Buried Higgs

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with C.Csaki, A.Weiler and A.Falkowski

Cornell, May 14, 2010

Preview

A model of EWSB where

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- Weird Higgs decay automatic

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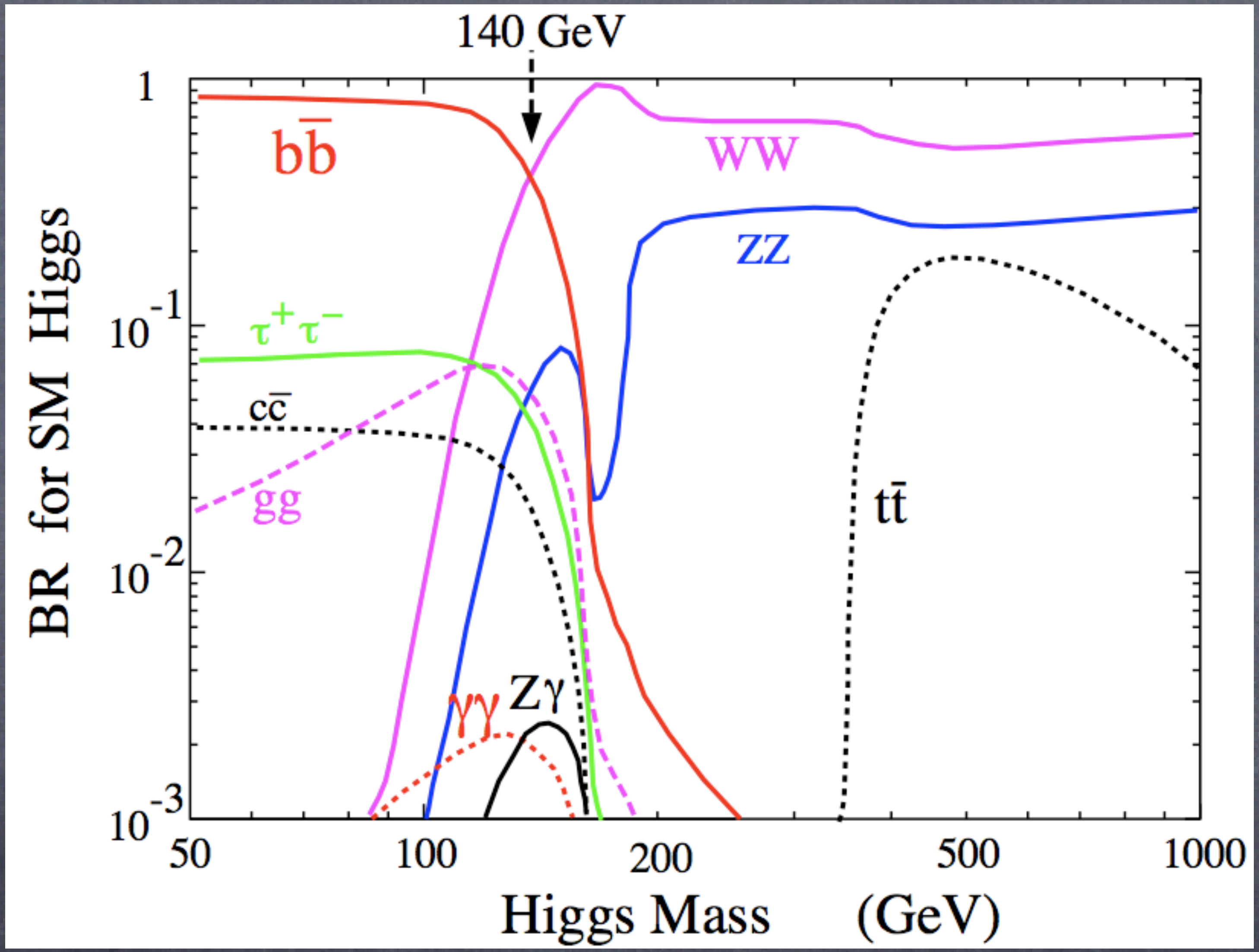
A model of EWSB where

- Weird Higgs decay automatic
- Higgs can evade the LEP bound
- No little hierarchy
- Lots of new particles at LHC (also a “fake” Higgs)
- Higgs deeply buried under QCD background

Outline

- Higgs decays and LEP bound
- Little Hierarchy
- The simplest SUSY pGB Higgs: SU(3)/SU(2)
  - goldstone counting: $8-3=4+1=h+\eta$
- Higgs cascade decays: $h \to \eta\eta \to 2c\bar{c}\,,\ 4g$
- A “fake” Higgs could be discovered
- Conclusions

Higgs BRs

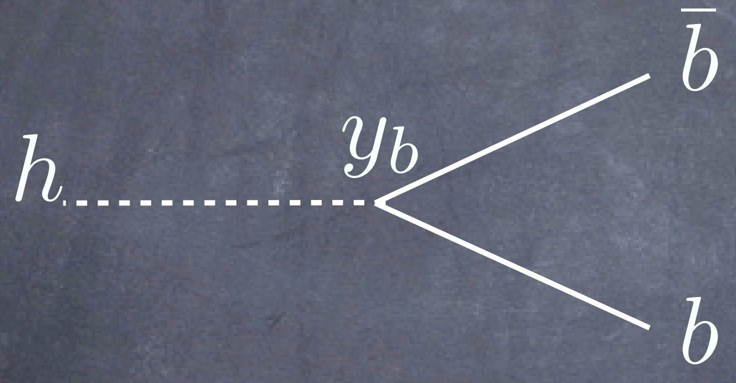


light Higgs
coupling=mass

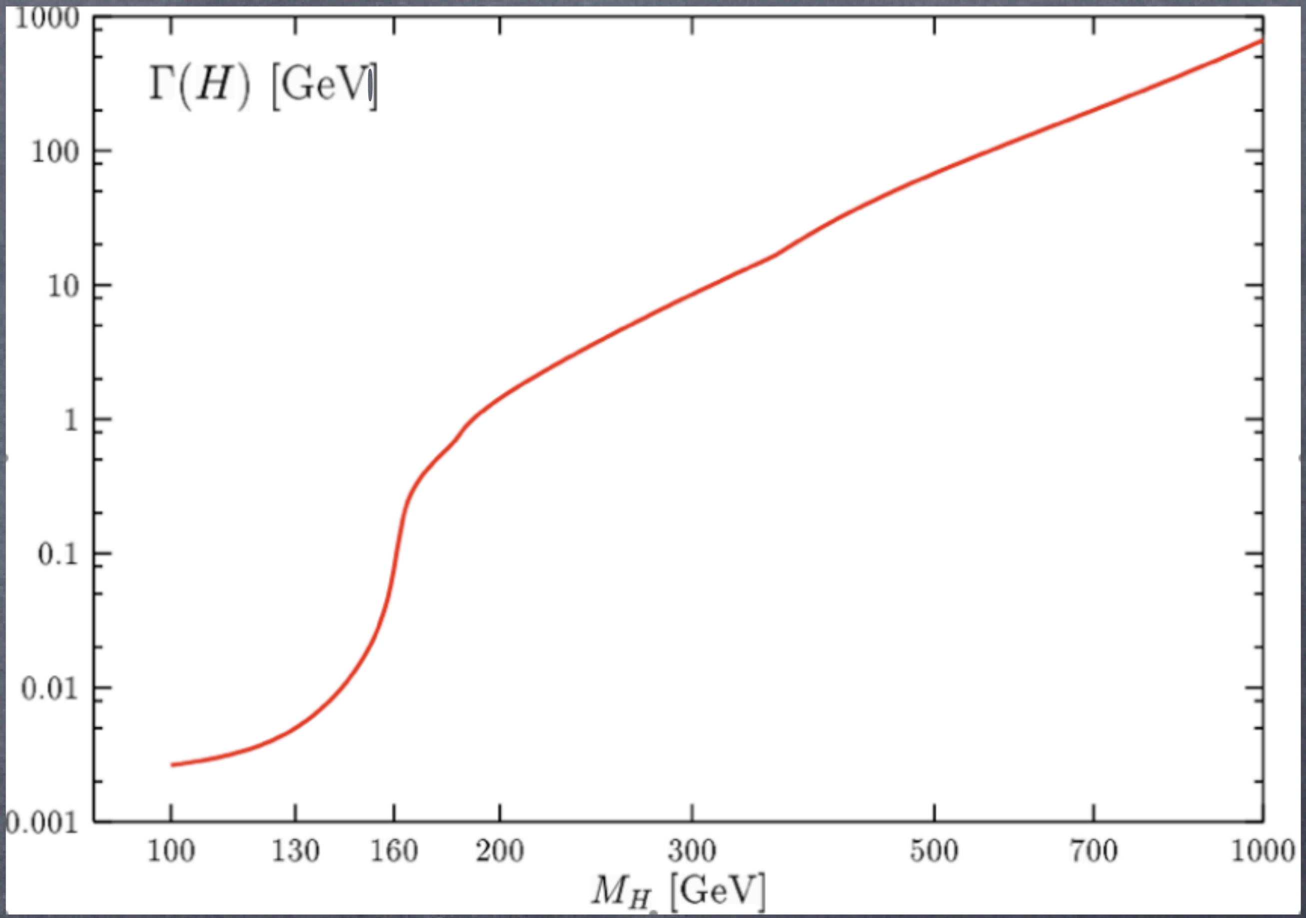
$$\longrightarrow \boxed{h \to b\bar{b}}$$

Higgs small Width

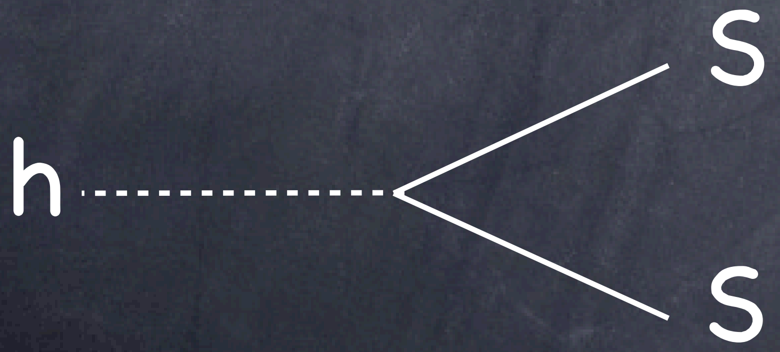
Small bottom Yukawa



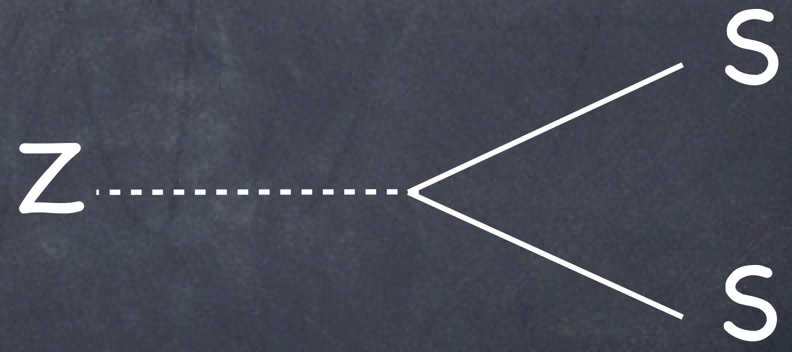
$$y_b \sim \frac{1}{60} \qquad \Gamma_{h\to b\bar{b}} \sim y_b^2$$



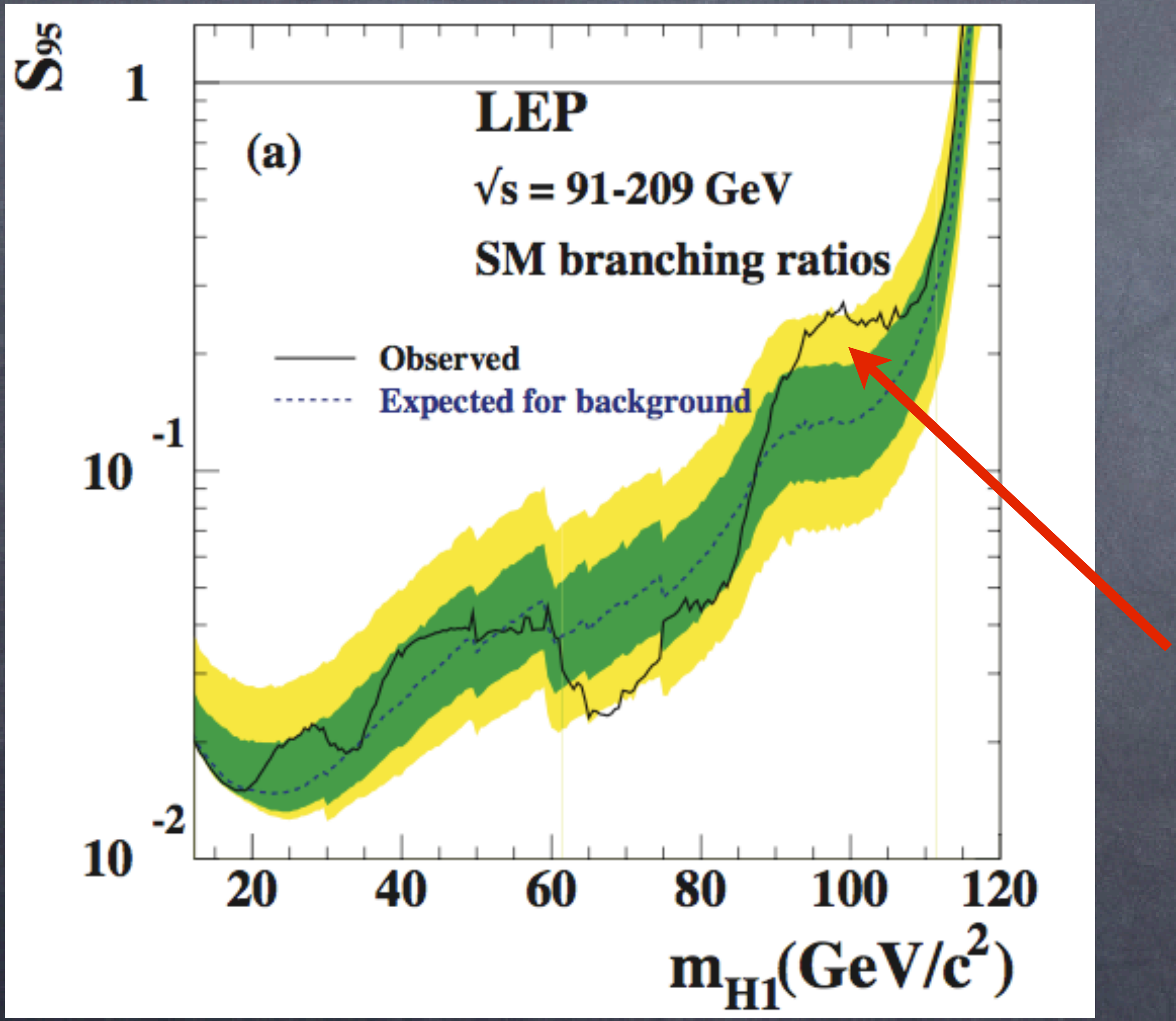
NP can easily change Γ_h



Caveat:

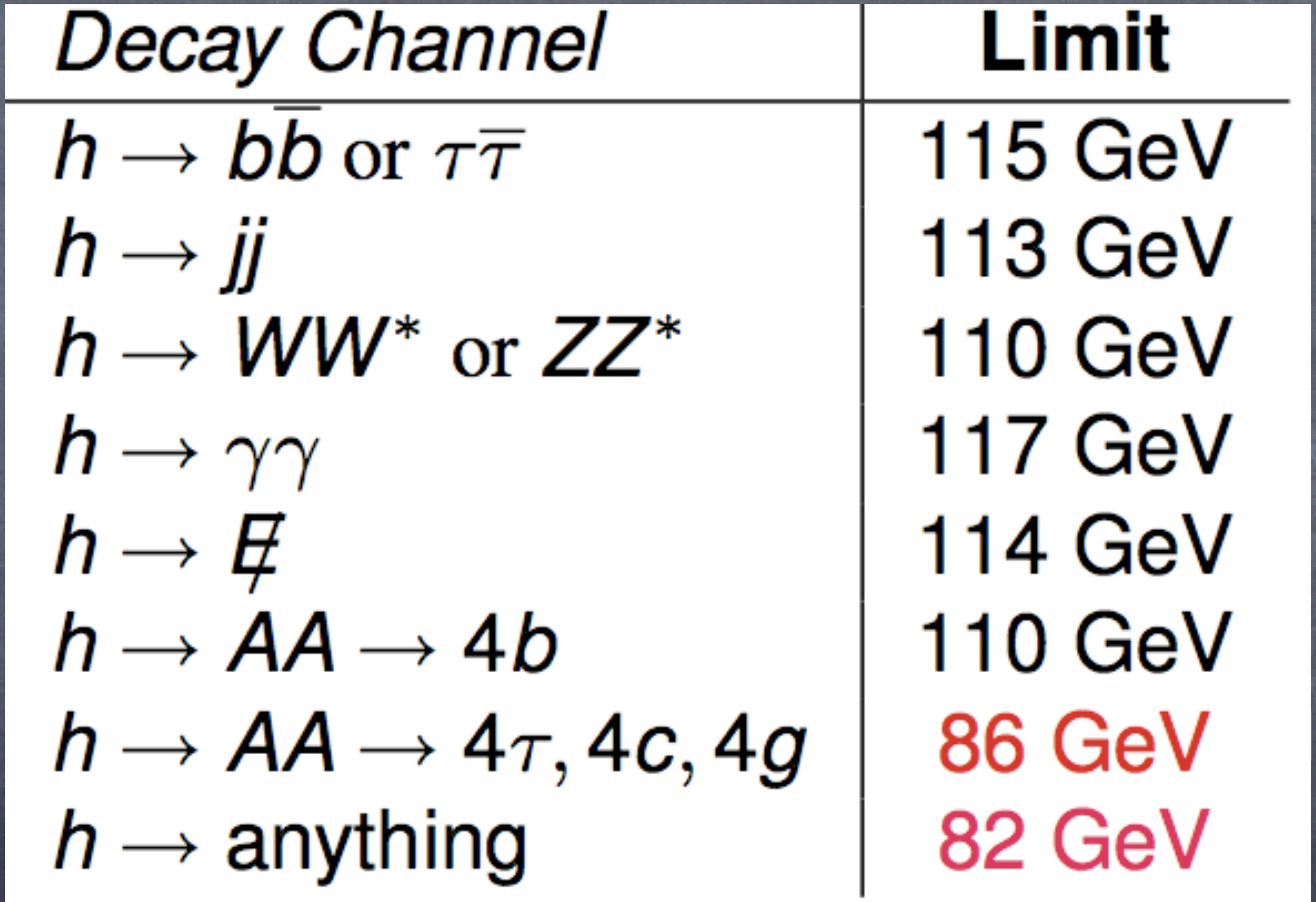


LEP Bound



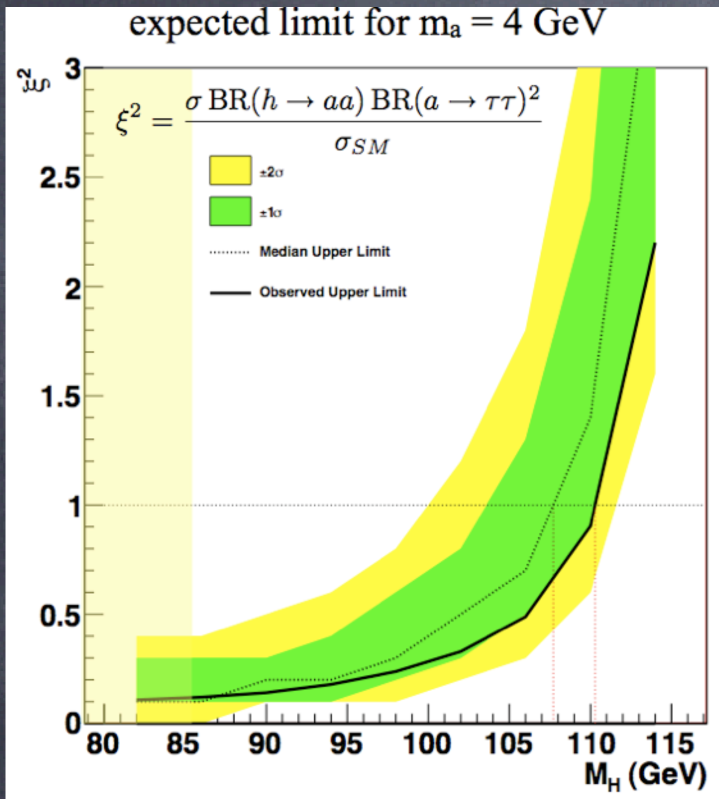
- New decays weaken the bound
- SM BRs at 20%

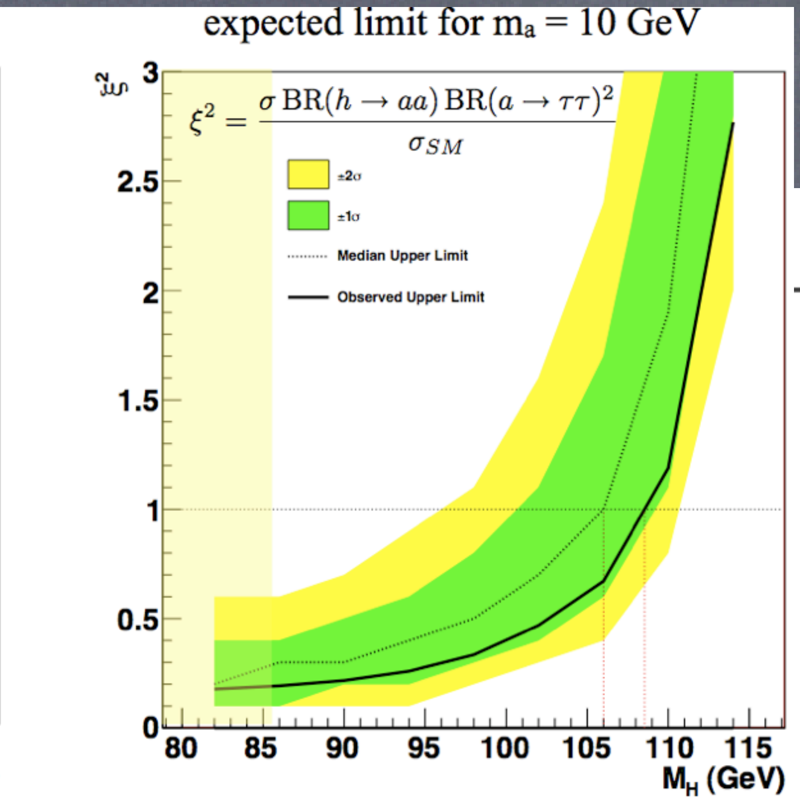
LEP Bound



Decay Channel	**Limit**
$h \to b\bar{b}$ or $\tau\bar{\tau}$	115 GeV
$h \to jj$	113 GeV
$h \to WW^*$ or ZZ^*	110 GeV
$h \to \gamma\gamma$	117 GeV
$h \to \not{E}$	114 GeV
$h \to AA \to 4b$	110 GeV
$h \to AA \to 4\tau, 4c, 4g$	86 GeV
$h \to$ anything	82 GeV

LEP Bound





	Limit
	115 GeV
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	114 GeV
$h \to AA \to 4b$	110 GeV
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$h \to$ anything	82 GeV

New ALEPH result!

arXiv:1003.0705

$$\boxed{\begin{array}{l} h \to AA \to 2\tau\bar{\tau} \\ m_h > 105 \div 110 \ \mathrm{GeV} \end{array}}$$

Little hierarchy in SUSY

MSSM:

Little hierarchy in SUSY

MSSM: $M_H^2 < M_Z^2 \cos^2 2\beta + \boxed{3 \frac{M_{top}^4}{v^2 4\pi^2} \log \frac{M_{stop}}{m_{top}}}$

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$$M_H > 115 \text{ GeV} \boxed{\rightarrow M_{stop} \gtrsim 1 \text{ TeV}}$$

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$$M_H > 115\ \text{GeV} \boxed{\rightarrow M_{stop} \gtrsim 1\ \text{TeV}}$$

$$\delta M_{H_u}^2 \boxed{= -\frac{3y_t^2 M_{stop}^2}{4\pi^2} \log \Lambda} \qquad (M_Z \sim -2M_{H_u})$$

SM cut-off

MSSM cut-off

Now what?

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    - F-Term (NMSSM)

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  - D-term (extended gauge structure)

Now what?

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SM cut-off

MSSM cut-off

- Raise tree-level Higgs mass (M_stop reduced)
  - F-Term (NMSSM)
  - D-term (extended gauge structure)
- Remove 1-loop divergences

$$\Lambda \rightarrow f \sim \text{ few TeV}$$

SUSY+Little Higgs

LH recipe

Add global symmetries

Break them collectively

→ Reduce 1-loop divergences

SM: $\delta m_H^2 \sim \quad \Lambda^2$

LH: $\delta m_H^2 \sim \quad f^2 \log \Lambda^2$

SUSY: $\delta m_H^2 \sim \quad M_{soft}^2 \log \Lambda^2$

SUSY Higgs as a pGB: $\delta m_H^2 \sim \quad M_{soft}^2 \log f^2$

Birkedal, Csacko , Gaillard;
Chankowski, Falkowski, Pokorski, Wagner;
Roy, Schmaltz; Csaki, Marandella, Shirman, Strumia

SU(3)/SU(2) in SUSY

Higgs sector

Extend $SU(2)_W \times U(1)_Y \longrightarrow$ $SU(3)_W \times U(1)_X$ gauge symmetry

	$SU(3)_C$	$SU(3)_W$	$U(1)_X$
$\mathcal{H}_u, \Phi_u$	1	3	$1/3$
$\mathcal{H}_d, \Phi_d$	1	$\bar{3}$	$-1/3$

No mixing terms $\Phi\mathcal{H}$

$$\mathcal{W} = \mathcal{W}_\Phi + \mathcal{W}_\mathcal{H} \longrightarrow$$

$SU(3)_\Phi \times SU(3)_\mathcal{H}$ global symmetry

Symmetry breaking: step I

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Φ sector takes a VEV $\langle\Phi_{u,d}\rangle = (0, 0, F \sim 10\ \mathrm{TeV})$

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Gauge symmetry

$$SU(3)_W \times U(1)_X \to SU(2)_W \times U(1)_Y$$

Global symmetry

$$SU(3)_\Phi \times SU(3)_\mathcal{H} \to SU(2)_\Phi \times SU(3)_\mathcal{H}$$

5 eaten GBs

$$Y = T^8/\sqrt{3} + X$$

Step II: pGBs

- Below 10 TeV $MSSM + SU(3)_{\mathcal{H}}$ Global symmetry
- Global symmetry breaking $SU(3)_{\mathcal{H}} \to SU_{\mathcal{H}}(2)$
- Goldstones: $8 - 3 = 4 + 1 = (3) + 1 + 1$

Step II: pGBs

- Below 10 TeV $MSSM + SU(3)_{\mathcal{H}}$ Global symmetry
- Global symmetry breaking $SU(3)_{\mathcal{H}} \rightarrow SU_{\mathcal{H}}(2)$
- Goldstones: $8 - 3 = 4 + 1 = (3) + 1 + 1$

$$\mathcal{H}_{u,d} = e^{\pm i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f_{u,d} \end{pmatrix} = f_{u,d} \begin{pmatrix} 0 \\ \sin(\tilde{h}/\sqrt{2}f) \\ e^{\pm i\eta/\sqrt{2}f}\cos(\tilde{h}/\sqrt{2}f) \end{pmatrix}$$

Step III: EWSB

$$\mathcal{H}_{u,d} = e^{\pm i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f_{u,d} \end{pmatrix} = f_{u,d} \begin{pmatrix} 0 \\ \sin(\tilde{h}/\sqrt{2}f) \\ e^{\pm i\eta/\sqrt{2}f}\cos(\tilde{h}/\sqrt{2}f) \end{pmatrix}$$

VEV=Misalignment between $SU(2)_W$ and $SU(2)_{\mathcal{H}}$

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VEV=Misalignment between $SU(2)_W$ and $SU(2)_{\mathcal{H}}$

$$\boxed{SU(2)_W \times U(1)_Y \to U(1)_{EM}}$$

Higgs and eta

$$\mathcal{H}_{u,d} = f_{u,d} \begin{pmatrix} 0 \\ \sin(\tilde{h}/\sqrt{2}f) \\ e^{\pm i\eta/\sqrt{2}f} \cos(\tilde{h}/\sqrt{2}f) \end{pmatrix}$$

$$\boxed{\begin{aligned} \tilde{h} &= \sqrt{2}\tilde{v} + h \\ \tilde{\eta} &= \eta/\cos(\tilde{v}/f) \end{aligned}}$$

Suppressed coupling to Z and W

$$g_{hVV} = g_{hVV}^{SM}\sqrt{1 - v_{EW}^2/f^2}$$

Suppressed coupling to SM fermions

$$y_{hf\bar{f}} = y_{hf\bar{f}}^{SM}\sqrt{1 - v_{EW}^2/f^2}$$

Higgs decays

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$$\boxed{h \rightarrow \eta\eta \text{ vs. } h \rightarrow b\bar{b}}$$??

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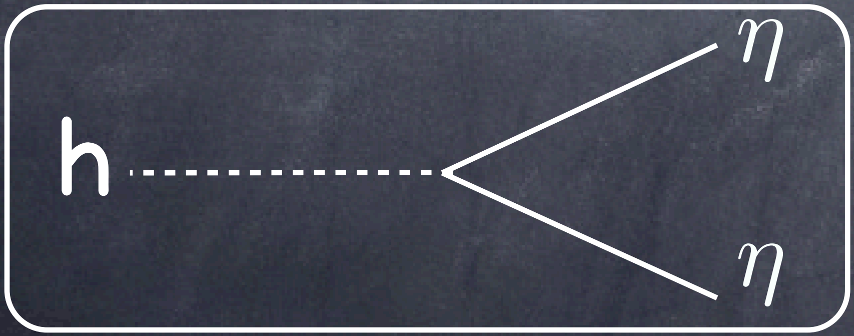
pGB interactions

$$\mathcal{L}_K \sim -h(\partial_\mu \eta)^2 \frac{\tan(\tilde{v}/f)}{\sqrt{2}f}$$

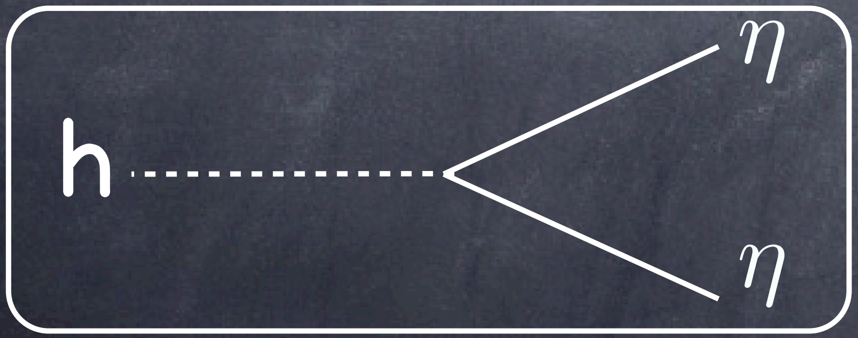


Higgs decays

$$\boxed{h \to \eta\eta \text{ vs. } h \to b\bar{b}} \quad ??$$

pGB interactions

$$\mathcal{L}_K \sim -h(\partial_\mu \eta)^2 \frac{\tan(\tilde{v}/f)}{\sqrt{2}f} \qquad \Gamma_{h\to\eta\eta} \sim \frac{1}{64\pi}(1-\frac{v_{EW}^2}{f^2})^{-1}\frac{m_h^3 v_{EW}^2}{f^4}$$



$$\Gamma_{h\to f\bar{f}} \sim \Gamma^{SM}_{h\to f\bar{f}}(1-\frac{v_{EW}^2}{f^2})$$

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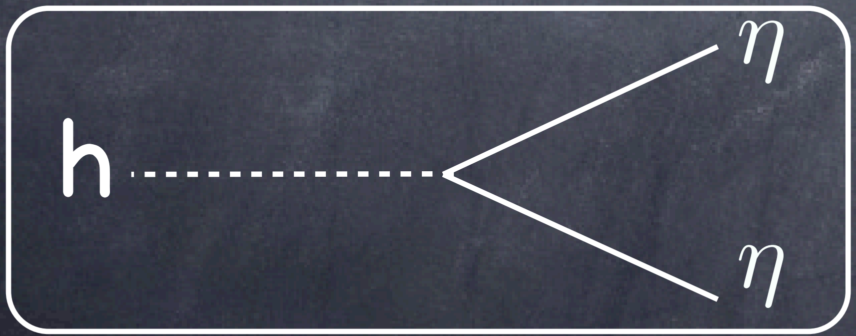

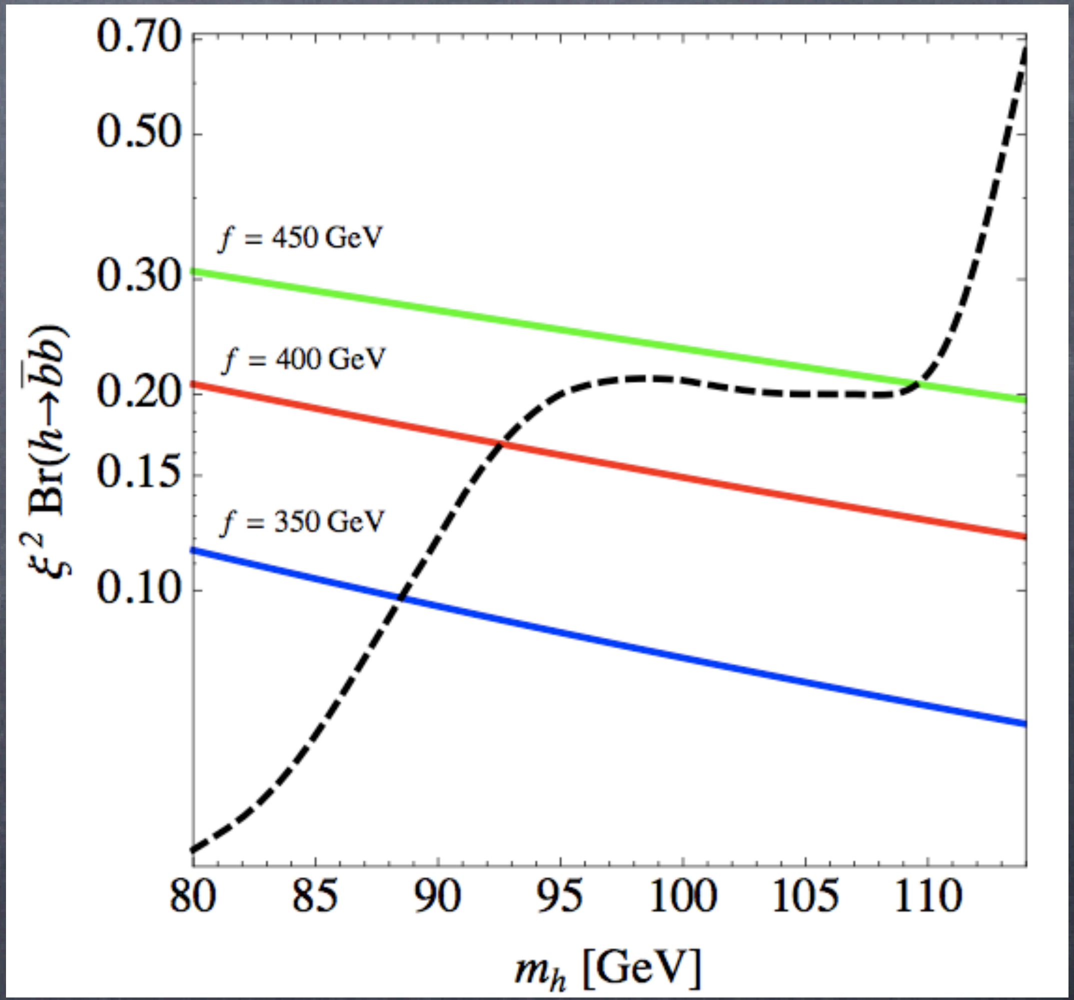

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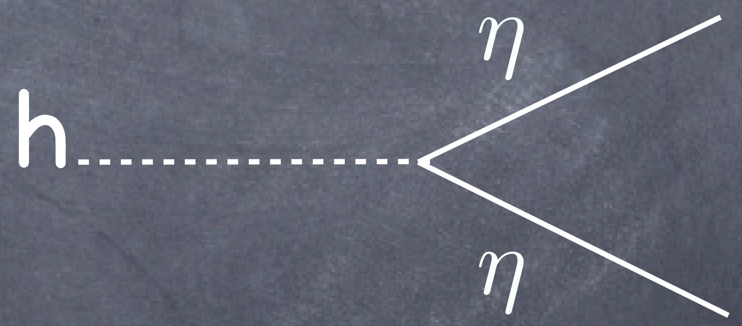

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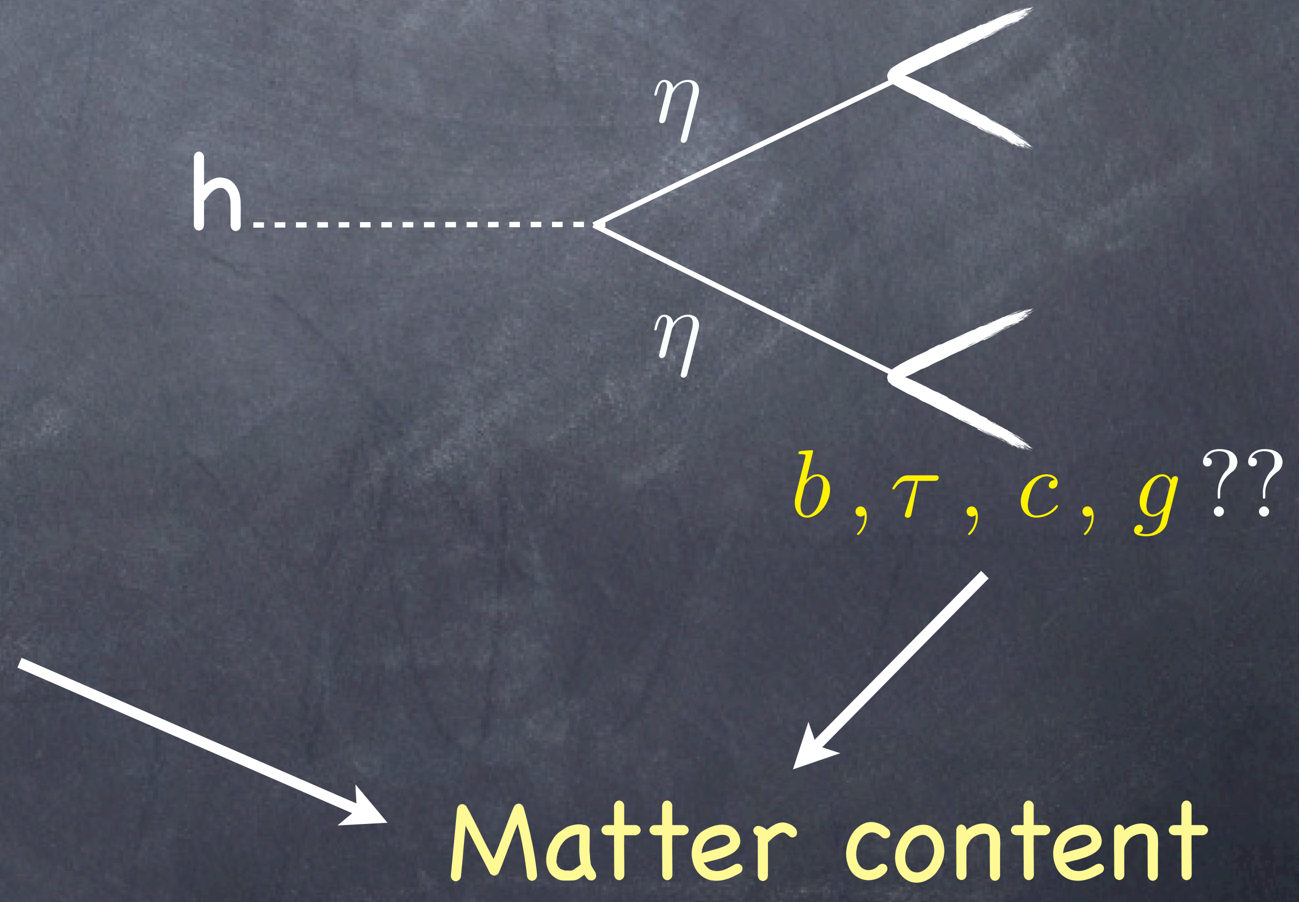
$m_h \overset{?}{=}$ $m_\eta \overset{?}{=}$



Matter content I: Buried

$$SU(3) \times SU(3) \times U(1) \subset SU(6)$$

$$\begin{array}{|c|}\hline \\ \hline \\ \hline \end{array} \quad +2\,\overline{\square}$$

B.B., Csaki, Falkowski, Weiler

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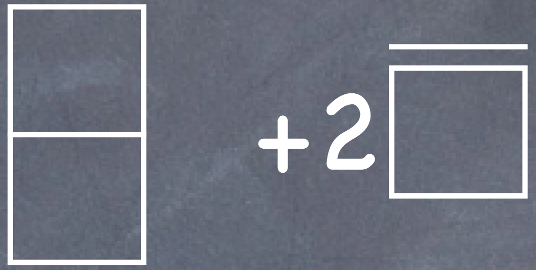

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	$SU(3)_C$	$SU(3)_W$	$U(1)_X$
$Q = (t^Q, b^Q, \hat{b}^Q)$	3	3	0
t_c	$\bar{3}$	1	$-2/3$
$b_c^{1,2}$	$\bar{3}$	1	$1/3$
$L_{1,2} = (\tau_{1,2}^L, \nu_{1,2}^L, \hat{\nu}_{1,2}^L)$	1	$\bar{3}$	$-1/3$
$E_c = (\nu_c^E, \tau_c^E, \hat{\tau}_c^E)$	1	$\bar{3}$	$2/3$
$\nu_c^{1,2,3}$	1	1	0

No Top partner, no top mass

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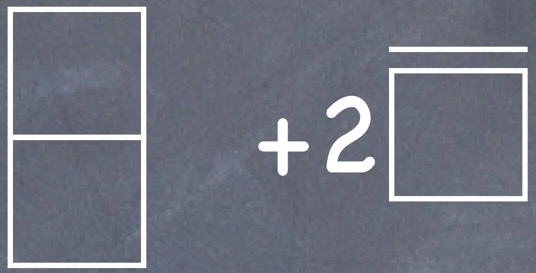

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$V = (b^V, t^V, \hat{t}^V)$	3	$\bar{3}$	$1/3$
$V_c = (b_c^V, t_c^V, \hat{t}_c^V)$	$\bar{3}$	3	$-1/3$
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$\nu_c^{1,2,3}$	1	1	0

Buried Yukawas

Collective breaking

$$\boxed{\mathcal{W}_{top}^{coll} = y_1 t_c V \Phi_u + y_2 \mathcal{H}_u V_c Q + \mu_V V_c V} + \tilde{y}_1 \xcancel{t_c V} \mathcal{H}_u + \tilde{y}_2 \xcancel{\Phi_u V_c} Q$$

$$\big\downarrow$$

$$\boxed{m_{top} \propto y_1 y_2 \mu_V}$$

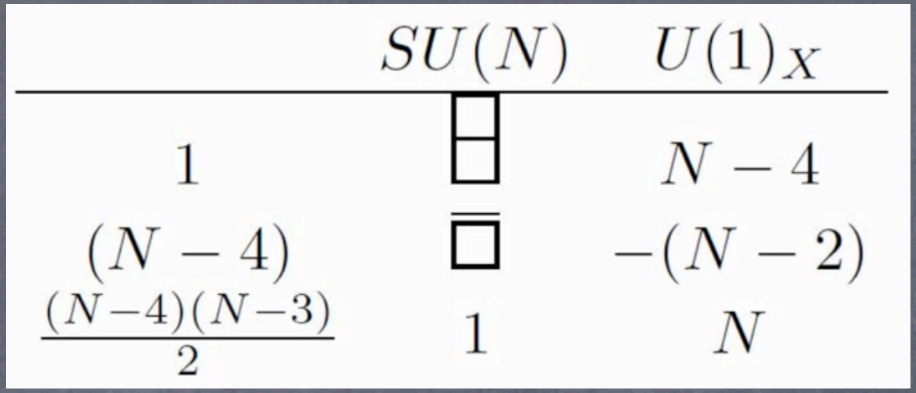
Higgs exact GB if either

$$y_1 = 0\,, \quad y_2 = 0\,, \quad \mu_V = 0$$

Matter content II: Charming

"Flipped" SU(6)

B.B., Csaki, Falkowski, Weiler



	$SU(N)$	$U(1)_X$
1	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	$N-4$
$(N-4)$	$\overline{\square}$	$-(N-2)$
$\frac{(N-4)(N-3)}{2}$	1	N

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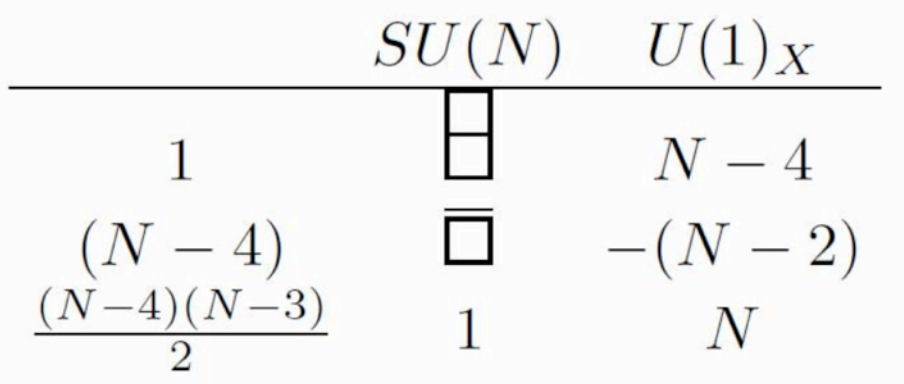

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$Q=(t^Q, b^Q, \hat{t}^Q)$	3	3	$1/3$
$t_c^{1,2}$	$\bar{3}$	1	$-2/3$
b_c	$\bar{3}$	1	$1/3$
$L_{1,2}=(\tau_{1,2}, \nu_{1,2}, \hat{\tau}_{1,2})$	1	$\bar{3}$	$-2/3$
$L_c=(\nu_c^L, \tau_c^L, \hat{\nu}_c^L)$	1	$\bar{3}$	$1/3$
$\tau_c^{1,2,3}$	1	1	1

no bottom partner, no bottom mass

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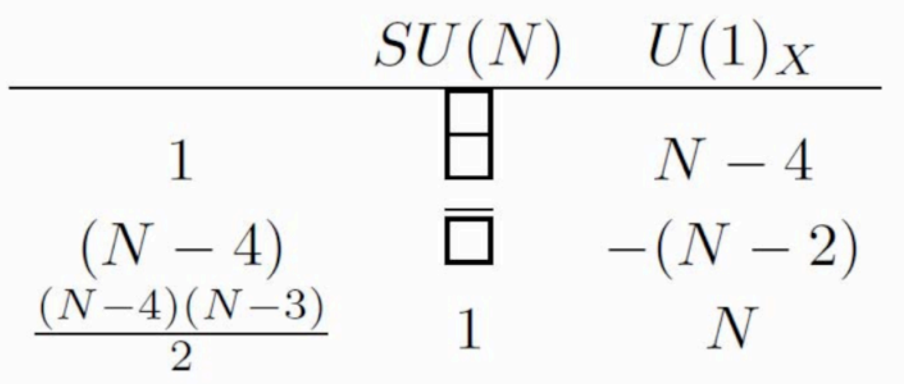

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$V_c=(b_c^V, t_c^V, \hat{b}_c^V)$	$\bar{3}$	3	0
$L_{1,2}=(\tau_{1,2}, \nu_{1,2}, \hat{\tau}_{1,2})$	1	$\bar{3}$	$-2/3$
$L_c=(\nu_c^L, \tau_c^L, \hat{\nu}_c^L)$	1	$\bar{3}$	$1/3$
$\tau_c^{1,2,3}$	1	1	1

Charming Yukawas

$$\boxed{\mathcal{L}_Y = y_1 t_c^1 \Phi_u Q + y_2 t_c^2 \mathcal{H}_u Q + \frac{y_b}{\mu_V} b_c^1 Q \Phi_d \mathcal{H}_d + \ldots}$$

Collective breaking: Higgs exact GB if either

$y_2 = 0$ or $y_1 = 0$

$$m_t \approx \frac{s_b y_1 y_2 F}{\sqrt{(y_1 F)^2 + 2(s_b y_2 f)^2}} v_{EW} \qquad m_b \approx y_b \cos\beta v_{EW} F/\mu_V$$

bottom mass from non-renorm. operator

Higgs potential I

Radial potential: f is generated at one loop

$$\begin{aligned} m^2_{\mathcal{H}_u} &\approx -\frac{3y_2^2\sin^2\beta}{2\pi^2}M^2_{soft}\log(\Lambda/M_T) \\ \delta\lambda &\approx \frac{3y_2^4\sin^4\beta}{8\pi^2}\log[(M^2_{soft}+M_T^2)/M_T^2] \end{aligned} \longrightarrow \boxed{m_r^2 \approx 4\delta\lambda f^2}$$

Radial mode

Small f needs mild tuning:

$$FT_3 = \frac{m_r^2}{|m^2_{\mathcal{H}_u}|} \sim \mathcal{O}(10\%)$$

Higgs potential II

Higgs potential: also v is generated at one loop

$$\Delta m^2 \approx -\frac{3m_t^2}{8\pi^2 v_{EW}^2}\left[M_T^2 \boxed{\log\frac{M_{soft}^2+M_T^2}{M_T^2} + M_{soft}^2\log\frac{M_{soft}^2+M_T^2}{M_{soft}^2}}\right]$$

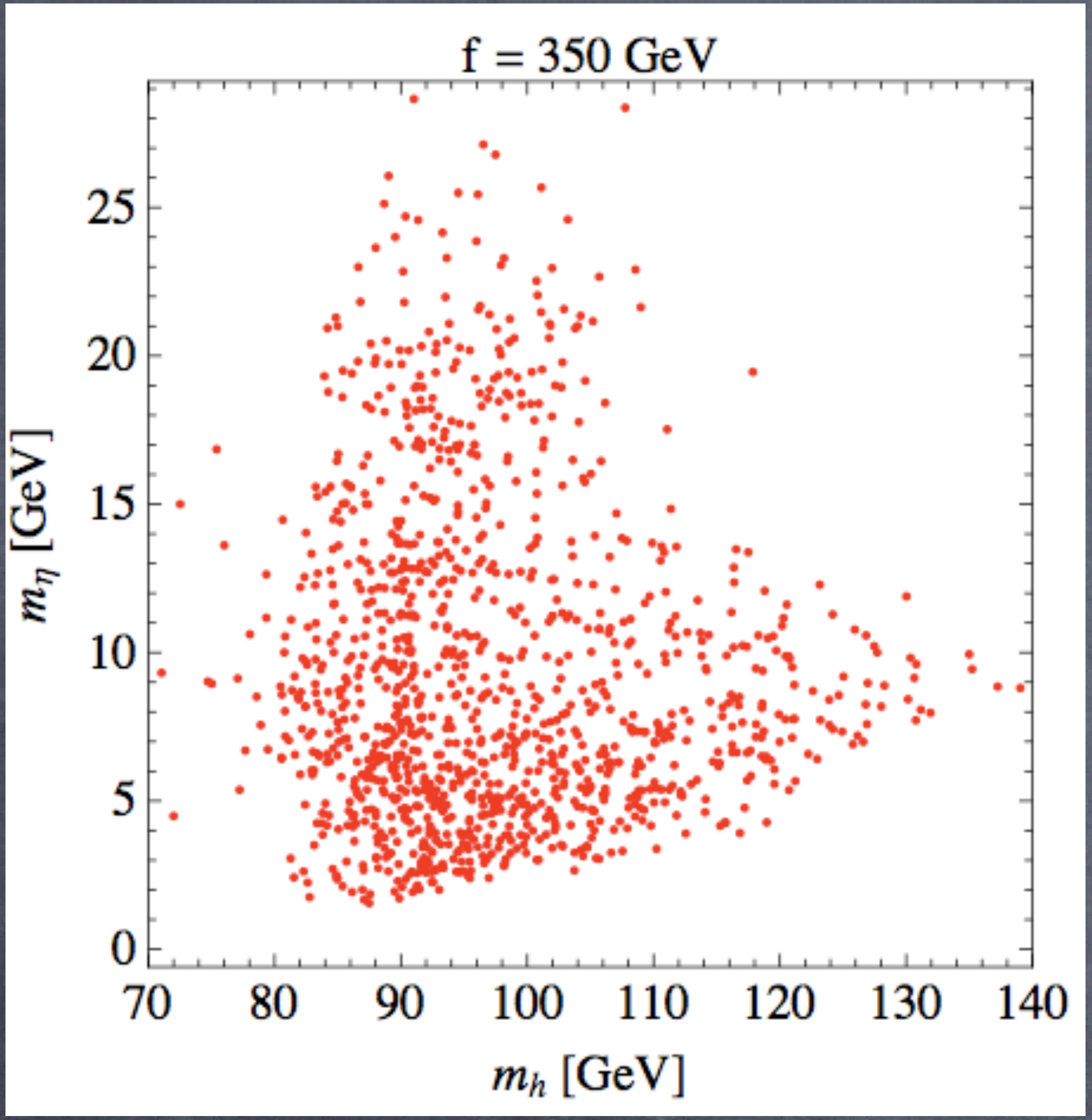
$$m_h^2 = \boxed{\left(1-\frac{v_{EW}^2}{f^2}\right)}\left\{m_Z^2\cos^2(2\beta)+\frac{3m_t^4}{4\pi^2 v_{EW}^2}\left[\log\left(\frac{M_{soft}^2 M_T^2}{m_t^2(M_{soft}^2+M_T^2)}\right) -2\frac{M_{soft}^2}{M_T^2}\log\left(\frac{M_{soft}^2+M_T^2}{M_{soft}^2}\right)\right]\right\}\approx 90\ \mathrm{GeV}$$

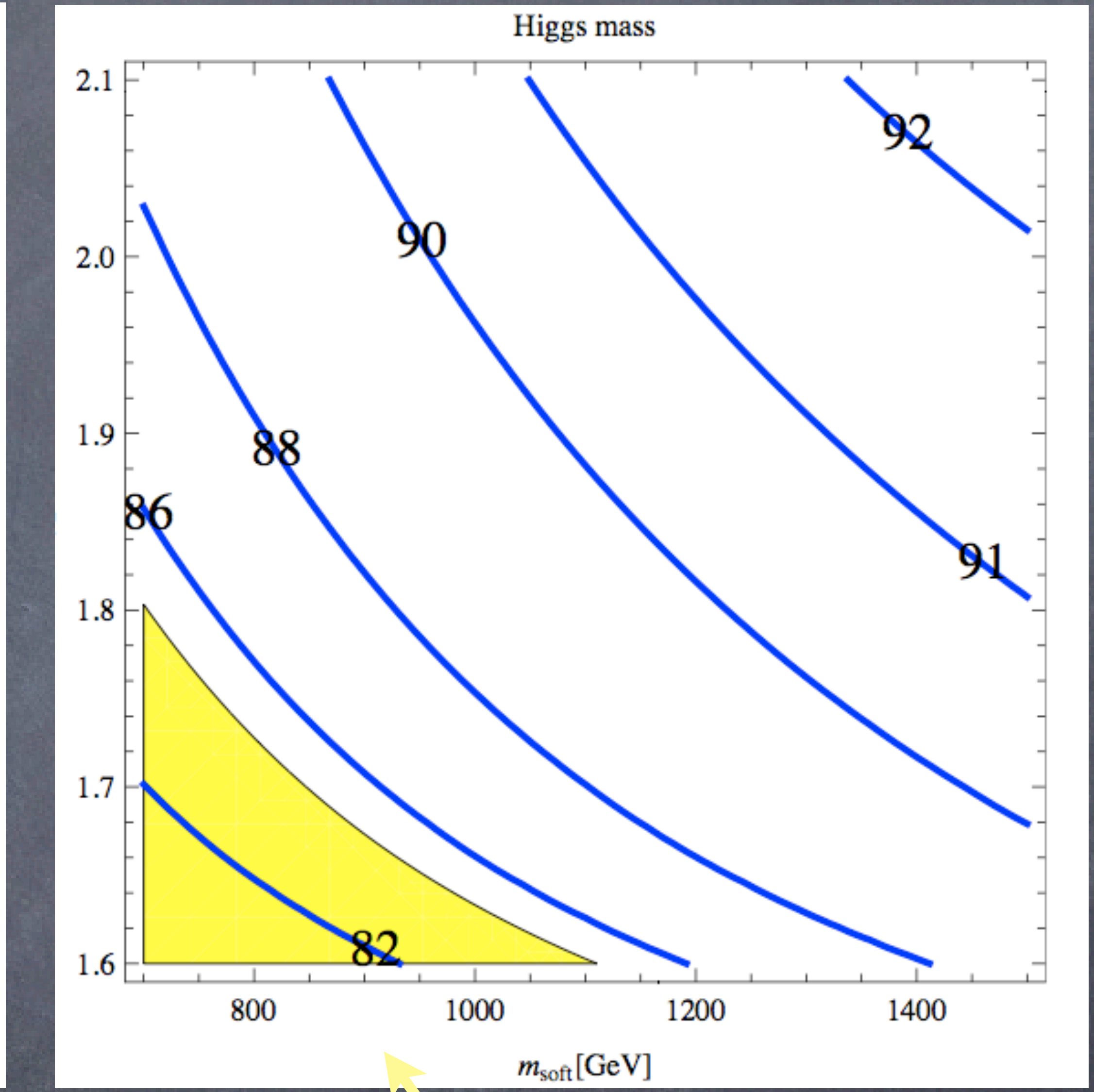
Mixing with singlet

Finite Logs! No FT

$$FT_2 = \frac{m_h^2}{|\Delta m^2|} \gtrsim 20\%$$

Masses





Perturbativity:

$$y_2 \quad = 1.8 \rightarrow \Lambda = 10^8 \text{TeV}$$

$$y_2 \quad = 2.1 \rightarrow \Lambda = 10^3 \text{TeV}$$

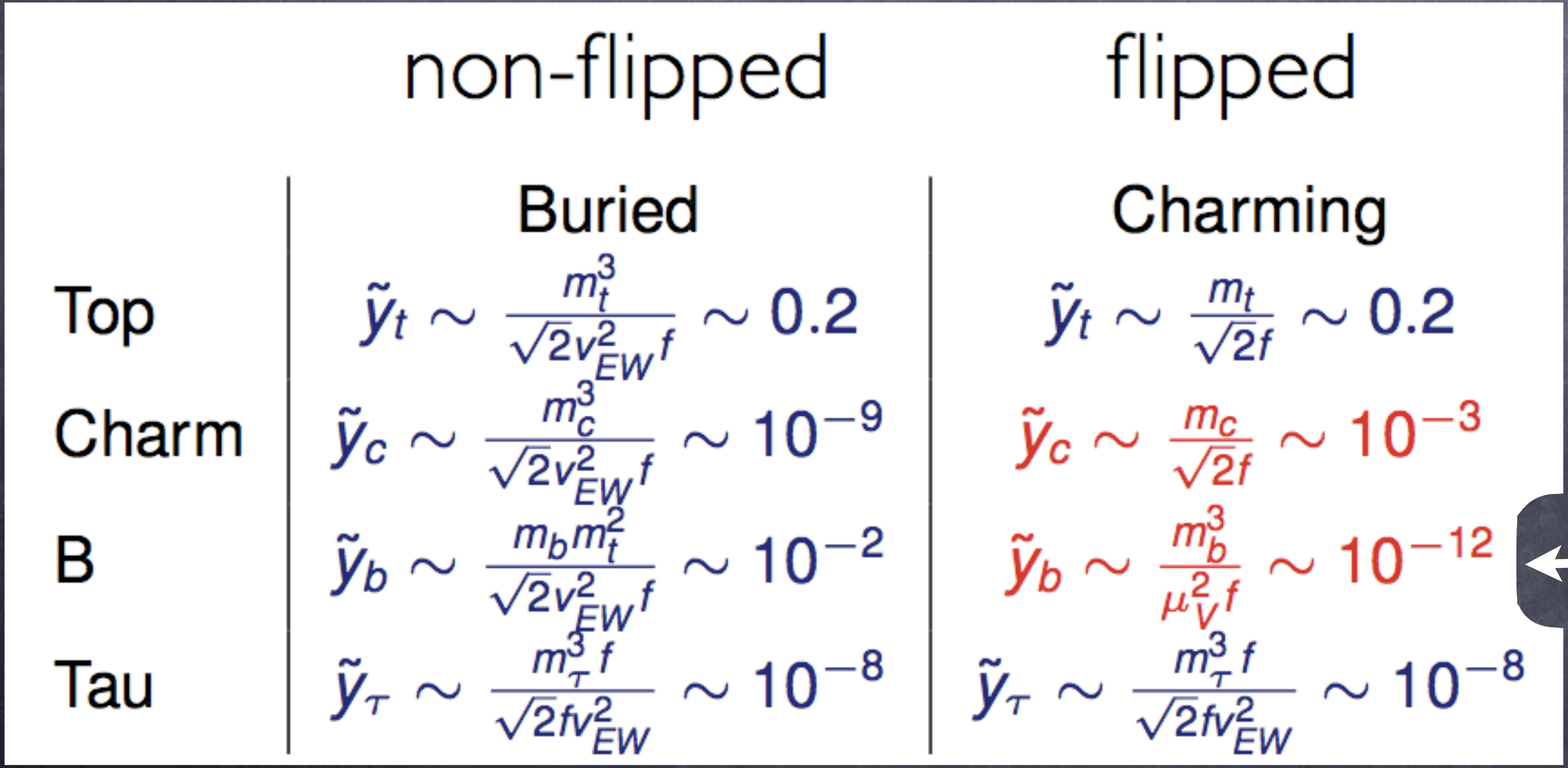
Excluded by LEP

$h \rightarrow \bar{b}b$

Eta couplings: Tree

$$\boxed{i\tilde{y}_f(\bar{f}\gamma^5 f)\eta}$$

Eta is SM singlet $\longrightarrow$ coupling $\sim$ mixing

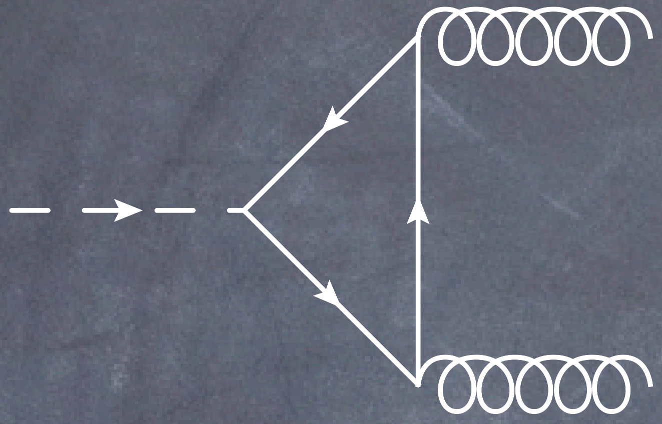


	non-flipped	flipped
	Buried	Charming
Top	$\tilde{y}_t \sim \frac{m_t^3}{\sqrt{2}v_{EW}^2 f} \sim 0.2$	$\tilde{y}_t \sim \frac{m_t}{\sqrt{2}f} \sim 0.2$
Charm	$\tilde{y}_c \sim \frac{m_c^3}{\sqrt{2}v_{EW}^2 f} \sim 10^{-9}$	$\tilde{y}_c \sim \frac{m_c}{\sqrt{2}f} \sim 10^{-3}$
B	$\tilde{y}_b \sim \frac{m_b m_t^2}{\sqrt{2}v_{EW}^2 f} \sim 10^{-2}$	$\tilde{y}_b \sim \frac{m_b^3}{\mu_V^2 f} \sim 10^{-12}$
Tau	$\tilde{y}_\tau \sim \frac{m_\tau^3 f}{\sqrt{2}f v_{EW}^2} \sim 10^{-8}$	$\tilde{y}_\tau \sim \frac{m_\tau^3 f}{\sqrt{2}f v_{EW}^2} \sim 10^{-8}$

Extra suppression

$$\boxed{\tilde{y}_b \sim \frac{m_b}{f} \times \frac{m_b^2}{\mu_V^2}}$$

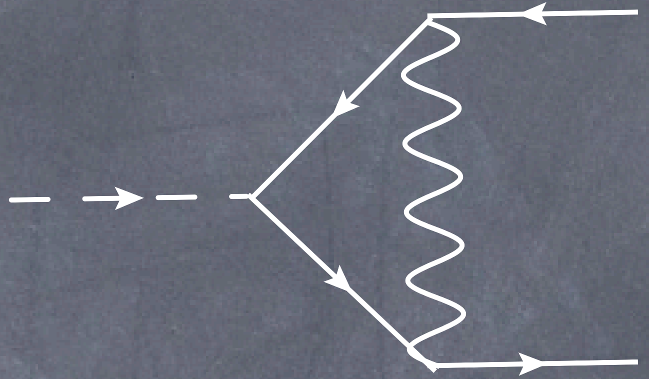
Eta couplings: loop



$$\kappa^g (\partial^2 \eta)\, G\tilde{G}$$

$$\kappa^g \simeq \frac{1}{12\sqrt{2}} \frac{g_s^2(m_\eta)}{64\pi^2} \frac{m_\eta^2}{m_b^2} \frac{m_t^2 f}{\mu_V^2 v_{EW}^2}$$

$$\Gamma_{\eta \to gg} = (N_c^2 - 1) \frac{|\kappa^g|^2}{\pi} m_\eta^3$$



$$i\tilde{y}_b(\bar{b}\gamma^5 b)\eta$$

$$\tilde{y}_b \sim \frac{\tilde{y}_t}{16\pi^2} \frac{m_t m_b}{v_{EW}^2} \log(m_T^2/m_t^2)$$

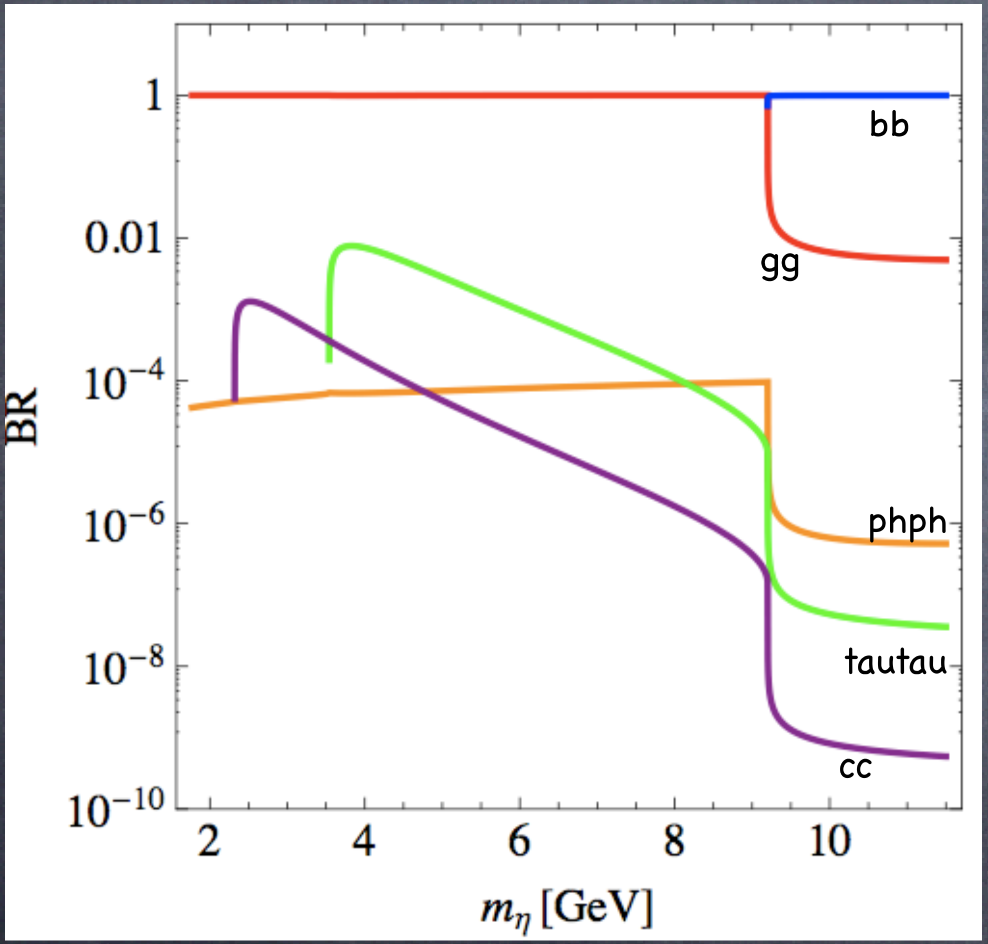
$$\Big\downarrow$$

$$\tilde{y}_c \gg \mathcal{O}(10^{-4}) \gg \tilde{y}_b|_{tree}$$

Eta decays

Eta decays

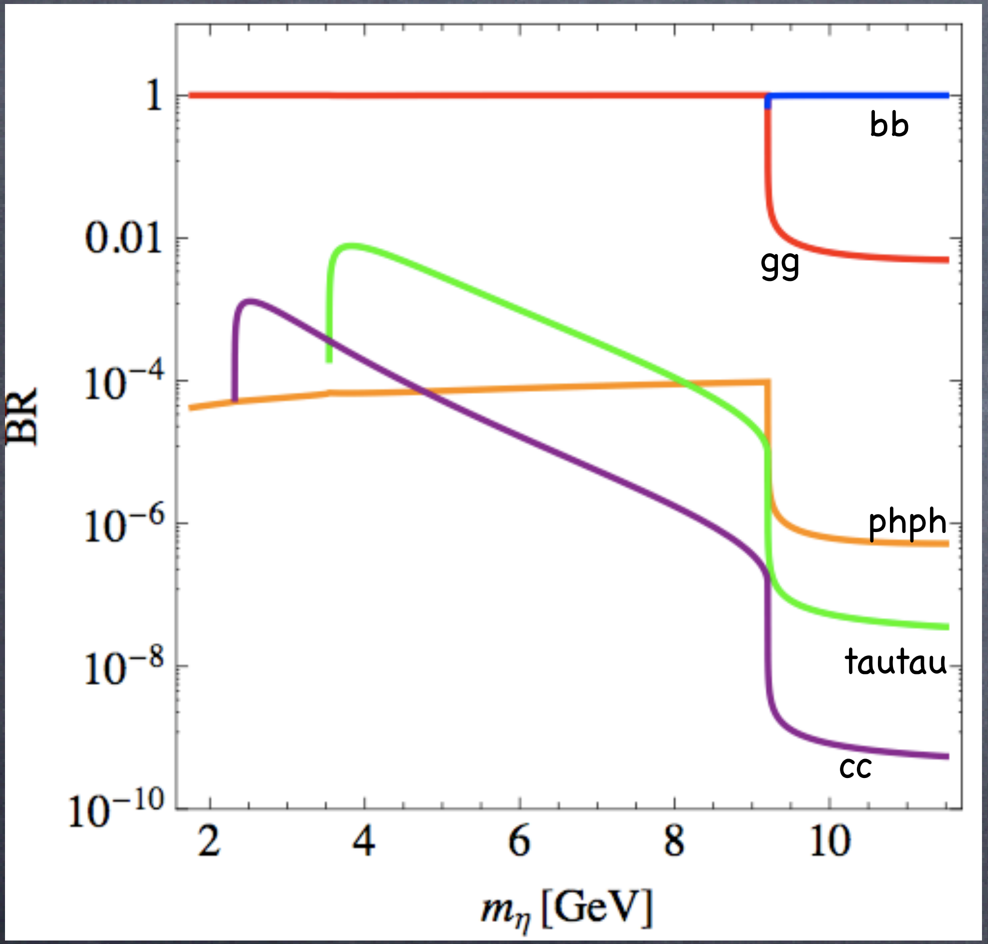
“Buried” -non flipped



$$h \to 2\eta \to 4g$$

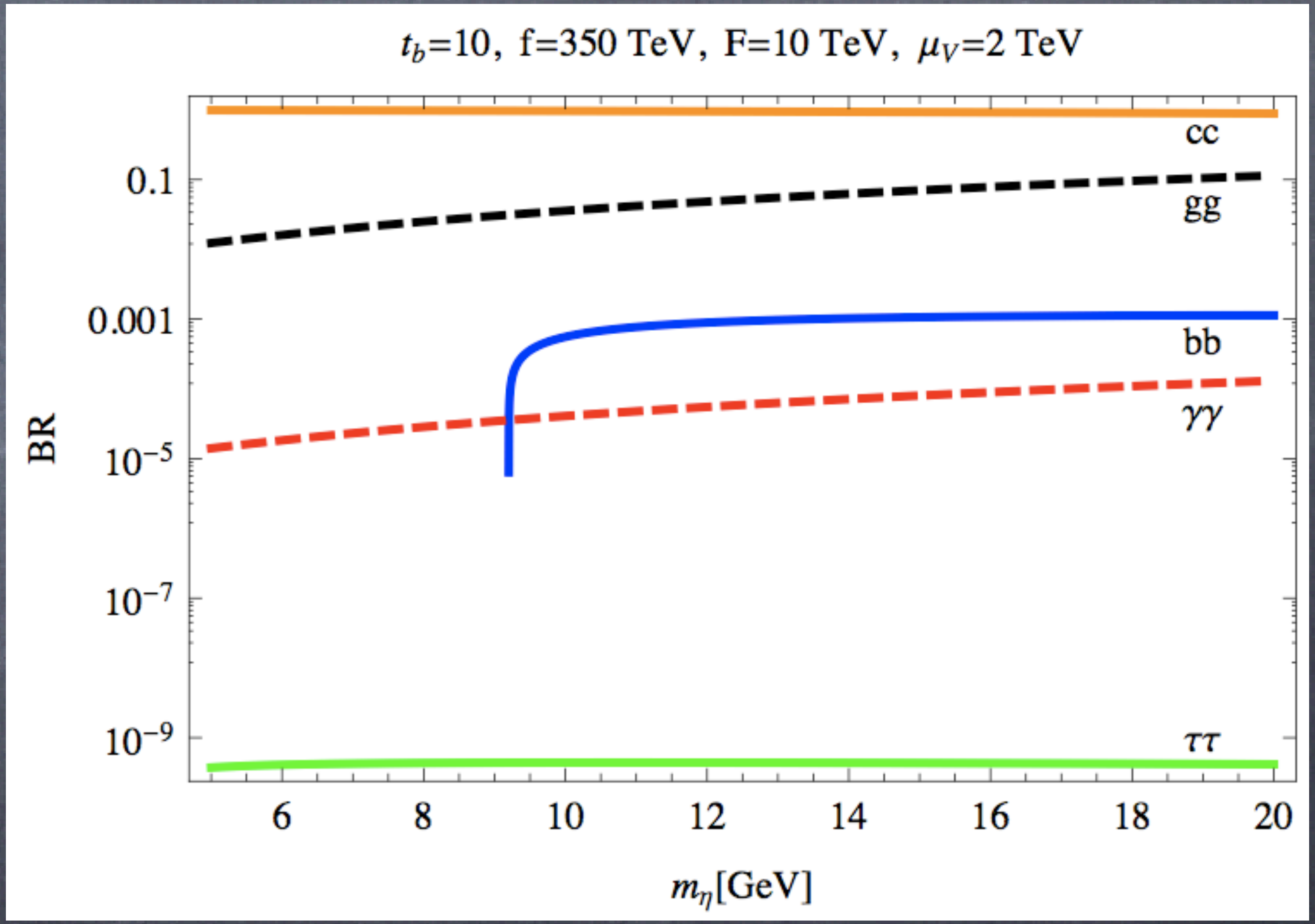
Eta decays

“Buried” -non flipped



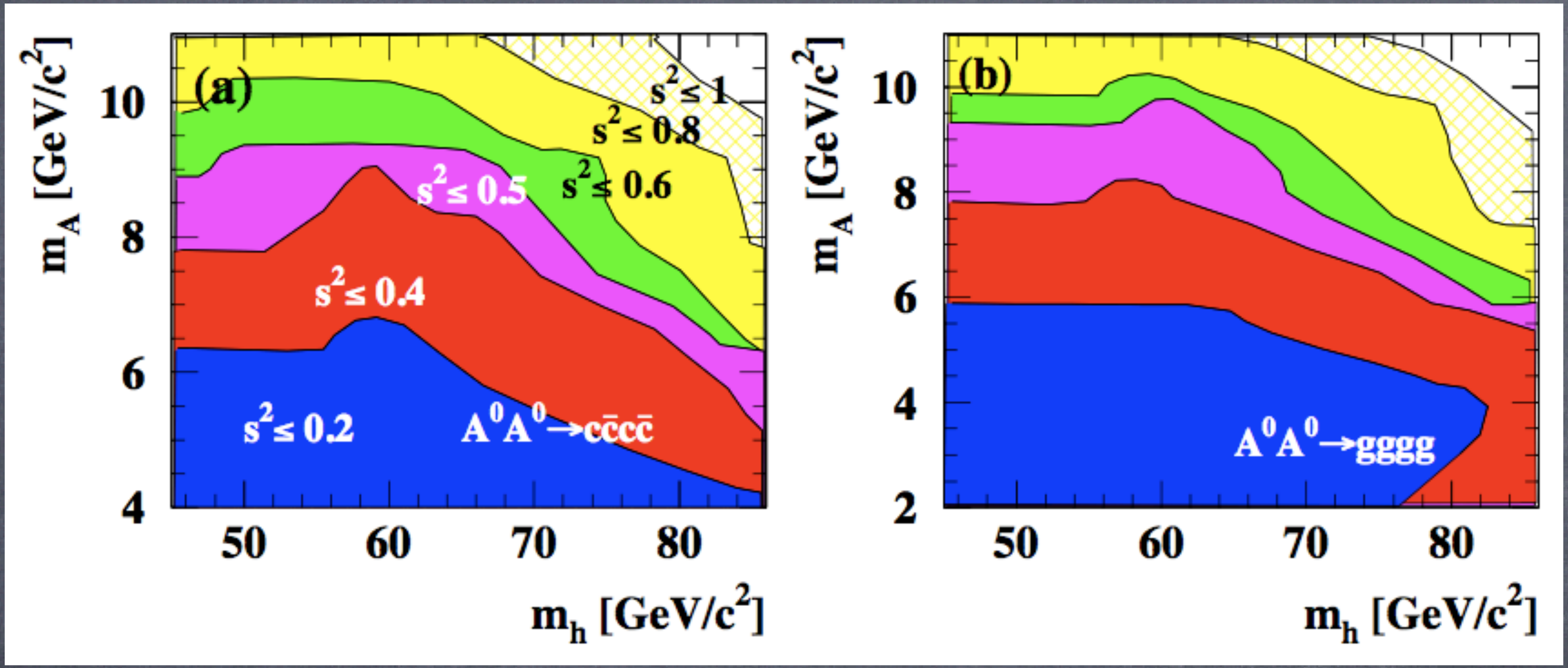
$$h \rightarrow 2\eta \rightarrow 4g$$

“Charming” -Flipped



$$h \rightarrow 2\eta \rightarrow 2c\bar{c}$$

OPAL limit on 4j



s=relative production cross section

$$\sigma_{ZZh} = \sigma^{SM}_{ZZh}(1 - v^2_{EW}/f^2)$$
$$BR = 80\%$$

$$\longrightarrow s \approx 0.6 \longrightarrow \boxed{m_\eta > 6 \text{ GeV}}$$

The "fake" Higgs

$$\mathcal{H}_u \approx (f + r/\sqrt{2}) \begin{pmatrix} 0 \\ \sin((\tilde{v} + h/f)) \\ \cos((\tilde{v} + h/f)) \end{pmatrix}$$

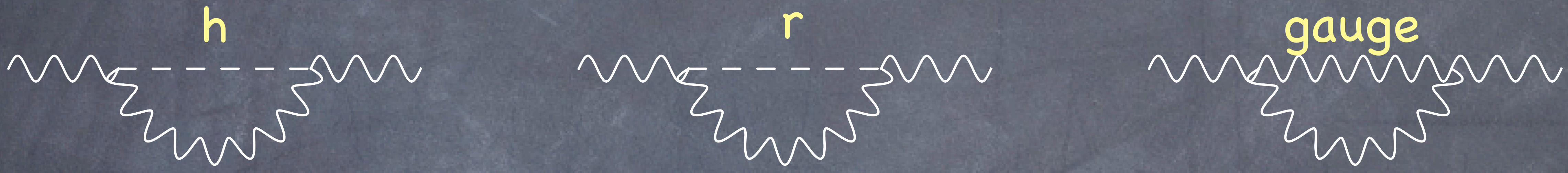
$$m_r^2 \approx 4\lambda_{\mathcal{H}} f^2 \sim 350 \text{ GeV}$$

It Couples like the Higgs but suppressed

$$g_{rVV} = g_{hVV}^{SM} \times (v_{EW}/f) \approx \frac{1}{2} \times g_{hVV}^{SM}$$

easily visible @ LHC: $gg \to r \to ZZ \to 4l$

EWPTs (S & T)

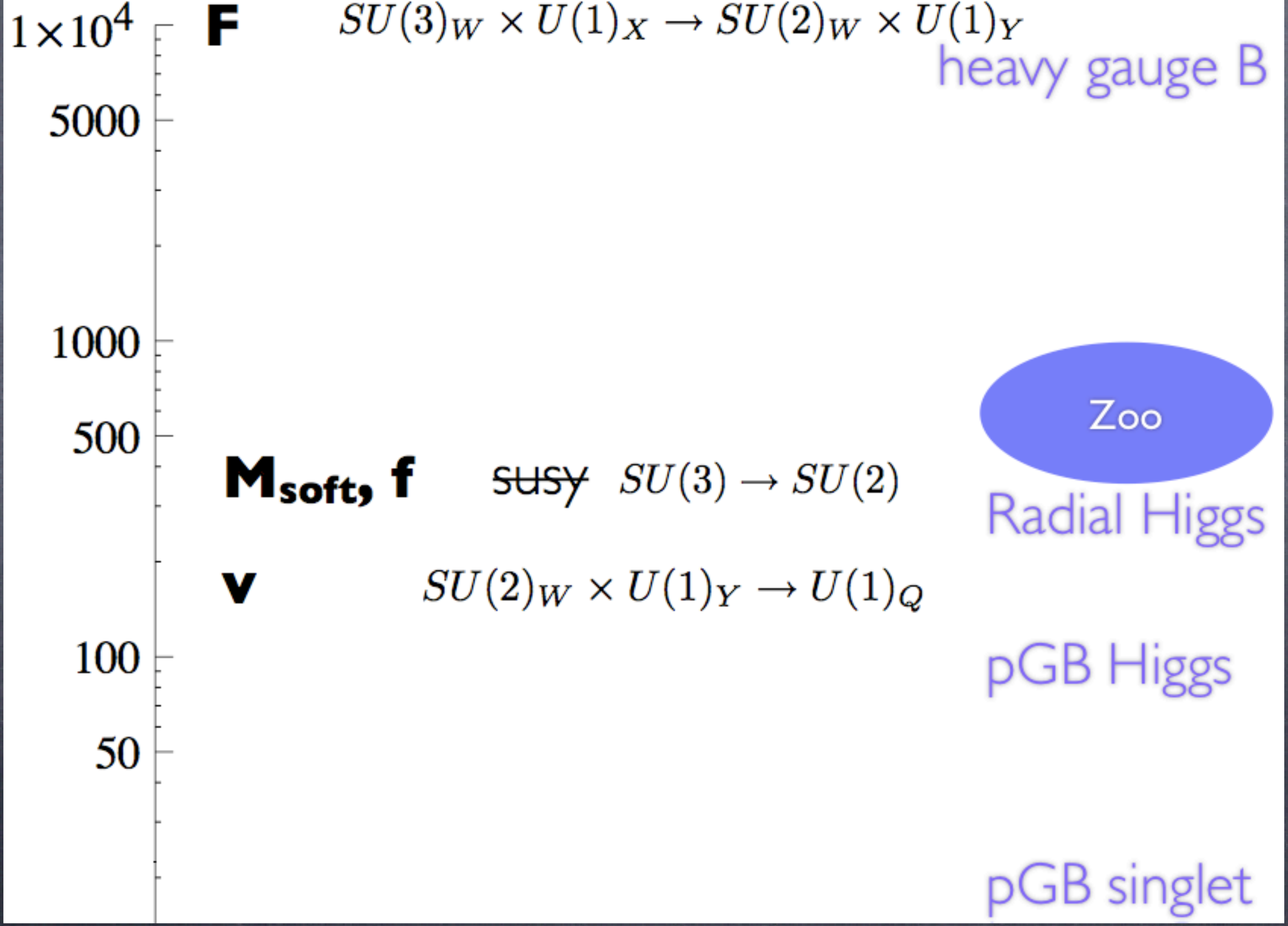


$\cos^2(\tilde{v}/f)\log(m_h/\Lambda)$ $\sin^2(\tilde{v}/f)\log(m_r/\Lambda)$ $\log(\Lambda/m_W)$

$$\longrightarrow \boxed{m_h^{EWPT} = m_h(\frac{m_r}{m_h})^{\sin^2(\tilde{v}/f)} \approx 120 \text{ GeV}}$$

like in the SM

Spectrum overview



F $SU(3)_W \times U(1)_X \rightarrow SU(2)_W \times U(1)_Y$

M$_{\text{soft}}$, f ~~susy~~ $SU(3) \rightarrow SU(2)$

v $SU(2)_W \times U(1)_Y \rightarrow U(1)_Q$

Conclusions

- Higgs and Eta pGBs of SU(3)/SU(2)
- Higgs → 2 Eta → 4j cascade $h \to \eta\eta \to 2c\bar{c}\,,\ 4g$
- Higgs below LEP bound, $m_h \approx 90\ \mathrm{GeV}$
- No little Hierarchy
- Light SUSY and LH spectrum at LHC
- Fake Higgs readily available
- Higgs deeply buried under QCD background