Electroweak theory after the Higgs boson discovery

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48th PNPI Winter School, 24 February - 1 March 2014

Granit workshop, 2-7 March 2014

Plan

- Introduction
- H program (Snowmass 2013, arXiv:1310.8361; M.E.Peskin, 1312.4974)
- New Particles
- H versus 4'th generation

History, fundamental particles

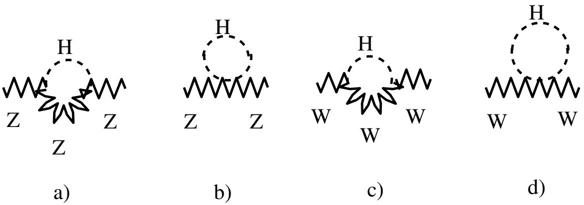
1967 - Weinberg; 1968 - Salam
1973 - neutral currents ($\nu_\mu N \to \nu_\mu X$)
1974, $J/\psi(c\bar{c})$ discovery, "November Revolution"
c quark - the last member of the 2nd family (c, s, μ, ν_μ)

1976, τ-lepton; 1978, $\Upsilon(b\bar{b})$
the 3rd family
1983, W, Z ($p\bar{p}$ collider, CERN)
1989, LEP, SLC (e^+e^- colliders): Z precision data
1994 - t-quark ($p\bar{p}$ collider, Fermilab)
1998 - neutrino oscillations; neutrinos are massive

2012 - H (pp collider, CERN)

2015 - ???

Electroweak precision data



2012 : $M_W = 80385 \pm 15$ MeV

$M_H = 94 + 29 - 24$ GeV;

$\chi^2/n_{d.o.f.} = 18/12$

2012, LHC, $M_H = 126 \pm 1$ GeV (!!)
Standard Model and nothing else?

Higgs data, $\mu \equiv \sigma/\sigma_{SM}$ $pp \to H \to f$

ATLAS

$H \longrightarrow \gamma\gamma: \quad 1.6 \pm 0.3$

$H \longrightarrow ZZ: \quad 1.4 \pm 0.4$

$H \longrightarrow WW: \quad 1.0 \pm 0.3$

$H \longrightarrow \tau\tau: \quad 1.4 \pm 0.5$

$VH \longrightarrow Vbb: \quad 0.2 \pm 0.7$

CMS

$H \longrightarrow \gamma\gamma: \quad 0.77 \pm 0.27$

$H \longrightarrow ZZ: \quad 0.92 \pm 0.28$

$H \longrightarrow WW: \quad 0.68 \pm 0.20$

$H \longrightarrow \tau\tau: \quad 0.78 \pm 0.27$

$VH \longrightarrow Vbb: \quad 1.00 \pm 0.49$

Standard Model and nothing else??

H in the future

LHC:

$\sigma(gg \longrightarrow H)$ in pb, pp collisions

7 TeV	15
8 TeV	19
14 TeV	49

errors in μ: now $\sim 30\%$;
with $300 fb^{-1} \sim 10\%$
with $3000 fb^{-1}$ - several $\%$ (HL-LHC)

ILC: $\leq 1\%$

NP corrections are suppressed as $(M_H/M_{NP})^2$

Higgs self-coupling

$V = \lambda^2/2[H^+H - \eta^2/2]^2$

$H = 1/\sqrt{2}\ \ (\eta + \rho)$

$V = m_H^2/2\ \ \rho^2 + m_H^2/(2\eta)\ \ \rho^3 + m_H^2/(8\eta^2)\ \ \rho^4$

$\eta = 246GeV, \quad m_H = 126GeV$

$\sqrt{s} = 14TeV \quad \sigma(gg \to \rho\rho) = 30fb$ - HL-LHC
$(\sigma(gg \to \rho) = 49pb)$

Deviations from SM: 2 Higgs doublets (MSSM):
$8 - 3 = 5 \Longrightarrow h, H, A, H^+$ - search at LHC (13-14)

New Physics, New Particles

1. Hierarchy problem, SUSY - many-many new particles (double the number of fundamental particles + a bit more)
But: $M_{SUSY} \approx M_{W,Z}$? Nothing since 1981... (1971, 1972...)
However: light higgs - natural for SUSY: $M_H < M_Z + \delta$
LHC (13-14)????

2. Cosmology: dark matter - (at least) one new particle,
But: if it interacts with known particles only by gravitation - we will never observe it at accelerators...
However: SUSY, LSP - photino, zino, (bino), higgsino.

3. Too many parameters in SM: almost 30 - too many for fundamental theory; we already have periodic table - so, we need more fundamental particles and "subquantum mechanics". Yukawa sector of SM.

Why 3 generations? What about 4'th generation?

Higgs versus 4'th generation

Z invisible width:

$$\Gamma(\text{invisible}) = 499 \pm 1.5\text{MeV}$$

Theory: $166 * 3 = 498$ - no space for extra neutrinos;
$n_g = 3$ - the only discovery made at SLC and LEP.

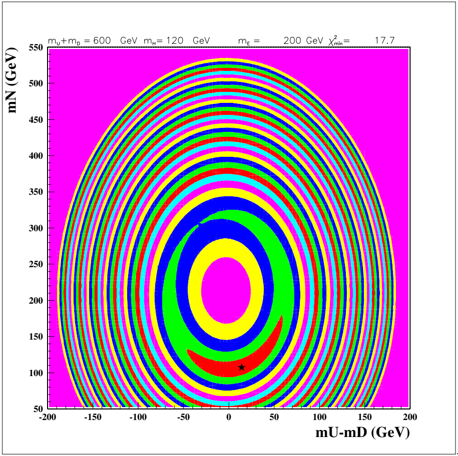
BUT: $m_N > M_Z/2$

Electroweak precision data (4)

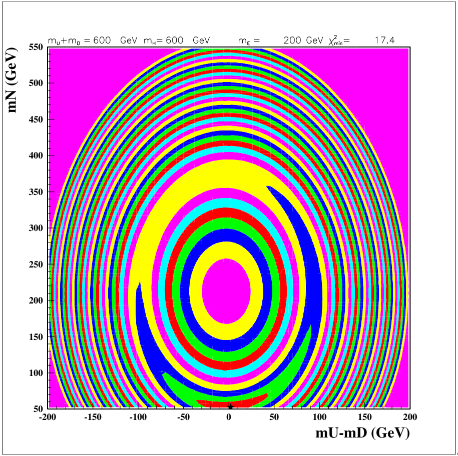
Since the fourh generation quarks and leptons contribute to the W and Z polarization operators
and since these contributions do not decouple in the limit of heavy new generation (the essence of electroweak theory; opposite to the case of QED, where $(g-2)_\mu \sim (m_\mu/m_t)^2$)
one can get constraints on the 4th generation from the precision measurements of M_W, m_t and Z-boson parameters.

Year 2000: Maltoni, Novikov, Okun, Rozanov, Vysotsky:
"One extra generation is still allowed".

What we had before LHC



$M_H = 120$ GeV, $m_E = 200$ GeV, $m_U + m_D = 600$ GeV, $\chi^2/d.o.f. = 17.7/11$, the quality of fit is the same as in SM.



$M_H = 600$GeV, $m_E = 200$ GeV, $m_U + m_D = 600$ GeV, $\chi^2/d.o.f. = 18.4/11$, the quality of fit is the same as in SM.

LHC direct bounds

ATLAS: $m_{t'} > 656$ GeV at 95% CL ($t't' \longrightarrow WbWb$, Phys. Lett. B 718 (2013) 1284);
$m_{b'} > 480$ GeV ($b'b' \longrightarrow WtWt$).
CMS has similar bounds.

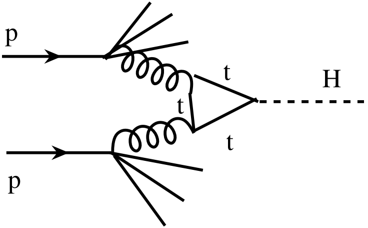
These bounds push heavy quarks out from the perturbative unitarity domain: $m_{q'} < 500$ GeV, strong dynamics.

$$\lambda_t = m_t/(\eta/\sqrt{2}) = 172/(246/\sqrt{2}) \approx 1$$

However these bounds depend on the pattern of heavy quarks decay and are not universal.

Much more interesting bounds follow from higgs boson production and decays.

H production cross section



$$t \longrightarrow t, t', b'$$

$$\sigma(gg \longrightarrow H)_{SM4} \approx 9\sigma(gg \longrightarrow H)_{SM3}$$

$H \to VV$ decay rates

Mainly because of $H \longrightarrow gg$ enhancement:

$$Br(H \longrightarrow ZZ^*, WW^*)_{SM4} \approx 0.6 Br(H \longrightarrow ZZ^*, WW^*)_{SM3}$$

Taking into account EW loop corrections $(G_F m_{t'}^2)$ (Passarino, Denner,... arXiv:1111.6395):

$$0.6 \longrightarrow 0.2$$

and for $H \longrightarrow ZZ^*, WW^*$

$$\sigma * Br(SM4) \approx 2\sigma * Br(SM3),$$

which is definetly excluded by CMS data on higgs production (slide #5).

light N

There is a possibility to diminish

$$Br(H \longrightarrow ZZ^*, WW^*)_{SM4}$$

by choosing

$$M_H/2 > m_N > M_Z/2$$

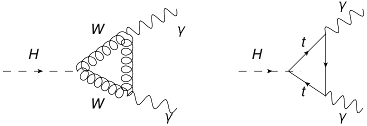
since $H \to NN$ becomes a dominant H decay mode.

From the ATLAS study of $ZH \to ll+$invisible
95% CL upper bound $Br(H \to$invisible$) < 0.65$ follows
(ATLAS-CONF-2013-011). According to CMS
$Br(H \to$invisible$) < 0.52$.
So, we can make $Br(H \longrightarrow \text{visible})$ up to three times smaller than in SM3.

$m_{\nu'}, m_{l'} \approx 600$GeV

Up to now we present the result of the 4th generation loop corrections for moderate values of the masses of new leptons. If their masses approach 600 GeV then factor 0.2 in the suppression of $H \longrightarrow VV$ decays becomes 0.15, and the product $\sigma * Br$ approaches its value for the 3 generation case (Djouadi, Lenz, arXiv 1204.1252).

$H \to \gamma\gamma$



$$A \sim 7 - 4/3 * 3 * (2/3)^2 = 7 - 16/9,$$

in the limit $M_H << 2M_W, 2m_t$.
For $M_W = 80.4$ GeV 7 should be substituted by 8.3, while for $m_t = 172$GeV 16/9 has 3% accuracy.
So, SM: $A \sim 8.3 - 16/9 = 6.5$

4 gen: $A \sim 8.3 - 16/9 - 16/9 - 4/9 - 4/3 = 3.0$

and taking into account the enhancement of the $H \longrightarrow gg$ decay in 4 gen case $(0.6 * 9 = 5.4)$ we obtain the same $\sigma * Br$ as in Standard Model.

BUT

(2) loop corrections in case of 4 generations greatly diminish $\sigma * Br(H \to 2\gamma)$; according to Denner et al, arXiv: 1111.6395 it equals $1/3$ of 3 generations result (or even less), while the average of ATLAS and CMS data is 1.2 ± 0.2, so the 4th generation is excluded at $4 - 5\sigma$ level. Would be good to calculate 3 loops.

$H \to \tau\tau, bb$

$\sigma * Br$ for $\tau\tau$ mode at tree level equals approximately 9 (H production) * 0.6(enhancement of H decay into gluons) ≈ 5 and electroweak loop corrections make the decay width larger by 30%. The experimental data on $H \to \tau\tau$ (slide $\#$5) exclude this huge enhancement (though light N helps to avoid the contradiction it is excluded by $H \to \gamma\gamma$).

Consideration differs for bb mode: it is seen only in associative higgs boson production $VH \to Vbb$, which unlike gluon fusion is not enhanced in the 4th generation case, and there is no contradiction with the LHC experimental data.

Conclusions

- H coupling constants will be measured with much better accuracy in 2 - 15 years; H selfcoupling in SM will be observed in 15 years; EW precision observables, Giga Z
- SUSY in 2 - 3 years? More neutral and charged higgses in 2 - 3 years?
- LHC data on 126 GeV Higgs boson production and decays exclude Standard Model with the sequential fourth generation in perturbation domain: too small $gg \longrightarrow H \longrightarrow \gamma\gamma$, too big $gg \longrightarrow H \longrightarrow \tau\tau$.
  However in two Higgs doublets model the fourth generation is still allowed (e.g. Geller, Bar-Shalom, Eilam, Soni, arXiv:1209.4081).

- Hadron colliders - good when you do know what you are looking for; e^+e^- colliders - clean, but (may be) not enough energy to find New Physics. Complementarity.