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].

OUTLINE

1. Introduction
    : overview of Higgs models

2. Our new model

3. Phenomenological Implications
    : Lepton Colliders
    : Hadron colliders

4. Cosmological implications

5. Conclusions

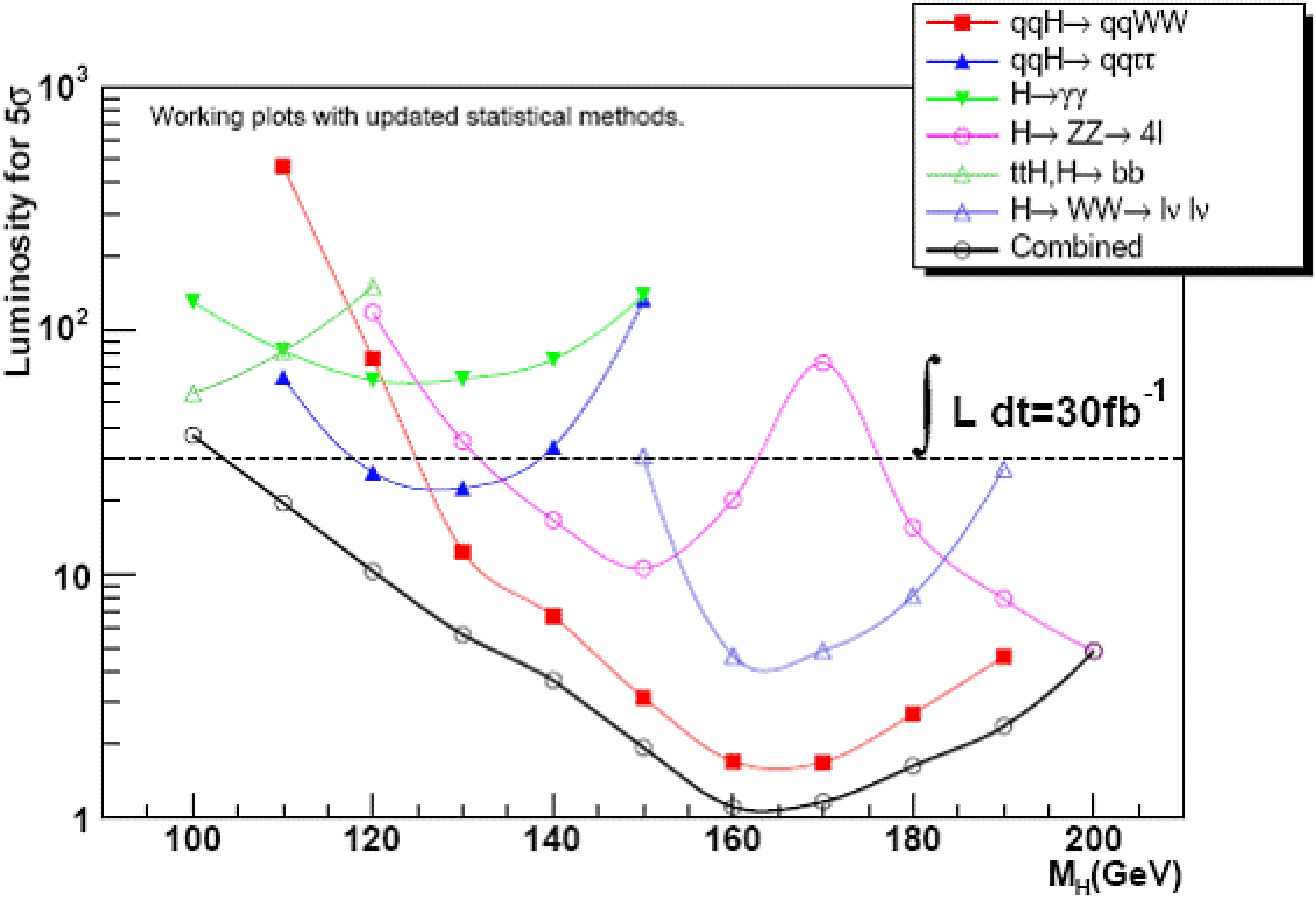
INTRODUCTION :Higgs Overview

- 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 :

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

- Experimentally, nothing currently known about Higgs sector

ATLAS TDR for Higgs Search at LHC



Two Higgs Doublet Model

- 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

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

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

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

or, more simply:

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

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

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

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

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

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

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

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

can be significant

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

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

Invisible Z width = 499 ± 1.5 MeV (PDG)

Phenomenological Implications

Pseudoscalar *ρ:*

Assume ρ has no strong coupling, so

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

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

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

If $m_\rho < m_Z$, then $\rho \to \nu\nu$ will be the dominant decay mode, and $Z \to \rho\sigma$ will be invisible

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

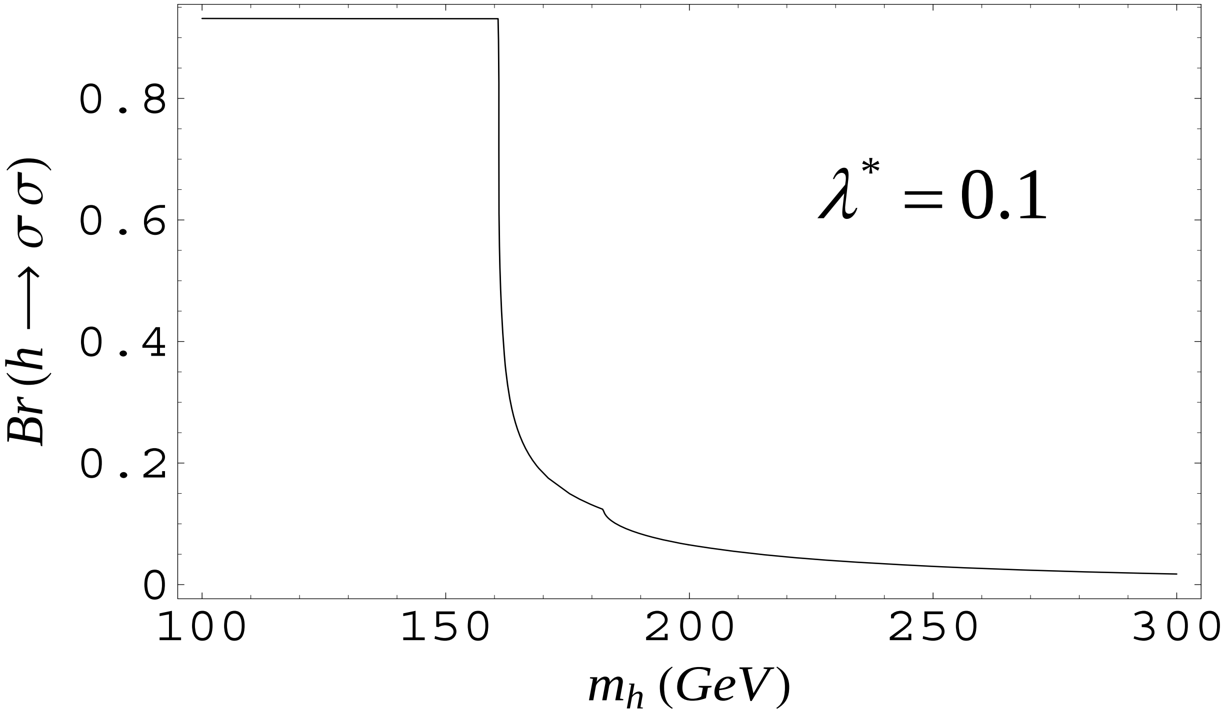
Invisible decay mode $h \to \sigma\sigma$:

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

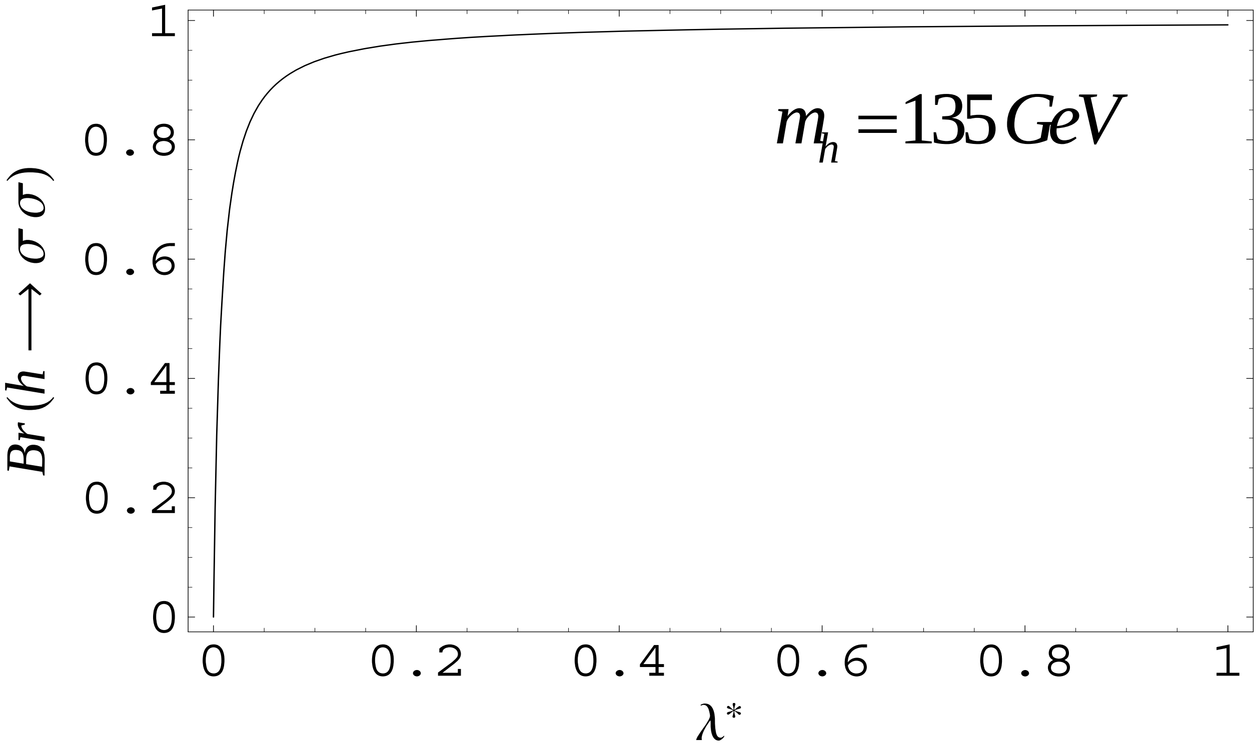
$$m_h{}^2 = 2\lambda_1 V_\chi{}^2 + O\left(V_\phi{}^2 / V_\chi{}^2\right)$$

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

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)

Invisible Higgs Signal at LHC

At LHC, invisibly decaying Higgs is observable through WBF:

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

Signal: Two q's with high p_T + invisible

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

Difficult to identify invisible particle as Higgs

Implications for Charged Higgs

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

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

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

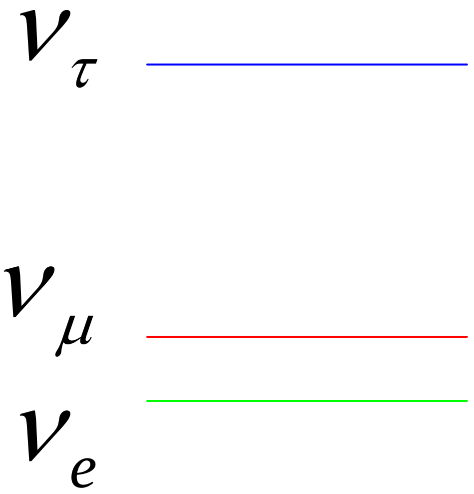
Main Decay Modes of *H*±

$$\begin{tikzcd} & \sigma W^{\pm} \\ H^{\pm} \arrow[ur] \arrow[r] \arrow[dr] & \rho W^{\pm} \\ & \ell \nu_{\ell},\ (\ell = \mathrm{e},\ \mu,\ \tau) \end{tikzcd}$$

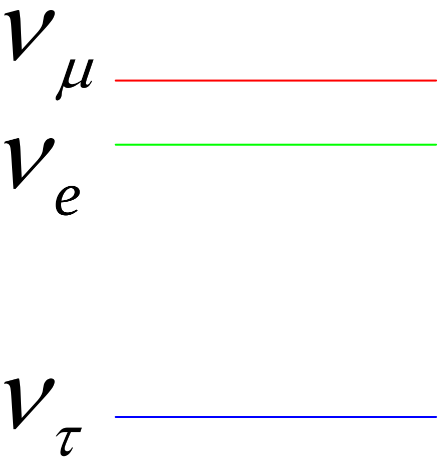
$$\text{leptonic coupling} \propto \frac{m_{\nu_\ell}}{V_\varphi}$$

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

Neutrino Mass Hierarchy



Normal Hierarchy



Inverted Hierarchy

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

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

Collider Signals of $H^{\pm}$

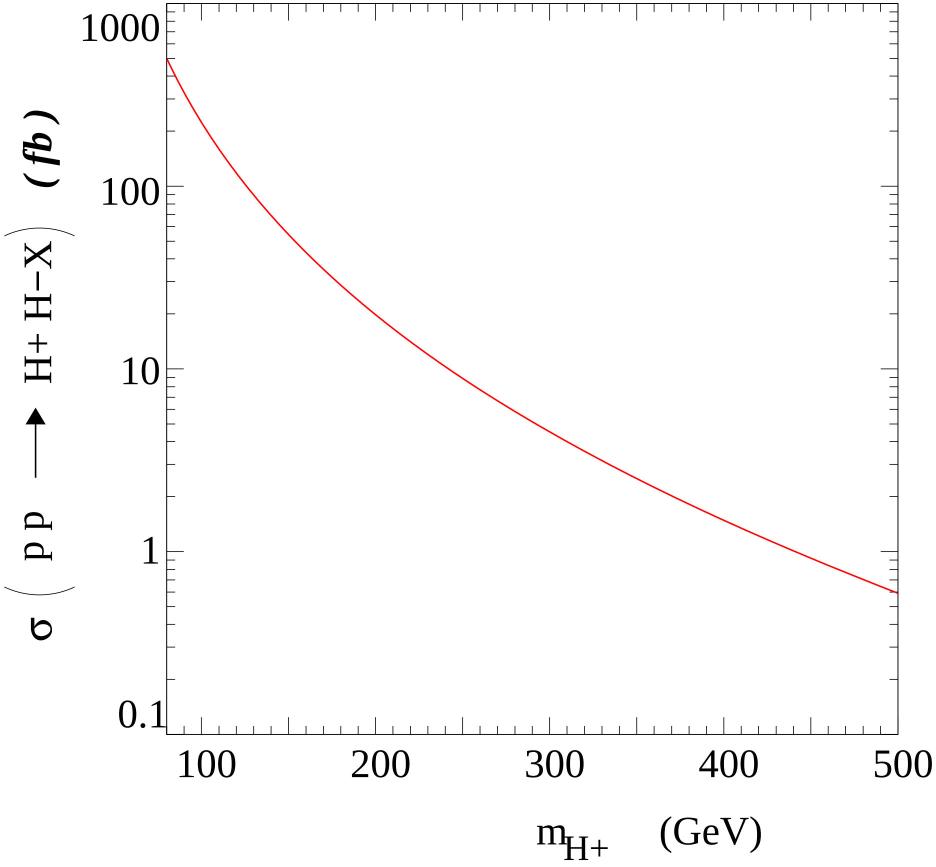
- Usual production of charged Higgs via:

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

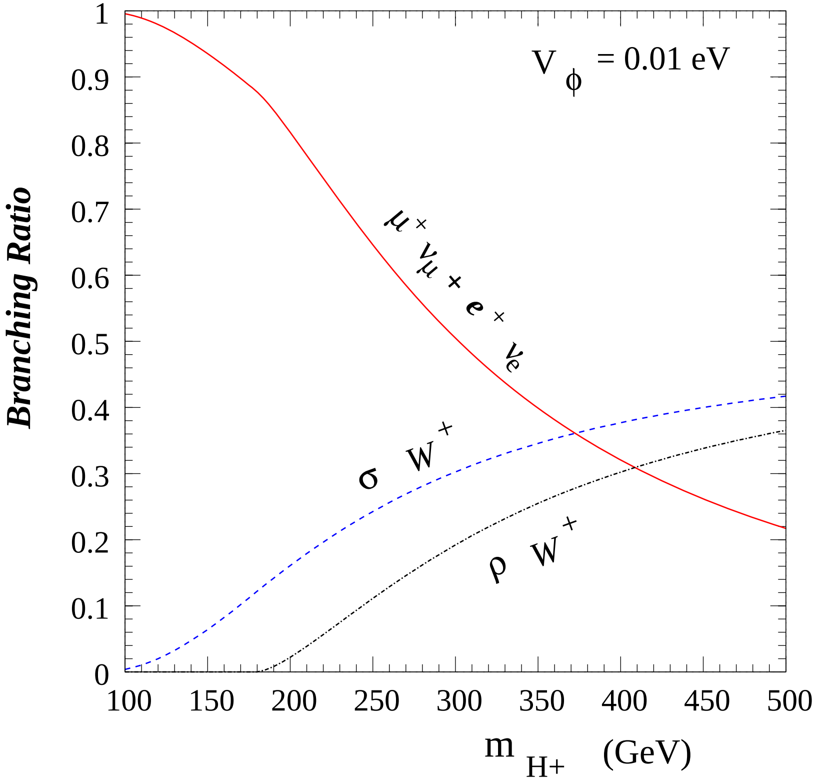
is **not** available

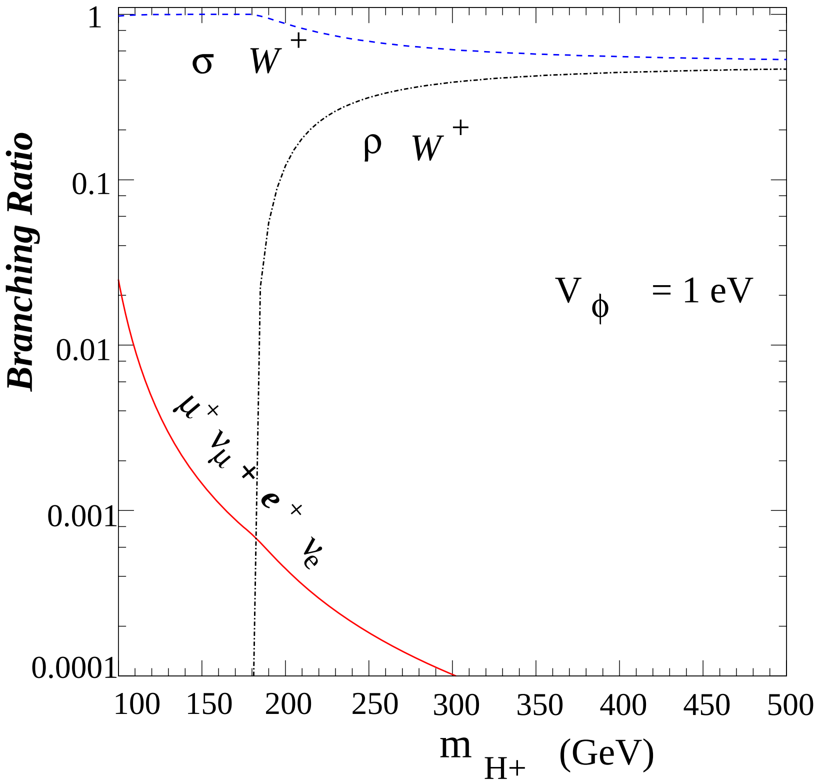
- In our model via Drell-Yan:

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



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





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

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

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*

Collider Signals of *H*±

- Signal:

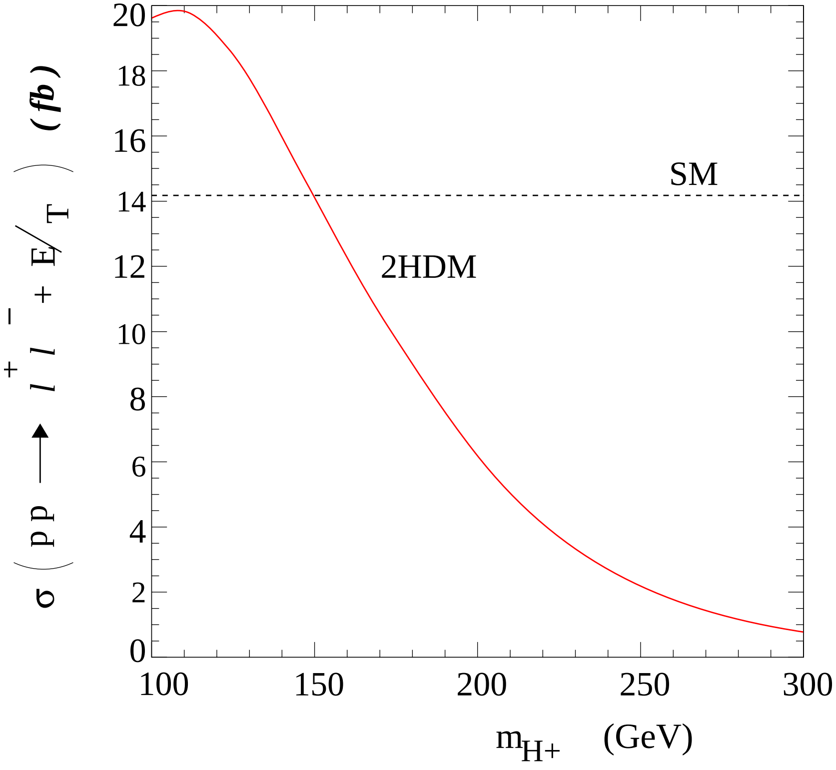
$$pp \rightarrow H^+H^- \rightarrow \ell^+\ell'^- + \text{ missing } E_T$$

- Background:

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

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

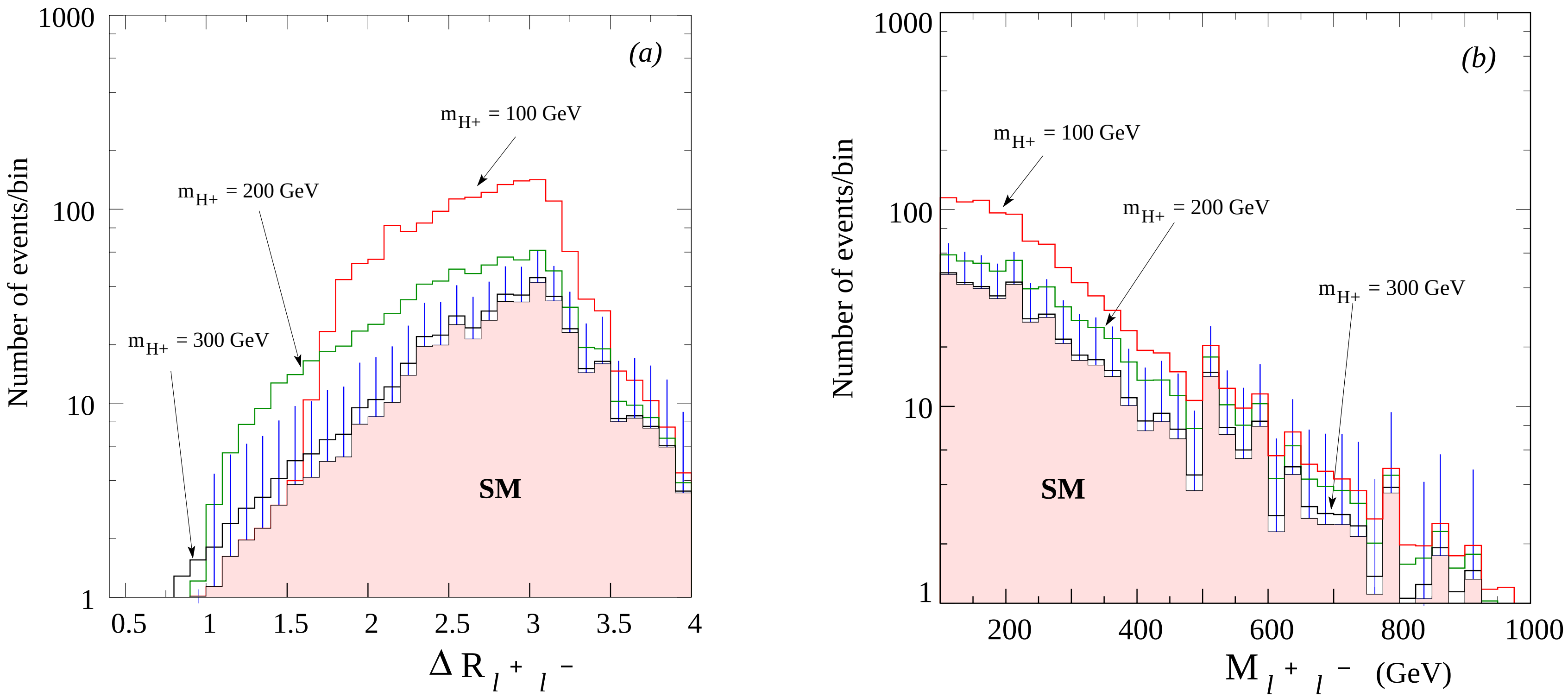
$$\ell = e,\ \mu$$



LHC: $\sqrt{s} = 14$ 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

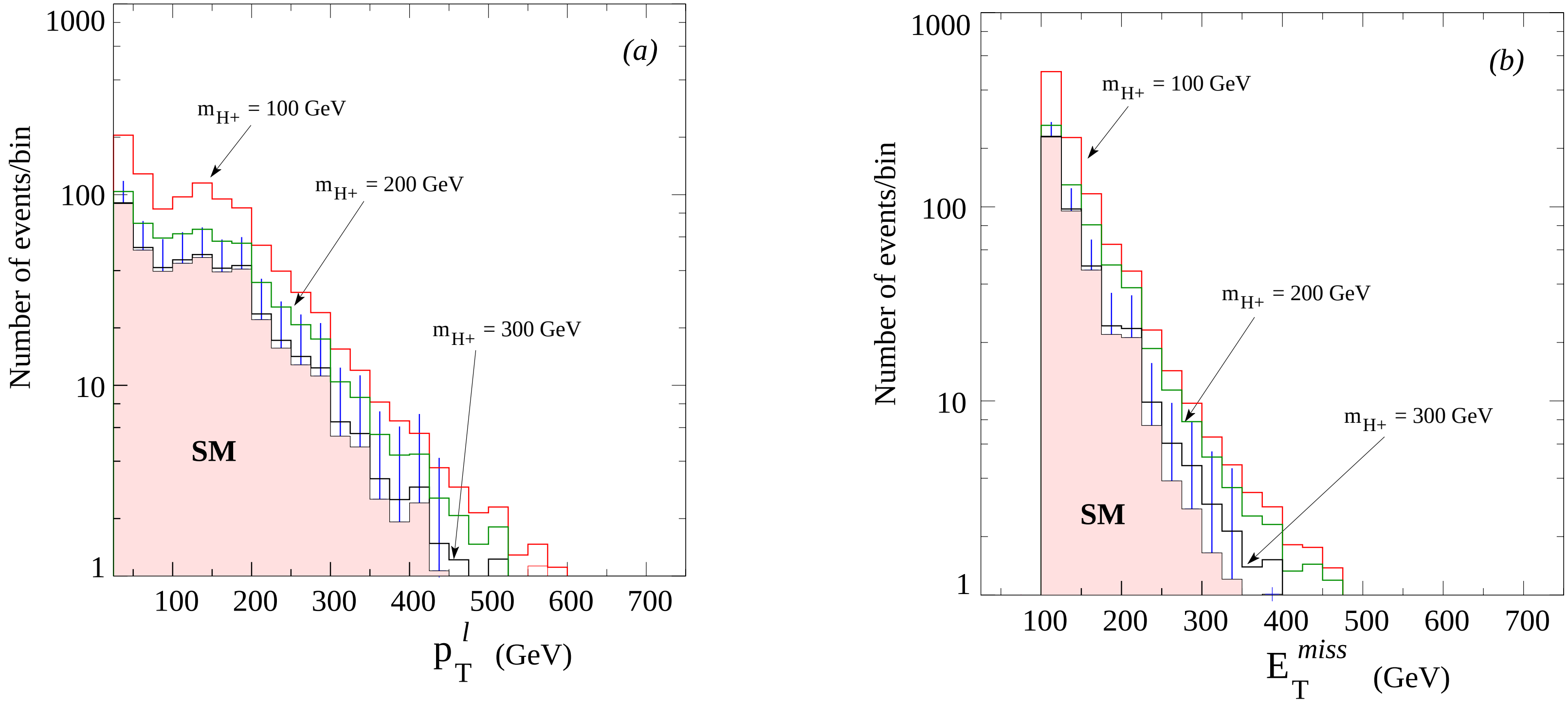


at LHC with $L = 30\ fb^{-1}$, with cuts:

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

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

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

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

- 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

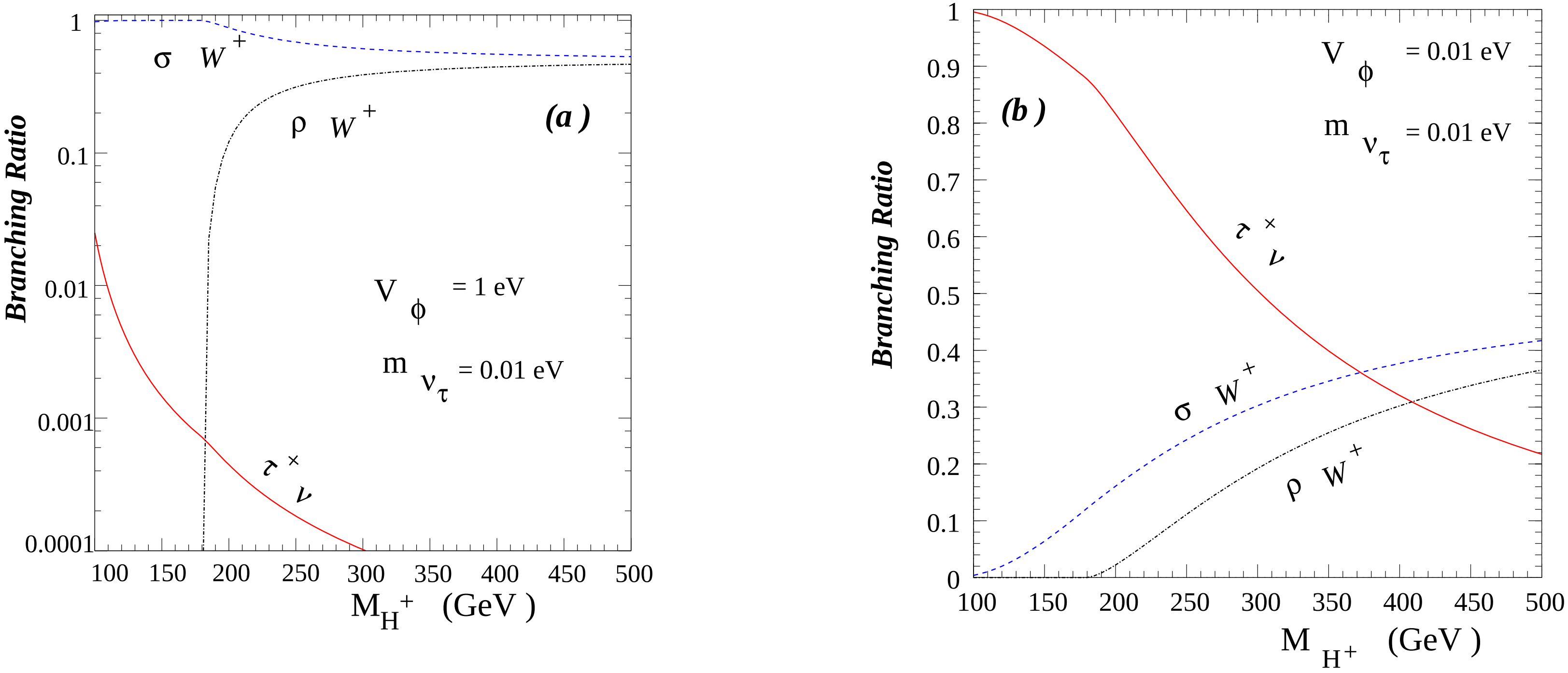
- The energetic decay products of a massive particle (m > a few GeV) that decays during or after nucleosynthesis can cause nuclear reactions among background nuclei, altering light element abundances

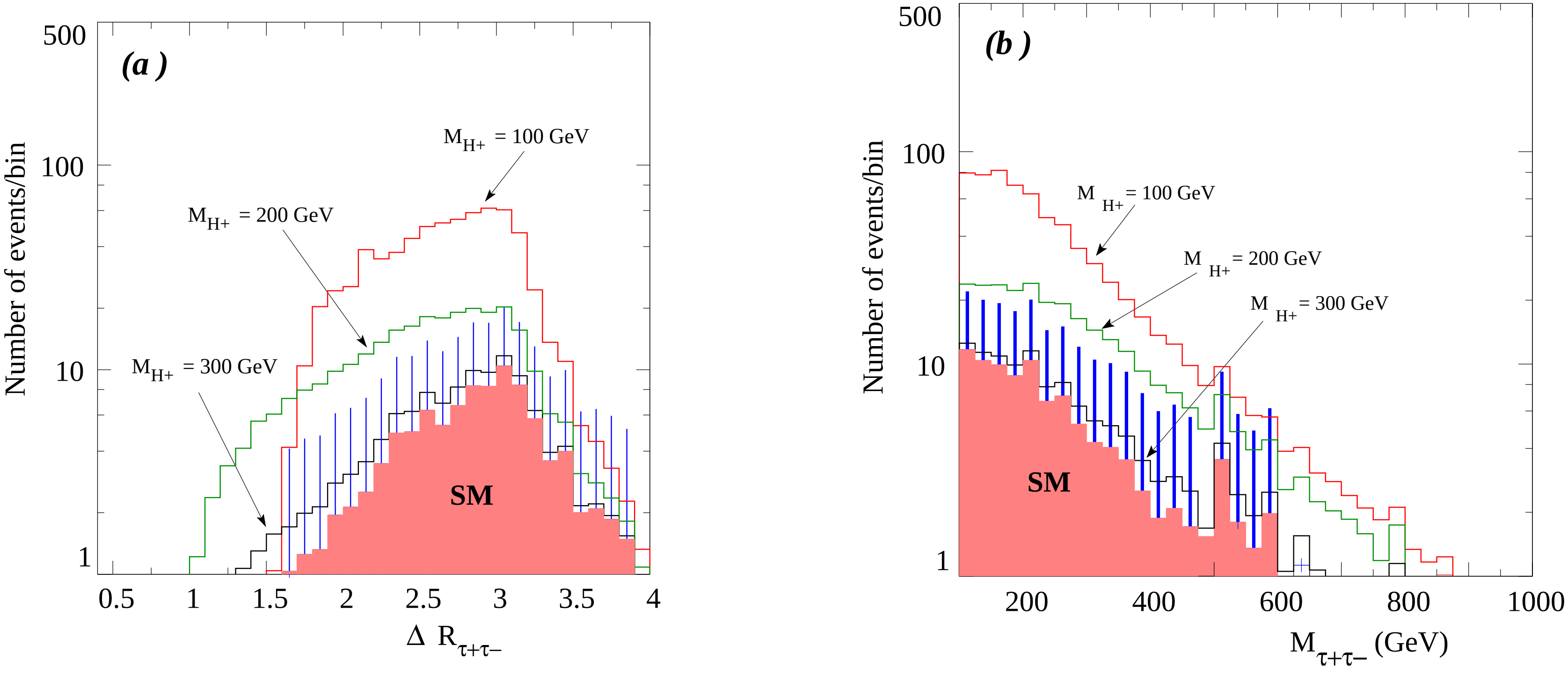
- **Non-BBN Bounds on Number of Neutrinos:**

- WMAP: $0.8 < N_\nu < 7.6$ (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 $SM\times Z_2$
- Z_2 broken at ~ 10^{-2} eV
- Gives new mechanism for tiny neutrino mass
- Neutrinos are Dirac particles, → no neutrinoless double beta decay
- Higgs: $H^{\pm}, h, \rho \rightarrow$ 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
- Unusual signal for $H^{\pm}$: e and μ in the final state at the LHC.
- cosmological implications: neutrino star, supernova and BBN


Branching Ratio
1
0.1
0.01
0.001
0.0001
100 150 200 250 300 350 400 450 500
M_{H^+} (GeV)
σ W^+
ρ W^+
τ × ν
(a)
V_ϕ = 1 eV
m_{ν_τ} = 0.01 eV
Branching Ratio
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100 150 200 250 300 350 400 450 500
M_{H^+} (GeV)
(b)
V_ϕ = 0.01 eV
m_{ν_τ} = 0.01 eV
τ × ν
σ W^+
ρ W^+


(a)
Number of events/bin
500
100
10
1
0.5
1
1.5
2
2.5
3
3.5
4
Δ R τ+τ−
M H+ = 100 GeV
M H+ = 200 GeV
M H+ = 300 GeV
SM
(b)
Number of events/bin
500
100
10
1
200
400
600
800
1000
M τ+τ− (GeV)
M H+ = 100 GeV
M H+ = 200 GeV
M H+ = 300 GeV
SM