Detecting H->hh in the Mirror Model at the LHC

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based on

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Outline

- Introduction
- Mirror Model
- Constraints from EWPO
- Higgs phenomenology
- Detail simulations
- Summary

Parity restoration

- Only left-handed fermions feel weak interaction in the SM.

  but **why**?

- A famous model to solve this issue : **Left-Right symmetric Model.**

$$SU(3)\otimes SU(2)_L\otimes SU(2)_R\otimes U(1)_{B-L}$$

J.C. Pati, A. Salam, Phys. Rev. D 10,275 (1974); R.N. Mohapatra, J.C.Pati, Phys. Rev. D 11,566 (1975).

- Another model may be **Mirror Model** in which the usual SM particles are accompanied by the mirror partners.

  This idea was first proposed by Lee and Yang in 1956.

  T.D. Lee, C.N. Yang, Phys. Rev. 104,254 (1956).

  In the near years, Foot did many work for this model. A review on this subject can be found in the article written by Okun recently.

  L.B. Okun, hep-ph/0606202.

Parity translation in Mirror Model

- In the quantum field theory parity, usual translation: $\vec{r} \leftrightarrow -\vec{r}, t \leftrightarrow t$

- In the Left-Right Model extended parity transforms the left-handed field to right-handed for the same fermion.

- In the Mirror Model a new Z_2 symmetry transform the left-handed sector of fermion to the right-handed sector of different fermion, namely the mirror fermion fields.

The new mirror particles are singlet of the SM gauge group. The minimal gauge group of the Mirror Model is

$$SU(3)\otimes SU(2)\otimes U(1)\otimes SU(3)'\otimes SU(2)'\otimes U(1)'$$

R. Foot, H. Lew ,R.R. Volkas, Phys. Lett. B 272,67(1991).

Parity translation in Mirror Model

- The gauge quantum numbers under $G_{SM} \otimes G_{Mir}$ are :

$$
\begin{aligned}
L_L^i &\sim (1,2,-1)(1,1,0) \;,\; (L'_R)^i \sim (1,1,0)(1,2,-1) \\
e_R^i &\sim (1,1,-2)(1,1,0) \;,\; (e'_L)^i \sim (1,1,0)(1,1,-2) \\
Q_L^i &\sim (3,2,\frac{1}{3})(1,1,0) \;,\; (q'_R)^i \sim (1,1,0)(3,2,\frac{1}{3}) \\
u_R^i &\sim (3,1,\frac{4}{3})(1,1,0) \;,\; (u'_L)^i \sim (1,1,0)(3,1,\frac{4}{3}) \\
d_R^i &\sim (3,1,-\frac{2}{3})(1,1,0) \;,\; (d'_L)^i \sim (1,1,0)(3,1,-\frac{2}{3})
\end{aligned}
$$

- The new parity defined now is :

$$
\vec{r} \leftrightarrow -\vec{r}, t \leftrightarrow t,\; G^\mu \leftrightarrow G'_\mu \;, W^\mu \leftrightarrow W'_\mu, B^\mu \leftrightarrow B'_\mu
$$

$$
L_L \leftrightarrow L'_R, e_R \leftrightarrow e'_L,\; Q_L \leftrightarrow Q'_R \;, u_R \leftrightarrow u'_L, d_R \leftrightarrow d'_L .
$$

Cosmological evidence

- The mirror particles have very weak interaction with ordinary SM particles, even someone can assume that there doesn't exit any interactions between two sectors except gravitational interaction.

- These mirror particles in the Mirror Model can provide natural candidates for dark matter.

R. Foot, hep-ph/0706.2694.

Direct detecting mirror particles

- The basic assumption here is that the mirror particles couple to usual SM particles.
- Three possible kinds of renormalizable gauge invariant interactions.
  - The mixing between SM and mirror neutrinos if neutrinos have masses . **R. Foot, R.R. Volkas, Phys. Rev. D 52,6595(1995)**
  - The 'kinetic mixing' between U(1) gauge part of two sectors .

$$L_{mix} = \varepsilon F^{\mu\nu} F'_{\mu\nu}$$

This mixing would give electric charge to mirror particles. Through the precisely QED testing, the mixing parameter is constrained to be extremely small.

S.N. Gninenko, Phys .Lett. B 326,317(1994) ; R .Foot, S.N. Gninenko, Phys. Lett. B 480,171(2001); A. Badertscher etc al , Phys. Rev. D 75,032004(2007) .

  - The 'scalar mixing' between Higgs sectors .

$$L_{mix} = \eta \phi^\dagger \phi \phi'^\dagger \phi'$$

The Scalar mixing

- The mirror Higgs can couple to SM Higgs through $\eta\phi^{\dagger}\phi\phi'^{\dagger}\phi'$

- After electroweak symmetry spontaneously breaking , there are two physical Higgs which are mixture of the SM and mirror scalar. This mechanic provide a possible method to investigate mirror particle through Higgs sector.

- The generic feature of Higgs is that Higgs can decay invisibly.

  Such invisible decay Higgs has been studied by many authors before through production modes

$$q\bar{q} \to HZ, q\bar{q} \to q\bar{q}V^{*}V^{*} \to q\bar{q}H$$

S.P. Martin and J.D. Wells, Phys. Rev. D 60,035006 (1999); and many other studies in Ref.[12] in hep-ph/0709.1586.

Higgs potential of Mirror Model

- Here we assume two scalar ϕ_1 , ϕ_2 under SU(2) and SU(2)' ,and we require Higgs potential is invariant under the symmetry $\phi_1 \leftrightarrow \phi_2$ to keep the parity in a broader sense.

$$V(\phi_1,\phi_2) = -\mu^2(\phi_1^+\phi_1 + \phi_2^+\phi_2) + \lambda(\phi_1^+\phi_1 + \phi_2^+\phi_2)^2 + \eta\,\phi_1^\dagger\phi_1\phi_2^\dagger\phi_2$$

- After EWSB, two Higgs can be written as :

$$\phi_i = \begin{pmatrix} \varphi_i \\ \frac{1}{\sqrt{2}}(v_i + H_i + \chi_i) \end{pmatrix}$$

The vacuum may have different modes due to the sign of η .

R. Foot , H. Lew, R.R. Volkas , JHEP 032, 0007 (2000); R. Barbieri, T. Gregoire , L.J. Hall, hep-ph/0509242.

Two spontaneous breaking ways

- If $\eta > 0$, then

$$v_1^2 = \frac{\mu^2}{\lambda}, v_2^2 = 0$$

The Higgs mass are $m_h^2 = \frac{\mu^2}{2}, m_H^2 = \frac{\eta v_1^2}{8}$, where we define

$$H_1 = \frac{1}{\sqrt{2}}(H+h), H_2 = \frac{1}{\sqrt{2}}(H-h)$$

- In this scenario , the vacuum is not invariant under the extended parity translation and the mirror particles would be massless. Though the mirror particles may obtain tiny mass through mirror QCD condensation, but we don't discuss this possibility since we want to get parity restoration for universal case.

R. Foot, H. Lew, hep-ph/9411390 ; R. Foot , H. Lew, R.R. Volkas , JHEP 032, 0007 (2000).

Two spontaneous breaking ways

- If $\eta < 0$, then

$$v^2 = v_1^2 = v_2^2 = \frac{2\mu^2}{4\lambda + \eta}$$

The Higgs mass are $m_h^2 = -\eta v^2, m_H^2 = (4\lambda + \eta) v^2$

In this case, vacuum is invariant under parity restoration and mirror particles have the same masses with SM particles .

- There also may exit some additional terms to break the invariant under the parity translation , but we don't add them here.

R. Barbieri, T. Gregoire , L.J. Hall, hep-ph/0509242.

- We would study the signal of H->hh in this scenario , we choose Higgs masses as input.

$$\lambda = \frac{m_H^2 + m_h^2}{4v^2}, \eta = -\frac{m_h^2}{v^2}$$

$$L_{int} = \frac{\sqrt{2}}{4} \frac{m_H^2 + 2m_h^2}{v} H h^2$$

Constraints from EWPO

- Current electro-weak precision observation give constraints to the new physics. A widely used set of parameters are the S,T,U.

  M.E. Peskin, T. Takeuchi, Phys. Rev. Lett 65, 964(1990); Phys. Rev. D 46, 1(1992).

- In our case here, we only consider the contributions to S,T from Higgs.

$$S = \frac{1}{2}(S_{SM}(m_h) + S_{SM}(m_H)) - S_{SM}(m_{ref})$$

$$T = \frac{1}{2}(T_{SM}(m_h) + T_{SM}(m_H)) - T_{SM}(m_{ref})$$

J.R. Forshaw, D.A. Ross, B.E. White, JHEP 0110, 007(2001).

- From the results, we choose $m_H = 260GeV, m_h = 115GeV$ as our benchmark point in our work.

Constraints from EWPO

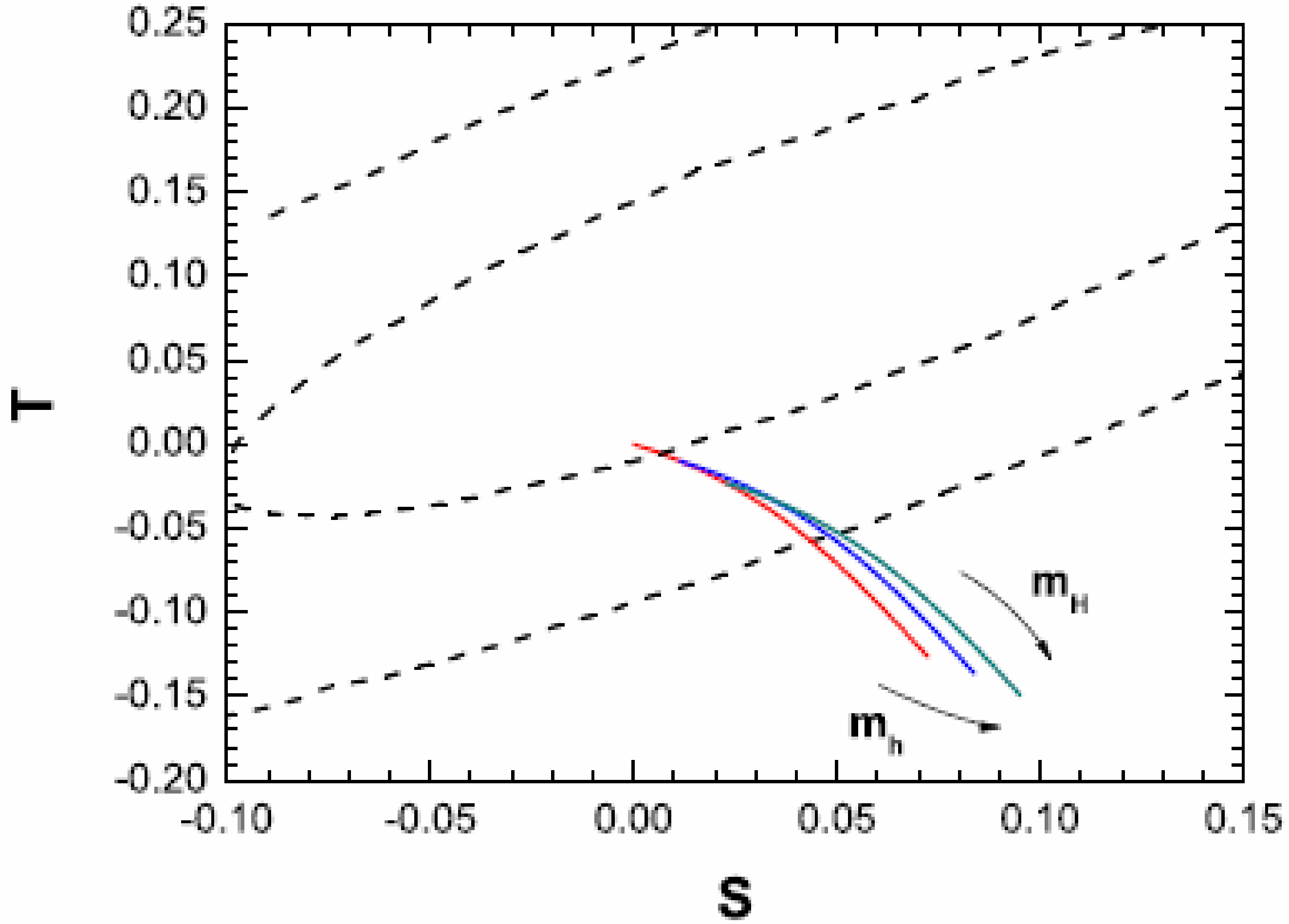

FIG. 1: The ellipses indicate the region of the S,T plane which is allowed by EWPO at 1σ (68%) and 2σ (95%) level [18]. Three curves represent three different m_h at 115, 150 and 200 GeV, and m_H increases from 100 ~ 1000 GeV for each curve.

Higgs boson decay

- Each Higgs boson is the mixture of the SM and mirror Higgs . Each Higgs can decay into mirror particles with the same possibilities as there SM partner in our case, so the branching ratio of Higgs must be changed. For example

$$Br(h \to b\bar{b}) = \frac{1}{2} Br(h_{SM} \to b\bar{b})$$

- The branching ratio of heavier Higgs would be a little different from above case if the mode of H->hh is allowed

$$Br(h \to b\bar{b}) = \frac{\Gamma(H_{SM} \to b\bar{b})}{2\Gamma(H_{SM} \to SM) + \Gamma(H_{SM} \to hh)}$$

- From the results, we can see that the branching ratio of H->hh is larger than H->ZZ if it's kinematically allowed .

Higgs boson decay

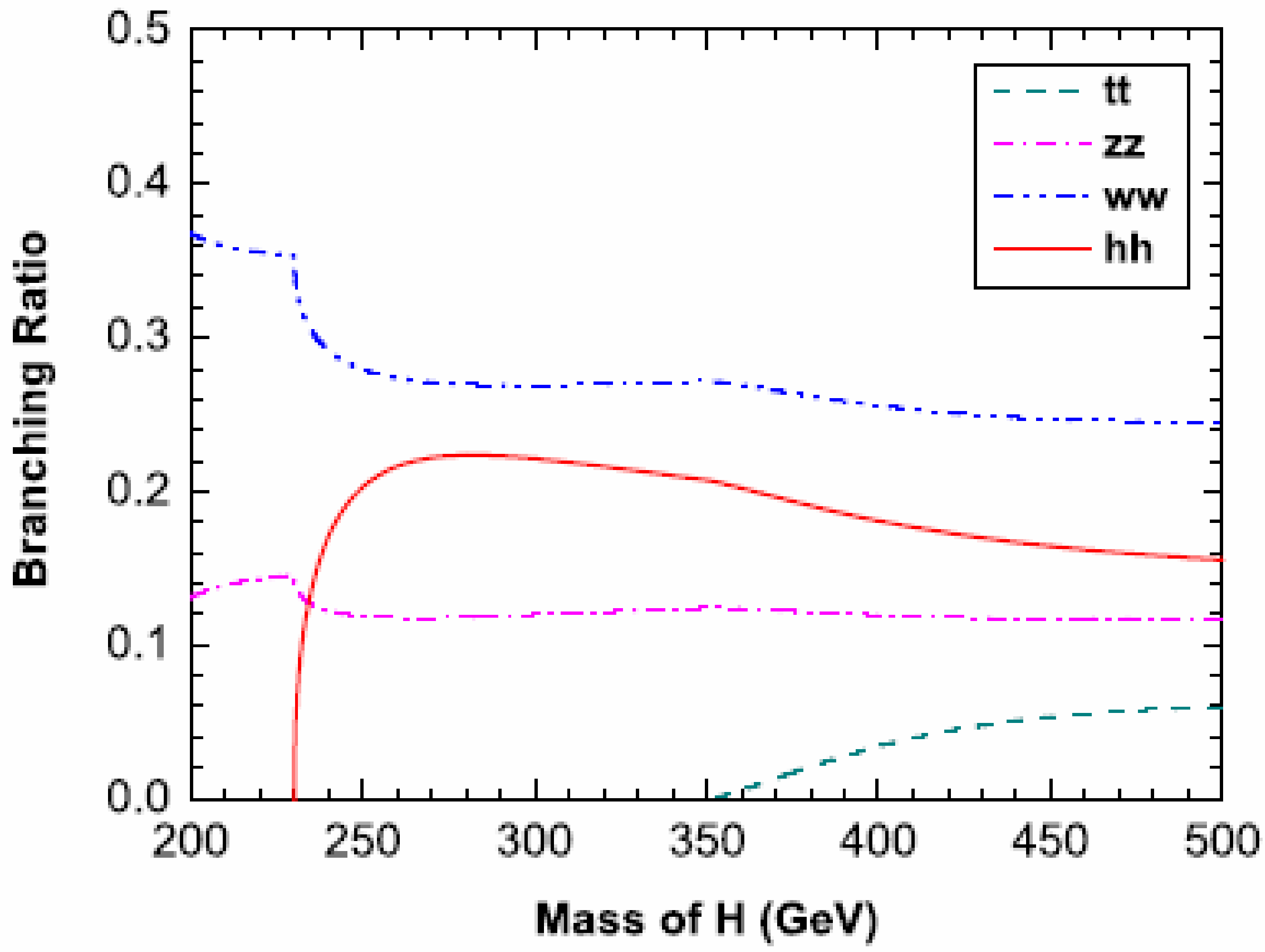

FIG. 2: Branching ratios of H as a function of m_H, where $m_h = 115\text{GeV}$.

Higgs production

- In our work, we consider main Higgs production channel gg->H and h pair production from H . For light Higgs another important production may be gg, qq->tth we don't discuss here.

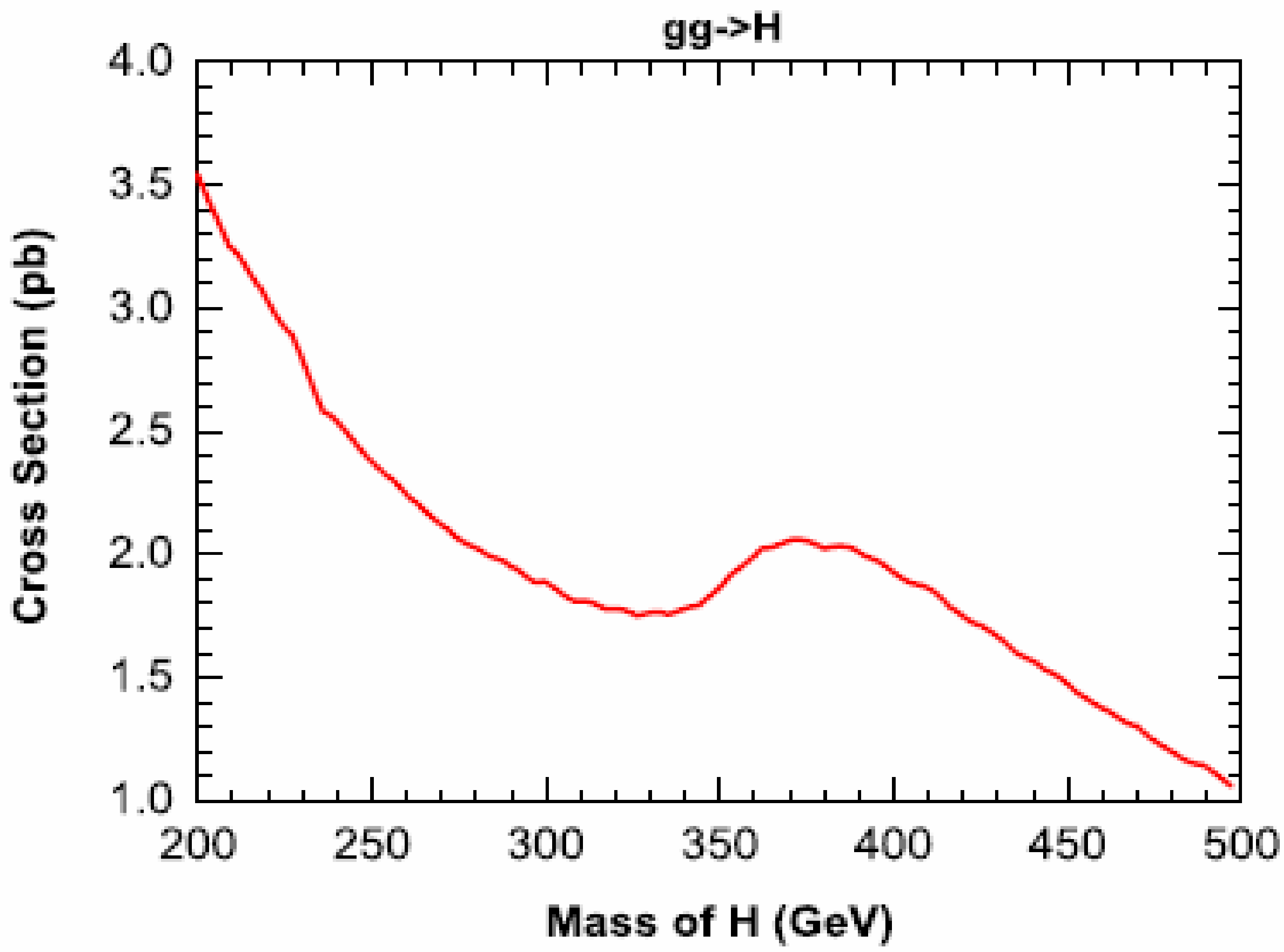

FIG. 3: Cross sections of $gg \to H$ as a function of m_H at the LHC.

Higgs production

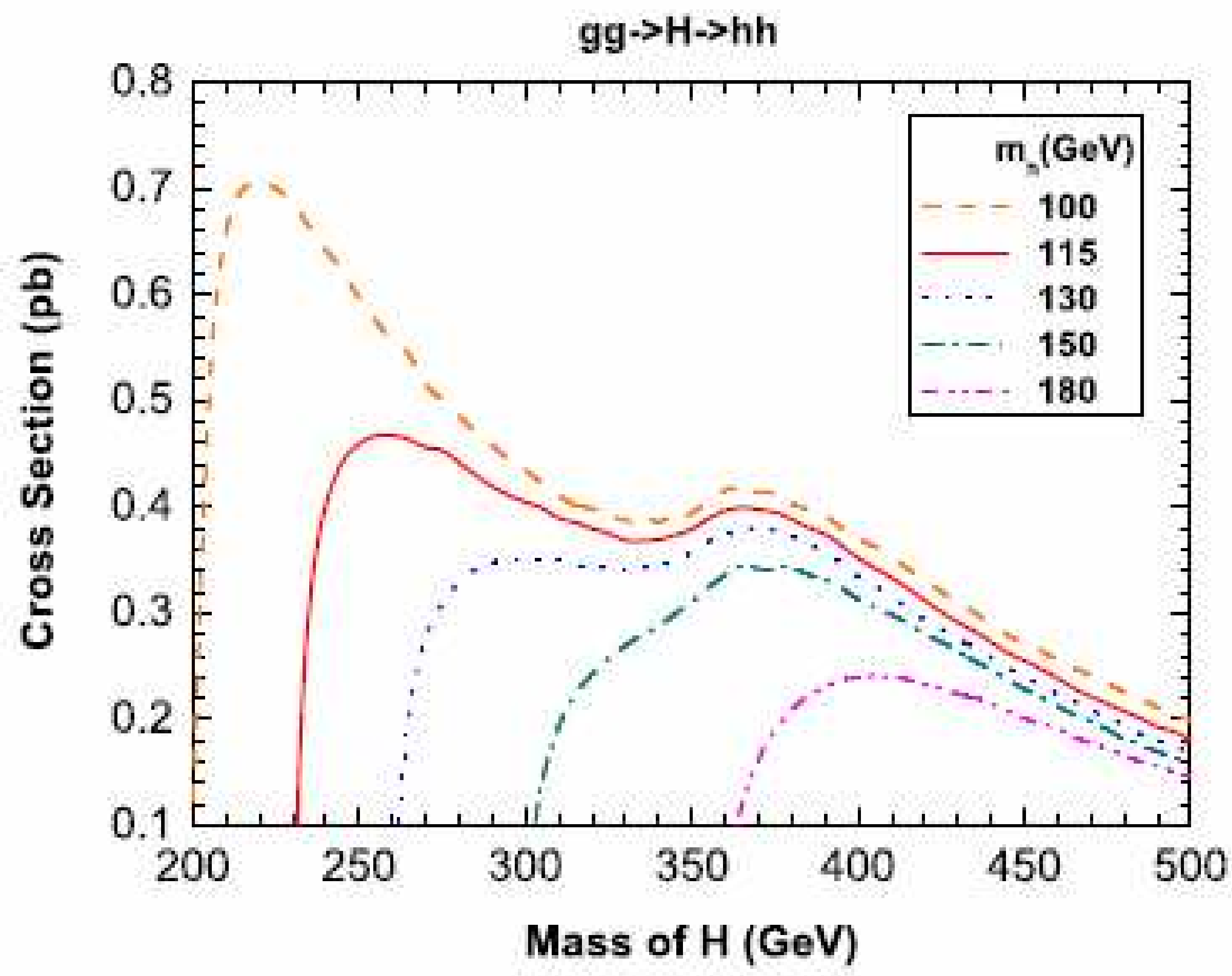

FIG. 4: Cross sections [in pb] of $gg \to H \to hh$ as a function of m_H at the LHC,where $m_h = 100, 115, 130, 150$ and 180 GeV from top to bottom .

The modes of h pair decay

- Many authors have studied similar process H->hh->light quarks and/or leptons and/or gammas . Here H is Higgs , h represents light scalar or pseudoscalar in specific models.

M. Bowen, Y. Cui, J.D. Wells, JHEP 0703,036 (2007); T. Stelzer, S. Wiesenfeldt, S. Willenbrock, Phys. Rev. D 75,077701 (2007) and many other studies in Ref[4] of that paper.

- If h is heavy enough, the channels H->hh->4W or 4Z are also possible , but this scenario is not favored here due to EWPT.

- In order to maintain signal rate , we're interest with one light Higgs decay into mirror particles and the other one decay into bb due to the large branching ratios.

- Other possible detect channel qq->VH->leptons+4b can be utilized here to study H->hh , but may suffer large tt and ttjj background.

K. Cheung, J. Song, Q.S. Yan, Phys. Rev. Lett 99,01901(2007).

Detail simulations

- We simulated the signals and backgrounds for process gg->H->hh with heavy Higgs mass of 260 Gev and light Higgs mass of 115 Gev
- We use

  Pythia 6.4.11

  T. Sjostrand, S. Mrenna, P. Skands, JHEP 0605,026 (2006).

  Madgraph/ MadEvent 4.1.27

  T. Stelzer, W.F. Long, Comput. Phys. Commun 81,357 (1994); F. Maltoni, T. Stelzer, JHEP 0302, 027 (2003).

  with the CTEQ5L PDF set.

- We assume b-tagging efficiency of 50% and mis-tagging efficiencies for c, g and light quarks of 10% , 1% , 1% and we require two b-tagged jets to suppress backgrounds.

Signal and background

- Signal process $pp \to gg \to H \to h(\to b\overline{b}) + h_{inv}$

  Final signal $b\overline{b} + \not{p}_T$

- The most important irreducible background

  $$pp \to Z(\to \nu\overline{\nu})b\overline{b}$$

  Other related backgrounds may be

  $Z(\to \nu\overline{\nu})jj$ $\quad$ $Z(\to \nu\overline{\nu})Z(\to b\overline{b})$

- Some contributions from bellow process where the W boson is mis-measured .

  $WZ(\to b\overline{b})$ $\quad$ $Wb\overline{b}$

  $t(\to W^+b)\overline{b}$ $\quad$ $t(\to W^+b)\overline{t}(\to W^-\overline{b})$

S. P. Martin, J. D. Wells, Phys. Rev. D 60, 035006 (1999)

Kinematical cuts

- Basic cuts

$$P_T(j_1), P_T(j_2) > 20GeV, 15GeV \qquad |\eta_j| < 2$$

$$\Delta R(jj) > 0.4 \qquad m_{jj} > 10GeV$$

- We suppress WZ, Wbb, tb, tt backgrounds by vetoing events from W decay with follow cuts.

$$P_T(j) > 15GeV, |\eta_j| < 2$$

$$P_T(l^{\pm}) > 10GeV, |\eta_j| < 2.5$$

- The results

Channel	$Zb\bar{b}$	$Zb\bar{c}$	Zbj	$Zc\bar{c}$	Zcj	Zjj
$\sigma(pb)$	3.250	0.011	0.107	0.001	0.027	0.063
Channel	ZZ	$W^-b\bar{b}$	W^-Z	$t\bar{b}$	$t\bar{t}$	
$\sigma(pb)$	0.072	0.417	0.032	0.017	0.346	

Other cuts

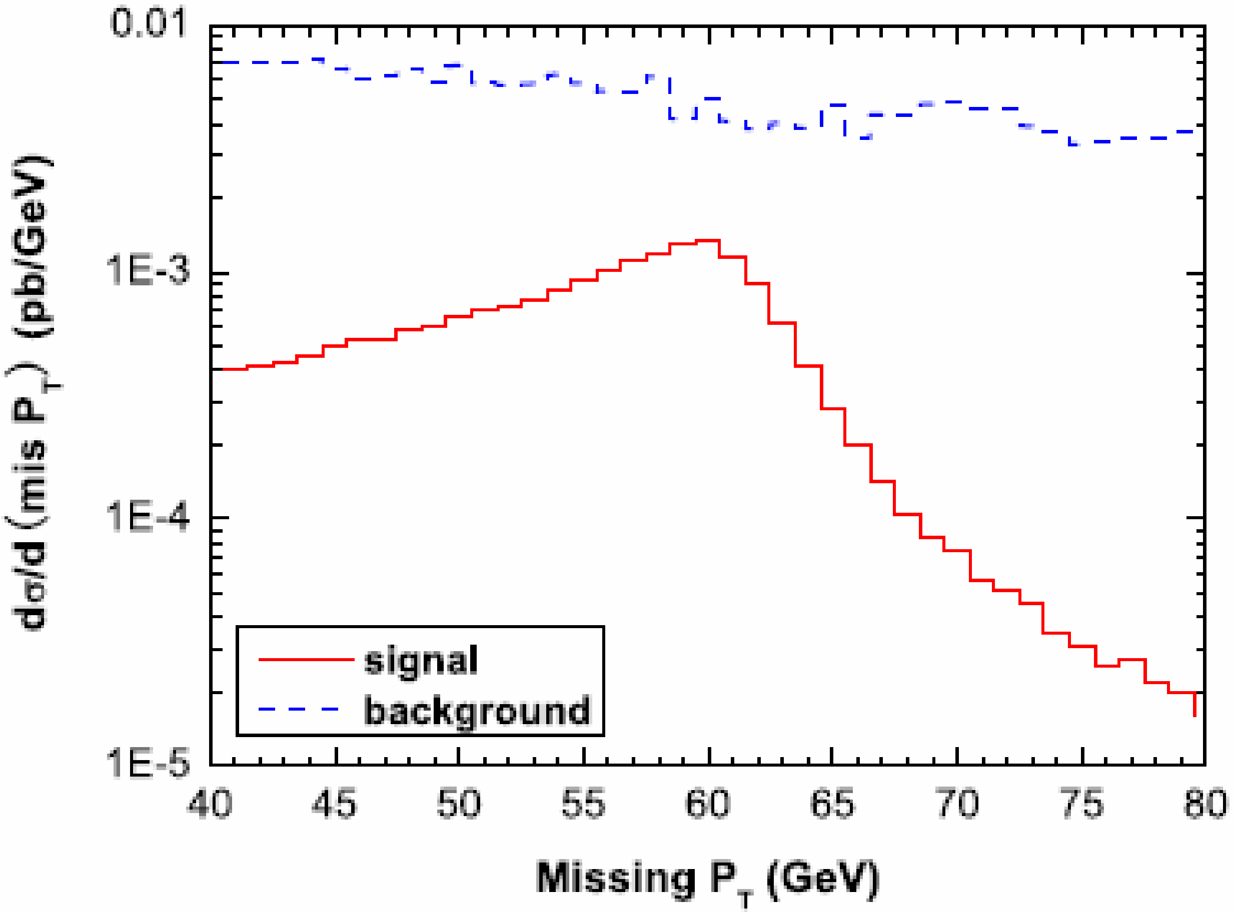

FIG. 5: The distribution of the signal and background for $b\bar{b} + \not{P}_T$ as a function of $\not{P}_T$ after applying cuts Eqs 24-29 and tagging efficiencies.

- Furthermore we require mass window

  $$|m_{jj} - m_h| < 15GeV$$

- $40GeV < \not{P}_T < 80GeV$

Other cuts

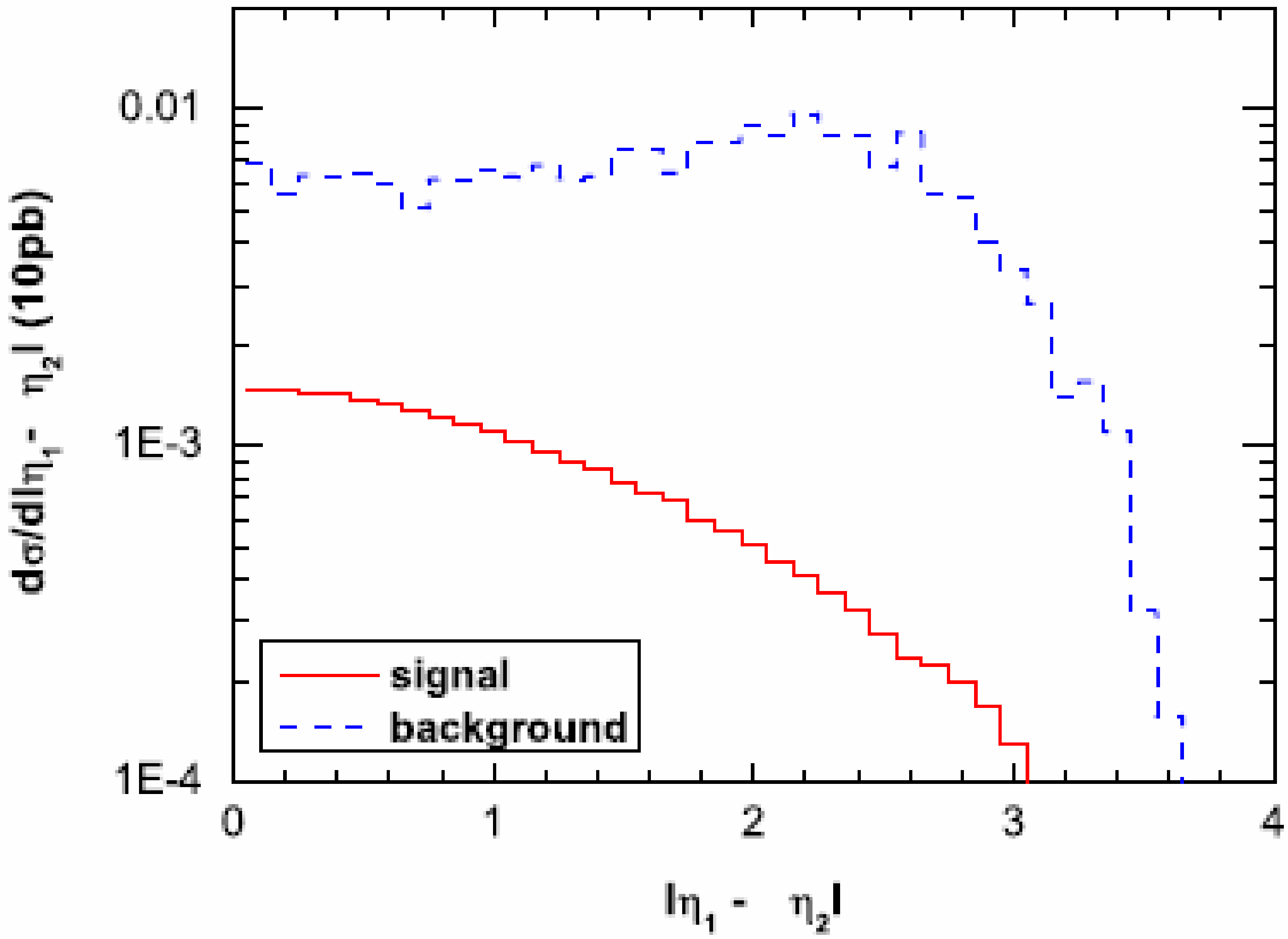

FIG. 6: The distribution of the signal and background for $b\bar{b} + \not{P}_T$ as a function of $|\eta_{j_1} - \eta_{j_2}|$ after imposing cuts Eqs. 24-31 and tagging efficiencies .

- $|\eta_{j_1} - \eta_{j_2}| < 1.5$

A possible method to suppress the background

- In order to suppress the largest $Zb\bar{b}$ background, we may utilize the precise measurement of $Z(\to \mu^+\mu^-)b\bar{b}$. Because this process has similar kinematics and shape to $Z(\to \nu^+\nu^-)b\bar{b}$.

  We can obtain improved background as

$$\sigma_{bkg}^{Zb\bar{b},imp} = \sigma_{bkg}^{Zb\bar{b}} - R \times \sigma^{b\bar{b}\mu^+\mu^-} \qquad R = \frac{\sum_i Br(Z \to \nu_i \bar{\nu}_i)}{Br(Z \to \mu^+\mu^-)}$$

  In our case R=5.94 .

  S. H. Zhu, Eur. Phys. J. C 47, 833(2006).

- However we are aware of the difficulties of this method . For example it's hard to reconstruct all the final state and it's hard to combine two measurements with different systematics etc.

Results

Cuts	$s(fb)$	$b(fb)$	S/B	$S/\sqrt{B_1}$	$S/\sqrt{B_2}$
basic cuts	26.6	4948	0.0054	1.19	2.07
$\lvert m_{jj} - m_h \rvert < 30\text{GeV}$	26.6	1133	0.023	2.50	4.32
$\lvert m_{jj} - m_h \rvert < 15\text{GeV}$	26.6	492	0.054	3.79	6.56
$20 < \not{P}_T < 120\text{GeV}$	25.0	401	0.062	3.94	6.83
$40 < \not{P}_T < 80\text{GeV}$	19.4	202	0.096	4.33	7.49
$\lvert \eta_{j_1} - \eta_{j_2} \rvert < 1.5$	15.2	95	0.16	4.93	8.54
improved backg	15.2	18	0.83	11.4	19.8

TABLE II: The effects on the cross sections of signal (s) and background (b), ratio of signal and background events S/B, $S/\sqrt{B_1}$ and $S/\sqrt{B_2}$, by imposing cuts of Eqs.24-33 step by step, are summarized. Here $m_H = 260$ GeV and $m_h = 115$ GeV. The significance $S/\sqrt{B_1}$ is for the luminosity of $10 fb^{-1}$ and $S/\sqrt{B_2}$ is for the luminosity of $30 fb^{-1}$. All the numbers shown here are after tagging efficiencies.

Results

	m_h = 100GeV	m_h = 115GeV	m_h = 130GeV
m_H = 260GeV	8.2(40,80)	8.3(10,60)	$--$
m_H = 310GeV	9.0(80,130)	9.6(60,110)	17.5(40,80)
m_H = 360GeV	5.5(100,150)	6.6(90,140)	11.6(80,120)

TABLE III: The integrated luminosity [in fb^{-1}], which is required to observe $H \to hh \to b\bar{b} + \not{P}_T$ with 5σ significance at the LHC, for several sets of m_H and m_h. The numbers in bracket are mass window of $\not{P}_T$. Note the Eq. 33 is not applied.

gg->H->hh>4b

- We also simulated the signals and backgrounds for H->hh->4b . This process suffer very large background from QCD multi-jet production .

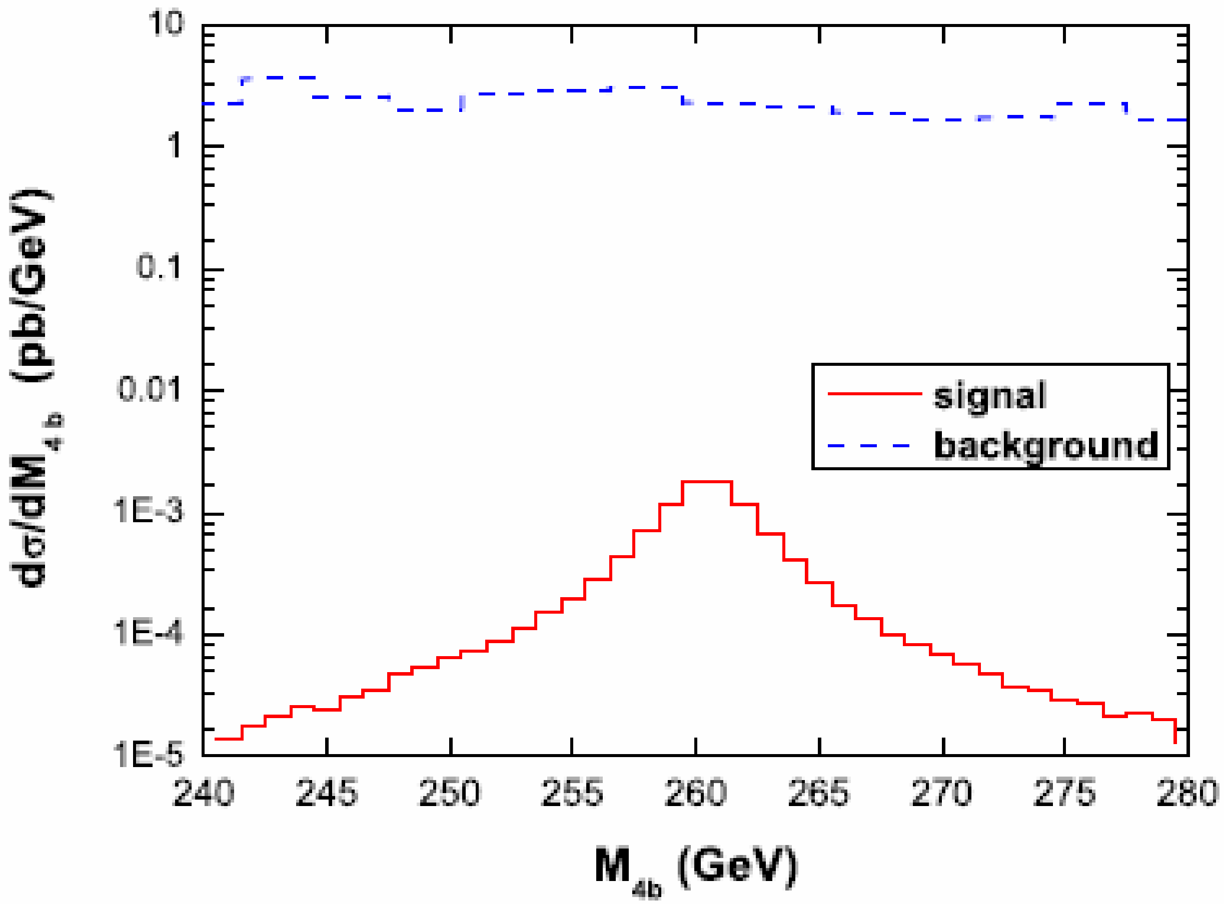

FIG. 7: The distribution of the signal and background for $b\bar{b}b\bar{b}$ as a function of invariant mass for $4b$ after applying cuts (see text) and tagging efficiencies.

- We use the same basic kinematical cuts and mass window of h as above work.

Summary

- Our work is based on special Mirror Model in which we can obtain parity restoration and symmetric vacuum after EWSB. We worked out Higgs spectrum and coupling . We showed constraints from EWPT and focused on the scenario that heavy Higgs decay into a pair of light Higgs.

- As the generic feature in this model, Higgs boson relate both usual world and mirror world. Then they can decay invisibly and we proposed to study this mechanic via pair production of light Higgs. Our simulations for this process showed that the observation of signal may be reach 5σ for $m_H = 260 GeV, m_h = 115 GeV$ with $10 fb^{-1}$ luminosity at the LHC.

- We also simulated the signals and backgrounds for H->hh->4b, the results showed it's difficult to isolate the signal from huge QCD background.

- We may need ILC to investigate the self couplings of Higgs.

THANK YOU