Extra Higgs bosons at the LHC and CLIC

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SM Higgs Boson

EWSB accomplished by a single Higgs boson.

$$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(h+v) + i\phi_1 \\ \phi_2 + i\phi_3 \end{pmatrix} \quad \text{where } v = 246\,\text{GeV}$$

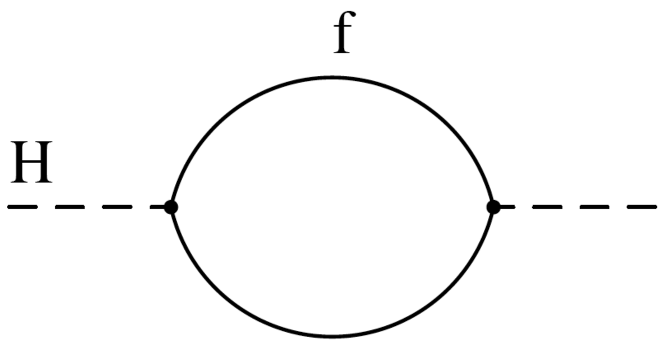
$$\{W_T^{\pm}, Z_T^0\} + \{\phi_1, \phi_2, \phi_3\} \Rightarrow \{W_T^{\pm}, W_L^{\pm}, Z_T^0, Z_L^0\}$$

$$L = \left[m_W^2 W^{+\mu} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu \right] \cdot \left(1 + \frac{h}{v}\right)^2 - m_f \bar{f}_L f_R \left(1 + \frac{h}{v}\right) + h.c.$$

Higgs mass is only free parameter.

Quadratic Sensitivity

A quantum loop is quadratically divergent. Higgs Mass, connected to Higgs vev, is unstable to the Highest mass scales in the theory.



$$m_H^2 \sim \frac{\alpha_f}{4\pi}\Lambda^2 \quad \Rightarrow \quad \Lambda^2 \sim M_{Pl}^2\ ?$$

Statics and Dynamics of Higgs Mass

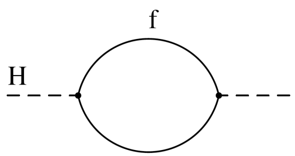
Principle: SUSY, Xdim,
Little Higgs, Compositeness, etc.

$$H^\dagger(m_{EW}^2 + \text{stabilizers} + \cdots)H + \Delta\mathcal{L}[\text{stabilizer dynamics}] + \cdots$$

Top squarks, radion,
T-odd top partners, etc.

Gluinos, KK Gravitons, etc.

SUSY:



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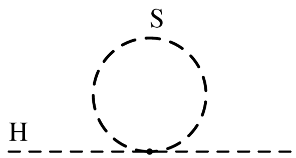


$$m_H^2 \sim \frac{\alpha_f}{4\pi}\Lambda^2 - \frac{\alpha_f}{4\pi}\Lambda^2 \sim 0 + \cdots$$

Minimal Supersymmetric Standard Model

Martin, hep-ph/9709356

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \;\; H_u^0)$	$(\widetilde{H}_u^+ \;\; \widetilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \;\; H_d^-)$	$(\widetilde{H}_d^0 \;\; \widetilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

If supersymmetry masses heavy (greater than all the SM masses), 4 Higgses $\{H^+,H^-,A,H\}$ form a heavy, decoupled doublet, and h remains a light field, which behaves just as the Standard Model Higgs boson.

Supersymmetry predicts mass of h field to be less than About 135 GeV. I.e., compatible with data.
Challenge: Superpartner masses accessible at LHC when m_H=126 GeV.

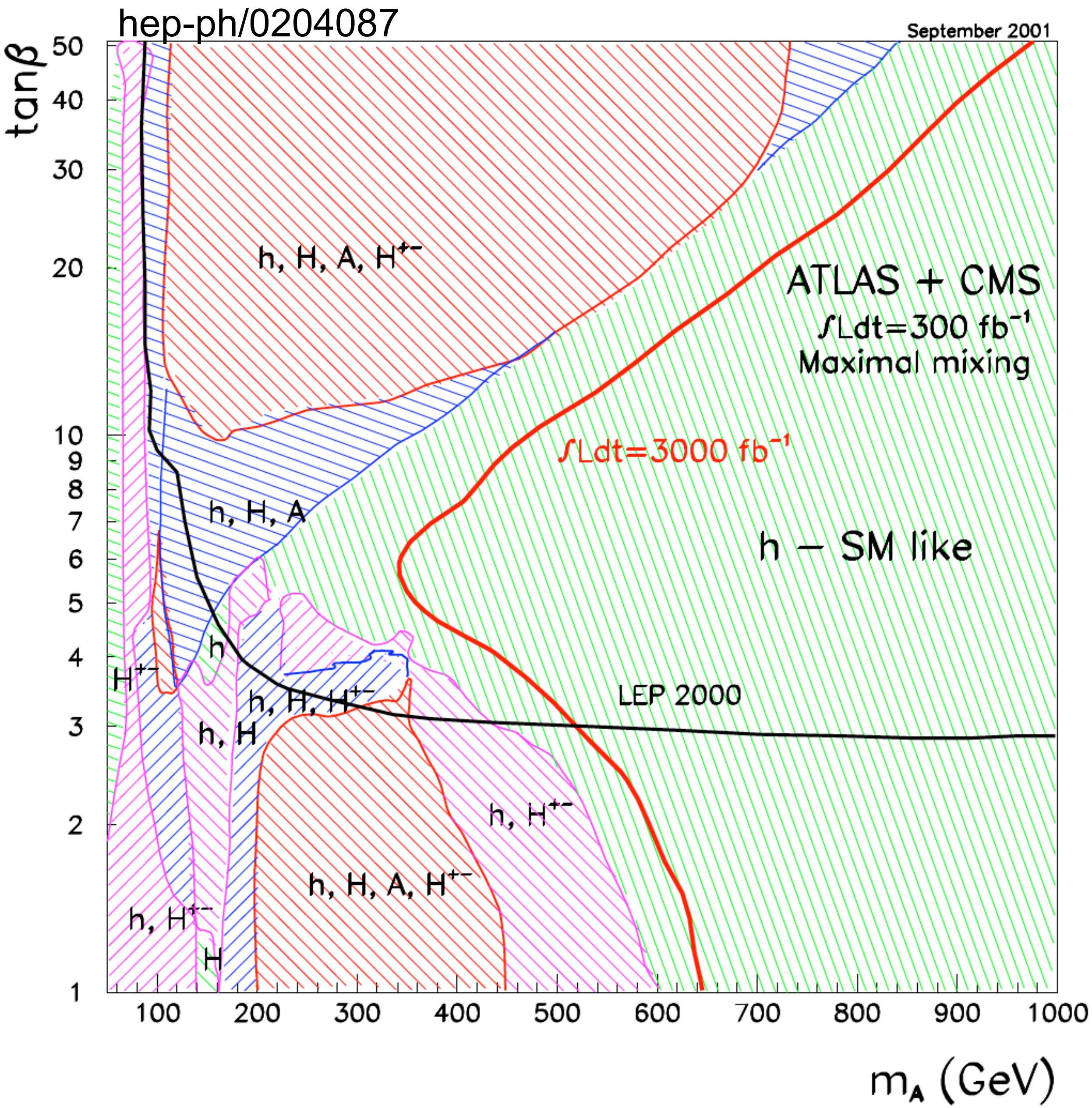
Two Higgs Doublets of Supersymmetry

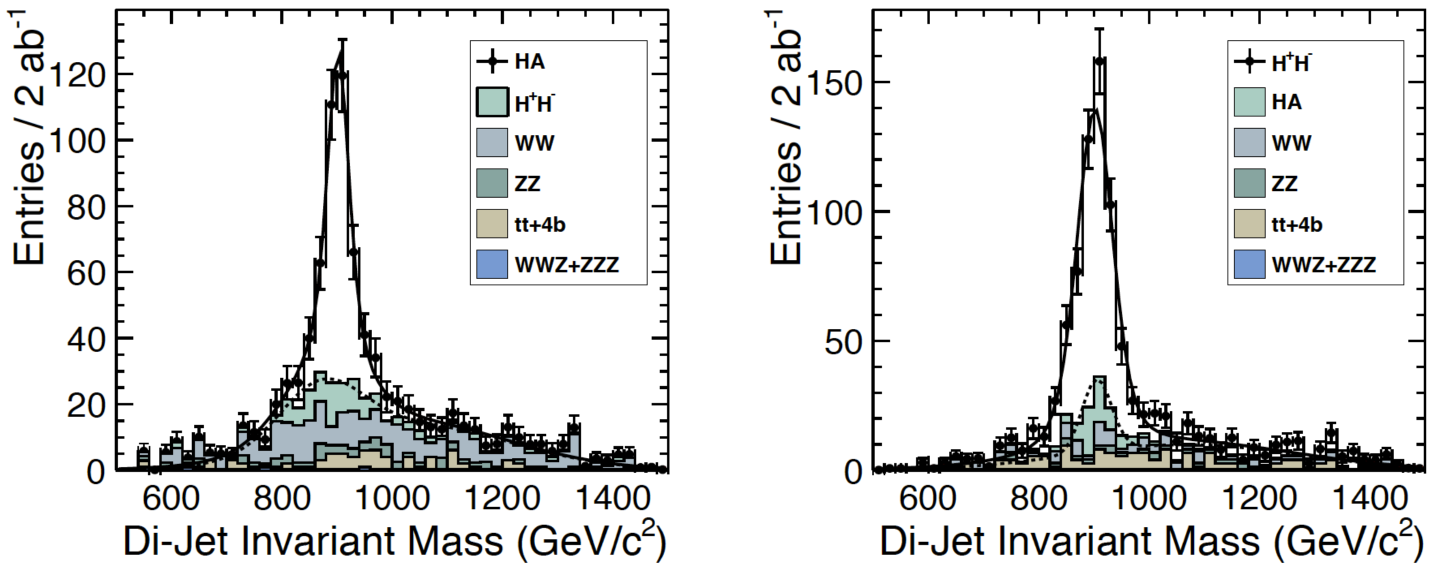
Supersymmetry requires two Higgs doublets. One to give mass to up-like quarks (H_u), and one to give mass to down quarks and leptons (H_d).

8 degrees of freedom. 3 are eaten by longitudinal components of the W and Z bosons, leaving 5 physical degrees of freedom: $H^{\pm}$, A, H, and h.

As supersymmetry gets heavier ($m_{3/2} >> M_Z$), a full doublet gets heavier together ($H^{\pm}$,A,H) while a solitary Higgs boson (h) stays light, and behaves just as the SM Higgs boson.

Heavy Higgs Prospects at the LHC





(a) $e^+e^- \to b\bar{b}b\bar{b}$ (b) $e^+e^- \to t\bar{b}b\bar{t}$

CLIC CDR 3 TeV, 2 ab^{-1} results

Precision measurements

Fig. 12.20: Di-jet invariant mass distributions for the $b\bar{b}b\bar{b}$ (left) and $t\bar{b}b\bar{t}$ (right) final states for model I. The distributions for the $e^+e^- \to$ HA and $e^+e^- \to H^+H^-$ processes and for the individual backgrounds are shown separately.

Table 12.7: Summary of the mass and width fit results for model I and II. The numbers extracted without and with background from $\gamma\gamma \to$ hadrons interactions are compared. All numbers are obtained assuming an integrated luminosity of 2 ab^{-1}. The given uncertainties are statistical only.

		SUSY model I		*SUSY model II*	
	State	Mass (GeV)	Width (GeV)	Mass (GeV)	Width GeV
Without $\gamma\gamma$	A/H	902.1 ± 1.9	21.4 ± 5.0	742.7 ± 1.4	21.7 ± 3.3
Without $\gamma\gamma$	$H^\pm$	901.4 ± 1.9	18.9 ± 4.4	744.3 ± 2.0	17.0 ± 4.7
With $\gamma\gamma$	A/H	904.5 ± 2.8	20.6 ± 6.3	743.7 ± 1.7	22.2 ± 3.8
With $\gamma\gamma$	$H^\pm$	902.6 ± 2.4	20.2 ± 5.4	746.9 ± 2.1	21.4 ± 4.9

Discovery of HA and H^+H^- nearly $E_{cm}/2$, and is nearly $\tan\beta$ independent.

Higgs boson is very special…

The $|H|^2$ operator is the only gauge-invariant, Lorentz invariant relevant operator in the Standard Model.

Other relevant operators include:

Neutrino physics.

$$B_{\mu\nu}, \qquad HL, \quad \nu_R^T i\sigma^2 \nu_R$$

Lorentz Tensor

Lorentz spinor

Lepton #
Not in SM.

New Opportunities with Higgs Relevant Operator

The $|H|^2$ operator gives us a chance to see states that we could never have otherwise seen before.

Generic couplings of Higgs to SM singlets, hidden sectors, etc

$|\Phi_{hid}|^2|H|^2$ (Generic coupling)

$X^{\mu\nu}B_{\mu\nu}$ (Possible coupling with extra $U(1)_{hid}$)

Simple, Non-Trivial Hidden World

Probably simplest theory is a Hidden-Sector Abelian Higgs Model.

A complex scalar charged under $U(1)_{X.}$ The particle spectrum is a physical Higgs boson and an X gauge field.

Lagrangian

Consider the SM lagrangian plus the following:

$$\mathcal{L}_X^{KE} = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\chi}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$$

$$\begin{aligned}\mathcal{L}_\Phi \; = \; & |D_\mu \Phi_{SM}|^2 + |D_\mu \Phi_H|^2 + m^2_{\Phi_H}|\Phi_H|^2 + m^2_{\Phi_{SM}}|\Phi_{SM}|^2 \\ & -\lambda|\Phi_{SM}|^4 - \rho|\Phi_H|^4 - \boxed{\kappa|\Phi_{SM}|^2|\Phi_H|^2}.\end{aligned}$$

Canonical Kinetic Terms

First, we make kinetic terms canonical by

$$\begin{pmatrix} X_\mu \\ Y_\mu \end{pmatrix} = \begin{pmatrix} \sqrt{1-\chi^2} & 0 \\ -\chi & 1 \end{pmatrix} \begin{pmatrix} \hat{X}_\mu \\ \hat{Y}_\mu \end{pmatrix}$$

The covariant derivative is shifted to

$$D_\mu = \partial_\mu + i(g_X Q_X + g' \eta Q_Y) X_\mu + i g' Q_Y B_\mu + i g T^3 W^3_\mu$$

$$\text{where } \eta \equiv \chi / \sqrt{1-\chi^2}$$

Higgs Masses and Mixings

$$\left(\begin{array}{c}\phi_{SM}\\ \phi_H\end{array}\right)=\left(\begin{array}{cc}c_h & s_h\\ -s_h & c_h\end{array}\right)\left(\begin{array}{c}h\\ H\end{array}\right)$$

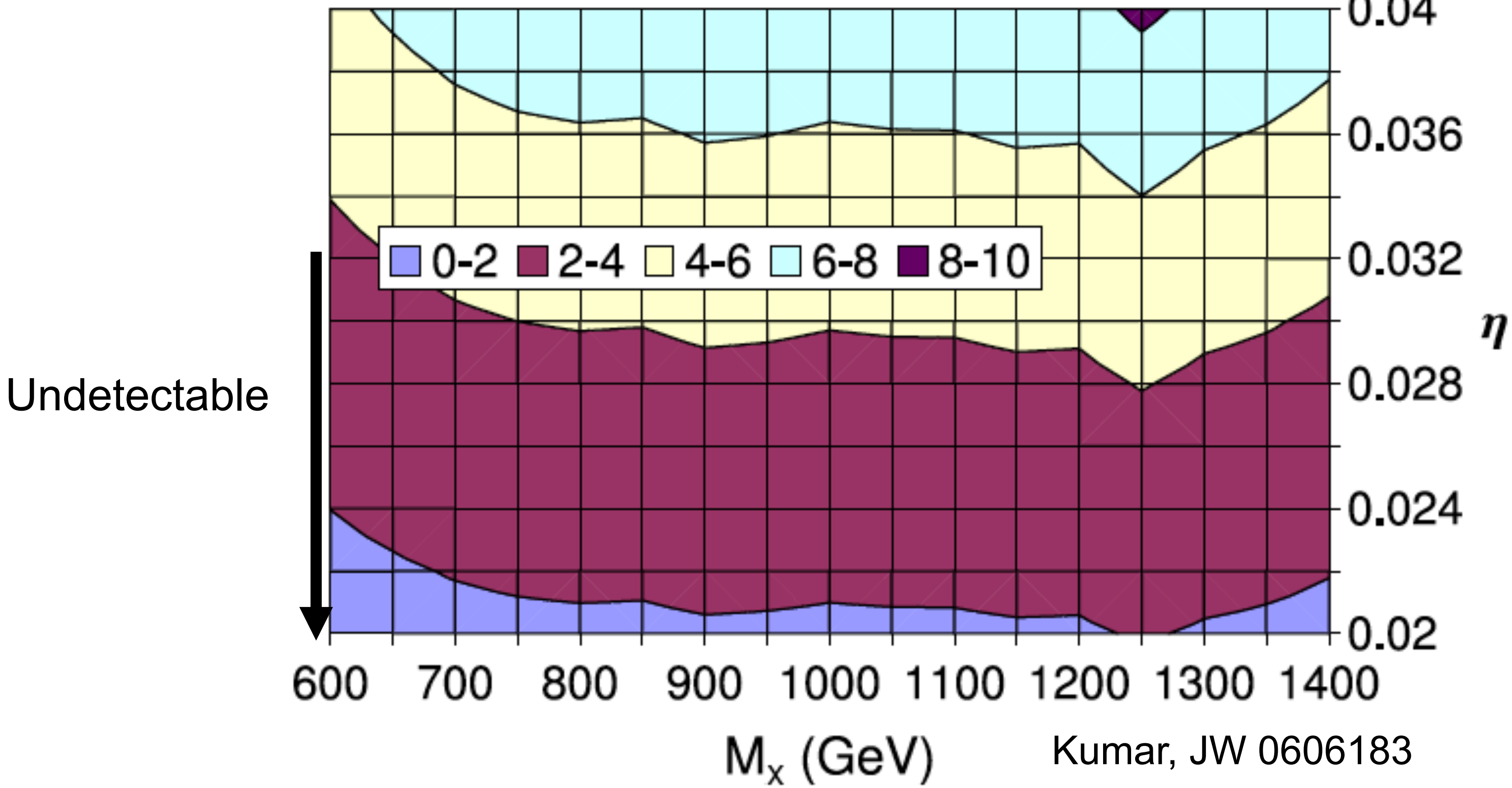
The mixing angle and mass eigenvalues are

$$\tan(2\theta_h) \;=\; \frac{\kappa v\xi}{\rho\xi^2-\lambda v^2}$$

$$M^2_{h,H}=\left(\lambda v^2+\rho\xi^2\right)\;\mp\;\sqrt{(\lambda v^2-\rho\xi^2)^2+\kappa^2v^2\xi^2}$$

Collider Searches for Z’

14 TeV LHC with 100 fb^{-1} of data



Kumar, JW 0606183

CLIC study should be done, especially for low $M_{Z'}$ and low η

As for the extra Heavy Higgs: Two Paths to LHC Discovery

Within this framework, we studied two ways to find Higgs boson at the LHC:

1) Narrow Trans-TeV Higgs boson signal

2) Heavy Higgs to light Higgs decays (ignore that here)

Bowen, Cui, JW, '07

Narrow Trans-TeV Higgs Boson

When the mixing is small, the heavy Higgs has smaller cross-section (bad), but more narrow (good).

	Point A	Point B	Point C
s_ω^2	0.40	0.31	0.1
m_h (GeV)	143	115	120
m_H (GeV)	1100	1140	1100
$\Gamma(H \to hh)$ (GeV)	14.6	4.9	10
$BR(H \to hh)$	0.036	0.015	0.095

Investigate Point C example

Signal

$$H \to WW \to l\nu jj$$

$$p_T(e,\mu) > 100\,\mathrm{GeV} \quad \text{and} \quad |\eta(e,\mu)| < 2.0$$

$$\text{Missing } E_T > 100\,\mathrm{GeV}$$

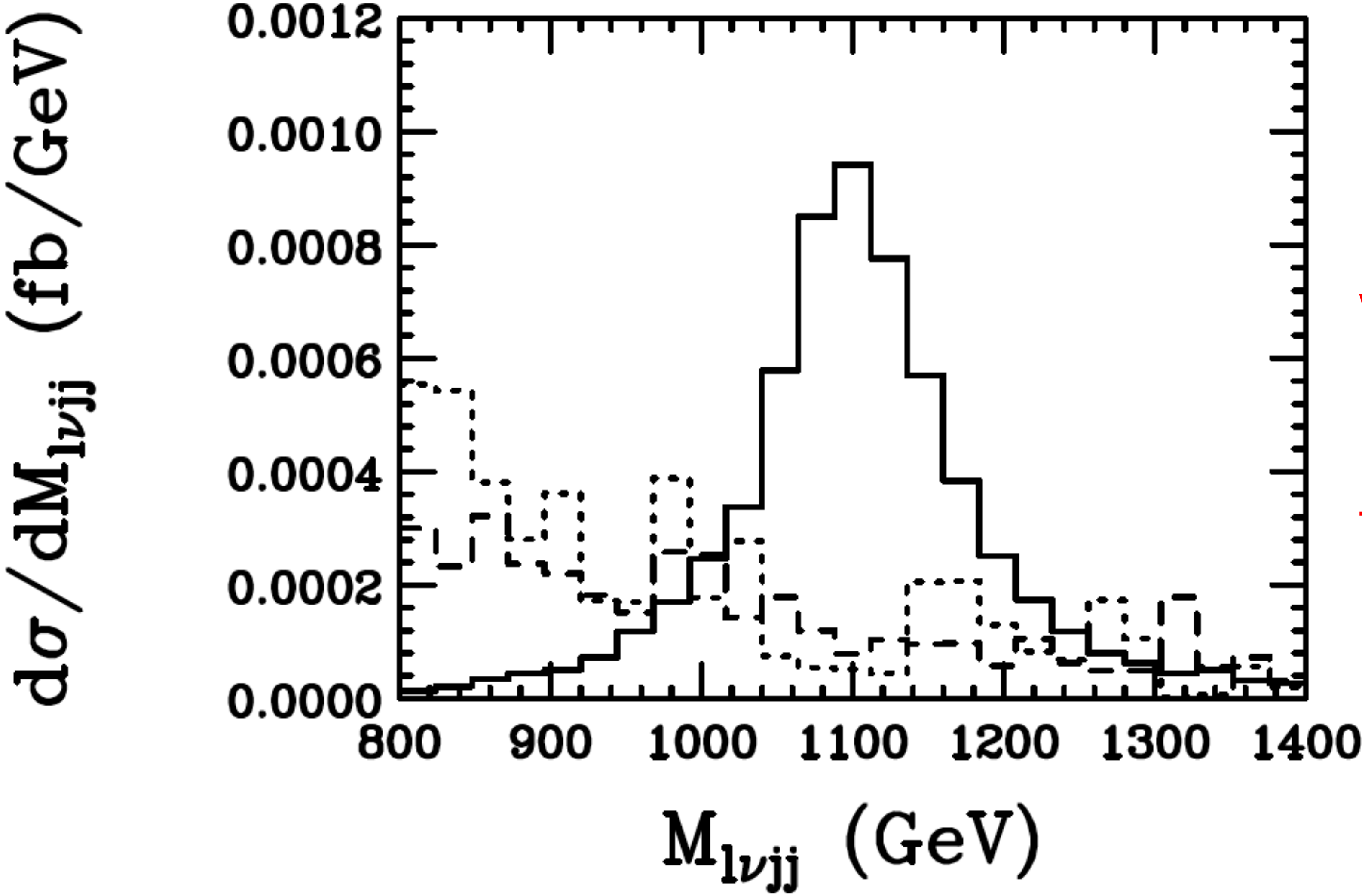
$$p_T(j,j) > 100\,\mathrm{GeV} \quad \text{and} \quad m_{jj} = m_W \pm 20\,\mathrm{GeV}$$

$$\text{“Tagging jets” with } |\eta| > 2.0$$

H->WW->jjlν

Techniques: Atlas & CMS TDRs and Iordanidis, Zeppenfeld, '97

Between 1.0 & 1.3 TeV 13 signal events in 100 fb^{-1} vs. 7.7 bkgd



H->WW (solid)

WWjj (dashed)

ttjj (dotted)

Difference from SUSY heavy Higgs boson

SUSY heavy Higgs has qualitatively different behavior:

ϕ		$g_{\phi\bar{t}t}$	$g_{\phi\bar{b}b}$	$g_{\phi VV}$
SM	H	1	1	1
MSSM	h^o	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
	H^o	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
	A^o	$1/\tan\beta$	$\tan\beta$	0

Haber et al. '01

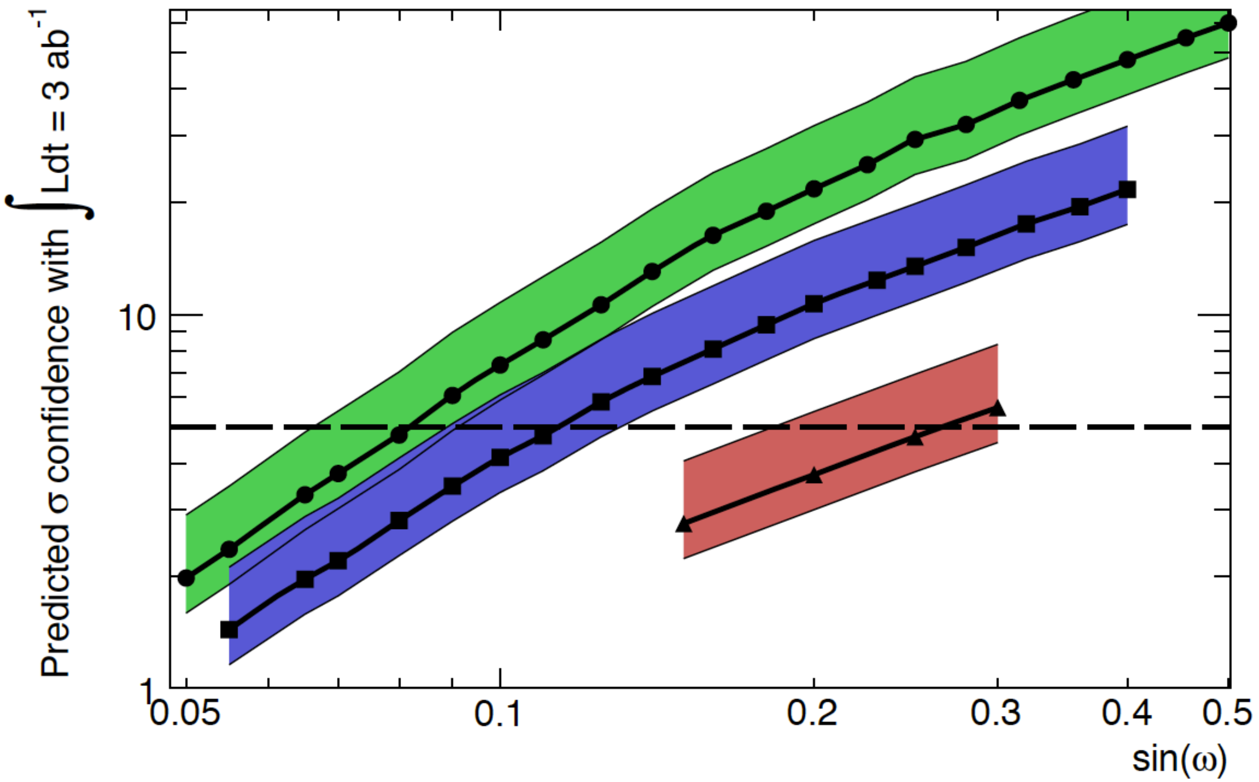
$$HVV: \quad \cos(\beta-\alpha) \rightarrow \boxed{0} + \mathcal{O}(m_Z^4/m_A^4)$$

$$H\bar{t}t: \quad \frac{\sin\alpha}{\sin\beta} \rightarrow \boxed{\frac{1}{\tan\beta}} + \mathcal{O}(m_Z^2/m_A^2)$$

$$H\bar{b}b: \quad \frac{\cos\alpha}{\cos\beta} \rightarrow \boxed{\tan\beta} + \mathcal{O}(m_Z^2/m_A^2)$$

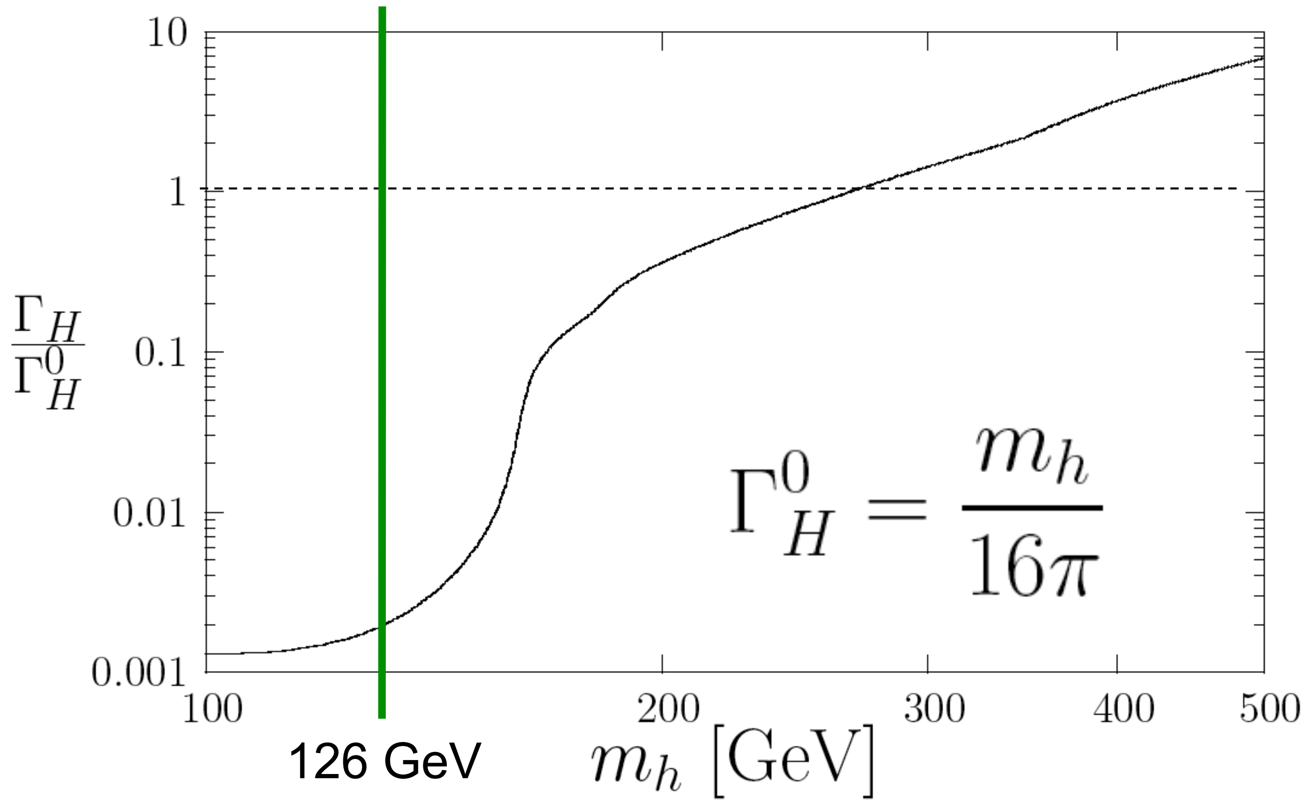
Heavy Higgs decays mostly into tops or bottoms (or susy partners) depending on tanβ.

Results at CLIC 3 TeV



Expected confidence level of discovery $\sigma_{\rm conf}$ with $\int Ldt = 3$ ab^{-1} from the signal $\bar{\nu}\nu H \to \bar{\nu}\nu ZZ \to l^+l^- jj + MET$. The markers represent the data points. From top to bottom, the curves correspond to $M_H = 1.0$, 1.5, 2.0 TeV. The filled regions represent the systematic error due to the unknown suppression of the background from the beamstrahlung luminosity spread, and are absolute bounds. The upper and lower limits represent beamstrahlung background suppression factors (see text) of 0.3 and 1.0 respectively, and the central line 0.65. Statistical errors are $\simeq 3\%$.

Light Higgs accidentally narrow



Light Higgs boson especially susceptible to new decay modes.

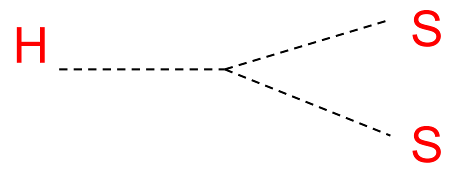
Sources of Invisible Decay Contributions

Many ideas lead to invisible Higgs decays -- possible connections to dark matter.

Joshipura et al. '93 ;
Binoth, van der Bij, '97, many others

Simplest of all is the addition of a real scalar field with Z_2.

$$\mathcal{L} = \frac{M_S^2}{2} S^2 + \lambda S^2 |\Phi_{SM}|^2 + \cdots$$



Example from Abelian Higgs Model with fermions:

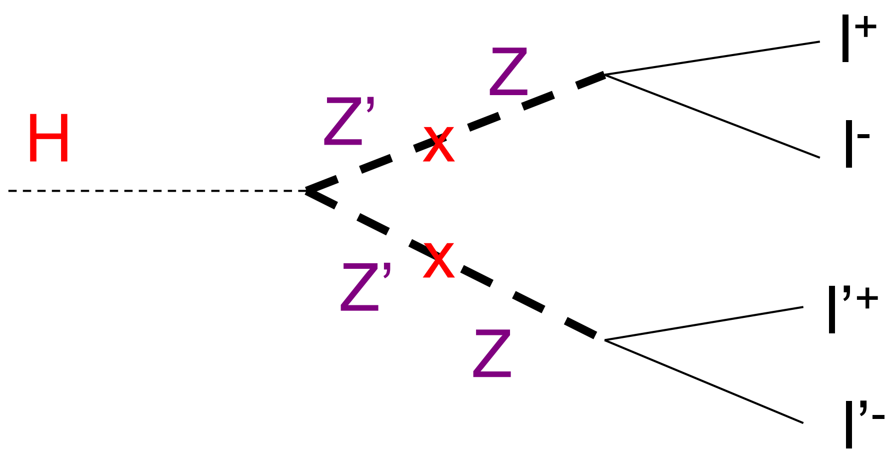
$U(1)_X$: $\{\Phi_H, \psi, \bar{\psi}, \chi, \bar{\chi}\} = \{3, -1, 1, -2, 2\}$ leads to

$$\mathcal{L} = y\Phi_H \psi\chi + y' \Phi_H^* \bar{\psi}\bar{\chi} + M_\psi \bar{\psi}\psi + M_\chi \bar{\chi}\chi \cdots$$

Light Z' and Higgs Decays

With tiny kinetic mixing, a very low Z' mass is possible in this framework. The light Higgs, however, could couple to it well with impunity. This leads to

H->Z'Z' -> 4 leptons signature



Gopalakrishna, Jung, JW, '08

Conclusions

CLIC enables discovery reach and precision measurements of supersymmetry's heavy Higgs bosons up to nearly $E_{cm}/2$, which can be much higher than LHC for $E_{cm} > 1$ TeV.

CLIC enables discovery of mixed-in heavy singlet Higgs bosons well beyond the LHC reach in both high mass and low mixing angle parameter space.