Higgs Theory

Scott Thomas

Lecture 2

Higgs Boson Decays

Couples and Decays most strongly to heaviest SM particle
kinematically available $m_h \simeq 125$ GeV

Two-Body: $h \to bb, cc, \tau\tau, \cdots, gg, \gamma\gamma$

$$\Gamma(h \to bb) \simeq \frac{3m_b^2 m_h}{8\pi v^2} \simeq 2.5 \text{ MeV}$$

$m_b/v \simeq 1.0 \times 10^{-2}$ small coupling - Higgs Vary Narrow State

$$\frac{\Gamma(h \to gg, \gamma\gamma)}{\Gamma(h \to bb)} \simeq \frac{\alpha^2\, m_h^2}{16\pi^2\, m_b^2} \sim 10^{-1}, 10^{-3}$$

Three-Body: $h \to WW^*, ZZ^* \to W\ell\nu, Z\ell\ell, \cdots$

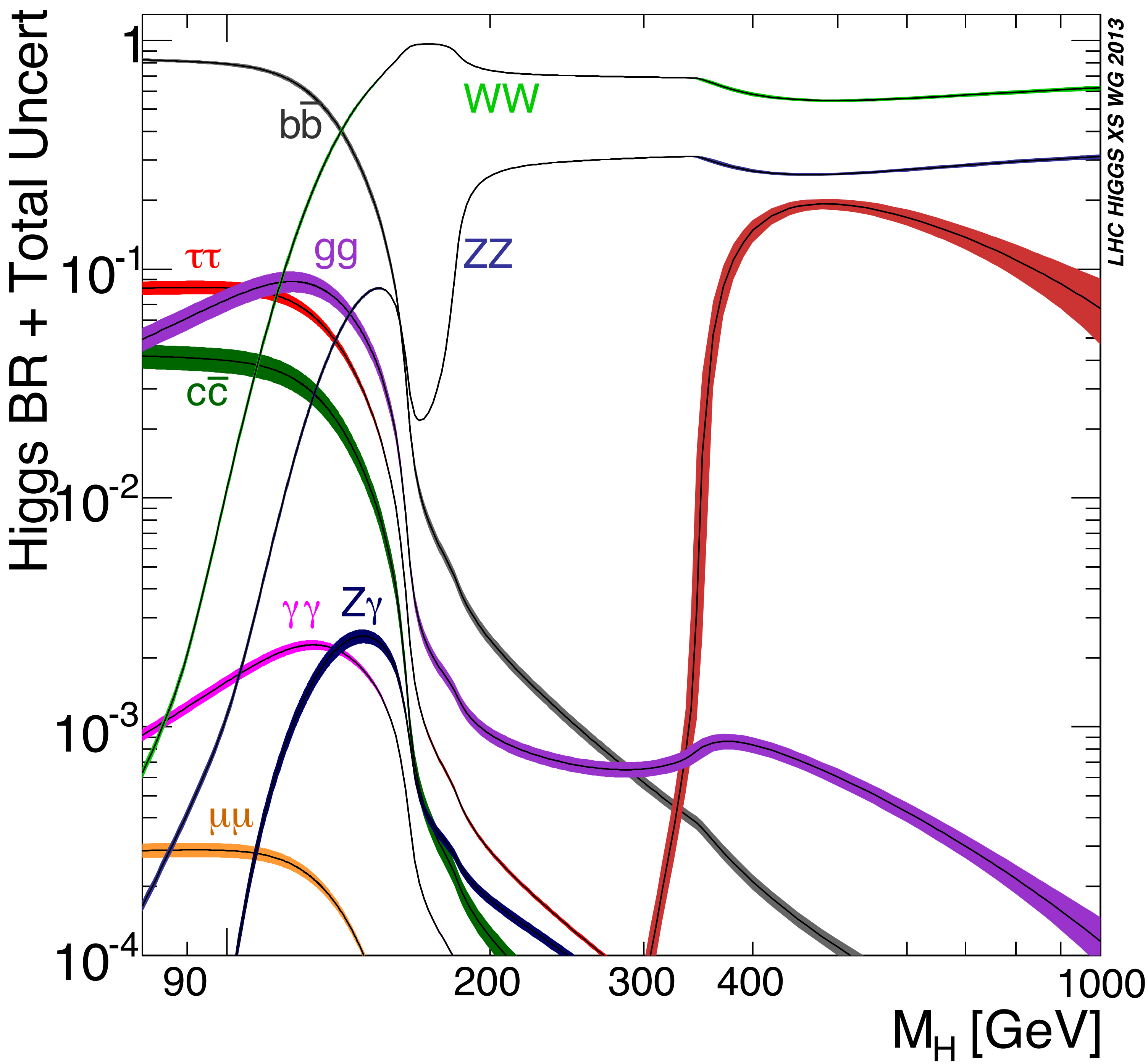
$$\frac{\Gamma(h \to WW^* \to W\ell\nu)}{\Gamma(h \to bb)} \simeq \frac{g^2 m_W^4}{16\pi^2\, m_b^2 m_h^2} \sim 1$$

$\Gamma(h \to \text{All}) \simeq 4.1$ MeV

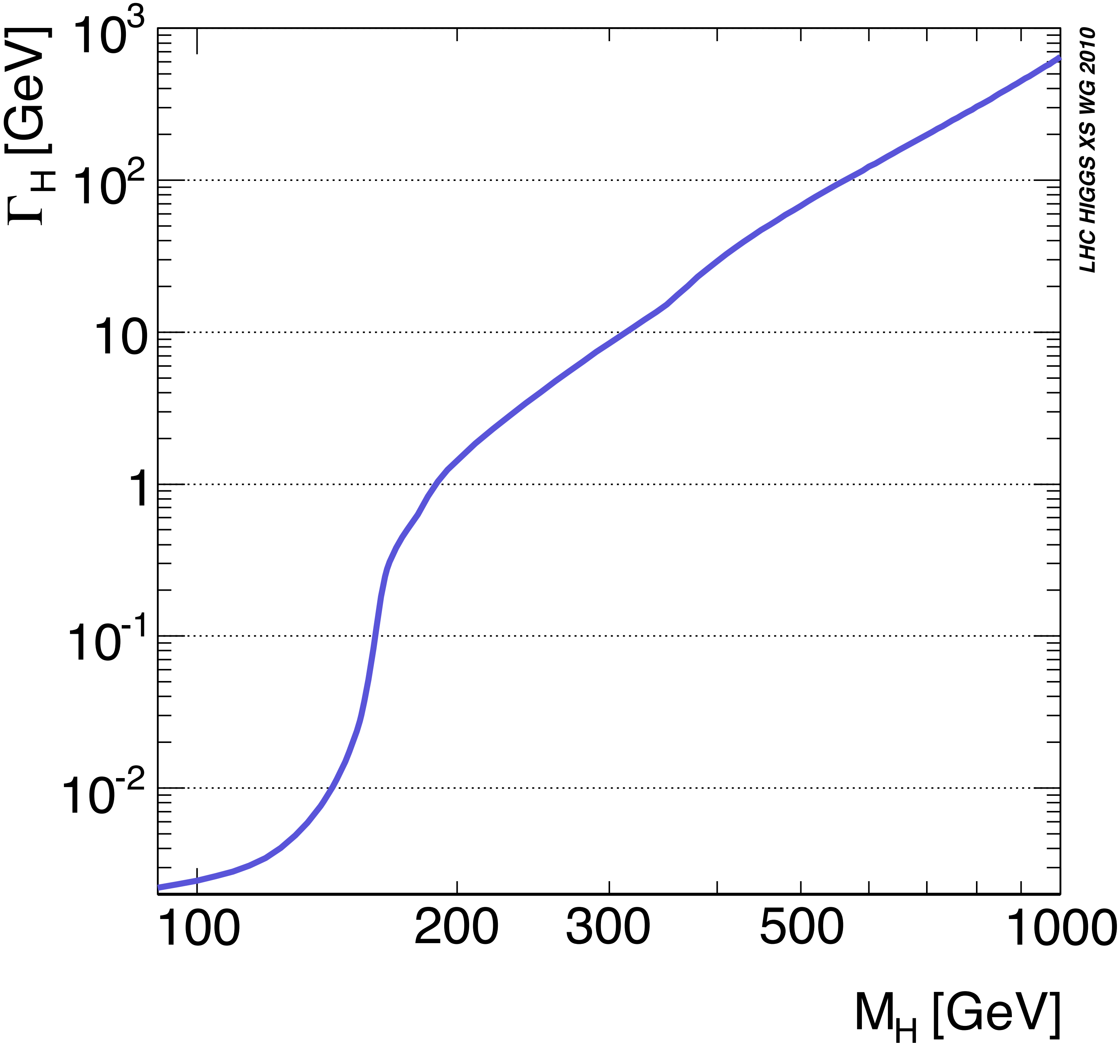
$m_h \simeq 125$ GeV

	$\text{Br}(h \to X)$
bb	0.58
WW^*	0.21
gg	0.086
$\tau\tau$	0.063
cc	0.029
ZZ^* ($\ell\ell\ell\ell$)	0.026 (1.2×10^{-4})
$\gamma\gamma$	2.3×10^{-3}
$Z\gamma$ ($\ell\ell\gamma$)	1.5×10^{-3} (1.0×10^{-4})
$\mu\mu$	2.2×10^{-4}

Resonant EM final state



Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$b\bar{b}$
WW
ZZ
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
$\mu\mu$
90
200
300
400
1000
M_H [GeV]



Γ_H [GeV]
10^3
10^2
10
1
10^{-1}
10^{-2}
100
200
300
500
1000
M_H [GeV]
LHC HIGGS XS WG 2010

Higgs Boson Production LHC

$\sigma(pp \to \text{final})$ is a convolution of $\sigma(\xi_1\xi_2 \to \text{final})$ with ξ_i parton distribution functions $f_i(x)$ $\quad x = p^\mu_\xi / p^\mu_p$

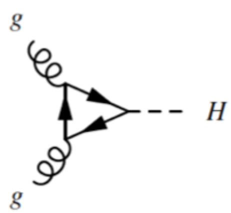
$$\sigma(pp \to \text{final} \,|\, s_{pp}) = \int_0^1 dx \int_0^1 dy \;\, f_1(x)\, f_2(y)\;\, \sigma(\xi_1\xi_2 \to \text{final} \,|\, s_{\xi_1\xi_2})$$

$$= \int_{\tau_{\text{min}}}^1 d\tau \int_\tau^1 \frac{dx}{x}\; f_1(x)\, f_2(\tau/x)\;\, \sigma(\xi_1\xi_2 \to \text{final} \,|\, \tau s_{pp})$$

$\tau_{\text{min}} = m^2_{\text{final}}/s_{pp} \quad m_{\text{final}} = \sum_i m_i \quad i = 1, \cdots, N_{\text{final}}$

Higgs Boson Production LHC

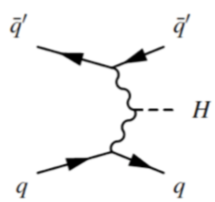
Gluon Fusion ggF



$$\sigma(gg \to h) \simeq \frac{\alpha_s^2\, m_h^2}{4\pi\, v^2}\, \delta(s_{gg} - m_h^2)$$

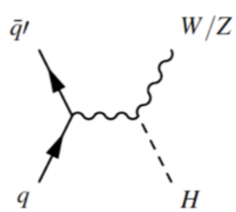
$$\sigma(pp \to gg \to h) \simeq \frac{\alpha_s^2}{4\pi\, v^2} f(s_{pp}/m_h^2) \qquad f(x) \sim \ln x$$

Vector Boson Fusion VBF



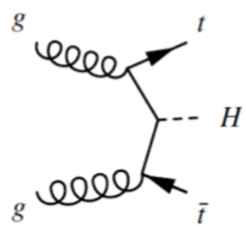
$$\sigma(pp \to qq\, WW^* \to qq\, h) \simeq \frac{\alpha_W^2\, m_W^4}{4\pi\, m_h^4\, v^2} \ln^2(s_{pp}/m_W^2)$$

Associated Vector Boson Production Wh, Zh



$$\sigma(pp \to Wh, Zh) \simeq \frac{\alpha_W\, m_W^4}{m_h^4\, v^2}$$

Associated Top Quark Production   tth



$$\sigma(pp \to t\bar{t}\,h) \simeq \frac{\alpha_s^2}{4\pi\, v^2}$$

Associated Bottom Quark Production   bbh

$$\sigma(pp \to b\bar{b}\,h) \simeq \frac{\alpha_s^2\, m_b^2}{4\pi\, m_h^2\, v^2} \ln^2(s_{pp}/m_b^2)$$

$m_h \simeq 125$ GeV $\quad \sqrt{s_{pp}} = 13$ TeV

	$\sigma(pp \to h)$ (fb)
ggF	43900
VBF	3750
Wh	1380
Zh	870
tth	510
bbh	510

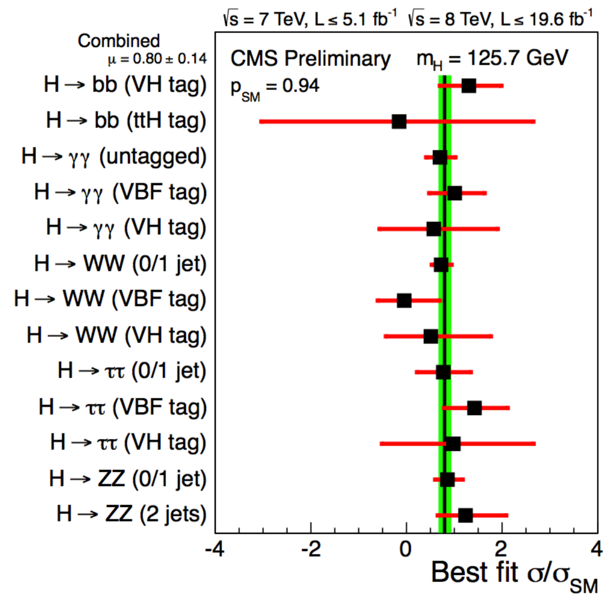
Rate$(pp \to h) \simeq \mathcal{O}(10^6)$ / 20 fb^{-1}

Higgs Boson Rate Measurements

Number of Channels Observed + Measured

σ.Br (Initial -> h -> Final)

Many Many More Eventually …



	Inclusive	VBF	Vh	tth
γγ	X (blue circle)	X (blue circle)	X (brown circle)	X (brown circle)
ZZ*	X (blue circle)	X	X	X (brown circle)
WW*	X (blue circle)	X (brown circle)	X (brown circle)	X (brown circle)
ττ	X (brown circle)	X (brown circle)	X (brown circle)	X (brown circle)
bb			X (brown circle)	X (brown circle)
Z γ	X	X	X	
μμ	X	X	X	X

◯ (blue) Discovery

◯ (brown) Run 1

X Run 2, 3 +

Higgs Boson Rate Measurements

Higgs is Window into EWSB Sector

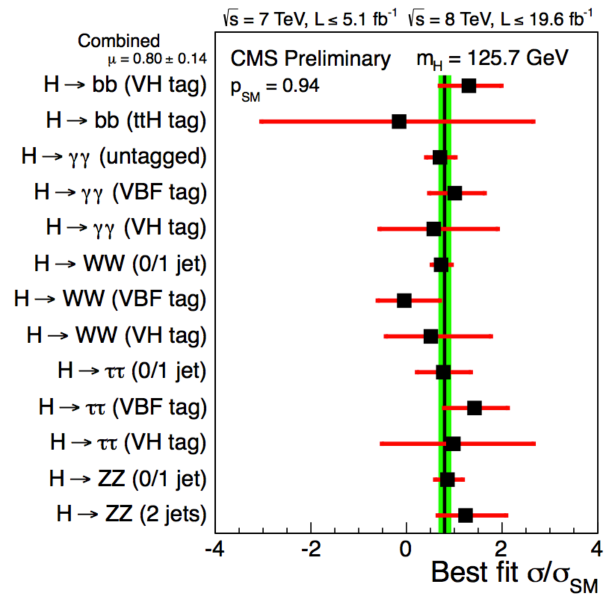
Signals of New Physics in
SM Higgs Rate Measurements

Deviations in SM Higgs Couplings

- Fit to SM Couplings
- Effective Operator Analysis
- Specific Underlying
  Theoretical Framework

  Extended Higgs Sector
  Supersymmetry
  ...

σ.Br (Initial -> h -> Final)

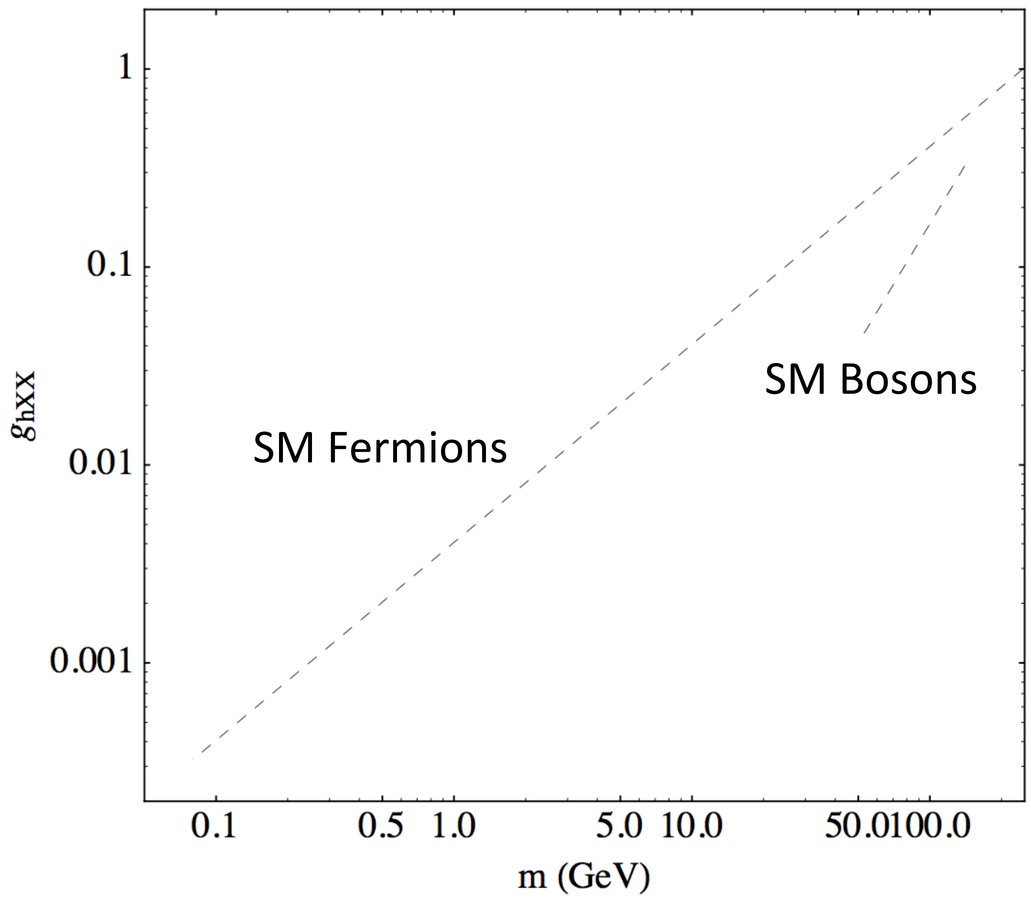


Any Deviations at Discovery Level
are by Definition Large ...

Higgs Boson Rate Measurements

New Tests of Standard Model – Higgs Sector

σ.Br (Initial -> h -> Final)



$g_{hXX} = (m_X/v)^n$

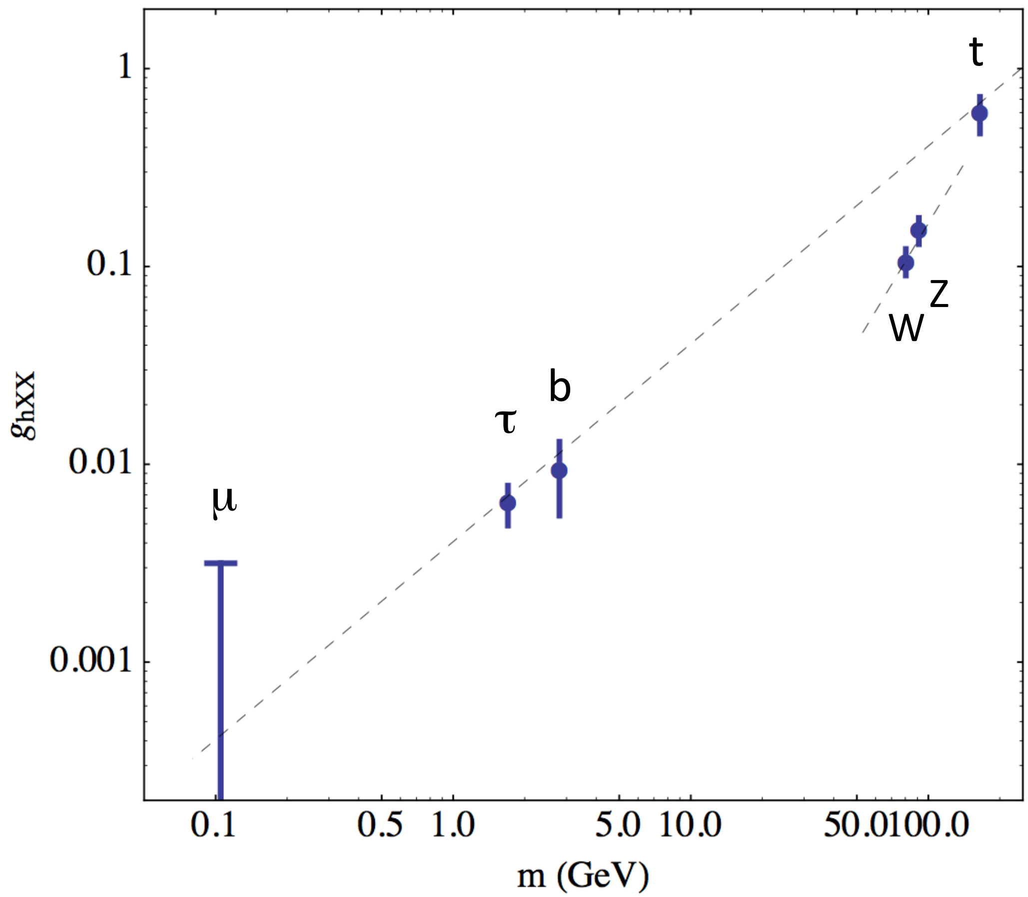
n = 1 Fermion
n = 2 Boson

Higgs Boson Rate Measurements

New Tests of Standard Model – Higgs Sector

σ.Br (Initial -> h -> Final)

It's the Higgs Boson !



CMS Global Fit
5 + 20 fb^{-1}

Standard Model Hypothesis

$g_{hXX} = (m_X/v)^n$

n = 1 Fermion
n = 2 Boson

Precision Probes of New Electroweak Physics

Electroweak Observables

G_F, m_W, m_Z, Γ_Z, $A_{Z\text{-}FB}$, ...

Renormalizable SM +
D=6 Operators

H = ‹H›

$$\frac{\xi_T}{M^2}\,(H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2}\; H^\dagger W_{\mu\nu} H\; B^{\mu\nu}$$

PDG

S = 0.01 +- 0.10 $\qquad M^2/\xi_{12} > (3.9\ \text{TeV})^2$

T = 0.03 +- 0.11

Systematics: m_t, $\ln(m_h)$, α_S , ...

$$\xi_{12} / M^2 = S_{12} / 8\pi v^2$$

Precision Electroweak Physics Through the Higgs

Higgs Observables

σ . Br (Initial -> h -> Final)

$$\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)} \simeq \left.\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)}\right|_{\mathrm{SM}} \left[1 + \mathcal{O}\left(\frac{\alpha}{4\pi v^2}\frac{M^2}{\xi}\right)\right]$$

Best Channels: (Ratios)

σ . Br (Inclusive -> h -> Resonant Final)

Renormalizable SM + D=6 Operators

H = ‹H› + h

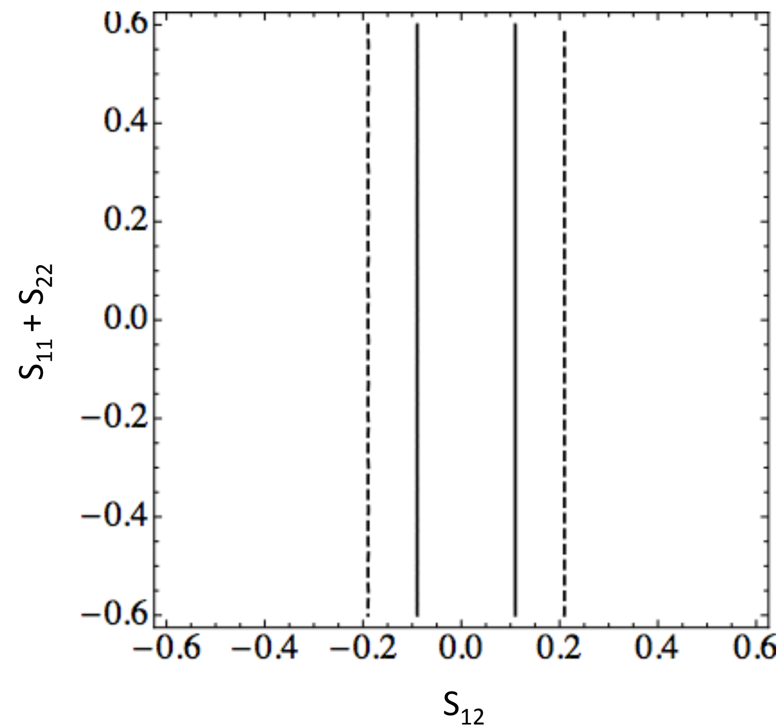
$$\frac{\xi_T}{M^2}\,(H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2}\; H^\dagger W_{\mu\nu} H\; B^{\mu\nu}$$

$$\frac{g_1^2 \xi_{S_{11}}}{2M^2}\; H^\dagger H\; B_{\mu\nu} B^{\mu\nu}$$

$$\frac{g_2^2 \xi_{S_{22}}}{2M^2}\; H^\dagger H\; W_{\mu\nu} W^{\mu\nu}$$

PEW



$\xi_{12} / M^2 = S_{12} / 8\pi v^2$

Precision Electroweak Physics Through the Higgs

Higgs Observables

σ . Br (Initial -> h -> Final)

$$\frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}(h\to ZZ)} \simeq \frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}(h\to ZZ)}\bigg|_{\mathrm{SM}}\left[1+\mathcal{O}\left(\frac{\alpha}{4\pi v^2}\frac{M^2}{\xi}\right)\right]$$

Best Channels: (Ratios)

σ . Br (Inclusive -> h -> Resonant Final)

Renormalizable SM + D=6 Operators

H = ‹H› + h

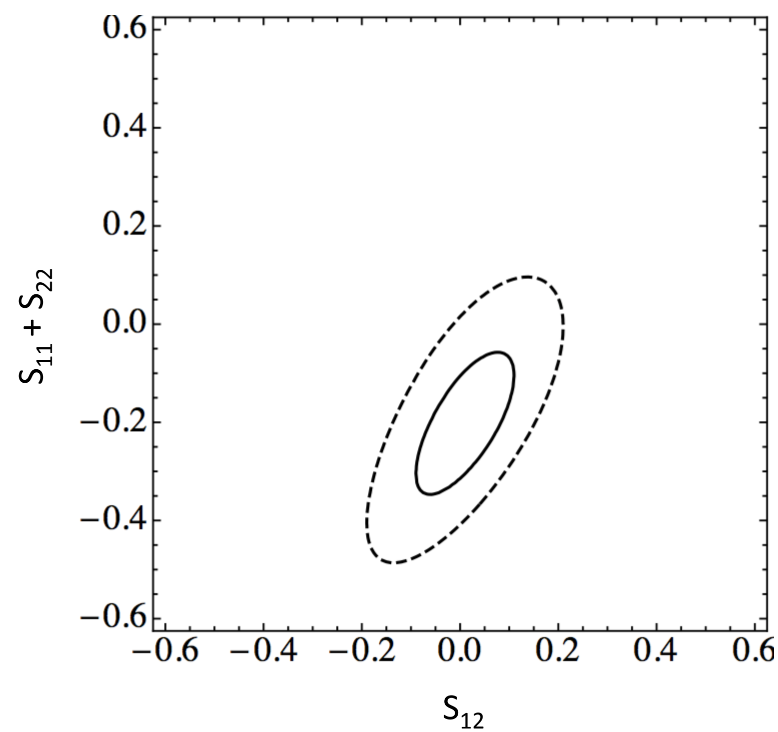
$$\frac{\xi_T}{M^2}\,(H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2}\; H^\dagger W_{\mu\nu} H\; B^{\mu\nu}$$

$$\frac{g_1^2 \xi_{S_{11}}}{2M^2}\; H^\dagger H\; B_{\mu\nu} B^{\mu\nu}$$

$$\frac{g_2^2 \xi_{S_{22}}}{2M^2}\; H^\dagger H\; W_{\mu\nu} W^{\mu\nu}$$

PEW + CMS 5 + 12(5) fb⁻¹ 7 + 8 TeV



Systematics: Statistics, Resonant-Continuum Separation + Interference, …

Precision Electroweak Physics Through the Higgs

Higgs Observables

σ . Br (Initial -> h -> Final)

$$\frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}(h\to ZZ)} \simeq \left.\frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}(h\to ZZ)}\right|_{\mathrm{SM}} \left[1+\mathcal{O}\left(\frac{\alpha}{4\pi v^2}\frac{M^2}{\xi}\right)\right]$$

Best Channels: (Ratios)

σ . Br (Inclusive -> h -> Resonant Final)

Renormalizable SM + D=6 Operators

H = ‹H› + h

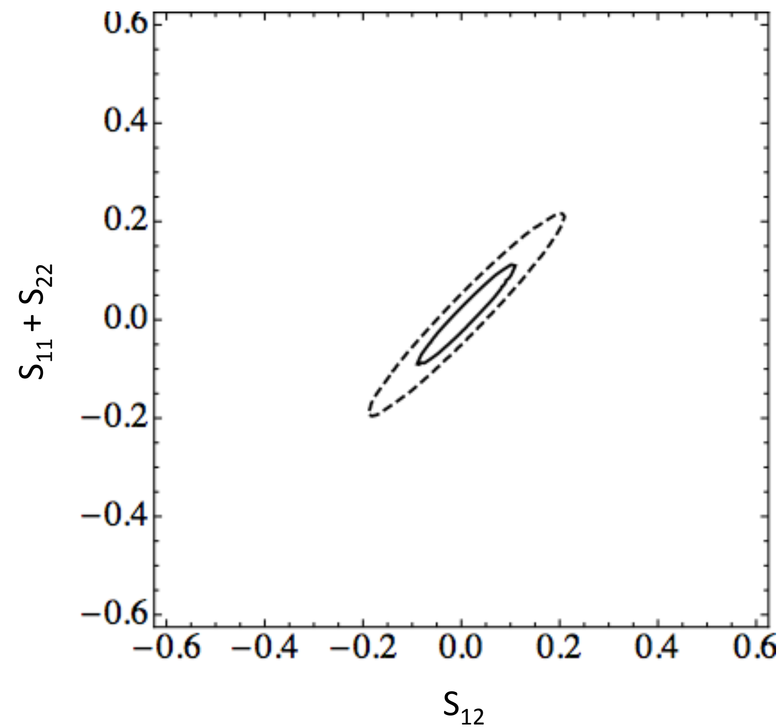
$$\frac{\xi_T}{M^2}\,(H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2}\; H^\dagger W_{\mu\nu} H\; B^{\mu\nu}$$

$$\frac{g_1^2 \xi_{S_{11}}}{2M^2}\; H^\dagger H\; B_{\mu\nu} B^{\mu\nu}$$

$$\frac{g_2^2 \xi_{S_{22}}}{2M^2}\; H^\dagger H\; W_{\mu\nu} W^{\mu\nu}$$

PEW + 5% Uncertainty Br(h->γγ)/Br(h->ZZ)



Systematics: Statistics, Resonant-Continuum Separation + Interference, …

Searching for 2nd Higgs Doublet in SM Higgs Boson Rate Measurements

Two Higgs Doublets h, A, H, H+-

(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

h-H mix

Large modifications of h couplings Possible

Four Discrete Two Doublet Models that Satisfy Glashow-Weinberg Condition

Two Parameters, α , β

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

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

Four couplings

	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	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Searching for 2nd Higgs Doublet in SM Higgs Boson Rate Measurements

Two Higgs Doublets h-H mix

(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	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

h-H mix

Large modifications of h couplings Possible

Four Discrete Two Doublet Models that Satisfy Glashow-Weinberg Condition

Two Parameters, α , β

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

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

Four couplings

Alignment Limit:

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

h couplings = h_{SM} couplings

Searching for 2nd Higgs Doublet in SM Higgs Boson Rate Measurements

Two Higgs Doublets h-H mix

h-H mix

Large modifications of h couplings Possible

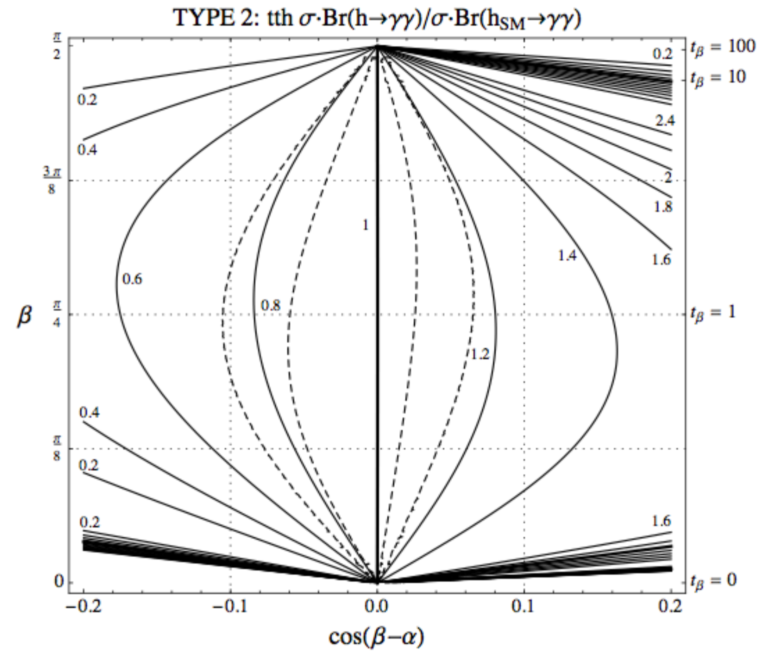
Four Discrete Two Doublet Models that Satisfy Glashow-Weinberg Condition

Two Parameters, α, β

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

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

Four couplings



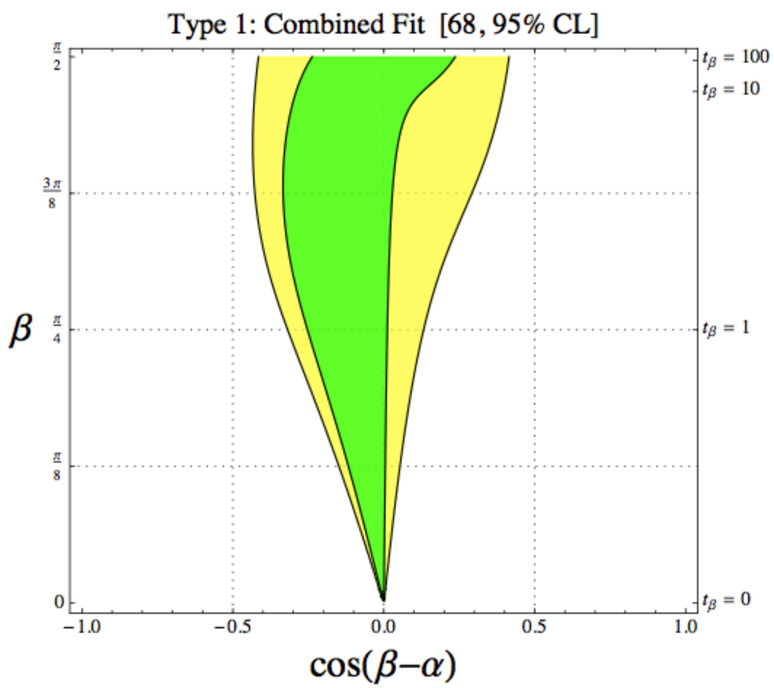
Alignment Limit:

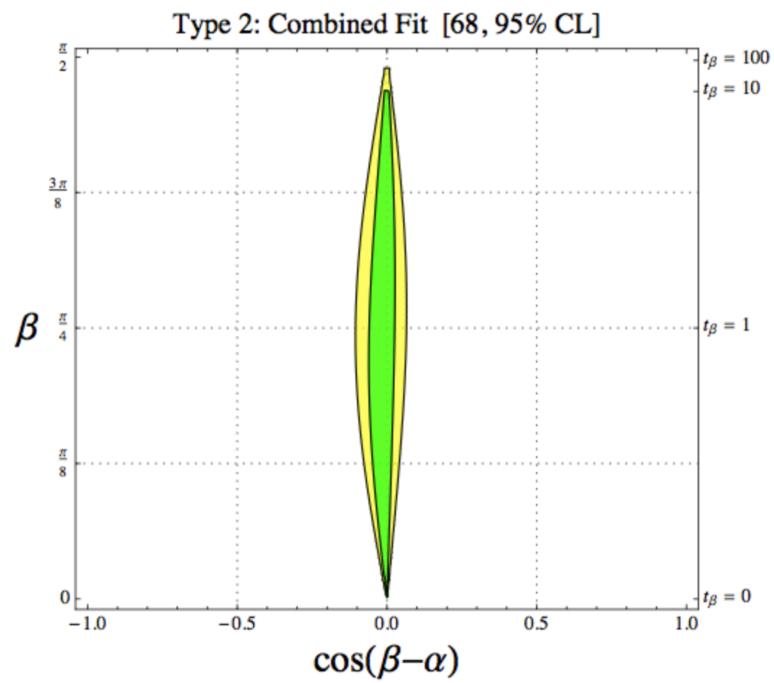
h mass Eigenstate || Expectation Values $\cos(\beta - \alpha) = 0$

h couplings = h_{SM} couplings

Searching for 2nd Higgs Doublet in SM Higgs Boson Rate Measurements

Two Higgs Doublets h-H mix





hQd , hQu $\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$

hQd $\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$

hQu $\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$

Searching for 2^{nd} Higgs Doublet in SM Higgs Boson Rate Measurements

Two Higgs Doublets h-H mix

Experimentally:

h Couplings ~ h_{SM} Couplings

Theoretically for 2HDM Implies:

Type I – Close to Alignment Limit
Type II – Very Close to Alignment Limit

Implications for Proximity to
Decoupling Limit - (Model Dependent)

Implications for A,H,H+- Couplings
Direct Searches …

Direct Searches for 2nd Higgs Doublet

Two Higgs Doublets h, A, H, H+-

h/A/H+-/H :

125/230/230/500 GeV

(105 Signal Topologies)

Production	Decay
$gg \to h$	$h \to 4\ell$
$VBF \to h$	$h \to 4\ell$
$gg \to H$	$H \to 4\ell$
	$H \to hh \to 4W, WW\tau\tau, 4\tau, ZZb\bar{b}, ZZWW, 4Z, ZZ\tau\tau$
	$H \to AA \to 4\tau$
	$H \to AA \to \tau\tau Zh \to \tau\tau ZWW, \tau\tau Z\tau\tau, \tau\tau Zb\bar{b}, \tau\tau ZZZ$
	$H \to AA \to ZhZh \to ZZWWWW, ZZWW\tau\tau, ZZWWb\bar{b}, ZZ\tau\tau b\bar{b}, ZZ\tau\tau\tau\tau$
	$H \to AA \to ZhZh \to ZZb\bar{b}b\bar{b}, ZZZZb\bar{b}, ZZZZ\tau\tau, ZZZZWW, ZZZZZZ$
	$H \to H^+H^- \to WhWh \to WWWWWW, WWWW\tau\tau, WWWWb\bar{b}, WW\tau\tau\tau\tau$
	$H \to H^+H^- \to WhWh \to WW\tau\tau b\bar{b}, WWZZb\bar{b}, WWWWZZ, WWZZZZ, WWZZ\tau\tau$
	$H \to H^+H^- \to \tau\nu Wh \to \tau\nu WWW, \tau\nu W\tau\tau, \tau\nu WZZ$
	$H \to H^+H^- \to tbWh \to tbWWW, tbW\tau\tau, tbWZZ$
	$H \to ZA \to Z\tau\tau$
	$H \to ZA \to ZZh \to ZZ\tau\tau, ZZWW, ZZb\bar{b}, ZZZZ$
$VBF \to H$	$H \to 4\ell$
	$H \to hh \to 4W, WW\tau\tau, 4\tau, ZZb\bar{b}, ZZWW, 4Z, ZZ\tau\tau$
	$H \to AA \to 4\tau$
	$H \to AA \to \tau\tau Zh \to \tau\tau ZWW, \tau\tau Z\tau\tau, \tau\tau Zb\bar{b}, \tau\tau ZZZ$
	$H \to AA \to ZhZh \to ZZWWWW, ZZWW\tau\tau, ZZWWb\bar{b}, ZZ\tau\tau b\bar{b}, ZZ\tau\tau\tau\tau$
	$H \to AA \to ZhZh \to ZZb\bar{b}b\bar{b}, ZZZZb\bar{b}, ZZZZ\tau\tau, ZZZZWW, ZZZZZZ$
	$H \to H^+H^- \to WhWh \to WWWWWW, WWWW\tau\tau, WWWWb\bar{b}, WW\tau\tau\tau\tau$
	$H \to H^+H^- \to WhWh \to WW\tau\tau b\bar{b}, WWZZb\bar{b}, WWWWZZ, WWZZZZ, WWZZ\tau\tau$
	$H \to H^+H^- \to \tau\nu Wh \to \tau\nu WWW, \tau\nu W\tau\tau, \tau\nu WZZ$
	$H \to H^+H^- \to tbWh \to tbWWW, tbW\tau\tau, tbWZZ$
	$H \to ZA \to Z\tau\tau$
	$H \to ZA \to ZZh \to ZZ\tau\tau, ZZWW, ZZb\bar{b}, ZZZZ$
$gg \to A$	$A \to Zh \to ZWW, Z\tau\tau, ZZZ$
$q\bar{q} \to Wh$	$Wh \to WWW, W\tau\tau, WZZ$
$q\bar{q} \to Zh$	$Zh \to ZWW, Z\tau\tau, ZZZ$
$t\bar{t}h$	$t\bar{t}h \to t\bar{t}WW, t\bar{t}\tau\tau, t\bar{t}ZZ$
$t\bar{t}A$	$t\bar{t}A \to t\bar{t}\tau\tau$
	$t\bar{t}A \to t\bar{t}Zh \to t\bar{t}ZWW, t\bar{t}Z\tau\tau, t\bar{t}Zb\bar{b}, t\bar{t}ZZZ$

Direct Searches for 2nd Higgs Doublet

Two Higgs Doublets h, A, H, H^{+-}

Consider Spectrum:

$m_A \sim m_H \sim m_{H+-} > m_h$

Splittings < $O(m_W^2 / m_A)$

Hierarchy of heavy Higgs leading LHC production channels that do not vanish in the 2HDM alignment limit

Single Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^2)$	$gg \to H\,,\ A$
Single Heavy Higgs Associated Strong Production	$\mathcal{O}(g_s^4\lambda_f^2)$	$gg \to bbH\,,\ bbA\,,\ tbH^\pm$ $ttH\,,\ ttA$
Single Heavy Higgs Associated Weak Production	$\mathcal{O}(g_s^2 g_w^4\lambda_f^2)$	$qg \to bq'\,bH^\pm\,,\ bq\,tH$ $bq\,tA$
Double Heavy Higgs Weak Production	$\mathcal{O}(g_w^4)$	$q\bar{q} \to HA\,,\ HH^\pm$ $AH^\pm\,,\ H^+H^-$
Light + Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^4)$	$gg \to hH\,,\ hA$
Double Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^4)$	$gg \to HH\,,\ HA$ $AA\,,\ H^+H^-$

Standard Model decay channels of 2HDM heavy Higgs bosons

		H	A	$H^\pm$
Standard Model Decay Channels	WW, ZZ	–		
	$tt, bb, \tau\tau, \mu\mu$	✓	✓	
	$\gamma\gamma$	✓	✓	
	Zh		–	
	hh	–		
	Wh			–
	$tb, \tau\nu$			✓

✓ Partial decay width approaches a Constant in alignment limit

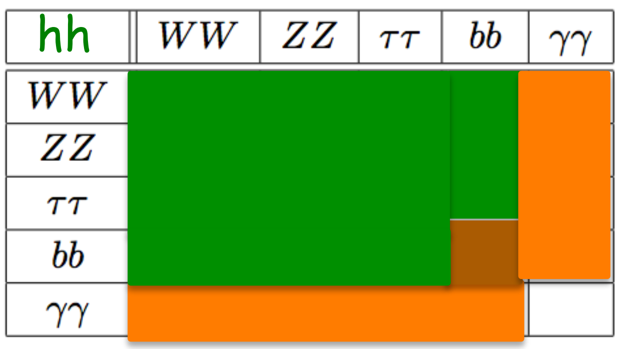
– Partial decay width Vanishes in the alignment limit

Direct Searches for 2nd Higgs Doublet

Two Higgs Doublets h, A, H, H^{+-}

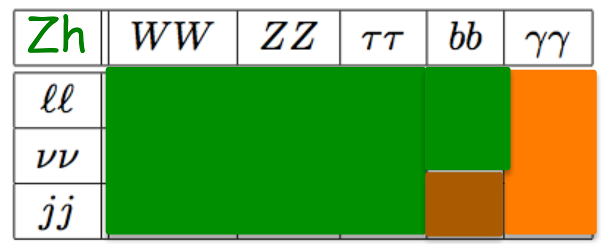
gg -> H -> hh , gg -> A -> Zh

hh Decay Modes



Leptons +X
Di-Photons + X
Quad-b-jets

Zh Decay Modes

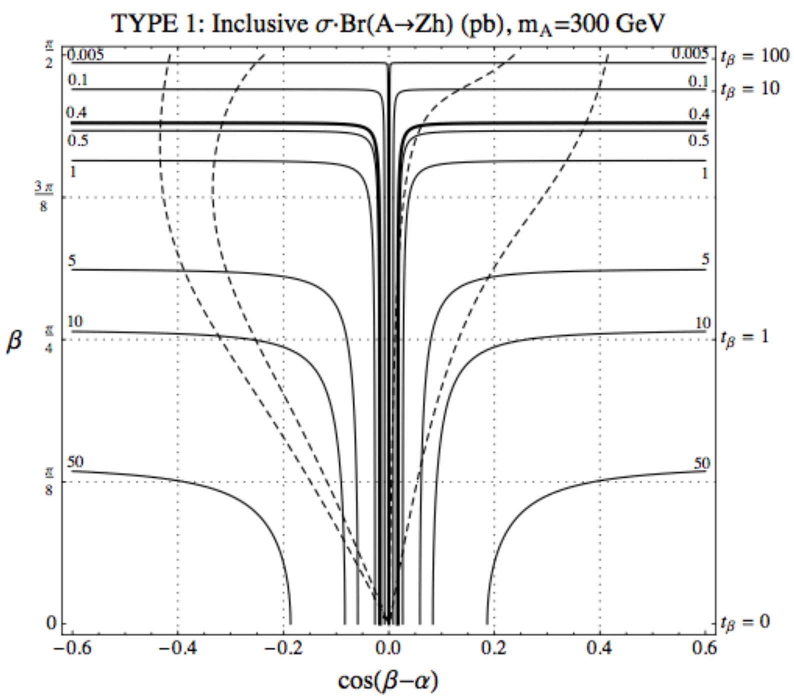


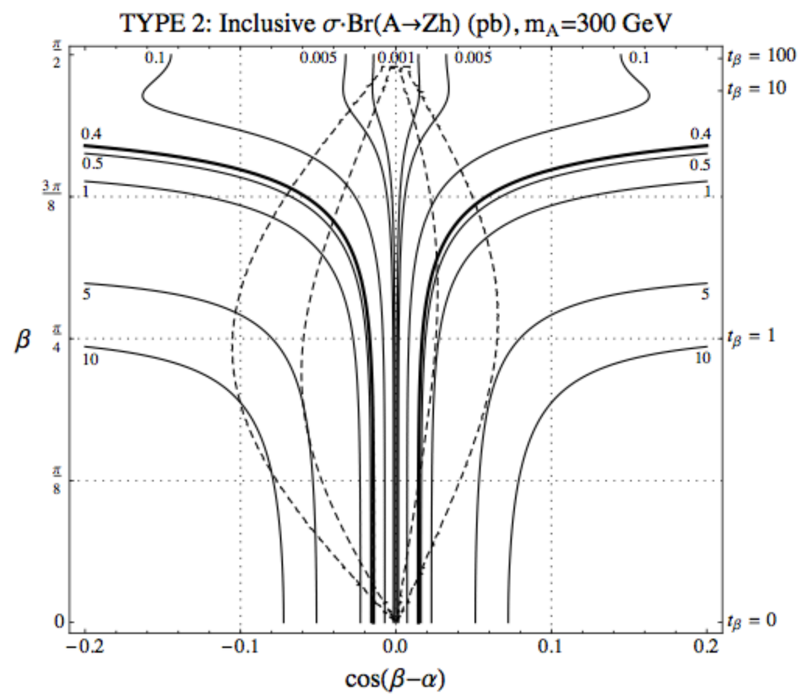
Leptons + X
Di-Photons + X
Di-b-jets + X

Direct Searches for 2nd Higgs Doublet

Two Higgs Doublets h, A, H, H+-

gg -> A -> Zh



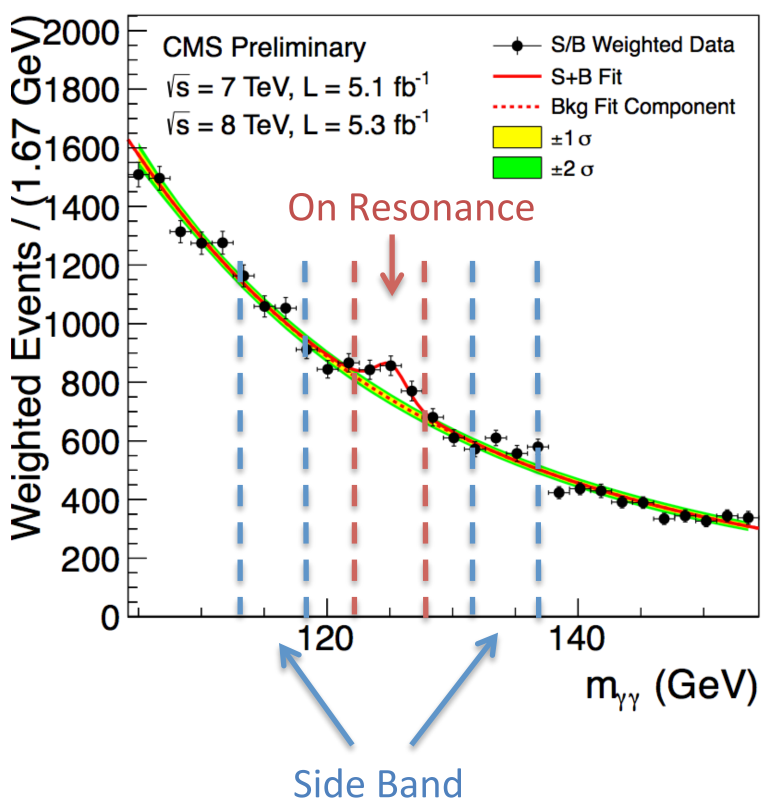


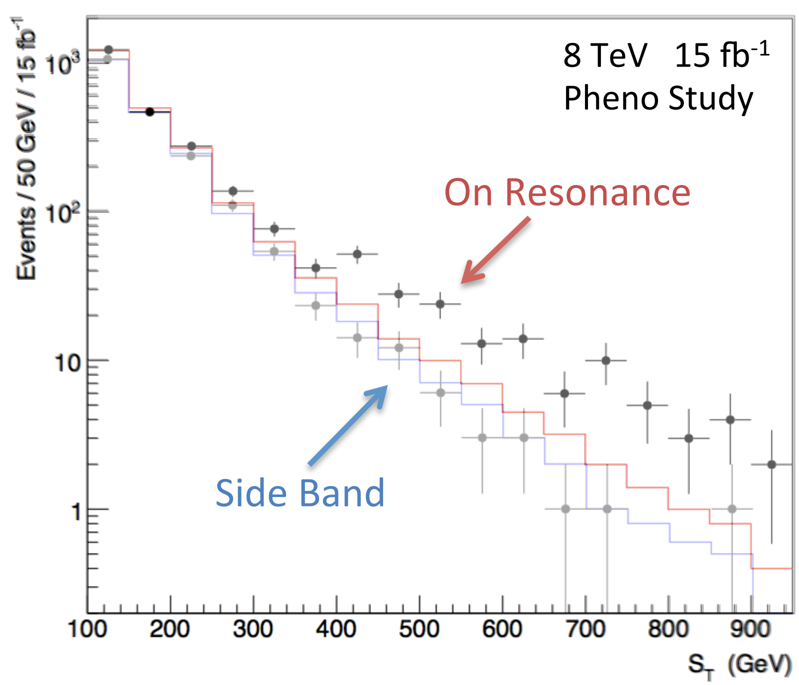
Using Higgs -> γγ to Discover New Physics

Use 125 GeV Higgs as Calibration to Search for New Physics

h -> γγ + X (Least Rare of the Resonant Decay Modes)

On-Resonance + Upper and Lower Side Bands
Even Blunt Variables Suffice + More focused + …





Blue = Side Band Background
Red = On Resonance SM Higgs + Background + Stop -> h + X

Using Higgs -> γγ to Discover New Physics

Use 125 GeV Higgs as Calibration to Search for New Physics

h -> γγ + X (Least Rare of the Resonant Decay Modes)

On-Resonance + Upper and Lower Side Bands
Even Blunt Variables Suffice + More focused + …

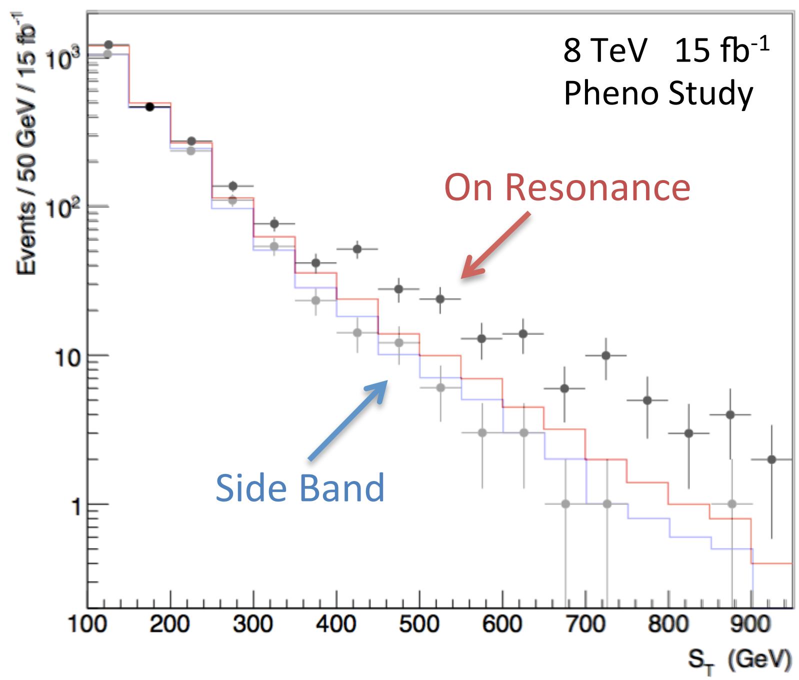
Natural Higgsino NLSP

Stop Pair Production 250 GeV
with stop -> b + Higgsino and
Higgsino -> h + Goldstino

Many other Examples …

More Focused ->

X = Multi-Channel Analysis



Blue = Side Band Background
Red = On Resonance SM Higgs + Background + Stop -> h + X

Higgs Boson Decay to Dark Matter

If the Dark Matter particle gets some of its mass from Higgs Condensate - it couples to the Higgs Boson
(Low Energy (Soft) Higgs Theorem)

Bino-Like Neutralino Dark Matter

$$-\frac{1}{2} m_\chi \chi\chi \qquad m_\chi \simeq m_1 - \frac{m_Z^2 \sin^2\theta \; (m_1 + \mu^* \sin 2\beta)}{|\mu|^2 - |m_1|^2} + \cdots$$

Higgs-χ-χ Coupling

$$-\frac{1}{2} \frac{\partial m_\chi}{\partial m_Z} \frac{\partial m_Z}{\partial v} h\, \chi\chi = -\frac{1}{2} m_Z \frac{\partial m_\chi}{\partial m_Z} \frac{h}{v} \chi\chi$$

$$= \frac{m_Z^2 \sin^2\theta \; (m_1 + \mu^* \sin 2\beta)}{|\mu|^2 - |m_1|^2} \; \frac{h}{v} \chi\chi + \cdots$$

So $\Gamma(h \to \chi\chi) \neq 0$ if $m_\chi < m_h/2$

Dilutes All Higgs $\to$ SM Branching Ratios

Dark Matter - Nucleon Coupling

In light quark chiral (massless) limit $\quad m_n = C\,\Lambda_{\text{QCD}}$

$$\Lambda_{\text{QCD}} = \mu\ \exp\left(-\int \frac{d(1/g^2)}{\beta_{1/g^2}}\right) \simeq \mu'\ \exp\left(-\frac{8\pi^2}{b\,g^2(\mu)}\right)$$

Heavy quark thresholds (c,b,t) gain mass from EWSB $\Rightarrow$
(Soft) Higgs couples to nucleon

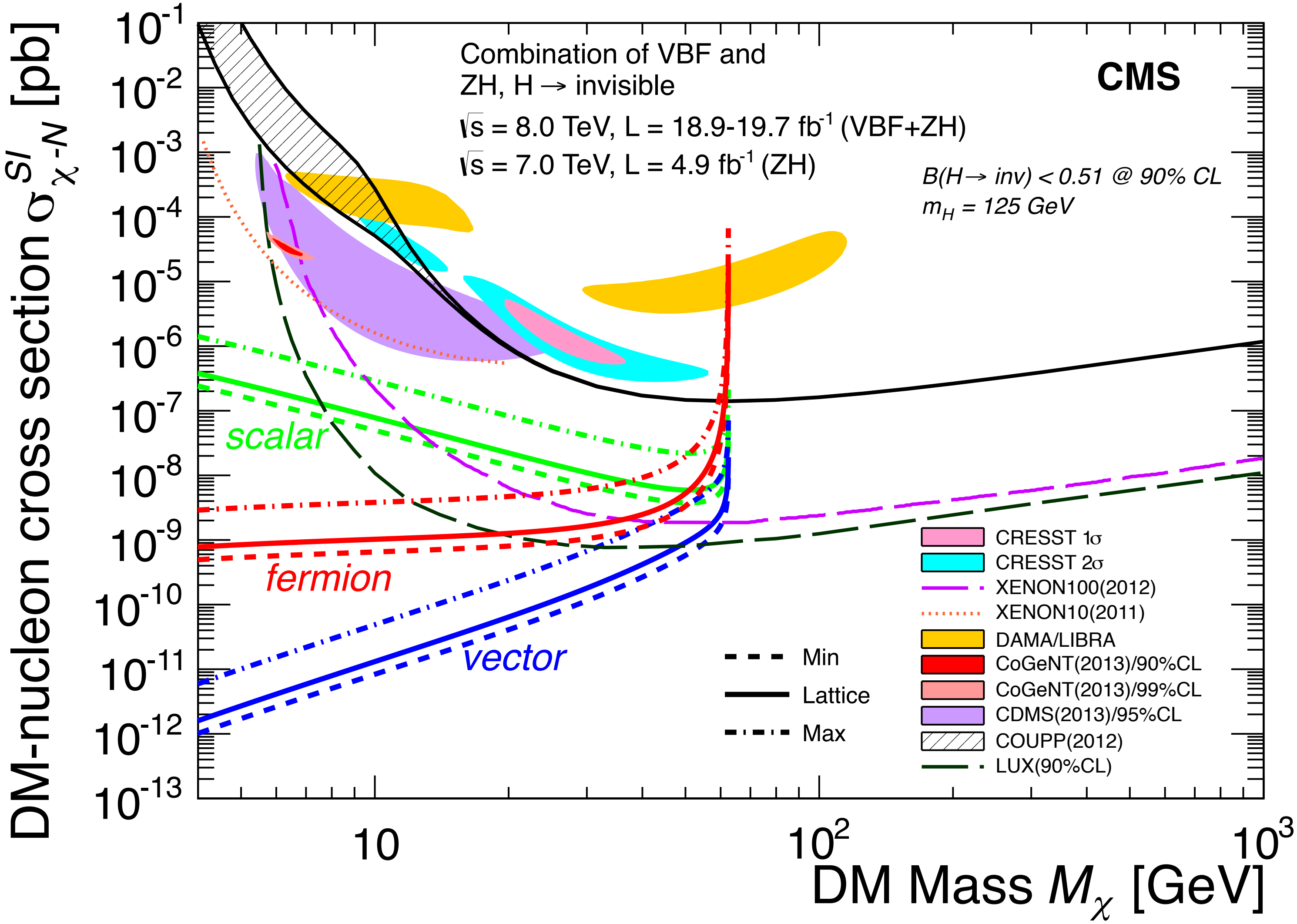
$$-\,m_n\,\bar{n}n \qquad\qquad m_n = C\,\Lambda_{\text{QCD}}(v)$$

(Soft) Higgs - nucleon - nucleon coupling

$$-\frac{\partial m_n}{\partial v}\,h\,\bar{n}n = -g_{\chi nn}\,m_n\,\frac{h}{v}\,\bar{n}n$$

$$\frac{\partial m_n}{\partial v} \simeq -m_n\,\frac{8\pi^2}{b_L}\,\frac{\partial}{\partial v}\,\frac{1}{g^2(m_Q)} = -m_n\,\frac{8\pi^2}{b_L}\,\frac{\Delta b}{8\pi^2}\,\frac{1}{v} = \frac{\Delta b}{b_L}\,\frac{m_n}{v} = \frac{2}{9}\,\frac{m_n}{v}$$

So Dark Matter couples to nucleons through s-channel Higgs



Combination of VBF and
ZH, H → invisible
√s = 8.0 TeV, L = 18.9-19.7 fb⁻¹ (VBF+ZH)
√s = 7.0 TeV, L = 4.9 fb⁻¹ (ZH)
CMS
B(H→ inv) < 0.51 @ 90% CL
m_H = 125 GeV
scalar
fermion
vector
Min
Lattice
Max
CRESST 1σ
CRESST 2σ
XENON100(2012)
XENON10(2011)
DAMA/LIBRA
CoGeNT(2013)/90%CL
CoGeNT(2013)/99%CL
CDMS(2013)/95%CL
COUPP(2012)
LUX(90%CL)
DM-nucleon cross section σ^SI_χ-N [pb]
DM Mass M_χ [GeV]
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10
10²
10³

Physics of the Higgs Sector Responsible for Electroweak Symmetry Breaking is the Only Physics that is Guaranteed to be at the Electroweak Scale

Experimental Investigation of the Higgs Sector has Just Begun

Still Lots of Room for New Ideas and Work - Please Join In