The Abdus Salam International Centre for Theoretical Physics

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IAEA International Atomic Energy Agency

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Signaling the Arrival of the LHC Era

8 - 13 December 2008

Higgs Theory at the LHC
III

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Hidden Sectors and the LHC:
Fragility of Higgs boson Predictions

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Trieste Lecture 3
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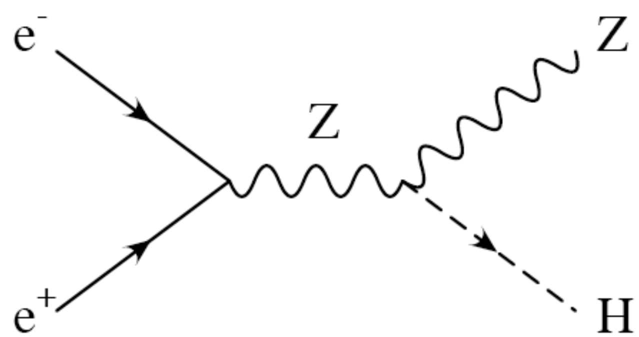
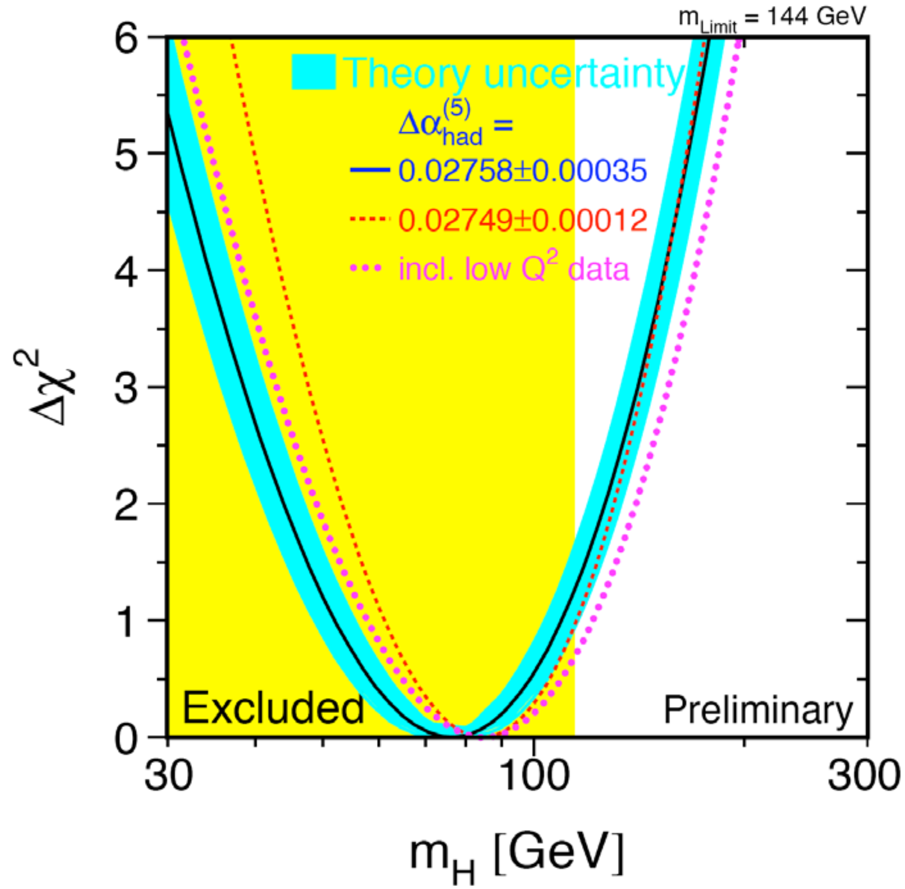
Higgs mass limits

Higgs boson mass upper limit (95% CL) from precision Electroweak is less than 182 GeV.

Lower limit from lack of direct signal at LEP 2 is about 115 GeV.





LEPEWWG, 0712.0929

Experiment: 115 GeV < m_h < 182 GeV

Higgs boson & New Physics

The mechanism of EWSB is still unknown.

Standard view: Naturalness/finetuning/hierarchy solutions require rich collection of beyond the SM physics to stabilize the weak scale.

Obviously, this can affect Higgs boson predictions at the LHC. (Loops of superpartners, multi-doublets, radion-Higgs mixing, etc.)

Standard new physics origins are not what I will discuss, although they do contribute to the fragility thesis.

Reduced philosophy viewpoint…

- Standard Model with single Higgs boson is the full explanation for EWSB and SM particle masses.

- Any extra states or interactions that exist at low scales are not there to solve our perceived philosophical problems (naturalness, finetuning, etc.).

Let us stipulate this viewpoint for the rest of the talk!

Finetuning: Coin drop from 1 meter

Why then more stuff?

Copernicus (NASA photo)

Copernicus Monument in Toruń
by Christian Friedrich Tieck (1853)

"There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy." -Hamlet

The SM is merely a description of the particles that make up our bodies, and copies of those particles, and the forces between those particles.

Why at our scale?

There is a definite scale in nature whose origin we do not understand: M_Z.

No strong reason to believe that SM is alone at that mass scale.

Hidden Worlds/Sectors

Definition: Hidden Sector or Hidden World is a collection of non-SM states that have no charge under any SM gauge group.

Related message & pheno in subsequent work:
Strassler, Zurek, ‘06 -- “Hidden Valleys”;
Patt, Wilczek, ‘06 -- “Higgs Portal”
Georgi, ‘07 -- “Unparticles”
Etc.

Challenges finding New Worlds

The Standard Model matter and gauge states saturate dimensionality of the lagrangian.

$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu \psi + \frac{1}{4} W^{a,\mu\nu} W^a_{\mu\nu} + \cdots$$

Any new states coupled in may come with a large suppression scale:

$$\mathcal{L} = \frac{1}{\Lambda^{\#}} \mathcal{O}_{SM} \mathcal{O}_{hid}$$

Relevant Operators

New physics connected to SM in relevant and marginal operators can be more powerful probes.

Build these interactions via relevant SM operators:

$$B_{\mu\nu} \quad \text{and} \quad |\Phi_{SM}|^2$$

Simple, Non-Trivial Hidden World

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

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

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

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

Gauge Boson Eigenstates

Diagonalize to mass eigenstates A, Z, and Z' by

$$\begin{pmatrix} B \\ W^3 \\ X \end{pmatrix} = \begin{pmatrix} c_W & -s_W c_\alpha & s_W s_\alpha \\ s_W & c_W c_\alpha & -c_W s_\alpha \\ 0 & s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} A \\ Z \\ Z' \end{pmatrix}$$

Where,

$$\tan(2\theta_\alpha) = \frac{-2 s_W \eta}{1 - s_W^2 \eta^2 - \Delta_Z}$$

$$\Delta_Z = M_X^2 / M_{Z_0}^2, \; M_X^2 = \xi^2 g_X^2 q_X^2$$

Higgs Masses and Mixings

$$\begin{pmatrix} \phi_{SM} \\ \phi_H \end{pmatrix} = \begin{pmatrix} c_h & s_h \\ -s_h & c_h \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

The mixing angle and mass eigenvalues are

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

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

Feynman Rules

$$\bar{\psi}\psi Z \ : \ \frac{ig}{c_W}\left[c_\alpha(1 - s_W t_\alpha \eta)\right]\left[T_L^3 - \frac{(1 - t_\alpha \eta / s_W)}{(1 - s_W t_\alpha \eta)} s_W^2 Q\right]$$

$$\bar{\psi}\psi Z' \ : \ \frac{-ig}{c_W}\left[c_\alpha(t_\alpha + \eta s_W)\right]\left[T_L^3 - \frac{(t_\alpha + \eta / s_W)}{(t_\alpha + \eta s_W)} s_W^2 Q\right]$$

$\mathcal{R}_{AW^+W^-} = 1$, $\mathcal{R}_{ZW^+W^-} = c_\alpha$ and $\mathcal{R}_{Z'W^+W^-} = -s_\alpha$

$$hff : -ic_h \frac{m_f}{v} \ , \qquad hWW : 2ic_h \frac{M_W^2}{v}$$

$$hZZ : 2ic_h \frac{M_{Z_0}^2}{v}(-c_\alpha + \eta s_W s_\alpha)^2 - 2is_h \frac{M_X^2}{\xi} s_\alpha^2 \ ,$$

$$hZ'Z' : 2ic_h \frac{M_{Z_0}^2}{v}(s_\alpha + \eta s_W c_\alpha)^2 - 2is_h \frac{M_X^2}{\xi} c_\alpha^2 \ ,$$

$$hZ'Z : 2ic_h \frac{M_{Z_0}^2}{v}(-c_\alpha + \eta s_W s_\alpha)(s_\alpha + \eta s_w c_\alpha) - 2is_h \frac{M_X^2}{\xi} s_\alpha c_\alpha \ .$$

Kinetic Mixing Origin

No position on how kinetic mixing occurs. Often,

$$\chi = \frac{\hat{g}_Y \hat{g}_X}{16\pi^2} \sum_i Q_X^i Q_Y^i \log\left(\frac{m_i^2}{\mu^2}\right)$$

“Kinetic messengers” can induce it if not there at the start.

Precision EW Effects of Kinetic Mixing

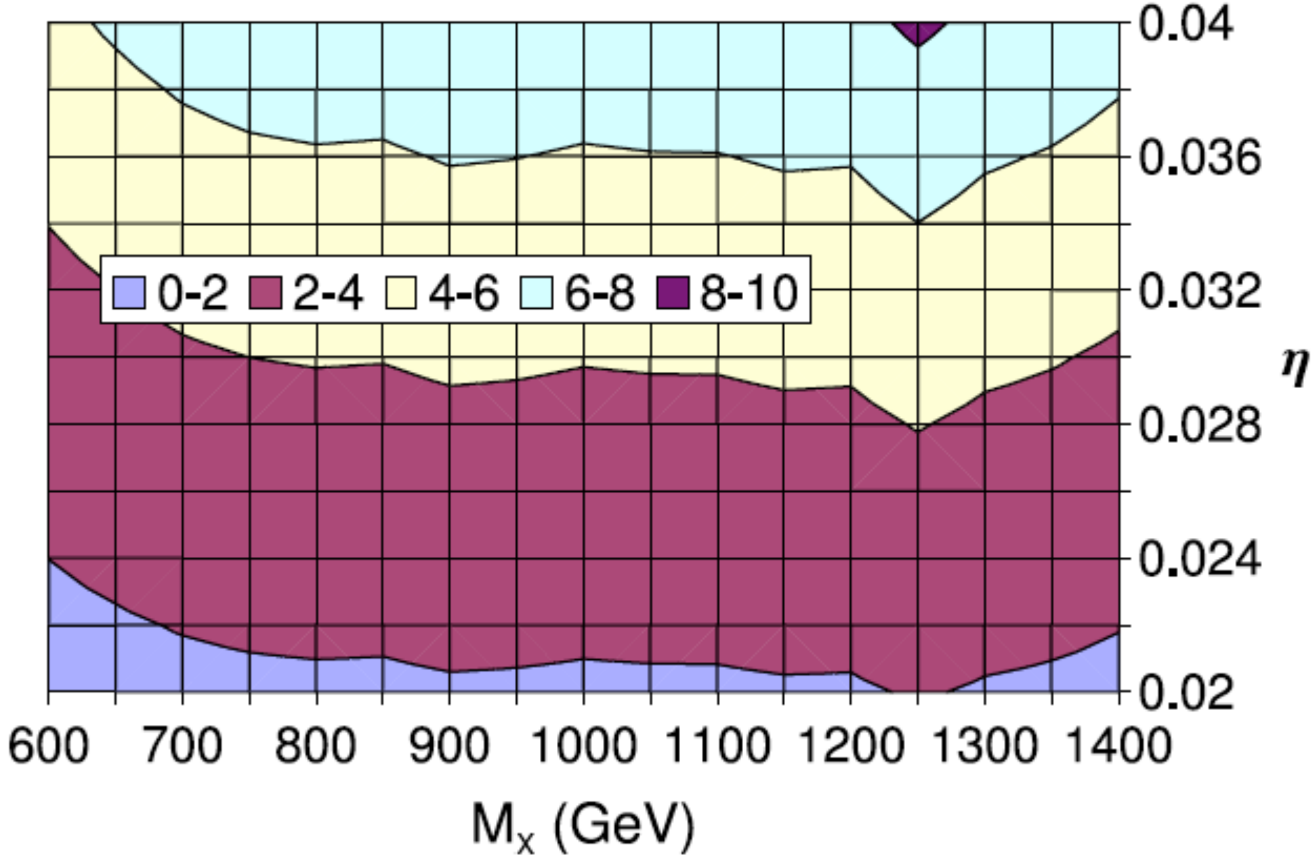
$$\Delta m_W = (17\,\mathrm{MeV})\,\Upsilon$$
$$\Delta \Gamma_{l^+l^-} = -(8\,\mathrm{keV})\,\Upsilon$$
$$\Delta \sin^2\theta_W^{eff} = -(0.00033)\,\Upsilon$$

$$\Upsilon \equiv \left(\frac{\eta}{0.1}\right)^2 \left(\frac{250\,\mathrm{GeV}}{m_X}\right)^2$$

Data limits suggest that $\Upsilon < 1$.

Kumar, JW, 0606183

Collider Searches for Z'



Kumar, JW 0606183

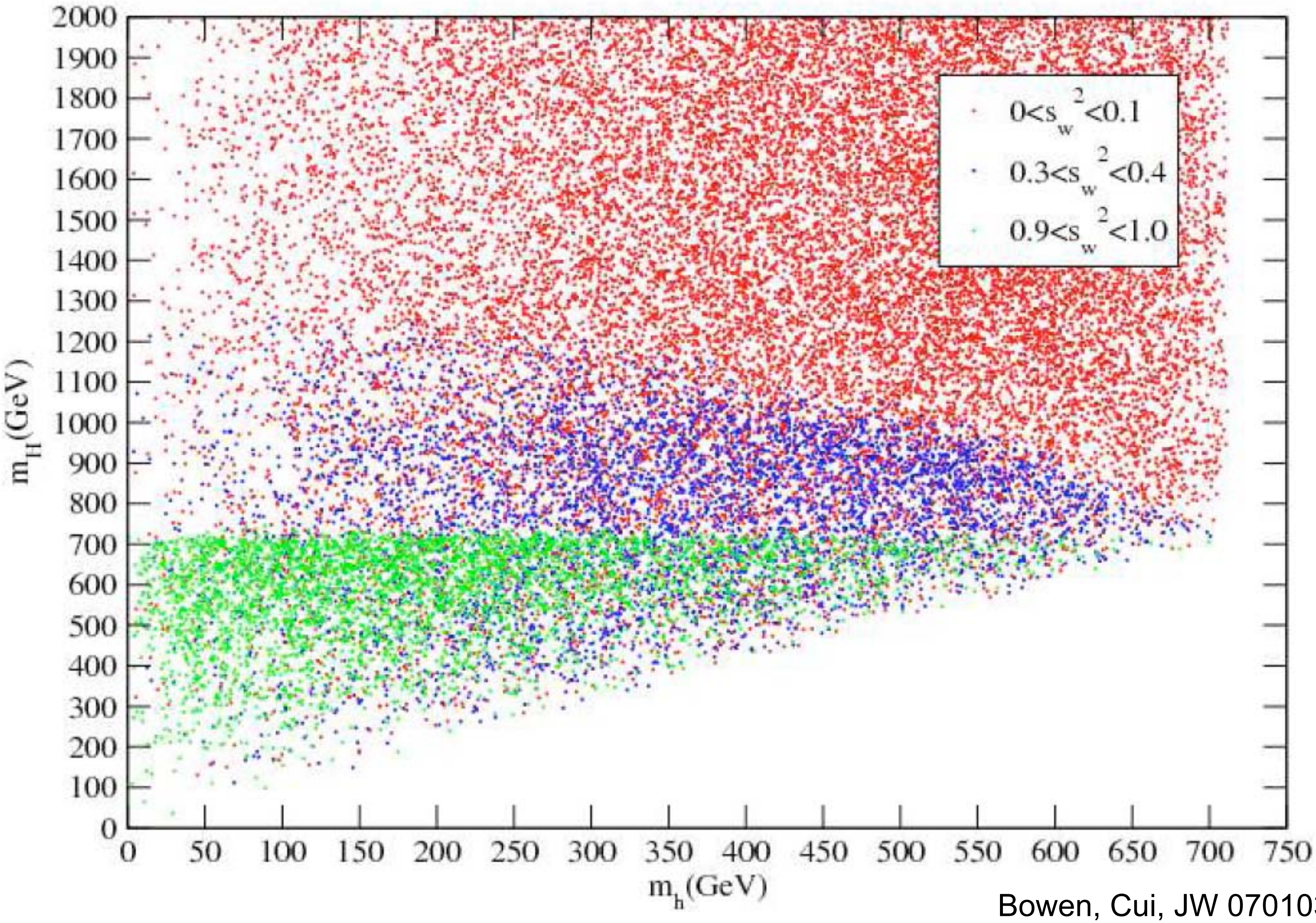
Higgs and Precision EW

When the Higgs bosons mix, neither state couples with full SM strength. The precision EW bound on the log is shared:

$$c_h^2 \log\left(\frac{M_h}{1\ \mathrm{GeV}}\right) + s_h^2 \log\left(\frac{M_H}{1\ \mathrm{GeV}}\right) \simeq 1.93^{+0.16}_{-0.17}$$

It is relatively easy to get high-mass Higgs when mixing angle is rather small. Precision EW can always be accommodated by adding new stuff.

Perturbative Unitarity of VV Scattering



Bowen, Cui, JW 0701035

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

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

Two Signals

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

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

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

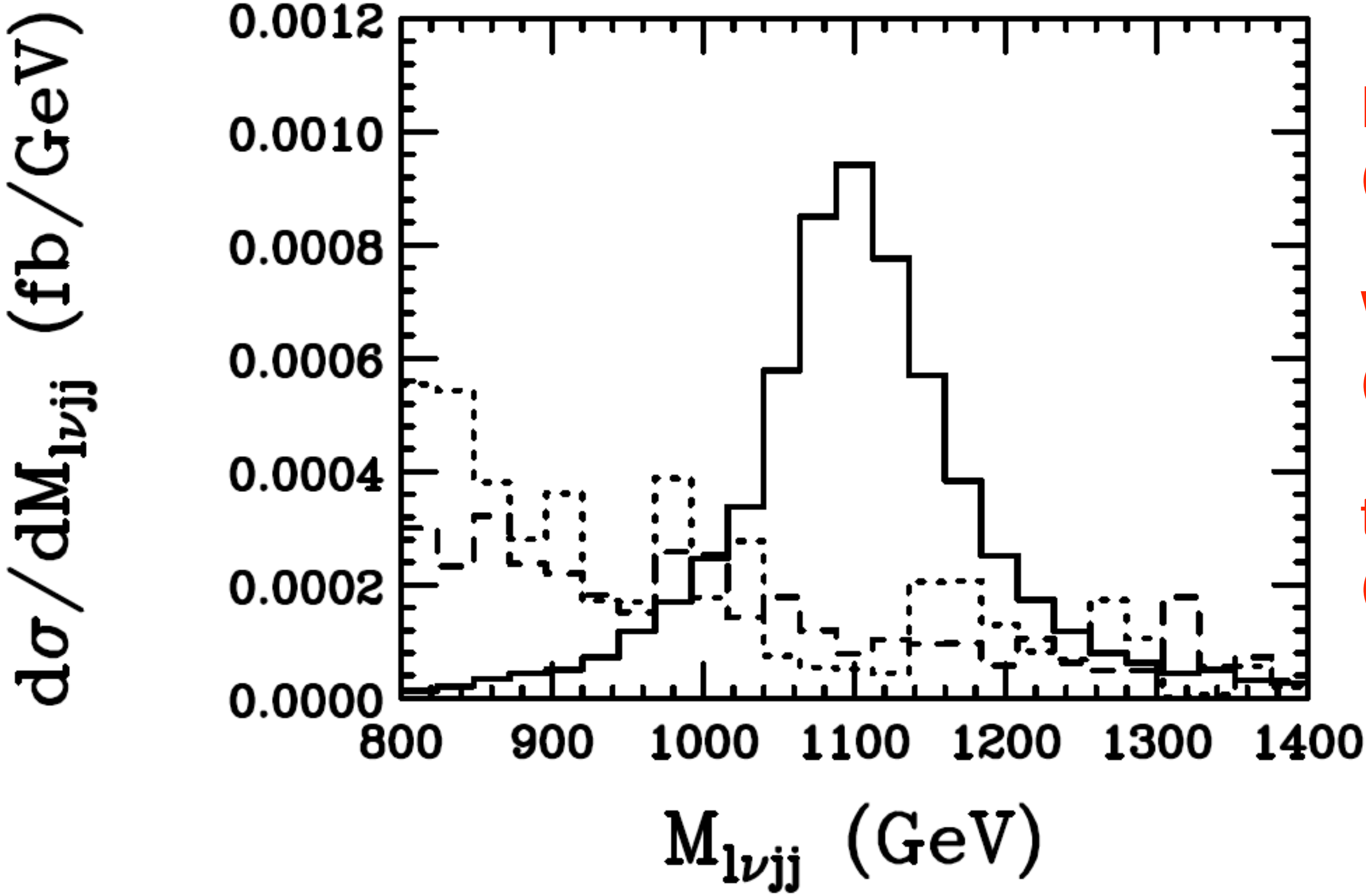
$$p_T(j,j) > 100\,\mathrm{GeV} \quad \text{and} \quad m_{jj} = m_W \pm 20\,\mathrm{GeV}$$

$$\text{``Tagging jets'' with } |\eta| > 2.0$$

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

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

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

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

Heavy Higgs decays mostly into tops or bottoms (or susy partners) depending on $\tan\beta$.

H decays to lighter Higgses

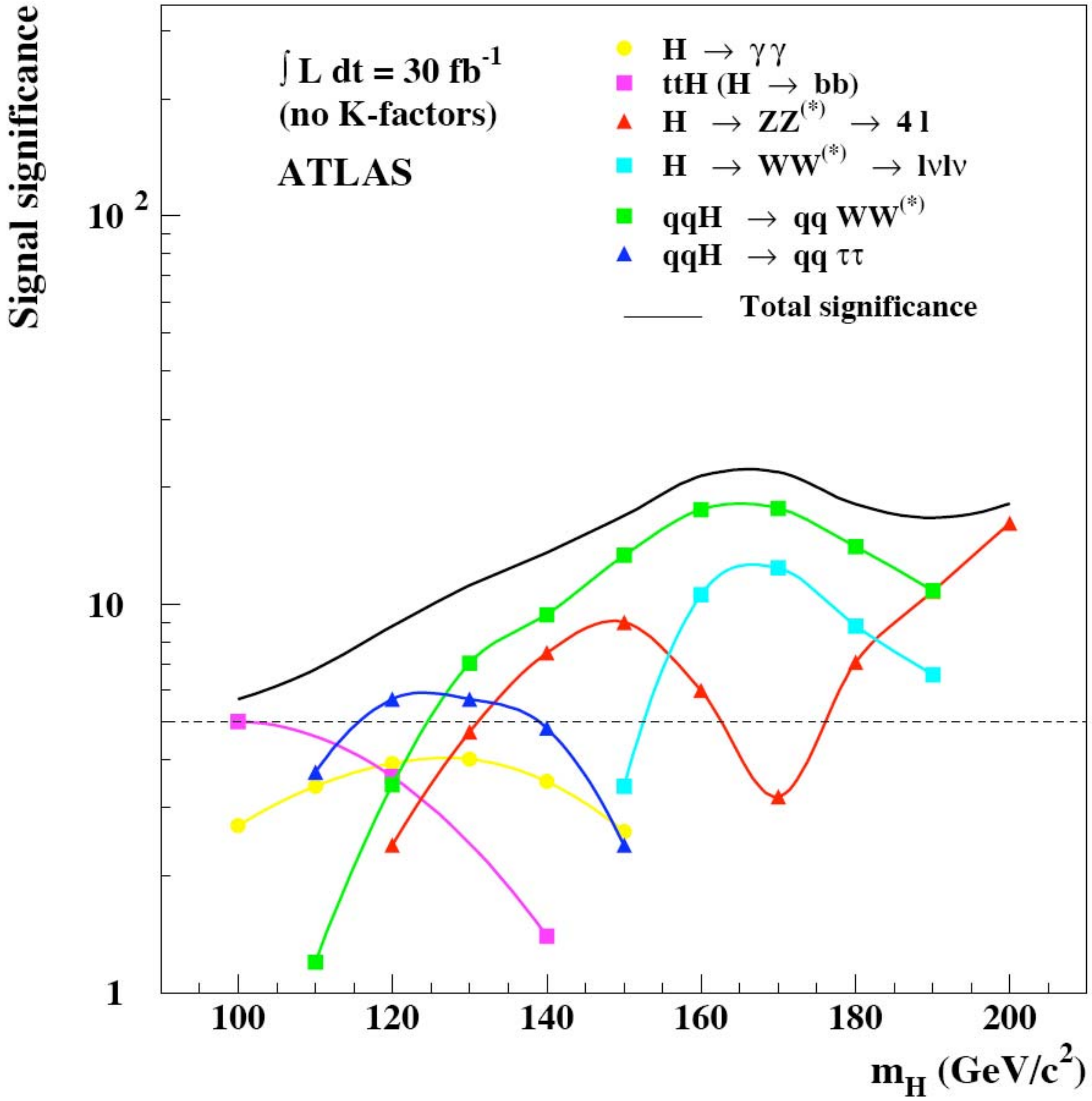
We can also have a heavier Higgs boson decaying into two lighter ones in this scenario.

	Point 1	Point 2	Point 3
s_ω^2	0.5	0.5	0.5
m_h (GeV)	115	175	225
m_H (GeV)	300	500	500
$\Gamma(H \to hh)$ (GeV)	2.1	17	17
$BR(H \to hh)$	0.33	0.33	0.33

Suppressed Discovery for Light Higgs Boson

The signal of the 115 GeV Higgs boson principally relies upon $gg \to h \to \gamma\gamma$ and $gg \to \bar{t}th \to \bar{t}t\bar{b}b$. In this scenario, the lighter Higgs production is reduced by a factor of $s_h^2 = 1/2$ which means twice is much data (i.e., time needed to discover it).

Higgs discovery significances

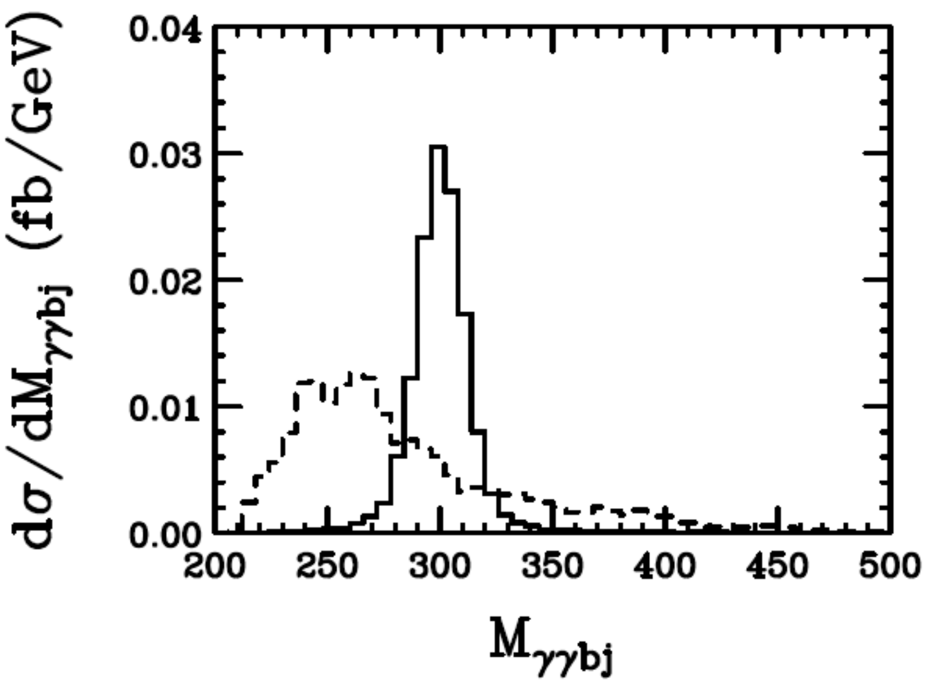


See K. Assamagan's talks for more recent update!

Heavy to Light Higgs rate

Considered discovery mode (Richter-Was et al.):

$$gg \to H \to hh \to \gamma\gamma\bar{b}b$$

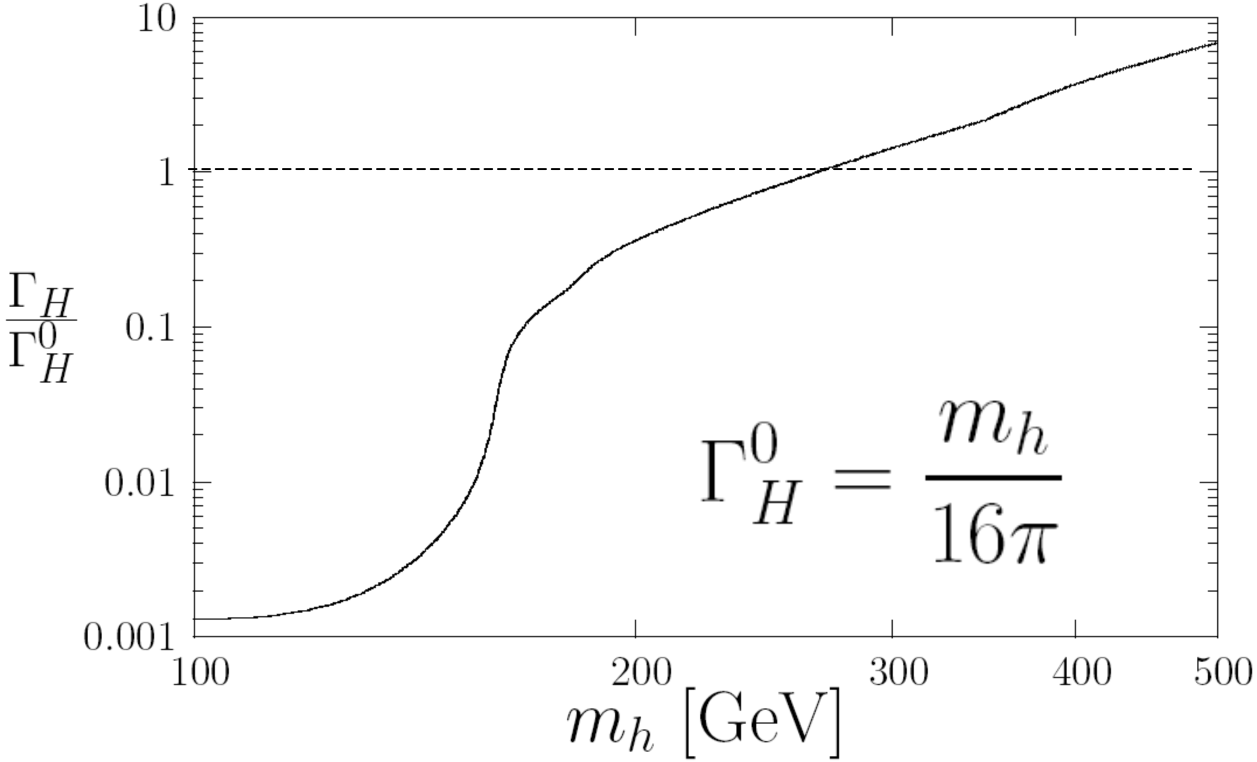


Channel	1 tag	2 tags
$H \to hh$	24	12
$\gamma\gamma bb$	0.4	0.2
$\gamma\gamma bc$	0.15	0.01
$\gamma\gamma bj$	1	0.009
$\gamma\gamma cc$	1.2	0.069
$\gamma\gamma cj$	3.6	0.042
$\gamma\gamma jj$	1.8	0.007
Total background	8.2	0.34

30 fb^{-1} bkgd estimates

Bowen, Cui, JW

Light Higgs accidentally narrow



Light Higgs boson especially susceptible to new decay modes.

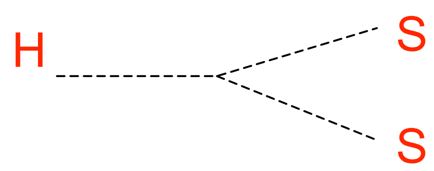
Sources of Invisible Decay

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

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

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:

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

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

Invisible Higgs at LHC

$\not{p}_T$ cut	$m_h = 120$ GeV S/B	$m_h = 120$ GeV $\mathrm{S}/\sqrt{\mathrm{B}}$ (10 fb^{-1})	$m_h = 120$ GeV $\mathrm{S}/\sqrt{\mathrm{B}}$ (30 fb^{-1})	$m_h = 140$ GeV $\mathrm{S}/\sqrt{\mathrm{B}}$ (30 fb^{-1})	$m_h = 160$ GeV $\mathrm{S}/\sqrt{\mathrm{B}}$ (30 fb^{-1})
65 GeV	0.22 (0.16)	5.6 (4.9)	9.8 (8.5)	7.1 (6.2)	5.2 (4.5)
75 GeV	0.25 (0.22)	5.7 (5.3)	9.9 (9.1)	7.3 (6.7)	5.4 (5.0)
85 GeV	0.29	5.7	9.8	7.4	5.6
100 GeV	0.33	5.4	9.3	7.3	5.7

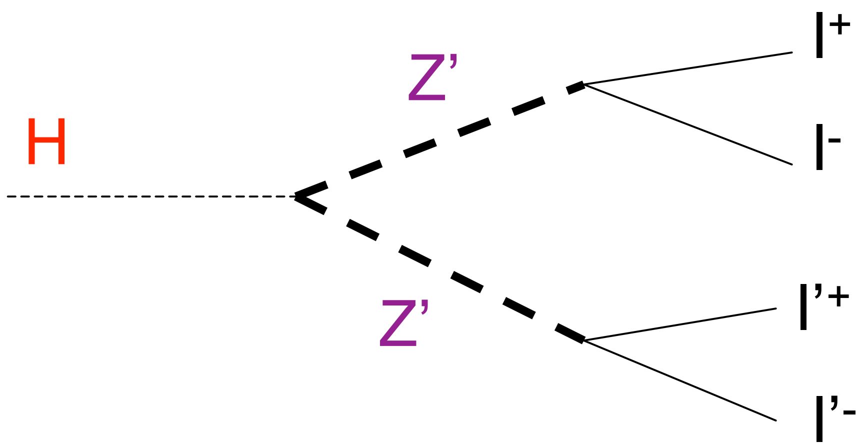
TABLE II: Signal significance for associated $\boxed{Z(\to \ell^+\ell^-) + h_{inv}}$ production at the LHC, combining the ee and $\mu\mu$ channels. The numbers in the parentheses include the estimated Z+jets background discussed in the text.

Davoudiasl, Han, Logan, ‘05

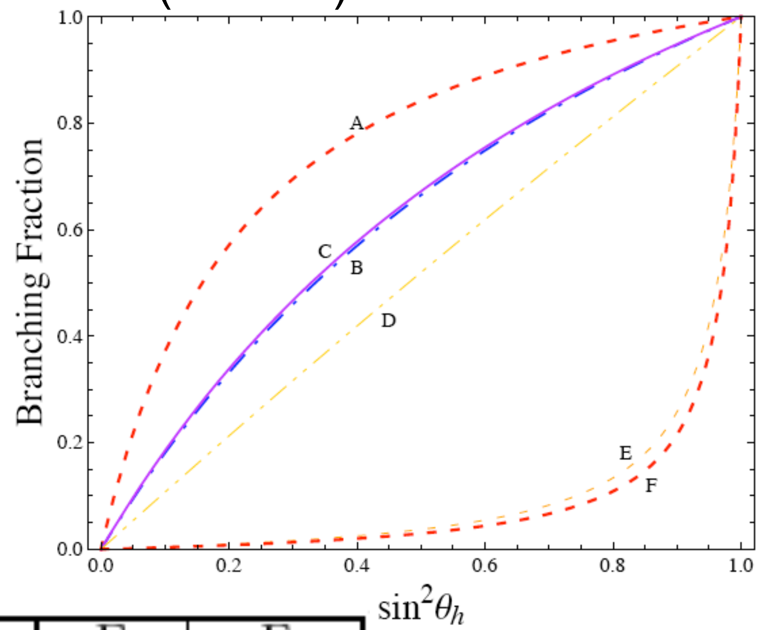
Light Z’ and Higgs Decays

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



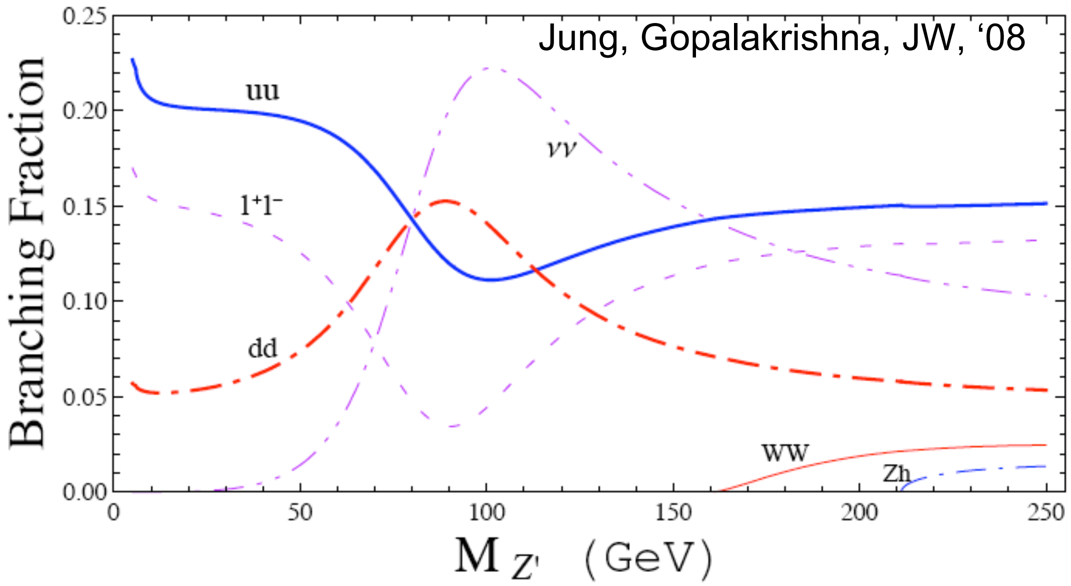
B(H->Z’Z’) $\chi \sim 10^{-4}$



Gopalakrishna, Jung, JW, ‘08

Point	A	B	C	D	E	F
$(M_h, M_{Z'})$ (GeV)	120, 5	120, 50	150, 5	150, 50	250, 5	250, 50

Leptonic branching fractions and collider sensitivity estimates



Apply basic kinematic cuts to look for two Z' resonances and overall Higgs resonance.

Tevatron: With 4 fb^{-1} see A & C; with 10 fb^{-1} see B & D also.
LHC: With 1 fb^{-1} A-D, and with 10 fb^{-1} E & F also.

Point	A	B	C	D	E	F
$(M_h, M_{Z'})$ (GeV)	120, 5	120, 50	150, 5	150, 50	250, 5	250, 50

Conclusions

Reasonable to imagine hidden world(s) that interact with Higgs boson at the renormalizable level.

Many opportunities for LHC to find evidence for it in the early phase (large kinetic mixing, light pairs of CP-even Higgses, H->Z'Z', etc.) and/or in the high-luminosity phase (trans-TeV Higgs, small kinetic mixing and heavy Z', etc.).

Favored light Higgs is a fragile creature, and knocked about very easily. Good chance that Higgs phenomenology will be complicated and confusing and subtle.