A New Two Higgs Doublet Model

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S. Gabriel and S. Nandi, Phys. Lett. B655:141 (2007);
S. Gabriel, B. Mukhopadhyaya, S. Nandi and S. K. Rai,
E-Print: arXiv:0804.1112 [hep-ph],Phys. Lett. B669 (2008)

OUTLINE

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2. Our new model

3. Phenomenological Implications
   : Invisible Higgs signal
   : New Charged Higgs Signals at the LHC
   : Cosmological Implications

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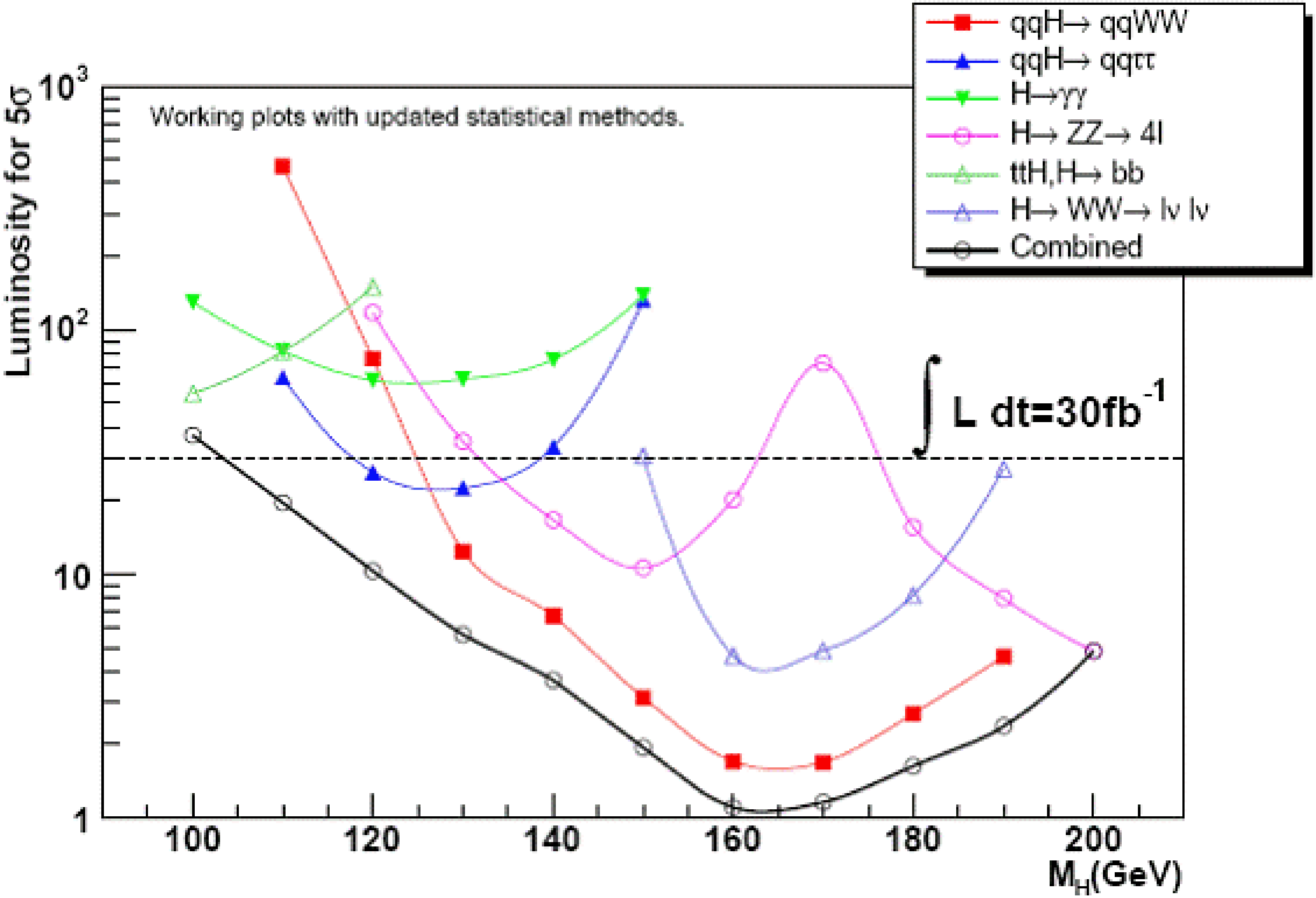
INTRODUCTION :Higgs Overview

- Responsible for breaking of electroweak gauge symmetry
- Gives mass to SM particles
- Mass bound: m_h > 114.4 GeV (LEP)
- Dominant decay modes, depending on m_h :

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

- Experimentally, nothing currently known about Higgs sector

ATLAS TDR for Higgs Search at LHC



S.Nandi, Talk at MIAMI 2008, December 16 – 21, 2008

Two Higgs Doublet Models

- Both doublets couple to all the fermions → serious FCNC problems
- One doublet couples to up-type fermions, the other to down-type fermions (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, Other doublet is innert. Motivation: Heavy Higgs, Higgs dark matter (Barbieri, Hall, and Rychkov)

Our new Model

- What’s new?
- 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

Model

- Symmetry $SU(3) \times SU(2) \times U(1) \times Z_2$
- 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
- $V_\varphi \sim 10^{-2}$ eV, and $V_\chi \sim 250$ GeV → large fine tuning $V_\varphi / V_\chi \sim 10^{-13}$ similar to m_h / M_{PL} in SM
- 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

Model

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 $H^\pm$
- Neutral pseudoscalar ρ
- Two neutral scalars h, σ

Model

In Unitary Gauge:

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

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

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

Model

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

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

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

or, more simply:

$$m_\sigma{}^2 = 2\lambda_2 V_\phi{}^2 + O(V_\phi{}^2 / V_\chi{}^2) \quad \longleftarrow$$

Very light scalar

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

Model

Mass Eigenstates of *h, σ*:

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

where,

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

This leads to very small mixing

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

Phenomenological Implications

Light Scalar *σ*:

Possible decay modes:

$$\sigma \rightarrow \nu\bar{\nu}, \quad if \quad m_\sigma > 2m_\nu$$

$$\sigma \rightarrow \gamma\gamma \quad (one\ loop)$$

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

→ *σ* only observable at colliders as missing energy

Couplings of *σ* to quarks and charged leptons are highly suppressed

Phenomenological Implications

$ZZ\sigma$ coupling is proportional to V_{Φ}, so

$$e^{+}e^{-} \rightarrow Z^{*} \rightarrow Z\sigma, \text{ and } Z \rightarrow Z^{*}\sigma \rightarrow f\,\overline{f}\sigma$$

are suppressed by a factor of $(V_{\Phi}/m_{Z})^{2}$

However, $ZZ\sigma\sigma$ coupling is unsuppressed:

$$Z \rightarrow Z^{*}\sigma\sigma \rightarrow f\,\overline{f}\sigma\sigma$$

$$\sum_{f}\Gamma(Z \rightarrow f\,\overline{f}\sigma\sigma) \simeq 2.5\times10^{-7}\,GeV$$

Total Z width = 2.4952 ± 0.0023 GeV (PDG)
At LEP1, ≈ 1.7×10^{7} Z's → ≈ 2 such events

Phenomenological Implications

Coupling of σ to neutrinos is relatively large, so

$$Z \rightarrow \nu\bar{\nu}\sigma$$

can be significant

$$\Gamma(Z \rightarrow \nu\bar{\nu}\sigma) \simeq \left(0.64\, MeV\right)\left(\sum y_{\nu}{}^{2}\right)$$

For $\Sigma y_\nu^2 \sim 1$, this is <1.5 MeV

Invisible Z width = 499 ± 1.5 MeV (PDG)

Further Implications

$$\Gamma(Z \to \rho\sigma) = \frac{G_F m_Z^{\ 3}}{24\sqrt{2}\pi}\left(1-\frac{m_\rho^{\ 2}}{m_Z^{\ 2}}\right)^3 < 1.5\ MeV \Rightarrow m_\rho > 78\ \mathrm{GeV}$$

For $m_\rho > m_Z$, 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 √s ~ 200 GeV and ~ 3000 pb^{-1} of data, < 1 event is expected for $m_\rho > 95$ GeV

Heavy Scalar *h*

Essentially SM Higgs

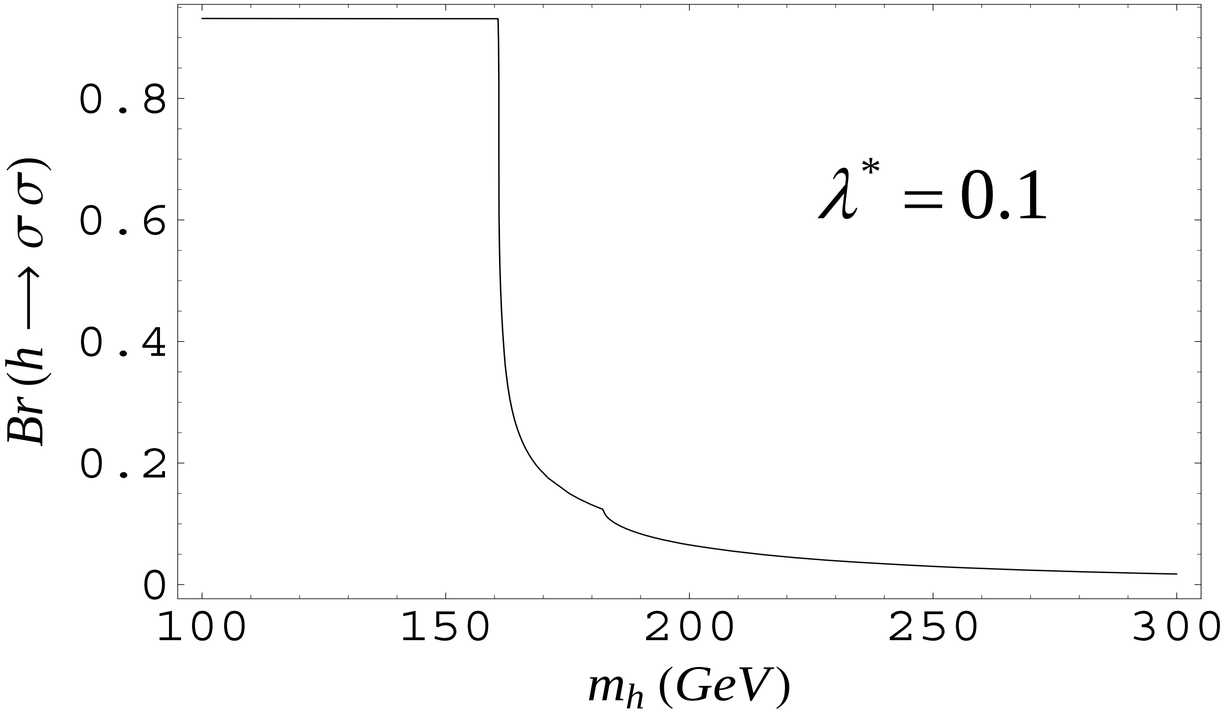
Invisible decay mode $h \to \sigma\sigma$:

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

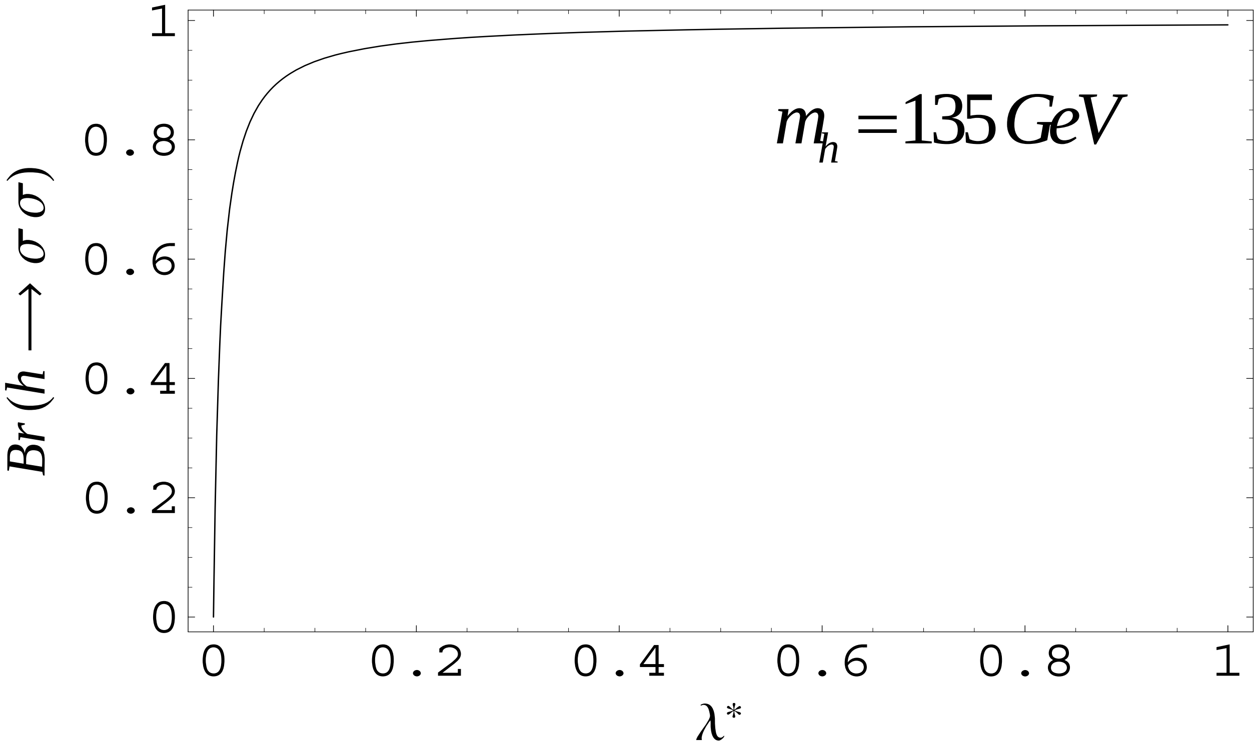
$$m_h{}^2 = 2\lambda_1 V_\chi{}^2 + O\left(V_\phi{}^2 / V_\chi{}^2\right)$$

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

Invisible Higgs Decay



Invisible Higgs Decay



For a wide range of λ^*, the invisible mode is dominant for $m_h < 160$ GeV

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

Implications for Charged Higgs

$$\chi = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\dfrac{V_\phi}{V}H^+ \\ h_0 + i\dfrac{V_\phi}{V}\rho + V_\chi \end{pmatrix}, \quad \phi = \frac{1}{\sqrt{2}}\begin{pmatrix} -\sqrt{2}\dfrac{V_\chi}{V}H^+ \\ \sigma_0 - i\dfrac{V_\chi}{V}\rho + V_\phi \end{pmatrix}$$

$$V^2 = V_\chi^2 + V_\phi^2, \quad V_\chi \sim V, \quad V_\phi \sim 10^{-2}\ \text{eV}$$

Charged Higgs essentially resides in φ

Its coupling with quarks is highly suppressed (Chromophobic charged Higgs)

Coupling with neutrinos and charged leptons *not* suppressed

Implications for Charged Higgs

$$L_Y = -\sqrt{2}\left(\frac{m_\nu}{V_\varphi}\right) r_\chi \left[\bar{\ell}_L \nu_R H^- + \bar{\nu}_L \ell_R H^+ + h.c.\right]$$

$$+\sqrt{2} r_\varphi \left[\left(\frac{m_d}{V_\chi}\right)\bar{u}_L d_R H^+ - \left(\frac{m_u}{V_\chi}\right)\bar{d}_L u_R H^- + h.c.\right]$$

where, $r_\chi = V_\chi / V$, and $r_\varphi = V_\varphi / V$

$\Rightarrow$ coupling with neutrinos $\propto$ neutrino masses

HWσ, *HWρ* : usual gauge interaction

Main Decay Modes of *H*±

$$H^{\pm} \to \sigma W^{\pm}$$

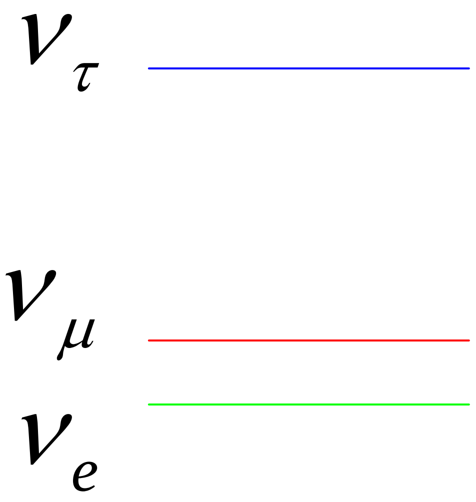
$$H^{\pm} \to \rho W^{\pm}$$

$$H^{\pm} \to \ell \nu_{\ell},\ (\ell = \mathrm{e},\ \mu,\ \tau)$$

$$\text{leptonic coupling} \propto \frac{m_{\nu_{\ell}}}{V_{\varphi}}$$

Thus the leptonic decay mode will be determined by the neutrino mass hierarchy

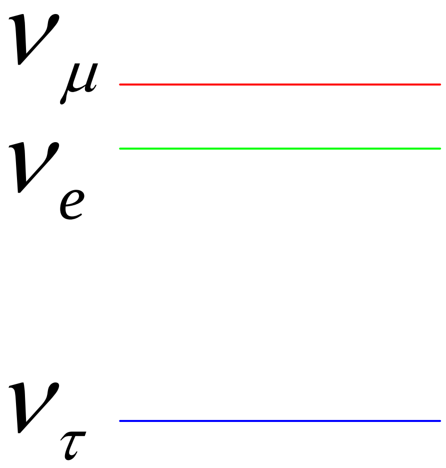
Neutrino Mass Hierarchy


ν_τ

ν_μ

ν_e

Normal Hierarchy


ν_μ

ν_e

ν_τ

Inverted Hierarchy

$$H^{\pm} \to \nu_\tau \tau$$

$$H^{\pm} \to \ell \nu_\ell, \ (\ell = e,\ \mu)$$

Collider Signals of $H^\pm$

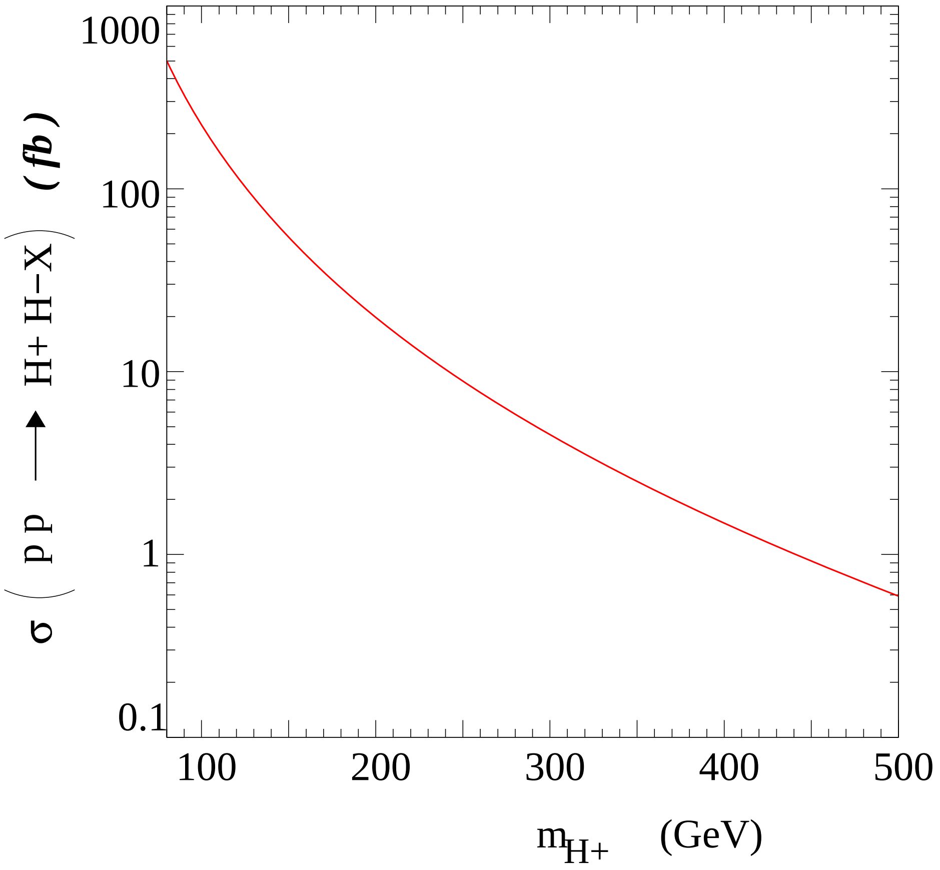
- Usual production of charged Higgs via:

$$bg \to tH^-, \text{ or } \bar{b}g \to \bar{t}H^+$$

is **not** available

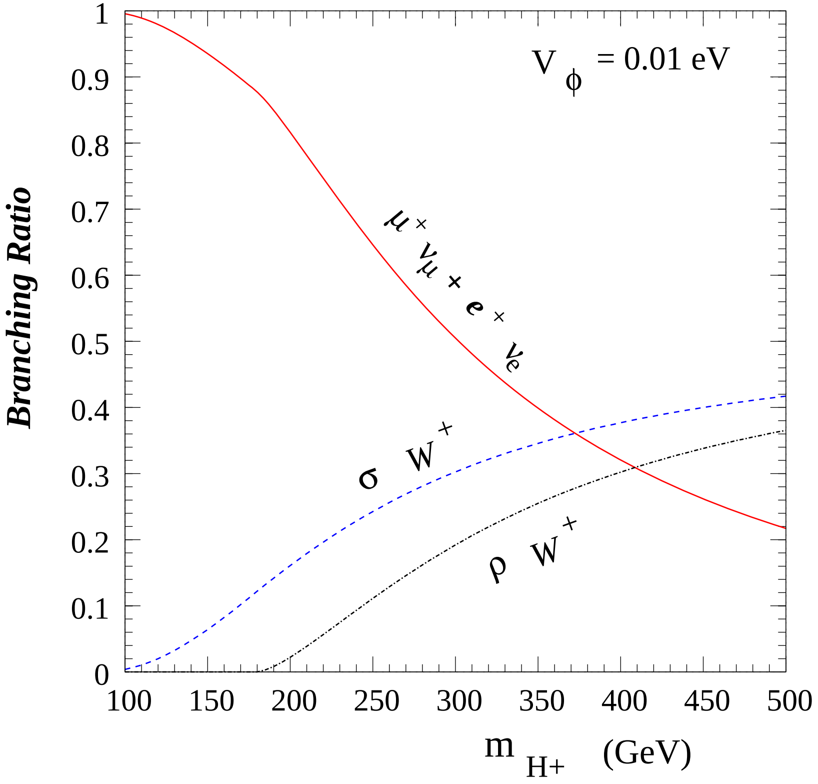
- In our model via Drell-Yan:

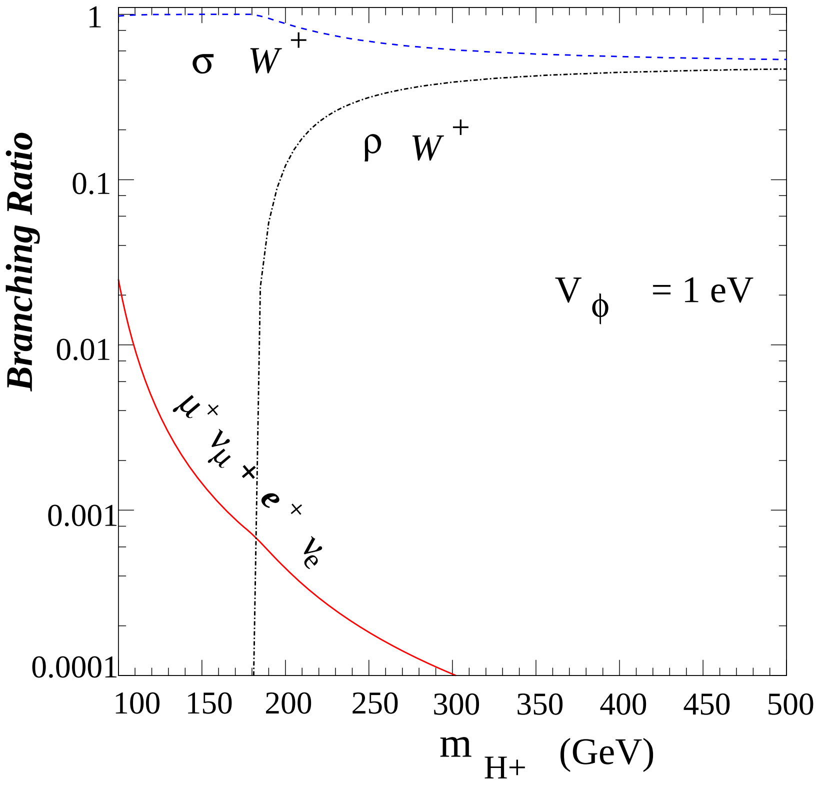
$$pp\ (\text{or } p\bar{p}) \xrightarrow[\gamma,Z]{\qquad} H^+H^-$$



$$pp\ (\text{or } p\bar{p}) \longrightarrow W^\pm + X$$: Huge background

Branching Ratios of $H^{\pm}$ (inverted hierarchy)





Parameters: $\lambda_1 = 0.12,\ \lambda_2 = 1.0,\ \lambda_3 = 2.0,$

$$\lambda_5 = \frac{m_\rho^2}{V^2},\ \lambda_4 = \frac{2m_{H^\pm}^2}{V^2} - \lambda_5$$

Collider Signals of *H*±

- Signal:

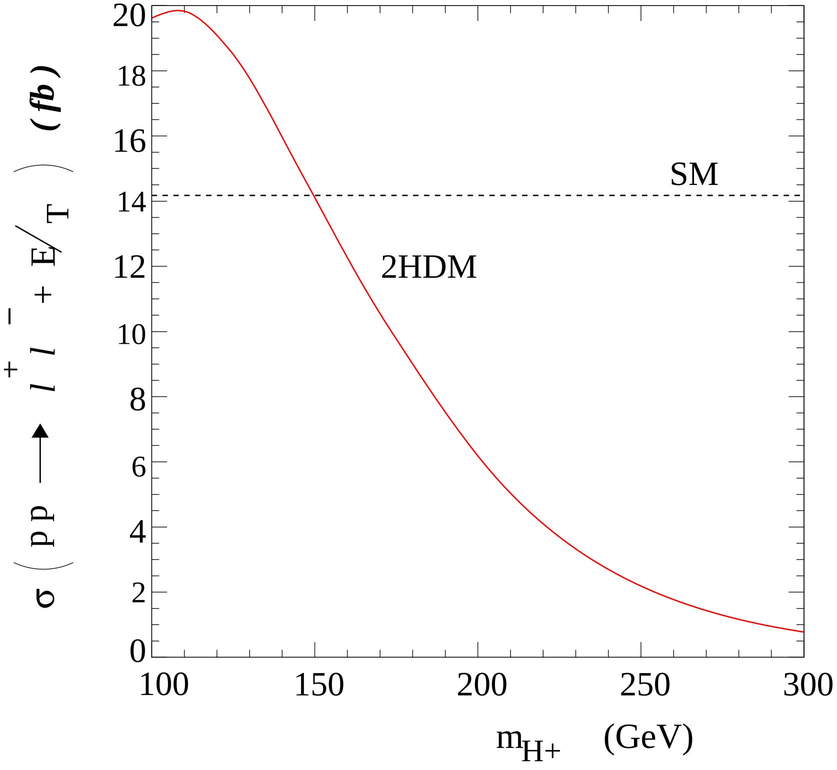
$$pp \rightarrow H^+H^- \rightarrow \ell^+\ell'^- + \text{ missing } E_T$$

- Background:

$$pp \rightarrow W^+W^- \rightarrow \ell^+\ell'^- + \text{ missing } E_T$$

$$pp \rightarrow Z^0Z^0 \rightarrow \ell^+\ell^- + \text{ missing } E_T$$

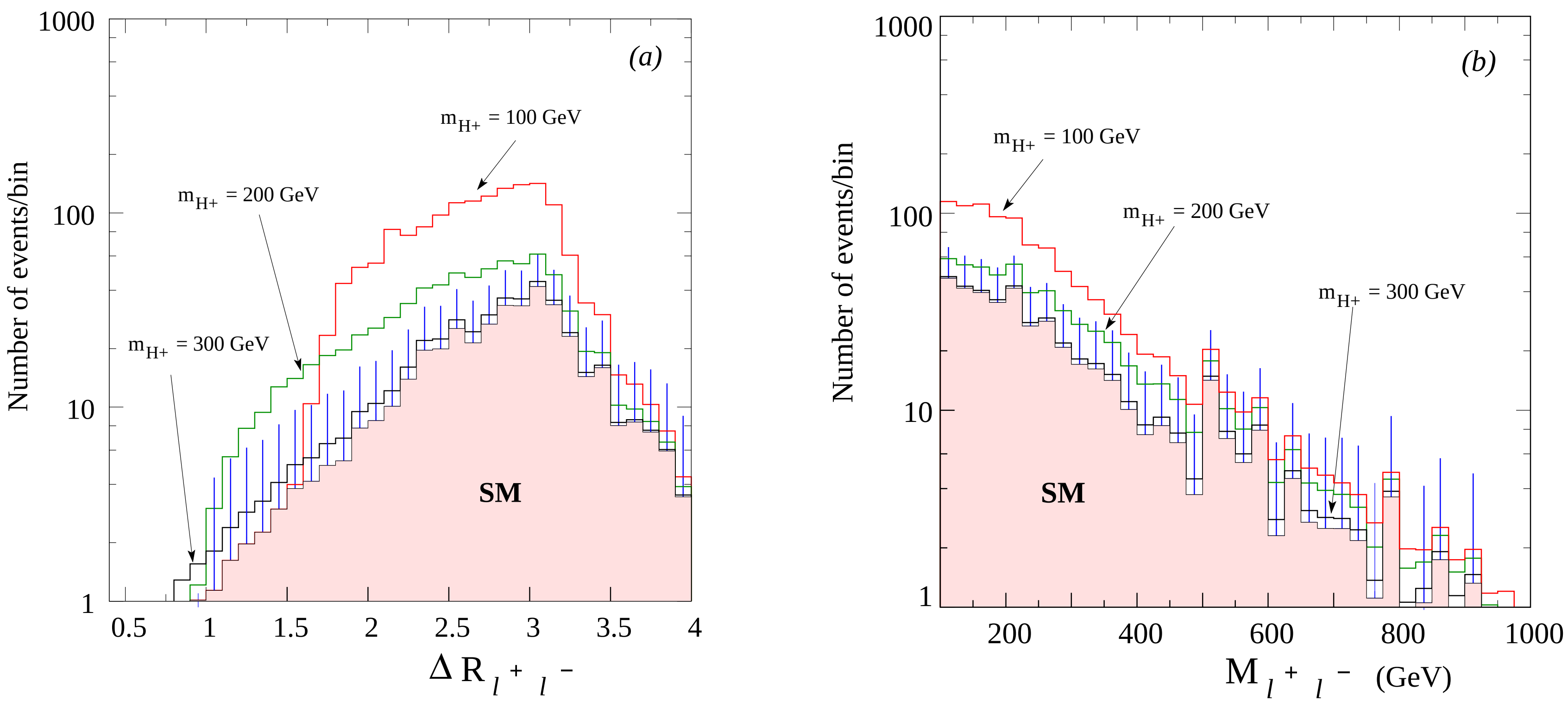
$$\ell = e,\ \mu$$



$$\text{LHC: } \sqrt{s} = 14 \text{ TeV}$$

- *H*± has a large BR to *e* or *μ* compared to *W*±
- Missing E$_T$ reduces the background since $m_{H\pm} > m_W$

Signal vs. Background with Cuts



at LHC with $L = 30\ fb^{-1}$, with cuts:

$p_T^\ell > 25$ GeV, $|\eta_\ell| < 2.5$, $\Delta R_{\ell\ell} \geq 0.4$

$M_{\ell\ell}^{inv} > 100$ GeV, missing $E_T > 100$ GeV

Reach for $H^{\pm}$ at LHC

- For 5σ significance:

- With L=10 fb^{-1} we can discover $H^{\pm}$ with a mass up to 200 GeV

- With L=100 fb^{-1} we can discover $H^{\pm}$ with a mass up to 250 GeV

Case for Normal Hierarchy

$$pp \rightarrow H^+H^- \rightarrow \tau^+\tau^- + \text{missing } E_T$$

- Signal is same as e,μ case
- Background is reduced by factor of 4
- However, tau's must decay which reduces the effective signal

Cosmological Implications

- **Neutrino star formation**

The interaction of the almost massless scalar, sigma, with the neutrinos are strong

→ neutrino star formation

- **Effect on supernova explosion**

Strong interaction with sigma will affect the neutrino emission during supernova explosion

→ will affect SN explosion dynamics

- **Effect on big bang nucleosynthesis**

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, $e^\pm$, ν'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

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

Big Bang Nucleosynthesis

- Reactions that interconvert protons and neutrons:

$$n \leftrightarrow p + e^- + \bar{\nu}, \quad \nu + n \leftrightarrow p + e^-, \; e^+ + n \leftrightarrow p + \bar{\nu}$$

- For $T \gg \Delta m = m_n - m_p = 1.293$ MeV, $\Gamma_{p\leftrightarrow n} \gg H$, and these reactions are in thermal equilibrium

$$\Rightarrow \frac{n}{p} = e^{-\frac{\Delta m}{T}} e^{\frac{\mu_e - \mu_\nu}{T}}$$

- We know $\mu_e/T \sim 10^{-10}$. Assume also that $\mu_\nu/T \approx 0$

$$\Rightarrow \frac{n}{p} = e^{-\frac{\Delta m}{T}}$$

Big Bang Nucleosynthesis

- The reactions that interconvert protons and neutrons freeze out when $\Gamma_{p\leftrightarrow n} \sim H$.

$$H = 1.66\sqrt{g_*}\,\frac{T^2}{M_{PL}}$$

$$\Gamma_{pe\to\nu n} = \frac{1}{1.636\tau_n}\int_{\Delta m/m_e}^{\infty} d\varepsilon\,\frac{\varepsilon(\varepsilon - \Delta m/m_e)^2\sqrt{\varepsilon^2 - 1}}{[1+\exp(\varepsilon\Delta m/T)][1+\exp([\Delta m - \varepsilon m_e]/T)]}$$

- In SBBN (with $g_* \approx 10.75$), this give $T_F \approx 0.8$ MeV

$$\Rightarrow \quad \frac{n}{p} = e^{-\frac{\Delta m}{T_F}} \simeq \frac{1}{6}$$

Big Bang Nucleosynthesis

- By the time nucleosynthesis begins at T ≈ 0.3 MeV, neutron decays have reduced n/p to ≈1/7
- → To a good approximation, all neutrons end up in He-4. The mass fraction of He-4 is

$$Y_P = \frac{4n_{He}}{n_N} \simeq \frac{4(n_n/2)}{n_p + n_n} = \frac{2(n/p)}{1+(n/p)} = 0.25$$

- Observed value: $Y_P = 0.249 \pm 0.009$ (PDG)

Big Bang Nucleosynthesis

- Larger g_* implies larger T_F

- For low temperature, $\Gamma_{p\leftrightarrow n} \sim T^5$

$$\Rightarrow \quad \frac{\Gamma_{p\leftrightarrow n}}{H} \sim \frac{T^3}{\sqrt{g_*}} \qquad \Rightarrow \quad T_F \sim g_*^{1/6}$$

- For $g_* = 17$, $T_F \approx 0.86$ MeV

$$\Rightarrow \quad \frac{n}{p} = e^{\Delta m\left(\frac{1}{0.8\,MeV} - \frac{1}{0.86\,MeV}\right)} \left(\frac{n}{p}\right)_{SBBN} \simeq 1.2 \left(\frac{n}{p}\right)_{SBBN}$$

$$\Rightarrow Y_P \simeq 0.30$$

Possible Solution: Large Neutrino Density

- Since relic neutrinos haven’t been detected, μ_ν is unknown

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

$$\mu_\nu \simeq 0.15\, MeV \quad \Rightarrow \quad e^{-\frac{\mu_\nu}{T}} \simeq \frac{1}{1.2}$$

- g_* is consistent with BBN for $\mu_\nu \approx 0.15$ MeV

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: $0.8 < N_v < 7.6$ (Ichikawa, Kawasaki, Takahashi, Nov. 2006)
- Seljak, Sloshar, McDonald (WMAP + several other astrophysical data sources) claim that more than 3 neutrinos is required (Sep. 2006)

Conclusions

- Proposed new two Higgs doublet model based on SM×Z_2
- Z_2 broken at ~ 10^{-2} eV
- Gives new mechanism for tiny neutrino mass
- Neutrinos are Dirac particles, → no neutrinoless double beta decay
- Higgs: $H^\pm$, h, ρ → mass at EW scale, σ → extremely light
- h like SM, but possibly dominant invisible decay mode $h \rightarrow \sigma\sigma$
- Alters Higgs signals at LHC, but observable through WBF
- Unusual signal for $H^\pm$: e and μ in the final state at the LHC.