Electroweak Symmetry Breaking after the first hints of a Higgs

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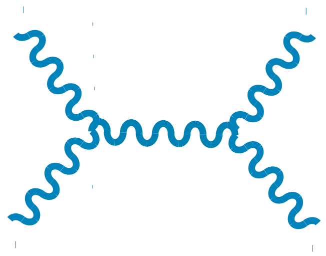
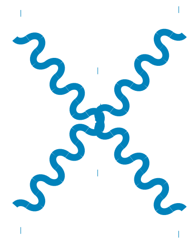
What is the dynamics of Electroweak Symmetry Breaking ?

Was the hierarchy problem a good problem?

- Is Dark Matter made of weakly interacting thermal relics?
- Why is the electron much lighter than the top
- Why 3 families?

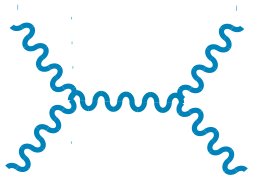
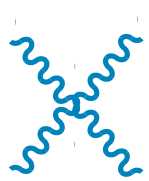
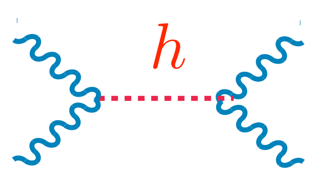
$m_{W,z} \neq 0$ 3 polarizations = $2_\perp$ + $1_\parallel$

not “pure” gauge int

$\mathcal{A}(V_L V_L \to V_L V_L) =$  +  $= \left(\frac{\sqrt{s}}{174\,\mathrm{GeV}}\right)^2$

New strong force at 2 TeV !

- EWSB implies new stuff below ~ 2 TeV’s
- Simplest option (or so it seems): just the Higgs boson

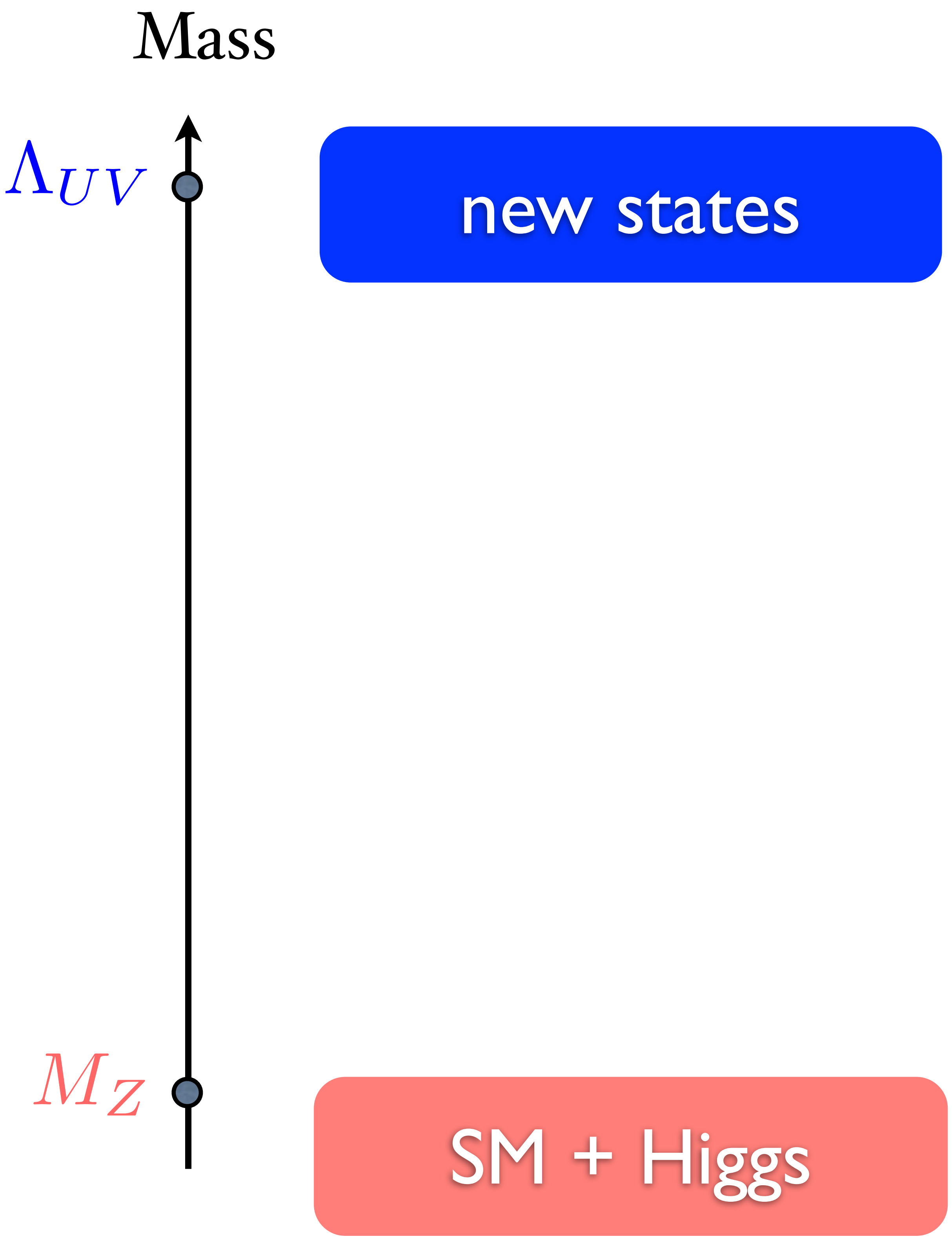
 +  + 

$\overset{s\to\infty}{=} \frac{m_h^2}{v^2}$

weak up to ultra-high scale

SM with Higgs boson can be extrapolated virtually to $E \sim M_{Pl}$

SM as an effective theory



beautifully simple

★ it explains

- B,L approx conservation
- small neutrino masses

★ nicely accounts for

- small flavor violation
- electroweak precision tests

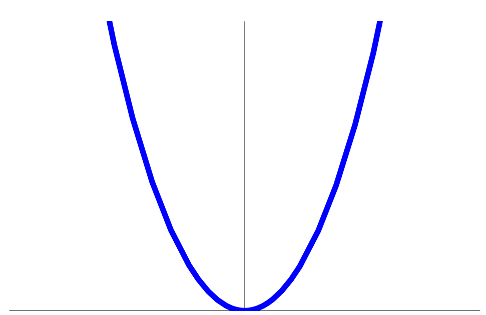
and it has a beautiful theoretical problem

The hierarchy problem

$$V(H) = \epsilon \Lambda_{UV}^2 H^2 + \lambda H^4$$

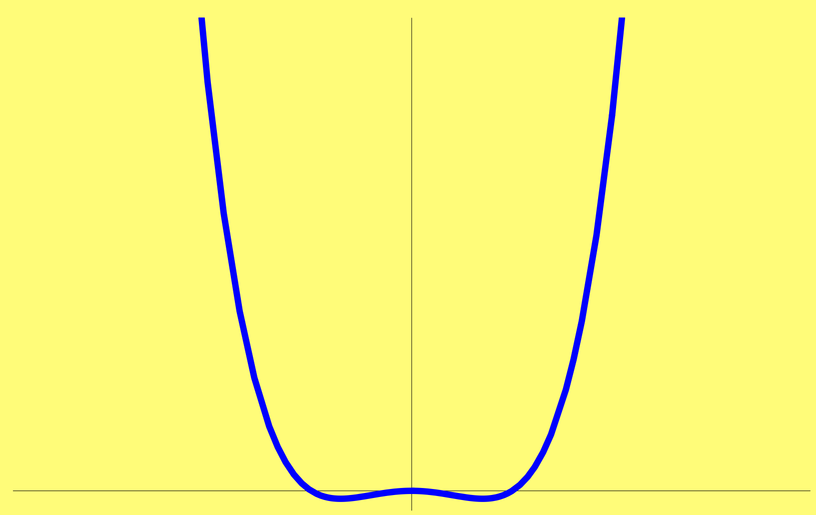
generically

$\epsilon \sim O(1)$



$< H >= 0$

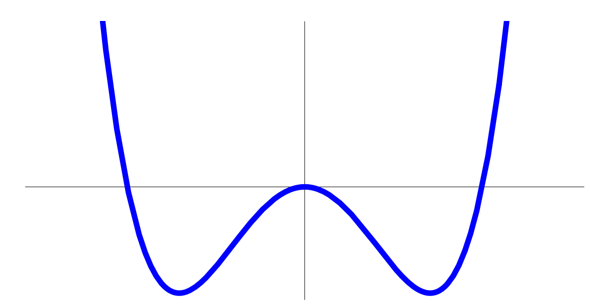
but we need



$\langle H \rangle = \sqrt{\epsilon}\Lambda_{UV}$

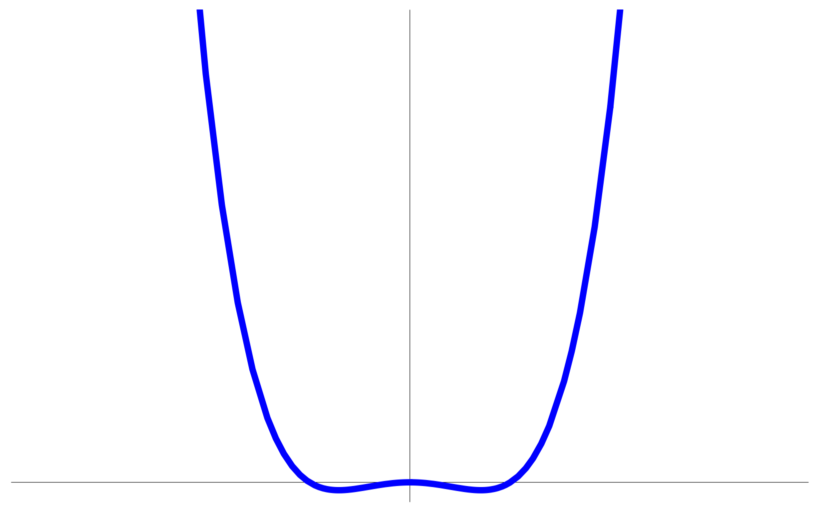
$\epsilon \sim 10^{-34}$

$\epsilon \sim -O(1)$



$\langle H \rangle \sim \Lambda_{UV}$

same tuning to reach boundary of 2^{nd} order phase transition



$$\epsilon \sim 10^{-34}$$

How did nature choose to deal with hierarchy problem?

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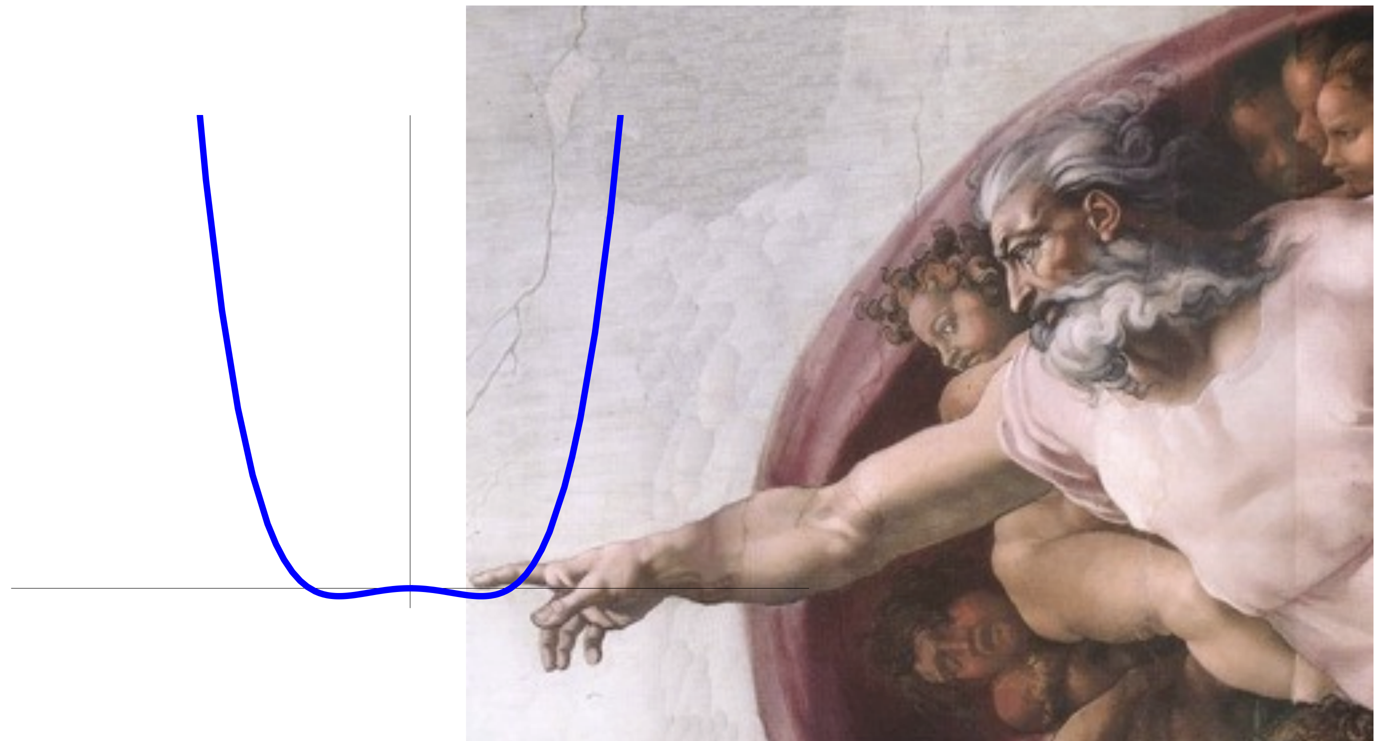


$\epsilon \sim 10^{-34}$

stolen from V. Rychkov

How did nature choose to deal with hierarchy problem?

Natural

I
Supersymmetry

II
Strong EWSB dynamics
(composite Higgs)

III
Large Extra Dimensions

Un-natural

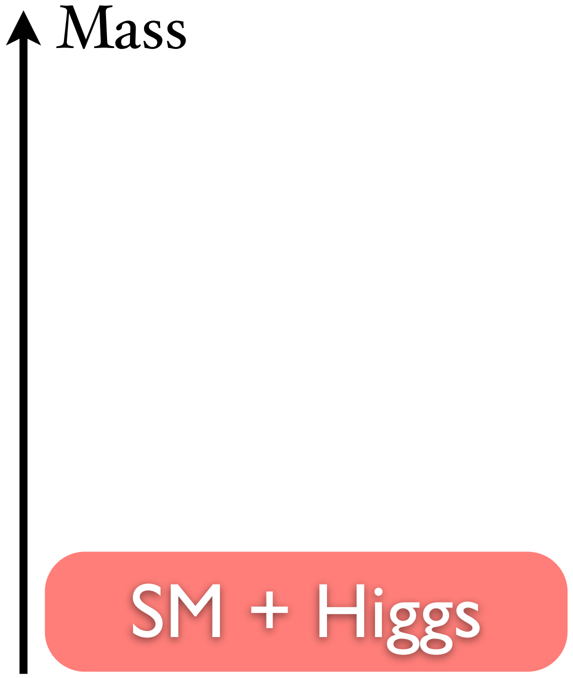
IV
Multiverse (anthropic principle)

$10^{1000\ldots}$ vacua
of which many have a hierarchy

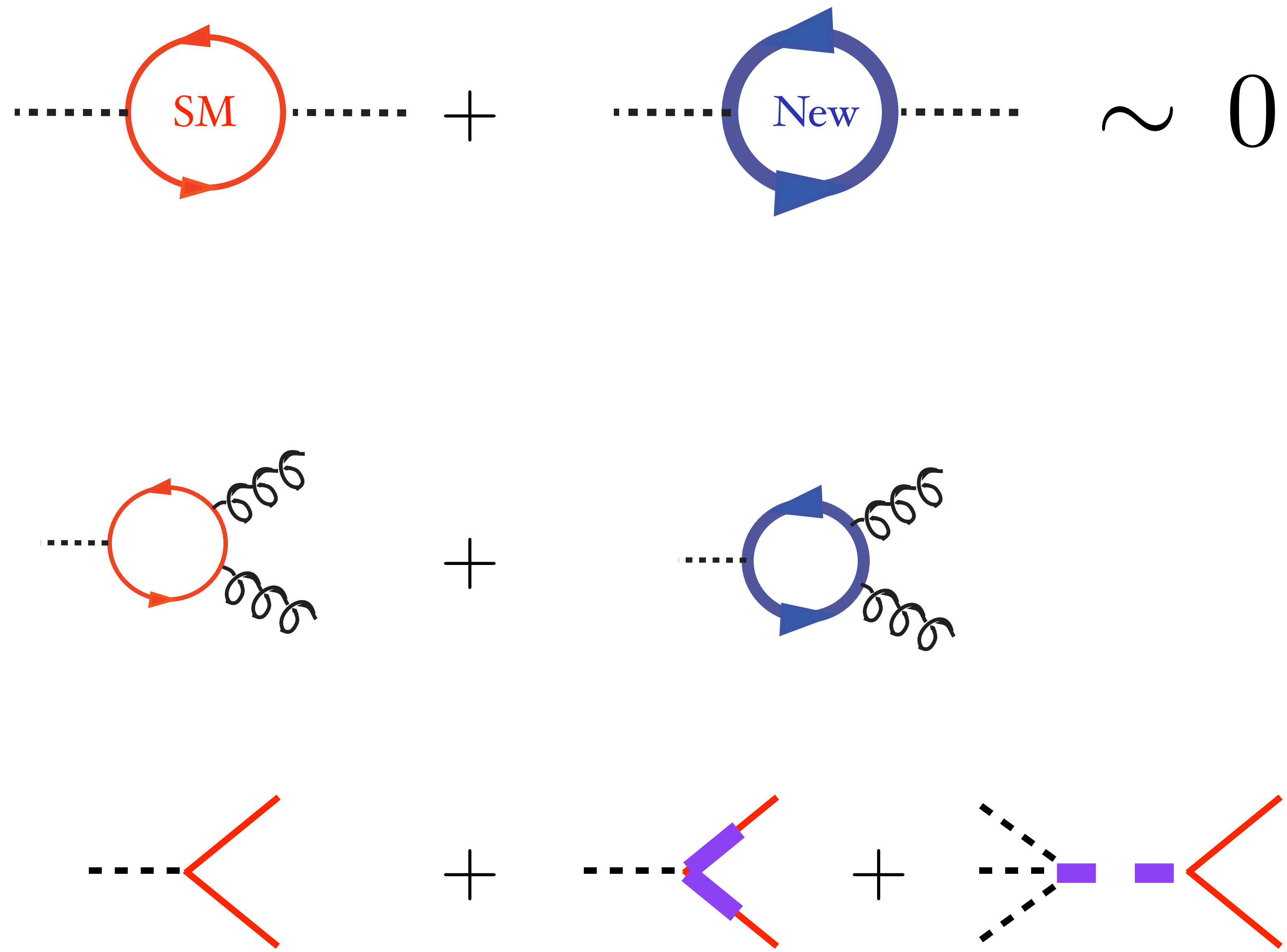
Expect: just SM + Higgs
+ (possibly weak scale DM)

see NYT Op-Ed
Cardinal Schönborn

Natural Theories

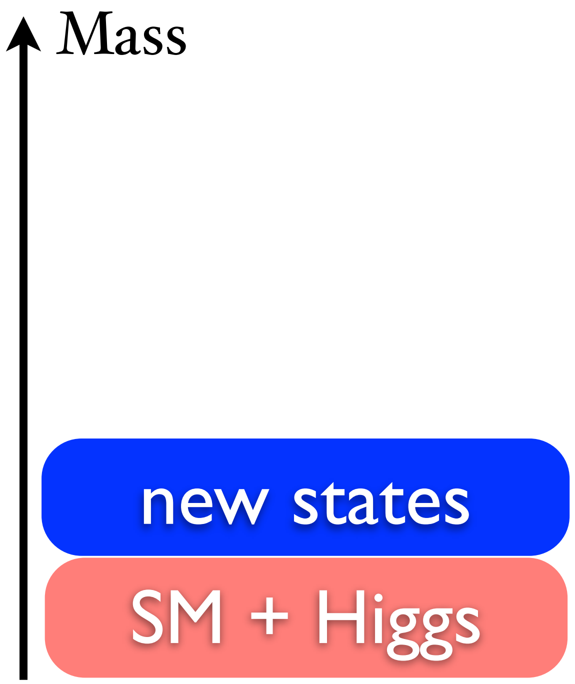


$\delta m_H^2 =$



The more natural the theory the more the Higgs rates deviate from SM

Natural Theories



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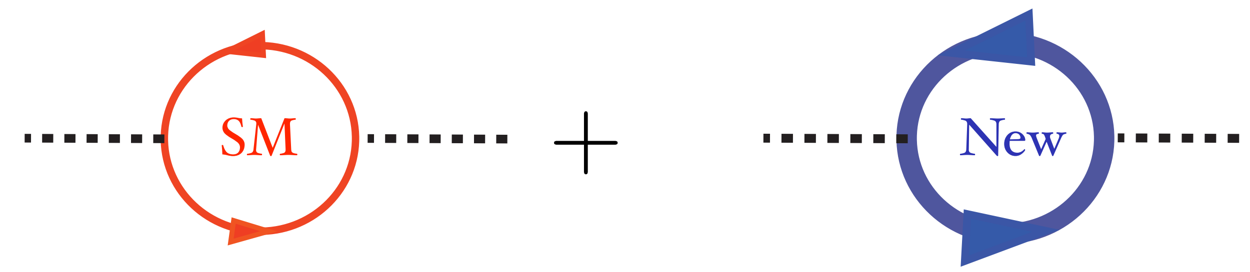
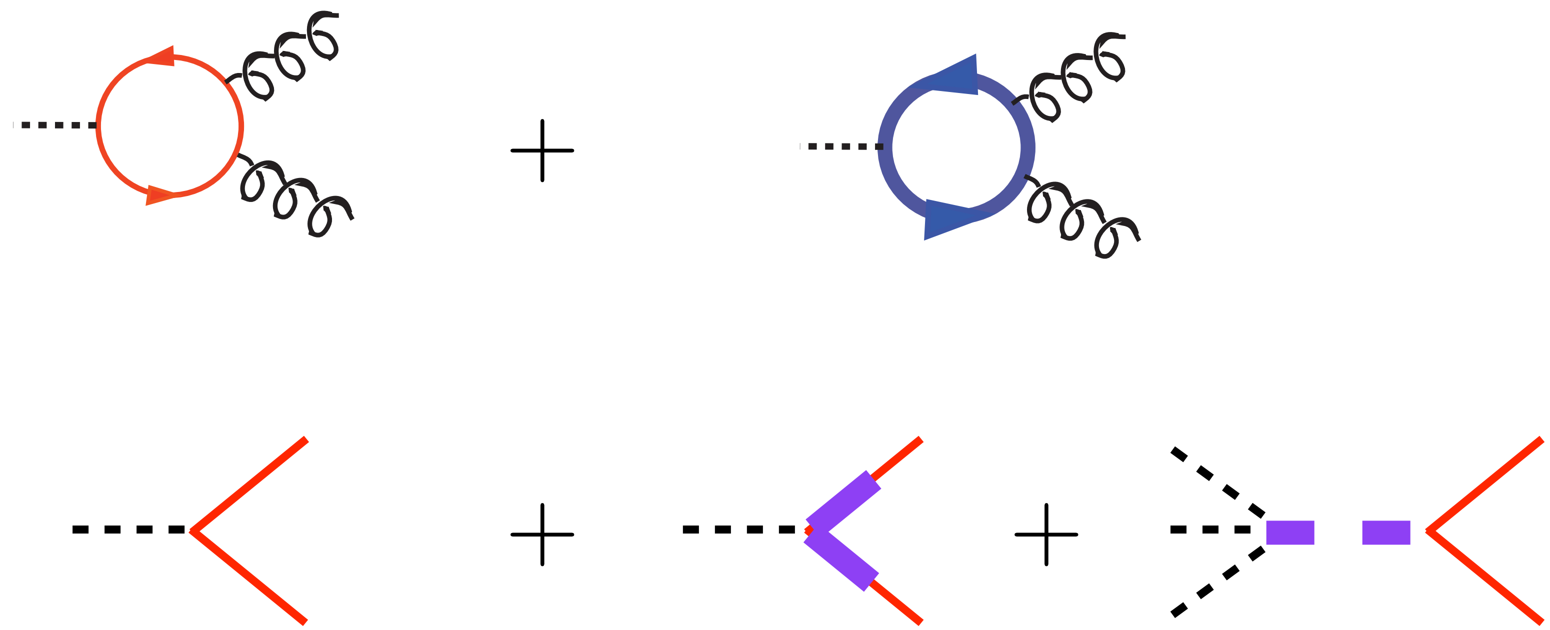


~ 0



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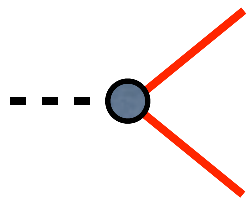
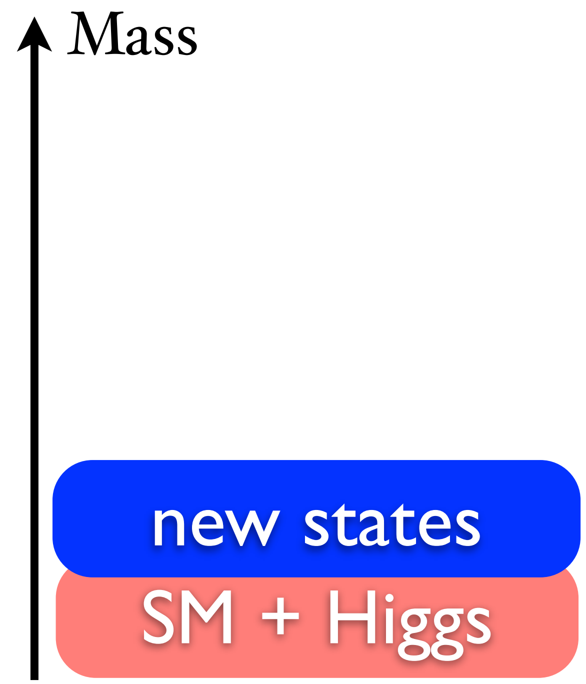
 = first probes into EWSB dynamics and into hierarchy puzzle

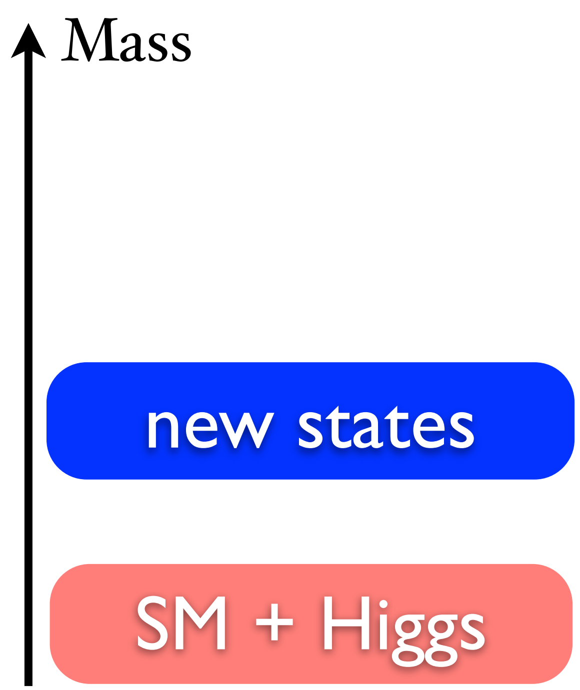
$115\,\mathrm{GeV} \lesssim m_h \lesssim 130\,\mathrm{GeV}$ lucky range to measure all couplings

It would be useful to develop a 'Higgs diagnostic': associate the possible patterns of deviation to broad/specific features of the underlying theory



Can use effective lagrangian to describe deviations from SM

= simple parametrization encompassing a large class of models



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I. Strong EWSB dynamics = ‘Composite Higgs’

II. Supersymmetry

III. Anthropics and all that

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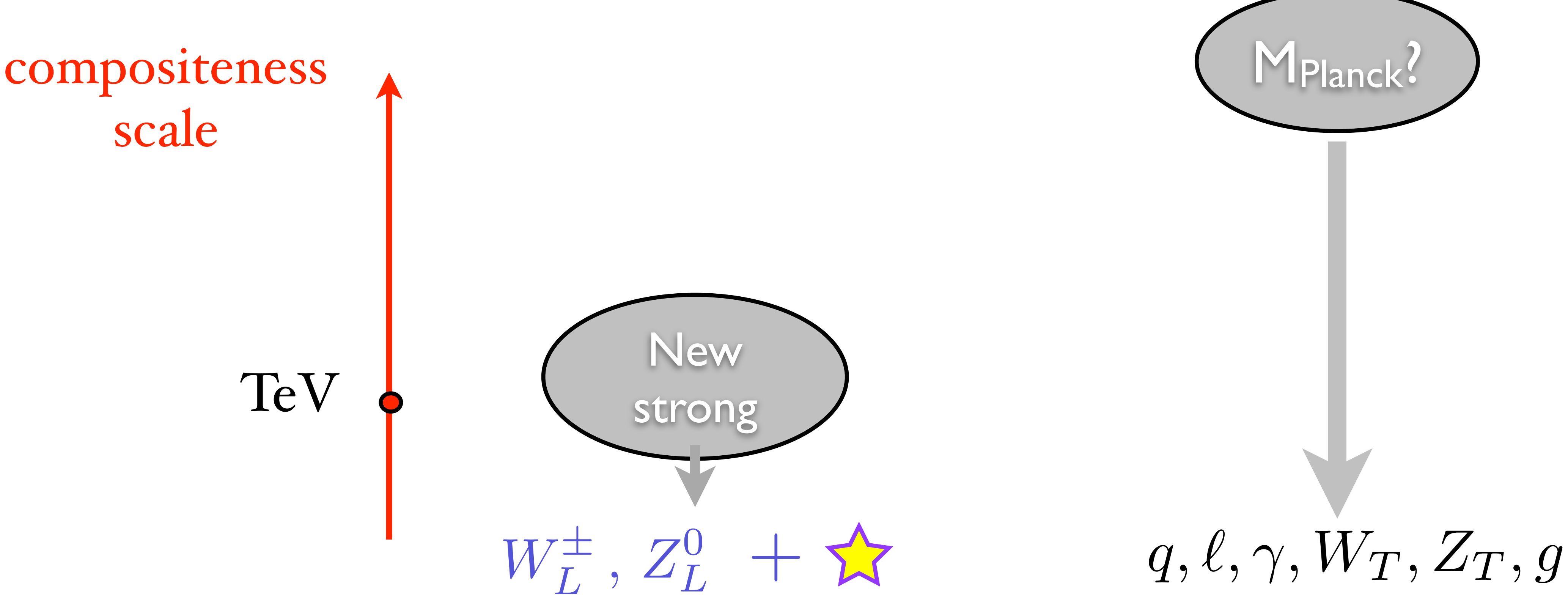
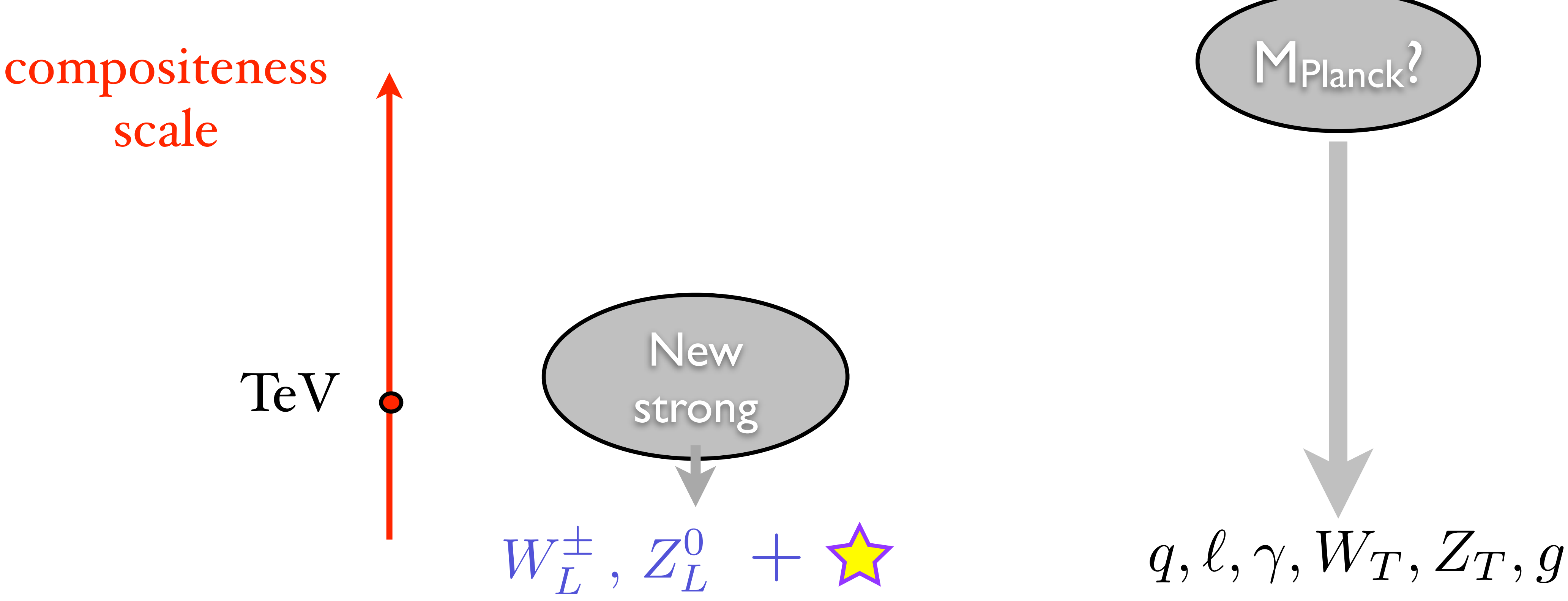

compositeness scale
TeV
New strong
$W_L^{\pm}$, Z_L^0 +
M_{Planck}?
$q, \ell, \gamma, W_T, Z_T, g$



✦ Technicolor SO(4)/SO(3): ☆ =nothing

Not feeling too well

✦ pseudo-NG Higgs SO(5)/SO(4): ☆ $= h$ $W_L^{\pm}, Z_L^0, h \to \begin{pmatrix} H^+ \\ H_0 \end{pmatrix}$

extended cosets SO(6)/SO(5), SO(6)/SO(4) x U(1) : additional light scalars

✦ pseudo-dilaton: ☆ $= \chi$ does **not** fit in SU(2) doublet

The main advantage of pseudo-NG Higgs

Georgi, Kaplan '84
Arkani-Hamed, Cohen, Katz, Nelson '02
Agashe, Contino, Pomarol '04

$$S = S_{TC} \times \frac{v^2}{f^2}$$

$f =$ Goldstone decay const

EWPT are OK with mild tuning $\frac{v^2}{f^2} \sim 0.1 - 0.3$

- Compositeness scale $4\pi f$ still as low as a few TeV
- Sizeable corrections to Higgs couplings: $O(\frac{v^2}{f^2})$
- Direct signatures

production of resonances

strong WW scattering

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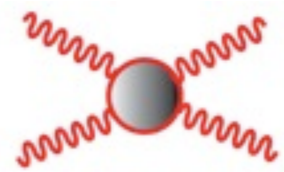
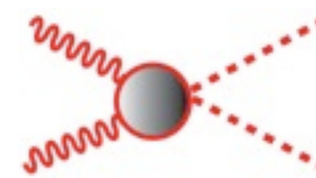




General parametrization of *Higgslike scalar h*

Contino, Grojean, Moretti, Piccinini, RR '10

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{M_V^2}{2}\mathrm{Tr}\,(V_\mu V^\mu)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right] - m_i\bar{\psi}_{Li}\left(1 + c\frac{h}{v}\right)\psi_{Ri} + \mathrm{h.c.}$$
$$+ \frac{1}{2}m_h^2 h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots$$
$$+ c_g\frac{\alpha_s}{4\pi}\frac{h}{v}G_{\mu\nu}G^{\mu\nu} + c_\gamma\frac{\alpha}{4\pi}\frac{h}{v}F_{\mu\nu}F^{\mu\nu}$$

c flavor universal in minimal flavor violating set up

✦ Standard Model: $a = b = c = d_3 = 1$ $c_g = c_\gamma = 0$

✦ h = pseudo-Goldstone implies additional constraints

$SO(5)/SO(4)$ Pseudo-Goldstone Higgs

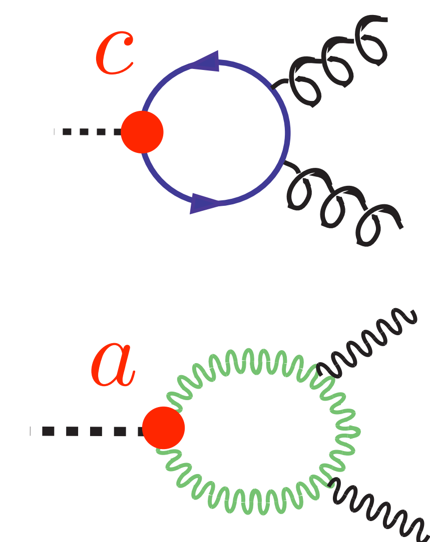
Agashe, Contino, Pomarol '04

$a = \sqrt{1 - v^2/f^2}$ $b = 1 - 2v^2/f^2$ model independent

$c = d_3 = \sqrt{1 - v^2/f^2}$ fermions in **4**

$c = d_3 = \dfrac{1 - 2v^2/f^2}{\sqrt{1 - v^2/f^2}}$ fermions in **5**

} model dependent



$c_g,\ c_\gamma \sim \dfrac{\alpha_t}{4\pi}$ controlled by small explicit SO(5) breaking

NEGLIGIBLE!

Interesting inequalities

$0 \leq a, |b| \leq 1$ robust

$0 < c < 1$ in range favored by EWPT

In specific models just one free parameter $\xi \equiv \frac{v^2}{f^2}$

In general 4 parameters $a, \; c_t, \; c_b, \; c_\tau$

$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)|_{SM}} = \frac{\Gamma(h \to t\bar{t})}{\Gamma(h \to t\bar{t})|_{SM}} = c_t^2$$

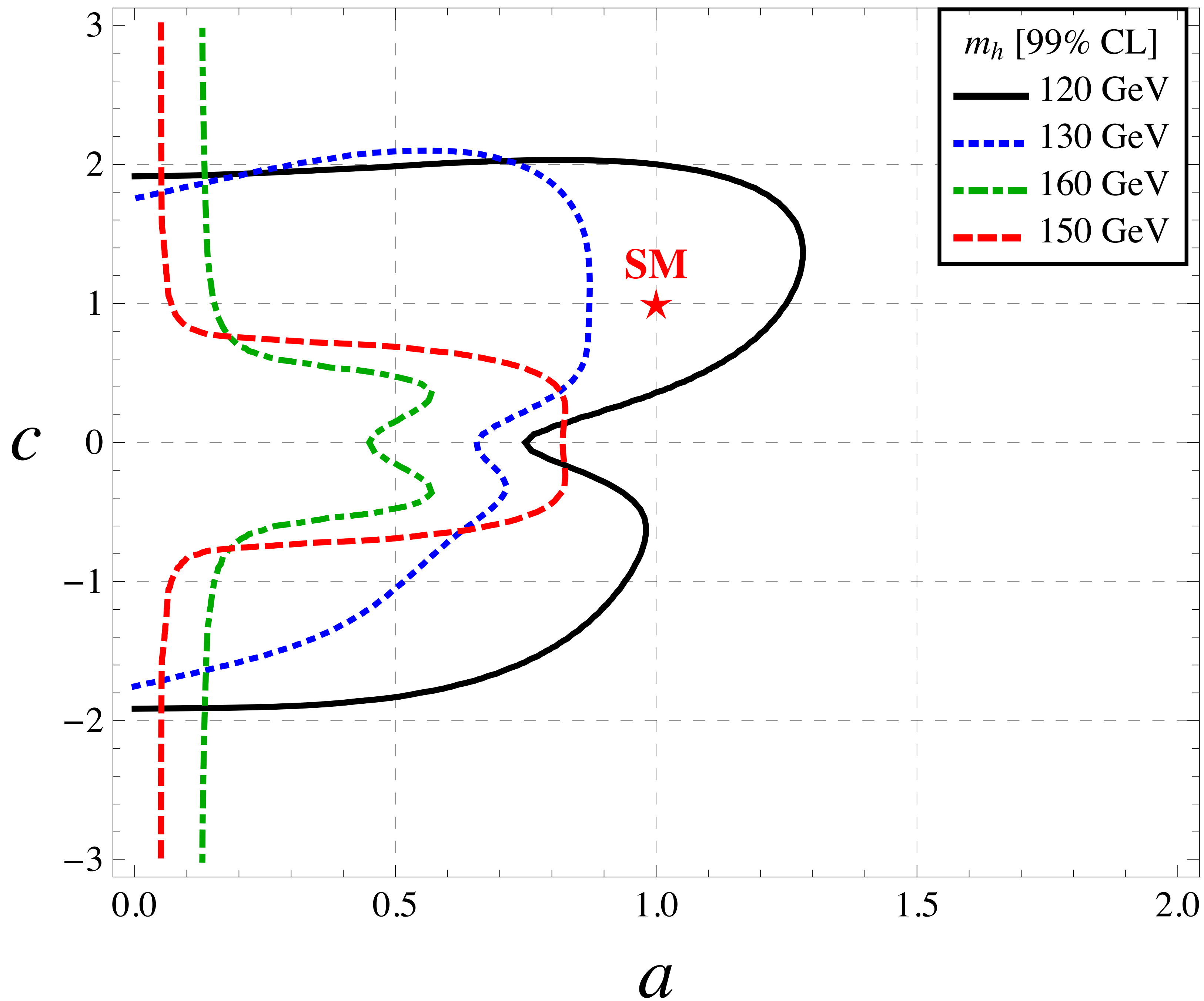
$$\frac{\Gamma(h \to f\bar{f})}{\Gamma(h \to f\bar{f})|_{SM}} = c_f^2$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)|_{SM}} = a^2 \left[1 + 0.28(1 - c_t/a)\right]^2 \sim a^2$$

$$\frac{\Gamma(h \to VV)}{\Gamma(h \to VV)|_{SM}} = a^2$$

In the preferred range all rates are reduced

Exclusion using CMS data [$\leq 4.7\ \text{fb}^{-1}$]



$$c_t = c_b = c_\tau \equiv c$$

preliminary by
Azatov, Contino, Galloway

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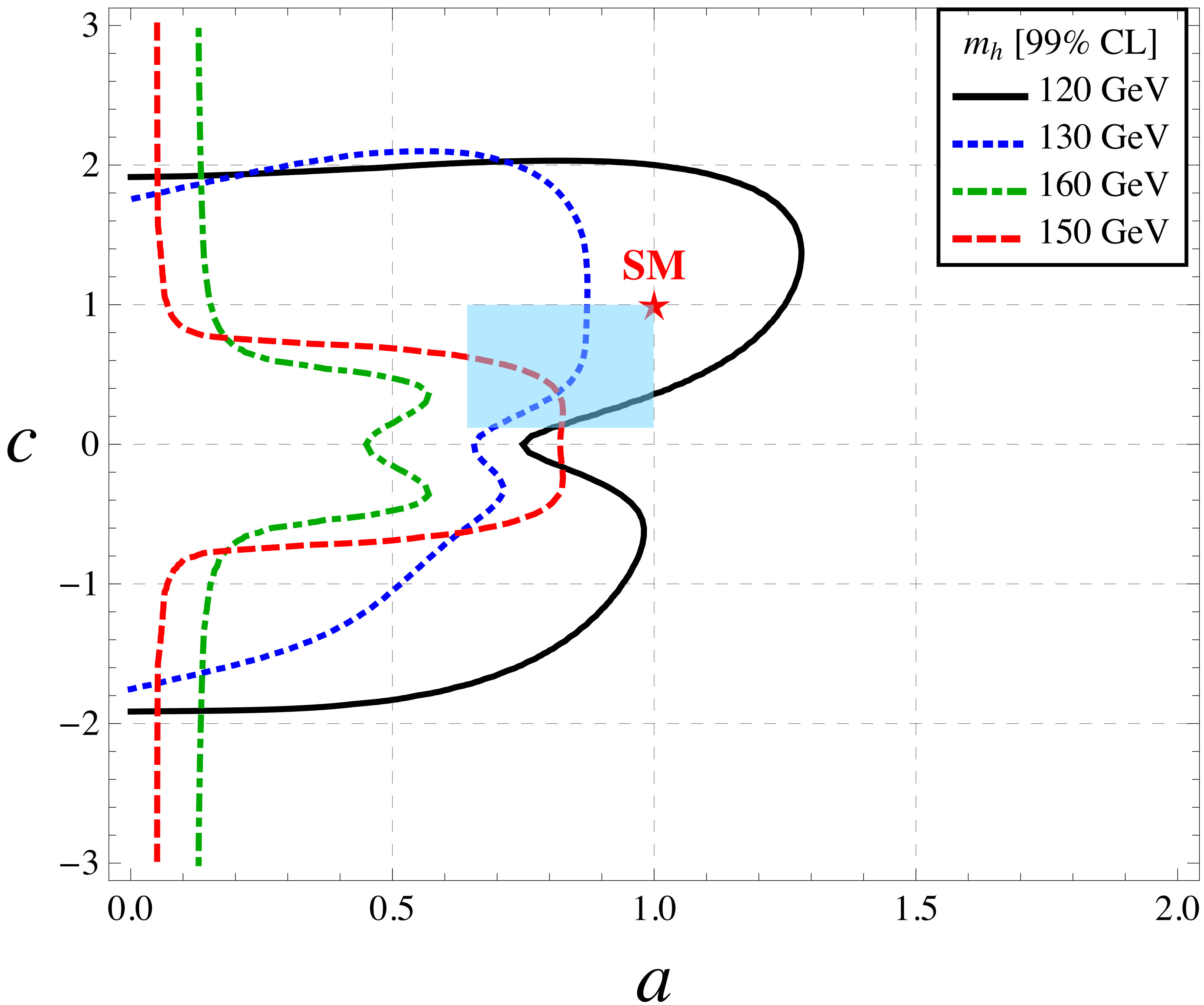

$$c_t = c_b = c_\tau \equiv c$$

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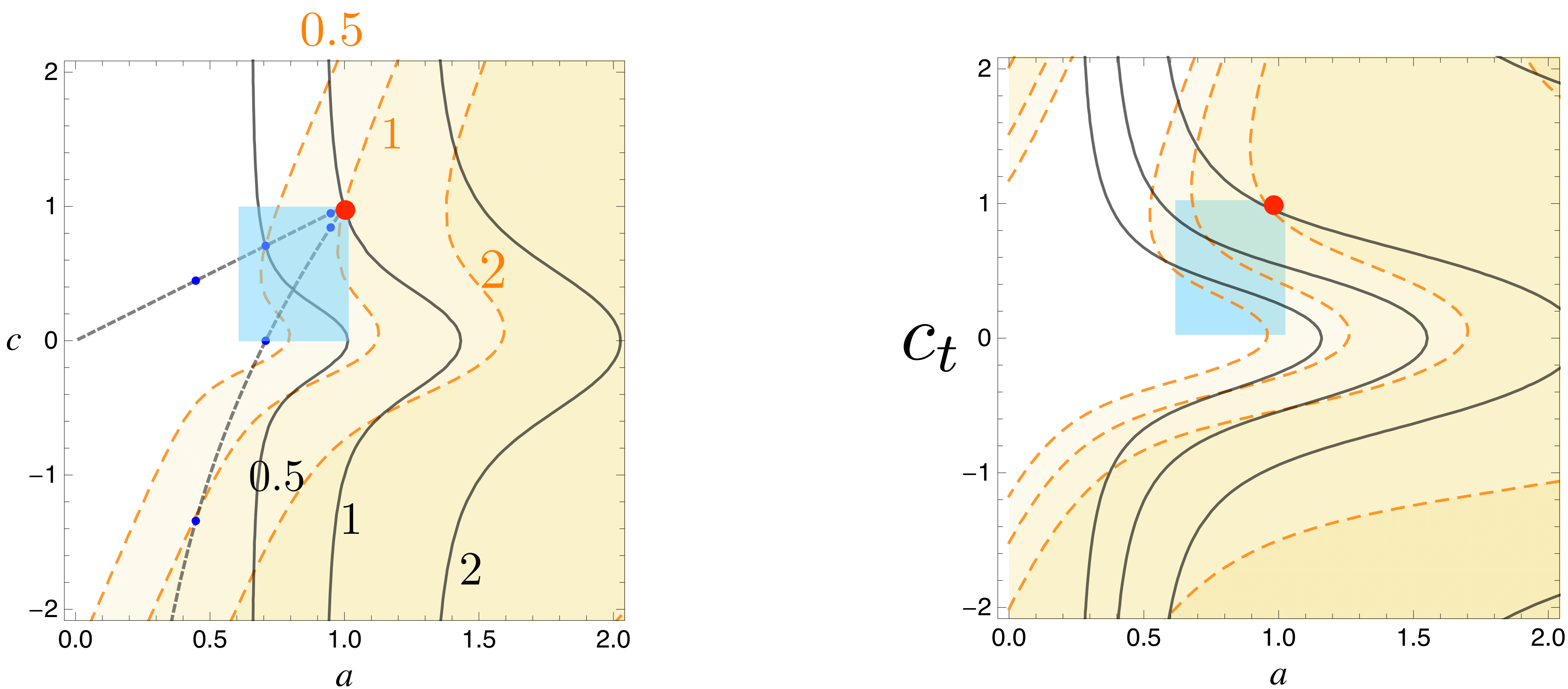
R_{ZZ} ———

$R_{\gamma\gamma}$ - - - - -

$m_h = 125$ GeV

prepared by R.Contino



$c_t = c_b = c_\tau \equiv c$

$c_b = c_\tau = 0.4$

Can increase $R_{\gamma\gamma}$, but at the price of R_{bb}

$$\frac{v^2}{f^2} \ll 1$$

SILH effective lagrangian

$$\mathcal{L}_{eff} = \frac{c_H}{2f^2}\partial^\mu \left(H^\dagger H\right)\partial_\mu \left(H^\dagger H\right) + y_f \frac{c_y}{f^2} H^\dagger H\,\bar{\psi}_L H \psi_R - \frac{c_6 \lambda}{f^2}\left(H^\dagger H\right)^3$$

$$0 \le a, b, c \le 1$$

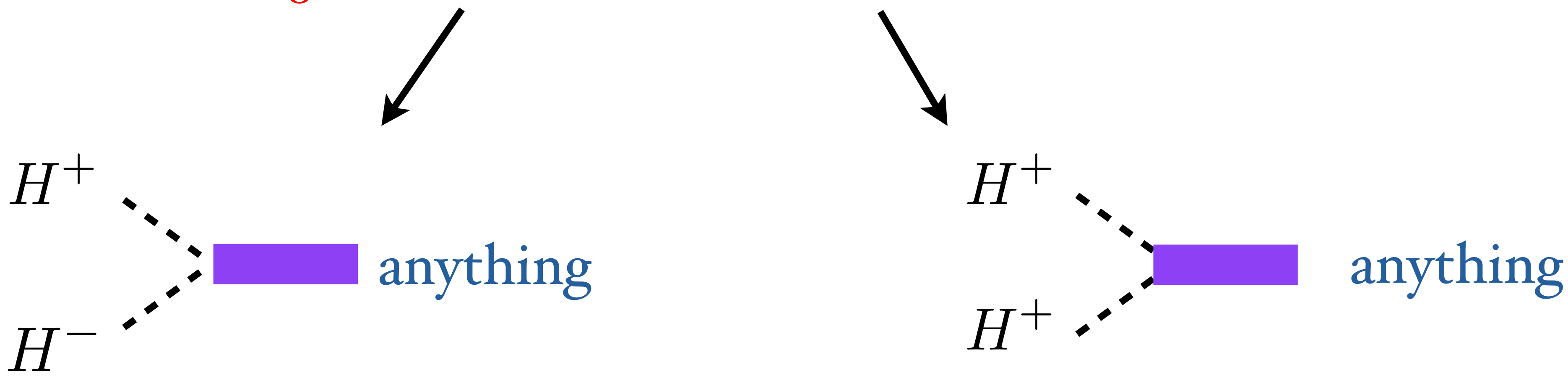
$$c_H, c_y > 0$$

true in larger class
including Little Higgs

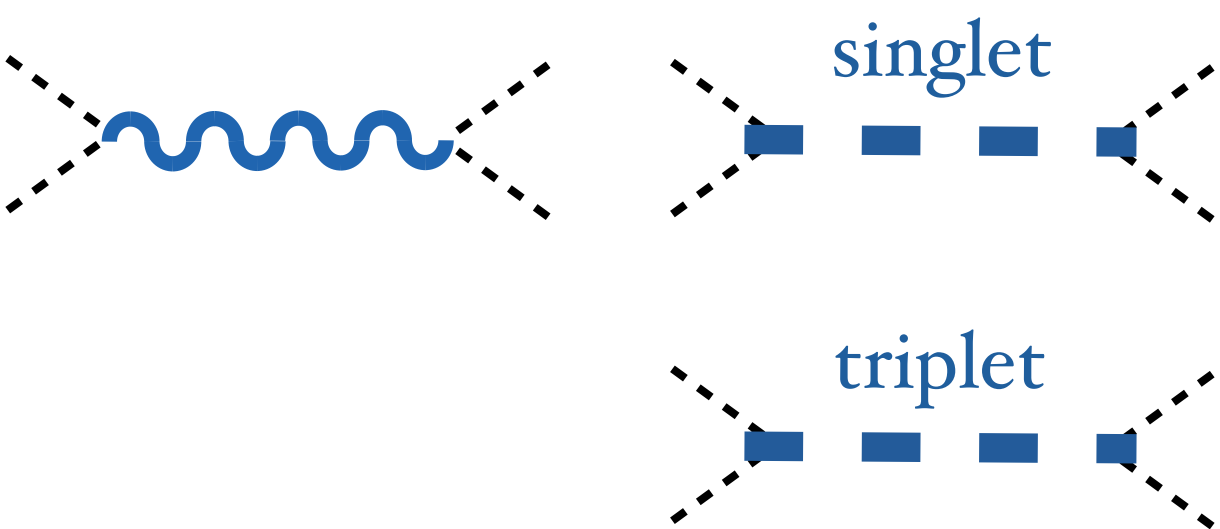
A dispersion relation for c_H

Low, Rattazzi, Vichi '09

$$c_H = \frac{f^2}{\pi}\int_0^\infty \left(\sigma_{+-}(s) - \sigma_{++}(s)\right)\frac{ds}{s}$$



c_H not positive definite, but almost so



$\Delta c_H > 0$

$\Delta c_H < 0$

Scalar triplets do not dominate in known models addressing hierarchy

Other roads to increase Higgs couplings

Dilaton

$$\begin{cases} a = \sqrt{b} = c = \dfrac{v}{f_D} \\ d_3 = \dfrac{5}{3}\dfrac{v}{f_D} + O(\epsilon) \\ c_g,\, c_\gamma = O(v/f_D) \end{cases}$$

$$a,\, b,\, c \lessgtr 1$$

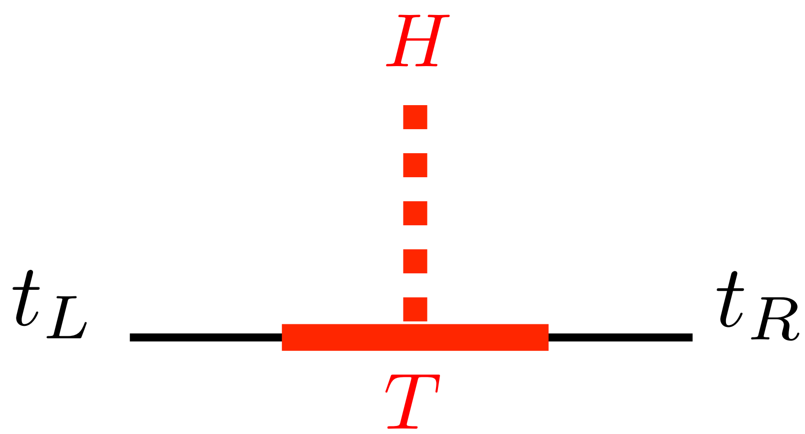
Non-Compact coset space

$H \in SO(4,1)/SO(4)$

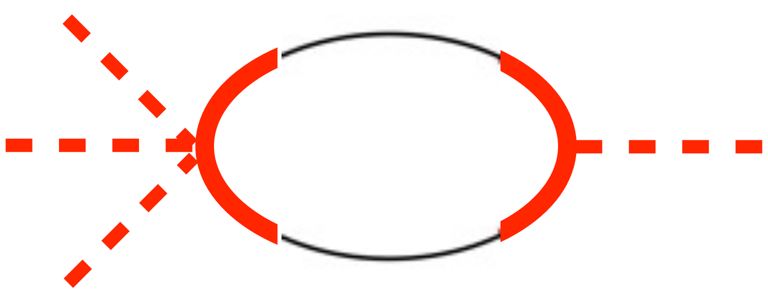
$$\begin{cases} \dfrac{v^2}{f^2} \to -\dfrac{v^2}{f^2} \\ a = \sqrt{1 + v^2/f^2} \qquad b = 1 + 2v^2/f^2 \end{cases}$$

No Unitary QFT as UV completion ➡ TeV scale Quantum Gravity ?

m_h, m_t and colored resonances

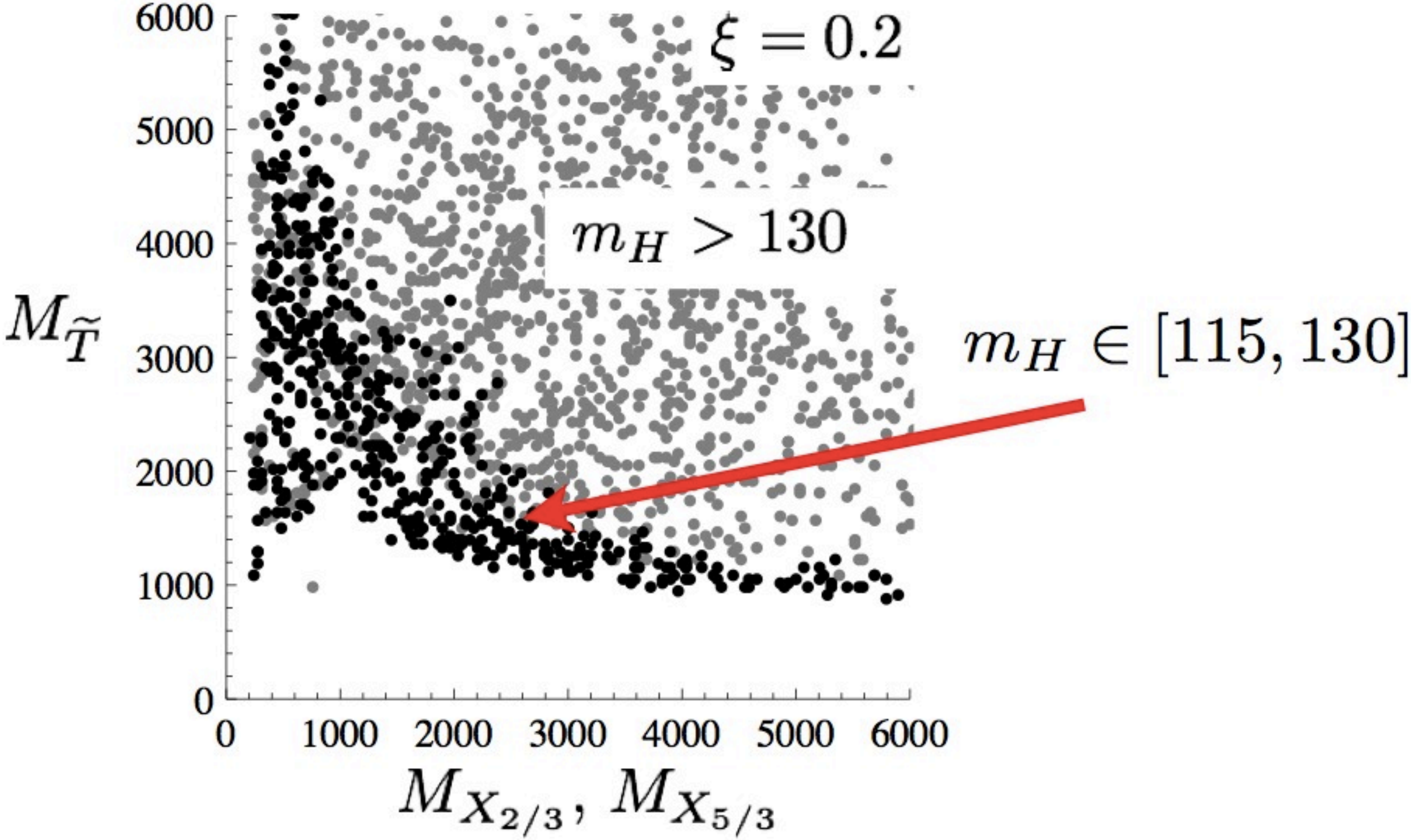


$$y_t \sim \frac{y_L y_R f}{M_T}$$



$+ \cdots$ → $$m_h \sim m_t \frac{M_T}{\pi f}$$

$m_h < 130$ GeV → $$M_T \lesssim 1 \text{ TeV} \left(\frac{0.5}{\frac{v}{f}} \right)$$

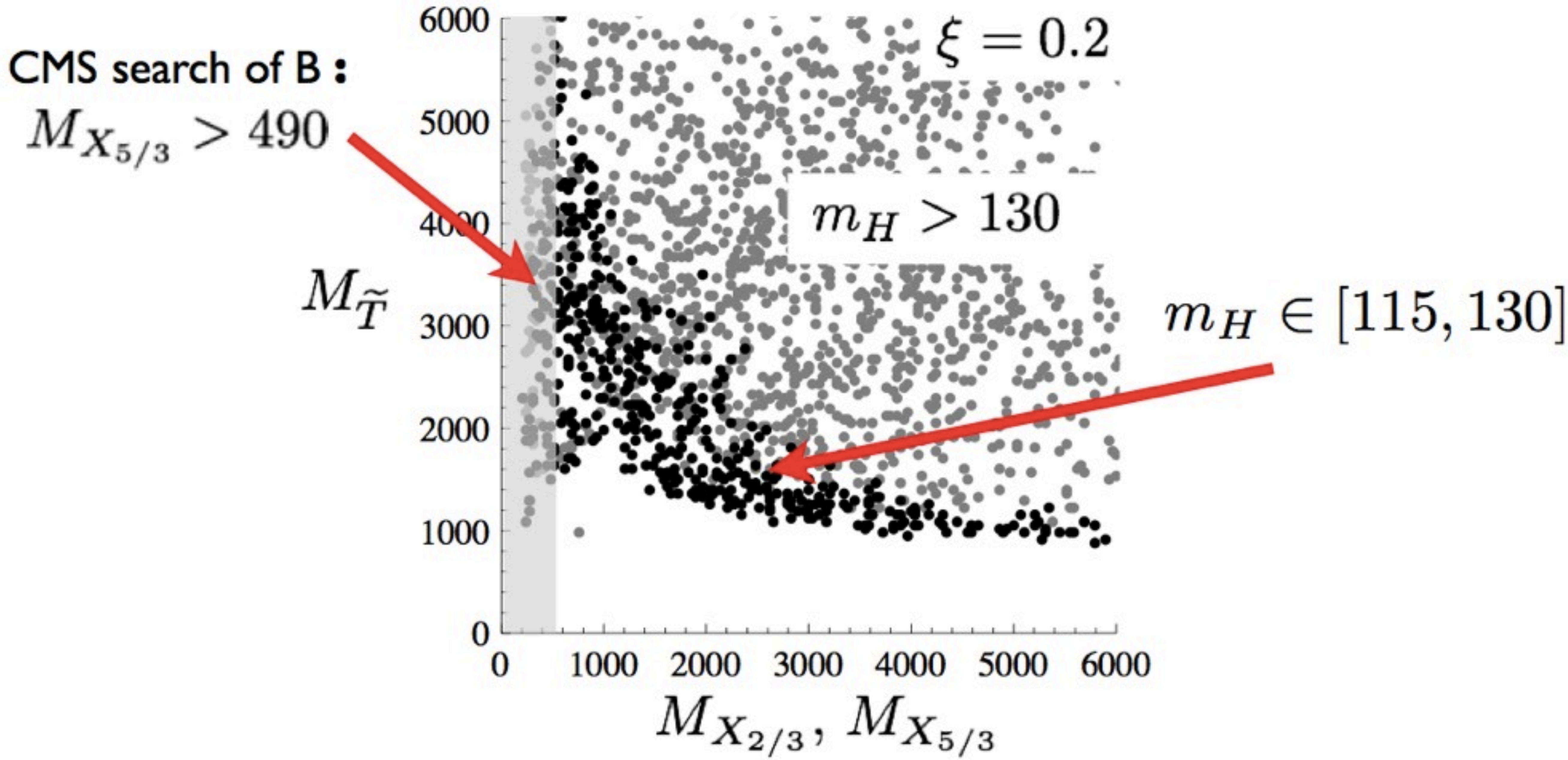


Panico, Wulzer (preliminary)

Contino, Servant '08
Mrazek, Wulzer '09

Dissertori, Furlan, Moortgat, Nef '10

LHC has **already probed** part of this plot :



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Λ_{SUSY}

RG evolution

m_H^2 affected by $m_{\tilde{t}}^2,\ m_{\tilde{g}}^2$ etc

m_{soft}

Naturalness bound

$$\sqrt{\frac{m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2}{2}} \lesssim \frac{400\ \text{GeV}}{\sqrt{1+X^2}} \left(\frac{3}{\ln \frac{\Lambda_{SUSY}}{\text{TeV}}}\right)^{\frac{1}{2}} \left(\frac{0.2}{\epsilon_T}\right)^{\frac{1}{2}}$$

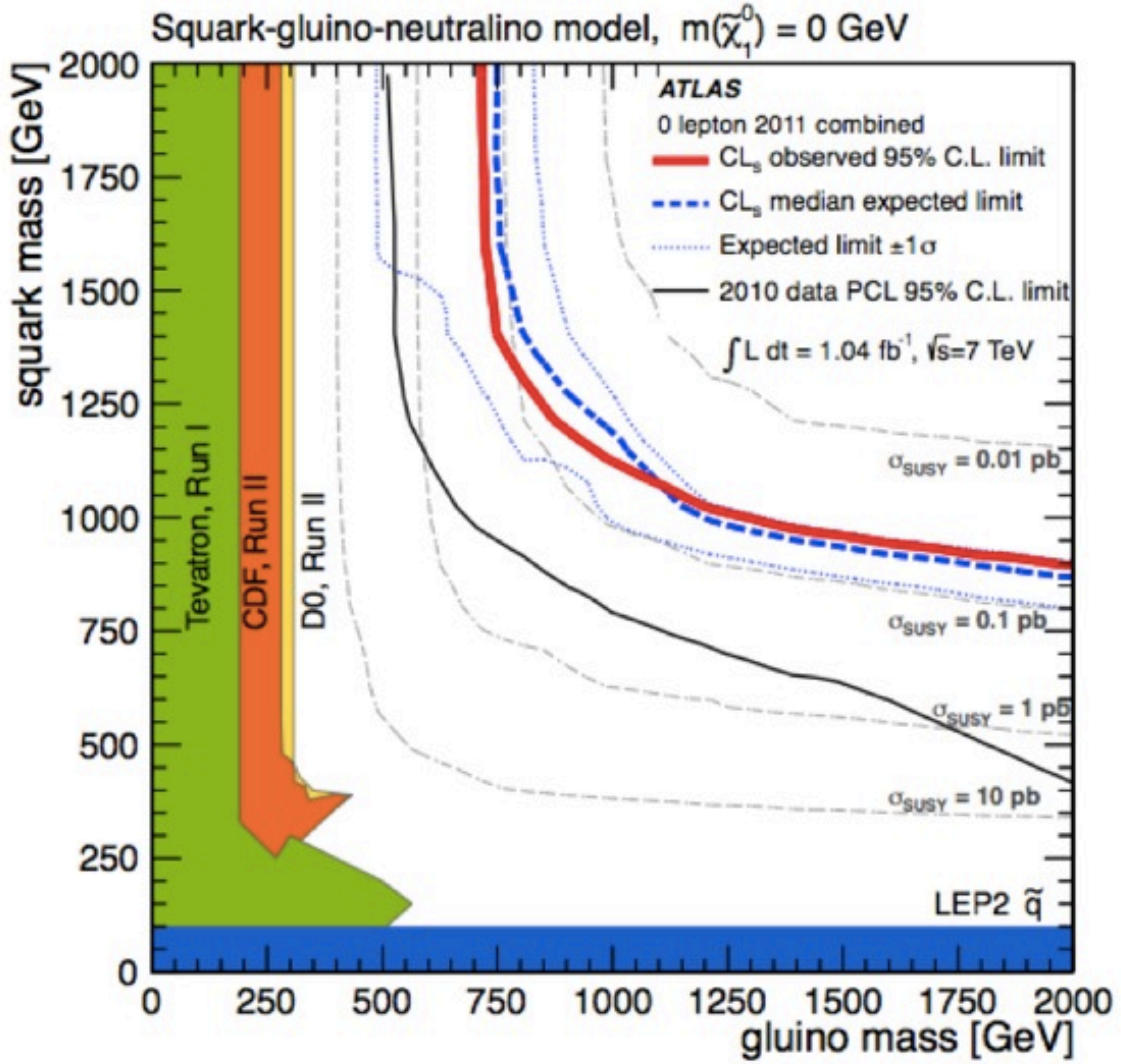
tuning smallest for: small $X^2 = \dfrac{A^2}{m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2}$ & low Λ_{SUSY}

High scale mediation $m_{\tilde{t}} \lesssim 100\,\text{GeV} \left(\dfrac{1}{\epsilon_T}\right)^{\frac{1}{2}}$

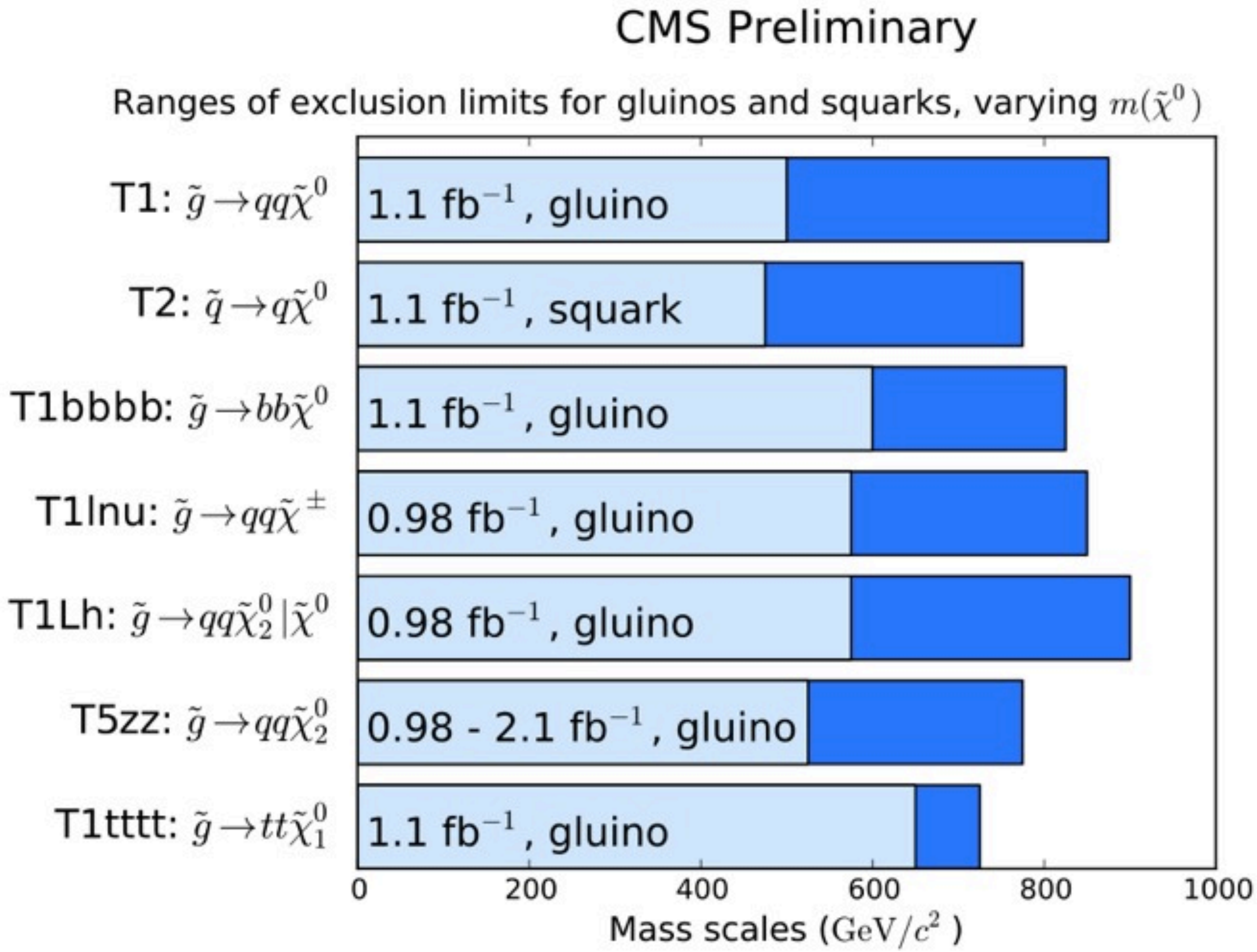
http://arxiv.org/pdf/1109.6572v1

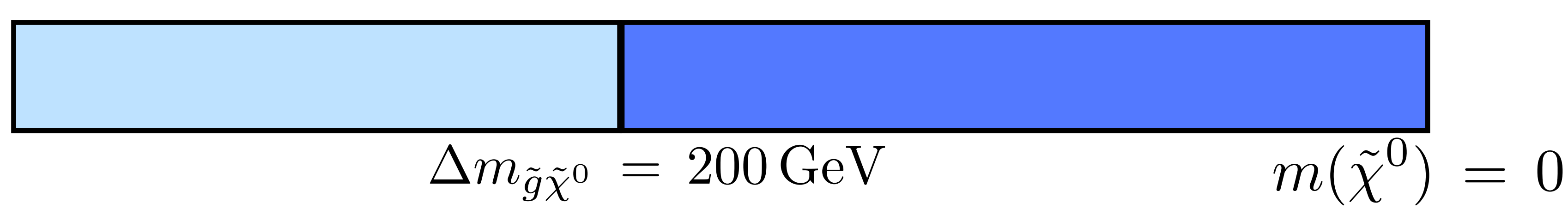
ATLAS

bound on gluinos and squarks of 1st 2nd family



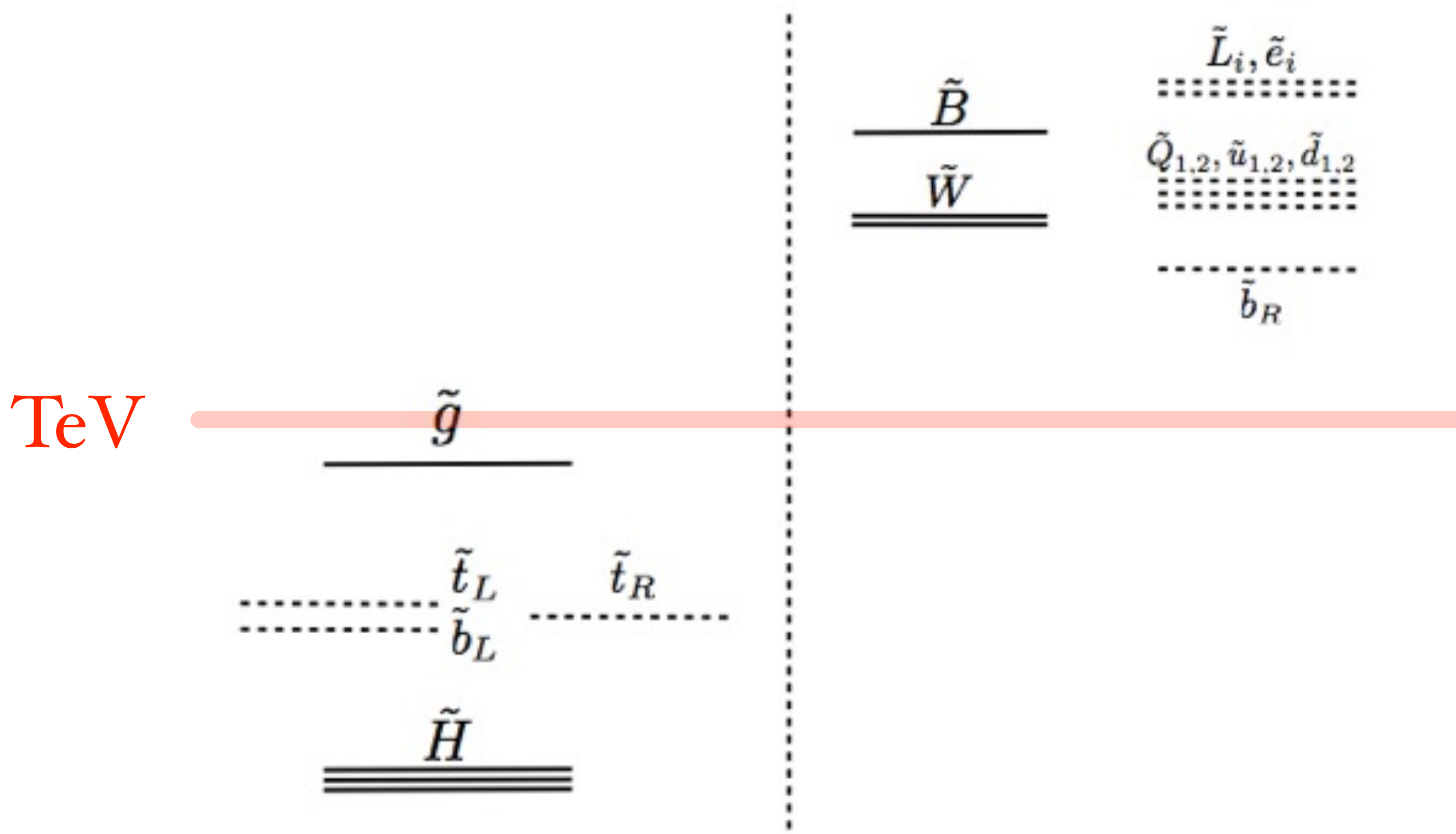
In simplest models $m_{\tilde{t}} \sim m_{\tilde{q}} \sim m_{\tilde{g}}$ it looks like 1% tuning





Squashed spectra slightly less constrained: less tuning

not-so-un-Natural SUSY



Still less constrained with ~1 fb^{-1} $$m_{\tilde{t}_L}, m_{\tilde{t}_R} \gtrsim 250\,\text{GeV}$$

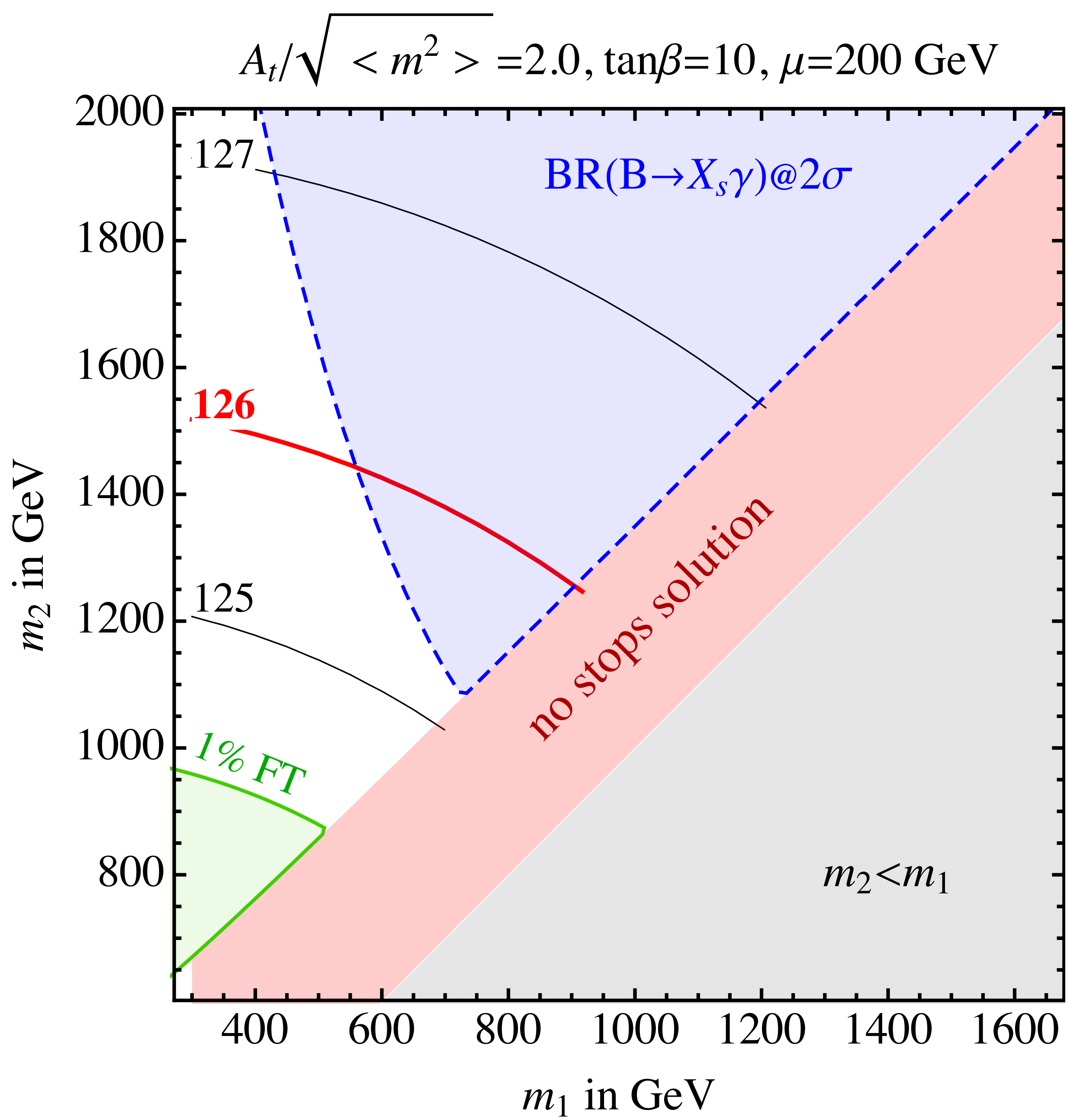
Papucci, Ruderman, Weiler ’11

The perspective changes appreciably if one buys the $m_h \sim 125$ GeV hint

In MSSM to push up Higgs quartic one needs

- stop masses ≳ 1 TeV
- large A-terms

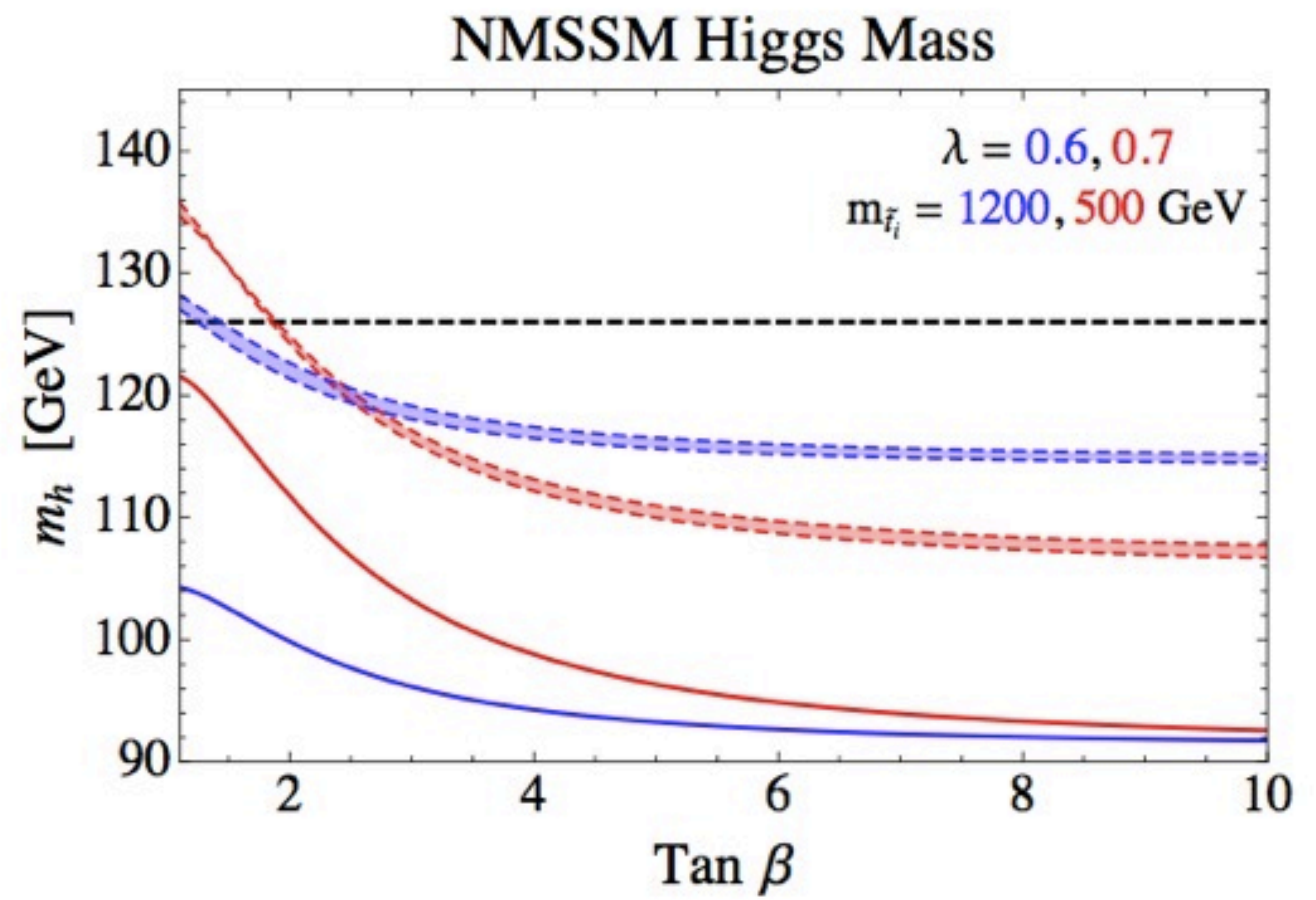
worst that 1% tuning + problematic for $b \to s\gamma$



Pappadopulo '12

NMSSM

$$m_h^2 \;=\; M_Z^2 \cos^2 2\beta \;+\; \lambda^2 v^2 \sin^2 2\beta \;+\; (\text{stop loops})$$



Hall, Pinner, Ruderman '11

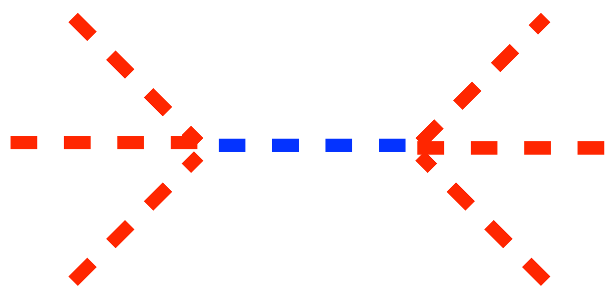
stop masses < 500 GeV
small A
small tan β

O(10%) tuning + ok for b → s γ

An exercise in Higgs diagnostic

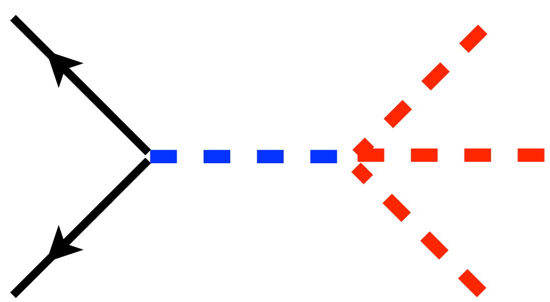
$H' = -\cos\beta H_2 + \sin\beta H_1$

$H = \cos\beta H_1 + \sin\beta H_2$

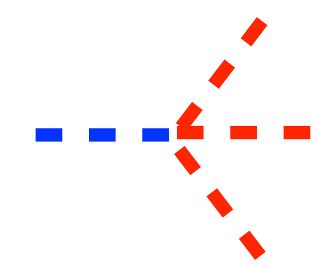


$\Delta c_H = 0$

dim 8 operator: quick decoupling in h $\gamma\,\gamma$ and hWW



sign depends on structure of quartic



MSSM	$(H_1^2 - H_2^2)^2$	$c_b > 1$ $c_t < 1$
NMSSM	$H_1^2 H_2^2$	$c_b < 1$ $c_t > 1$

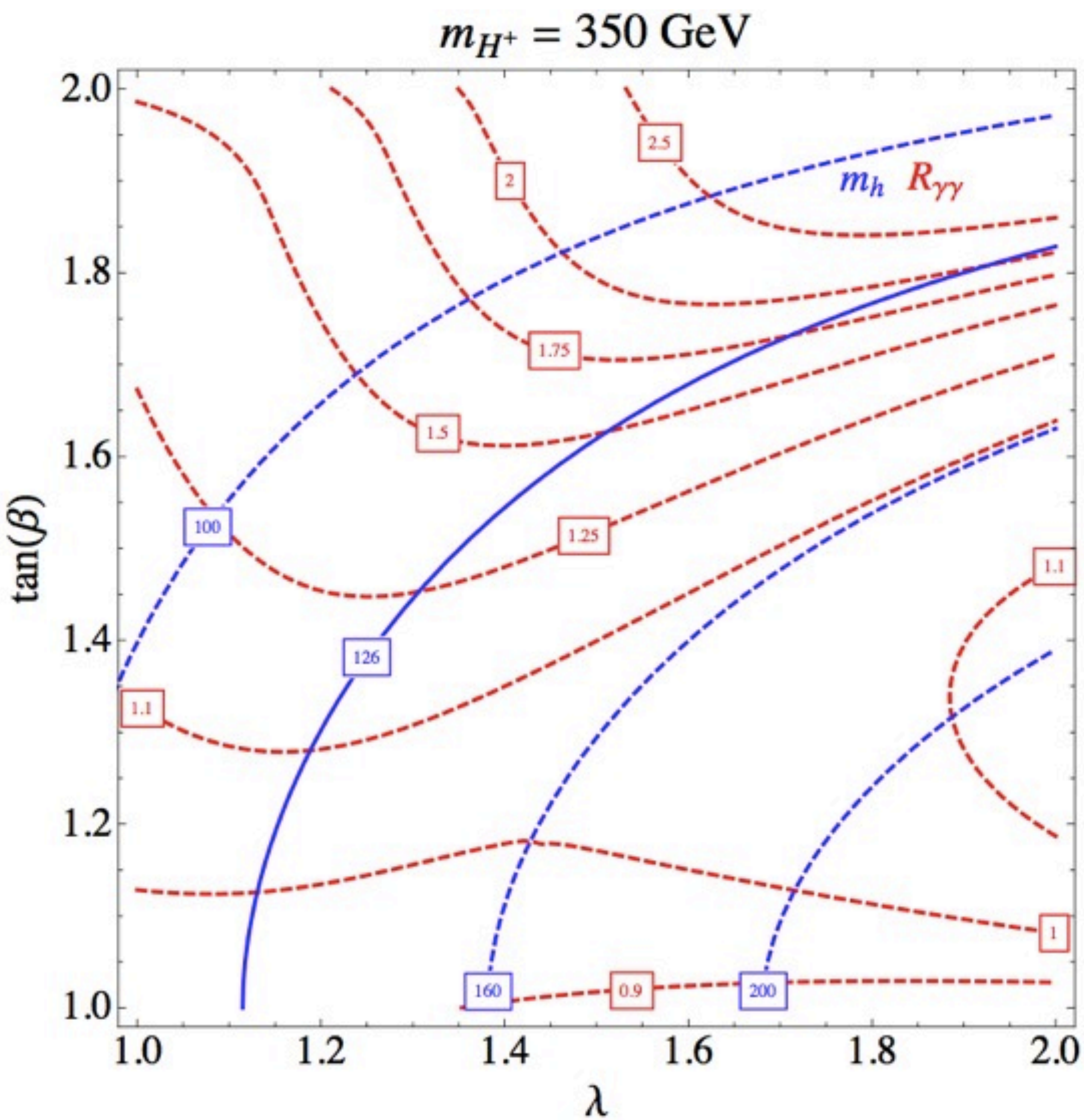
λ-SUSY = NMSSM with $\lambda > 1$

cut-off is below GUT scale

λ dominates the quartic

$$R_{\gamma\gamma}\,,\ R_{ZZ} > 1$$

$$R_{b\bar{b}} < 1$$



generic
MSSM

natural
MSSM

NMSSM

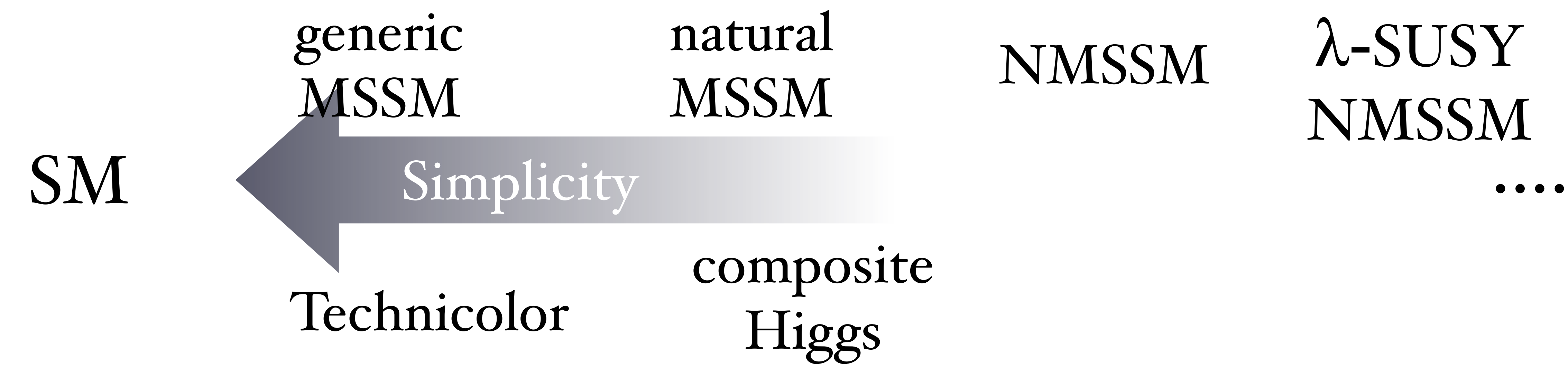
λ-SUSY
NMSSM

SM

....

Technicolor

composite
Higgs

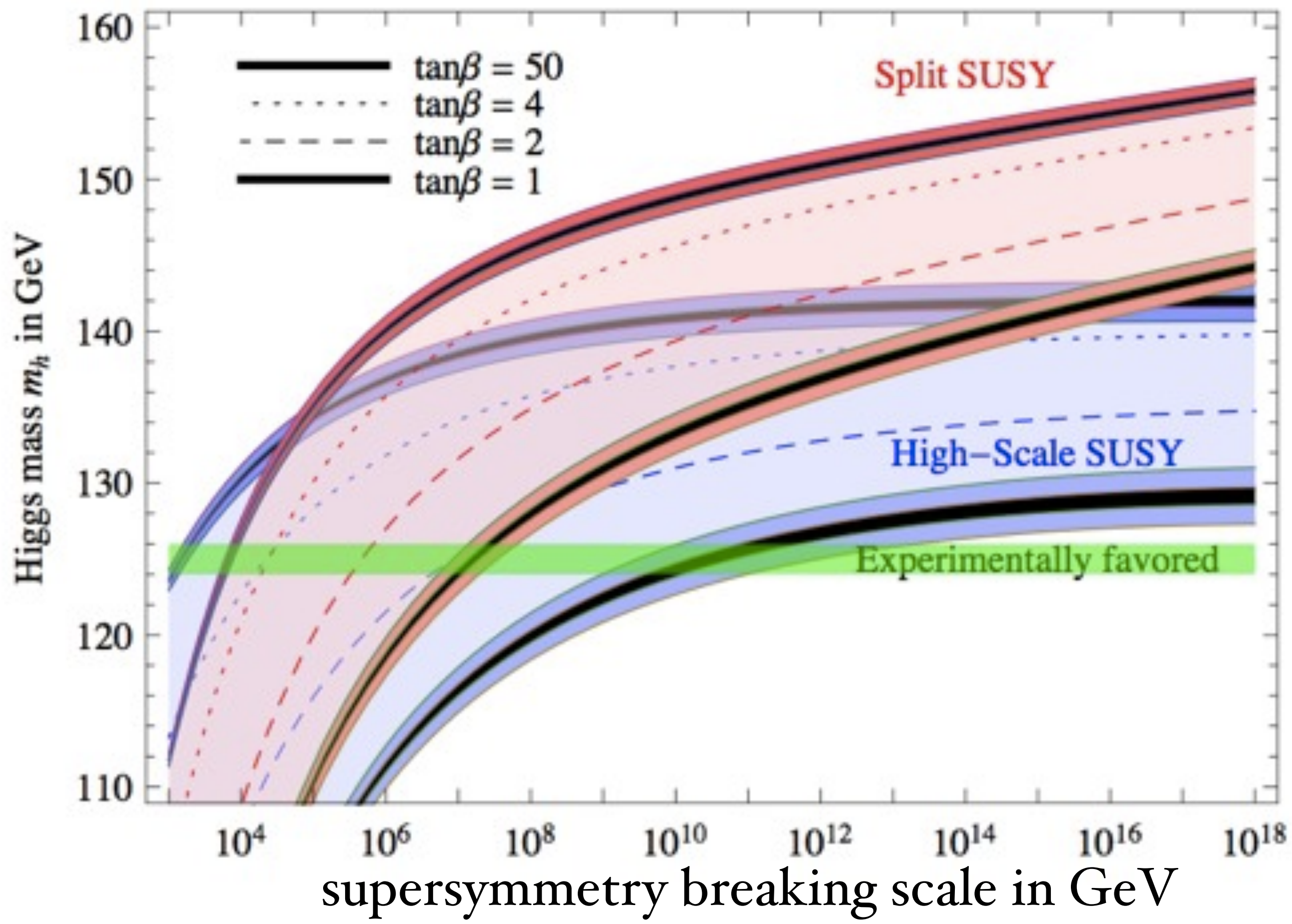


perhaps, rather than naturalness, the guidelines should be

A) existence of a complex world (anthropic selection)
B) structure (Ex.: unification, strings)
C) cosmological obs: existence of Dark Matter, baryon asymmetry,...
D) minimality

Ex

- ✦ Split-SUSY (ABCD) — Arkani-Hamed, Dimopoulos '04
- ✦ High-Scale SUSY (ABD) — Hall, Nomura '10
- ✦ nuMSM (CD) — Asaka, Blanchet, Shaposhnikov '05



Giudice, Strumia, ‘11

$\lambda_h(M_P)$ curiously close to zero in RG extrapolated SM

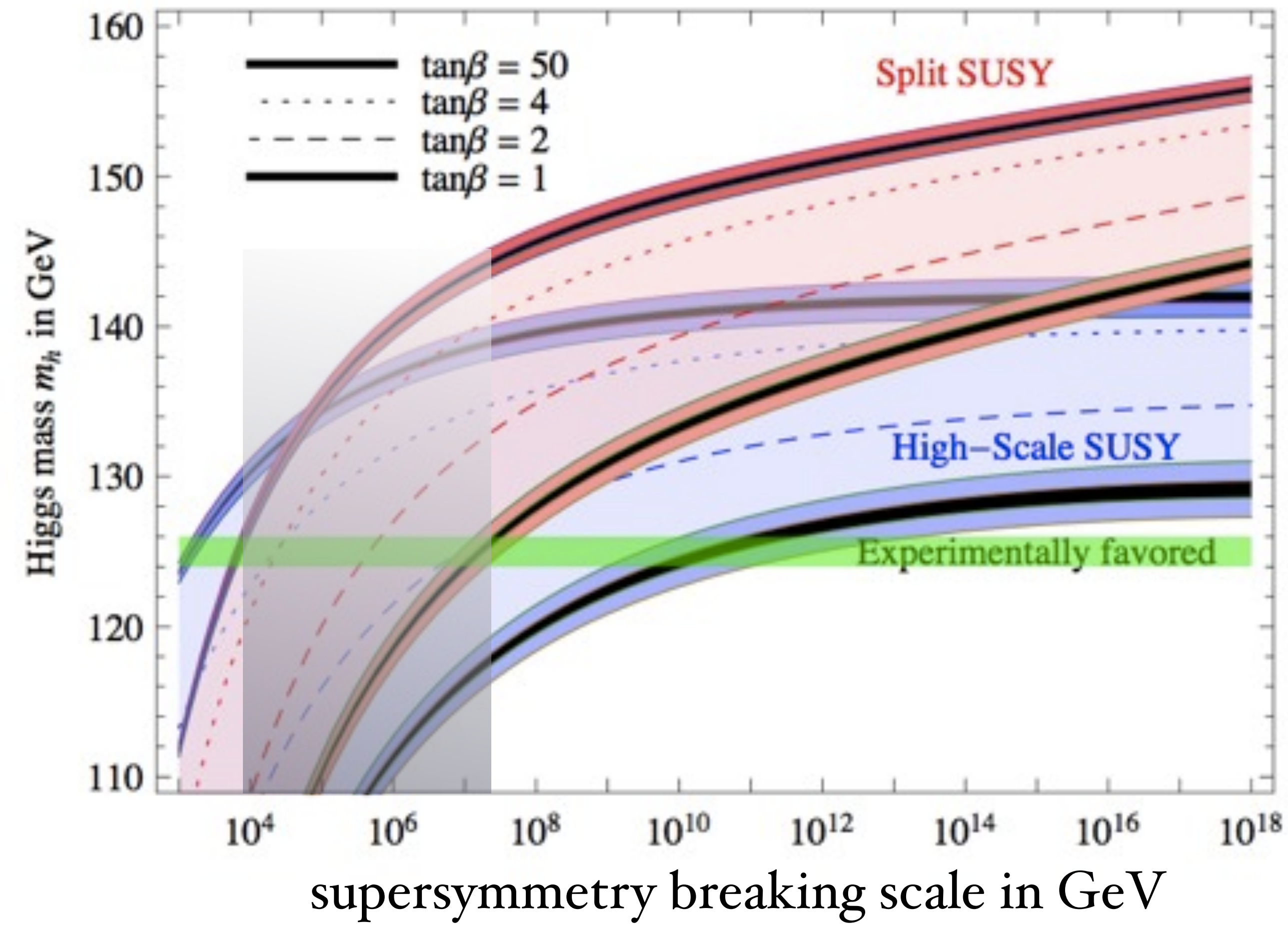
- Is it just High-Scale SUSY at tanβ = 1 ?
- Is the Higgs a pseudo-NG-boson, ... but at the Planck scale?
- Is there a deeper explanation (ex asymptotic safety)? Shaposhnikov, Wetterich ’10

Would we ever know?

Split SUSY

$$10 \text{ TeV} \leq m_{\tilde{f}} \leq 10^4 \text{ TeV}$$

$$\tau_{\tilde{g}} \simeq \left(\frac{\text{TeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{m_{\tilde{f}}}{10^4 \text{ TeV}}\right)^4 4 \times 10^{-8}\, s$$

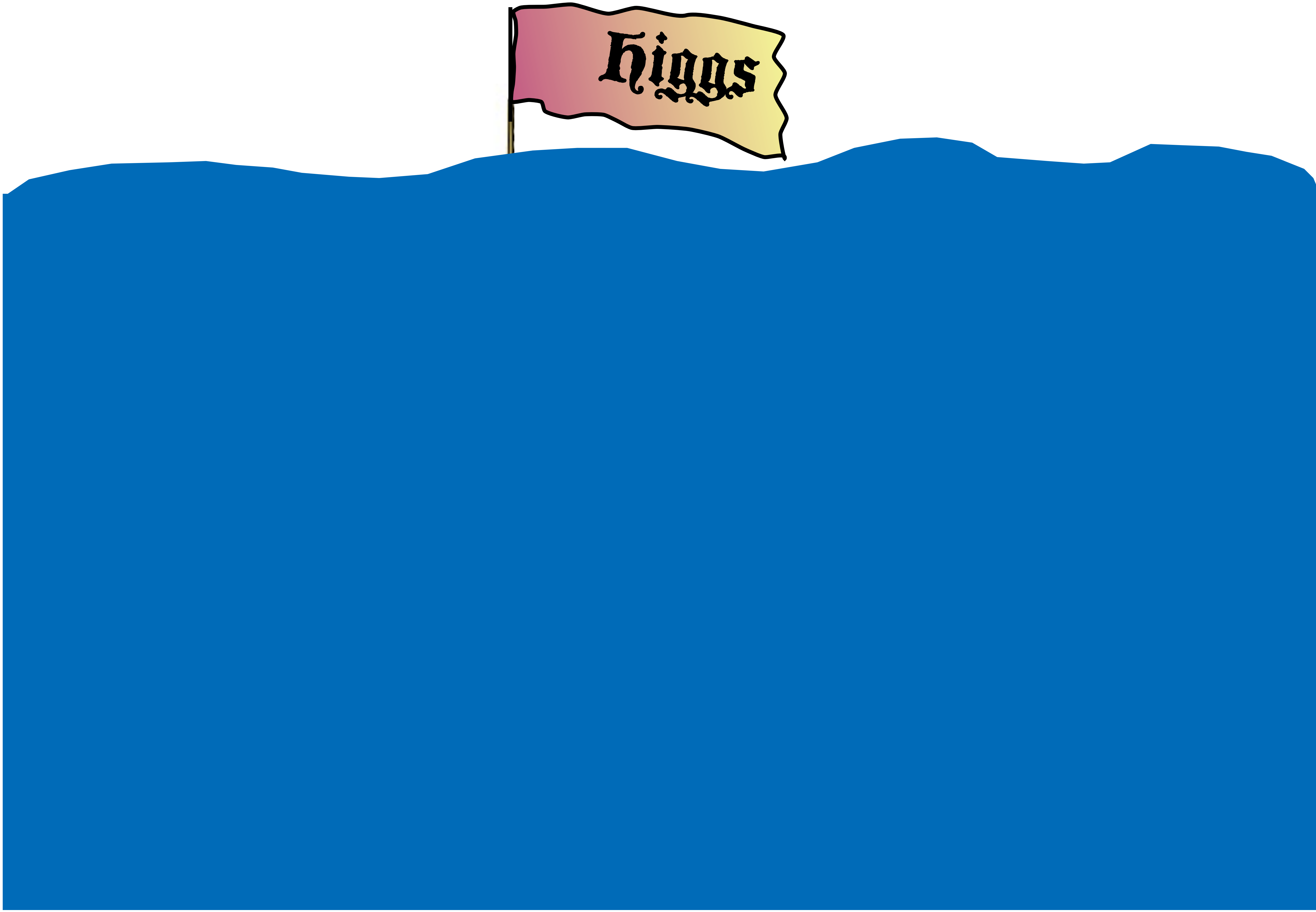


- search for displaced vertices from gluino decays
- compatible with 'SUSY breaking without singlets'
  simplest anomaly mediated scenario

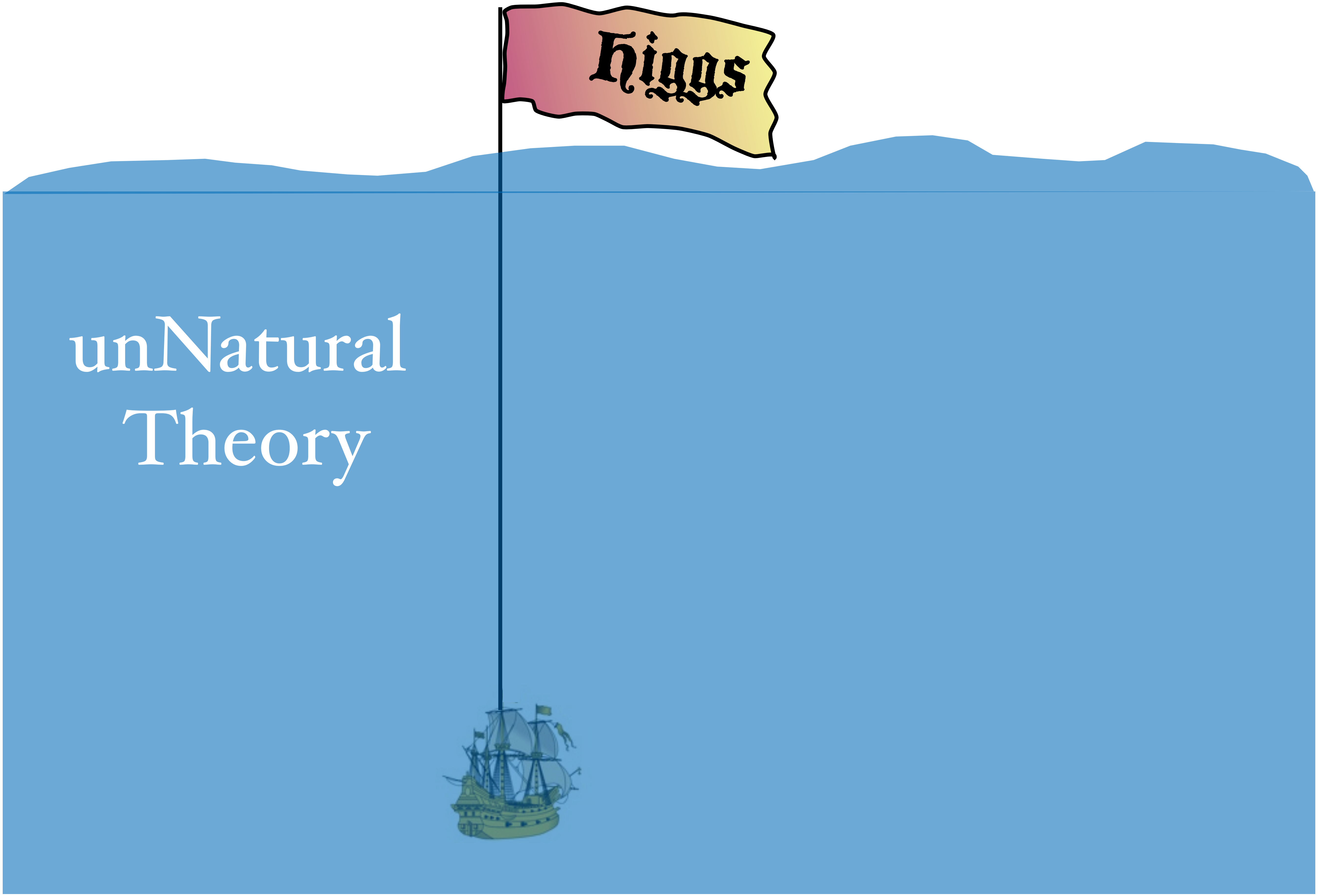
Giudice, Luty, Murayama, Rattazzi '98

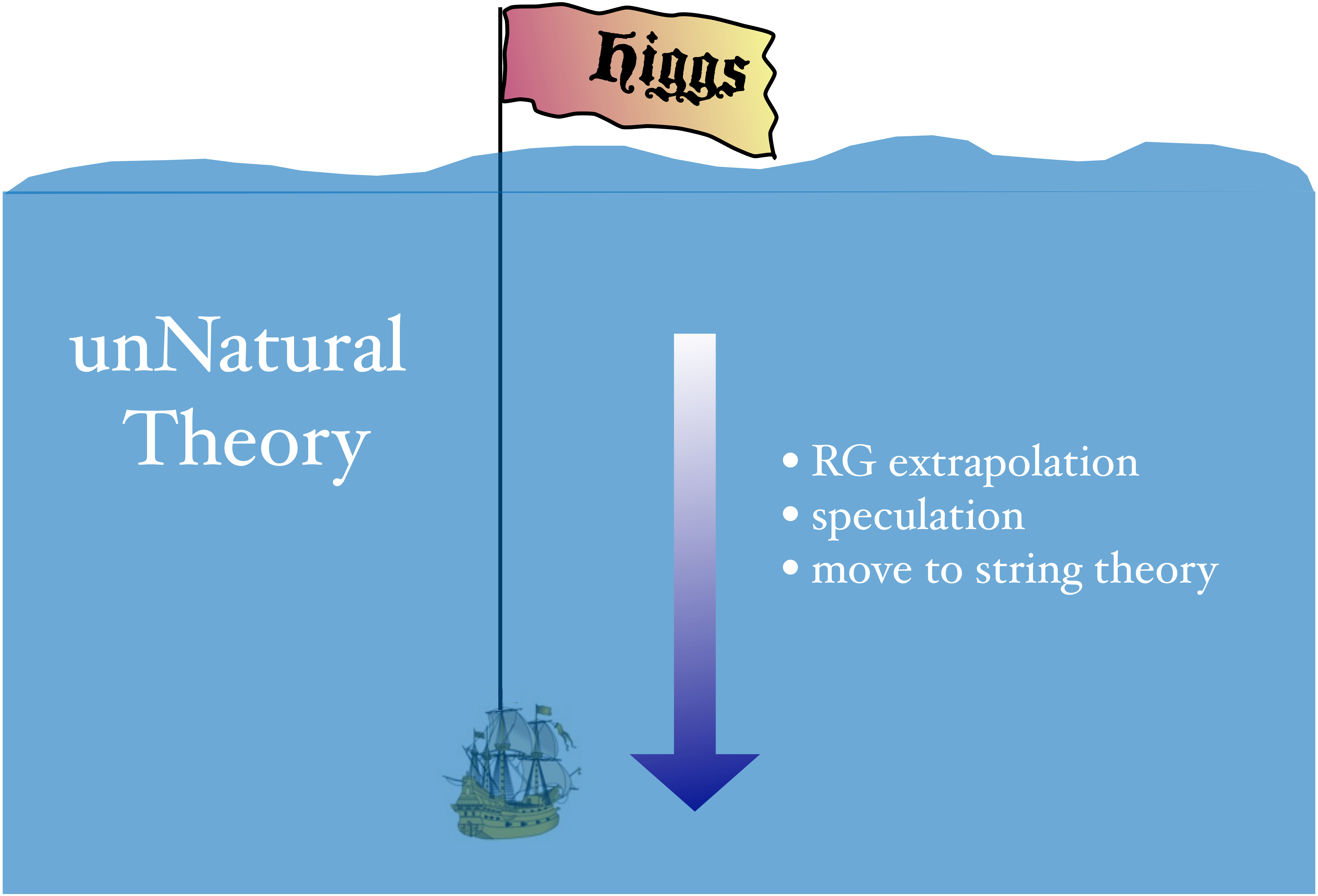
$$m_{\tilde{f}} \sim m_{3/2} \sim 10^2 \text{ TeV}$$

$$m_{\lambda_i} = \frac{\beta_i(g_i)}{2g_i^2} m_{3/2} \sim \text{ TeV}$$

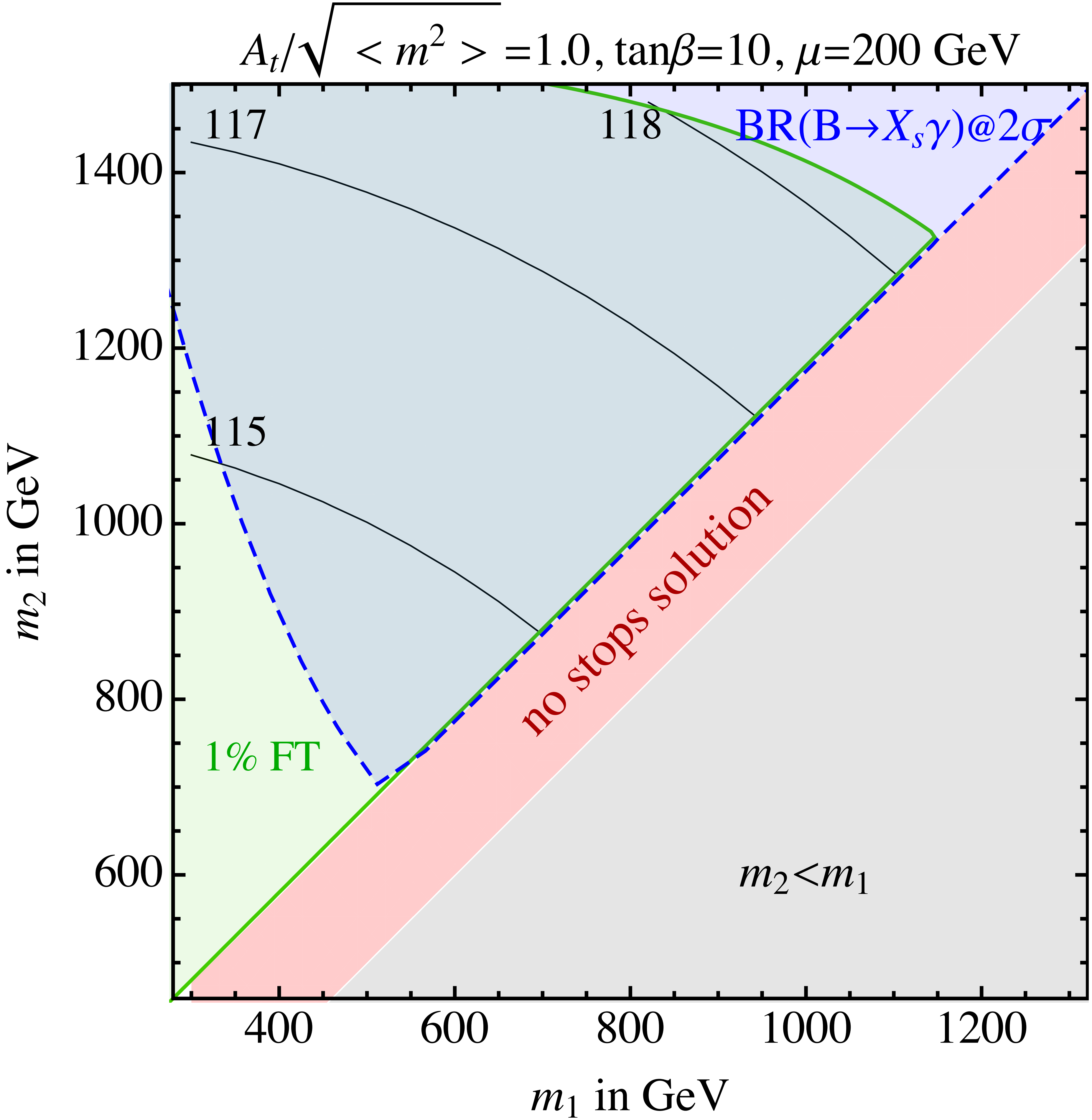

higgs


higgs
Natural
Theory

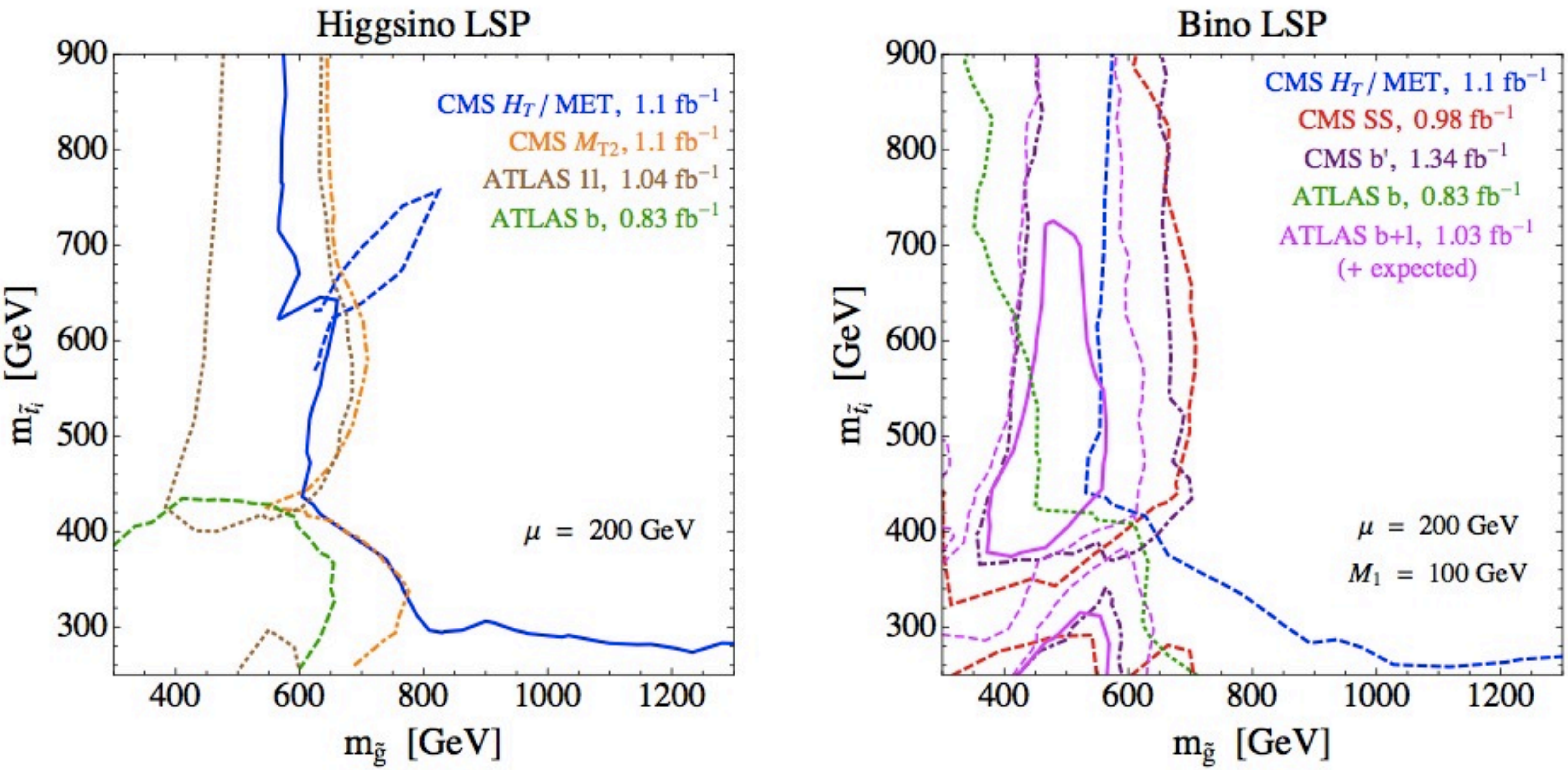

higgs
unNatural
Theory


higgs
unNatural
Theory
• RG extrapolation
• speculation
• move to string theory

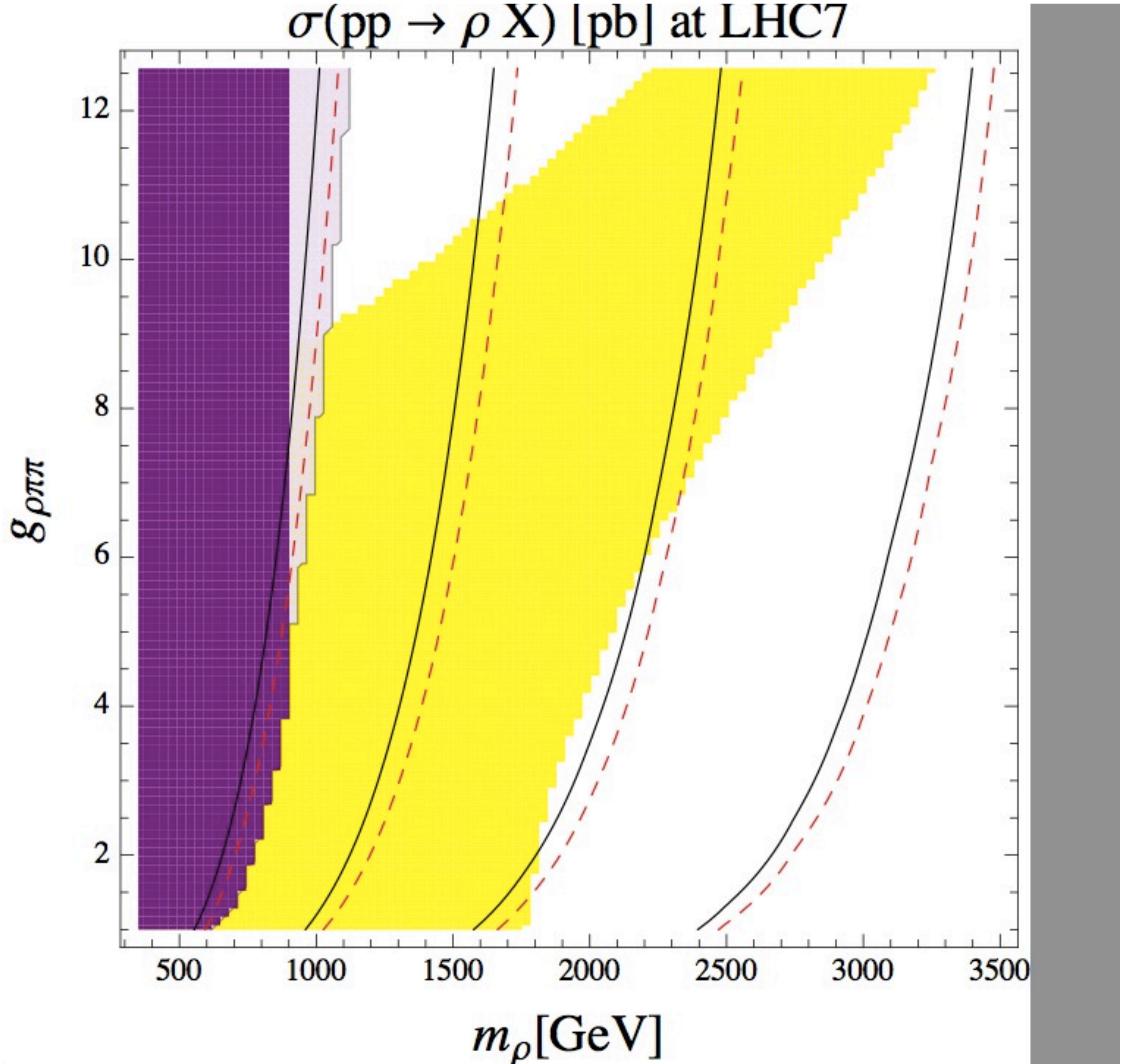
Back up slides



$A_t/\sqrt{<m^2>}$ =1.0, tanβ=10, μ=200 GeV
117
118
115
BR(B→$X_s\gamma$)@2σ
1% FT
no stops solution
$m_2<m_1$
1400
1200
1000
800
600
400
600
800
1000
1200
m_2 in GeV
m_1 in GeV



Higgsino LSP
CMS H_T / MET, 1.1 fb^{-1}
CMS M_{T2}, 1.1 fb^{-1}
ATLAS 1l, 1.04 fb^{-1}
ATLAS b, 0.83 fb^{-1}
μ = 200 GeV
Bino LSP
CMS H_T / MET, 1.1 fb^{-1}
CMS SS, 0.98 fb^{-1}
CMS b', 1.34 fb^{-1}
ATLAS b, 0.83 fb^{-1}
ATLAS b+l, 1.03 fb^{-1}
(+ expected)
μ = 200 GeV
M_1 = 100 GeV
$m_{\tilde{t}_i}$ [GeV]
$m_{\tilde{g}}$ [GeV]


σ(pp → ρ X) [pb] at LHC7
$g_{\rho\pi\pi}$
12
10
8
6
4
2
500
1000
1500
2000
2500
3000
3500
m_ρ[GeV]