A New Extension of the Standard Model

S. Nandi
Oklahoma State University

In collaboration with S. Gabriel

Talk presented at SUSY '07, Karlsruhe, Germany

Higgs Overview

•Responsible for breaking of electroweak gauge symmetry
→ Gives mass to SM particles

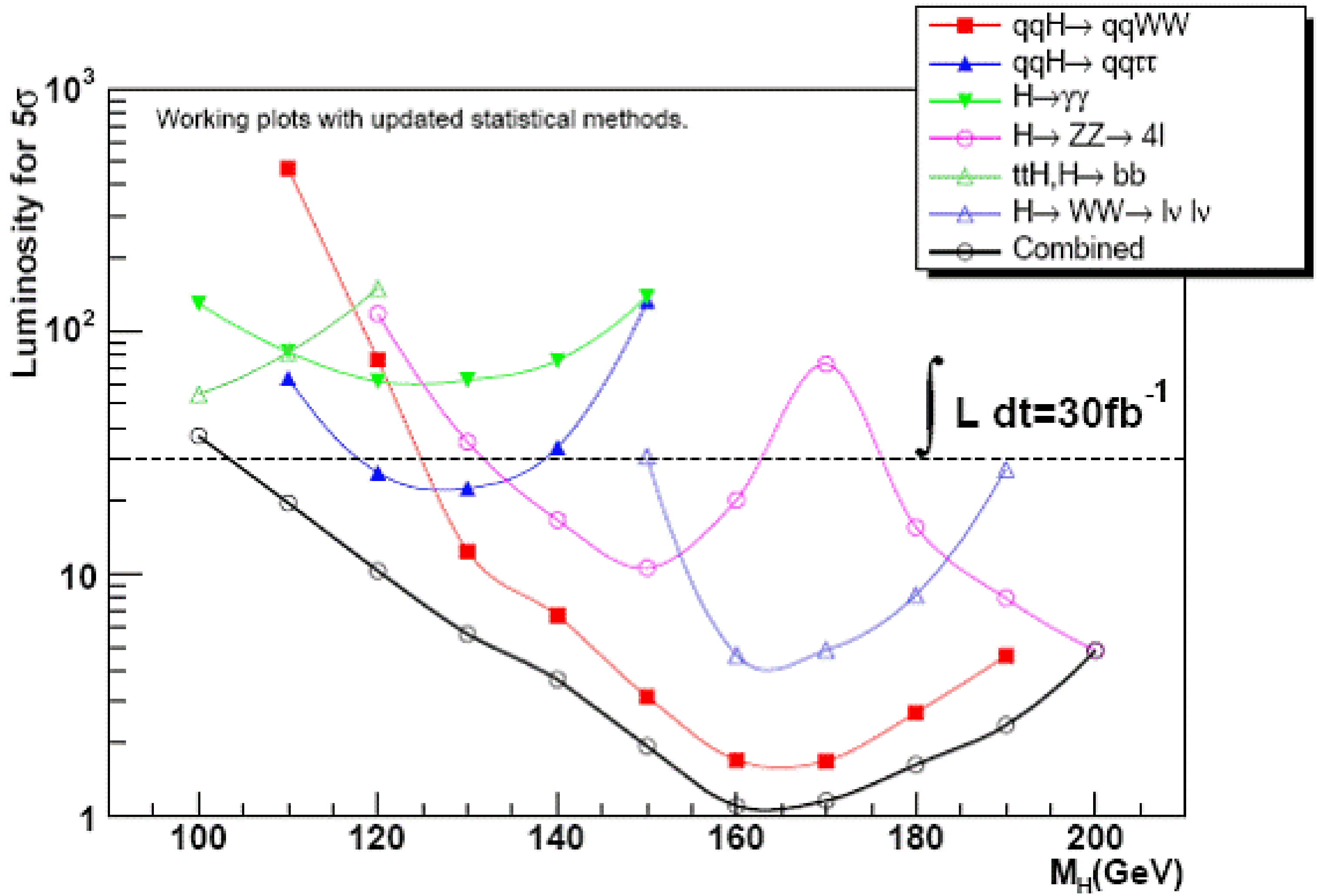
•Mass bound: m_h > 114.4 GeV (LEP)

•Dominant decay modes:

$$b\bar{b},\ WW,\ ZZ,\ t\bar{t}$$

depending on the mass

•Experimentally, nothing currently known about Higgs sector



Luminosity for 5σ
Working plots with updated statistical methods.
qqH→ qqWW
qqH→ qqττ
H→γγ
H→ ZZ→ 4l
ttH,H→ bb
H→ WW→ lν lν
Combined
∫ L dt=30fb^-1
10^3
10^2
10
1
100
120
140
160
180
200
M_H(GeV)

Two Higgs Doublet Models

- One doublet gives mass to up-type fermions only, the other to down-type fermions only. Motivated by SUSY

- Only one doublet couples to fermions, but both have VEV

- Only one doublet couples to fermions, and only that doublet has VEV. Motivation: Heavy Higgs, Higgs dark matter (Barbieri, Hall, and Rychkov)

Our Model

- One doublet gives mass to all SM fermions except neutrinos
- Other doublet gives mass only to neutrinos
- Gives an alternative explanation of small neutrino masses

- Symmetry $SM \times Z_2$
- Right-handed neutrinos N_R and two Higgs doublets χ, φ
- SM fermions, χ even under Z_2
- N_R, φ odd under Z_2
- $\langle \chi \rangle \simeq 250\, GeV, \quad \langle \phi \rangle \sim 10^{-2} - 1\, eV$

- Lepton Yukawa interactions:

$$y_l \overline{\Psi}^l_L l_R \chi + y_{\nu_l} \overline{\Psi}^l_L N_R \tilde{\phi} + h.c., \quad \overline{\Psi}^l_L = (\bar{\nu}_l, \bar{l})_L$$

→ Neutrinos get tiny mass from breaking of Z_2 symmetry

- Neutrinos are Dirac particles

→ No neutrino-less double beta decay

Higgs Potential:

$$V = -\mu_1{}^2 \chi^\dagger \chi - \mu_2{}^2 \phi^\dagger \phi + \lambda_1 (\chi^\dagger \chi)^2 + \lambda_2 (\phi^\dagger \phi)^2$$

$$+\lambda_3 (\chi^\dagger \chi)(\phi^\dagger \phi) - \lambda_4 \left| \chi^\dagger \phi \right|^2 - \tfrac{1}{2} \lambda_5 \left[\left(\chi^\dagger \phi \right)^2 + \left(\phi^\dagger \chi \right)^2 \right]$$

Physical Higgs Particles:

- Charged Higgs $H^{+/-}$
- Neutral pseudoscalar ρ
- Two neutral scalars h, σ

In Unitary Gauge:

$$\chi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\,\frac{V_\phi}{V} H^+ \\ h_0 + i\frac{V_\phi}{V}\rho + V_\chi \end{pmatrix}$$

$$V^2 = V_\chi^{\ 2} + V_\phi^2$$

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} -\sqrt{2}\,\frac{V_\chi}{V} H^+ \\ \sigma_0 - i\frac{V_\chi}{V}\rho + V_\phi \end{pmatrix}$$

Higgs Masses:

$$m_H{}^2 = \tfrac{1}{2}\left(\lambda_4 + \lambda_5\right)V^2, \quad m_\rho{}^2 = \lambda_5 V^2$$

$$m_{h,\sigma}{}^2 = \left(\lambda_1 V_\chi{}^2 + \lambda_2 V_\phi{}^2\right)$$

$$\pm\sqrt{\left(\lambda_1 V_\chi{}^2 - \lambda_2 V_\phi{}^2\right)^2 + \left(\lambda_3 - \lambda_4 - \lambda_5\right)V_\chi{}^2 V_\phi{}^2}$$

→ very light scalar: $m_\sigma{}^2 = 2\lambda_2 V_\phi{}^2 + O\left(V_\phi{}^2 / V_\chi{}^2\right)$

$$m_h{}^2 = 2\lambda_1 V_\chi{}^2 + O\left(V_\phi{}^2 / V_\chi{}^2\right)$$

Mass Eigenstates h, σ:

$$h_0 = ch + s\sigma , \quad \sigma_0 = -sh + c\sigma$$

$$c = 1 + O(V_\phi{}^2 / V_\chi{}^2), \quad s = -\frac{\lambda_3 - \lambda_4 - \lambda_5}{2\lambda_1}(V_\phi / V_\chi) + O(V_\phi{}^2 / V_\chi{}^2)$$

→ Mixing is very small

Note: h behaves essentially like the SM Higgs in interactions with fermions and gauge bosons

Phenomenological Implications

Light scalar σ

Possible decay modes:

- $\sigma \to \nu\bar{\nu}, \quad if \quad m_\sigma > 2m_\nu$
- $\sigma \to \gamma\gamma \quad (one\ loop)$

$$\Gamma \sim \frac{e^8 m_\sigma{}^5}{m_q{}^4} \Rightarrow \tau \sim 10^{20}\, yrs$$

→ σ only observable at colliders as missing energy

Couplings of σ to quarks and charged leptons are highly suppressed

ZZσ coupling is proportional to V_Φ

$$\Rightarrow \quad e^+e^- \to Z^* \to Z\sigma, \quad Z \to Z^*\sigma \to f\overline{f}\sigma$$

are suppressed by a factor of $(V_\Phi/m_Z)^2$

However, ZZσσ coupling is unsuppressed:

$$Z \to Z^*\sigma\sigma \to f\overline{f}\sigma\sigma$$

$$\sum_f \Gamma(Z \to f\overline{f}\sigma\sigma) \simeq 2.5\times 10^{-7}\,GeV$$

Total Z width = 2.4952 +/- 0.0023 GeV (PDG)

At LEP1, ≈ 1.7×10^7 Z's → ≈ 2 such events

Coupling of σ to neutrinos is relatively large

$\Rightarrow \quad Z \rightarrow \nu \, \overline{\nu \; \sigma}$ can be significant

$$\Gamma (Z \rightarrow \nu \overline{\nu} \sigma) \simeq (2.5 \, MeV) \, y_{\nu}^{2}$$

$$\Rightarrow \sum y_{\nu}^{2} < 0.6$$

Invisible Z width = 499 +/- 1.5 MeV (PDG)

Can also have $\pi \rightarrow \mu \, \nu \, \sigma$

$$B(\pi \rightarrow \mu\nu\sigma) \simeq 0.05 \, y_{\nu}^{2}$$

$$\Rightarrow y_{\nu} < 0.02$$

Pseudoscalar ρ

No strong coupling

$\rightarrow \quad \frac{\lambda_5}{4\pi^2} \leq 1 \quad \Rightarrow \quad m_\rho \leq 470\ GeV$

$$Z \rightarrow \rho\sigma, \quad Z \rightarrow \rho^*\sigma \rightarrow \nu\bar{\nu}\sigma$$

Note: Couplings of ρ to quarks and charged leptons are VEV suppressed

→ For $m_\rho < m_Z, \quad \rho \rightarrow \nu\bar{\nu}$ dominant decay mode

$\Rightarrow \quad Z \rightarrow \rho\sigma$ invisible

Invisible Z width = 499 +/- 1.5 MeV (PDG)

$$\Gamma(Z \to \rho\sigma) = \frac{G_F m_Z^{\ 3}}{24\sqrt{2}\pi}\left(1 - \frac{m_\rho^{\ 2}}{m_Z^{\ 2}}\right)^3 < 1.5\ MeV$$

For m_ρ > 78 GeV

For m_ρ > m_Z, we have $e^+e^- \to Z^* \to \rho\sigma$

$$\sigma = \frac{G_F m_Z^{\ 4}(g_V^{\ 2} + g_A^{\ 2})s}{24\pi}\left(\frac{1}{s - m_Z^{\ 2}}\right)^2 \left(1 - \frac{m_\rho^{\ 2}}{s}\right)^3$$

At LEP2, with $\sqrt{s}$ ~ 200 GeV and ~ 3000 pb^{-1} of data, < 1 event is expected for m_ρ > 95 GeV

Heavy scalar h

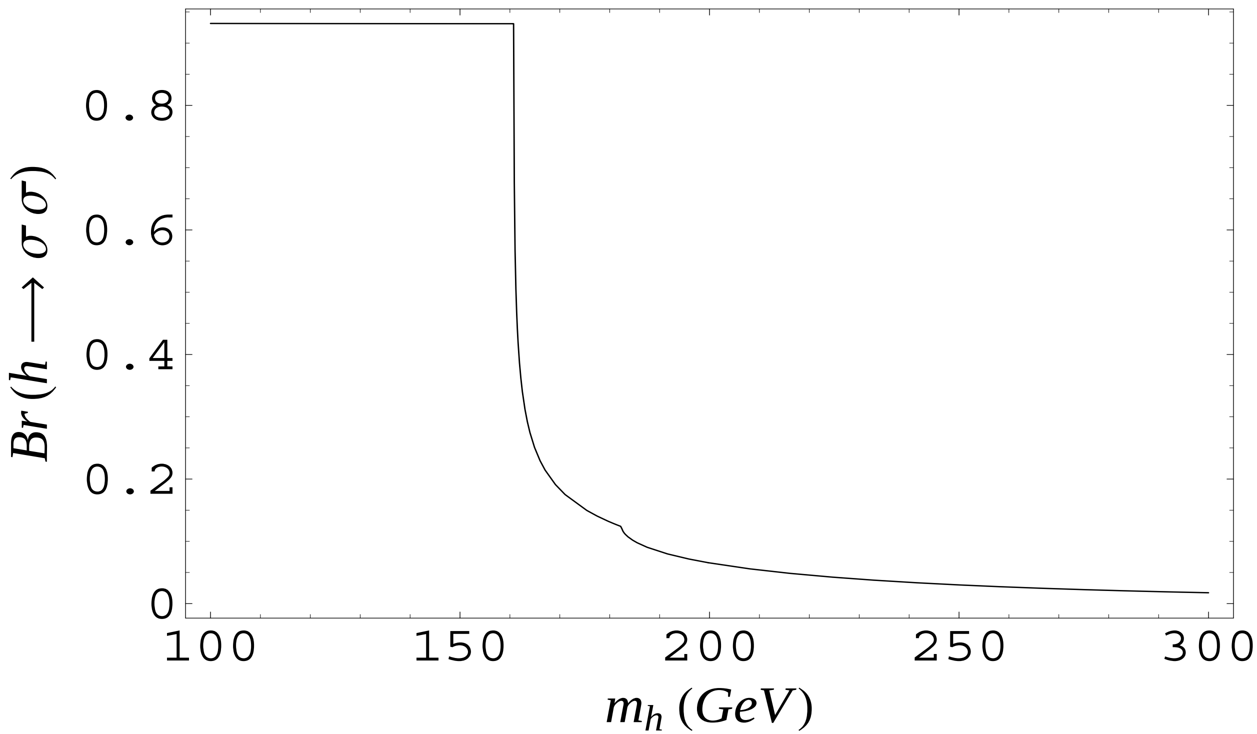
Essentially SM Higgs

Invisible decay mode: $h \rightarrow \sigma\,\sigma$

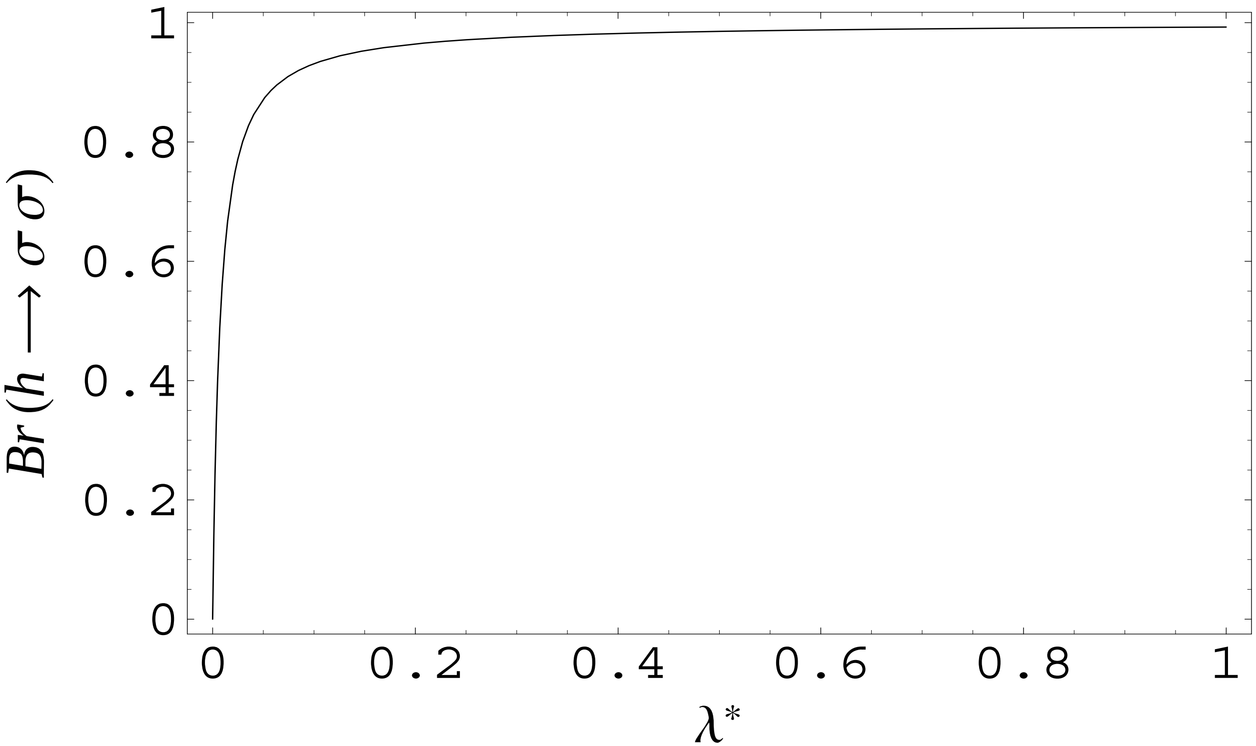
$$\Gamma(h \rightarrow \sigma\sigma) = \frac{(\lambda_3 + \lambda_4 + \lambda_5)^2 V_\chi^{\,2}}{32\pi m_h}$$

$$m_h^{\,2} = 2\lambda_1 V_\chi^{\,2} + O(V_\phi^{\,2} / V_\chi^{\,2})$$

$$\Gamma(h \rightarrow \sigma\sigma) = \frac{(\lambda_3 + \lambda_4 + \lambda_5)^2 m_h}{64\pi\lambda_1} \equiv \frac{\lambda^* m_h}{64\pi}$$


0.8
0.6
0.4
0.2
0
100
150
200
250
300
$Br(h \longrightarrow \sigma\sigma)$
$m_h\,(GeV)$

$\lambda^* = 0.1$



1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
$Br(h \longrightarrow \sigma\sigma)$
λ^*

$m_h = 135\,GeV$

For a wide range of λ^*, this mode dominant for m_h < 160 GeV

Current limit for invisible Higgs: m_h > 112.3 GeV (L3)

At LHC, invisibly decaying Higgs observable through WBF:

$$qq \rightarrow qqWW \rightarrow qqh, \quad qq \rightarrow qqZZ \rightarrow qqh$$

Signal: Two q's with high p_T + invisible

This signal can be observed at 95% CL with >10 fb^{-1} of data if B($h \rightarrow$invisible) > 30% and m_h < 400 GeV (Eboli and Zeppenfeld)

Difficult to identify invisible particle as Higgs

Cosmological Implications

Big-Bang Nucleosynthesis

•Predicted light element abundances depend on the number g_* of light spin degrees of freedom in thermal equilibrium at T ~ 1 MeV

$$g_* = g_b + \tfrac{7}{8} g_f$$

•In the standard scenario (SBBN), this includes γ, $e^{+/-}$, ν_L's:

$$(g_*)_{SBBN} = 2 + \tfrac{7}{8}(4) + \tfrac{7}{8}(6) = 10.75$$

•In our model, relatively strong interactions between left- and right-handed neutrinos and the light scalar σ will keep them in thermal equilibrium

$$g_* = (g_*)_{SBBN} + 1 + \tfrac{7}{8}(6) = 17$$

$$N_{eff} = 6 + \tfrac{4}{7}$$

•Reactions that interconvert protons and neutrons fall out of thermal equilibrium at a higher temperature ($T \sim g_*^{1/6}$)

•Leads to larger ratio of neutrons to protons during BBN

•Gives a mass fraction of He-4 produced during BBN of $Y_P \approx 0.30$

•Observed value: $Y_P \approx 0.25$

Possible Solution: Large Neutrino Degeneracy

•SBBN assumes $\mu_\nu \approx 0$, but it has not been measured directly

•Alters equilibrium value of neutron to proton ratio to

$$\frac{n}{p} = e^{-\frac{\mu_\nu}{T}} \left(\frac{n}{p} \right)_{\mu_\nu = 0}$$

•We require μ_ν/T to be order 0.1

•Studies that allow μ_ν/T, N_{eff}, and Ω_B to vary within observational constraints from BBN+WMAP find an upper bound on N_{eff} from 7.1 to 8.7 (Barger *et al.*, 2003; Cuoco *et al*., 2004, Steigman, 2005)

Another Possible Solution: Late-Decaying Particles

•The energetic decay products of a massive particle (m > a few GeV) that decays during or after nucleosynthesis can cause nuclear reactions among background nuclei, altering light element abundances

Non-BBN Bounds on Number of Neutrinos

•WMAP+LRG's: $0.8 < N_{eff} < 7.6$ (Ichikawa, Kawasaki, Takahashi, Nov. 2006)
•Seljak, Sloshar, McDonald (WMAP + several other astrophysical data sources) claim that more than 3 neutrinos is required (Sep. 2006)

Domain Walls

- Breaking of discrete Z_2 symmetry will lead to cosmological domain walls

- Energy per unit area: $\eta \sim V_\varphi^3$

→Produces temperature anisotropies:

$$\frac{\delta T}{T} \simeq G \eta H_0^{-1} \sim 10^{-20}$$

- Observed level of temperature anisotropies is 10^{-5}

Conclusions

- Proposed new two Higgs doublet model based on SM$\times Z_2$
- Z_2 broken at ~ 10^{-2} eV
- Gives new mechanism for tiny neutrino mass
- Neutrinos are Dirac particles
- Higgs: $H^{+/-}$, h, ρ $\rightarrow$ mass at EW scale, $\sigma \rightarrow$ extremely light
- h like SM, but possibly dominant invisible decay mode $h \rightarrow \sigma\sigma$
- Alters Higgs signals at LHC, but observable through WBF
- BBN problem solvable