Higgs phenomenology beyond the Standard Model

Heather Logan
Carleton University

Physics at the LHC 2011
Perugia, June 6–11

Outline

Introduction: how to search for BSM Higgs

Survey of models

Extracting Higgs couplings from LHC data

Conclusions

Three ways to search for BSM Higgs:

1) Exotic decays of SM-like neutral Higgs

- $H \to aa \to 4b$, $2b2\tau$, 4γ

- $H \to$ dark matter; "hidden valley" states; etc.

2) Production and decay of exotic BSM Higgs-sector states

- H^+ search, e.g. in top decays

- $H^{++} \to \ell^+\ell^+$ search

- MSSM A/H via decays to $\tau\tau$

3) Production and decay of BSM Higgs in SM Higgs channels

3) Production and decay of BSM Higgs in SM Higgs channels

"BSM-ness" manifests via modified coupling(s) to SM particles:

- New particles in the loop
  - $gg \to H$ modified;
  - $H \to \gamma\gamma$ modified

- Sharing of EWSB vev among two or more mass eigenstates
  - VBF $\to H$ and WH, ZH modified;
  - $H \to WW, ZZ$ modified
  - $H \to \gamma\gamma$ can be modified: W in the loop

- Masses of different fermions from different Higgs doublets
  - $gg \to H$ can be modified;
  - ratios of decays to different fermions modified
  - Can affect all other BRs by changing Higgs total width

3) Production and decay of BSM Higgs in SM Higgs channels

Examples:

- 4th generation

- MSSM

- more general 2HDMs

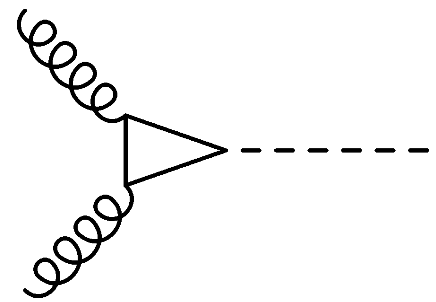
- Top-Higgs

- Lee-Wick Standard Model

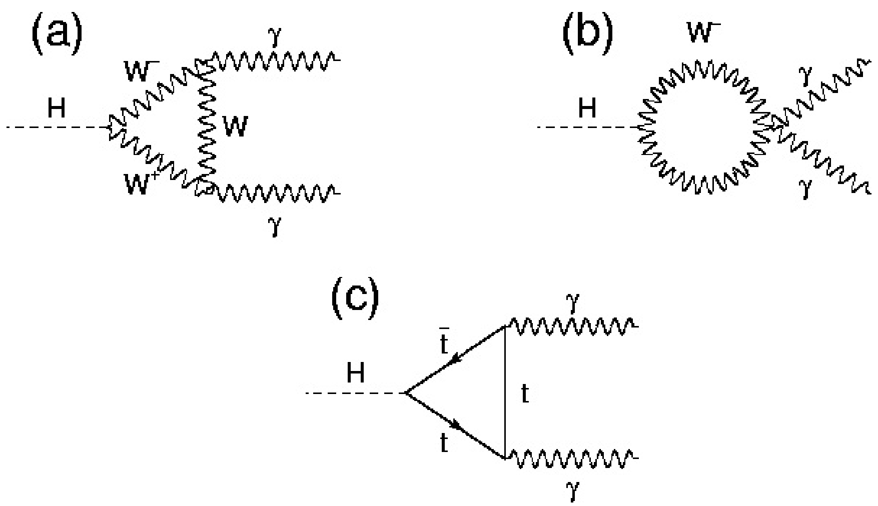
4th generation

New heavy quarks contribute substantially to $gg \to H$ and $H \to \gamma\gamma$

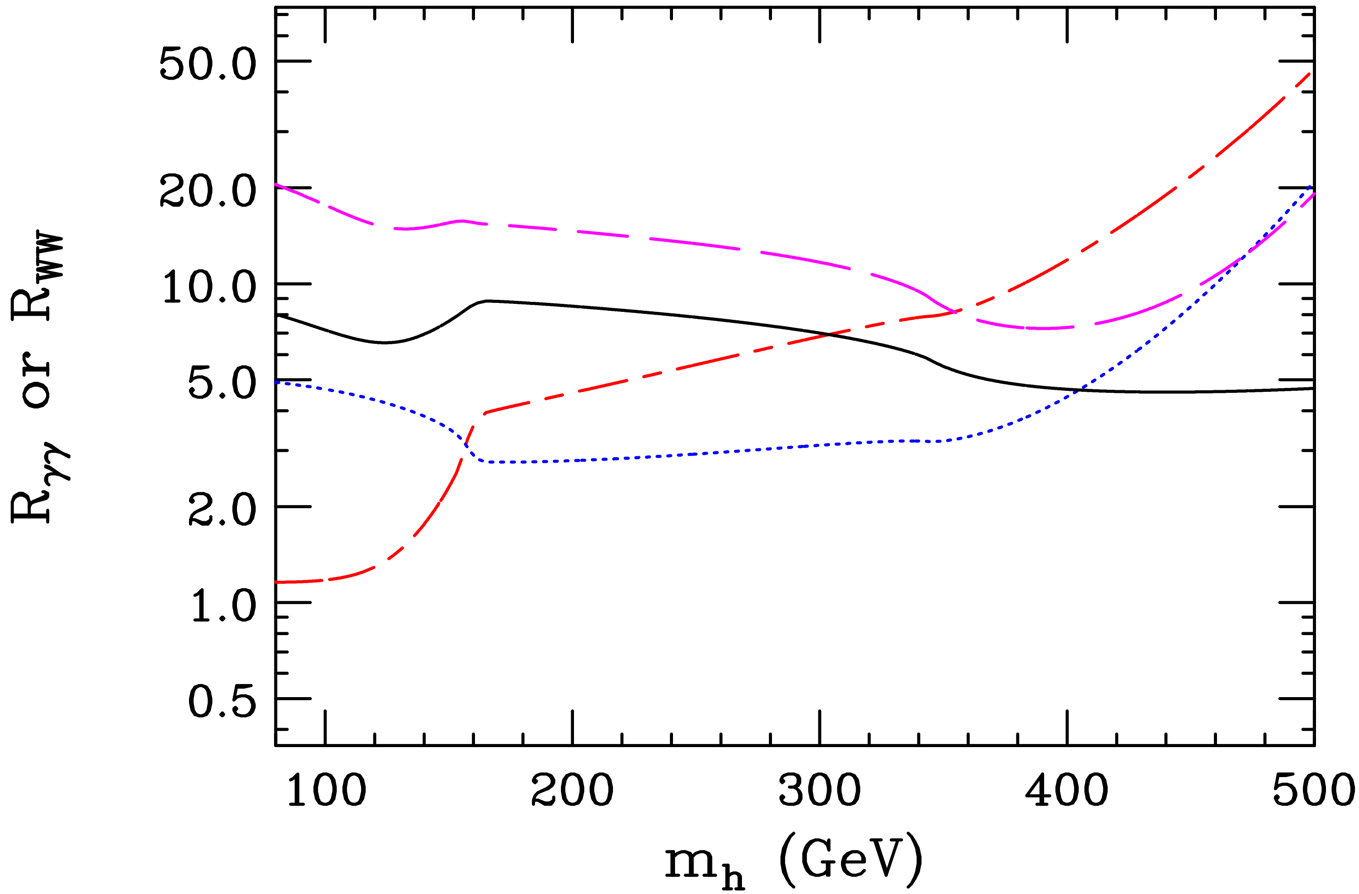
$gg \to H$:
Loop is independent of m_t for $m_t \gg M_H$.
4th gen t', b' together triple SM amplitude: cross section $9\times$ SM.



$H \to \gamma\gamma$:
W loop dominates for light Higgs; SM top loop interferes destructively ($\sim -30\%$).
4th gen t', b', τ' generally suppress partial width to $\gamma\gamma$.



4th generation



Gunion, arXiv:1105.3965

Black: $gg \to H \to WW$/SM with 4th generation

Red: $gg \to H \to \gamma\gamma$/SM with 4th generation

Blue: $gg \to H \to \gamma\gamma$/SM with sequential W'

Magenta: $gg \to H \to \gamma\gamma$/SM with 4th generation and sequential W'

MSSM

Squarks, charginos in the loops for ggH and $H\gamma\gamma$

But more important: MSSM has 2 Higgs doublets:
- share in EWSB, mix to form mass eigenstates

$$\bar{g}_{h^0WW} = \bar{g}_{h^0ZZ} = \sin(\beta-\alpha) \qquad \bar{g}_{H^0WW} = \bar{g}_{H^0ZZ} = \cos(\beta-\alpha)$$

- have a nontrivial coupling pattern to fermions

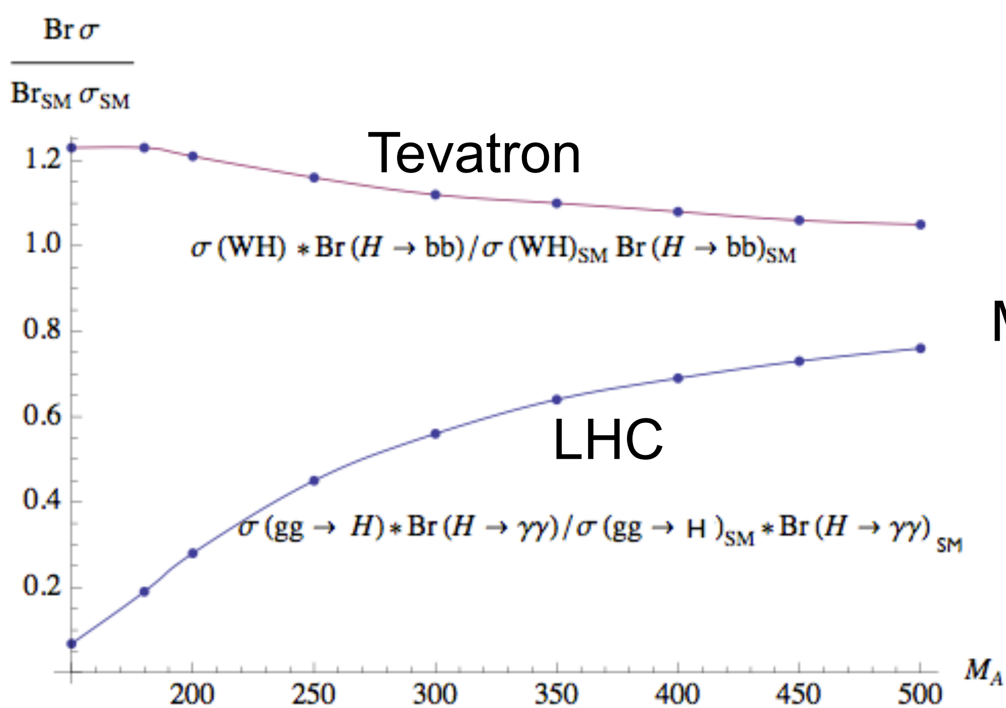
$$-\mathcal{L}_{\text{Yuk}} = Y_u u_R^c H_u Q_L + Y_d d_R^c H_d Q_L + Y_\ell e_R^c H_d L_L + \text{h.c.}$$

$$\bar{g}_{h^0t\bar{t}} = \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$$
$$\bar{g}_{h^0b\bar{b}} = \bar{g}_{h^0\tau\tau} = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$

Significant effects when all the Higgs states are relatively light

MSSM: $\cos(\beta-\alpha) \simeq \frac{1}{2}\sin 4\beta \frac{m_Z^2}{M_A^2}$

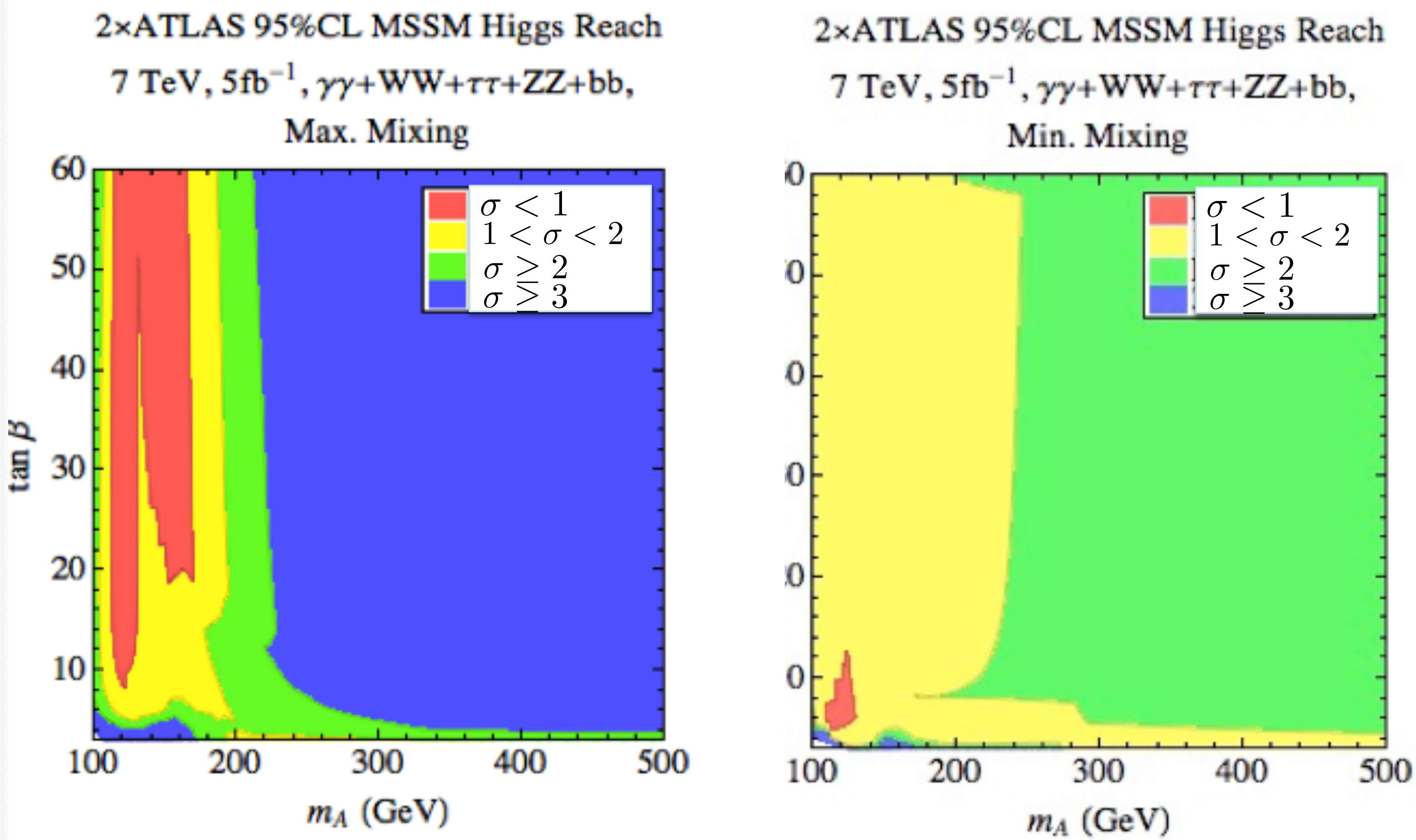
For a large region of parameter space suppression of the $\gamma\gamma$ mode at the LHC



$M_h \sim 115$ -125 GeV

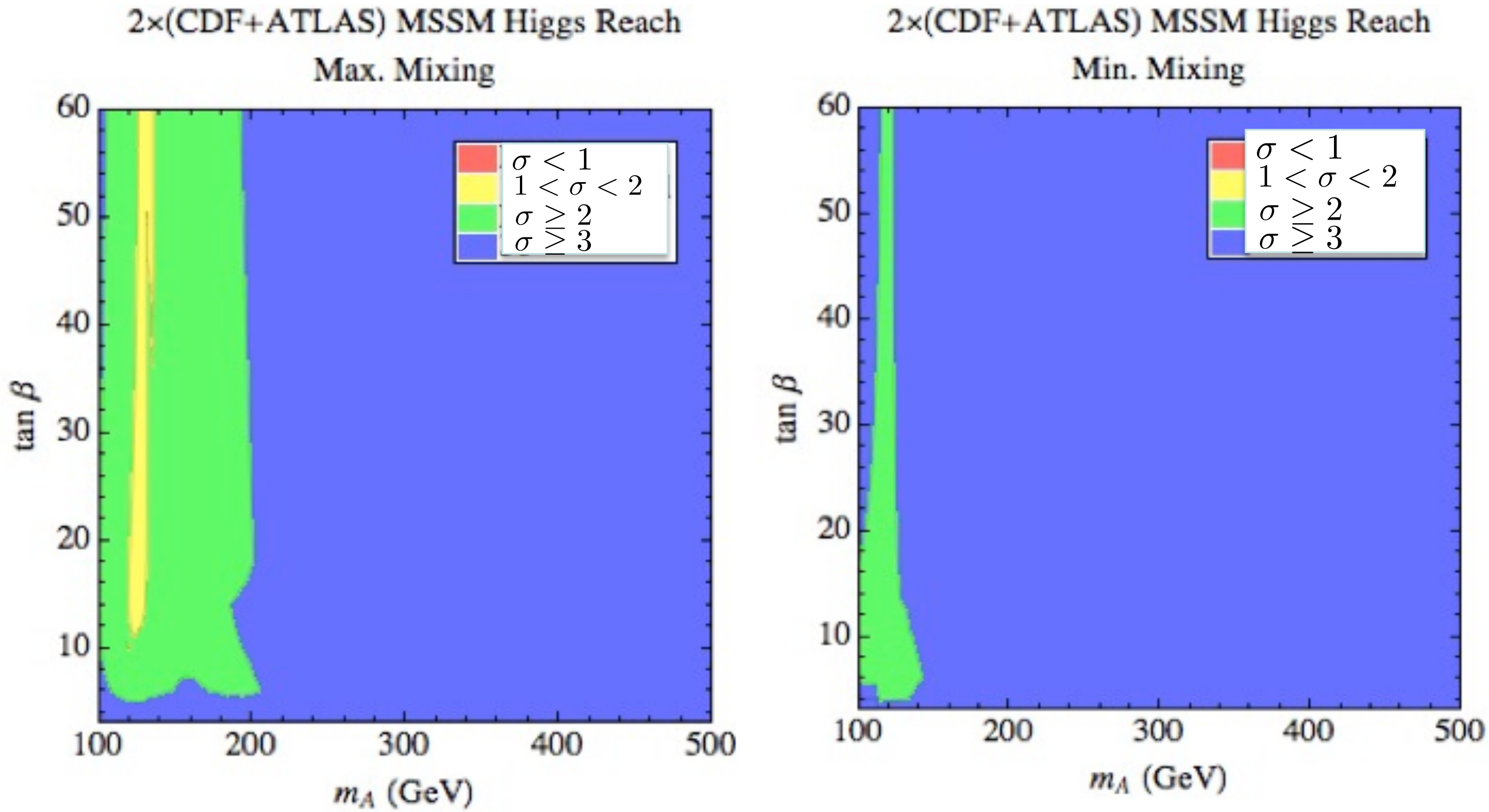
Suppression still sizable for m_A as large as 500 GeV

LHC reach for the MSSM SM-like Higgs



Important to improve on early LHC reach in tau tau mode

Tevatron - early LHC combined reach : MSSM SM-like Higgs



3 sigma evidence of the SUSY Higgs responsible for EWSB

More general 2HDMs

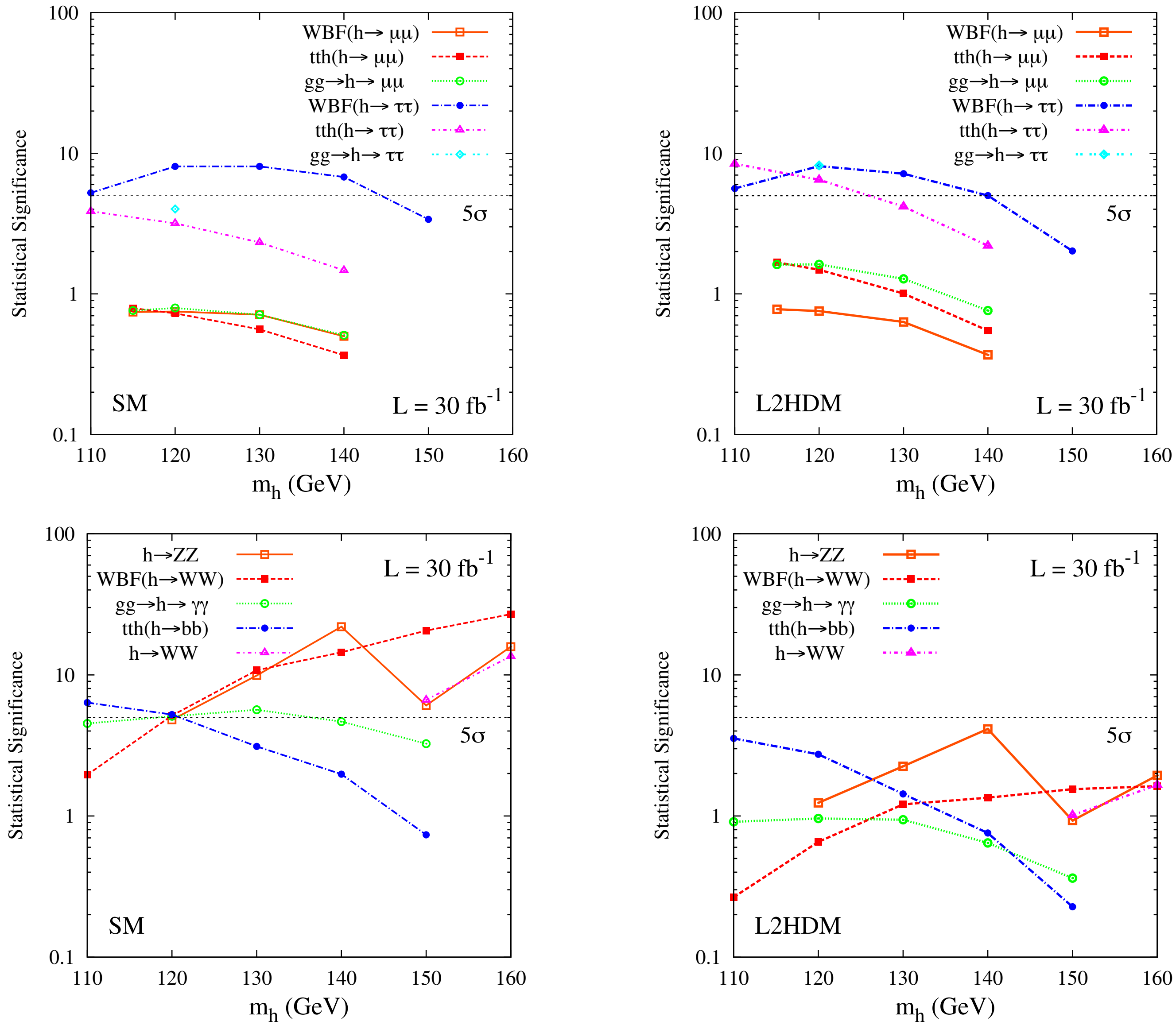
Some similar features to MSSM but generally less constrained

New possibilities for Yukawa structure:

"Lepton-specific" 2HDM: H_q couples to u, d; H_ℓ couples to ℓ
can suppress Hqq while enhancing $H\ell\ell$

"Flipped" 2HDM: H_u couples to u and ℓ; H_d couples to d
can have large Hbb while suppressing $H \to \tau\tau$

More general 2HDMs: Lepton-specific 2HDM benchmark point



Su & Thomas, PRD 79, 095014 (2009)

Top-Higgs

Dedicated Higgs doublet (possibly composite) to generate most of top quark mass

Add-on for models of dynamical EWSB: technicolor, 3-site Moose

Top-Higgs doublet has vev $f = v_{\text{SM}} \sin\omega$

Top-Higgs particle H_T couples only to $t\bar{t}$, WW, ZZ at tree level
- WW, ZZ couplings suppressed $\sim \sin\omega$
- $t\bar{t}$ coupling enhanced $\sim 1/\sin\omega$

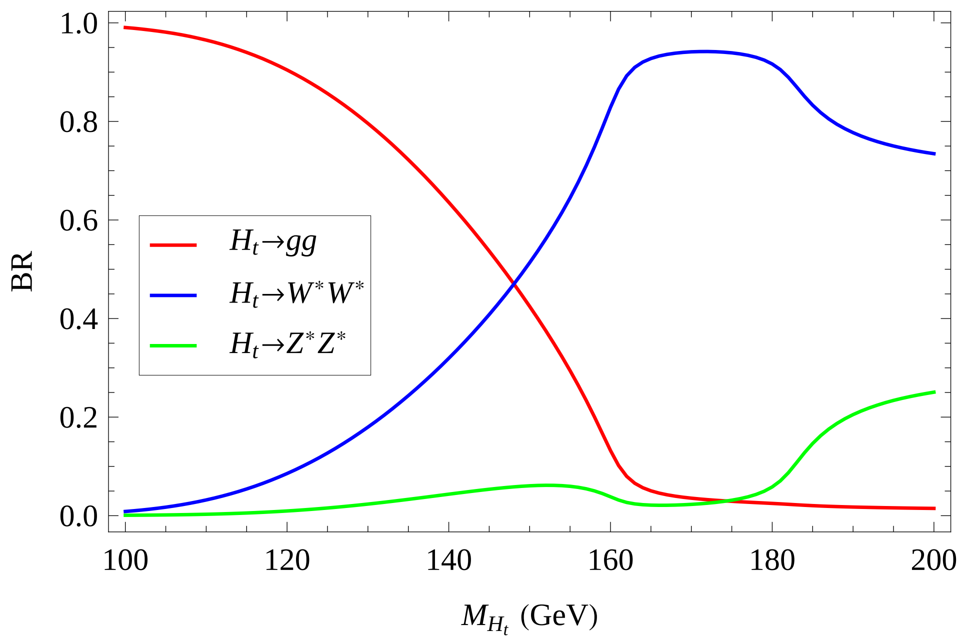
$gg \to H_T$ enhanced $\sim 1/\sin^2\omega$

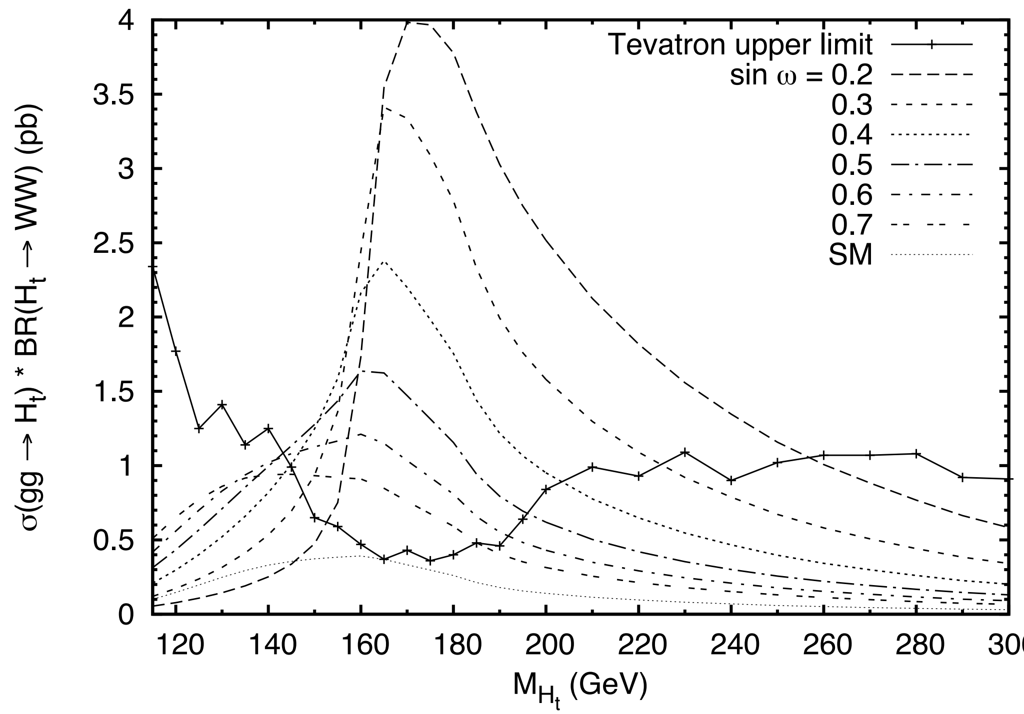
H_T BRs significantly modified below WW threshold:
no $b\bar{b}$, $\tau\tau$ decays; gg dominates

Top-Higgs

$\sin\omega = 0.5 \longrightarrow \sigma(gg \to H_T)/\mathrm{SM} \simeq 4$

Tevatron-combined dedicated $gg \to H \to WW$ limit from arXiv:1005.3216





Chivukula, Simmons, Coleppa, HEL, & Martin, PRD83, 055013 (2011)

Lee-Wick Standard Model

Exotic approach to solve hierarchy problem by implementing Pauli-Villars with actual physical fields.

Grinstein, O'Connell, & Wise, PRD 77, 025012 (2008)

Partner fields have opposite sign quadratic Lagrangian terms.
- Seems to violate microscopic causality (!!!)
- Macroscopically all right; unitary at all orders; EW precision constraints satisfied.

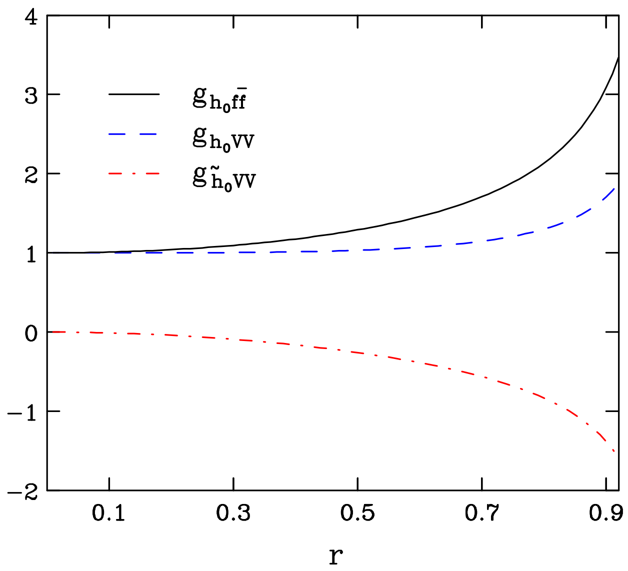
Interesting Higgs sector feature is novel mixing structure:

$$\begin{pmatrix} h \\ \tilde{h} \end{pmatrix} = \begin{pmatrix} \cosh\theta & \sinh\theta \\ \sinh\theta & \cosh\theta \end{pmatrix} \begin{pmatrix} h_0 \\ \tilde{h}_0 \end{pmatrix}$$

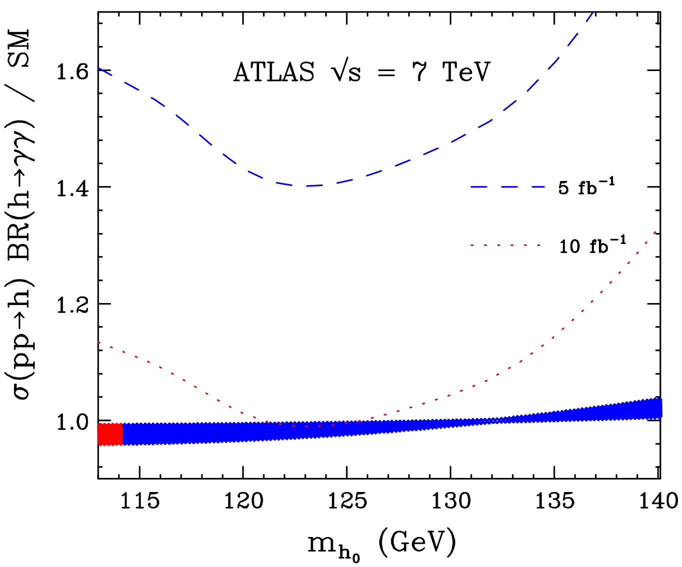
Usual $\bar{g}^2_{hWW} + \bar{g}^2_{HWW} = 1$ sum rule becomes $\bar{g}^2_{h_0 WW} - \bar{g}^2_{\tilde{h}_0 WW} = 1$.
Simultaneously get enhancement of fermion couplings.
Only new free parameter is mass ratio $r = M_{h_0}/M_{\tilde{h}_0}$.

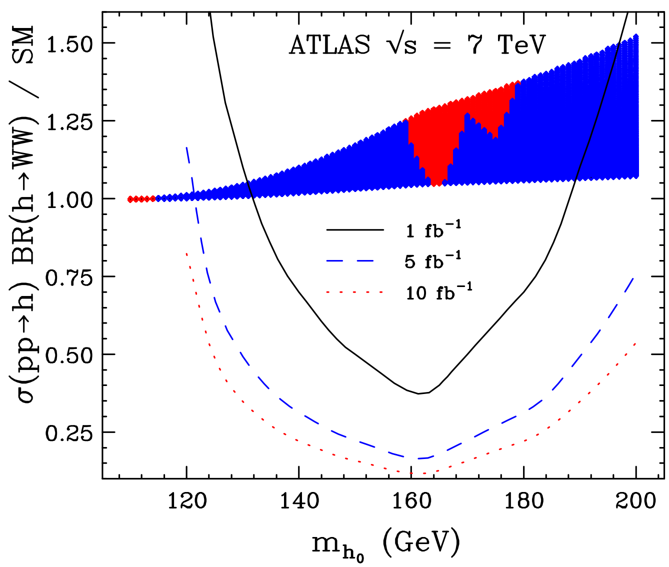
Lee-Wick Standard Model

Alvarez, Leskow, & Zurita, arXiv:1104.3496



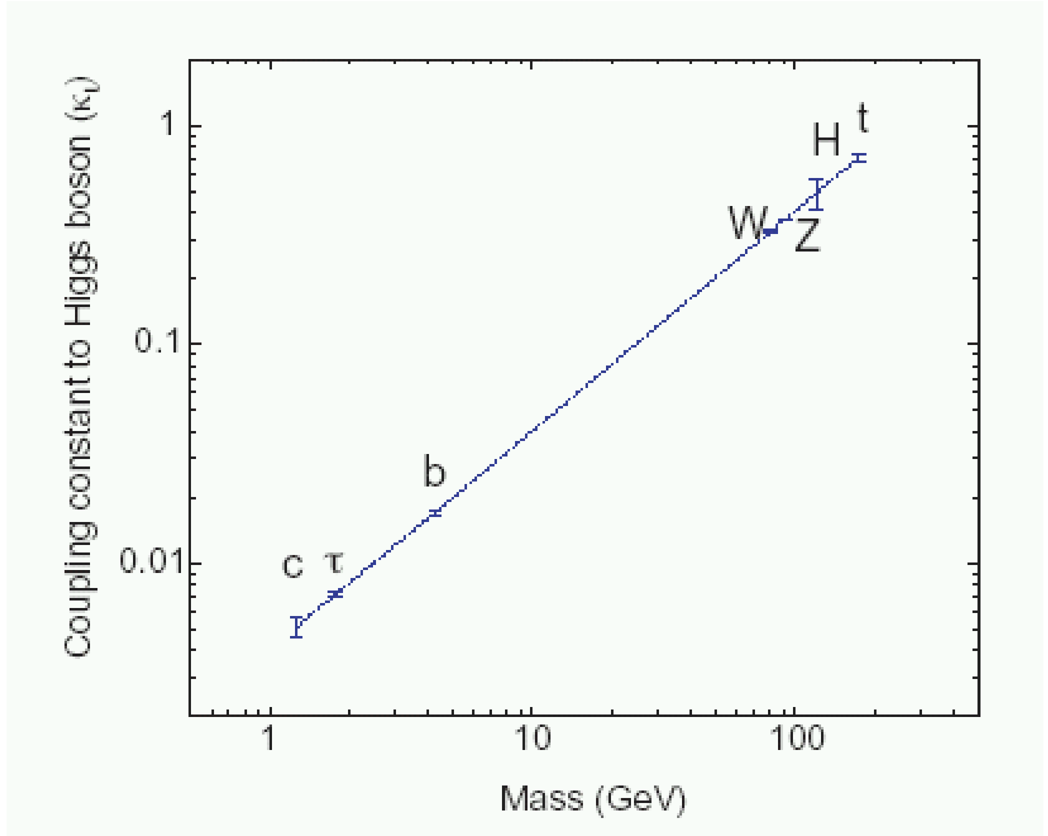
$$r = M_{h_0}/M_{\tilde{h}_0}$$





To test SM Higgs mechanism, need to measure Higgs couplings.

SM: coupling of Higgs to each SM particle already fixed by known particle masses.



BSM: pattern of deviations from SM expectations characterizes BSM model.

Model-independent Higgs coupling measurements are one of the main selling points of ILC.

Coupling extraction more challenging at LHC due to absence of direct measurement of Higgs production cross section(s).

Measure event rates at LHC: sensitive to production and decay couplings.

$$\text{Rate}_{ij} = \sigma_i \text{BR}_j = \sigma_i \frac{\Gamma_j}{\Gamma_{\text{tot}}}$$

Main difficulty: "flat direction" in the fit.
Allow an unobserved decay mode while simultaneously increasing all couplings by a factor a:

$$\text{Rate}_{ij} = a^2 \sigma_i^{\text{SM}} \frac{a^2 \Gamma_j^{\text{SM}}}{a^2 \Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{new}}}$$

Ways to deal with this:
- assume no unobserved decays
- assume HWW, HZZ couplings no larger than in SM
- include direct measurement of Higgs width (heavier masses)*

*new

Get ratios of Higgs couplings-squared from taking ratios of rates. Full coupling extraction: assume no unexpected decay channels, assume $b\bar{b}/\tau\tau$ = SM value. $M_H = 100$–190 GeV

Zeppenfeld, Kinnunen, Nikitenko, Richter-Was, PRD62, 013009 (2000); Les Houches 1999

Add $t\bar{t}H$, $H \to \tau\tau$ channel to improve $t\bar{t}H$ constraint.

$M_H = 110$–180 GeV Belyaev & Reina, JHEP0208, 041 (2002)

Fit assuming WWH, ZZH couplings bounded from above by SM value. $M_H = 110$–190 GeV

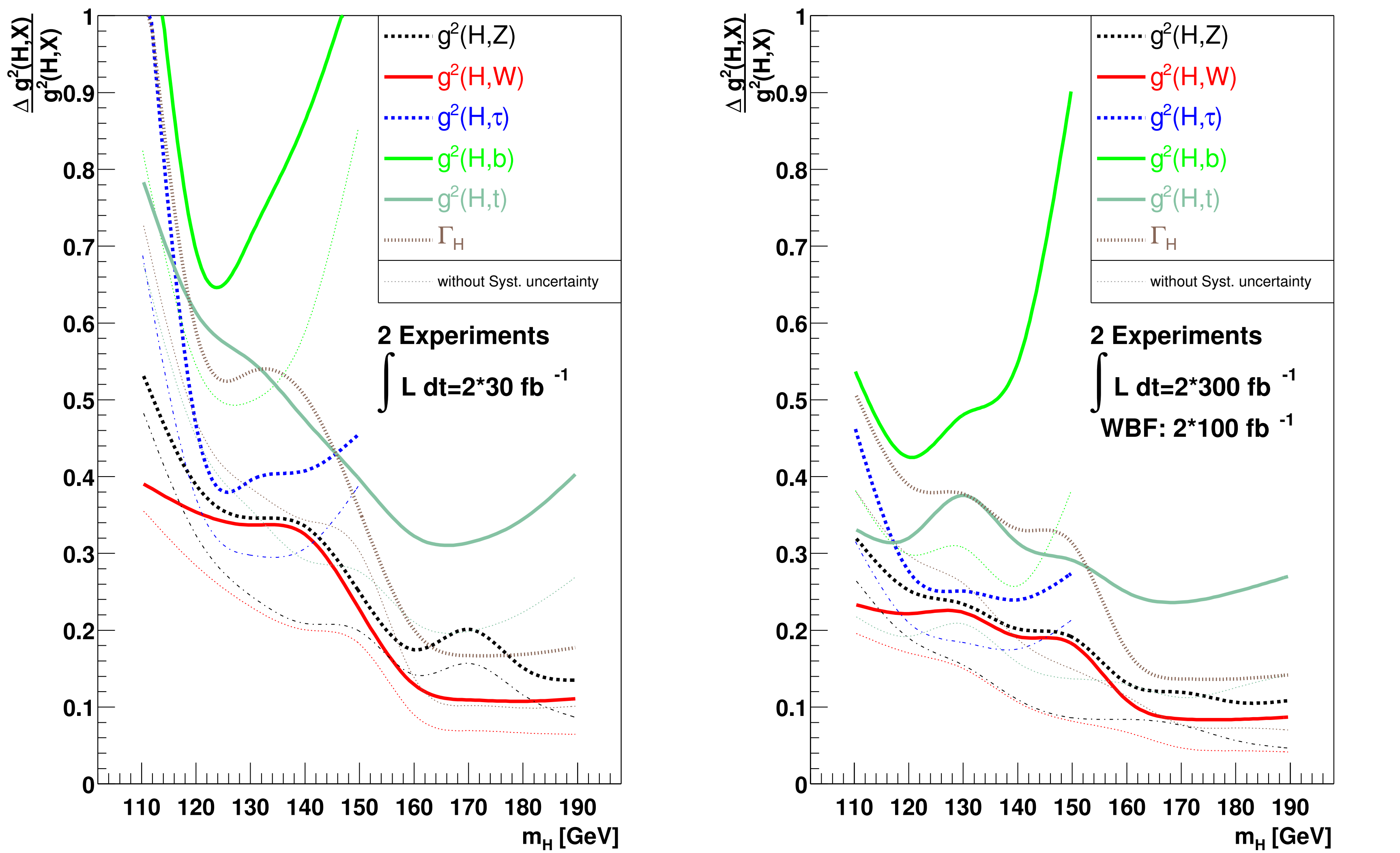
Dührssen, Heinemeyer, HEL, Rainwater, Weiglein, & Zeppenfeld, PRD70, 113009 (2004)

More careful analysis of probability density and correlations, using updated expt studies. Assume no unexpected decay channels.

$M_H = 120$ GeV Lafaye, Plehn, Rauch, D. Zerwas, & Dührssen, JHEP0908, 009 (2009)

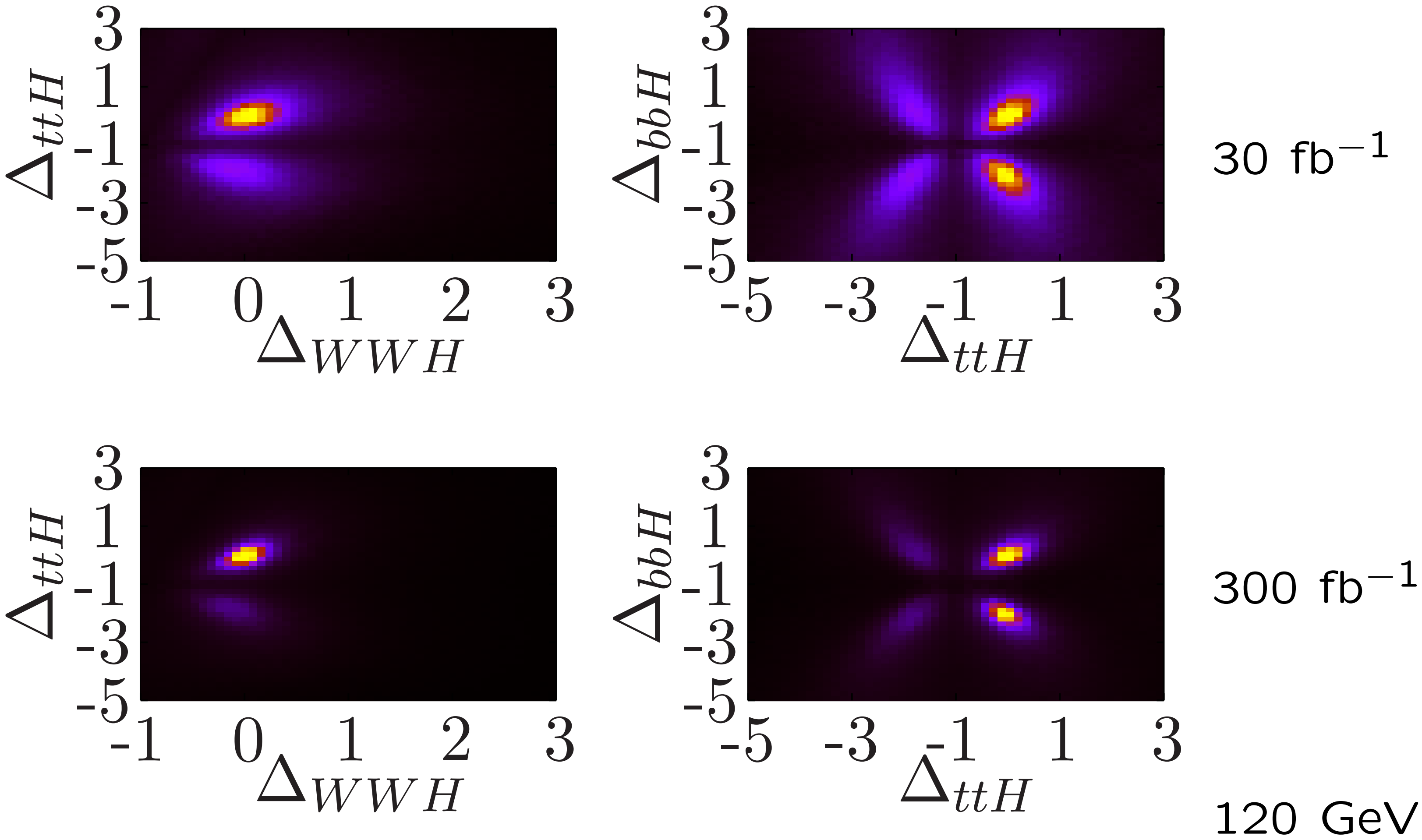
New approach for heavier Higgs ($\gtrsim 190$ GeV) using direct Higgs width measurement from $H \to ZZ \to 4\ell$ lineshape. $M_H = 190$ GeV

HEL & Salvail, in preparation



Dührssen, Heinemeyer, HEL, Rainwater, Weiglein, & Zeppenfeld, PRD70, 113009 (2004)

- 10%–50%+ uncertainties on couplings-squared.
- Systematic & theory uncertainties are important.



Lafaye, Plehn, Rauch, D. Zerwas, & Dührssen, JHEP 0908, 009 (2009)

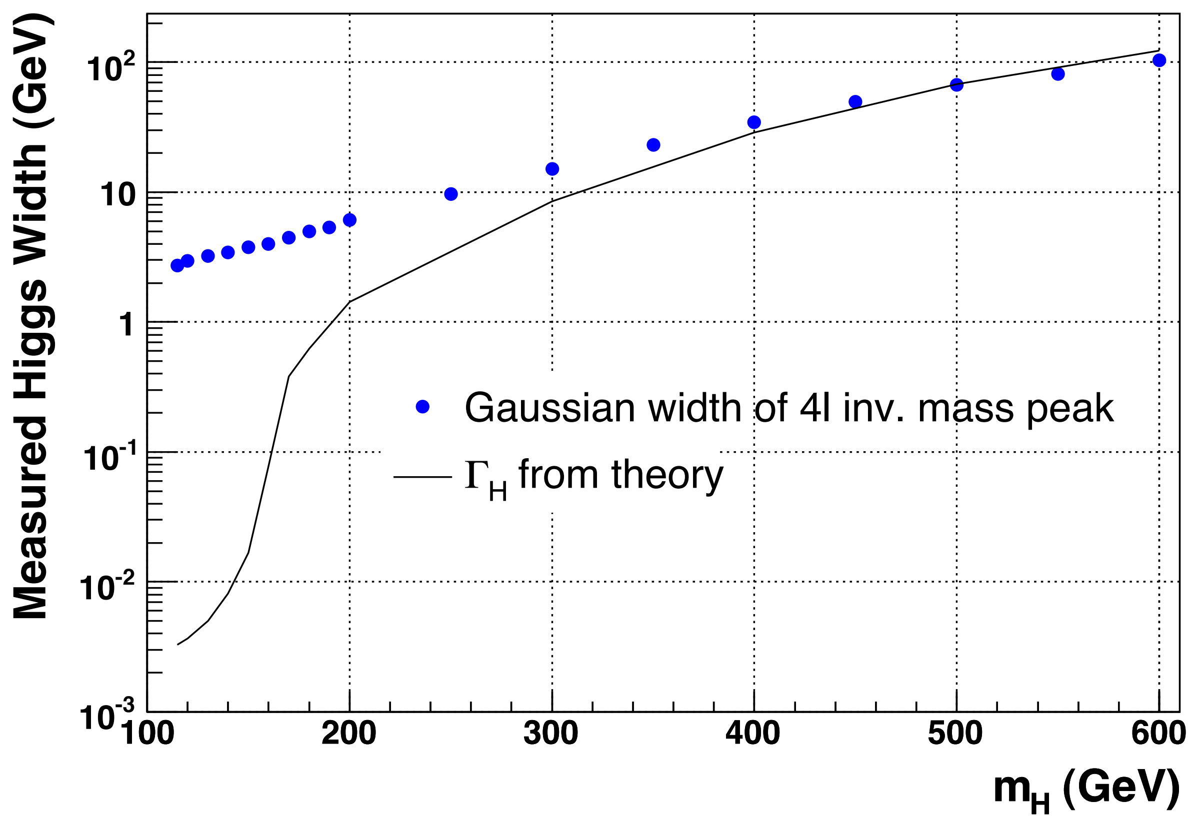
- Correlations in parameters are also important
- Results depend on what coupling freedom is assumed

(here: no additional Hgg, $H\gamma\gamma$ contributions)

Can we make model-independent measurements?

$$\text{Rate}_{ij} = a^2 \sigma_i^{\text{SM}} \frac{a^2 \Gamma_j^{\text{SM}}}{a^2 \Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{new}}}$$

Consider extraction of Higgs couplings when Higgs total width is a directly measurable observable.



We study $M_H = 190$ GeV.

Method applicable also at higher Higgs masses.

CMS TDR (2006), Vol. 2 (Physics), chap. 10

Total width:

17.6% for 30 fb^{-1}, 9.6% for 100 fb^{-1} CMS TDR (2006), Vol. 2 (Physics)

Rates:

Production	Decay	30 fb^{-1}	100 fb^{-1}	"contamination"	
GF	$ZZ \to 4\ell$	14%	7.9%	VBF $\sim$ 14%	[a]
VBF	$ZZ \to 4\ell$	24%	13%	GF $\sim$ 21%	[a]
GF	$WW \to \ell\ell p_T^{\text{miss}}$	9.6%	5.3%	VBF $\sim$ 2.8%	[a]
VBF	$WW \to e\mu p_T^{\text{miss}}$	14%	7.6%	GF $\sim$ 7.8%	[a]
VBF	$WW \to (ee, \mu\mu) p_T^{\text{miss}}$	15%	8.1%	GF $\sim$ 7.2%	[a]
VBF	$WW \to \ell\nu jj$	16%	8.9%	(none)	[b]

[a] Dührssen, ATL-PHYS-2003-030 [b] Pi et al, CMS-NOTE-2006-092

- All uncertainties statistical only.
- All studies 30 fb^{-1} at 1 detector at 14 TeV; we scale by $\sqrt{3/10}$ for 100 fb^{-1} estimate.

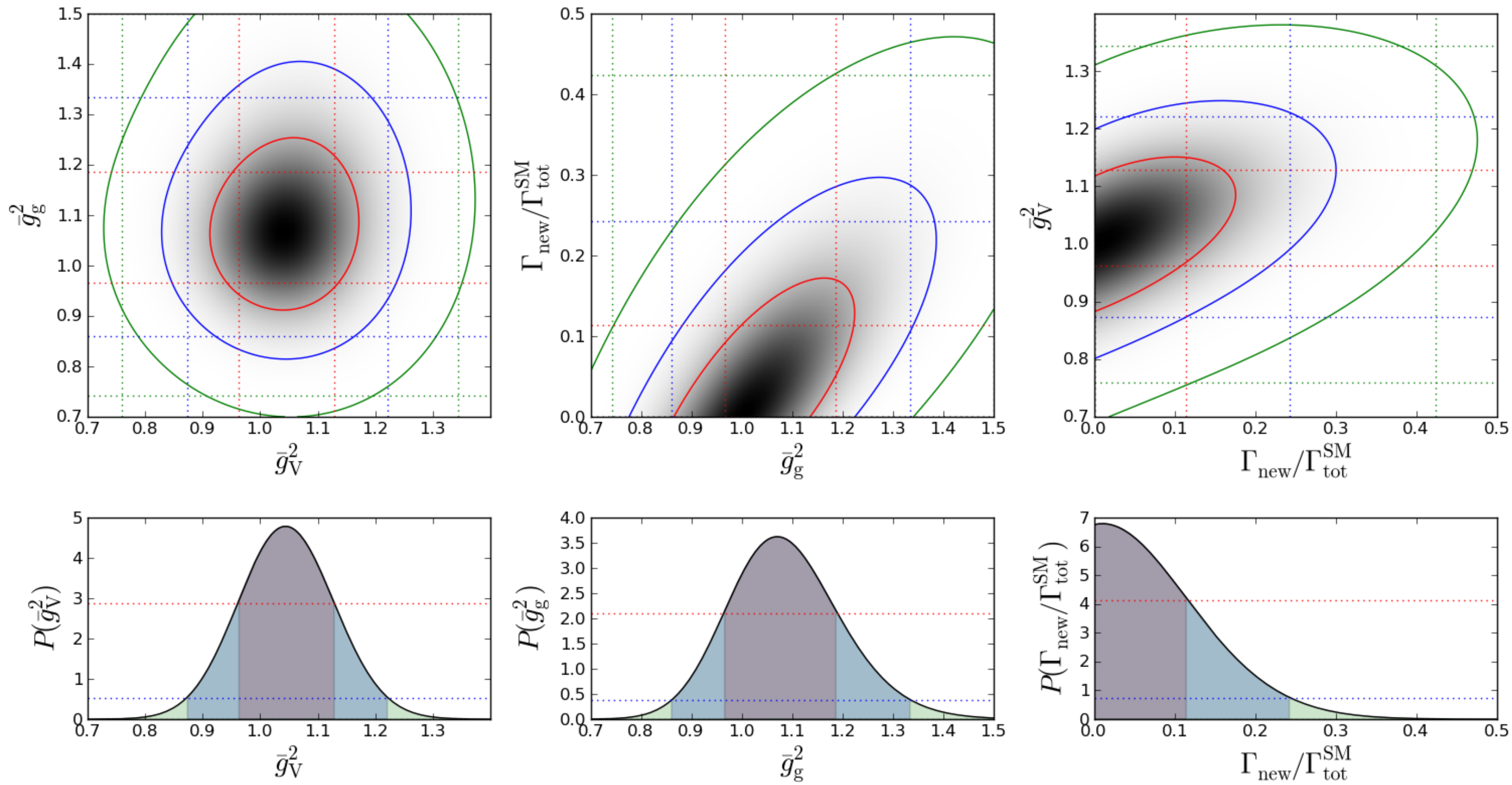
Parametrization of new physics:

$$\Gamma_{\text{tot}} = \Gamma_W + \Gamma_Z + \Gamma_{\text{new}} \qquad \Gamma_W = \bar{g}_W^2 \Gamma_W^{\text{SM}} \qquad \Gamma_Z = \bar{g}_Z^2 \Gamma_Z^{\text{SM}}$$

$$\sigma_{\text{GF}} = \bar{g}_g^2 \sigma_{\text{GF}}^{\text{SM}} \qquad \sigma_{\text{VBF}} = [0.73\bar{g}_W^2 + (1-0.73)\bar{g}_Z^2]\sigma_{\text{VBF}}^{\text{SM}}$$

Results: 3-parameter fit, 30 fb^{-1}

$\bar{g}_V^2 \equiv \bar{g}_W^2 = \bar{g}_Z^2$, $\bar{g}_g^2$, $\Gamma_{\rm new}/\Gamma_{\rm tot}^{\rm SM}$

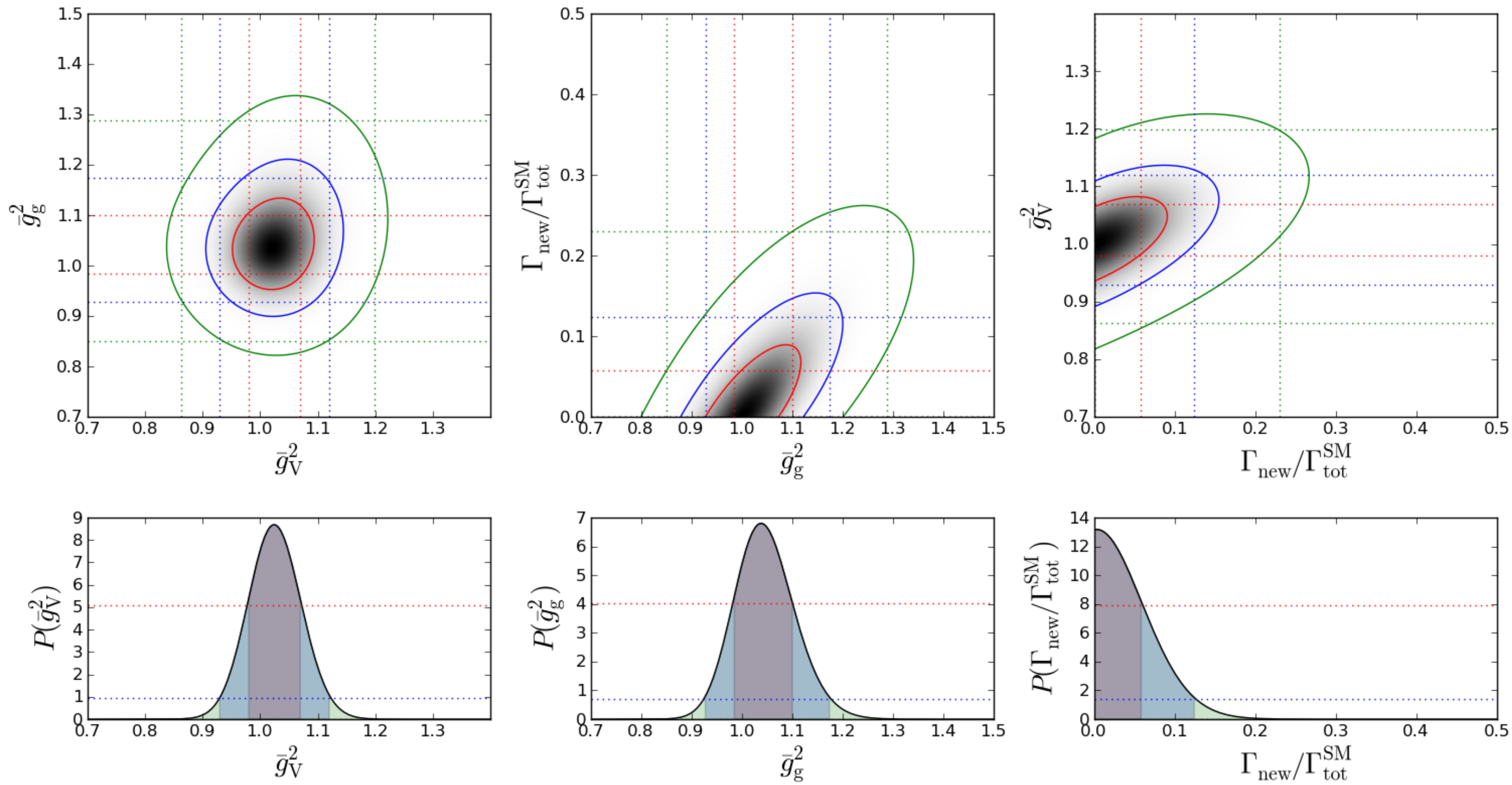


HEL & Salvail, in preparation

$\delta \bar{g}_V^2 \simeq 8\%$, $\delta \bar{g}_g^2 \simeq 11\%$, $\Gamma_{\rm new}/\Gamma_{\rm tot}^{\rm SM} \lesssim 24\%$ at 95% CL

Results: 3-parameter fit, 100 fb^{-1}

$\bar{g}_V^2 \equiv \bar{g}_W^2 = \bar{g}_Z^2$, $\bar{g}_g^2$, $\Gamma_{\rm new}/\Gamma_{\rm tot}^{\rm SM}$



HEL & Salvail, in preparation

$\delta\bar{g}_V^2 \simeq 4.5\%$, $\delta\bar{g}_g^2 \simeq 5.8\%$, $\Gamma_{\rm new}/\Gamma_{\rm tot} \lesssim 12\%$ at 95% CL

Conclusions

SM Higgs discovery or exclusion is imminent!

A signal in one of the SM Higgs search channels will have immediate impact on BSM Higgs scenarios.

Higgs coupling measurements are key to understanding structure of Higgs sector.