Searching for Electroweak Scale Physics in the Higgs Sector

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Search for Electroweak Scale Physics in the Higgs Sector

- Higgs Rate Measurements

- Search for Additional States Directly in the Higgs Sector

- Searching for New Physics Produced in Association with Higgs

- Search for Additional States Related to the Higgs Sector

- Searching for New Physics Produced from Decay of Higgs

- Precision Higgs Measurements to Search for New Physics

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7+8 TeV 25 fb^{-1}

Experimental Investigation of Electroweak Physics at the Electroweak Scale Has Begun

Reached an Important Milestone !

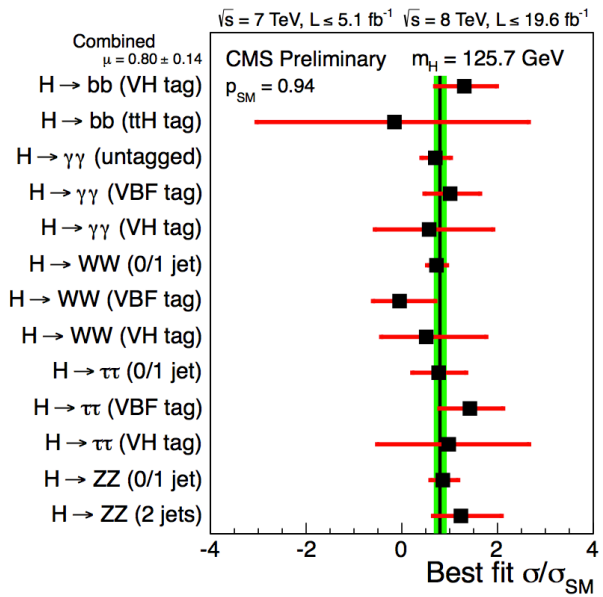
Higgs Boson Rate Measurements

Number of Channels Observed + Measured

σ.Br (Initial -> h -> Final)

Many Many More Eventually …

	Inclusive	VBF	Vh	tth
$\gamma\gamma$	X	X	X	X
ZZ*	X	X	X	X
WW*	X	X	X	X
$\tau\tau$	X	X	X	X
bb			X	X
$Z\gamma$	X	X	X	
$\mu\mu$	X	X	X	X



Higgs Boson Rate Measurements

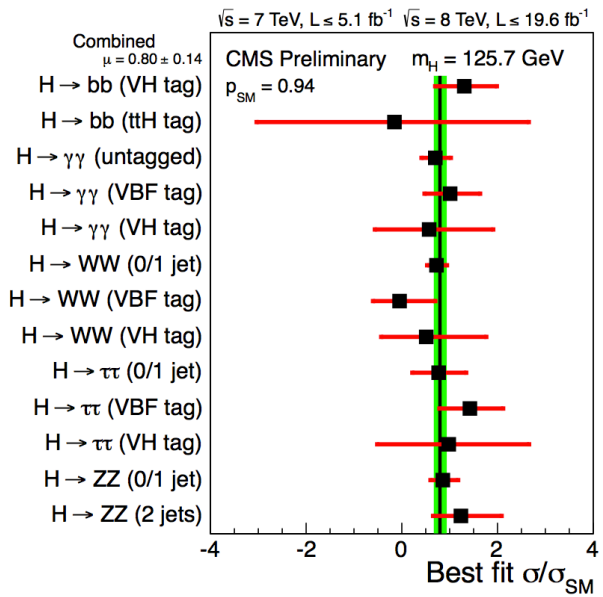
Signals of New Physics in
SM Higgs Rate Measurements

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

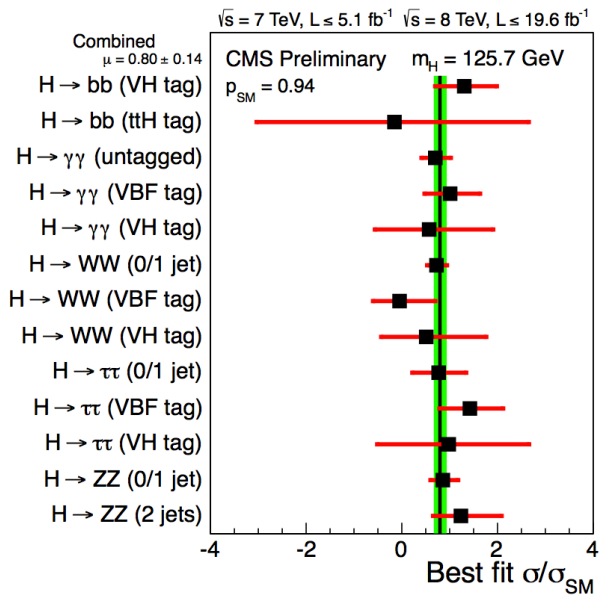
Modifications of
SM Higgs Rate Measurements

Specific Underlying Framework

Higgs Mixing	$O(1)$	$(m_h/M)^2$
Yukawa Form Factor	$O(1)$	$(m_h/M)^2$
Partner Loops	$O(1)$	$(m_h/M)^2$

No (effective) Loop Suppression !

σ.Br (Initial -> h -> Final)



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Higgs Boson Rate Measurements

New Tests of Standard Model – Higgs Sector

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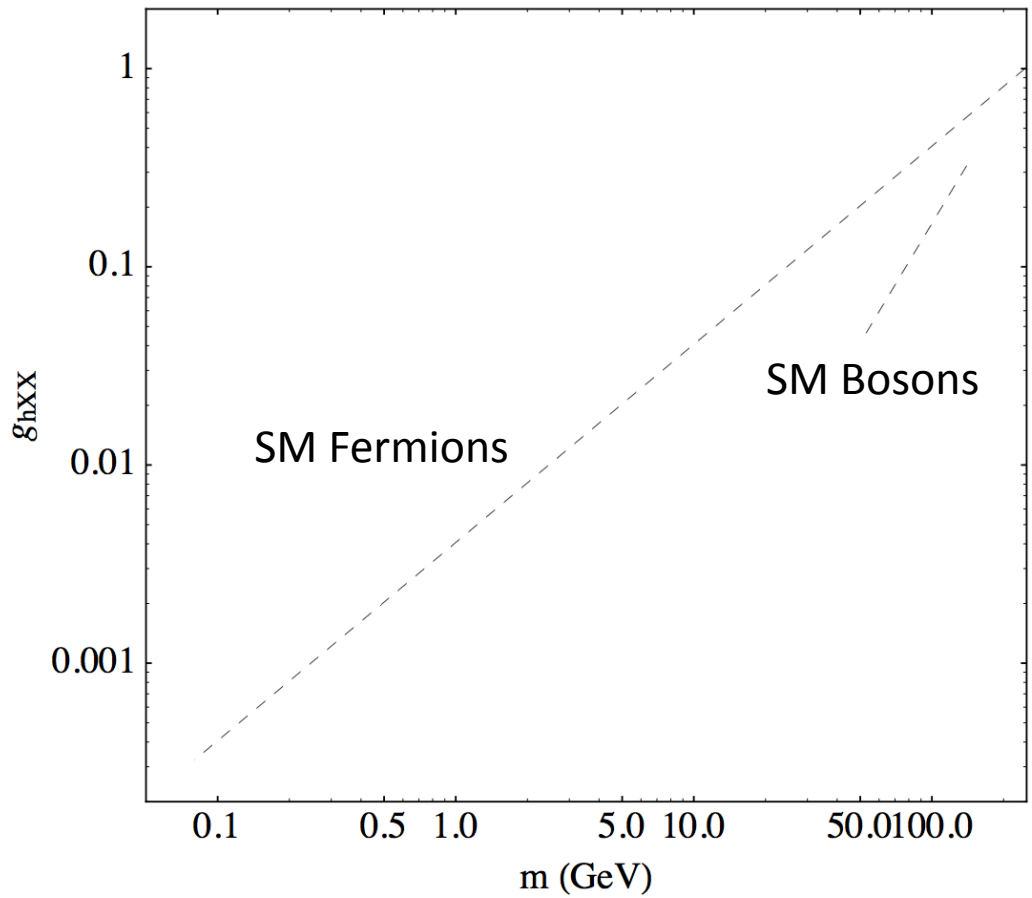


$g_{hXX} = (m_X/v)^n$

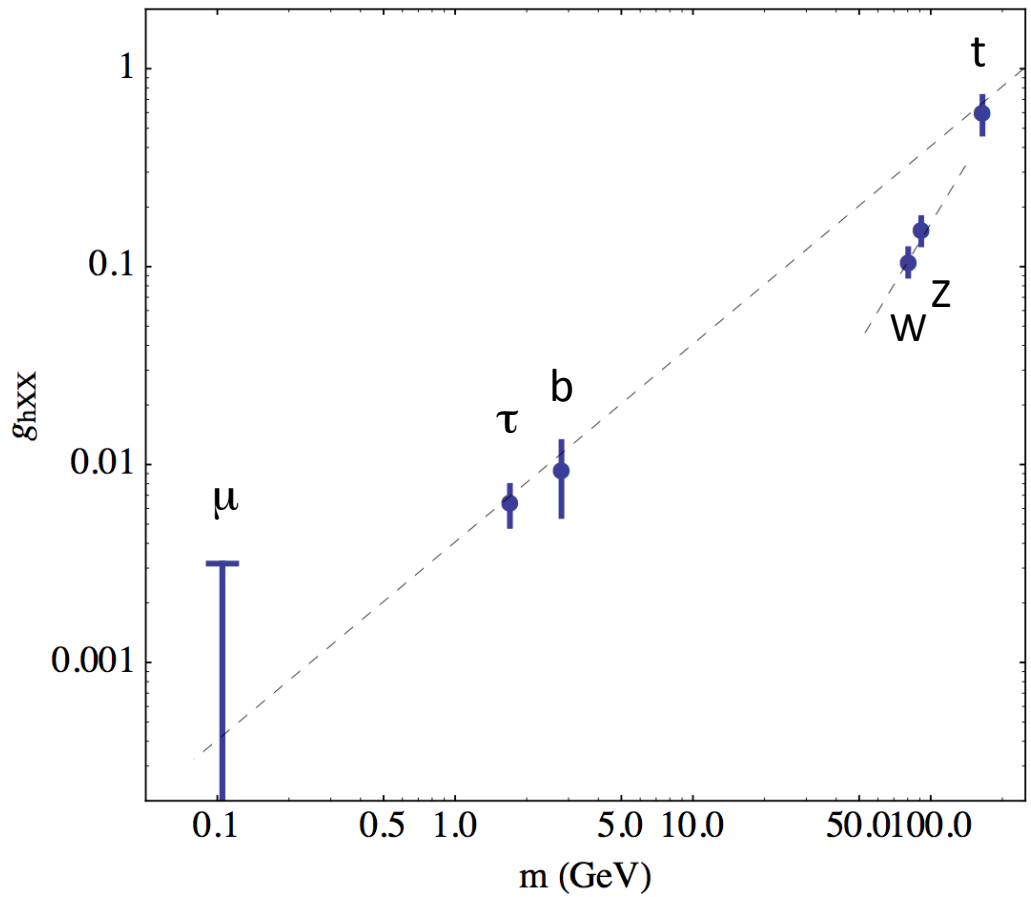
n = 1 Fermion
n = 2 Boson

Higgs Boson Rate Measurements

(CMS)

New Tests of Standard Model – Higgs Sector

σ.Br (Initial -> h -> Final)



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

Standard Model Hypothesis

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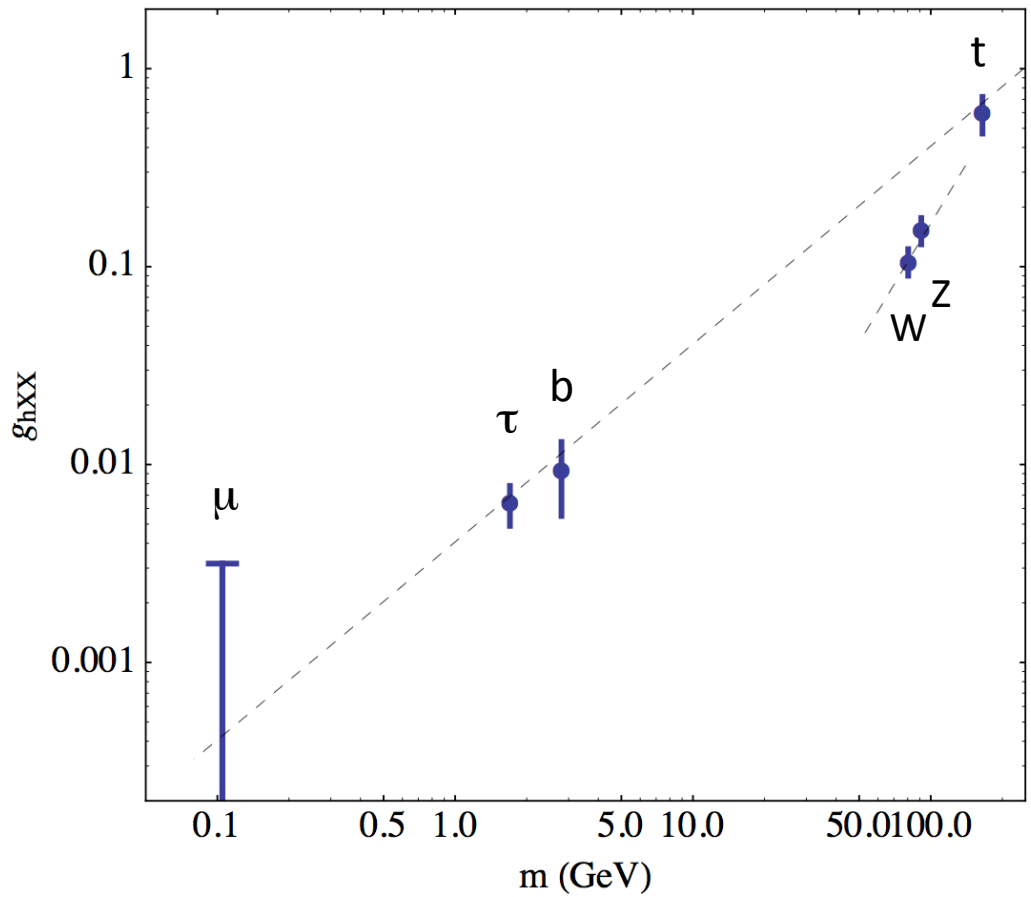
It's the Higgs Boson !



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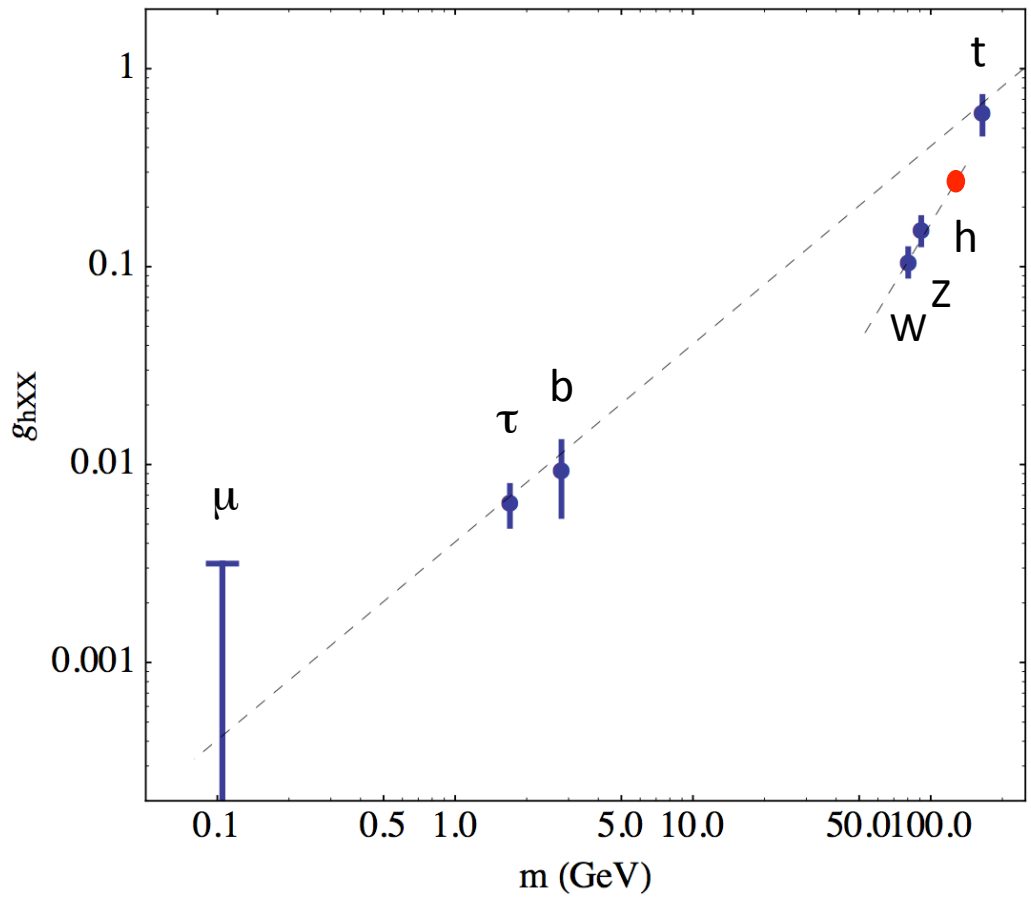

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Standard Model
Hypothesis

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Higgs Boson General Couplings

(Craig, Thalapillil, ST)

tt, WW, ZZ, bb, ττ, gg, γγ Higgs Couplings

σ.Br (Initial -> h -> Final)

All these Couplings Roughly Equally Important in Rate Measurements

Effective Operator Description
If Scale Uniformly Small or Bounded

Smallest Couplings are Most Susceptible to Largest Fractional Modifications

A Consistent Operator Expansion - Include at Leading Order Only

Leading Irrelevant Operators for Small Couplings bb, ττ, gg, γγ

Marginal Operators for Large Couplings tt, WW, ZZ

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Leading Irrelevant Operators for Small Couplings bb, ττ, gg, γγ

Marginal Operators for Large Couplings tt, WW, ZZ

Applies to Wide Class of UV Completions

If Perturbative + All Irrelevant Operators Loop Suppressed

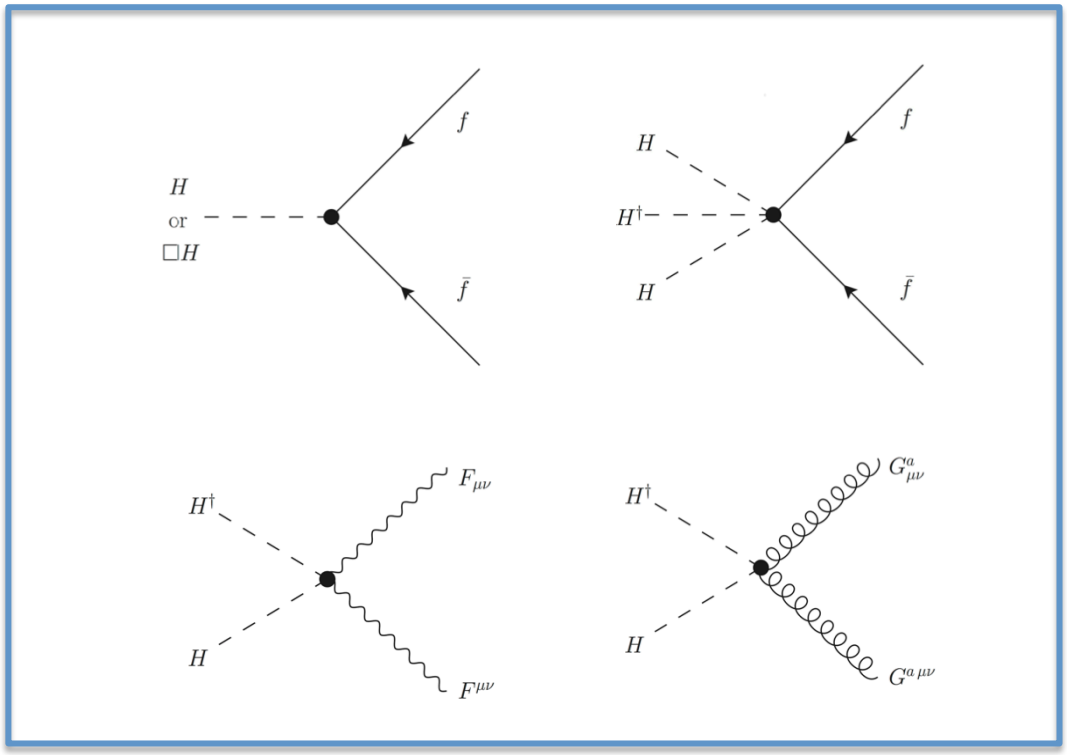
Potentially Large Fractional Effects on Small Couplings

Gauge and Yukawa Form Factors of the Higgs (Craig, Thalapillil, ST)

Effective Operators - Coupling General Function of Higgs to bb, ττ, gg, γγ

(Non)-Linear + Momentum Dependent Form Factors

Dimension Six:



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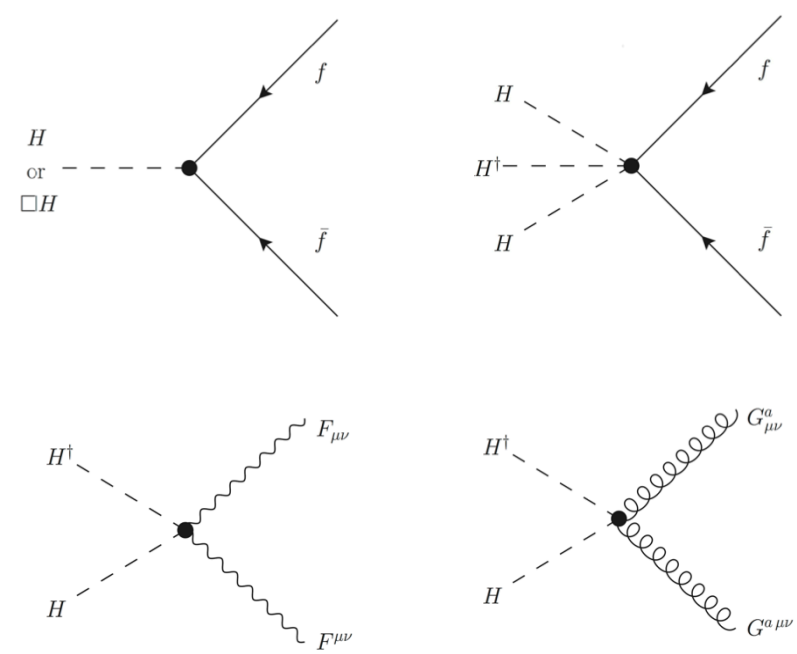


At this Order Momentum Dependence "Identical" to that from Marginal Interactions

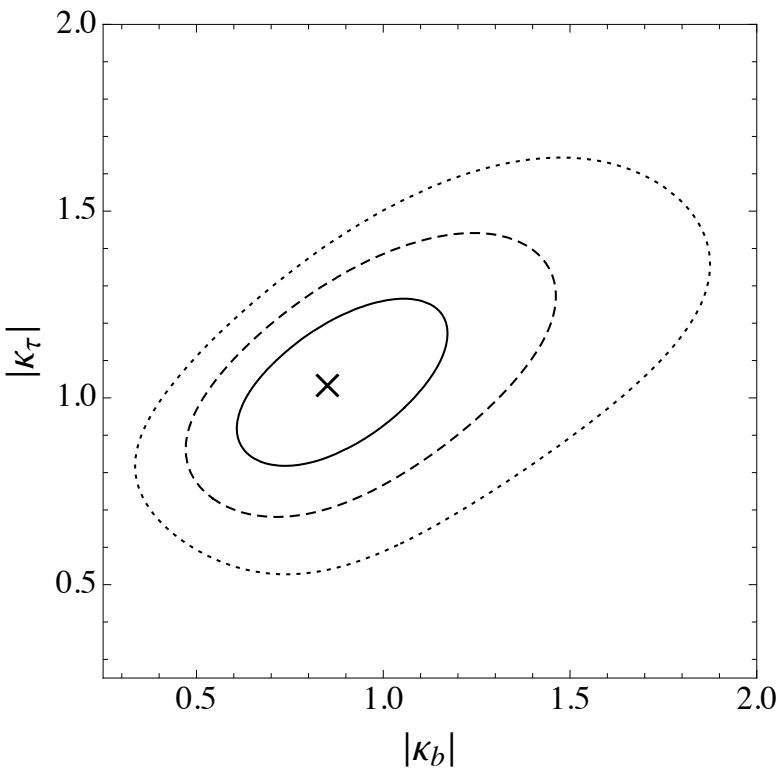
Consistent to Fit to Overall Multiplier of SM ff, gg, γγ Couplings

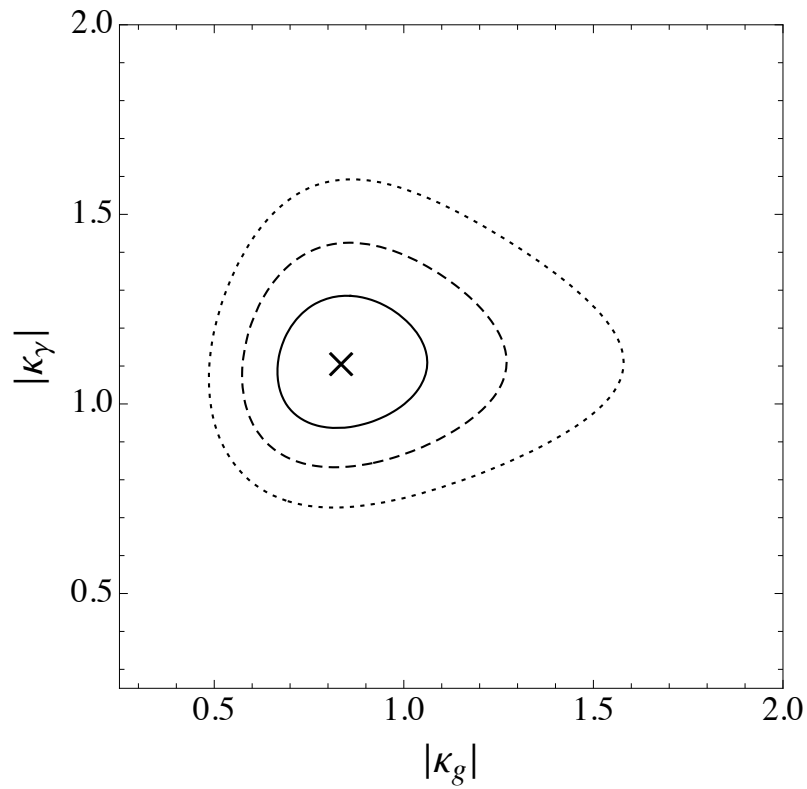
Gauge and Yukawa Form Factors of the Higgs (Craig, Thalapillil, ST)

Effective Operators - Coupling General Function of Higgs to bb, ττ, gg, γγ

Dimension Six: Small Couplings

CMS + ATLAS Global Fit



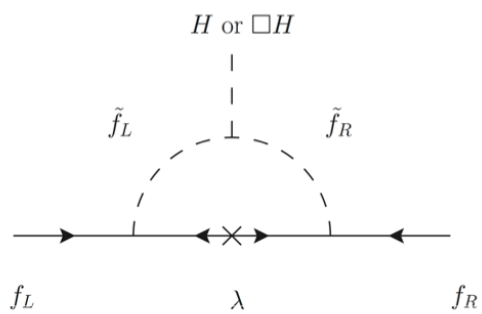


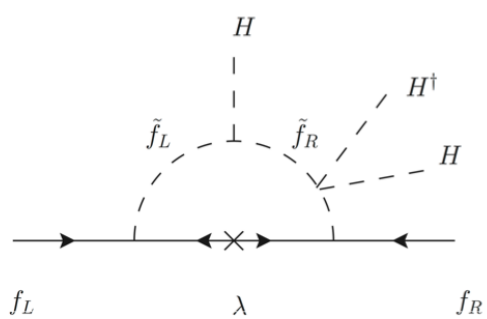
Yukawa Form Factors from Radiative Fermion Masses

(Thalapillil, ST)

SUSY

Large $\tan\beta$ $\quad m_\lambda \mu \tan\beta / (16 \pi^2 m^2) \sim 1 \rightarrow$ Soft Down-Type Yukawa Couplings



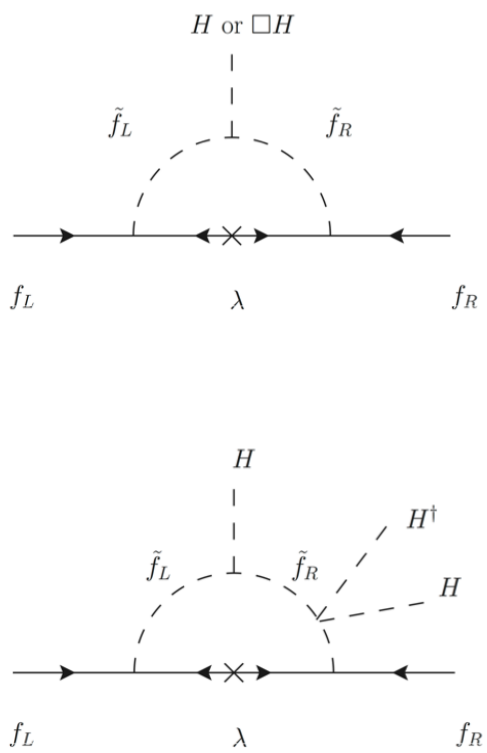


Yukawa Form Factors from Radiative Fermion Masses

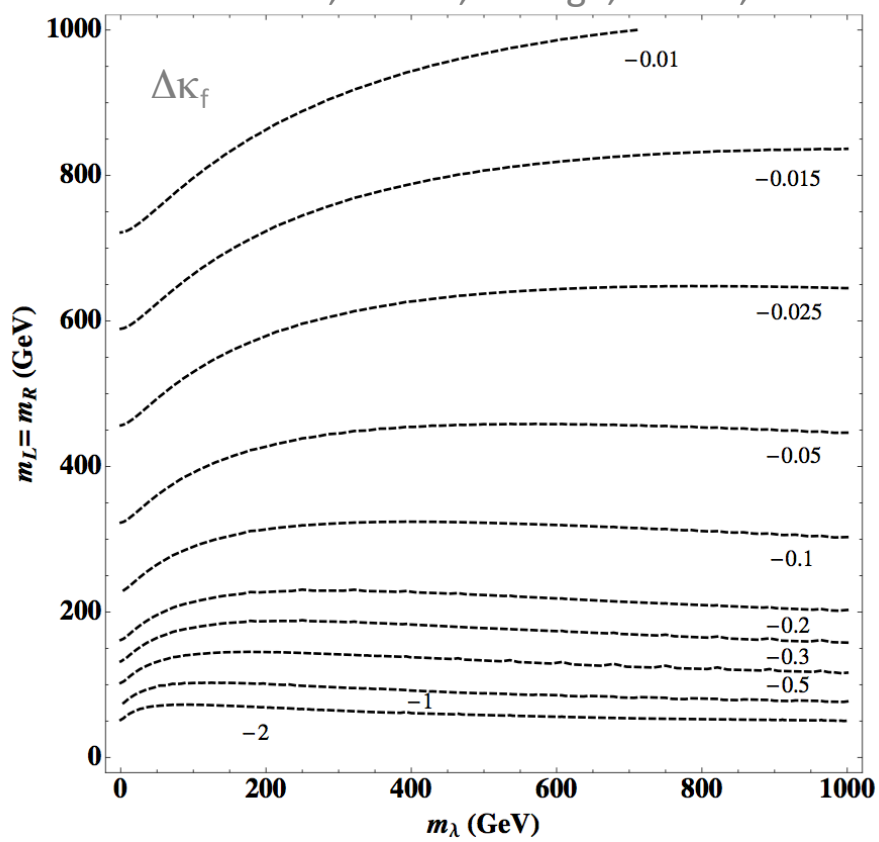
(Thalapillil, ST)

SUSY

Soft Chirality Violation >> Hard Chirality Violation → Soft Yukawa Couplings



bottom ; charm, strange, muon ; …



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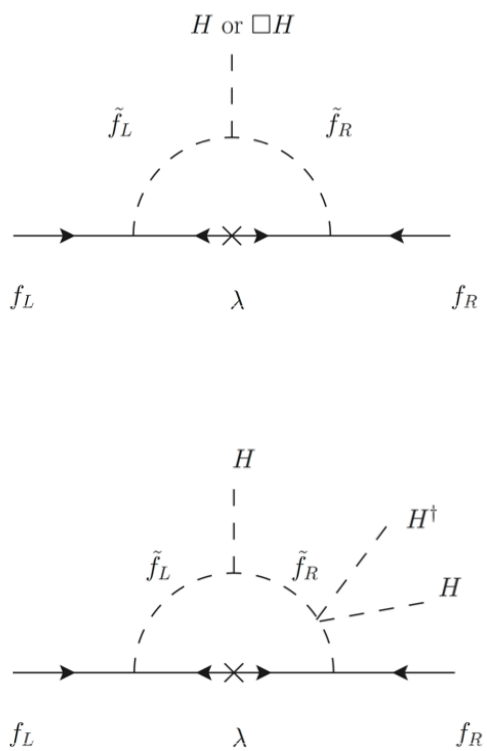
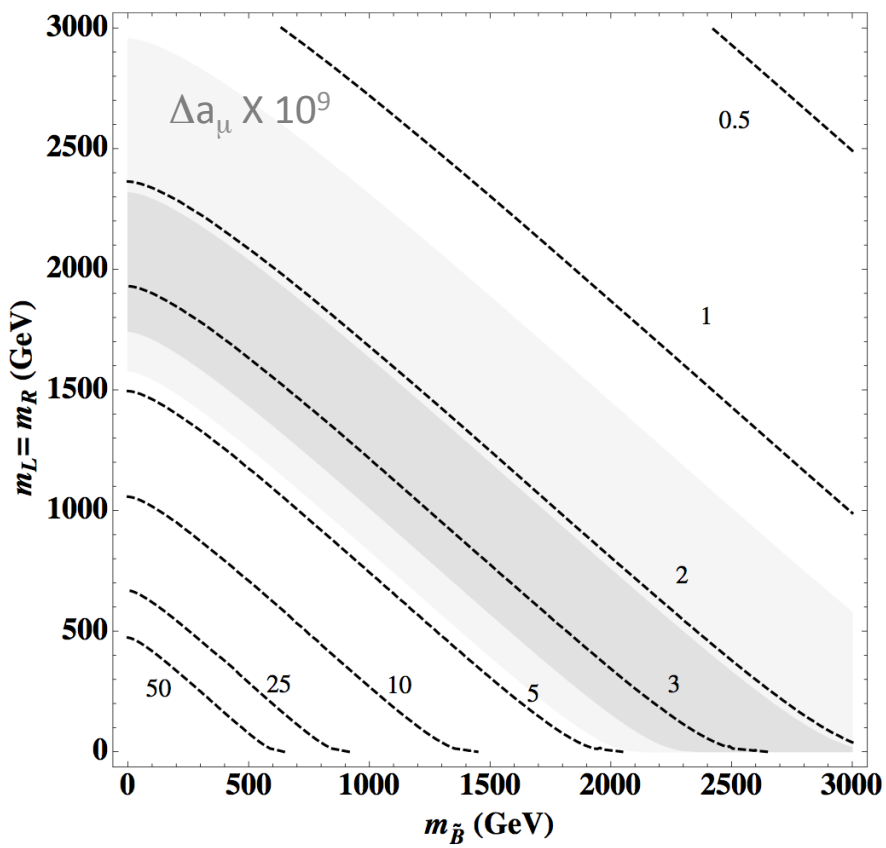


muon



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

$H = \langle H \rangle$

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

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

PDG

S = 0.01 +- 0.10

T = 0.03 +- 0.11

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

Precision Electroweak Physics Through the Higgs (Craig, ST)

Higgs Observables

σ . Br (Initial -> h -> Final)

Precision Electroweak Physics Through the Higgs (Craig, ST)

Higgs Observables

σ . Br (Initial -> h -> Final)

Best Channels:

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

Precision Electroweak Physics Through the Higgs (Craig, ST)

Higgs Observables

σ . Br (Initial -> h -> Final)

$$\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)}$$

Best Channels: (Ratios)

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

Precision Electroweak Physics Through the Higgs (Craig, ST)

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

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

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

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

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

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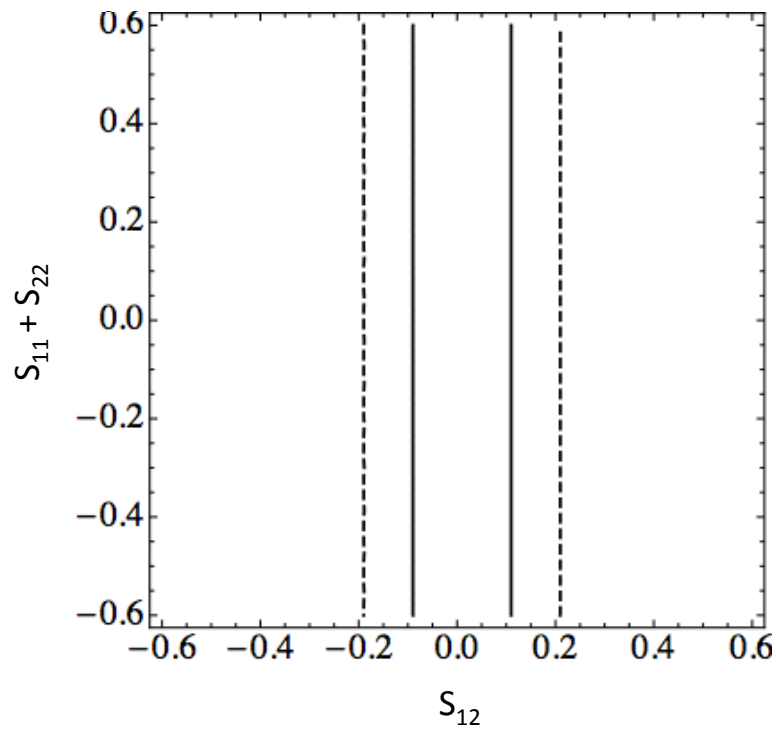
PEW



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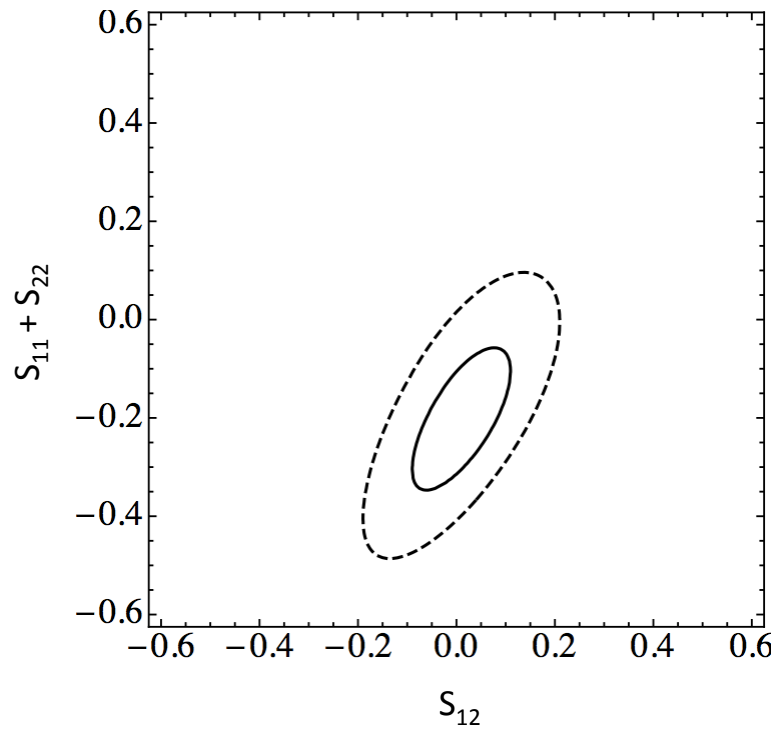
PEW + CMS 5 + 12(5) fb^{-1} 7 + 8 TeV



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

Precision Electroweak Physics Through the Higgs (Craig, ST)

Higgs Observables

σ . Br (Initial -> h -> Final)

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

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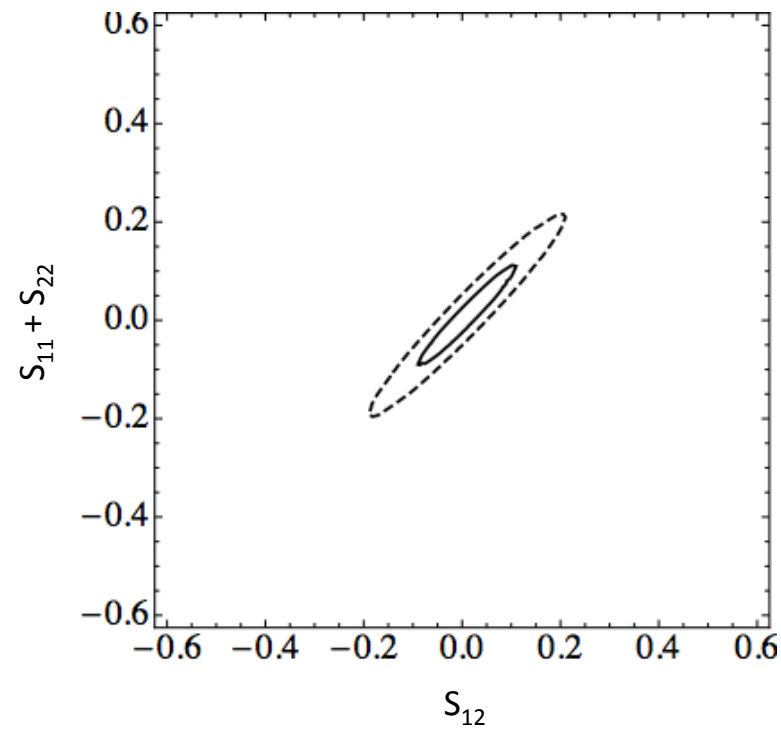
PEW + 5% Uncertainty Br(h->γγ)/Br(h->ZZ)



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

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

(Craig, ST)

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

(see paper for correlations)

	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

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Two Higgs Doublets h-H mix

(MSSM)

	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
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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	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

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

(Craig, Galloway, ST)

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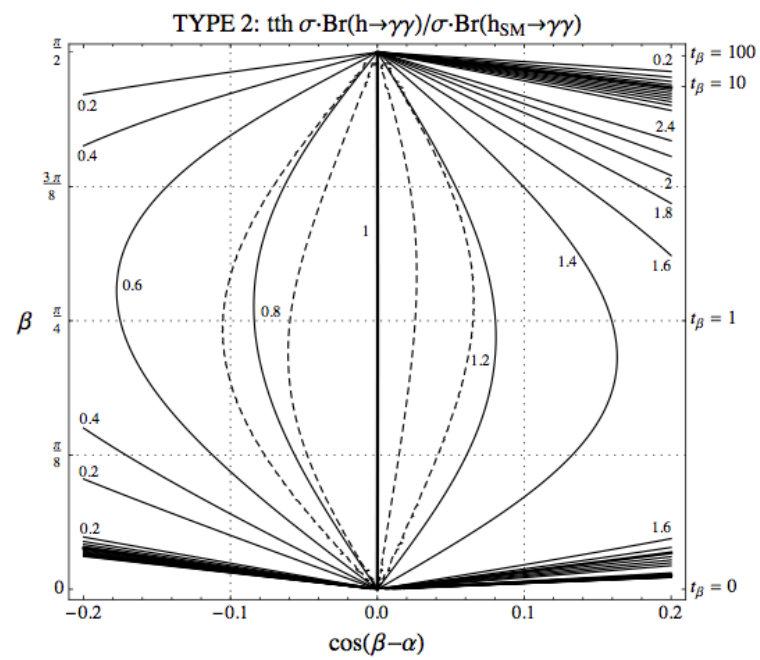
Four couplings

(see paper for correlations)



Alignment Limit:

h mass Eigenstate || Expectation Values

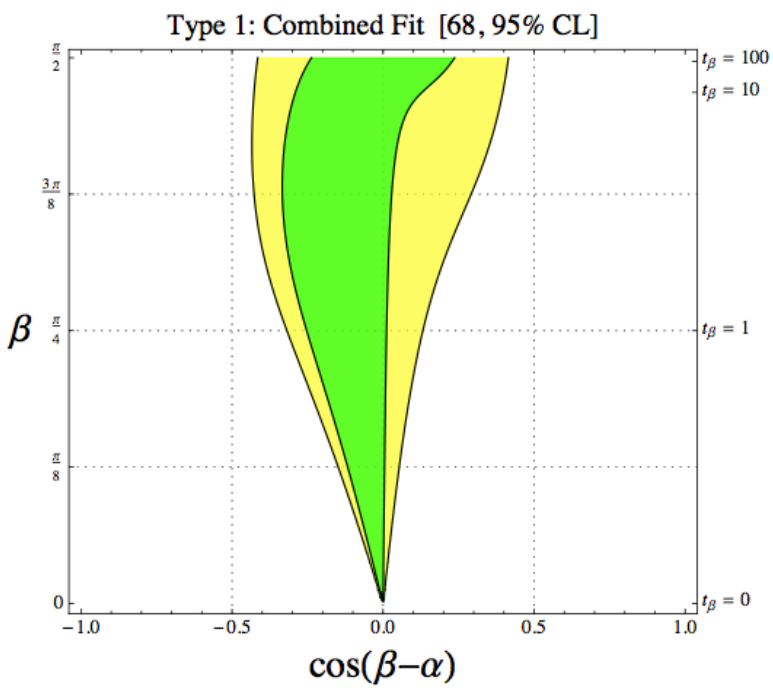
$\cos(\beta - \alpha) = 0$

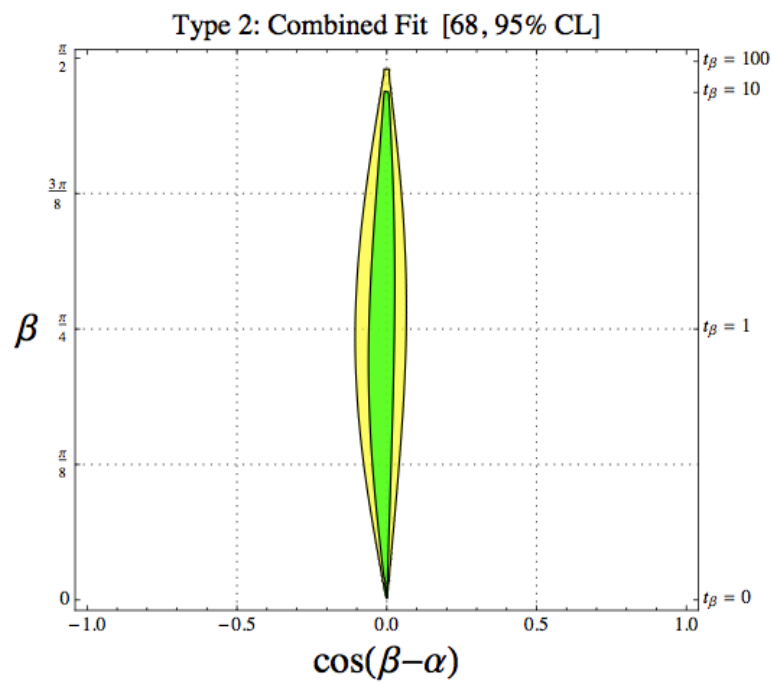
h couplings = h_{SM} couplings

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

(Craig, Galloway, ST)

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 2nd Higgs Doublet in SM Higgs Boson Rate Measurements

(Craig, Galloway, ST)

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

(Craig, Galloway ST; Evans, Kilic, Park, ST)

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

Consider Spectrum:

$2\, m_h < m_A \sim m_H \sim m_{H^{+-}} < 2\, m_t$

splittings < $O(m_W)$

Leading Topologies with Unsuppressed Production Cross Sections Near Alignment Limit

Second Higgs Doublet Decay Topology	Alignment Limit
$H \to WW, ZZ$	–
$H, A \to \gamma\gamma$	✓
$H, A \to \tau\tau, \mu\mu$	✓
$H, A \to tt$	✓
$A \to Zh$	–
$H \to hh$	–
$t \to H^{\pm} b$	✓

Checkmark ≡ Constant in Alignment Limit
Dash ≡ Vanishes in Alignment Limit

Direct Searches for 2nd Higgs Doublet

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$H \to hh$	–
$t \to H^{\pm} b$	✓

SM Higgs Search Channels
Non-Standard Channels

Checkmark ≡ Constant in Alignment Limit
Dash ≡ Vanishes in Alignment Limit

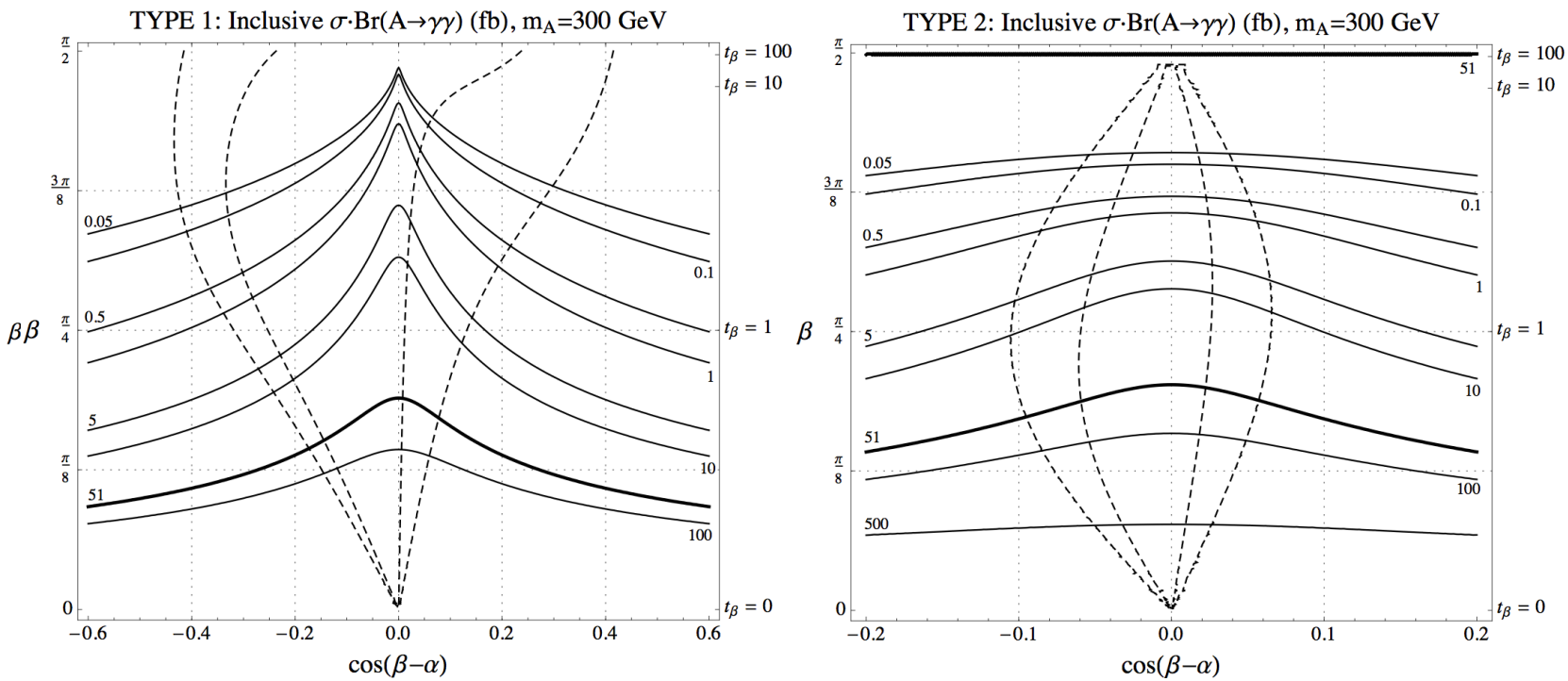
Direct Searches for 2nd Higgs Doublet

(Craig, Galloway, ST)

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

gg -> A,H -> γγ

σ . Br(A -> γγ) = few . σ . Br(H -> γγ)

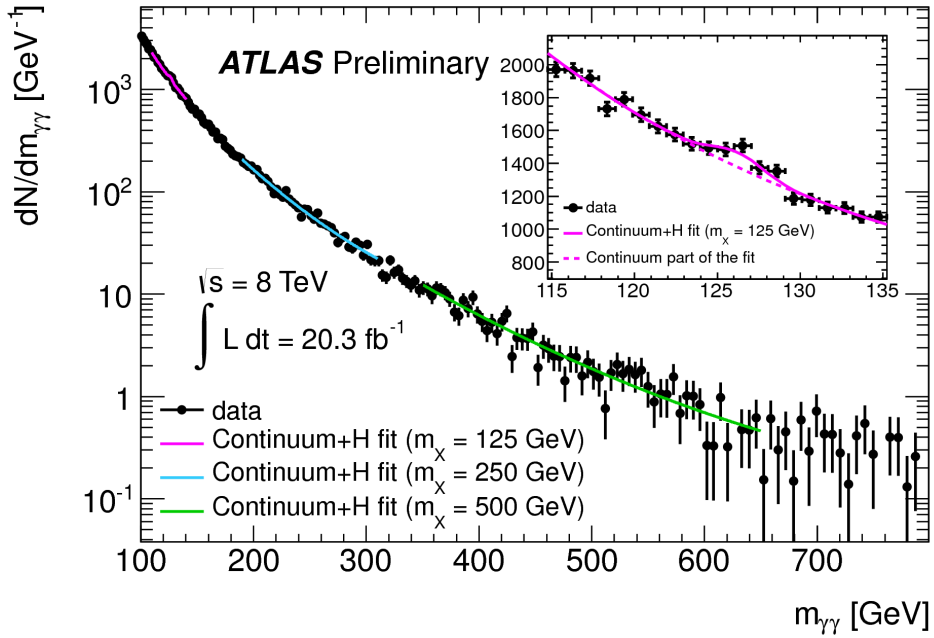


σ . Br(h_{SM} -> γγ) = 51 fb
for m_h = 125 GeV

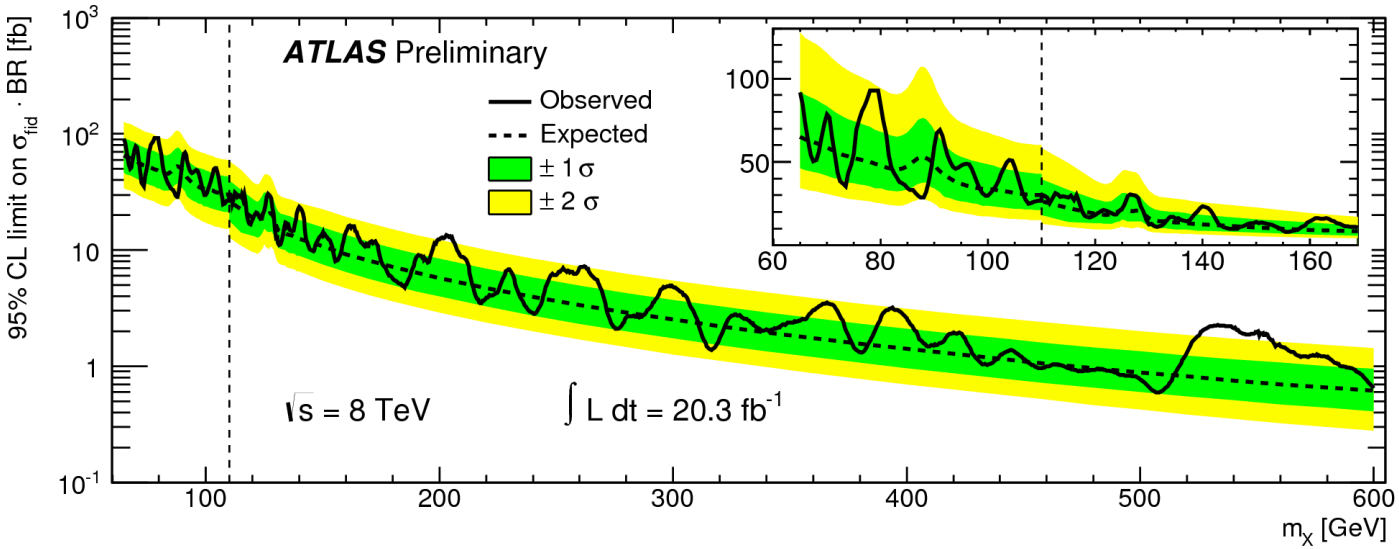
Direct Searches for 2nd Higgs Doublet

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

gg -> A,H -> γγ



σ . Br(h_{SM} -> γγ) < 5 fb
for m_A = 300 GeV

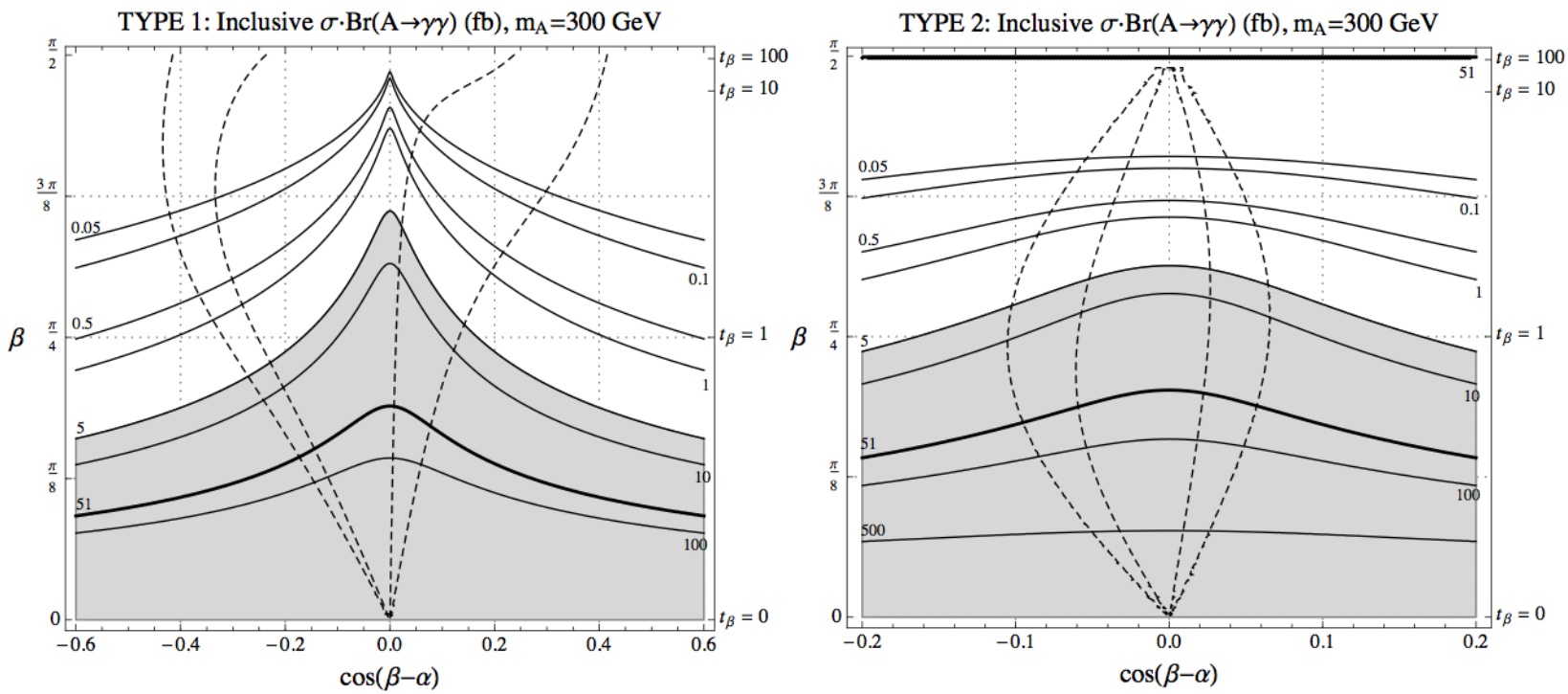


Direct Searches for 2nd Higgs Doublet

(Craig, Galloway, ST)

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

gg -> A -> γγ



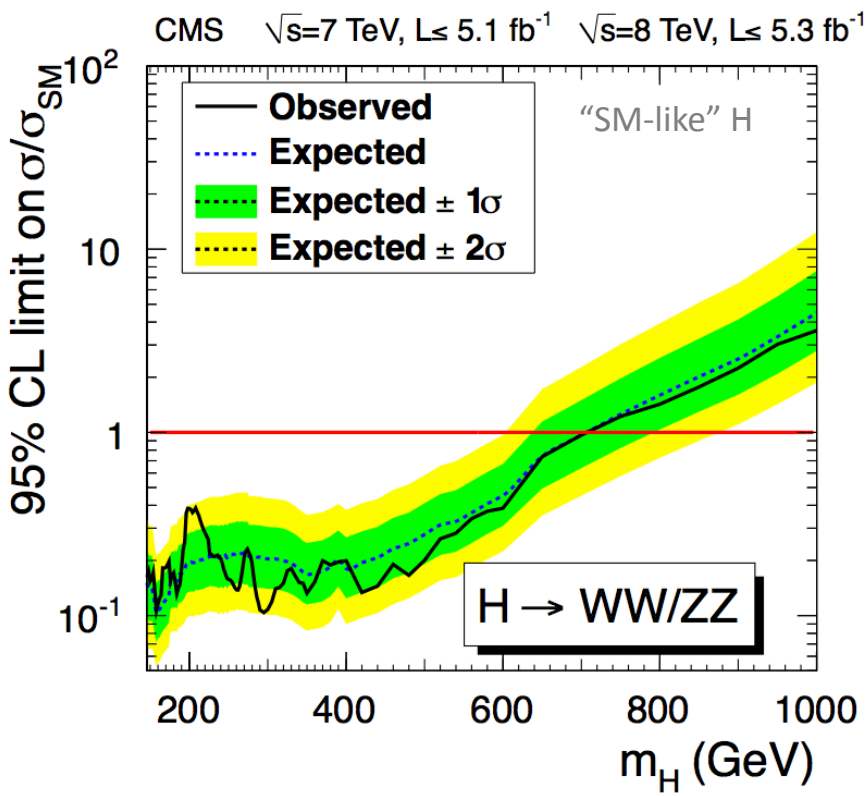
σ . Br(h_{SM} -> γγ) < 5 fb
for m_A = 300 GeV

Direct Searches for 2nd Higgs Doublet

(CMS)

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

h – H mix gg -> H -> WW, ZZ



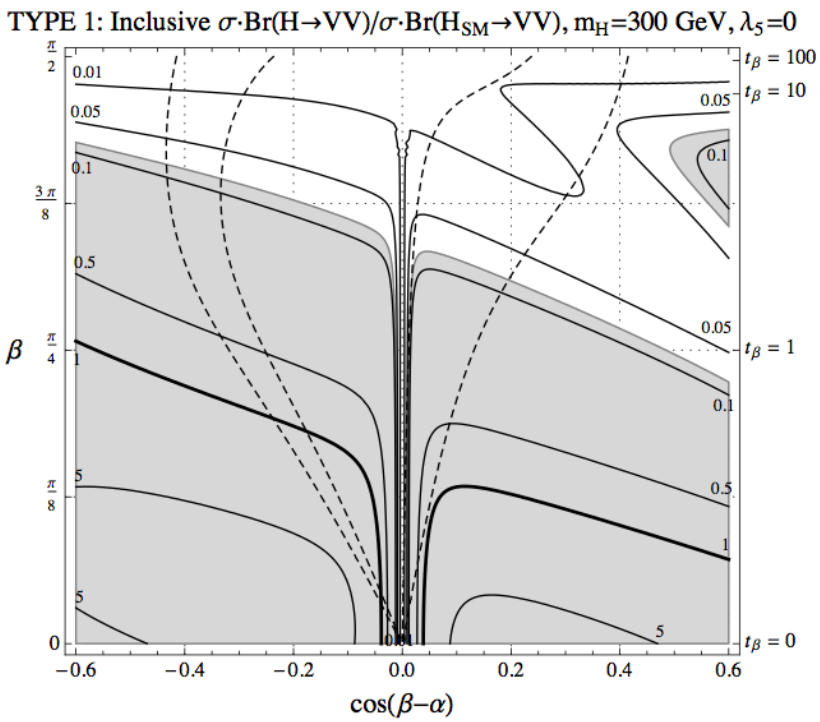
m_h = 300 GeV Γ(h->All) = 8 GeV

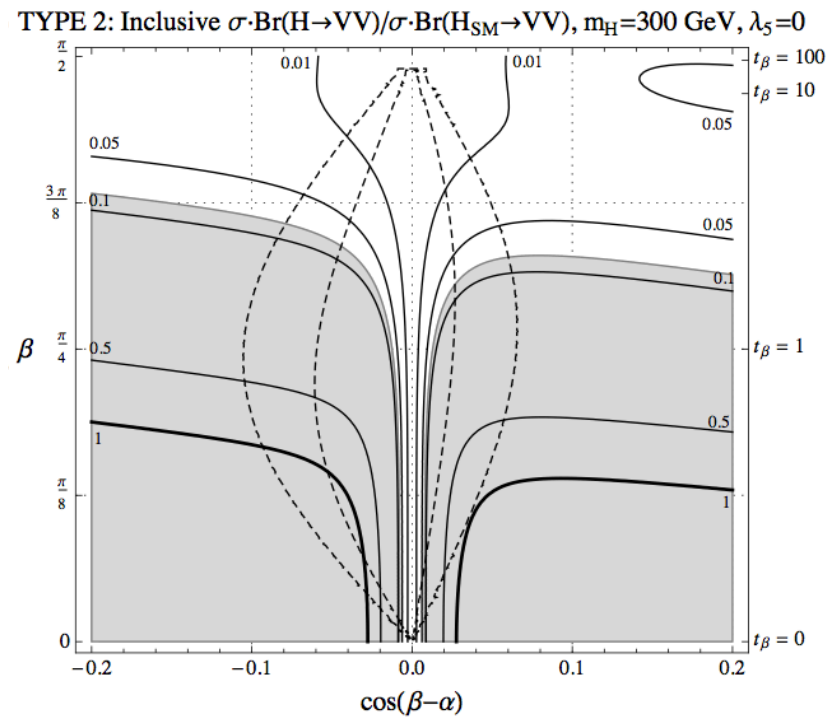
Direct Searches for 2nd Higgs Doublet

(Craig, Galloway, ST)

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

h – H mix gg -> H -> WW, ZZ



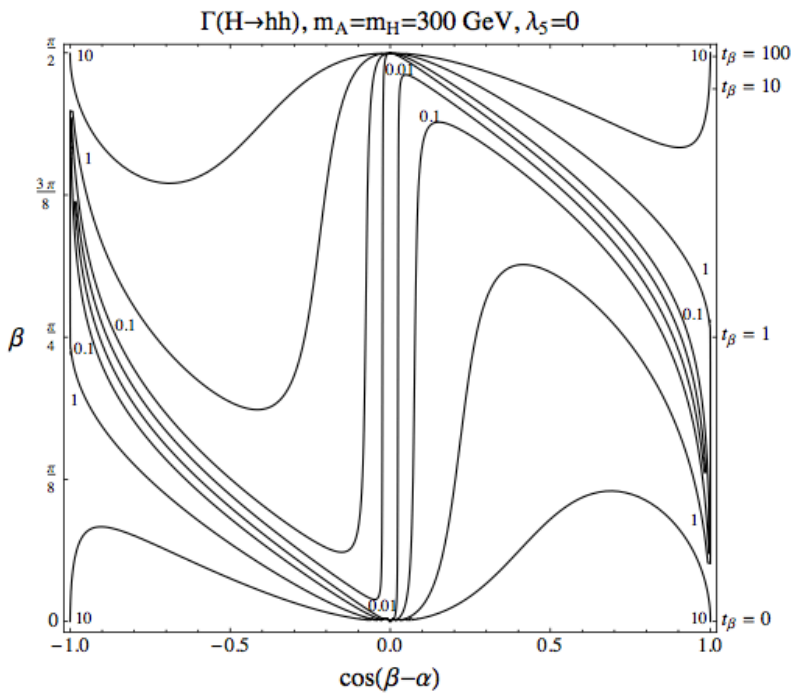


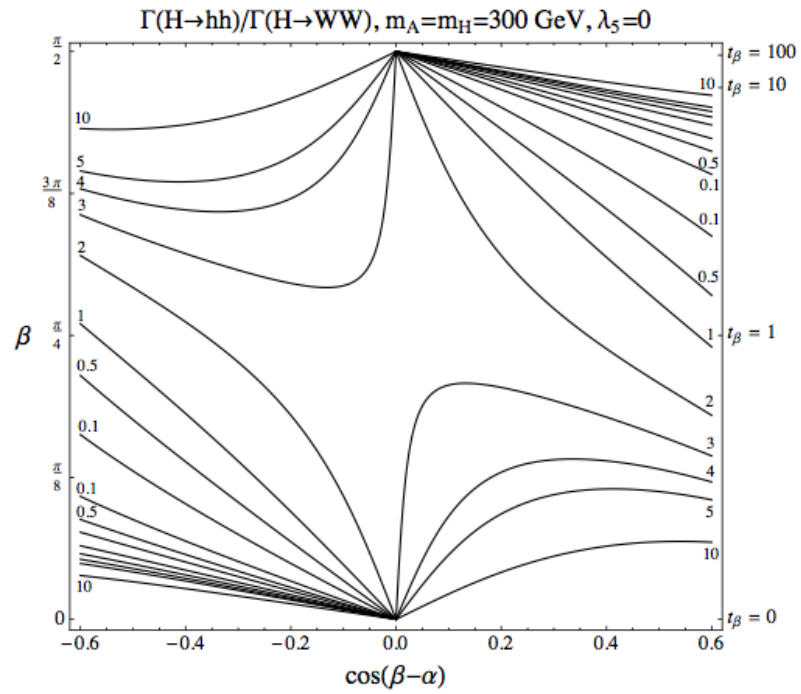
Could do a bit better with Narrow Width H-> ZZ -> llll Search

Direct Searches for 2nd Higgs Doublet

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

gg -> H -> hh



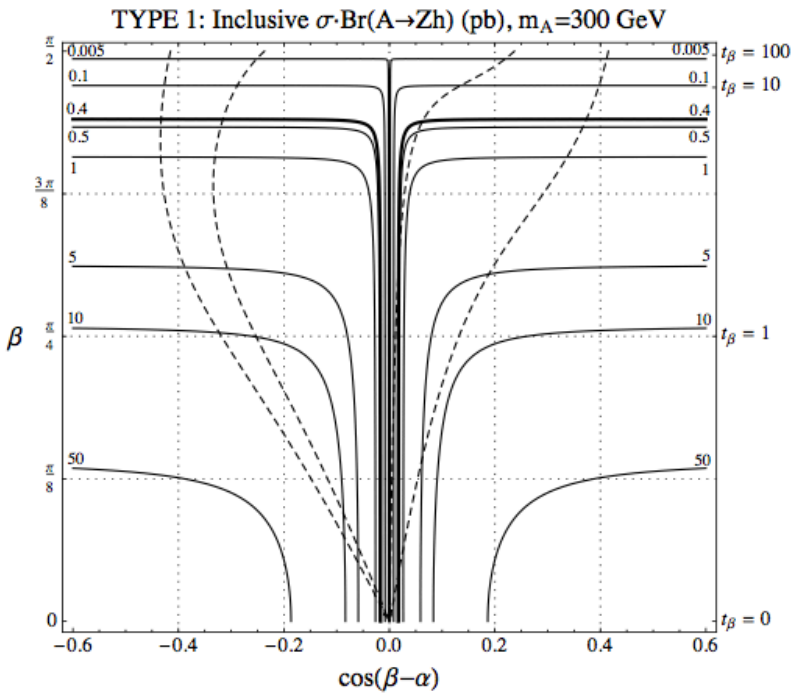


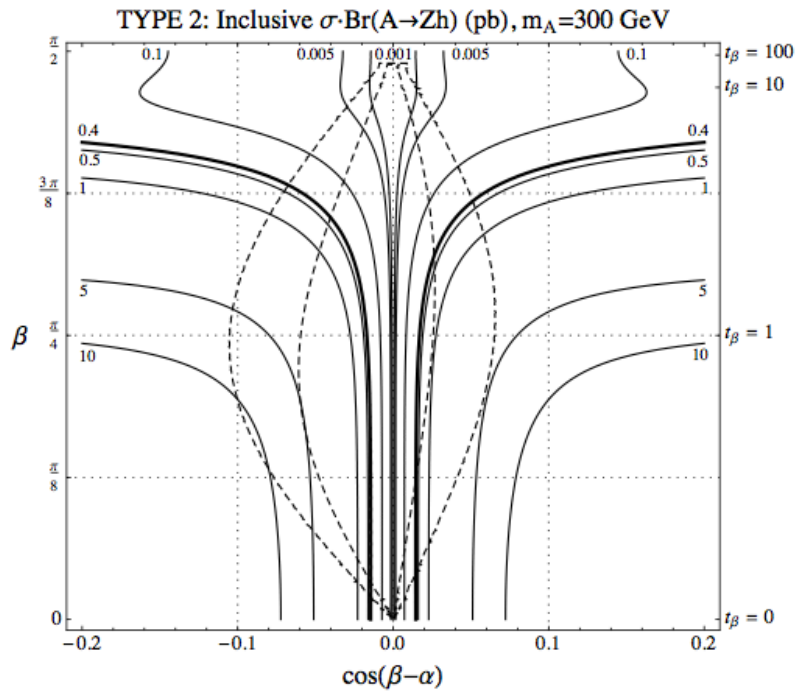
Direct Searches for 2nd Higgs Doublet

(Craig, Galloway, ST)

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

gg -> A -> Zh





Direct Searches for 2nd Higgs Doublet

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

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

hh Decay Modes

hh	WW	ZZ	$\tau\tau$	bb	$\gamma\gamma$
WW					
ZZ					
$\tau\tau$					
bb					
$\gamma\gamma$					

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

Zh Decay Modes

Zh	WW	ZZ	$\tau\tau$	bb	$\gamma\gamma$
$\ell\ell$					
$\nu\nu$					
jj					

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

See Experimental Talks ...

Experimental Investigation of ElectroWeak Physics at the ElectroWeak Scale has (Finally) Begun !!

Search for New Physics in Higgs Rate Measurements
Relatively Large Deviations Possible (Expected)

Higgs Boson Gauge and Yukawa Form Factors
Consistent Operator Expansion – Small Higgs Couplings Only
D=6 Kinematic Structure "=" SM - Consistent Fit to Higgs Rates

Yukawa Form Factors
Soft Yukawa Couplings – SUSY Large tanβ or Radiative Masses

Higgs -> $\gamma\gamma$, ZZ* , Zγ
The New Precision Physics (Will Complement + Surpass Old PEW)

Higgs Rate Measurements Sensitive to 2nd Higgs Doublet
Type (II)I (Very) Close to Alignment Limit

Search for Extended Higgs Sectors in
Standard Channels H,A -> $\gamma\gamma$, ZZ, WW, …

Search for Extended Higgs Sector in
New Channels H->hh , A->Zh, … Enhance Sensitivity ! …

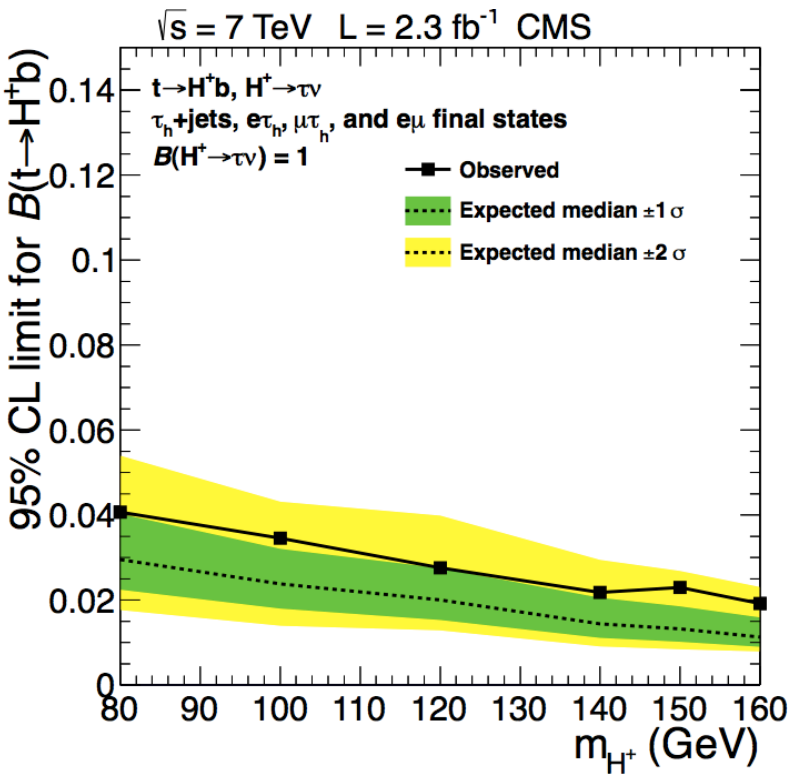
Extra Slides

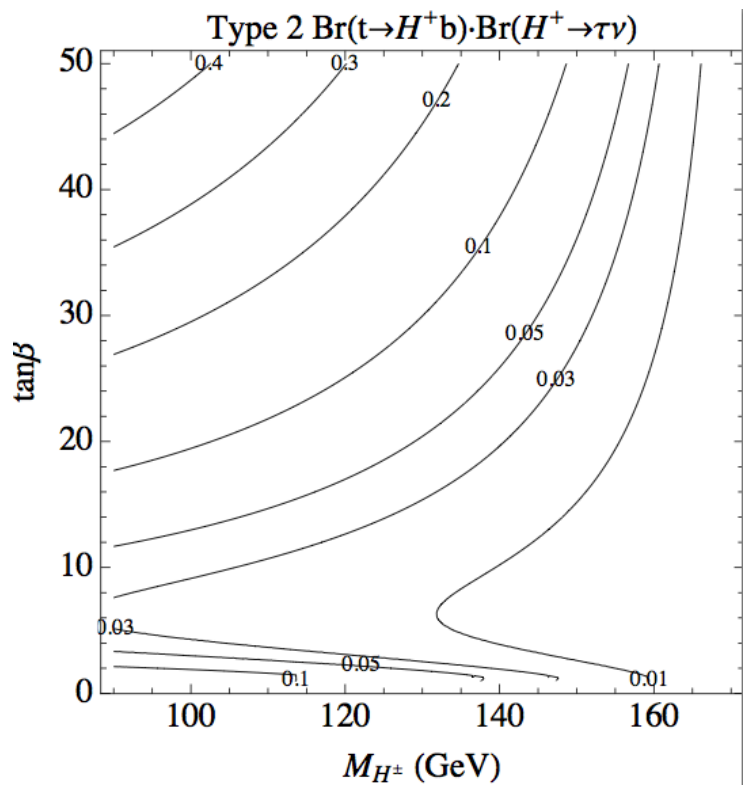
Direct Searches for 2nd Higgs Doublet

(CMS)

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

$t \to H^{+-} b$ $H^{+-} \to \tau \nu$





Direct Searches for 2nd Higgs Doublet

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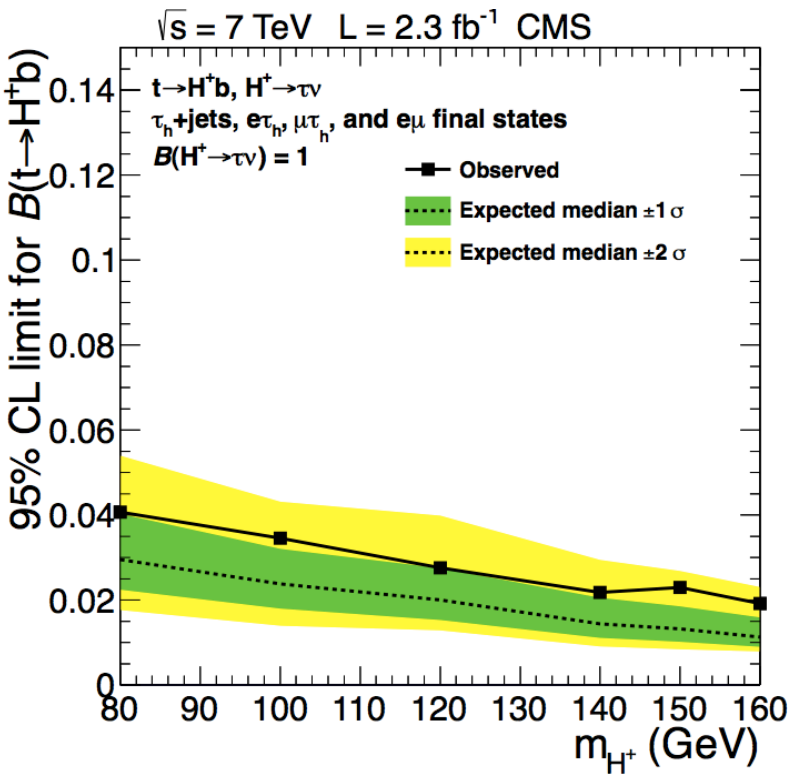
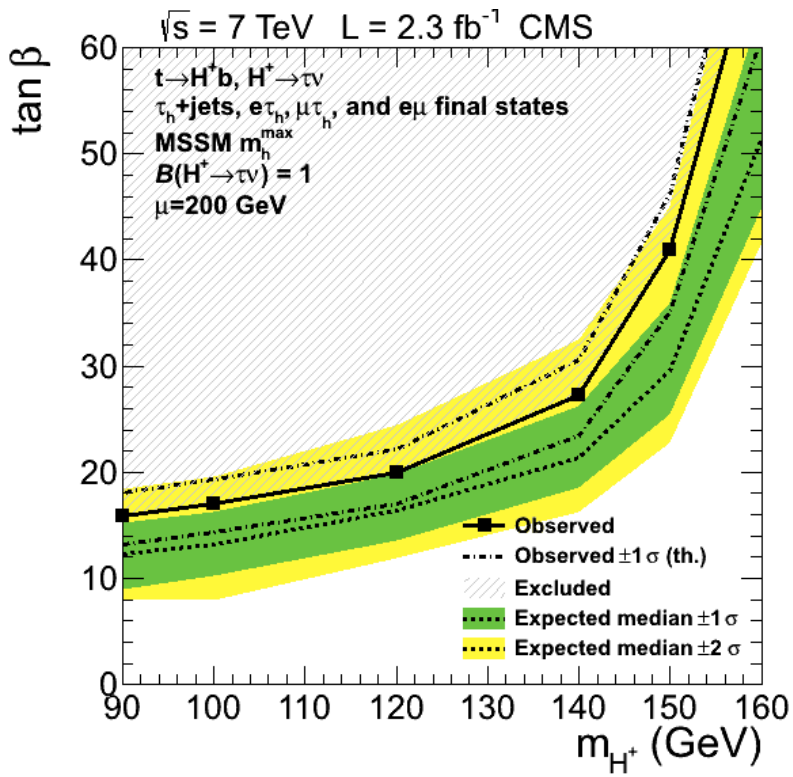
$t \to H^{+-} b$ $H^{+-} \to \tau \nu$



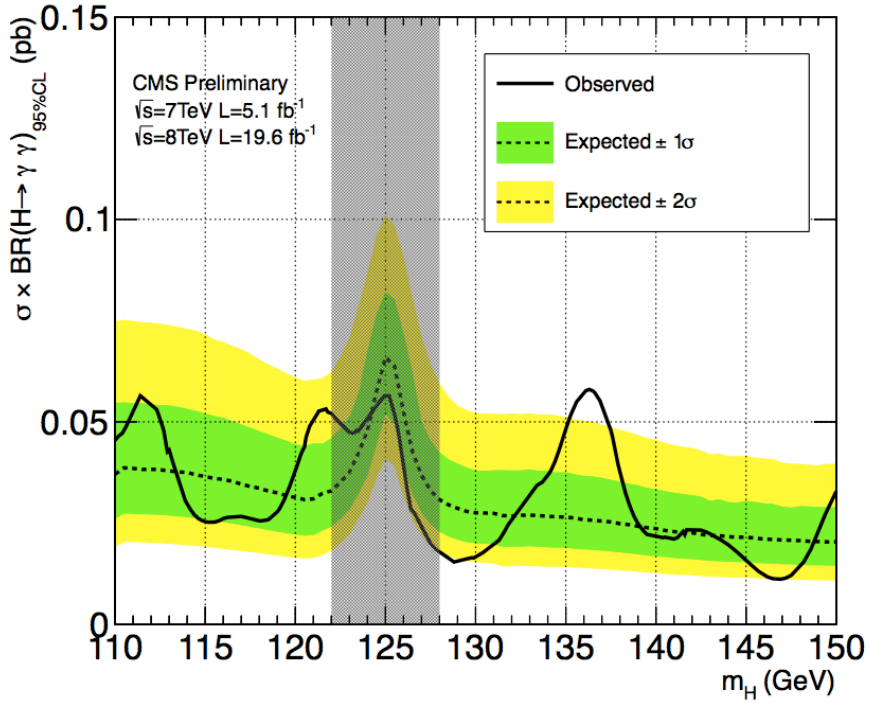


Direct Searches for 2nd Higgs Doublet

(CMS ; Craig, ST)

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

A,H -> $\gamma\gamma$



2HDM Predictions

	Type I	Type II
$\frac{\sigma \,.\, Br(A \to \gamma\gamma)}{\sigma \,.\, Br(H \to \gamma\gamma)}$	~ 6	~ 3