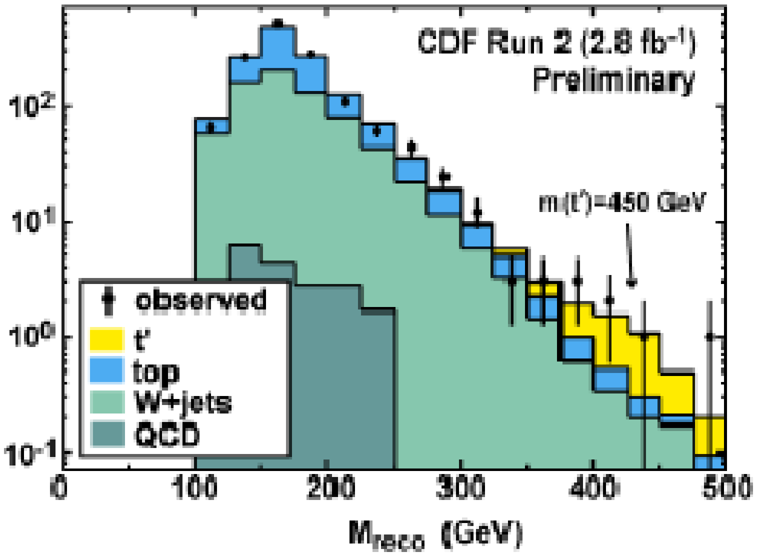
EW – Flavor Democracy

[#] In debris of the MSSM, SUGRA and so on, we forgot the SM itself. For example, MSSM-3 contains ~ 200 free parameters put by hand !!! (or **infinite** number of SUGRA points)

2. Why The Four SM Families

- SM does not determine the number of fermion families
  - LEP data (& Cosmology) $N \geq 3$ ($N = 3$ for "massless" ν, $2m_\nu < m_Z$)
  - QCD Asymptotic Freedom: $N \leq 8$
- Precision EW data: SM-3 and SM-4 have the same status (SM-3: $m_H < 180$ GeV, SM-4: $m_H \sim 300$ GeV)
- **Flavor Democracy → Fourth SM Family**
- There are some indications:
  - B-decays, BAU
  - CDF bump (but cross-section!)

For interpretation of the CDF Excess see



Hints from Tevatron, a prelude to what?

V. E. Özcan[1] , S. Sultansoy[2,3] and G. Ünel[4]

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[1] Department of Physics and Astronomy, University College London, London, UK.
[2] Institute of Physics, Academy of Sciences, Baku, Azerbaijan.
[3] TOBB ETU, Physics Department, Ankara, Turkey.
[4] University of California at Irvine, Physics Department, USA.

Abstract

We comment on the recent results from the Tevatron experiments in the W+jets channel and consider some models as the possible underlying physical theories. We also list some channels for further studies.

1 Introduction

The Standard Model (SM) is expected to be the low energy limit of a more fundamental theory [1]. The known candidates for such a theory have more fundamental particles than what is experimentally known today. Therefore, searches for new particles hence for the new model of elementary particles and their interactions, continue in both the precision physics and collider experiments. In a recent public note, CDF experiment at Tevatron excluded a standard model fourth-generation t' quark with mass below 311 GeV at 95% CL using 2.8 fb^{-1} of data (see figure 1)[2]. The shown theoretical model shows the tree-level cross section of a new quark with q=2/3 charge.

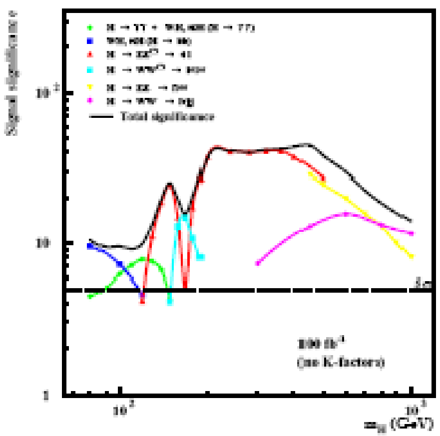
The same note also reports an excess of about 5 events in the W+jets channel in the region between 375-500 GeV. Although this small number of excessive events can be explained by a detector over-efficiency or by some unknown SUSY process, in the following text we will consider some theoretical models where an additional heavy quark is predicted. Some of these models were also mentioned in the above mentioned note.

2 Recent CDF measurement on W+jet

The CDF result on the reconstructed invariant mass in the W+jet channel is presented in figure 1. The number of observed events in the range 375 - 500 GeV is 7 with an expected background of about 1.8 events. The Poisson probability of such a statistical deviation is 0.2%, which is rather low. Taking this excess at its face value, we calculate its significance, using the well known estimator [3] $S = \sqrt{2 \times [(s+b)\ln(1+\frac{s}{b}) - s]}$, to be about 2.9$\sigma$, perhaps a hint for a new quark decay. However the candidate underlying model has to be investigated in the

Before the LHC actual data (2011 ?), Tevatron will collect 10 -15 fb^{-1} per experiment and, therefore, has the chance to discover fourth family quarks if m_4 < 500 GeV

ATLAS DETECTOR AND PHYSICS PERFORMANCE



Technical Design Report

Volume II

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Revision:	0
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Last modified:	25 May 1999
Prepared By:	ATLAS Collaboration

Periodic Table of the Elementary* Particles

family	ν	*l*	*u*	*d*
1	< 2 eV	510.998910(13) keV	1.5 to 4 MeV	4 to 8 MeV
2	< 190 keV	105.658367(4) MeV	1.15 to 1.35 GeV	80 to 130 MeV
3	< 18.2 MeV	1.77684(17) GeV	171.2(521) GeV	4.1 to 4.4 GeV
4	> 45 GeV, …	> 100.8 GeV	> 256 GeV	> 128 GeV

Also,

$m_\gamma = 0$ ($<10^{-18}$ eV) $m_g = 0$ (< few MeV)

$m_W = 80.398(25)$ GeV $m_Z = 91.1876(21)$ GeV

$m_H > 114.4$ GeV

+ CKM and PMNS matrices

* *Elementary in the SM framework. At least one more level (preons) could exist.*

PDG 2008

Quark Summary Table

b' (4^{th} Generation) Quark, Searches for

Mass $m >$ 190 GeV, CL = 95% ($p\overline{p}$, quasi-stable b')
Mass $m >$ 199 GeV, CL = 95% ($p\overline{p}$, neutral-current decays)
Mass $m >$ 128 GeV, CL = 95% ($p\overline{p}$, charged-current decays)
Mass $m >$ 46.0 GeV, CL = 95% (e^+e^-, all decays)

t' (4^{th} Generation) Quark, Searches for

Mass $m >$ 256 GeV, CL = 95% ($p\overline{p}$, $t'\overline{t}'$ prod., $t' \to Wq$)

Free Quark Searches

All searches since 1977 have had negative results.

CDF 2009:

$m_{t'} >$ 311 GeV (2.8 fb^{-1})

$m_{b'} >$ 325 GeV (2.7 fb^{-1})

Heavy Charged Lepton Searches

$L^{\pm}$ – charged lepton

Mass $m >$ 100.8 GeV, CL = 95% [h] Decay to νW.

$L^{\pm}$ – stable charged heavy lepton

Mass $m >$ 102.6 GeV, CL = 95%

Heavy Neutral Leptons, Searches for

For excited leptons, see Compositeness Limits below.

Stable Neutral Heavy Lepton Mass Limits

Mass $m >$ 45.0 GeV, CL = 95% (Dirac)
Mass $m >$ 39.5 GeV, CL = 95% (Majorana)

Neutral Heavy Lepton Mass Limits

Mass $m >$ 90.3 GeV, CL = 95%
(Dirac ν_L coupling to e, μ, τ; conservative case(τ))
Mass $m >$ 80.5 GeV, CL = 95%
(Majorana ν_L coupling to e, μ, τ; conservative case(τ))

Yukawa couplings

In standard approach: $m_f = g_f \eta$ ($\eta \approx 245$ GeV) $g_t / g_e = 0\ (m_t / m_e) \approx 340000$

Moreover, $g_t / g_{\nu e} \approx 1.75 \cdot 10^{11}$ (if $m_{\nu e} = 1$ eV) compare with $m_{GUT}/m_W \sim 10^{13}$

However, see-saw mechanism …

For same type fermions: $g_t / g_u \approx 35000 \div 175000$, $g_b / g_d \approx 300 \div 1500$,

$g_\tau / g_e \approx 3500$

Within third family: $g_t / g_b \approx 40$, $g_t / g_\tau \approx 100$, $g_t / g_{\nu\tau} > 10000$

et cetera

Therefore, 3 family case is unnatural

Hierarchy: $m_u << m_c << m_t$ $m_d << m_s << m_b$ $m_e << m_\mu << m_\tau$

Mass and mixings pattern of the SM fermions is the most important problem of Particle Physics !!!

Flavor Democracy and the Standard Model

It is useful to consider three different bases:

- Standard Model basis $\{f^0\}$,
- Mass basis $\{f^m\}$ and
- Weak basis $\{f^w\}$.

According to the three family SM, before the spontaneous symmetry breaking quarks are grouped into the following SU(2)×U(1) multiplets:

$$\begin{pmatrix} u_L^0 \\ d_L^0 \end{pmatrix}, u_R^0, d_R^0; \quad \begin{pmatrix} c_L^0 \\ s_L^0 \end{pmatrix}, c_R^0, d_R^0; \quad \begin{pmatrix} t_L^0 \\ b_{Ll}^0 \end{pmatrix}, t_R^0, b_R^0.$$

In **one family** case all bases are equal and, for example, d-quark mass is obtained due to Yukawa interaction

$$L_Y^{(d)} = a_d \left(\bar{u}_L \quad \bar{d}_L \right) \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} d_R + h.c. \Rightarrow L_m^{(d)} = m_d \bar{d} d$$

where $m_d = a_d \eta/\sqrt{2}$, $\eta = \langle\varphi^0\rangle \cong 247$ GeV. In the same manner $m_u = a_u \eta/\sqrt{2}$, $m_e = a_e \eta/\sqrt{2}$ and $m_{\nu e} = a_{\nu e} \eta/\sqrt{2}$ (if neutrino is Dirac particle).

In ***n*** **family** case

$$L_Y^{(d)} = \sum_{i,j=1}^{n} a_{ij}^d \left(\bar{u}_{Li}^0 \quad \bar{d}_{Li}^0 \right) \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} d_{Rj}^0 + h.c. = \sum_{i,j=1}^{n} m_{ij}^d \bar{d}_i^0 d_j^0, \quad m_{ij}^d = a_{ij}^d \eta/\sqrt{2}$$

where d_1^0 denotes d^0, d_2^0 denotes s^0 etc.

Flavor Democracy assumptions

Before the spontaneous symmetry breaking all quarks are massless and there are no differences between d^0, s^0 and b^0. In other words fermions with the same quantum numbers are indistinguishable. This leads us to the ***first assumption***, namely, **Yukawa couplings are equal within each type of fermions**:

$$a_{ij}^{d} \cong a^{d}, \quad a_{ij}^{u} \cong a^{u}, \quad a_{ij}^{l} \cong a^{l}, \quad a_{ij}^{\nu} \cong a^{\nu}.$$

The first assumption result in *n-1* massless particles and one massive particle with $m = n \cdot a^F \cdot \eta / \sqrt{2}$ (F = u, d, l, ν) *for each type of the SM fermions.*

This assumption is valid for any mass generation mechanism if the same-type fermions (e.g. all u type quarks) acquire mass in the same way.

Because there is only one Higgs doublet which gives Dirac masses to all four types of fermions (up quarks, down quarks, charged leptons and neutrinos), it seems natural to make the ***second assumption***, namely, **Yukawa constants for different types of fermions should be nearly equal**:

$$a^d \approx a^u \approx a^l \approx a^\nu \approx a$$

For 3SM case this means:

$$m_{\nu_\tau} = m_\tau = m_b = m_t = 3a\eta / sqrt(2)$$

Taking into account the mass values for the third generation

$$m_{\nu_\tau} << m_\tau < m_b << m_t$$

the second assumption leads to the statement that ***according to the flavor democracy the fourth SM family should exist.***

Alternative to Flavor Democracy – 4 Higgs doublets (1 per fermion type).

Above arguments, in terms of the mass matrix, mean

$$M^0 = a\eta/\mathrm{v}2 \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix} \Rightarrow M^m = 4a\eta/\mathrm{v}2 \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Therefore, the fourth family fermions are almost degenerate, in good agreement with experimental value $\rho = 0.9998 \pm 0.0008$.

If $a = 1$ the predicted mass value is coincide with the upper limit on heavy quark masses, $m_Q \leq 700$ GeV, which follows from partial-wave unitarity at high energies.

If $a \approx g_w$ flavor democracy predicts **$m_4 \approx 450$ GeV**.

First three family fermions masses arise due to small deviations from full democracy

First three neutrino masses are doubly suppressed, by both flavor democracy and see-saw

Arguments against the Fifth SM Family

The **first argument** disfavoring the fifth SM family is the large value of $m_t \approx 175$ GeV. Indeed, partial-wave unitarity leads to $m_Q \leq 700$ GeV ($\approx 4\, m_t$) and in general we expect that $m_t << m_4 << m_5$.

Second argument: neutrino counting at LEP results in fact that there are only three "light" ($2m_\nu << m_Z$) non-sterile neutrinos, whereas in the case of five SM families four "light" neutrinos are expected.

Impact on Higgs

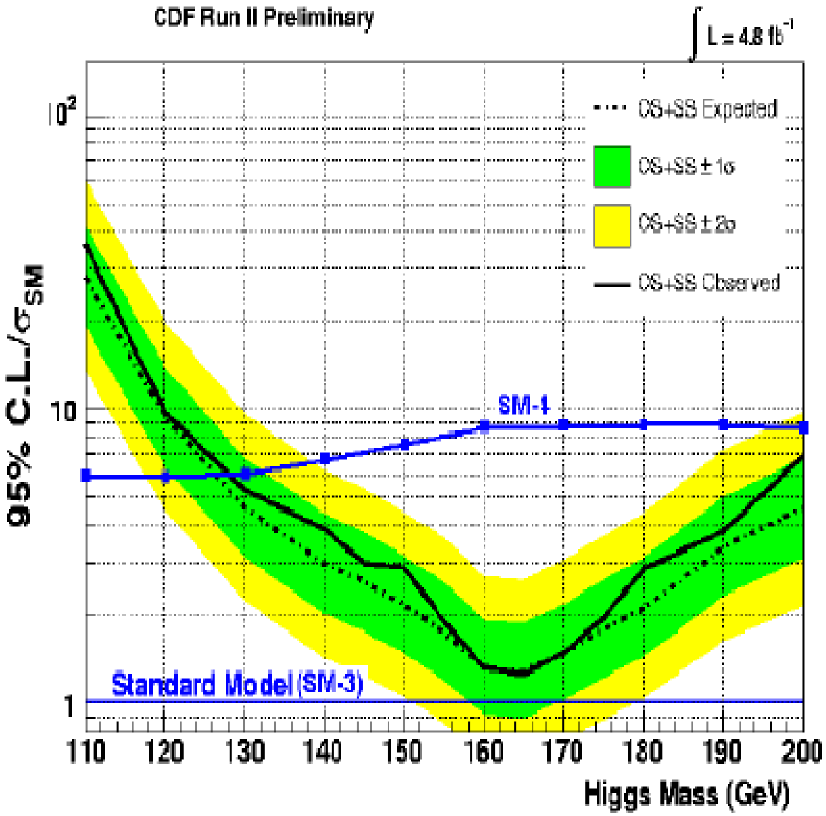

Fig. 8. Exclusion plot from CDF [25] experiment.

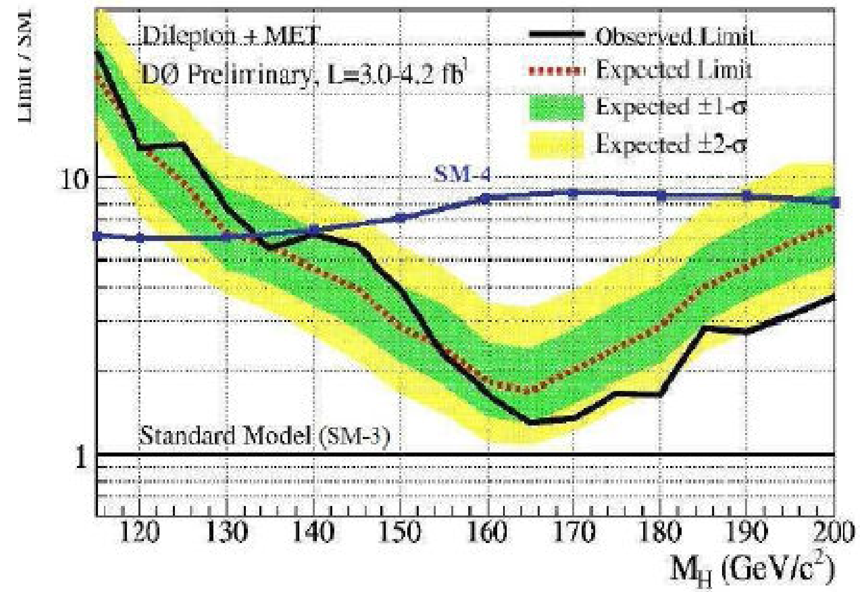

Fig. 9. Exclusion plot from D0 [26] experiment.

Impact on Higgs (cont.)

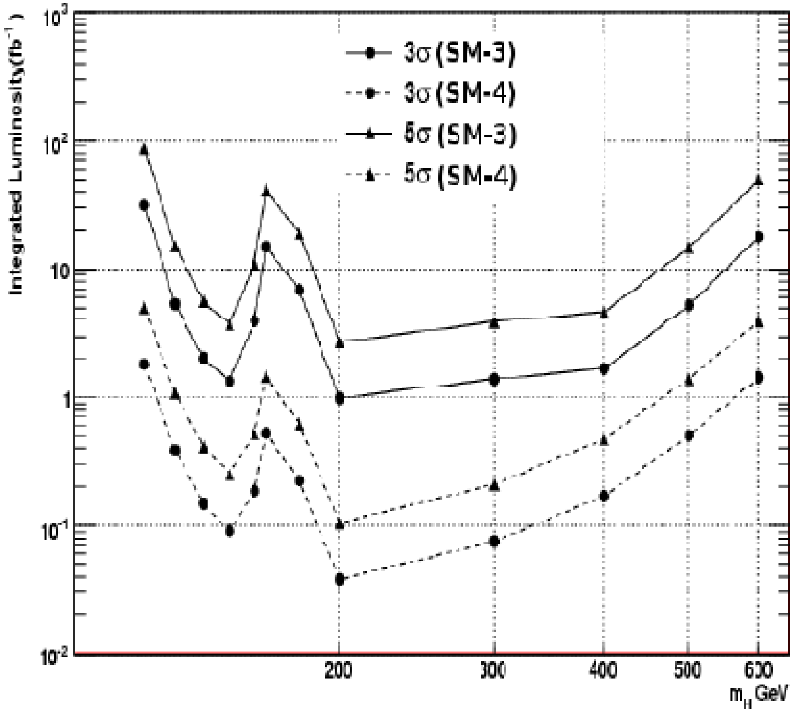

Fig. 11. Integrated luminosity needed at 14 TeV for 3σ and 5σ for $gg \to H \to ZZ^{(*)} \to 4\ell$ channel considering SM-3 and SM-4 cases.

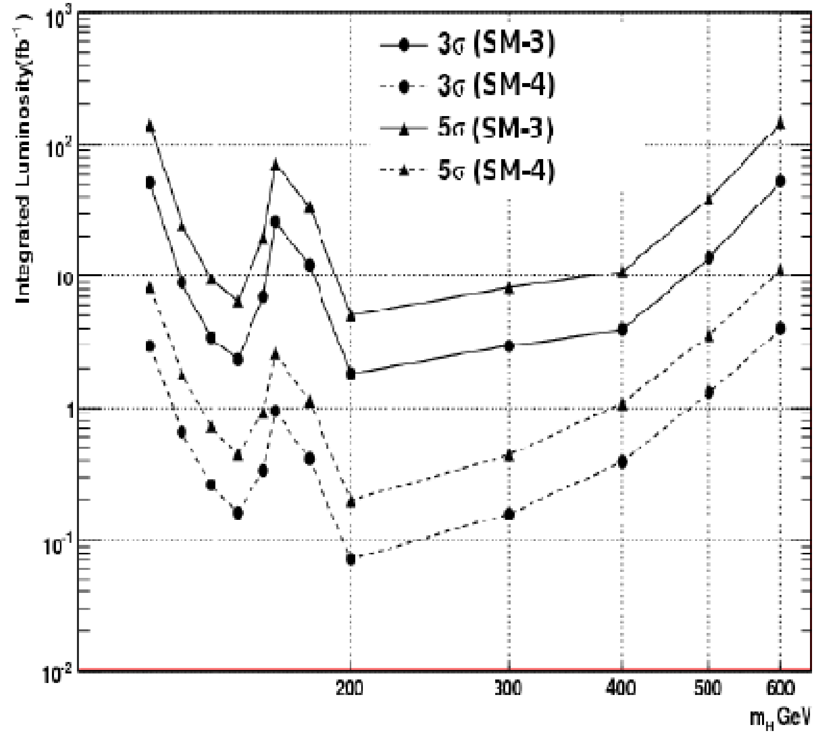

Fig. 12. Integrated luminosity needed at 10 TeV for 3σ and 5σ for $gg \to H \to ZZ^{(*)} \to 4\ell$ channel considering SM-3 and SM-4 cases.

Impact on Higgs (cont.)

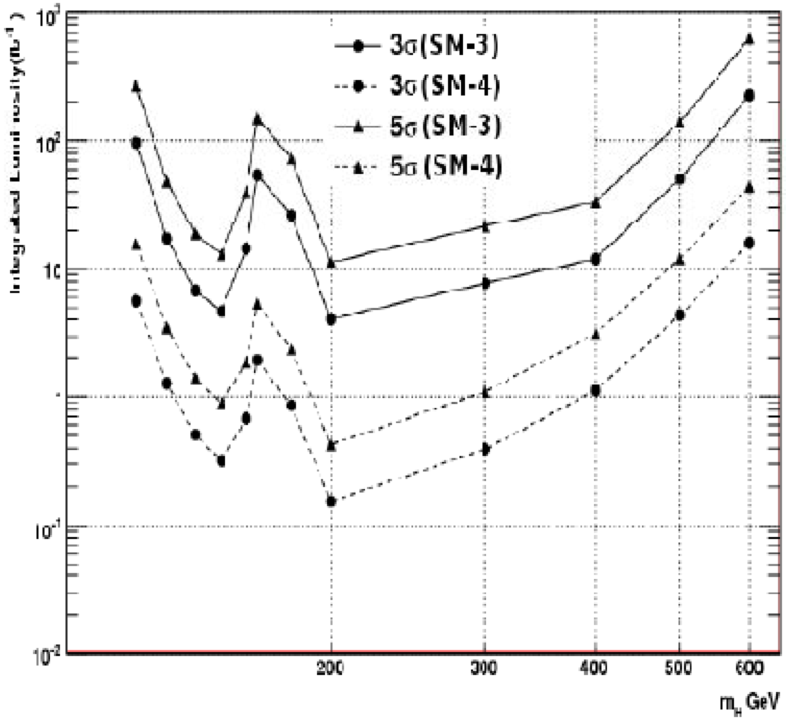

Fig. 13. Integrated luminosity needed at 7 TeV for 3σ and 5σ for $gg \to H \to ZZ^{(*)} \to 4\ell$ channel considering SM-3 and SM-4 cases.

$a \approx g_W \longrightarrow m_4 \approx 450$ GeV

m_{q4}(pole) ≈ 500 GeV

$h \approx g_W \longrightarrow m_H \approx 300$ GeV

in this case:

Table 10. Integrated Luminosities (in fb^{-1}) needed to achieve 3 or 5 σ significance at different center of mass energies.

Energy	$L_{int}(fb^{-1})$ for 3σ	$L_{int}(fb^{-1})$ for 5σ
14 TeV	0.07	0.21
10 TeV	0.16	0.44
7 TeV	0.39	1.09

Fourth Family Hadrons (ongoing study)

The condition for forming new hadron states is well known:

$$|V_{Qq}| < (100\ \text{GeV} / m_Q)^{3/2}$$

i.e. $|V_{Qq}| < 0.09$ for $m_{q4} = 500$ GeV.

Let us consider the process $pp \rightarrow u_4\overline{u}_4+X$, where $\overline{u}_4$ is hadronized into $D^0{}_4=(u_4u)$ and the latter oscillates into $\overline{D^0}{}_4=(u_4\overline{u})$.

This can result in $\mu^+\mu^+$, $e^+\mu^+$, e^+e^+ + 2 (b)jets events, (depending on 4x4 CKM).

…

4. Future Colliders

	u_4, d_4	l_4	ν_4	η_4	ψ_4	**Hadrons**
LHC	P, S, A(R)	$W \to l_4 \nu_4$	$Z,H \to \nu_4 \nu_4$	?	?	P
SLHC,..	P, S, A(R)	$W \to l_4 \nu_4$	$Z,H \to \nu_4 \nu_4$	R, R	S, S	P
QCD-E(ep)	A(R)	S	S	-	-	
QCD-E(γp)	A(R)	-	-	-	-	
e^+e^- if KA	P, A	P, A	P, A	-	R	P
γe if KA	-	A(R)	-	-	-	
$\gamma\gamma$ if KA	P, A	P, A	-	R	-	P
$\mu^+\mu^-$	P, A	P, A	P, A	-	R	P

P – pair, S – single, A – anomalous single, R – resonant production

Black – good, Blue – very good, if KA – if kinematically allowed

Epilogue

My personal feelings:

$m_{d4} \approx 500$ GeV,

m_{u4} is a little bit lighter,

$m_{l4} \approx 450$ GeV,

$m_{\nu 4} \approx 150$ GeV ($m_R \approx 1 \div 2$ TeV),

$m_H \approx 300 \div 350$ GeV.

This picture will be confirmed (or excluded) in mid 2010's