Top Partners and Fermion Masses

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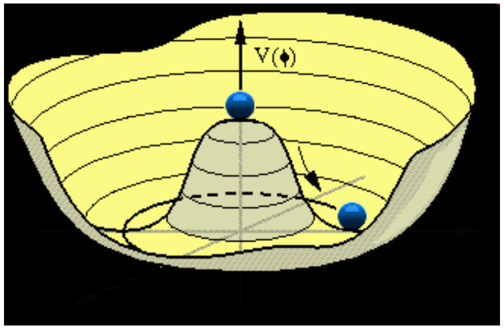
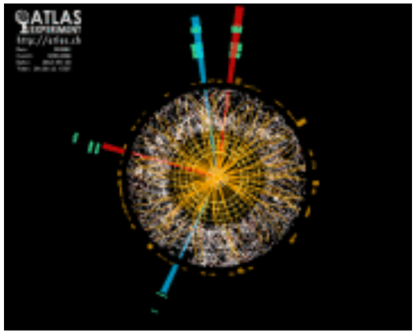
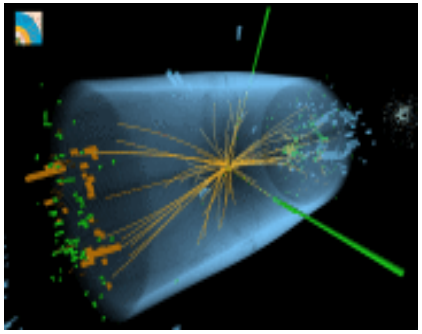
S. Dawson, E Furlan, hep-ph/1205.4733
S. Dawson, E. Furlan, I. Lewis, hep-ph/1210.6663
S. Dawson, E. Furlan, coming soon







The Higgs and Fermion Masses

- SM Higgs couples to fermion mass
  - Largest coupling is to heaviest fermion

$$L = -\frac{m_f}{v}\bar{f}fH = -\frac{m_f}{v}\left(\bar{f}_L f_R + \bar{f}_R f_L\right)H$$

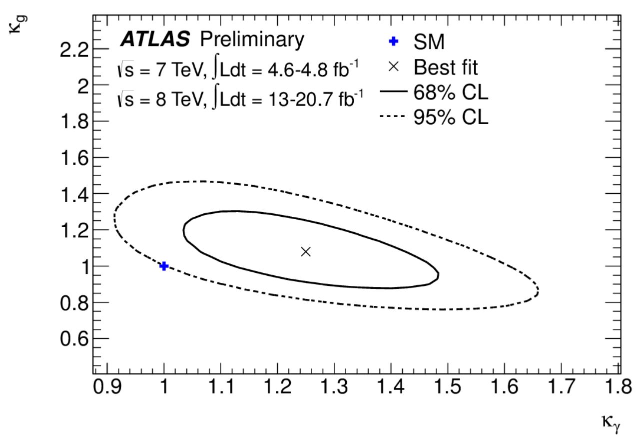
- Higgs couples to gauge boson masses
- Only free parameter is Higgs mass

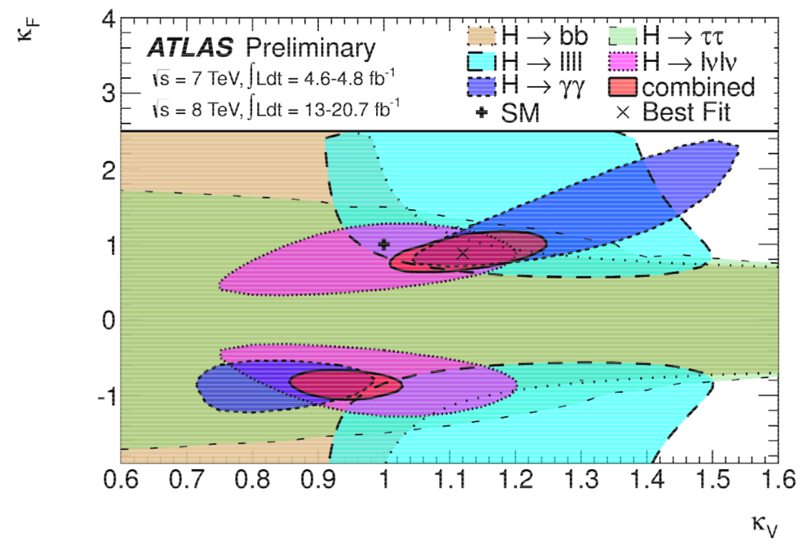
Are fermion masses from SM Yukawa interactions?

$$L \sim \kappa_t \frac{m_t}{v}\bar{t}tH + \kappa_g \frac{\alpha_s}{12\pi}\frac{H}{v}G^A_{\mu\nu}G^{A,\mu\nu}$$

LHC Measures σ•BR

- Global fits extract couplings*
- ATLAS now





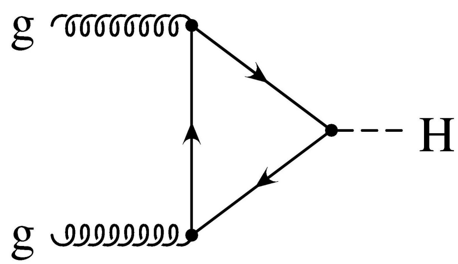
- CMS future

L (fb^{-1})	κ_γ	κ_V	κ_g	κ_b	κ_t	κ_τ
300	[5, 7]	[4, 5]	[6, 8]	[10, 13]	[14, 15]	[6, 8]
3000	[2, 5]	[2, 3]	[3, 5]	[4, 7]	[7, 10]	[2, 5]

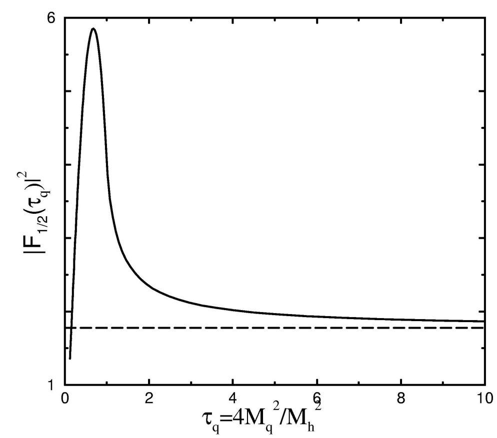
* Assumptions about invisible decays required

Gluon Fusion

- Sensitive to colored particles in loop
  - Heavy quarks: $F_{1/2} \rightarrow -4/3$
  - Assumes SM Yukawa coupling



$$\hat{\sigma}_{gg\rightarrow h}(\hat{s}) = \frac{\alpha_s(\mu_R)^2}{1024\pi v^2}\left|\sum_q F_{1/2}(\tau_q)\right|^2 \delta\left(1-\frac{M_h^2}{\hat{s}}\right)$$



Chiral 4th generation excluded

What can we learn about fermion masses from Higgs production and decay?

Theory Precision

- What precision are we aiming for in order to claim discovery of new physics?
  - Parametric uncertainties (mostly m_b and α_s)
  - Theory uncertainties (scale, missing higher order EW)

$M_H = 126$ GeV	BR uncertainties		
Decay	TU [%]	PU [%]	Total [%]
$H \to \gamma\gamma$	± 2.7	± 2.2	± 4.9
$H \to b\bar{b}$	± 1.5	$\pm$ 1.9	± 3.3
$H \to \tau\tau$	± 3.5	± 2.1	± 5.6
$H \to WW$	± 2.0	± 2.2	± 4.1
$H \to ZZ$	± 2.0	± 2.2	± 4.2

[Higgs cross section working group]

Top Partners

- Many possibilities
- Simplest:
  - Fermion with charge 2/3, $\mathcal{T}_L^2$, $\mathcal{T}_R^2$
  - $\mathcal{T}_L^2$, $\mathcal{T}_R^2$ have identical $SU(2)_L$ couplings (vector-like)
- Mixes with SM fermions: $\psi_L=(\mathcal{T}_L^1, \mathcal{B}_L^1)$, $\mathcal{T}_L^1$, $\mathcal{B}_R^1$
- Motivated by Little Higgs and composite Higgs models which have vector-like top partner

Top Partners can have Dirac Masses

- Physical t's are combinations of $\mathcal{T}_L^1, \mathcal{T}_L^2$

$$\chi_L = \begin{pmatrix} t_L \\ T_L \end{pmatrix} \equiv U_L \begin{pmatrix} \mathcal{T}_L^1 \\ \mathcal{T}_L^2 \end{pmatrix}$$

- Most general mass terms:

$$-\mathcal{L}_{M,SM} = \lambda_2 \overline{\psi}_L^1 \tilde{H} \mathcal{T}_R^1 + h.c.$$

$$-\mathcal{L}_{M,1} = \lambda_3 \overline{\psi}_L^1 \tilde{H} \mathcal{T}_R^2 + \lambda_4 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^1 + \lambda_5 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^2 + h.c.$$

  – λ_4 can be rotated away by redefinition of $\mathcal{T}_R^2$
  – 4 physical parameters, m_b, m_t, M_T, θ_L
- Higgs, neutral current, charged couplings changed

Decoupling of Heavy Top Partners

- Remember SM top doesn't decouple

$$M^t = \begin{pmatrix} \frac{\lambda_2 v}{\sqrt{2}} & \frac{\lambda_3 v}{\sqrt{2}} \\ \lambda_4 & \lambda_5 \end{pmatrix}$$

- Small mixing: $$\lambda_2 \sim \frac{\sqrt{2} m_t}{v}\left[1 + \frac{s_L^2}{2}\left(\frac{M_T^2}{m_t^2} - 1\right)\right]$$

$$\lambda_5 \sim M_T\left[1 - \frac{s_L^2}{2}\left(\frac{M_T^2 - m_t^2}{M_T^2}\right)\right]$$

- Decoupling of T requires:

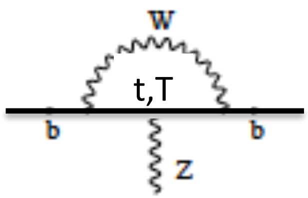
$$s_L \sim \frac{v}{M_T}$$

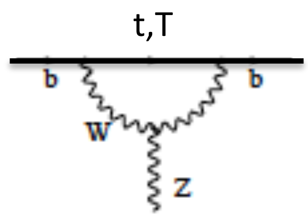
Couplings to W/Z/H Modified

- t-T mixing modifies $Z \to b\bar{b}$ at one loop

$$L_W \sim \frac{g}{\sqrt{2}} W_\mu^+ \left\{ c_L \bar{t}_L \gamma^\mu b_L + s_L \overline{T}_L \gamma^\mu b_L \right\}$$

$$\delta L \sim \frac{g}{c_W} Z_\mu \left\{ \bar{t}_L \gamma^\mu (-\frac{s_L^2}{2}) t_L + \overline{T}_L \gamma^\mu (-\frac{c_L^2}{2}) T_L + \bar{t}_L \gamma^\mu (\frac{s_L c_L}{2}) T_L + hc \right\}$$





$$\delta g_L^b \sim \delta g_L^{b,SM} \left\{ 1 + s_L^2 \left[-(1 + c_L^2) + s_L^2 \frac{M_T^2}{M_t^2} + 2 c_L^2 \frac{M_T^2}{M_T^2 - m_t^2} \log\left(\frac{M_T^2}{m_t^2} \right) \right] \right\}$$

- *Vector-like top partners only decouple when $s_L \sim v/M_T$*

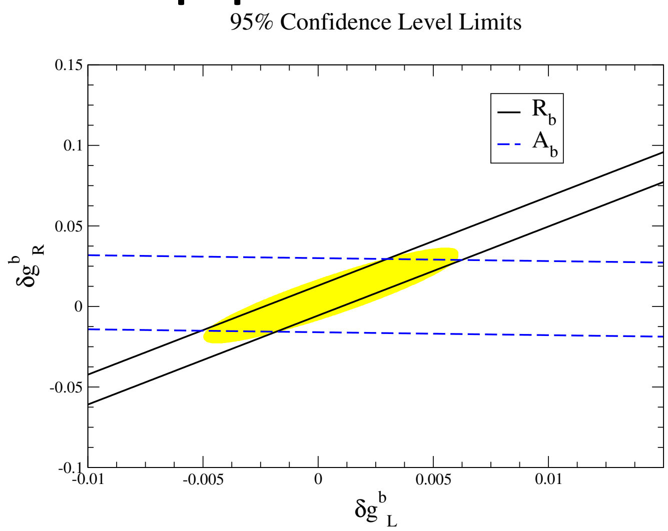
Limits from $Z \to b\bar{b}$

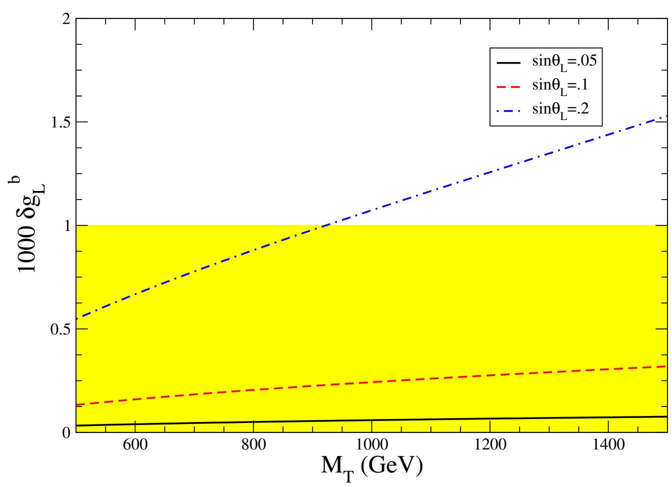
- Top partner (& top) couplings to Z change $Z \to b\bar{b}$

$$R_b \sim R_b^{SM}\left\{1 - 3.6\delta g_L^b + .65\delta g_R^b\right\}$$

$$A_b \sim A_b^{SM}\left\{1 - .32\delta g_L^b - 1.7\delta g_R^b\right\}$$

- Top partner increases $\delta g_L{}^b$ and reduces R_b





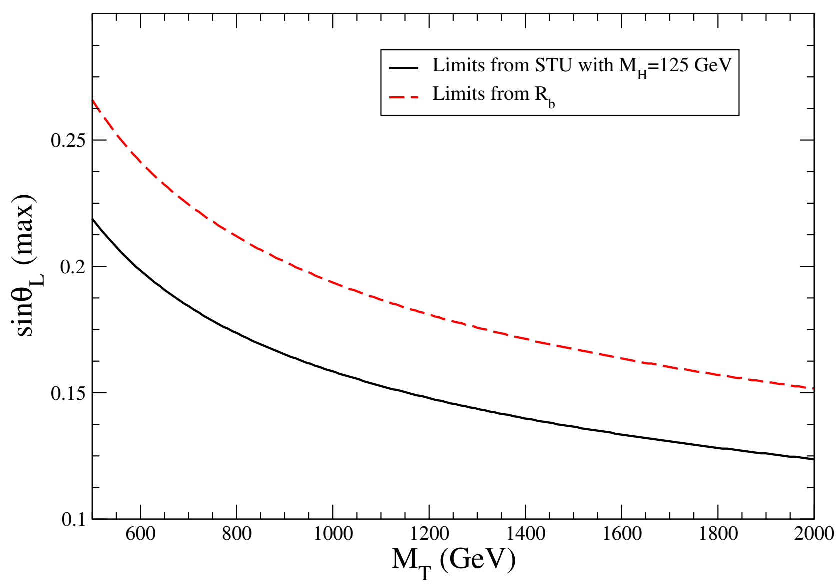
[Dawson, Furlan; Similar results in Aguilar-Saavedra, 1306.0572]

Top Partner Mixing Limited by Precision EW

$$\Delta T \sim T_{SM} s_L^2 \left[-(1+c_L^2) + s_L^2 \frac{M_T^2}{m_t^2} + 2c_L^2 \log\left(\frac{M_T^2}{m_t^2}\right)\right.$$

$$\Delta S \sim -\frac{s_L^2}{6\pi}\left[5c_L^2 + (1-3c_L^2)\log\left(\frac{M_T^2}{m_t^2}\right)\right]$$

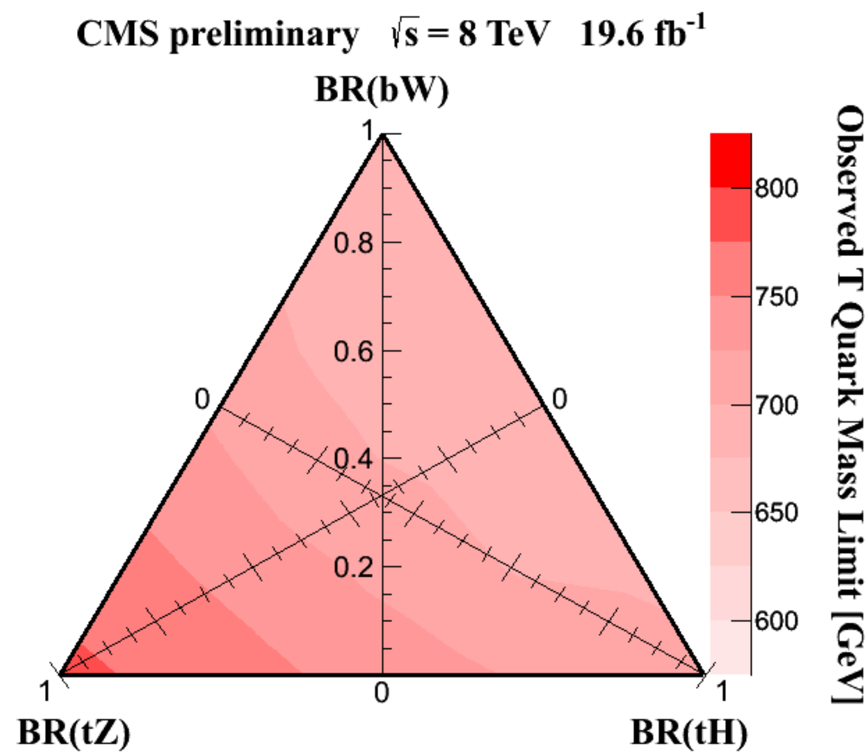
95% CL Upper Limits



Top Partner limits

- LHC limits model dependent, but $M_T > 600\text{-}700$ GeV
  - $T \to bW$, $T \to tH$, $T \to tZ$
  - $gg \to T\bar{T}$ model independent
- Unitarity

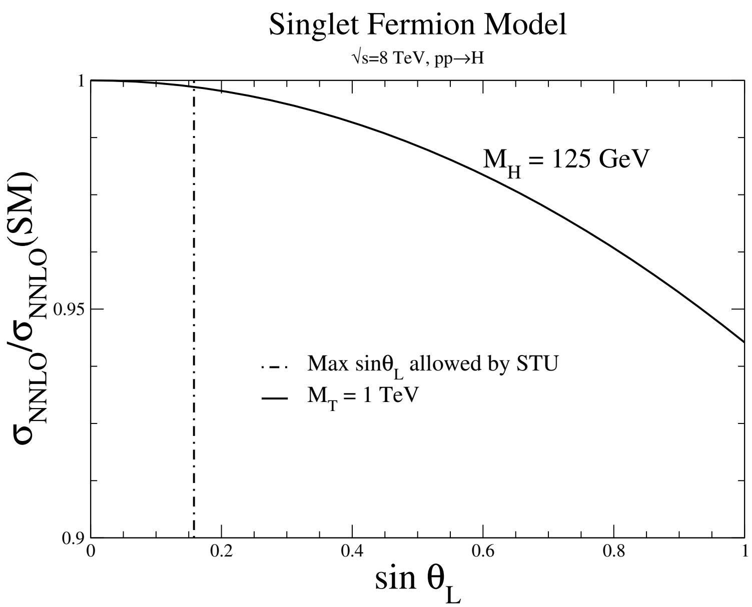
$$M_T < \frac{550\ GeV}{s_L^2}$$



CMS-PAS-B2G-12-015

Top Partners and gluon fusion

- Top partner: $\sigma \sim \sigma_{SM}\left\{1-\frac{7M_H^2}{60m_t^2}s_L^2\left(1-\frac{m_t^2}{M_T^2}\right)\right\}$

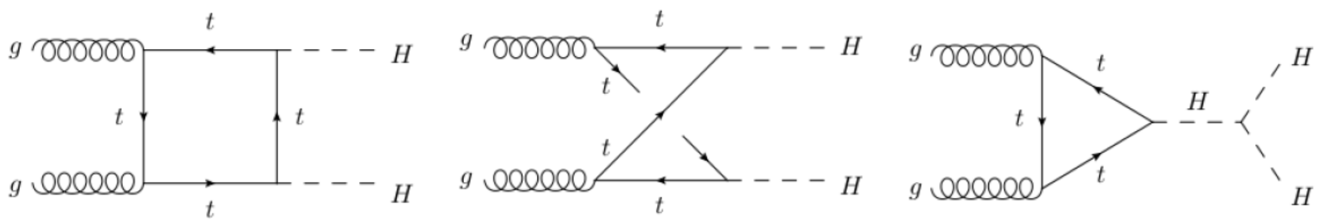


Large effects not possible due to precision EW

$$L_H \sim \frac{m_t}{v}c_L^2 t\bar{t}H + \frac{M_T}{v}s_L^2 T\overline{T}H$$

→ Leading piece in M_H^2/M_t^2 expansion independent of top partner mixing

Two Higgs Production and Top Partners

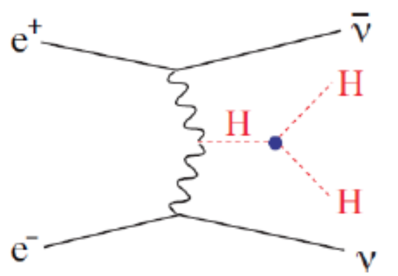


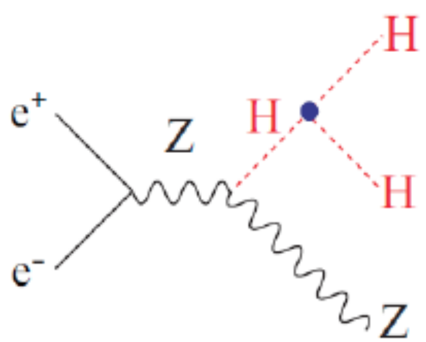
- Sensitive to HHH coupling and new particles in loops
  - Cancellation between box and triangle reduces sensitivity
- Small rate: 3 fb at 8 TeV, 15 fb at 14 TeV
  - $bb\gamma\gamma$ gives 3σ with 3 ab^{-1} (270 events with 3 ab^{-1})
  - 30% measurement of λ_{HHH}

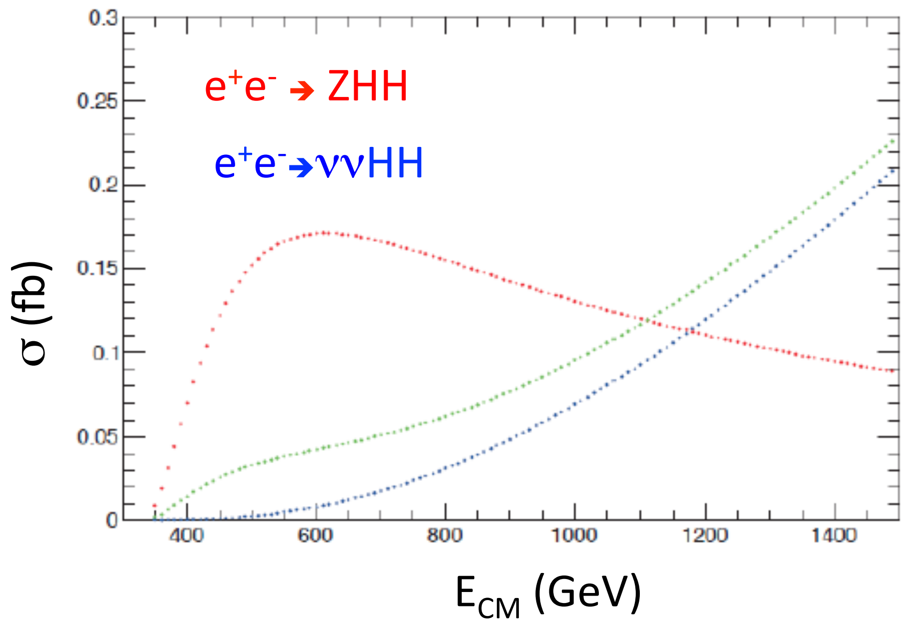
[ATLAS/CMS HL-LHC study]

ILC doesn't do that much better with HHH

- Low rates: 400 events at 500 GeV, 1000 events at 3 TeV
- Large backgrounds







$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} \sim 25\%(ILC), 15\%(CLIC)$$

Two Higgs Production at LHC

- Cross section has spin-0 and spin-2 contributions

$$\frac{d\sigma(gg \to HH)}{dt} = \frac{\alpha_s^2}{32768\pi^3 v^4}\left(| F_0 |^2 + | F_2 |^2 \right)$$

- $M_t^2 >> s$ (low energy theorem)

$$F_0 \to -\frac{4}{3} + \frac{4M_H^2}{s - M_H^2}(\delta\lambda_{HHH})$$

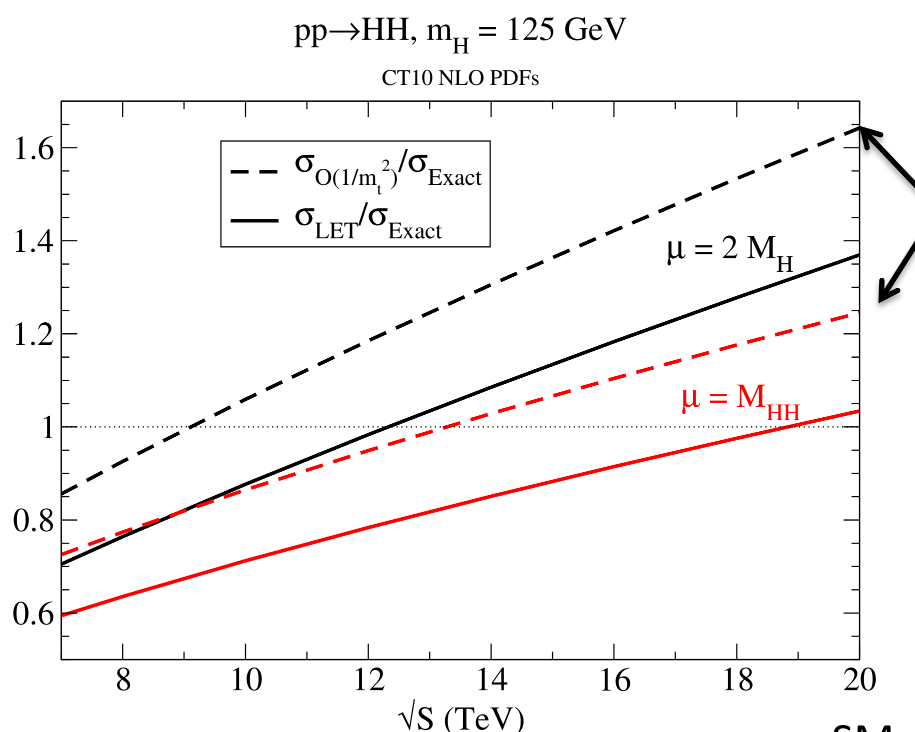
$$F_2 \to 0$$

HHH coupling (1 for SM)

- Singlet top partner model has s_L and c_L in appropriate places
- Also has new diagrams with tTH vertices

Low Energy Expansion (M_H<<M_t)

- Works spectacularly well for gg→H
  - Not so well for gg→ HH (more scales in problem)
  - Same conclusion for gg→ gH [Harlander et al., 1206.0157]

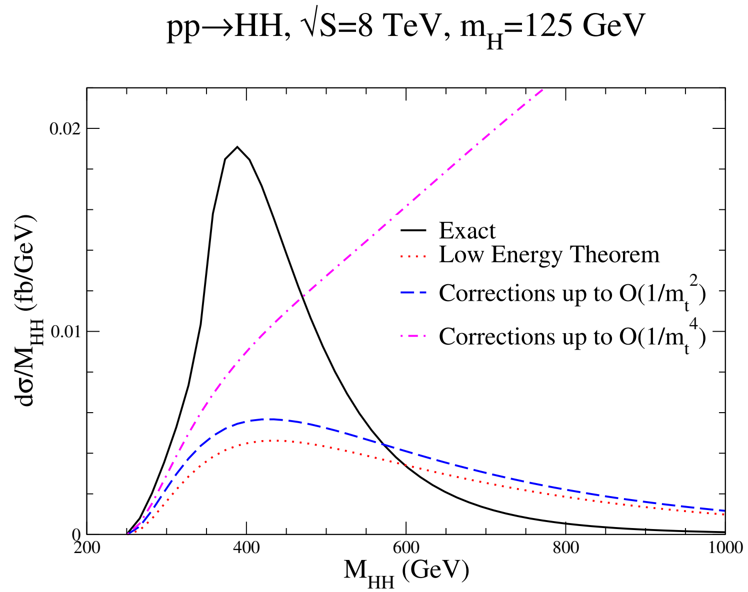


Add in first term of s/M_t^2 expansion

SM

Low Energy Expansions and Distributions

Low energy expansion doesn't work for distributions



Could show similar plots for top partner singlet model, but they aren't interesting!! They look like SM

Mirror Fermions

- Can have very different effects on single and double Higgs production

$$\psi_L^1 = \begin{pmatrix} \mathcal{T}_L^1 \\ \mathcal{B}_L^1 \end{pmatrix}, \quad \mathcal{T}_R^1, \mathcal{B}_R^1 ; \qquad \psi_R^2 = \begin{pmatrix} \mathcal{T}_R^2 \\ \mathcal{B}_R^2 \end{pmatrix}, \quad \mathcal{T}_L^2, \mathcal{B}_L^2$$

$$-\mathcal{L} = \lambda_A \overline{\psi}^1_L \Phi \mathcal{B}_R^1 + \lambda_B \overline{\psi}^1_L \tilde{\Phi} \mathcal{T}_R^1 + \lambda_C \overline{\psi}^2_R \Phi \mathcal{B}_L^2 + \lambda_D \overline{\psi}^2_R \tilde{\Phi} \mathcal{T}_L^2$$
$$+ \lambda_E \overline{\psi}^1_L \psi_R^2 + \lambda_F \overline{\mathcal{T}}^1_R \mathcal{T}_L^2 + \lambda_G \overline{\mathcal{B}}^1_R \mathcal{B}_L^2 + \text{h.c.}$$

- 7 parameters in Lagrangian. Assume $M_{T1}=M_{B1}=M$, $M_{T2}=M_{B2}=M(1+\delta)$
  - Leading terms in H, HH production independent of M
  - Δ : Deviation from SM gg→ H
  - θ_-^t, θ_+^b

Assume for simplicity no mixing with SM fermions

Relationships among Parameters

- In the limit of small mixing

$$(s_L^t)^2 \sim \frac{m_t^2}{M_T^2}(s_R^t)^2, \ (s_L^b)^2 \sim \frac{m_b^2}{M_B^2}(s_R^b)^2$$

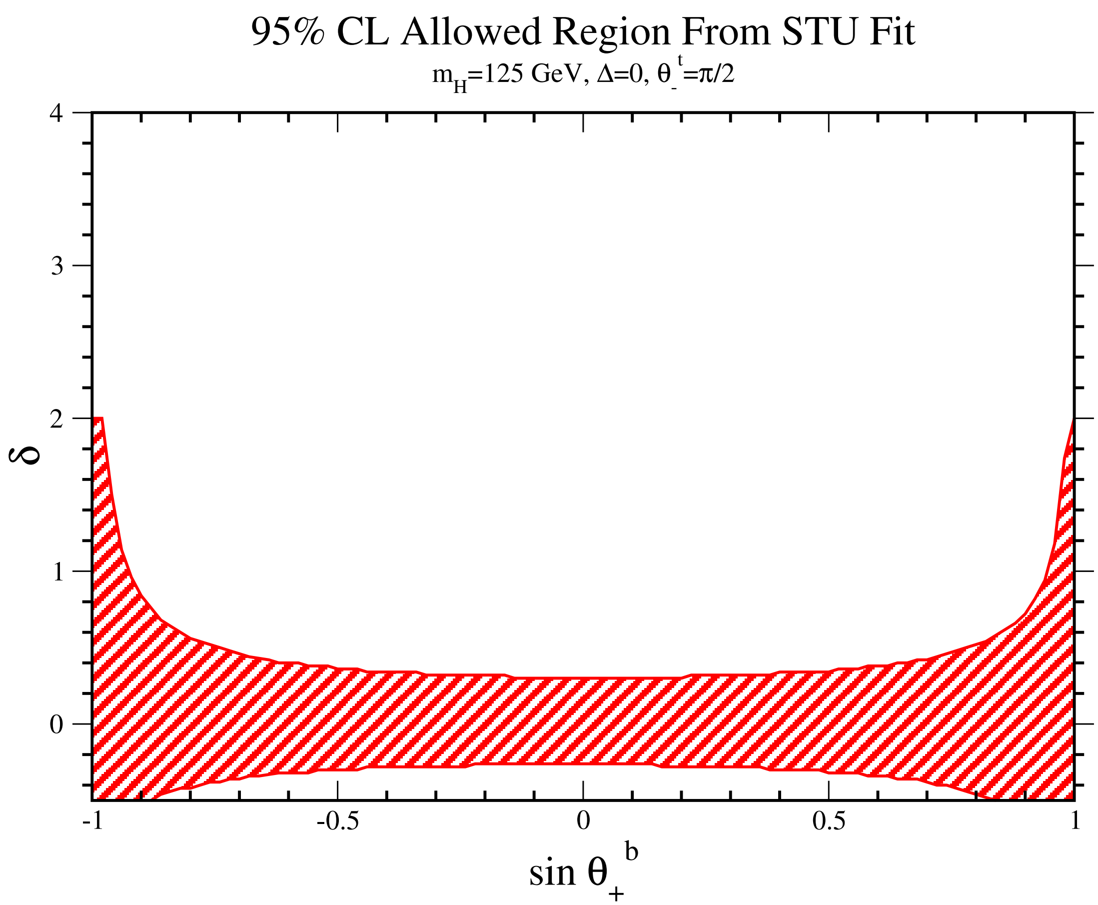
$$(s_R^t)^2 \sim (S_R^b)^2 + \mathcal{O}(\delta)$$

- W/Z/H couplings modified by s_L^t, s_L^b
- Limits from STU require (for M_T=1 TeV), $\delta < 2$

Interesting Regions of Parameter Space

- All parameters in this plot give SM gg→H rate

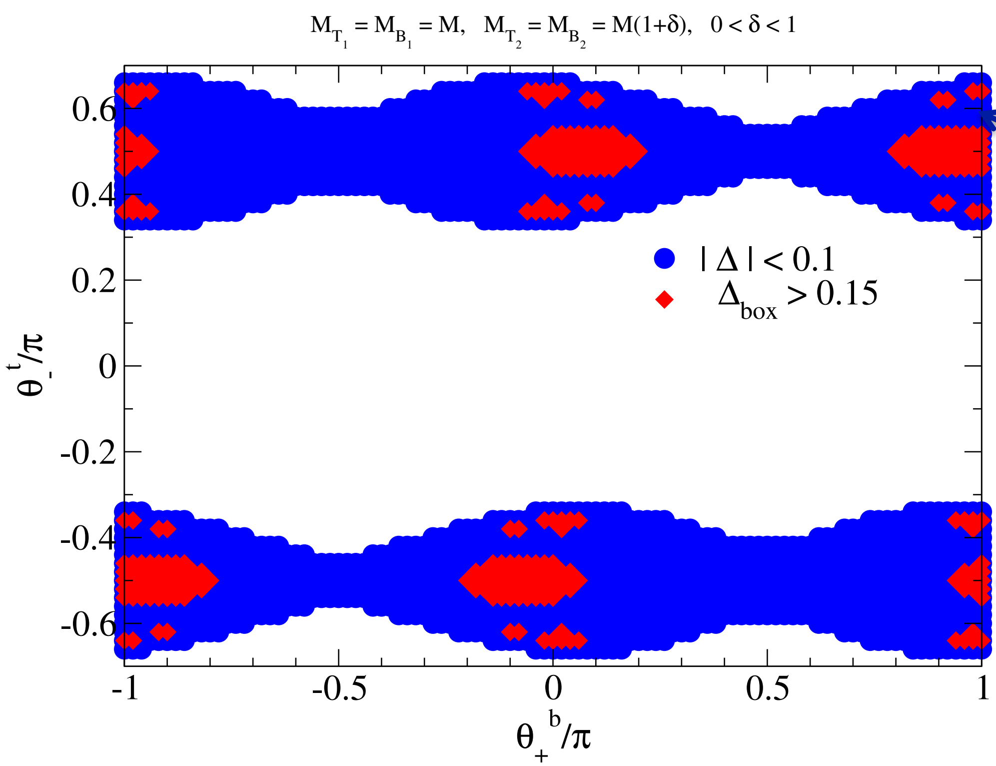
Fermion mass splitting



Dawson, Furlan, Lewis; Early work by He, Polonsky, and Su, hep-ph/0102144

Significant Deviations Possible in HH Production

- Parameter scan:

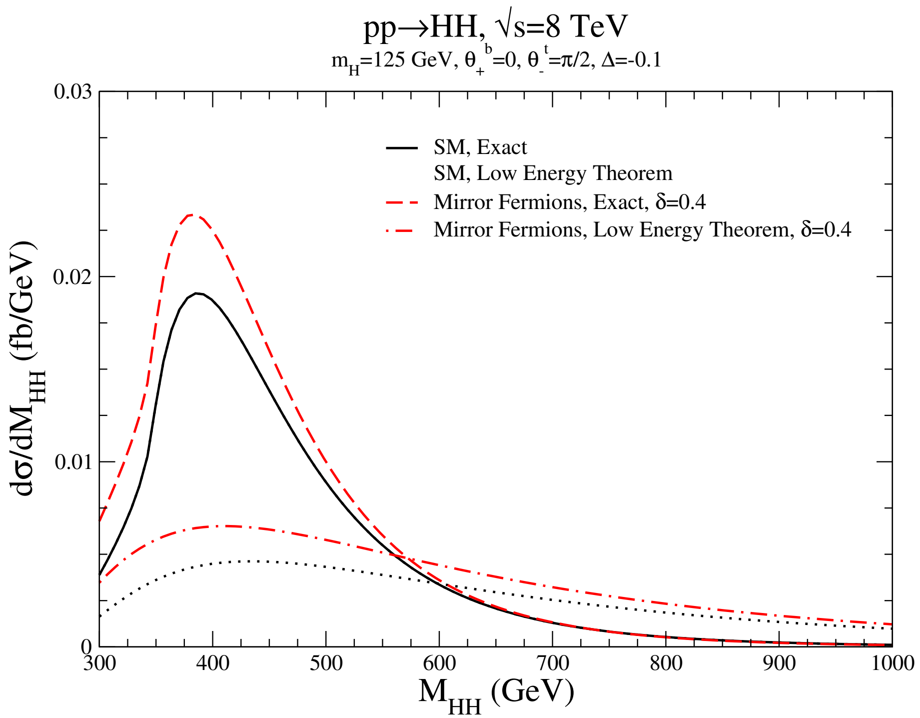


Single Higgs production within 10% of SM

Box contribution to gg→ HH more than 15% greater than SM

Double Higgs Rate

- gg→HH rate increased by 17% relative to SM
- gg→H rate assumed to be 90% of SM

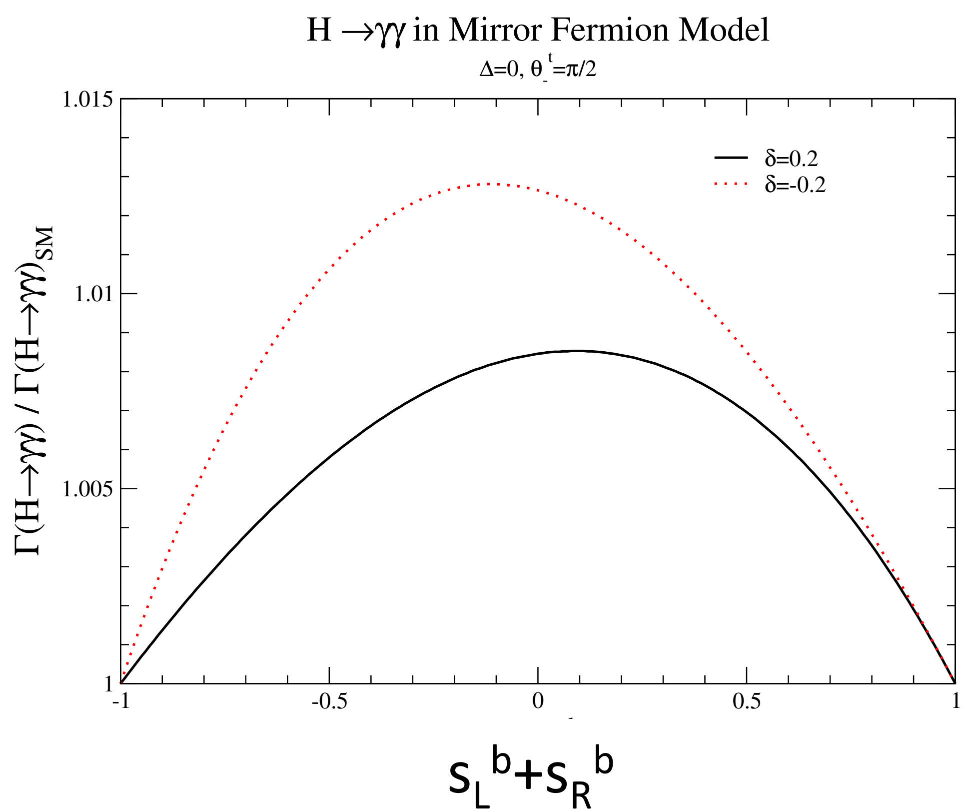


Optimal choice of parameters

H → γγ

- Top singlet model, H→ γγ is within .5% of SM rate
- Mirror Fermion model can have ~1% deviations

(Require gg→H rate to be SM; can have ~10% differences without this requirement)



Effective Higgs Gluon Interactions

- If fermion masses arise from electroweak symmetry breaking, they have the form

$$C_2 O_{LE} = \frac{\alpha_s}{24\pi} C_2 G^A_{\mu\nu} G^{A,\mu\nu} \log\left(\frac{H^+ H}{v^2}\right) = \frac{\alpha_s}{12\pi} C_2 G^A_{\mu\nu} G^{A,\mu\nu} \left(\frac{H}{v} - \frac{H^2}{2v^2}\right)$$

- A general expansion could generate

SM: $C_1=0$, $C_2=1$

$$C_1 O_{eff} = \frac{\alpha_s}{12\pi} C_1 G^A_{\mu\nu} G^{A,\mu\nu} \left|\frac{H^+ H}{v^2}\right|^2 = \frac{\alpha_s}{12\pi} C_1 G^A_{\mu\nu} G^{A,\mu\nu} \left(\frac{H}{v} + \frac{H^2}{2v^2}\right)$$

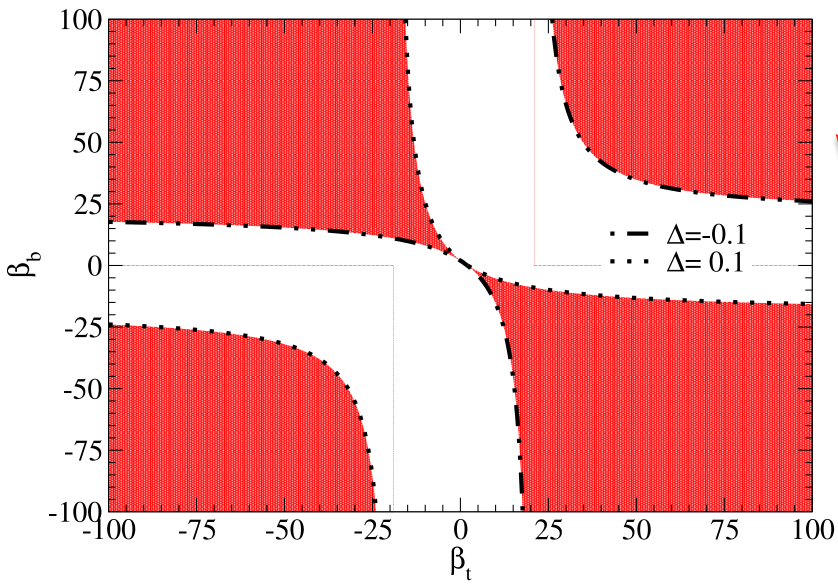
- Measuring single and double Higgs production is window into source of EWSB

$C_H = C_1+C_2 \rightarrow 1+\Delta$
$C_{HH}= C_1-C_2 \rightarrow 2C_1-(1+\Delta)$

[Pierce, Thaler, Wang, hep-ph/0609049; Dawson, Furlan, Lewis, hep-ph/ 1205.4733]

Large effects in HH?

- Mirror model: $C_1^i = \frac{-2\beta_i}{(1-\beta_i)^2}, \; C_2^i = 1 + \frac{2}{(1-\beta_i)^2}$
- $\beta_i \rightarrow 0$, $C_i \rightarrow$ SM (β is function of Yukawa couplings)
  - Happens when Dirac mass term for partners vanish



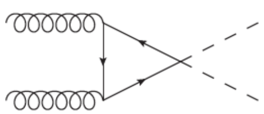
gg→ H within 10% of SM

Compare Double Higgs Production

- Effective Lagrangian with mirror fermions and δ=0:

$$L_{eff} = \frac{\alpha_s}{12\pi} G^A_{\mu\nu} G^{A,\mu\nu} \left[(1 + 4\cos^2\theta^b_-) \frac{H}{v} - (1 - 4\cos^2\theta^b_- + 8\cos^4\theta^b_-) \frac{H^2}{2v^2} \right]$$

- Composite Models (or Little Higgs)
  - Non-renormalizable $t\bar{t}HH$ interaction can give enhancement of factors of 2
  - Partially due to cancellation in SM between diagrams



[Gillioz et al, hep-ph/1206.7120]

Conclusions

- Vector like top partners are natural extensions of SM
- Parameters allowed by EW precision observables give $gg \rightarrow H$ rate close to SM
- *STU + Higgs production the new precision EW parameters*
- $gg \rightarrow HH$ can be enhanced by ~17%
  - Small effects in $H \rightarrow \gamma\gamma$
  - Higgs branching ratio deviations much smaller than theory uncertainties
- Aside: Low energy limit not valid for $2 \rightarrow 2$ processes
- Look for top partners directly in single T production*
  - σ < 20 fb at 8 TeV for M_T~1 TeV

[* Aguilar-Saavedra, hep-ph/1306.0572]