Role of $h \to \eta\eta$ in the search of intermediate-mass Higgs boson at the LHC

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Outline

- Motivations of the $h \to \eta\eta$ decay mode
- Possibility in the NMSSM (this talk)
- Possibility in the simplest little Higgs model (Song's talk)
- Detection at the LHC

SM Higgs boson searches

- For m_h upto about 130 GeV, $h \to b\bar{b}$ dominates. But due to QCD background only associated production $Wh, Zh, t\bar{t}h$ are considered.
- $h \to \gamma\gamma$ is one of the important channel for the discovery of intermediate Higgs boson.
- For $m_h \gtrsim 160$ GeV the mode $h \to WW^* \to (\ell\nu)(\ell\nu)$ becomes important.
- For even heavier Higgs $h \to ZZ \to (\ell\bar{\ell}\ell\bar{\ell})$ is the golden mode.

Current limits on Higgs boson mass

- Search at LEPI and II:

$$Z \to f\bar{f}h\,, \qquad e^+e^- \to Zh \to (\ell^+\ell^-,\, b\bar{b},\, \nu\bar{\nu},\, q\bar{q})\,(b\bar{b},\, \tau^+\tau^-)$$

Negative results put $m_h > 114.4$ GeV

- Search at the Tevatron:

$$p\bar{p} \to W^\pm h \to (\ell\nu,\, q\bar{q})\,(b\bar{b},\, \tau^+\tau^-)$$

Negative results

- One of the scientific programs for the LHC is search for the Higgs boson.

$$h \to \gamma\gamma, \qquad h \to ZZ \to \ell^+\ell^-\ell^+\ell^-$$

Little hierarchy problem in SUSY

Higgs boson mass $m_H > 115$ GeV. From the radiative corrections to m_H^2:

$$m_H^2 \leq m_Z^2 + \frac{3}{4\pi^2} y_t^2 m_t^2 \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

we require $m_{\tilde{t}} \gtrsim 1000\text{GeV}$.

RGE effect from $M_{\rm GUT}$ to $M_{\rm weak}$:

$$\Delta m_{H_u}^2 \approx -\frac{3}{4\pi^2} y_t^2 m_{\tilde{t}}^2 \ln\left(\frac{M_{\rm GUT}}{M_{\rm weak}}\right) \approx -m_{\tilde{t}}^2$$

We need to obtain

$$O(100^2\ \text{GeV}^2) = (1000\ \text{GeV})^2 - (990\ \text{GeV})^2$$

a fine tuning of $O(10^{-2})$.

Motivations for the $h \to \eta\eta$ decay mode

- Besides the little hierarchy problem, to some extent, the Higgs bound is contradictory to the EW precision data.
- To evade the LEP2 bound by reducing
  1. the $h \to b\bar{b}$ branching ratio, and/or
  2. the ZZh coupling.

  such that $e^+e^- \to Zh \to Z\,(b\bar{b})$ is reduced.
- Singlet extensions of the MSSM have additional pseudoscalar bosons that the Higgs can decay into. E.g. NMSSM.
- The simplest little Higgs model also has a pseudoscalar η that the Higgs can decay into, and g_{ZZh} is substantially reduced.
- MSSM with CP violation in the Higgs sector can allow a large BR for $h_2 \to h_1 h_1$.
- This unconventional Higgs decay mode

$$h \to \eta\eta \qquad (\eta = a_1, \eta, h_1)$$

  relieves the little Hierarchy problem.

Effects on the standard search modes

- The new mode $h \to \eta\eta$ for m_h around $100 - 140$ GeV affects significantly $h \to \gamma\gamma$ mode and $h \to b\bar{b}$ mode.
- So that

$$gg \to h \to \gamma\gamma$$

$$q\bar{q}' \to Wh/Zh \to (\ell\nu)/(\ell\ell) + b\bar{b}$$

are significantly worsen.

- However, new search modes are stimulated:

$$h \to \eta\eta \to (4b,\ 2b2\tau,\ 4\tau)$$

- We look at

$$pp \to Wh/Zh \to W/Z + \eta\eta \to (\ell\nu)/(\ell\ell) + 4b$$

Scenario in NMSSM

The NMSSM Superpotential

Superpotential:

$$W = \mathbf{h_u}\hat{Q}\,\hat{H}_u\,\hat{U}^c - \mathbf{h_d}\hat{Q}\,\hat{H}_d\,\hat{D}^c - \mathbf{h_e}\hat{L}\,\hat{H}_d\,\hat{E}^c + \lambda\hat{S}\,\hat{H}_u\,\hat{H}_d + \frac{1}{3}\kappa\,\hat{S}^3.$$

When the scalar field S develops a VEV $\langle S\rangle = v_s/\sqrt{2}$, the μ term is generated

$$\mu_{\rm eff} = \lambda\frac{v_s}{\sqrt{2}}$$

It was motivated by the μ problem.

Higgs Sector

Higgs fields:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad S \; .$$

Tree-level Higgs potential: $V = V_F + V_D + V_{\rm soft}$:

$$\begin{aligned} V_F &= |\lambda S|^2(|H_u|^2 + |H_d|^2) + |\lambda H_u H_d + \kappa S^2|^2 \\ V_D &= \frac{1}{8}(g^2 + g'^2)(|H_d|^2 - |H_u|^2)^2 + \frac{1}{2} g^2 |H_u^\dagger H_d|^2 \\ V_{\rm soft} &= m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + [\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + {\rm h.c.}] \end{aligned}$$

Minimization of the Higgs potential links $M_{H_u}^2$, $M_{H_d}^2$, M_S^2 with VEV's of H_u, H_d, S.

In the electroweak symmetry, the Higgs fields take on VEV:

$$\langle H_d \rangle = \frac{1}{\sqrt{2}} \binom{v_d}{0}, \qquad \langle H_u \rangle = \frac{1}{\sqrt{2}} \binom{0}{v_u}, \qquad \langle S \rangle = \frac{1}{\sqrt{2}} v_s$$

Then the mass terms for the Higgs fields are:

$$\begin{aligned} V &= \begin{pmatrix} H_d^+ & H_u^+ \end{pmatrix} \mathcal{M}^2_{\rm charged} \begin{pmatrix} H_d^- \\ H_u^- \end{pmatrix} \\ &+ \frac{1}{2} \begin{pmatrix} \Im m H_d^0 & \Im m H_u^0 & \Im m S \end{pmatrix} \mathcal{M}^2_{\rm pseudo} \begin{pmatrix} \Im m H_d^0 \\ \Im m H_u^0 \\ \Im m S \end{pmatrix} \\ &+ \frac{1}{2} \begin{pmatrix} \Re e H_d^0 & \Re e H_u^0 & \Re e S \end{pmatrix} \mathcal{M}^2_{\rm scalar} \begin{pmatrix} \Re e H_d^0 \\ \Re e H_u^0 \\ \Re e S \end{pmatrix} \end{aligned}$$

We rotate the charged fields and the scalar fields by the angle β to project out the Goldstone modes. We are left with

$$V_{\rm mass} = m^2_{H^\pm} H^+ H^- + \frac{1}{2}\,(P_1 \quad P_2)\mathcal{M}_P^2 \left(\begin{array}{c} P_1 \\ P_2 \end{array}\right) + \frac{1}{2}\,(S_1 \quad S_2 \quad S_3)\mathcal{M}_S^2 \left(\begin{array}{c} S_1 \\ S_2 \\ S_3 \end{array}\right)$$

where

$$\begin{aligned}
\mathcal{M}^2_{P\,11} &= M_A^2\;, \\
\mathcal{M}^2_{P\,12} &= \mathcal{M}^2_{P\,21} = \frac{1}{2}\cot\beta_s\,\left(M_A^2 \sin 2\beta - 3\lambda\kappa v_s^2\right)\;, \\
\mathcal{M}^2_{P\,22} &= \frac{1}{4}\sin 2\beta \cot^2\beta_s\,\left(M_A^2 \sin 2\beta + 3\lambda\kappa v_s^2\right) - \frac{3}{\sqrt{2}}\kappa A_\kappa v_s\;,
\end{aligned}$$

with

$$M_A^2 = \frac{\lambda v_s}{\sin 2\beta}\left(\sqrt{2}A_\lambda + \kappa v_s\right)$$

The charged Higgs mass:

$$M^2_{H^\pm} = M_A^2 + M_W^2 - \frac{1}{2}\lambda^2 v^2$$

Pseudoscalar Higgs bosons

The pseudoscalar fields, P_i $(i = 1,\, 2)$, is further rotated to mass basis A_1 and A_2, through a mixing angle:

$$\begin{pmatrix} A_2 \\ A_1 \end{pmatrix} = \begin{pmatrix} \cos\theta_A & \sin\theta_A \\ -\sin\theta_A & \cos\theta_A \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \end{pmatrix}$$

with

$$\tan\theta_A = \frac{\mathcal{M}^2_{P\,12}}{\mathcal{M}^2_{P\,11} - m^2_{A_1}} = \frac{1}{2}\cot\beta_s \, \frac{M_A^2 \sin 2\beta - 3\lambda\kappa v_s^2}{M_A^2 - m^2_{A_1}}$$

In large $\tan\beta$ and large M_A, the tree-level pseudoscalar masses become

$$\begin{aligned} m^2_{A_2} &\approx M_A^2 \, (1 + \frac{1}{4}\cot^2\beta_s \sin^2 2\beta), \\ m^2_{A_1} &\approx -\frac{3}{\sqrt{2}}\kappa v_s A_\kappa \end{aligned}$$

Small $2m_{A_1} < m_{h_1}$

A very light m_{A_1} is possible if

$$\kappa \to 0 \qquad \text{and/or} \qquad A_\kappa \to 0$$

while keeping v_s large enough. It is made possible by a PQ-type symmetry.

Parameters of NMSSM: NMHDECAY

Additional parameters other than the usual MSSM's

$$\lambda, \quad \kappa, \quad A_\lambda, \quad A_\kappa, \quad \mu_{\rm eff}$$

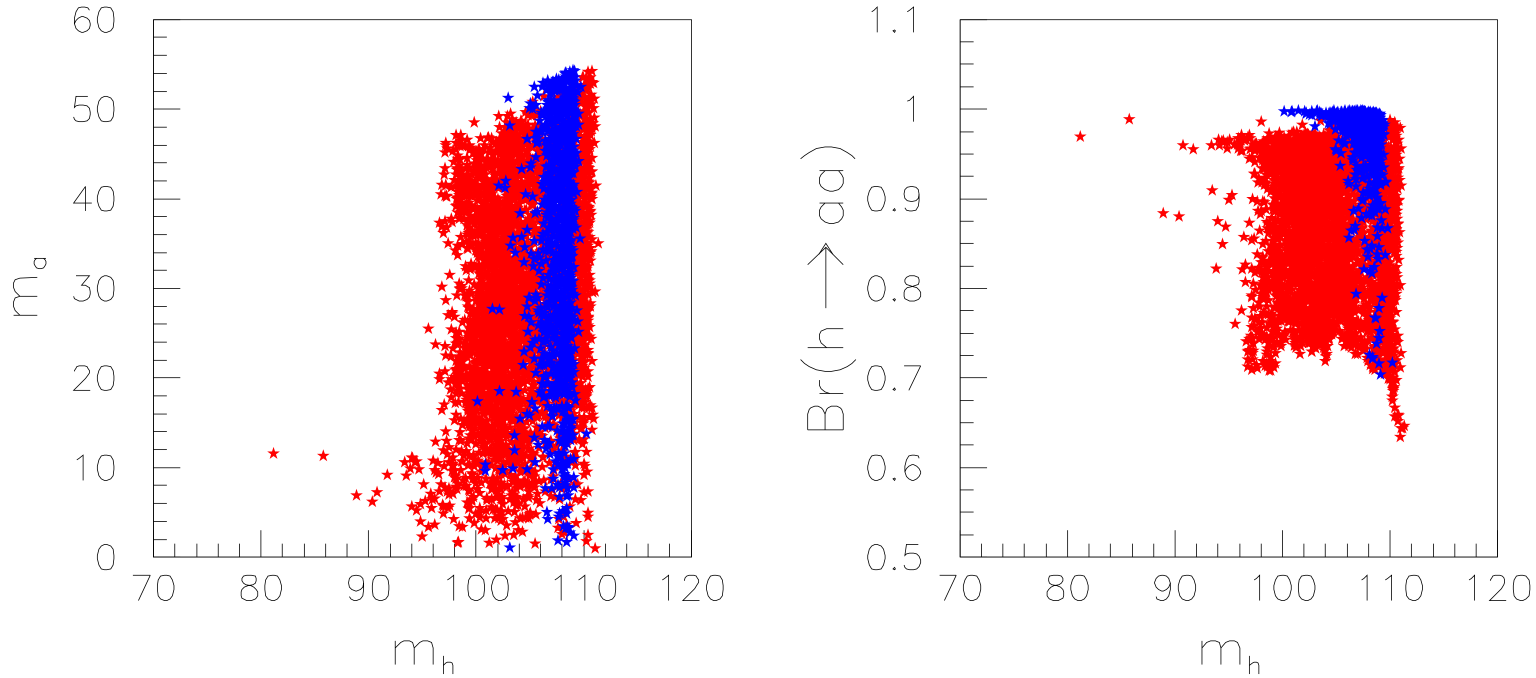
Constraints inside the NMHDECAY (Ellwanger, Gunion, Hugonie):

- One-loop radiative corrections to Higgs potential
- $b \to s\gamma$ constraint
- Dark matter relic density constraint: $[0.095, 0.112]$
- LEP2 bounds

Two bench-mark points in NMSSM

NMSSM (A)	NMSSM (B)
$\lambda = 0.18,\ \kappa = -0.43$	$\lambda = 0.26,\ \kappa = 0.51$
$\tan\beta = 29$	$\tan\beta = 23$
$A_\lambda = -437$ GeV	$A_\lambda = -222$ GeV
$A_\kappa = -4$ GeV	$A_\kappa = -13$ GeV
$\mu_{\rm eff} = -143$ GeV	$\mu_{\rm eff} = 144$ GeV
$m_{h_1} = 110$ GeV	$m_{h_1} = 109$ GeV
$m_{a_1} = 30$ GeV	$m_{a_1} = 39$ GeV
$B(h_1 \to a_1 a_1) = 0.92$	$B(h_1 \to a_1 a_1) = 0.99$
$B(a_1 \to b\bar{b}) = 0.93$	$B(a_1 \to b\bar{b}) = 0.92$
$g_{VVh_1}/g^{\rm SM}_{VVh} = 0.99$	$g_{VVh_1}/g^{\rm SM}_{VVh} = -0.99$
$g_{tth_1}/g^{\rm SM}_{tth} = 0.99$	$g_{tth_1}/g^{\rm SM}_{tth} = -0.99$
$g_{tta_1}/g^{\rm SM}_{tth} = -2.4 \times 10^{-3}$	$g_{tta_1}/g^{\rm SM}_{tth} = -1.2 \times 10^{-2}$
$C^2_{4b} = 0.80$	$C^2_{4b} = 0.83$

$$C^2_{4b} \equiv \left(\frac{g_{ZZh}}{g^{\rm SM}_{ZZh}} \right)^2 \times B(h \to a_1 a_1) \times B^2(a_1 \to b\bar{b})$$



$\star$: bench-mark point A-like

$\star$: bench-mark point B-like

All evade the Higgs mass bound

Further decay in $h \to a_1 a_1$

Further decay of a_1 includes

$$h \to a_1 a_1 \to (2\gamma,\ 2\tau,\ 2b,\ 2g)\ (2\gamma,\ 2\tau,\ 2b,\ 2g)$$

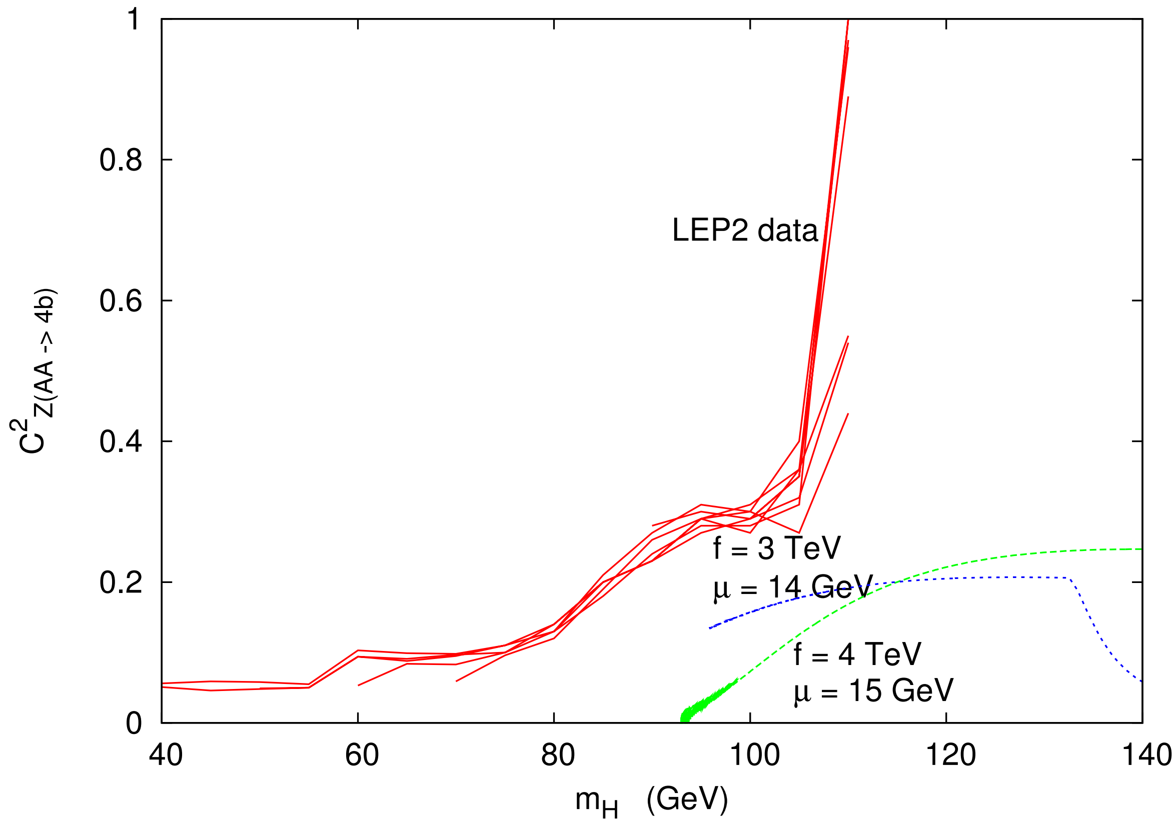
- If a_1 is very light and so energetic that the two photons are very collimated. It may be difficult to resolve them. Effectively, like $h \to \gamma\gamma$.
- If the mixing angle is larger than 10^{-3} and a_1 is heavier than a few GeV, it can decay into $\tau^+\tau^-$. Thus, 4τs in the final state (Graham, Pierce, Wacker 2006).
- If a_1 is heavier than $2m_b$, a_1 will dominately decay into $b\bar{b}$.
- The gluon mode suffers from QCD background.

Scenario in Little Higgs

(see Song's talk)

Two bench-mark points of the SLHμ model

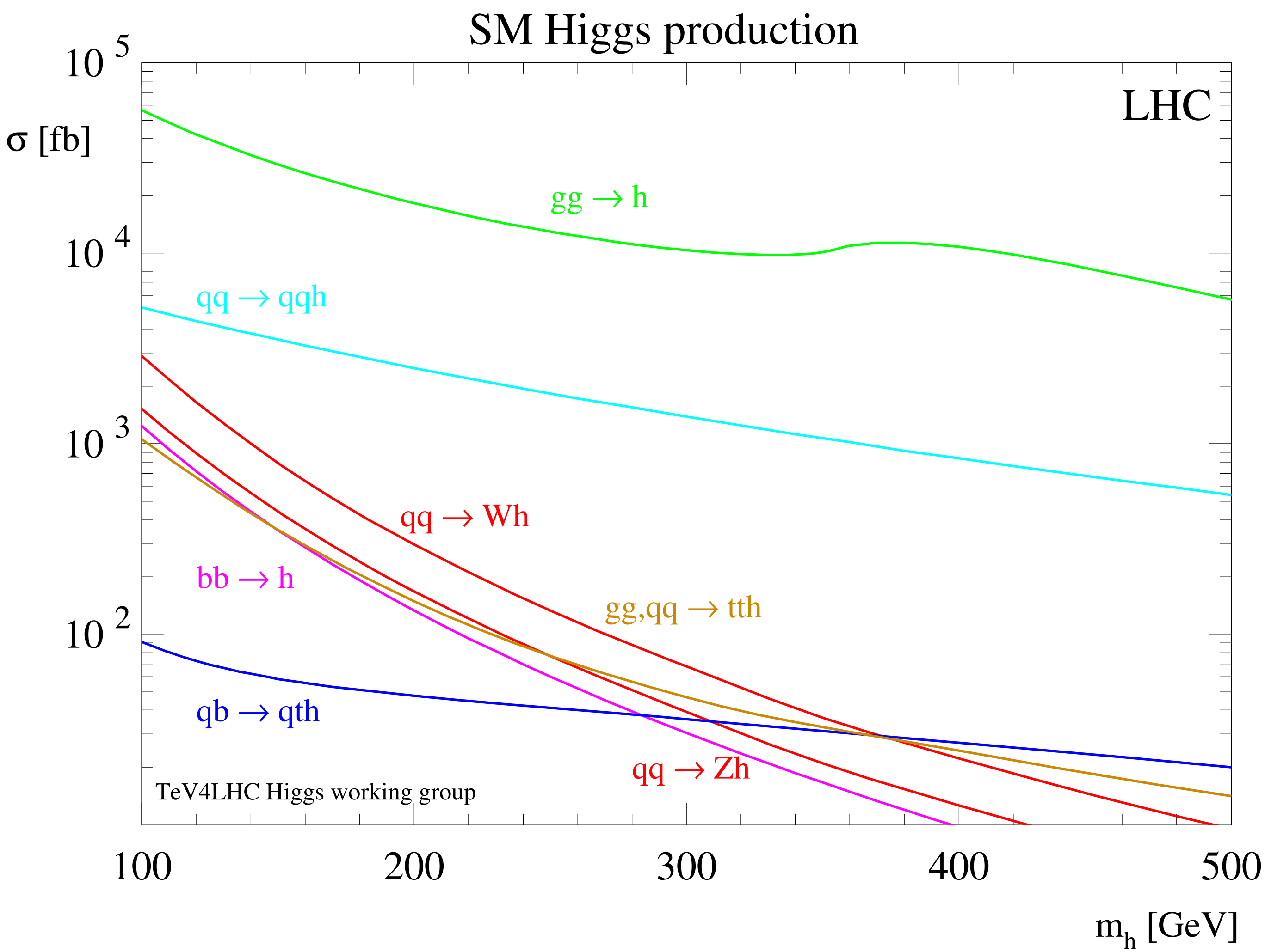
SLHμ (A)	SLHμ (B)
$f = 4$ TeV	$f = 2$ TeV
$\mu = 20$ GeV	$\mu = 20$ GeV
$x_\lambda = 5.86$	$x_\lambda = 10$
$\tan\beta = 17$	$\tan\beta = 9.47$
$m_h = 146.2$ GeV	$m_h = 135.2$ GeV
$m_\eta = 68.6$ GeV	$m_\eta = 47.9$ GeV
$B(h \to \eta\eta) = 0.65$	$B(h \to \eta\eta) = 0.75$
$B(\eta \to b\bar{b}) = 0.85$	$B(\eta \to b\bar{b}) = 0.86$
$g_{VVh}/g^{\rm SM}_{VVh} = 0.57$	$g_{VVh}/g^{\rm SM}_{VVh} = 0.44$
$g_{tth}/g^{\rm SM}_{tth} = 0.79$	$g_{tth}/g^{\rm SM}_{tth} = 0.93$
$g_{tt\eta}/g^{\rm SM}_{tth} = -0.89$	$g_{tt\eta}/g^{\rm SM}_{tth} = -1.38$
$C^2_{4b} = 0.16$	$C^2_{4b} = 0.11$



LEP data (2006) for $15\,\mathrm{GeV} < m_a < 55\,\mathrm{GeV}$

$$C^2_{Z(AA\to 4b)} = \left(\frac{g_{ZZH}}{g^{\rm SM}_{ZZH}}\right)^2 \times B(H \to AA) \times B(A \to b\bar{b})^2 .$$

Detection at the LHC



(hep-ph/0612172)

Higgs Production at the LHC

- Gluon fusion $gg \to h \to \eta\eta \to 4b$ suffers from huge QCD background.
- WW fusion $qq \to qqWW \to qqh \to qq(4b)$ also suffers from QCD background.
- Wh, Zh associated production:

$$Wh \to (\ell\nu) + (4b)\,, \quad Zh \to (\ell\ell) + (4b)$$

  The charged lepton removes most QCD background.

- $t\bar{t}h \to (bW)(bW) + (4b)$, combinatorial background.

Require at least one charged lepton and 4 b-tagged jets in the final state.

Production and decay

- We used MADGRAPH with the effective vertex g_{vvh} to calculate the signal cross sections. Decay of the W/Z and h:

$$p_T(\ell) > 15\,\text{GeV}, \qquad |\eta(\ell)| < 2.5\,,$$
$$p_T(b) > 15\,\text{GeV}, \qquad |\eta(b)| < 2.5\,, \quad \Delta R(bb, b\ell) > 0.4\,,$$

- We employ a B-tagging efficiency of 70% for each B tag, and a probability of 5% for a light-quark jet faking a B tag.

  The mis-tag probability for a u-jet is 1%, a charm-jet is $12-14\%$. Taking into account the fact that a jet coming from W decay is much less frequently a charm-jet, the average of 5% is reasonable.

Backgrounds

- It is possible for the photon in $\gamma + nj$ background to fake an electron in the EM calorimeter.
- The backgrounds from $W + nj$ and $Z + nj$ contribute at a very low level and are reducible as we require 4 b-tagged jets in the final state.
- The background from $WZ \to \ell\nu b\bar{b}$ is also reducible by the 4 b-tagging requirement.
- $t\bar{t}$ production with one of the top decay hadronically and the other semi-leptonically. The jet from the W may fake a b jet.
- $t\bar{t}b\bar{b}$ production, irreducible.
- $W/Z + 4b$ production, irreducible.

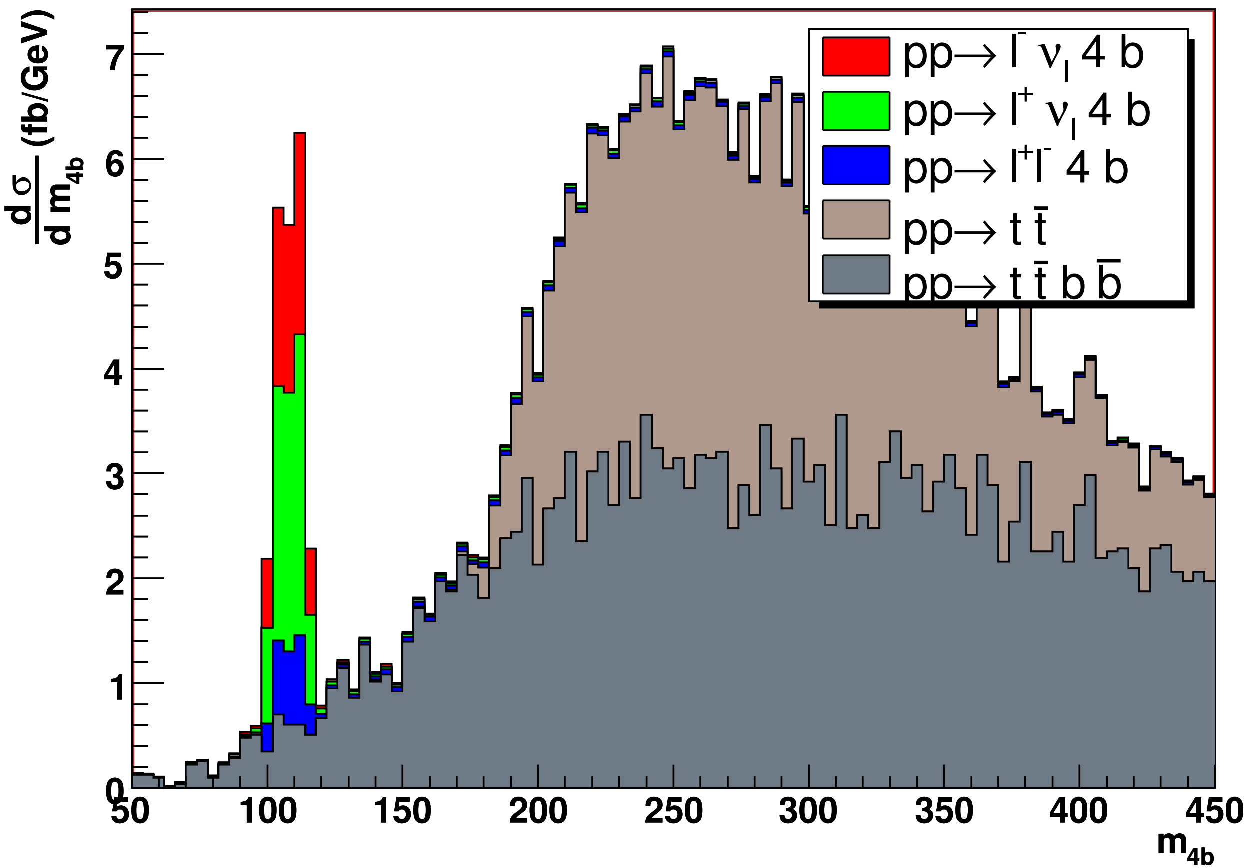
Event rates

Channels	NMSSM (A)	NMSSM (B)	SLHμ (A)	SLHμ (B)
W^+h signal	3.13 fb	9.54 fb	1.27 fb	0.63 fb
W^-h signal	2.35 fb	6.55 fb	0.87 fb	0.44 fb
Zh signal	1.05 fb	2.76 fb	0.36 fb	0.18 fb

Background

Channels	cross sections (fb)
$t\bar{t}$	172 (NMSSM & SLHμ)
$t\bar{t}b\bar{b}$	236 (NMSSM), 284 (SLHμ A), 429 (SLHμ B)
$W+4b$	3.80 (NMSSM), 4.16 (SLHμ A), 4.63 (SLHμ B)
$Z+4b$	3.85 (NMSSM & SLHμ)

$t\bar{t}b\bar{b}$ background is enhanced by $t\bar{t}\eta$ production in SLH model.



Apply the invariant mass cuts:

$$m_h - 15\ \mathrm{GeV} < M_{4b} < m_h + 15\ \mathrm{GeV}\ ,$$

Significance of the signal

Total signal and background cross sections under the signal peak:

	NMSSM (A)	NMSSM (B)	SLHμ (A)	SLHμ (B)
signal	6.53 fb	18.85 fb	2.50 fb	1.25 fb
bkgd	4.83 fb	4.77 fb	13.83 fb	22.45 fb
$S/\sqrt{B}$	29.7	86.3	6.7	2.6

$S/\sqrt{B}$ for $L = 100$ fb^{-1}

Conclusions

- In order to evade the Higgs mass bound, $B(h \to b\bar{b})$ is substantially reduced, which can be done by additional mode, $h \to \eta\eta$.
- $h \to \eta\eta$ stimulates other search modes for the Higgs boson.
- We showed that $Wh, Zh \to \ell + 4b$ is feasible at the LHC with $4b$-tagging.
- The $4b$ invariant mass spectrum distinguishes the signal from $t\bar{t}$, $t\bar{t}b\bar{b}$, $W/Z + 4b$ backgrounds.
- One can also reconstruct the mass bump of η's.