2HDM Cross Sections and Branching Ratios

Nathaniel Craig
Scott Thomas
Rutgers University

S. Arora, A. Barker, K. Chan, C. Contreras-Campana,
E. Contreras-Campana, D. Feld, Y. Gershtein,
R. Gray, A. Lath, K. Mei, S. Panwalkar, M. Park,
R. Patel, S. Somalwar, S. Thomas, P. Thomassen,
M. Walker, P. Zywicki

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2HDM Cross Sections and Branching Ratios

Wide Classes of SM Higgs fits and
BSM Higgs Searches can be couched in terms of 2HDM

Useful Description

1. Theory - Many New Physics Models include or reduce to 2HDM
2. Practical – Manageable Parameter Space (most cases)

Presentations and comparisons of Fits and Searches within 2HDM parameter space require Cross Sections and Branching Ratios for h, H, A, H^{+-} (CP conserving 2HDM)

Here:

Report on General Procedures (Common Sense)

No discussion of CMS fits, searches, or results (open meeting)

Some Refs:

hep-ph arXiv:1305.2424, hep-ph arXiv:1207.4835

2HDM Cross Sections and Branching Ratios

Strategies Employed follow closely Higgs Cross Section Working Group
(some of the work pre-dates 2HDM discussions begun in this group)

Strategy:

Make use of extensive work available on QCD, etc. Corrections to SM Higgs Cross Sections and Branching Ratios

Modify these results by leading tree-level coupling modifications of 2HDMs (that satisfy the Glashow-Weinberg condition: type I – IV)

Work to Leading order in Higgs Couplings …

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Note: Everything in Physics/Life is an Approximation

Employ Strategy for BSM Higgs Searches + Current Generation of Higgs fits with this in Mind – This is NOT high precision comparison of Measurements of Known Processes within an Established Theory !

It is Parameterization of Search Results using an Idealization of a Hypothetical Model Framework. Percent Level is not really Warranted

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Approximations Described Below are Adequate for Parameterizing SM Higgs fits and BSM Higgs Searches in Relevant Regions 2HDM

2HDM Search Topologies

For BMS Higgs searches, either in SM Higgs Channels or BSM Channels

Most useful Presentation of Results is in terms of

σ.Br[pp -> (B)SM Higgs Intermediate State -> Final State(s)]

Assuming SM Br's for all SM particles (including h)
(simplest assumption in absence of specific model framework)

Such results are parameterized ONLY by BSM Higgs Masses

1. 2HDM – only in that it inspired given production and decay topology
2. Most model independent
3. Most useful to theorists

(Had this inserted into Snowmass 2013 Recommendations as highest priority for BMS Higgs searches)

Can further Refine Interpretations in terms of Model Dependent Cross Sections and Branching Ratios (Rest of this Talk)

2HDM Couplings

Couplings that include only One or Two h, H, A, H^{+-} are Parameterized by ONLY Two Couplings

h-H mix

Large modifications of h couplings Possible

Four Discrete Two Doublet Models that Satisfy Glashow-Weinberg Condition

Two Parameters, α , β

$$\tan\beta \equiv |\langle\Phi_2^0\rangle/\langle\Phi_1^0\rangle|$$

$$\begin{pmatrix} \sqrt{2}\,\mathrm{Re}(\Phi_2^0) - v_2 \\ \sqrt{2}\,\mathrm{Re}(\Phi_1^0) - v_1 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

(MSSM)

	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2

	2HDM I	2HDM II	2HDM III	2HDM IV
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
AVV	0	0	0	0
AQu	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

So α , β and h, H, A, H^{+-} Masses Completely Specify Leading Order Processes with Single h, H, A, H^{+-}

2HDM Couplings

Couplings that include only One or Two h, H, A, H^{+-} are Parameterized by ONLY Two Couplings

Alignment Limit:

h mass Eigenstate || Expectation Values -> $\cos(\beta - \alpha) = 0$

h couplings = h_{SM} couplings
H couplings = A couplings
HVV, Hhh, ... couplings Vanish

	2HDM I	2HDM II	2HDM III	2HDM IV
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
AVV	0	0	0	0
AQu	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

$$-\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \simeq 1 - \tan\beta\cos(\beta-\alpha) - \frac{1}{2}\cos^2(\beta-\alpha)$$

$$\frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) \simeq 1 + \cot\beta\cos(\beta-\alpha) - \frac{1}{2}\cos^2(\beta-\alpha)$$

$$\frac{\cos\alpha}{\cos\beta} = \tan\beta\sin(\beta-\alpha) + \cos(\beta-\alpha) \simeq \tan\beta[1 + \cot\beta\cos(\beta-\alpha) - \frac{1}{2}\cos^2(\beta-\alpha)]$$

$$-\frac{\sin\alpha}{\sin\beta} = \cot\beta\sin(\beta-\alpha) - \cos(\beta-\alpha) \simeq \cot\beta[1 - \tan\beta\cos(\beta-\alpha) - \frac{1}{2}\cos^2(\beta-\alpha)]$$

2HDM Couplings

Couplings that include only One or Two h, H, A, H^{+-} are Parameterized by ONLY Two Couplings

Alignment Limit:

h mass Eigenstate || Expectation Values -> $\cos(\beta - \alpha) = 0$

h couplings = h_{SM} couplings
H couplings = A couplings
HVV, Hhh, ... couplings Vanish

Strongly Recommend:
Use $\cos(\beta - \alpha)$ and

Important Region

1. $\tan\beta$ — Large $\tan\beta$
2. β — Small $\tan\beta$
3. $\log_{10}(\tan\beta)$ — All $\tan\beta$

(Snowmass 2013)

	2HDM I	2HDM II	2HDM III	2HDM IV
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
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So α, β and h, H, A, H^{+-} Masses Completely Specify Leading Order Processes with Single h, H, A, H^{+-}

2HDM Couplings

Couplings that include Three h, H, A, H^{+-} require Additional Parameters

(Renormalizable) Tree-Level Potential

$$
\begin{aligned}
V =& \, m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \\
&+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2) + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
&+ \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2) \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]
\end{aligned}
$$

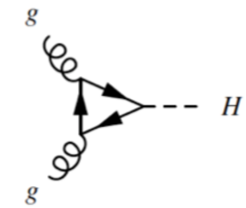
Can Trade: α, β, m_h, m_H, m_A, m_{H+-}, vev for m_{11}, m_{22}, m_{12}, λ_1, λ_2, λ_3, λ_4

So λ_5, λ_6, λ_7 can be taken to Complete the Determination of Tri-Linear Higgs Couplings. Useful - tree-level MSSM $\lambda_5 = \lambda_6 = \lambda_7 = 0$

"Benchmark" Values for Additional Parameters (When Tri-Linear Relevant)

1. $\lambda_5 = \lambda_6 = \lambda_7 = 0$ Specified Completely by α, β, m_h, m_H, m_A, m_{H+-}, v (MSSM)
2. $\lambda_5 = \lambda_6 = \lambda_7 \sim m^2 / v^2$ where m = m_H or m_A as Appropriate (Motivation – "All" Heavy Higgs Self Couplings Same Order)

2HDM Cross Sections: gg->H



Top and Bottom Loops: $|M(gg\to H)|^2 = tt + 2tb + bb$

QCD Corrections: Independent K-factor for each term

LL: Universal K-factor (Radiation from External States Only)

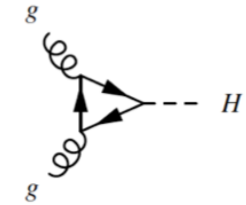
Beyond LL: NLO, NNLO, … Most of Correction from (Partially) Resuming Logs for Radiation from External States

Universal K-factor Approximation
(Differences are Finite Only)

Small tan β – Very Good Approximation for Heavy Higgs tb / tt ~ few %

Can Use SM gg->h K-factors - NNLO + NNLL (finite m_t)

2HDM Cross Sections: gg->H



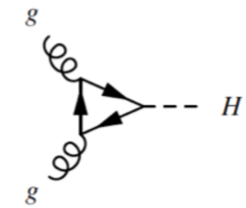
Top and Bottom Loops: $|M(gg\to H)|^2$ = tt + 2tb + bb

QCD Corrections: Independent K-factor for each term

SM Higgs 300 GeV σ(gg->h) (pb)

	GGH@NNLO (LO QCD) $\mu = m_h/2$ m_b^{MSbar} = 4.18 GeV	GGH@NNLO (NLO QCD) $\mu = m_h/2$ m_b^{MSbar} = 4.18 GeV	GGH@NNLO (NNLO QCD) $m = m_h/2$ m_b^{Msbar} = 4.18 GeV
tt	1.748	3.078	3.501
2tb	-0.0476	-0.0954	-0.1138
bb	0.0006	0.00140	0.00180
tot	1.701	2.984	3.389
2tb/tt	-0.0272	-0.031	-0.0325

2HDM Cross Sections: gg->H



Top and Bottom Loops: $|M(gg\to H)|^2$ = tt + 2tb + bb

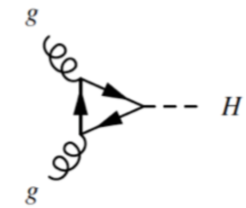
QCD Corrections: Independent K-factor for each term

SM Higgs 300 GeV σ(gg->h) (pb)

	HIGLU (NNLO QCD) $\mu = m_h/2$ m_b^{pole} = 4.78 GeV	GGH@NNLO (NNLO QCD) $\mu = m_h/2$ m_b^{MSbar} = 4.18 GeV
tt	3.486	3.501
2tb	-0.0631	-0.1138
bb	0.00109	0.00180
tot	3.424	3.389

2HDM Cross Sections: gg->H

Top and Bottom Loops: $|M(gg\to H)|^2 = tt + 2tb + bb$

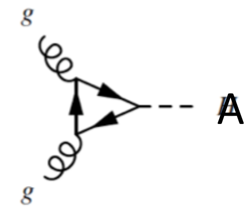


QCD + EW Corrections:

SM Higgs 300 GeV $\sigma(gg\to h)$ (pb)

	HIGLU (NNLO QCD) $\mu = m_h/2$ $m_b^{pole} = 4.78$ GeV	HIGLU (NNLO QCD + EW) $\mu = m_h/2$ $m_b^{pole} = 4.78$ GeV	HXSWG (NNLL QCD + EW)
tt			
2tb			
bb			
tot	3.424	3.360	3.594

2HDM Cross Sections: gg->A



Top and Bottom Loops: $|M(gg\to A)|^2$ = tt + 2tb + bb

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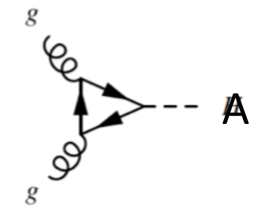


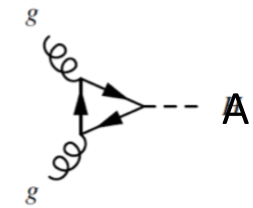
Top and Bottom Loops: $|M(gg\to A)|^2$ = tt + 2tb + bb

QCD Corrections: Independent K-factor for each term

PseuduoScalar Higgs 300 GeV $\sigma(gg\to A)$ (pb)

	GGH@NNLO (LO QCD) $\mu = m_h/2$ m_b^{MSbar} = 4.18 GeV	GGH@NNLO (NLO QCD) $\mu = m_h/2$ m_b^{MSbar} = 4.18 GeV	GGH@NNLO (NNLO QCD) $m = m_h/2$ m_b^{Msbar} = 4.18 GeV
tt	5.249	9.321	10.647
2tb	-0.0876	-0.179	-0.2149
bb	0.0006	0.0015	0.0019
tot	5.162	9.144	10.434
2tb/tt	-0.0166	-0.192	-0.020
A/H tot	3.03	3.06	3.08

2HDM Cross Sections: gg->A



Top and Bottom Loops: $|M(gg \to A)|^2$ = tt + 2tb + bb

QCD Corrections: Independent K-factor for each term

PseudoScalar Higgs 300 GeV $\sigma(gg \to A)$ (pb)

	<u>HIGLU</u> (NNLO QCD) $\mu = m_h/2$ m_b^{pole} = 4.78 GeV	<u>GGH@NNLO</u> (NNLO QCD) $\mu = m_h/2$ m_b^{MSbar} = 4.18 GeV
tt	10.851	10.647
2tb	-0.124	-0.215
bb	0.00115	0.0019
tot	10.728	10.434

2HDM h,H,A Branching Ratios

Assume h.H,A Decay Modes are Same as SM h (Can be Generalized)
So only Br's are Modified

Consider:

h,H,A -> bb, tt, cc, gg, $\mu\mu$, WW, ZZ, $\gamma\gamma$, Zγ

Br(h->f) = Γ(h->f) / Γ(h->All) (Use NLO qq, gg, $\gamma\gamma$, LO Otherwise)

Work to Leading order in h Couplings

$$\Gamma(h\to f) = \Gamma(h_{SM}\to f)\ \Sigma_i\ f(\alpha,\beta\,;\,i)\ \frac{|\,A(h\to f\,;\,i)_{(N)LO}\,|^2}{|\,A(h\to f\,)_{(N)LO}\,|^2}$$

Note: Tree Processes – No sum (Improvements Beyond (N)LO Available)
Loop Processes – Sum over Contributing Loops
h,H,A->gg : b and t Loops
h.H,A->$\gamma\gamma$, Zγ : W, t, and b Loops

2HDM h,H,A Branching Ratios

Assume h Decay Modes are Same as SM h (Can be Generalized)
So only Br's are Modified

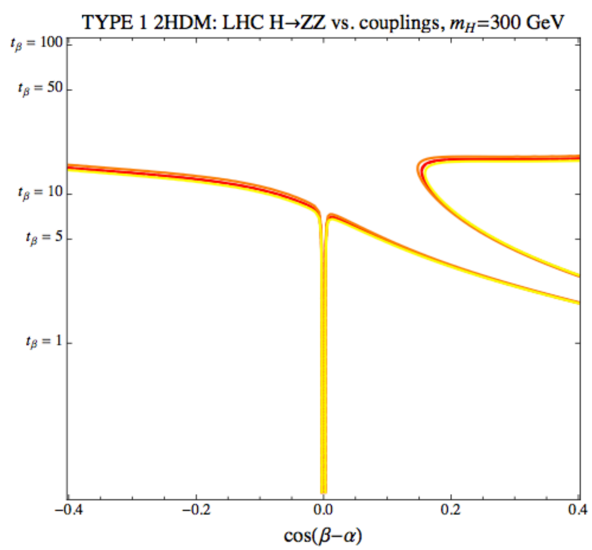
Beyond LO:

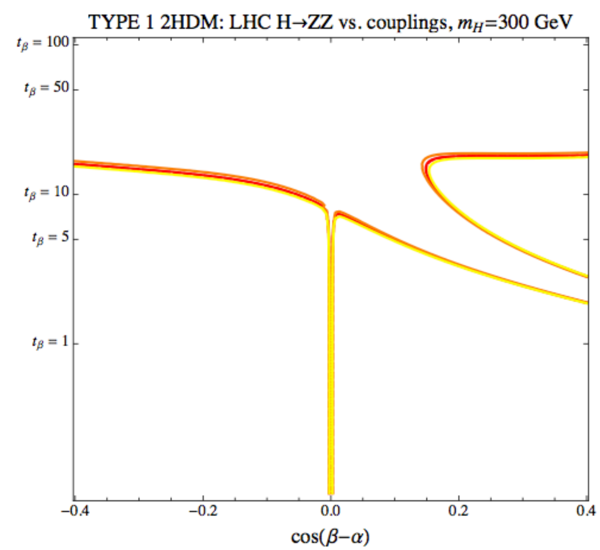
h,H -> qq HDECAY
gg HIGLU
$\gamma\gamma$ NLO hep/ph-0509189

A -> qq NLO hep/ph-9705337, 9505358
gg HIGLU
$\gamma\gamma$ NLO hep/ph-0509189

2HDM σ.Br(H->ZZ)

Projection of future LHC reach 300 GeV H->ZZ:





LL K-factor + Br Approximation

Full Approximations Described Above

Pixelization Systematic