EXTRACTING PARAMETERS FROM SUSY HEAVY HIGGS

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FERMILAB

GOAL: MEASURE YUKAWA COUPLINGS + $\tan\beta$ AT LC VIA HIGGS PRODUCTION / DECAY

h^0 (LIGHT HIGGS):
- METHODS SIMILAR TO LIGHT SM HIGGS
- IN "HIGGS DECOUPLING LIMIT" ($m_A \to \infty$) h^0 BEHAVES IDENTICALLY TO SM HIGGS

HOWEVER, COUPLINGS MEASURED IN h^0 PROCESSES MAY NOT REFLECT UNDERLYING COUPLINGS — HIGGS DECOUPLING CONSPIRES TO HIDE UV PHYSICS FROM h^0 SECTOR.

H^0, A^0 (HEAVY HIGGS):

NO DECOUPLING LIMIT — CAN BEHAVE VERY FAR FROM SM HIGGS GENERICALLY.

WELL KNOWN (TREE) PROPERTIES:

$$H^0 \bar{u} u \sim \frac{\sin\alpha}{\sin\beta} \to \cot\beta \qquad A^0 \bar{u} u \sim \cot\beta$$

$$H^0 \bar{d} d \sim \frac{\cos\alpha}{\cos\beta} \underbrace{\to \tan\beta}_{\text{DECOUPLING LIMIT}} \qquad A^0 \bar{d} d \sim \tan\beta$$

TAKE $\tan\beta$ LARGE:

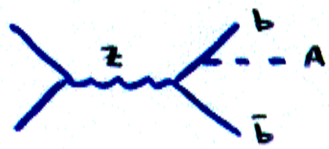
$$g_{Ab\bar{b}} \simeq g_{Hb\bar{b}} \simeq \frac{m_b}{\sqrt{2}\,\mu} \tan\beta \sim O(1) \text{ FOR } \tan\beta \sim 50.$$

SIMILAR ENHANCEMENTS FOR $\left\{\begin{matrix} H \\ A \end{matrix}\right\} \mu\mu$ AND $\left\{\begin{matrix} H \\ A \end{matrix}\right\} \tau\tau$.

DJOUADI, KALINOWSKI, ZERWAS
DAWSON, REINA

CONSIDER $e^+e^- \to b\bar{b}H$ OR $b\bar{b}A$:

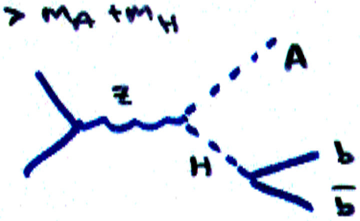
- WHEN $\sqrt{s} < m_A + m_H \simeq 2m_A$



DOMINATES

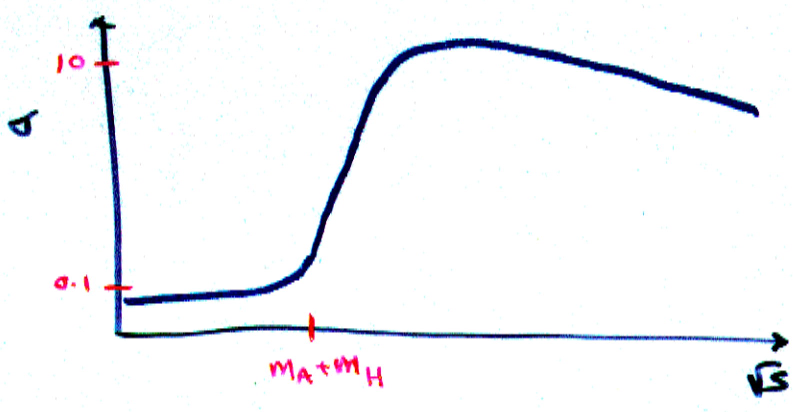
$\rightsquigarrow$ GREAT FOR MEASURING g_{bbA} SINCE $\sigma \sim g^2_{bbA}$.

- WHEN $\sqrt{s} > m_A + m_H$



DOMINATES

$\rightsquigarrow$ BAD FOR MEASURING g_{bbA} OR g_{bbH} SINCE $\sigma \sim g^2_{AHZ}$ AND $BR(H \to b\bar{b}) \simeq 1$ AT LARGE $\tan\beta$ REGARDLESS.



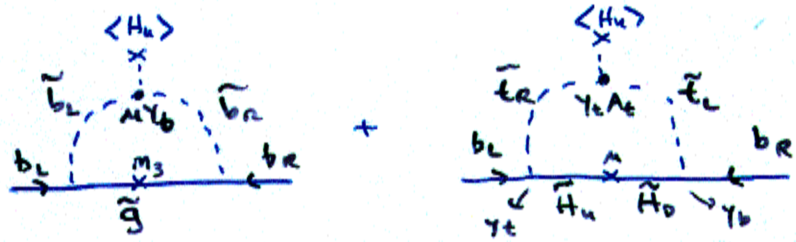
QCD CORRECTIONS HAVE BEEN CALCULATED FOR $b\bar{b}H/A$ PRODUCTION BY SEVERAL GROUPS

DAWSON + REINA
SPIRA

BUT THERE EXISTS A POTENTIALLY MUCH LARGER CORRECTION FROM SUSY THRESHOLD EFFECTS.

→ WELL-KNOWN SUSY-BREAKING CONTRIBUTIONS TO D-QUARK MASSES!

HALL-RATTAZZI-SARID



$$\equiv y_b \epsilon_b$$

$$\mathcal{L} = y_b \bar{b}_L b_R H_D + y_b \epsilon_b \bar{b}_L b_R H_u^* + \text{h.c.}$$

$$= y_b v \sin\beta \,(1 + \epsilon_b \tan\beta)\, \bar{b}_R b_L$$

$$+ \frac{y_b}{\sqrt{2}} \bar{b}_R b_L \left\{ \tan\beta \left(1 + \cancelto{0}{\epsilon_b \cot\beta}\right) A^\circ + \frac{\cos\alpha}{\cos\beta}\left(1 + \cancelto{0}{\epsilon_b \frac{\sin\alpha}{\cos\alpha}}\right) H^\circ \right\}$$

BUT $m_b = y_b v \sin\beta \,(1 + \epsilon_b \tan\beta)$:

$$\rightarrow \mathcal{L} = \frac{m_b}{\sqrt{2}\, v \sin\beta} \left(\frac{1}{1 + \epsilon_b \tan\beta}\right) \left(\tan\beta\, A^\circ + \frac{\cos\alpha}{\cos\beta} H^\circ\right) \bar{b}_R b_L + \text{h.c.}$$

$$+ \; m_b\text{-term}$$

CARENA, MRENNA, WAGNER

BABU + KOLDA

HOW LARGE IS $\delta m_b / m_b \equiv \epsilon_b \tan\beta$?

$$\epsilon_b = \frac{2\alpha_3}{3\pi} \frac{\mu M_3}{m_{\tilde{Q}}^2} + \frac{y_t^2}{16\pi^2} \frac{\mu A_t}{m_{\tilde{Q}}^2}$$

N.B. AS $\mu \sim M_3 \sim m_{\tilde{Q}} \sim A_t \to \infty$, $\epsilon_b \to$ CONSTANT.

But how large should we expect $\delta m_b/m_b$ to be??? For guidance we turn to ...

$\boxed{1}$ Quick and Dirty Estimates

As before, for universal masses $\epsilon_g \simeq \frac{1}{80}$ and $\epsilon_u \simeq \pm\frac{1}{4}\epsilon_g$. Then

$$\frac{\delta m_b}{m_b} = (\epsilon_g + \epsilon_u y_t^2)\tan\beta \simeq \left(\frac{1}{64} \text{ to } \frac{1}{107}\right)\tan\beta$$

$\boxed{2}$ Grand Unified Theories (GUT's)

GUT's with simple Higgs structure tend to predict $y_b = y_\tau$ at M_X to within a few %. Compare this to result in MSSM, running y_b and y_τ from m_Z to M_X:

$$\begin{aligned}
\frac{dy_b}{d\log Q} &= \frac{y_b}{16\pi^2}\left\{-\frac{7}{15}g_1^2 - 3g_2^2 - \frac{16}{3}g_3^2 + y_t^2 + 6y_b^2 + y_\tau^2\right\} \\
\frac{dy_\tau}{d\log Q} &= \frac{y_\tau}{16\pi^2}\left\{-\frac{9}{5}g_1^2 - 3g_2^2 + 3y_b^2 + 4y_\tau^2\right\}
\end{aligned}$$

Obviously there is strong interplay between size of y_t and strength of strong interaction in the running of y_b.

Numerically, $b - \tau$ unification only appears to occur for:

$$* \quad m_t = (205\,\text{GeV})\sin\beta \quad *$$

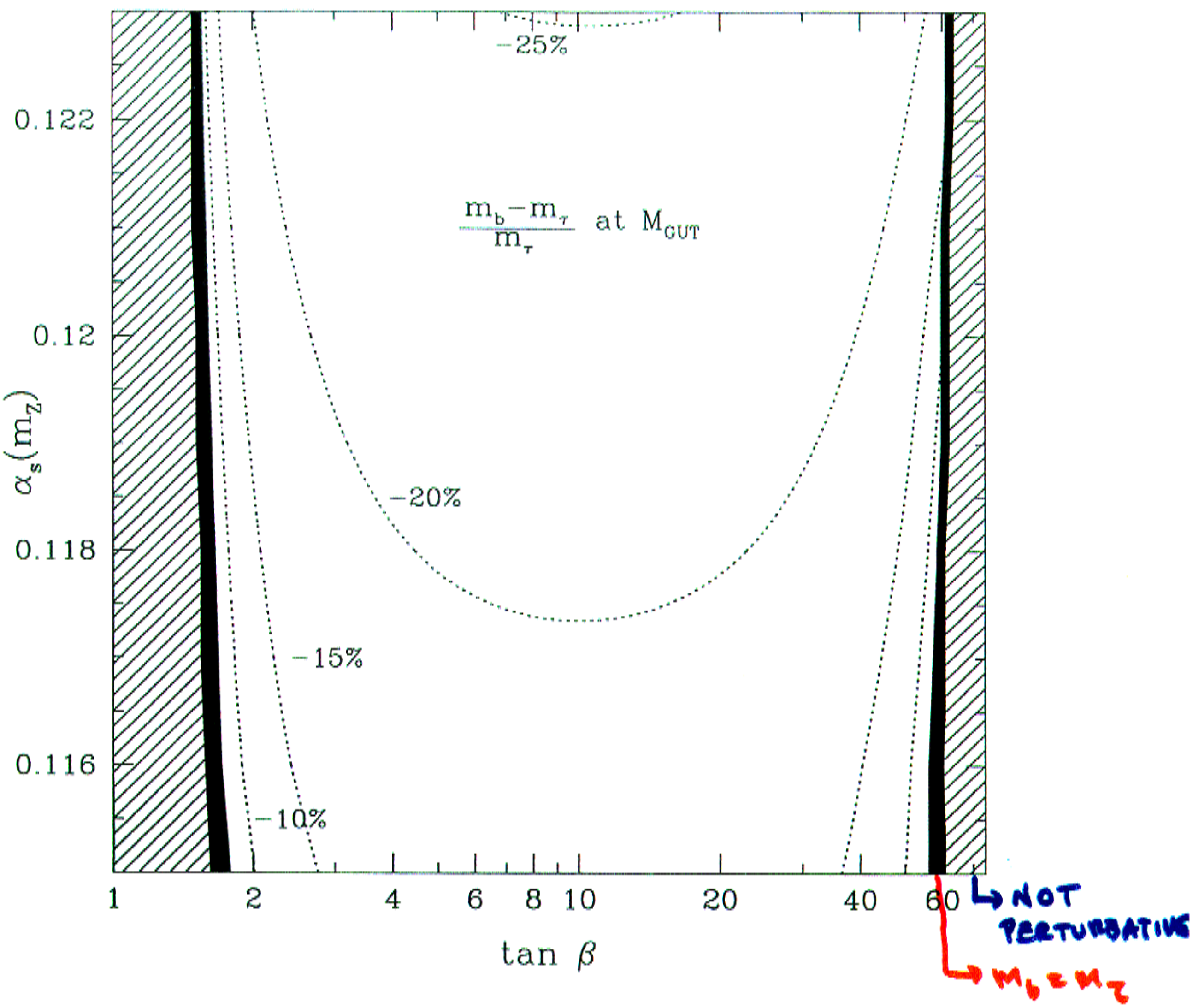
($y_t(m_Z)$ near its infrared quasi-fixed point, or $y_t(M_X)$ near its Landau pole) or

$$* \quad \tan\beta \simeq 60 \text{ to } 65. \quad *$$

Otherwise,

$$y_b(M_X) < y_\tau(M_X) \Longleftrightarrow m_b^{\text{GUT}} > m_b^{\text{obs}}.$$

Plot of $(y_b - y_\tau)/y_\tau$ evaluated at $Q = M_X$:



In most of parameter space, finite corrections are needed to <u>diminish</u> $m_b(m_Z)$ from its GUT-predicted value:

$$\boxed{-25\% \lesssim \frac{\delta m_b}{m_b} \lesssim -18\%.}$$

5

CONSIDER FOLLOWING [redacted] CASES :

- $\tan\beta = 50$, $\epsilon_b \tan\beta = \pm\frac{1}{2}$

  $+\frac{1}{2}$: $m_b = y_b v_d \left(1+\frac{1}{2}\right) \rightarrow y_b = \frac{2}{3} \times$ TREE VALUE

  $-\frac{1}{2}$: $m_b = y_b v_d \left(1-\frac{1}{2}\right) \rightarrow y_b = 2 \times$ TREE VALUE

- $\tan\beta = 25$, $\epsilon_b \tan\beta = \pm\frac{1}{2}$

  - $\pm\frac{1}{2}$: (same as above)

ABOVE $m_A + m_H$ THRESHOLD, WE MEASURE $g^2_{ZAH} \equiv \sin^2(\alpha-\beta) = 1$
(FOR LARGEST $\tan\beta$, SOME g_{bbA} LEAKS IN)

BELOW $m_A + m_H$ THRESHOLD, WE MEASURE YUKAWA COUPLING:

$g^2_{bbA} = \left(\frac{m_b}{\sqrt{2}v}\right.$ [redacted] $\left.\frac{1}{\cos\beta}\right)^2 \simeq \left(\frac{m_b}{\sqrt{2}v}\tan\beta\right)^2$

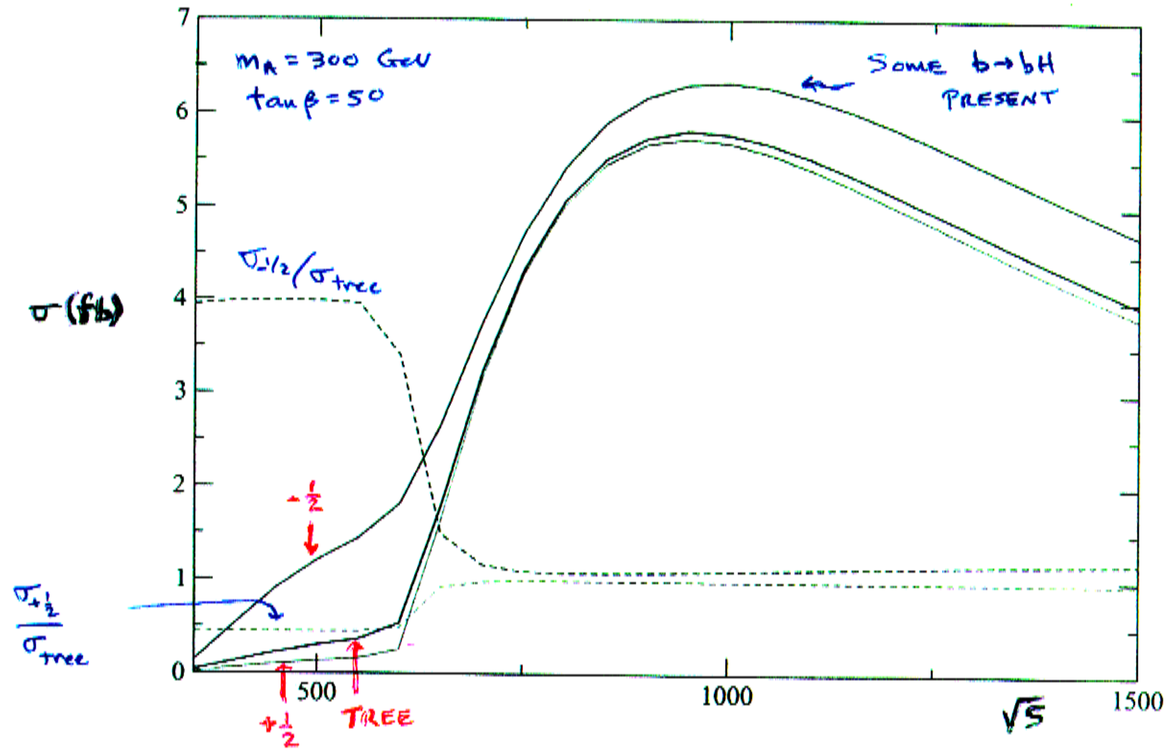
As $\tan\beta$ DECREASES, THIS ALWAYS BECOMES HARDER.

IS $\sigma(\sqrt{s} > m_A + m_H)$ USEFUL? (σ ABOUT $10-30 \times \sigma(\sqrt{s} < m_A + m_H)$)

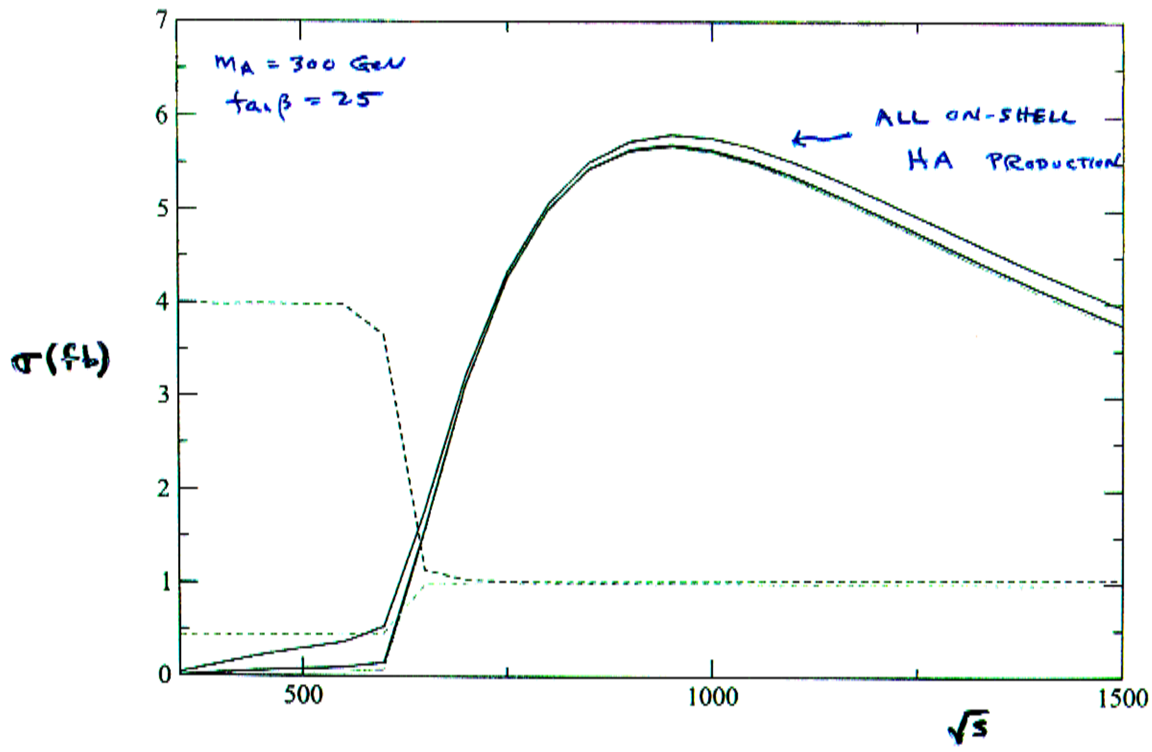
YES, IF WE CAN MEASURE $Br(A^0, H^0 \rightarrow \tau^+\tau^-, cc, VV)$

- $Br(\rightarrow \tau\tau) = f(\epsilon_b \tan\beta)$
- $Br(\rightarrow cc, VV) = f(\epsilon_b, \tan\beta)$

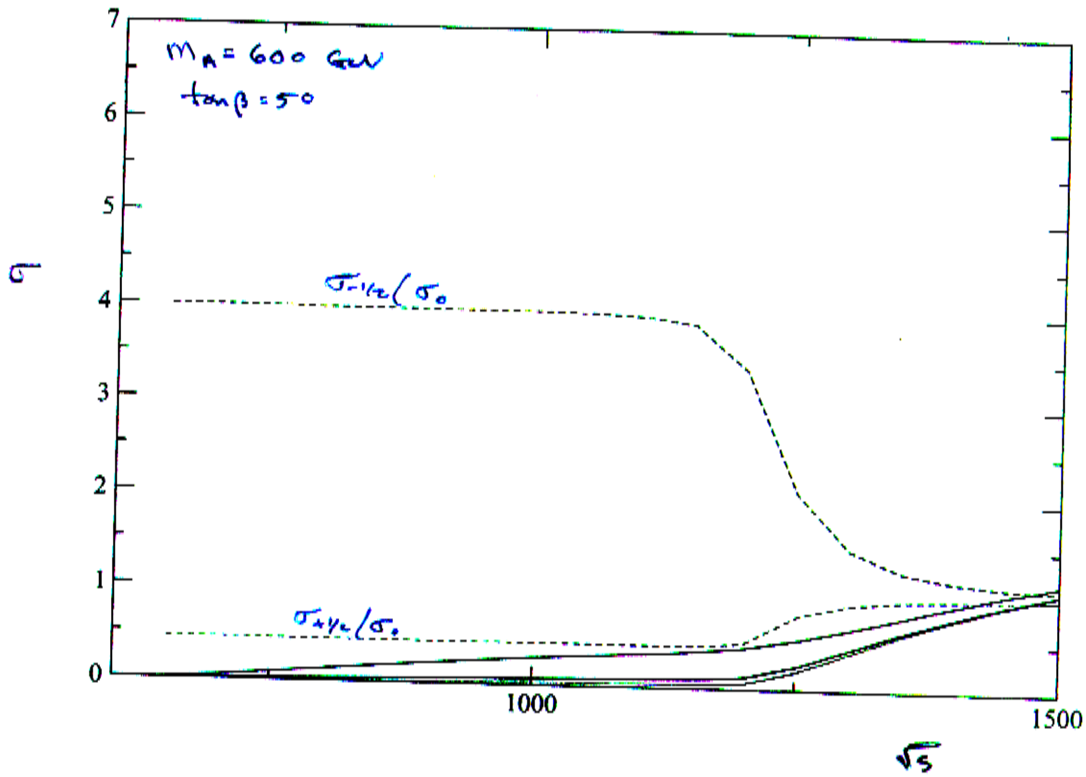
} ASSUMING MSSM

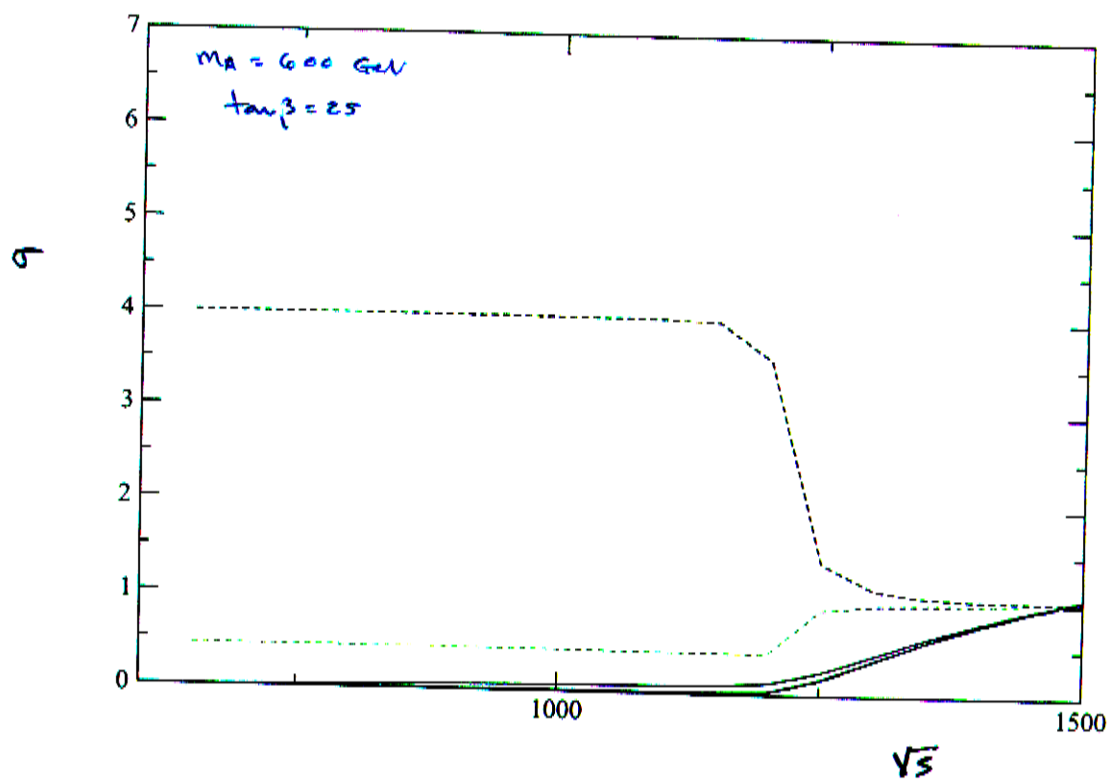


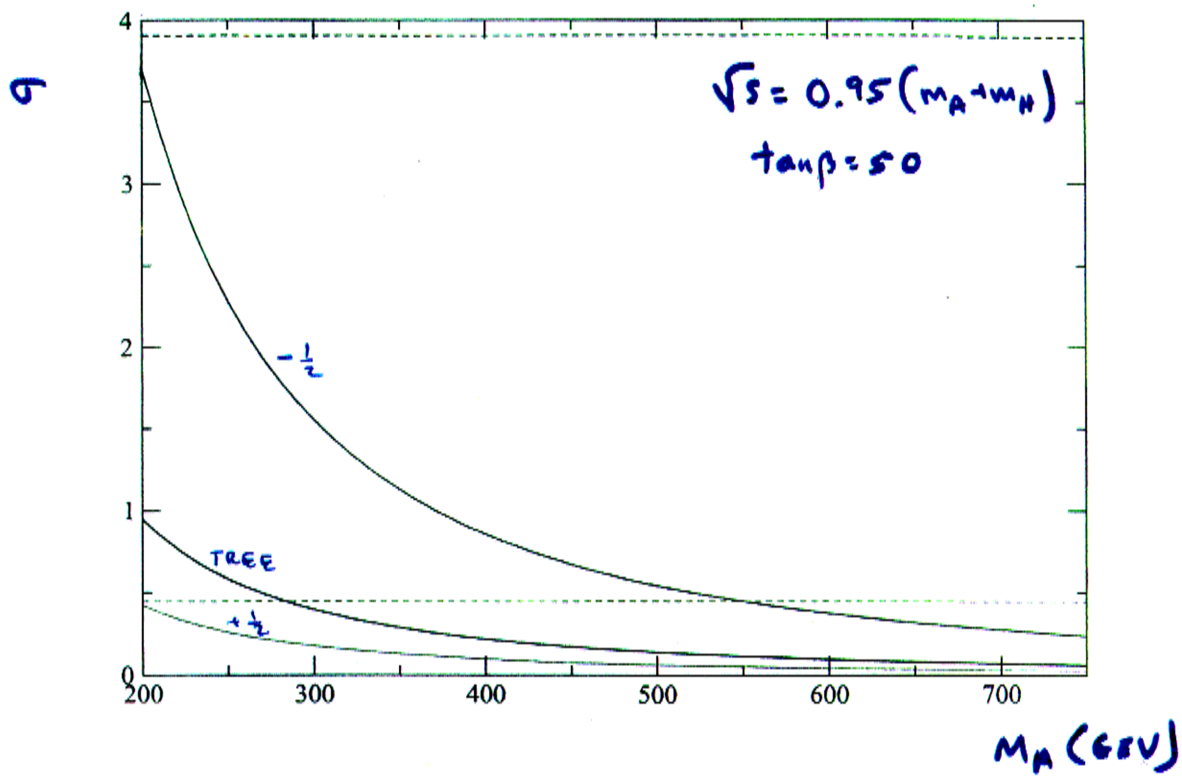
$m_A = 300$ GeV
$\tan\beta = 50$
SOME $b \to bH$ PRESENT
$\sigma_{-1/2}/\sigma_{tree}$
$\sigma(fb)$
$-\frac{1}{2}$
$\sigma_{+\frac{1}{2}}/\sigma_{tree}$
$+\frac{1}{2}$
TREE
$\sqrt{s}$

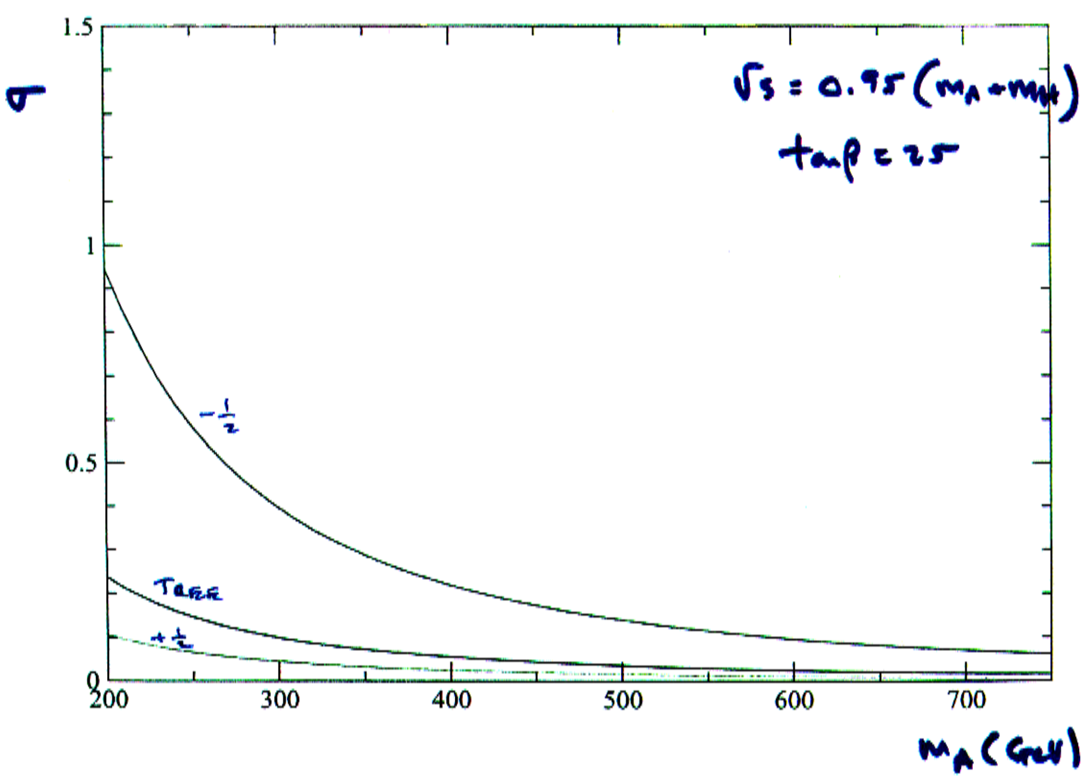


$m_A = 300$ GeV
$\tan\beta = 25$
ALL ON-SHELL HA PRODUCTION
$\sigma(fb)$
$\sqrt{s}$


$m_A = 600$ GeV
$\tan\beta = 50$
$\sigma_{-1/2}/\sigma_0$
$\sigma_{+1/2}/\sigma_0$
σ
$\sqrt{s}$
0
1
2
3
4
5
6
7
1000
1500


$m_A = 600$ GeV
$\tan\beta = 25$
σ
$\sqrt{s}$
0
1
2
3
4
5
6
7
1000
1500


σ
√s = 0.95 (mA + mH)
tanβ = 50
−½
TREE
+½
0
1
2
3
4
200
300
400
500
600
700
MA (GeV)


σ
√s = 0.95 (mA + mH)
tanβ = 25
−½
TREE
+½
0
0.5
1
1.5
200
300
400
500
600
700
mA (GeV)

τ- CASE :

MEASURE $e^+e^- \to HA \to bbbb,\ bb\tau\tau,\ \tau\tau\tau\tau$

WITH H, A ON-SHELL. $\to$ DERIVE $B_R(H \to bb)$,

$B_R(H \to \tau\tau)$

IN STANDARD MODEL: $\dfrac{B_{bb}}{B_{\tau\tau}} = 3\,\dfrac{m_b^2}{m_\tau^2} \times (\text{QCD - CORR})$

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IN MSSM : $\dfrac{B_{bb}}{B_{\tau\tau}} = 3\,\dfrac{m_b^2}{m_\tau^2}\left(\dfrac{1}{1+\epsilon_b \tan\beta}\right)^2 \times (\text{QCD})$

So FOR $\epsilon_b \tan\beta < 0 \to \tau$'s SUPPRESSED (GUT)

$\epsilon_b \tan\beta > 0 \to \tau$'s ENHANCED

THIS SAME PHYSICS ALSO APPEARS IN h° PROCESSES,

BUT CORRECTIONS $\sim$ $\dfrac{(1-\epsilon_b/\tan\alpha)}{(1+\epsilon_b \tan\beta)} \to 1$ AS $m_A \to \infty$

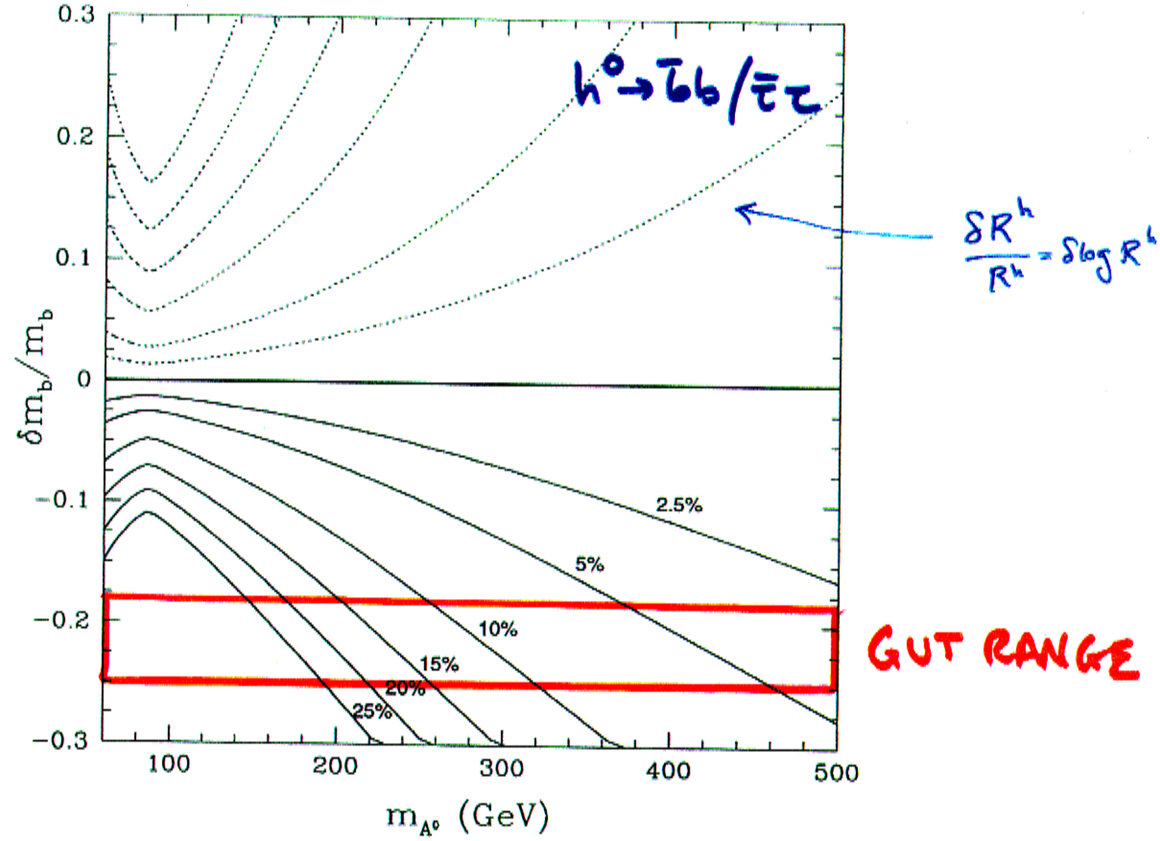
$\to$ HIGGS DECOUPLING !

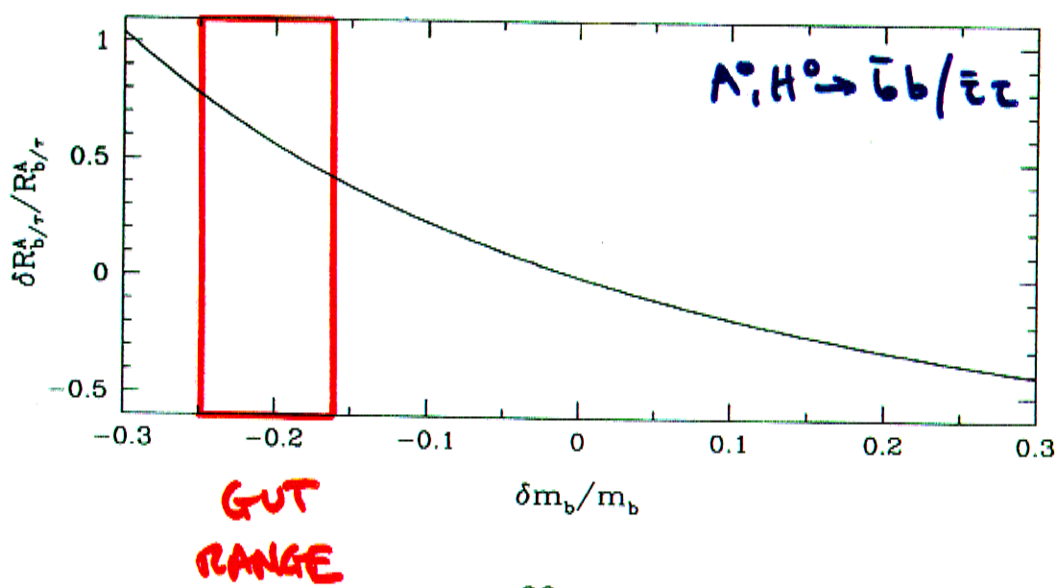
C - CASE :

$$\frac{B_{bb}}{B_{cc}} = \frac{m_b^2}{m_c^2}\left(\frac{\tan\beta}{1+\epsilon_b \tan\beta}\right)^2 \times (\text{QCD})$$

If $\epsilon_b \tan\beta$ MEASURED IN $\tau\tau$, THEN $\tan\beta$ MEASURED HERE.

What does that mean for the predicted $R_{b/\tau}$ and $R^{A,H}_{b/\tau}$?





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SUMMARY:

BAD NEWS:

- CANNOT EXTRACT (LARGE) $\tan\beta$ FROM $b\bar{b}A$, $b\bar{b}H$ BECAUSE WE DON'T KNOW y_b!
- HARD TO EXTRACT YUKAWA INFO IF $\sqrt{s} > m_A + m_H$ (MAYBE SOMEWHAT POSSIBLE AT HIGHEST $\tan\beta$) IN $bbbb$ CHANNEL.

GOOD NEWS:

- GIVEN $\tan\beta$, WE CAN EXTRACT y_b AND δy_b
- CAN EXTRACT INFO ABOVE $m_A + m_H$ FROM $\phi \to \tau\tau$ AND/OR $\phi \to cc$.

PROBING GUT PHYSICS WITH HIGGS DECAYS/PRODUCTION!

SO(10)-LIKE GUTS PREDICT LARGE $\tan\beta$ AND LARGE YUKAWA CORRECTIONS

$\rightsquigarrow$ TYPICALLY INCREASE BELOW-THRESHOLD σ BY ABOUT 2.

$\rightsquigarrow$ TYPICALLY SUPPRESS $\tau\bar{\tau}$, $c\bar{c}$ IN H, A DECAYS BY ABOUT 2.

IN RELATED NEWS ...

THESE δy CORRECTIONS CAN ALSO SHOW UP IN

- h^0 PROCESSES
- $B_s \to \mu\mu$, $B \to X_s \mu\mu$
- $B \to \phi K_s$ (CPV)