

Theory evaluation of LHC data for Physics beyond the Standard Model

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After the Higgs and Nothing Else

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Effective Quantum Field Theory ideology

- ◆ gauge symmetry
- ◆ field content
- ◆ local effective lagrangian

* renormalizability

* global symmetries

needn't be fundamental
but just accidental
low energy features

The Standard Model as effective field theory

with fundamental scale $\Lambda_{UV}^2 \gg 1 \text{ TeV}$

$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F} \gamma_\mu F + Y_{ij} \bar{F}_i H F_j + \lambda (H^\dagger H)^2$$

d=4

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d=4

$$\begin{aligned} &+ \frac{b_{ij}}{\Lambda_{UV}} L_i L_j H H \\ &+ \frac{c_{ijkl}}{\Lambda_{UV}^2} \bar{F}_i F_j \bar{F}_k F_\ell + \frac{c_{ij}}{\Lambda_{UV}} \bar{F}_i \sigma_{\mu\nu} F_j G^{\mu\nu} + \dots \\ &+ \dots \end{aligned}$$

d>4

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 &+ \dots
 \end{aligned}$$

d>4

$\Lambda_{UV} \gg \text{TeV}$ (pointlike limit) nicely accounts for 'what we see'

$$+ \theta \tilde{G}_{\mu\nu} \tilde{G}^{\mu\nu}$$

d=4

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$\Lambda_{UV} \gg \text{TeV}$ (pointlike limit) nicely accounts for ‘what we see’

$$+ c\Lambda_{UV}^2 H^\dagger H$$

d=2

$$+ \theta \tilde{G}_{\mu\nu} \tilde{G}^{\mu\nu}$$

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$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F} \gamma_\mu F + Y_{ij} \bar{F}_i H F_j + \lambda(H^\dagger H)^2$$

d=4

$$+ \frac{b_{ij}}{\Lambda_{UV}} L_i L_j H H$$

$$+ \frac{c_{ijkl}}{\Lambda_{UV}^2} \bar{F}_i F_j \bar{F}_k F_\ell + \frac{c_{ij}}{\Lambda_{UV}} \bar{F}_i \sigma_{\mu\nu} F_j G^{\mu\nu} + \dots$$

$$+ \dots$$

d>4

$\Lambda_{UV} \gg \text{TeV}$ (pointlike limit) nicely accounts for ‘what we see’

the three problems

$$+ \Lambda_{UV}^4 \sqrt{g}$$

d=0

$$+ c\Lambda_{UV}^2 H^\dagger H$$

d=2

$$+ \theta \tilde{G}_{\mu\nu} \tilde{G}^{\mu\nu}$$

d=4

$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F} \gamma_\mu F + Y_{ij} \bar{F}_i H F_j + \lambda(H^\dagger H)^2$$

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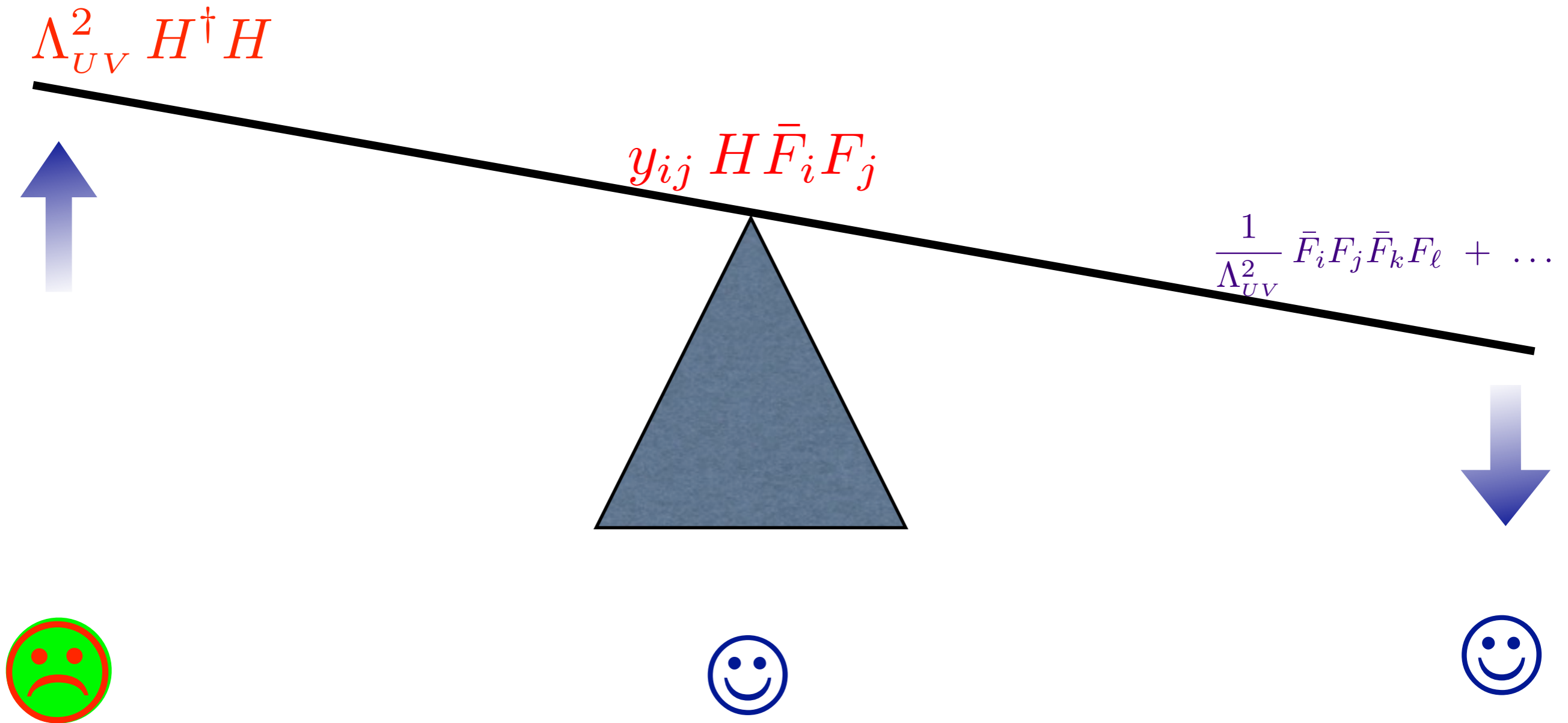
$$+ \dots$$

d>4

$\Lambda_{UV} \gg \text{TeV}$ (pointlike limit) nicely accounts for 'what we see'

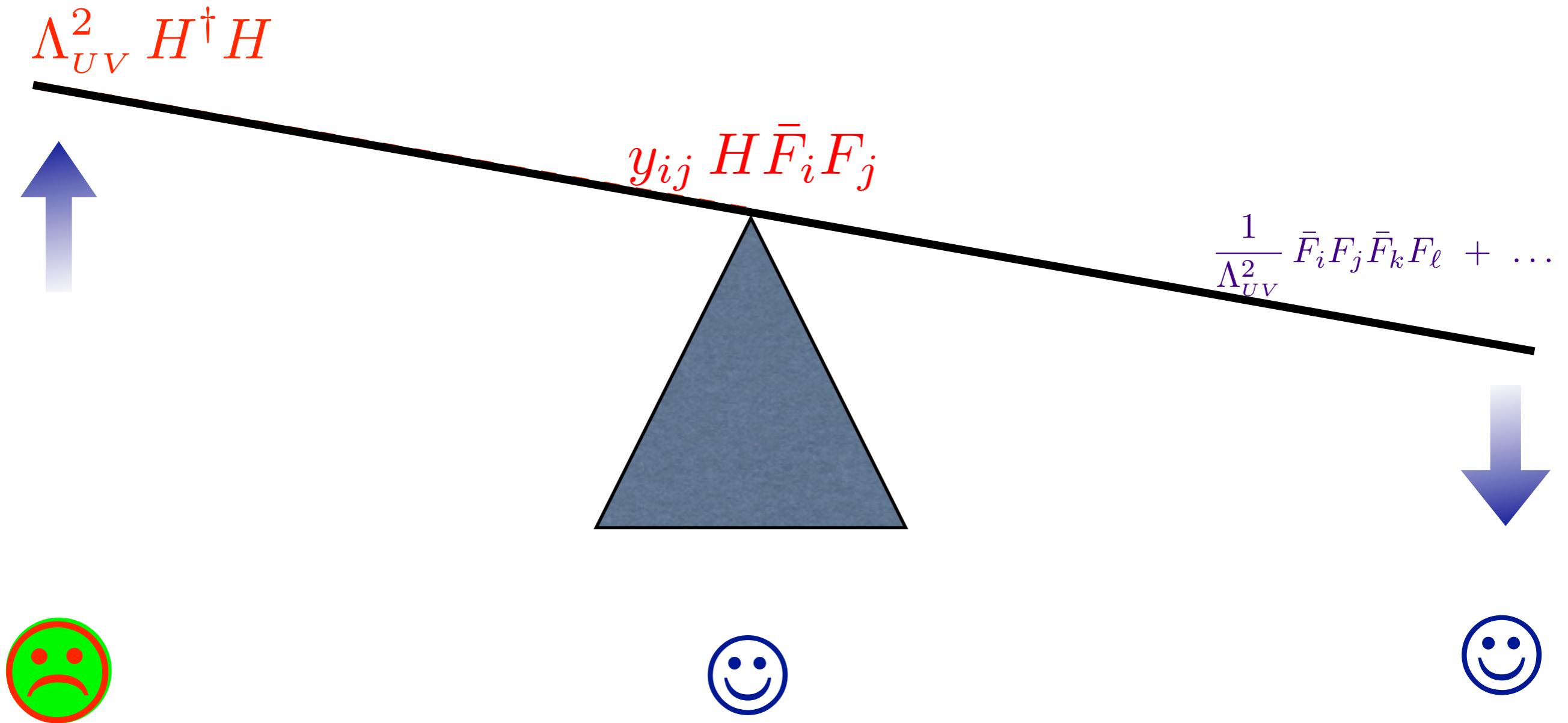
Hierarchy see-saw

Standard Model up to some $\Lambda_{UV}^2 \gg 1 \text{ TeV}$



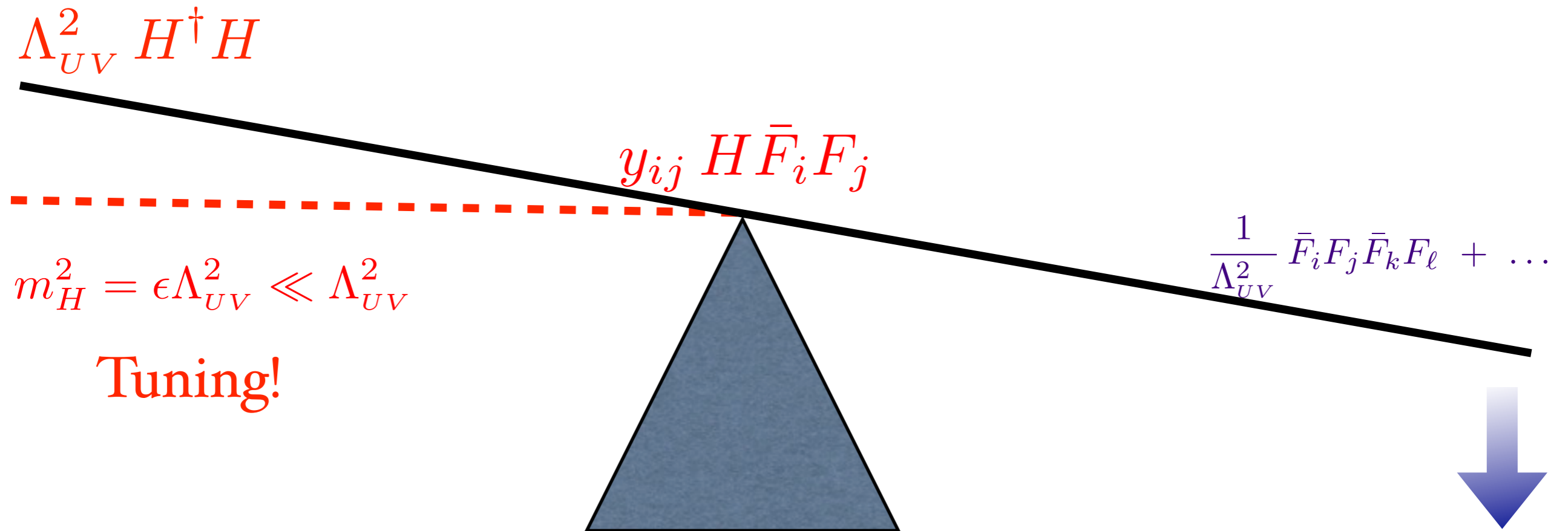
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Hierarchy see-saw

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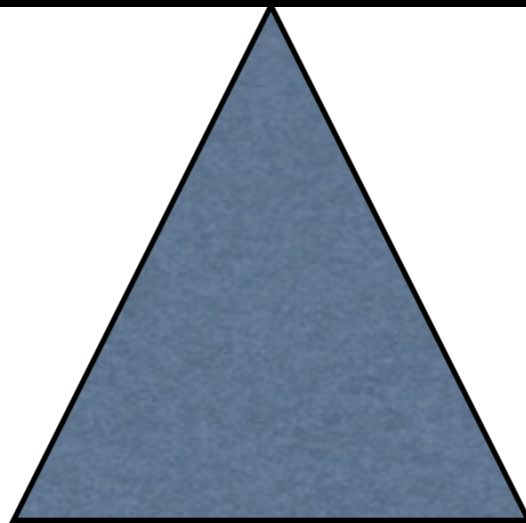
Natural SM :

$$\Lambda_{UV}^2 \lesssim 1 \text{ TeV}$$

$$\Lambda_{UV}^2 H^\dagger H$$

$$y_{ij} H \bar{F}_i F_j$$

$$\frac{1}{\Lambda_{UV}^2} \bar{F}_i F_j \bar{F}_k F_\ell + \dots$$



The two possible microphysics scenarios

I. The SM is the correct description up to $\Lambda_{UV} \gg TeV$

- B, L and Flavor: beautifully in accord with observation
- Hierarchy remains a mystery, probably hinting that the question was not correctly posed
 - anthropic principle
 - failure of effective field theory ideology (UV/IR connection)

II. The SM is not the correct description already at $\Lambda_{UV} \sim 1 TeV$

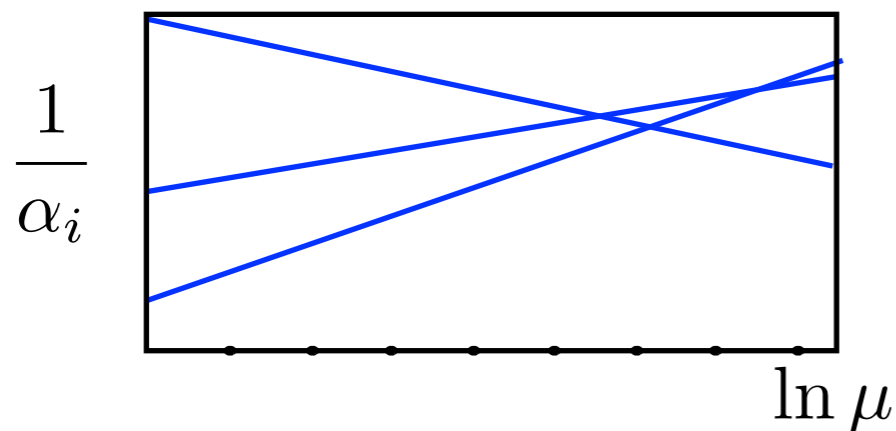
- In the correct theory the hierarchy problem does not even arise (naturalness)
- What about B, L and Flavor? In all models not nearly as nice as in SM

A high scale scenario

- $\mathcal{L}^{d=4}$ experimental success (some 2-3- σ glitches here and there)

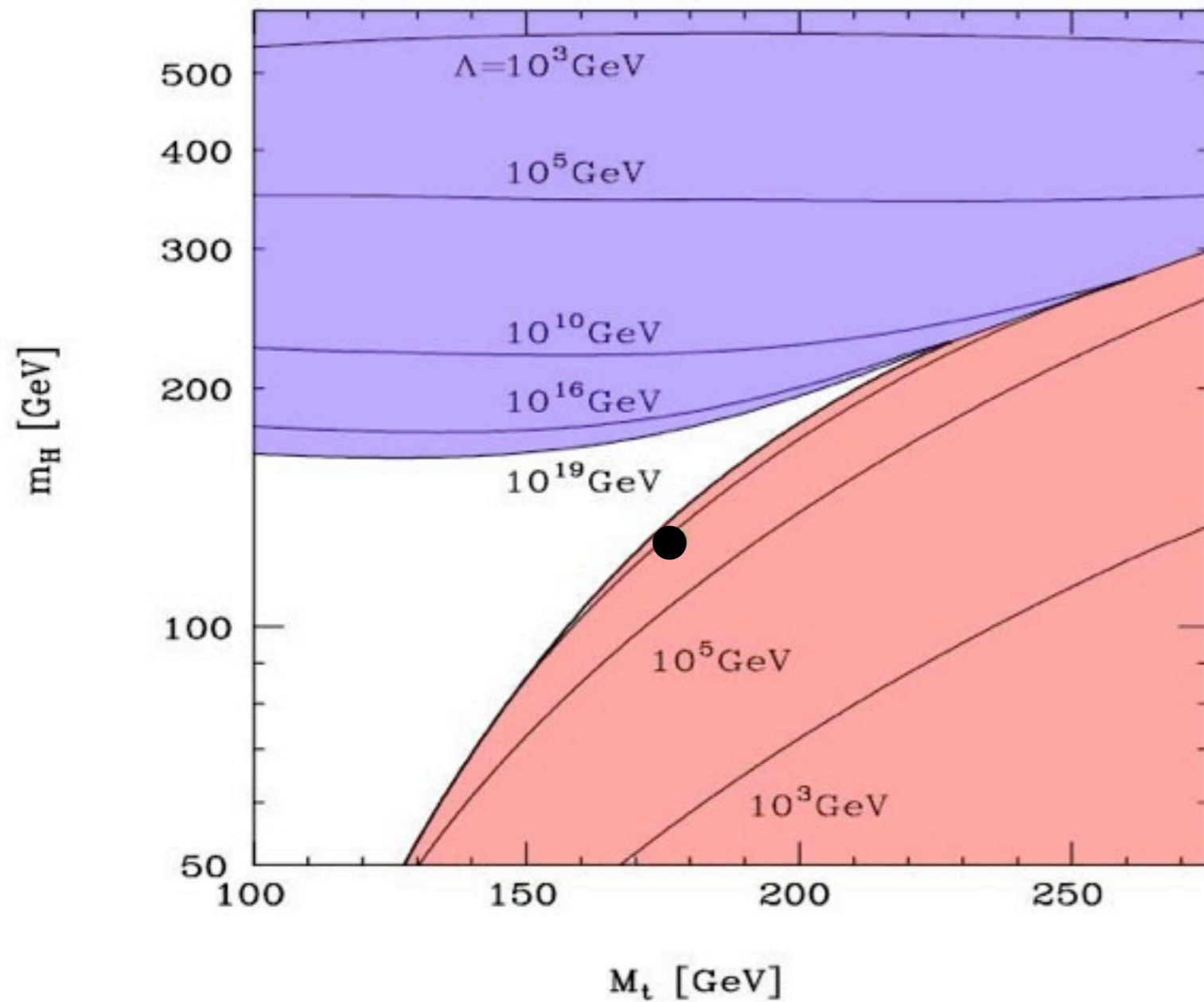
- Θ -QCD and Dark Matter \rightarrow high scale axion $f_a \sim 10^{12}$ GeV

- gauge couplings ready to unify around $10^{15} \lesssim M \lesssim M_{Planck}$

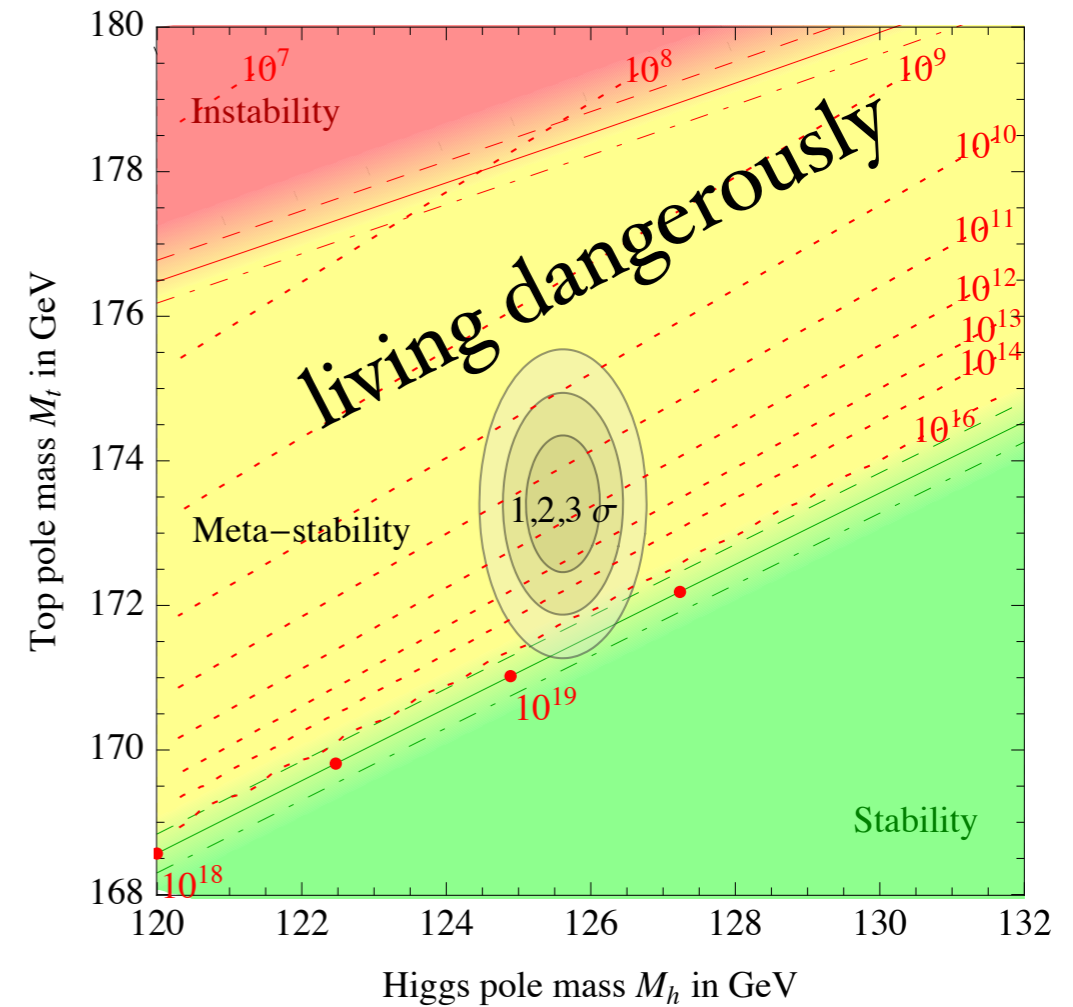


- neutrino masses $\frac{\ell\ell HH}{\Lambda} \rightarrow m_\nu \sim \frac{v^2}{\Lambda}$ $\Lambda \sim 10^{14}$ GeV

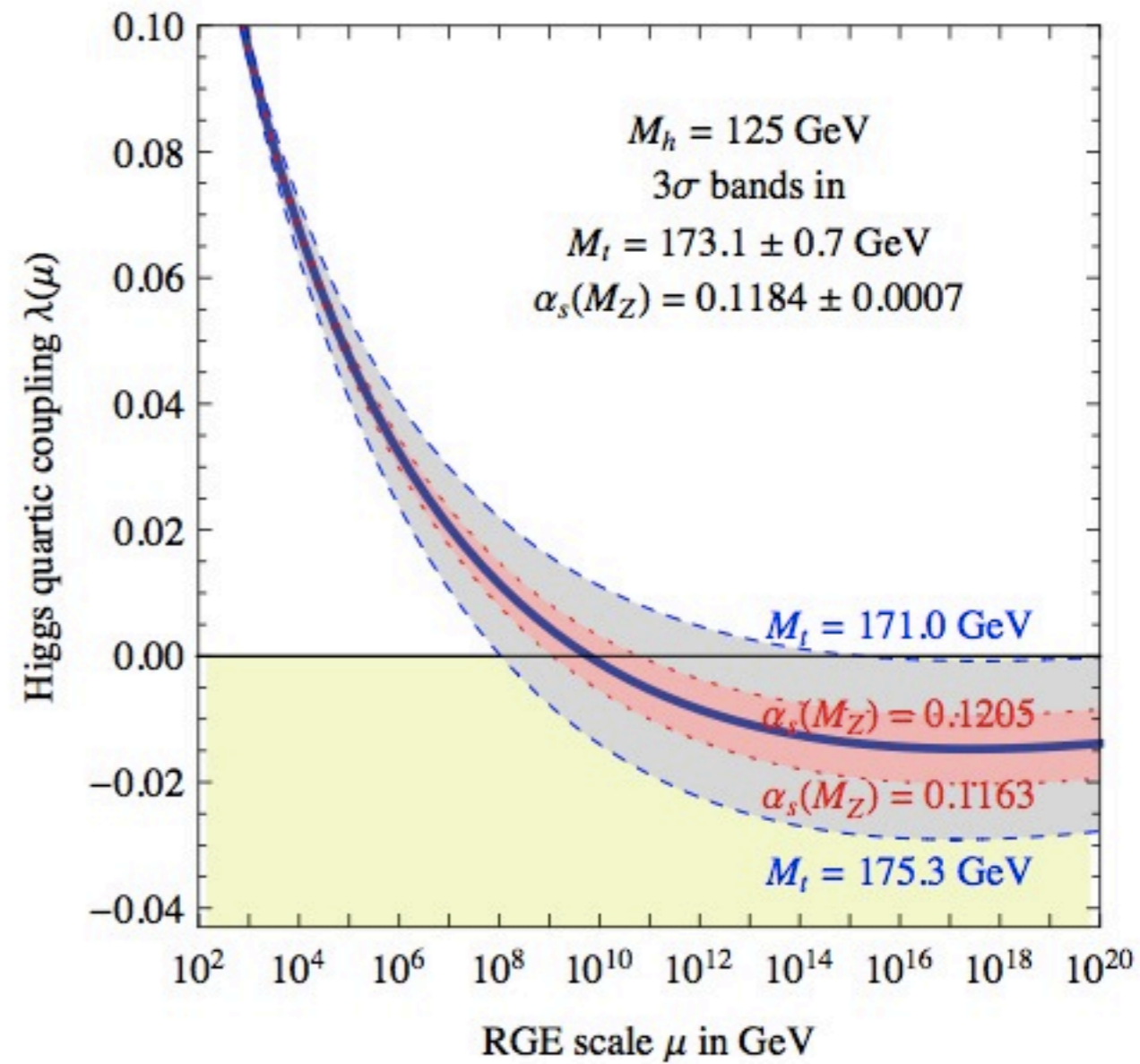
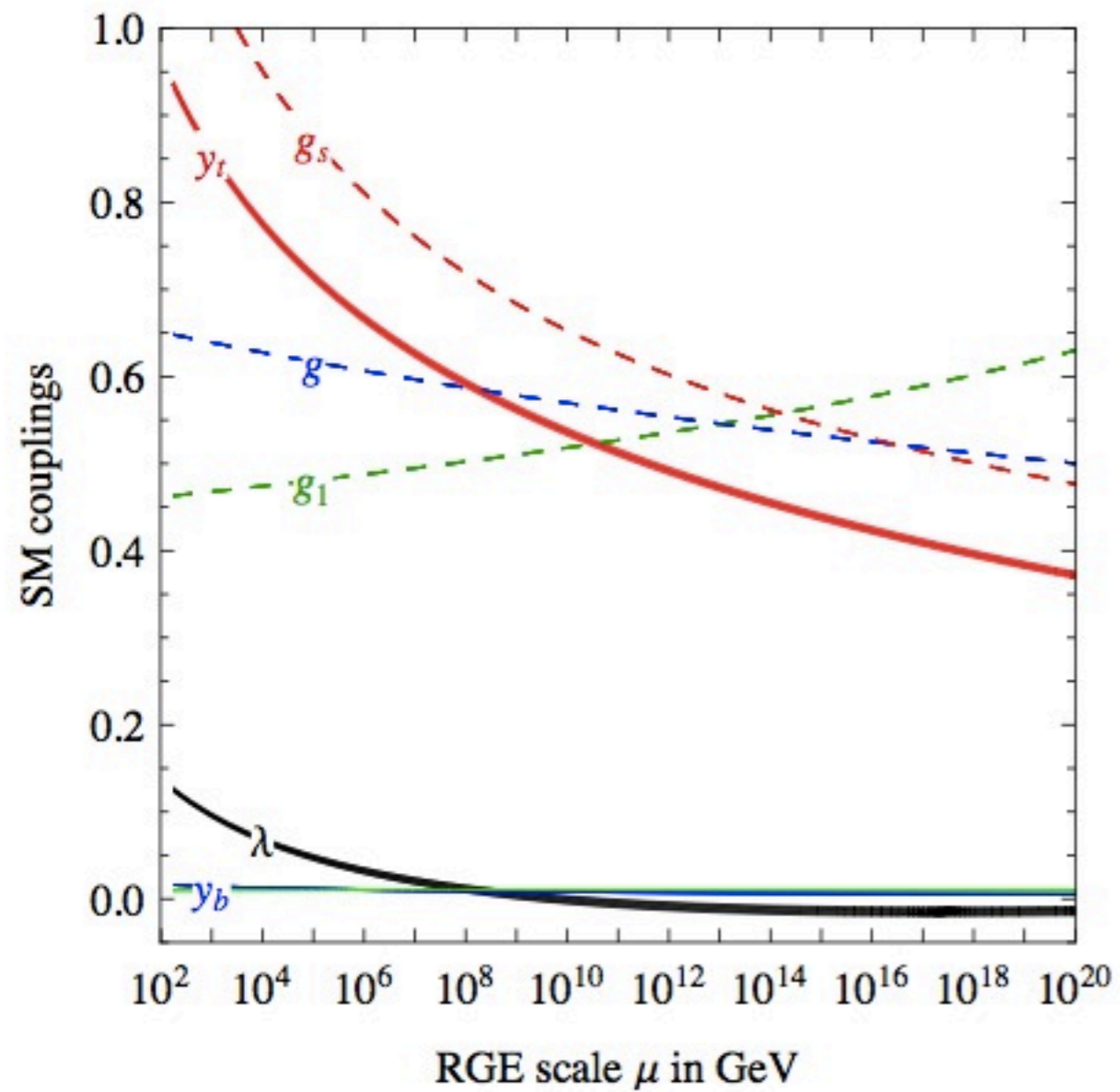
- RG-evolution of SM couplings, including λ_h remarkably do not require lower scales

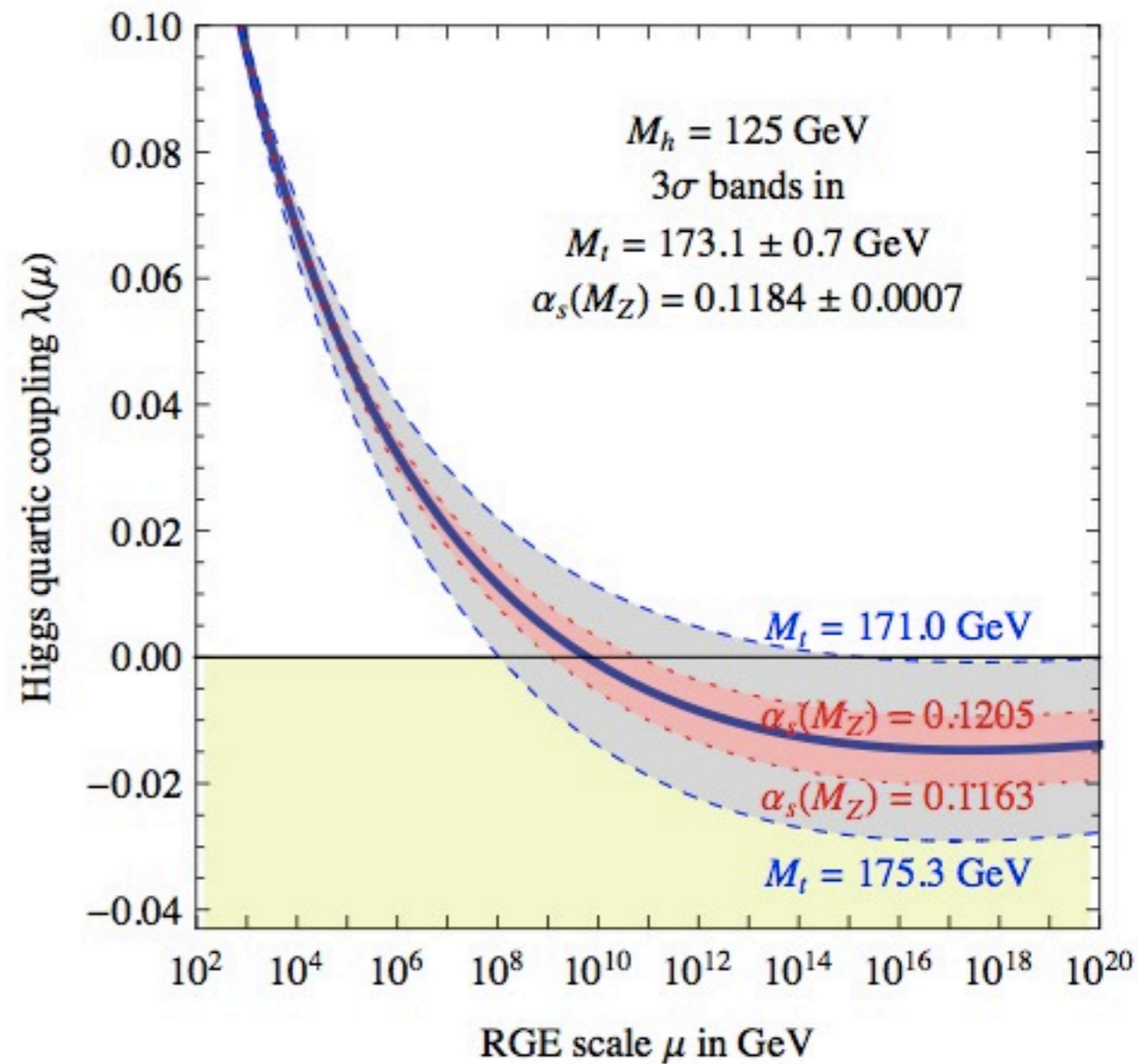
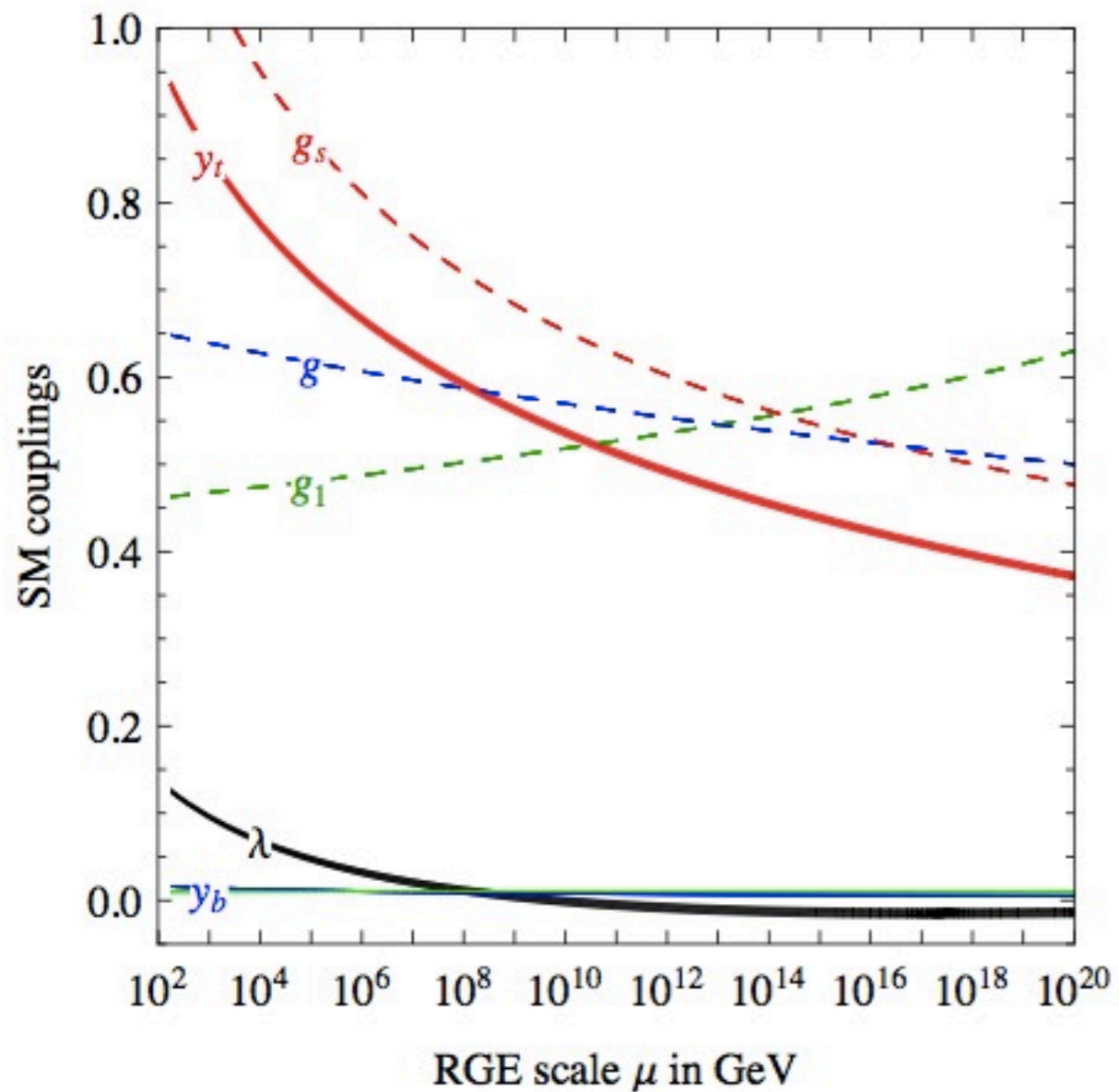


Elias-Miro, Espinosa, Giudice,
Isidori, Riotto, Strumia '11

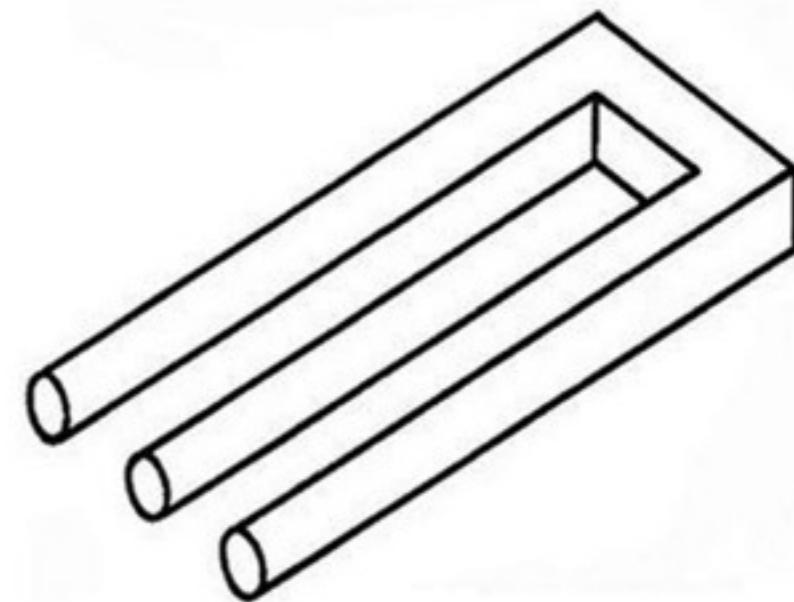


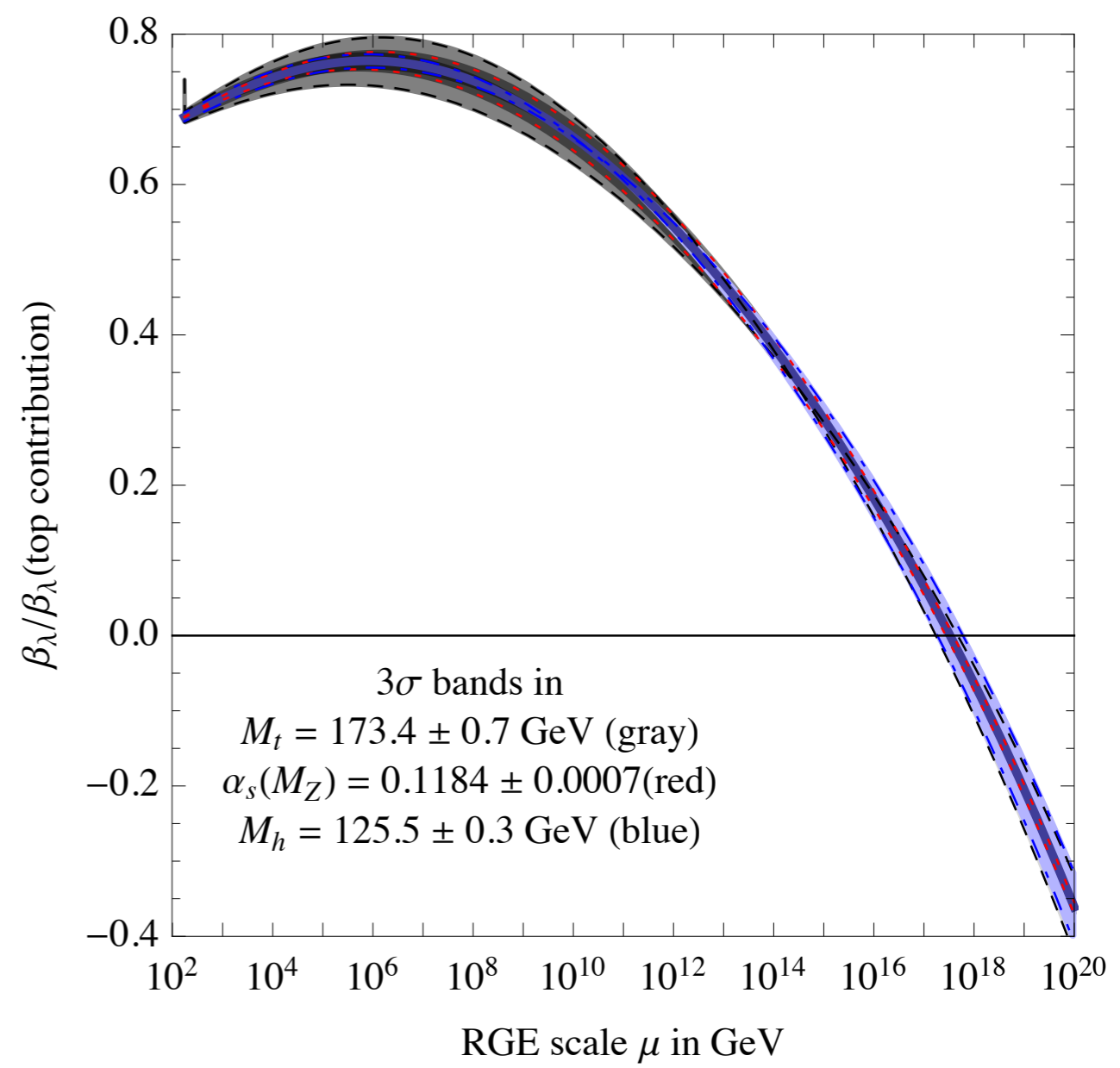
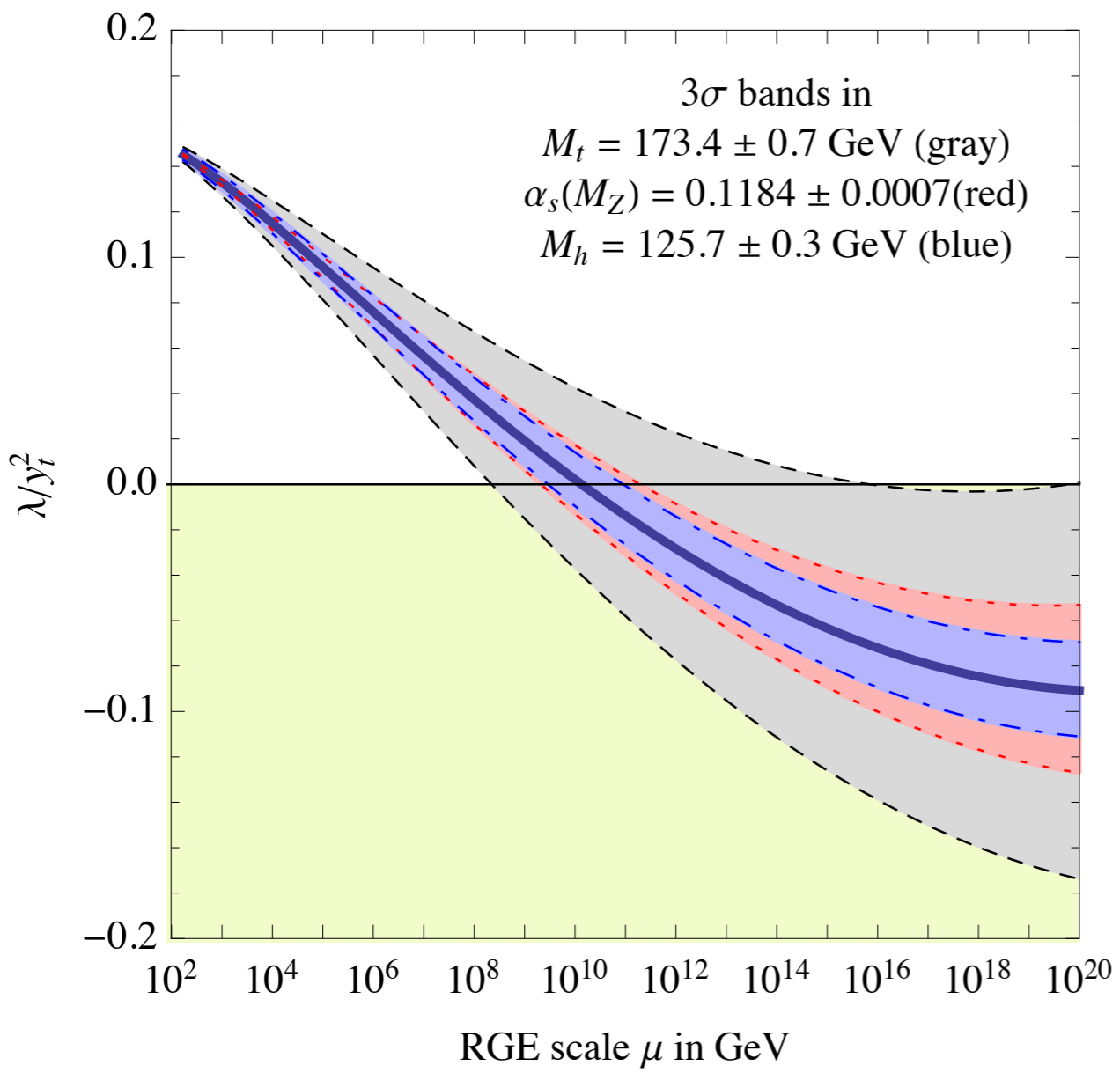
the fact that the SM lives dangerously perhaps points to
an anthropic selection of parameters
though it is hard to tell





but watch your eyes





Strumia's courtesy

The two natural scenarios for electroweak symmetry breaking

Elementary Higgs exists
but a symmetry
protects its mass



Supersymmetric Models

No elementary Higgs
exists



Technicolor,
Composite Light Higgs
(and its holograms)

Large Extra Dimensions: exciting, fantastic, great, but not very plausible without extra mass scale separation

Plus a list of not even wrong scenarios...

Flavor ?

Supersymmetry: the existence of scalar matter fields introduces a myriad of $\mathbf{d} \leq 4$ terms violating F, B and L

$$\mathcal{L}^{d \leq 4} = m_{ij}^2 \tilde{Q}_i^\dagger \tilde{Q}_j + A_{ij} Y_{ij}^D \tilde{Q}_i \tilde{D}_j H_d + \lambda_{ijk} \tilde{U}_i D_j D_k + \dots$$

Naive Composite Higgs (TC) : the Yukawa themselves are $\mathbf{d} > 4$

$$Y_{ij} H \bar{Q}_L^i Q_R^j \rightarrow Y_{ij} \frac{1}{\Lambda_F^2} (\bar{\Psi} \Psi) Q_L^i Q_R^j \quad m_{ij} = Y_{ij} \frac{v_F^3}{\Lambda_F^2}$$

Λ_F must be not too far above weak scale: expect unwanted FCNC

In all natural models, extra assumptions (often clever) are needed to meet flavor physics constraints

Approaches

Symmetry

pick a subgroup of $U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$
pick a set of spurions to break it
construct a lagrangian using the selection rules

Dynamics

mass mixing hierarchy from radiative corrections
flavor from geography in extra-dim
flavor from partial compositeness



holography

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Dynamics

unfortunately disfavored in natural theories

mass mixing hierarchy from radiative corrections
flavor from geography in extra-dim
flavor from partial compositeness

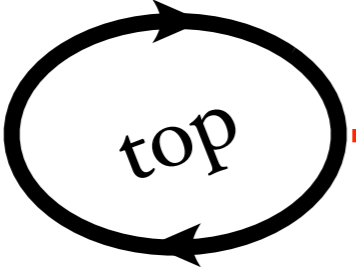


holography

What naturalness demands

▲ **supersoft models:** Higgs mass parameter fully saturated by IR physics

- dirac gauginos in supersymmetry
- general composite Higgs

$$\delta m_H^2 = \text{---} \text{---} \text{---} \text{---} \sim \frac{3\lambda_t^2}{8\pi^2} M^2 \xrightarrow{m_h = 125 \text{ GeV}} \text{tuning} \left(\frac{400 \text{ GeV}}{M} \right)^2$$


▲ **soft models:** Higgs mass logarithmically sensitive to UV

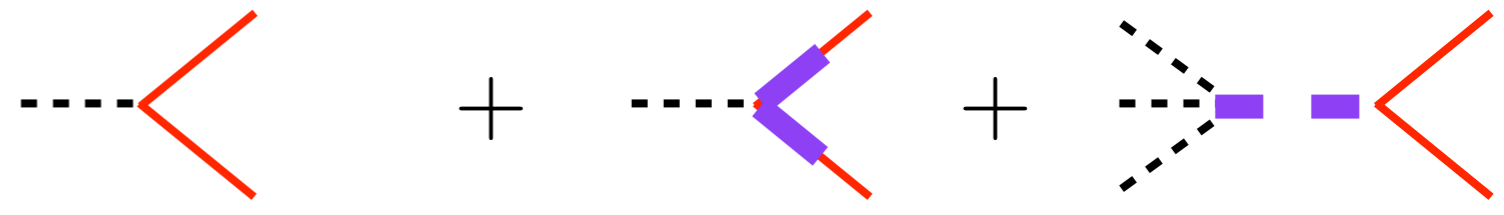
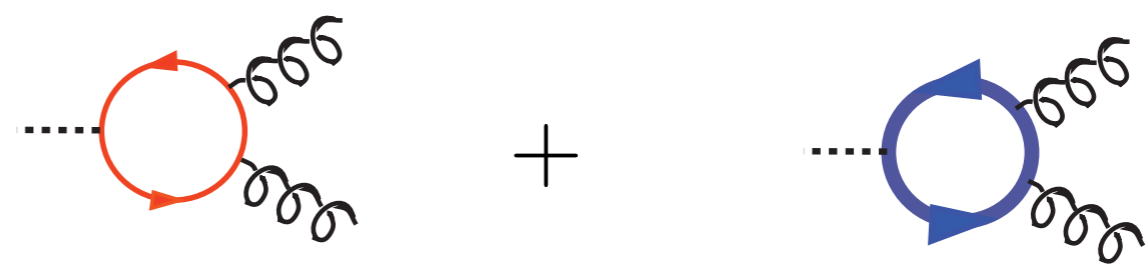
- MSSM and its extensions with high scale mediation

$$m_h^2 \sim m_Z^2 \sim m_{\tilde{t}}^2 \xrightarrow{m_h = 125 \text{ GeV}} \text{tuning} \left(\frac{125 \text{ GeV}}{\tilde{m}} \right)^2$$

Mass

$$\delta m_H^2 = \text{---} \circlearrowleft \text{SM} \text{---} + \text{---} \circlearrowleft \text{New} \text{---} \sim 0$$

SM + Higgs



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

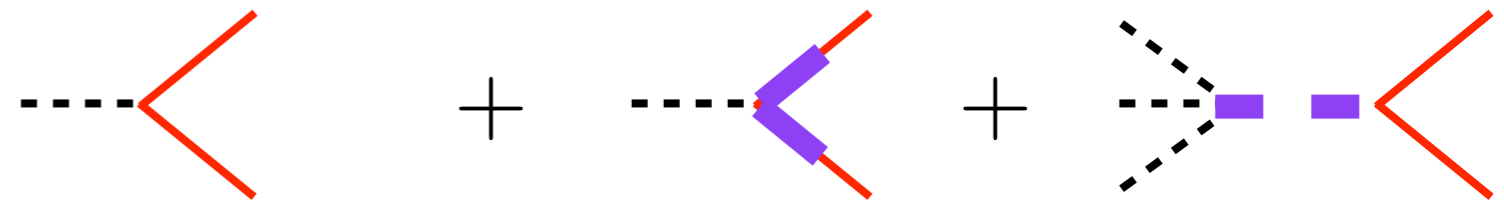
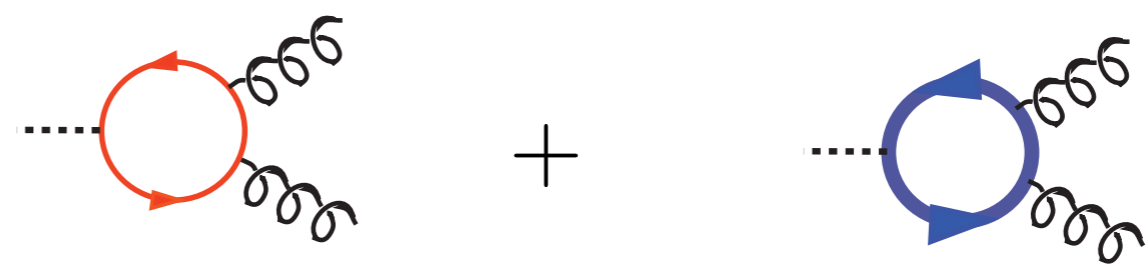
Mass

$$\delta m_H^2$$



new states

SM + Higgs



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Supersymmetry

- higgs couplings
- EWPT ($\epsilon_1, \epsilon_2, \epsilon_3$)
- $b \rightarrow s\gamma$
- ...

$$\frac{\delta\mathcal{O}}{\mathcal{O}_{SM}} \sim \frac{m_{weak}^2}{\tilde{m}^2}$$

$\xrightarrow{\text{soft}} O(1)$

$\xrightarrow{\text{super-soft}} O(\alpha_t/4\pi)$

Compositeness

$$\frac{\delta\mathcal{O}}{\mathcal{O}_{SM}} \sim \frac{v^2}{f^2}$$

$\xrightarrow{\text{minimal}} O(1)$

$\xrightarrow{\text{Little Higgs with T-parity}} O(\alpha_t/4\pi)$

- EWPT ($\epsilon_1, \epsilon_2, \epsilon_3$)
- $b \rightarrow s\gamma$
- direct searches (susy)

imply $\frac{\delta\mathcal{O}}{\mathcal{O}_{SM}} < 1$ (10%)

in most cases, O(1) deviations in Higgs rates were already disfavored

Perspective on Supersymmetry before and after LHC 7/8

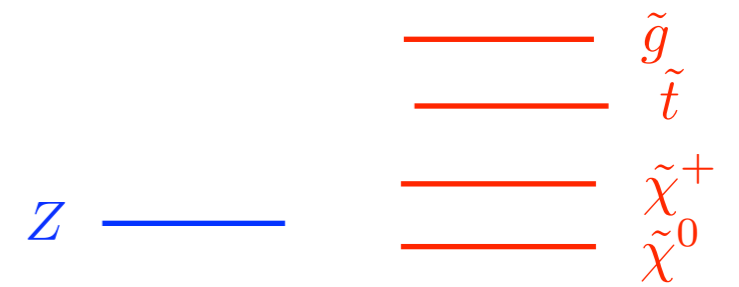
once upon a time, expectation in the less clever models was



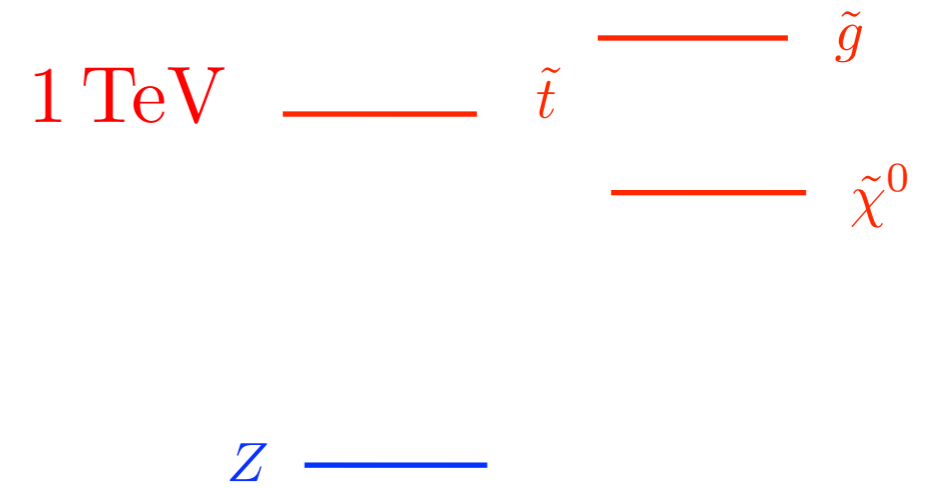
LEP/Tevatron

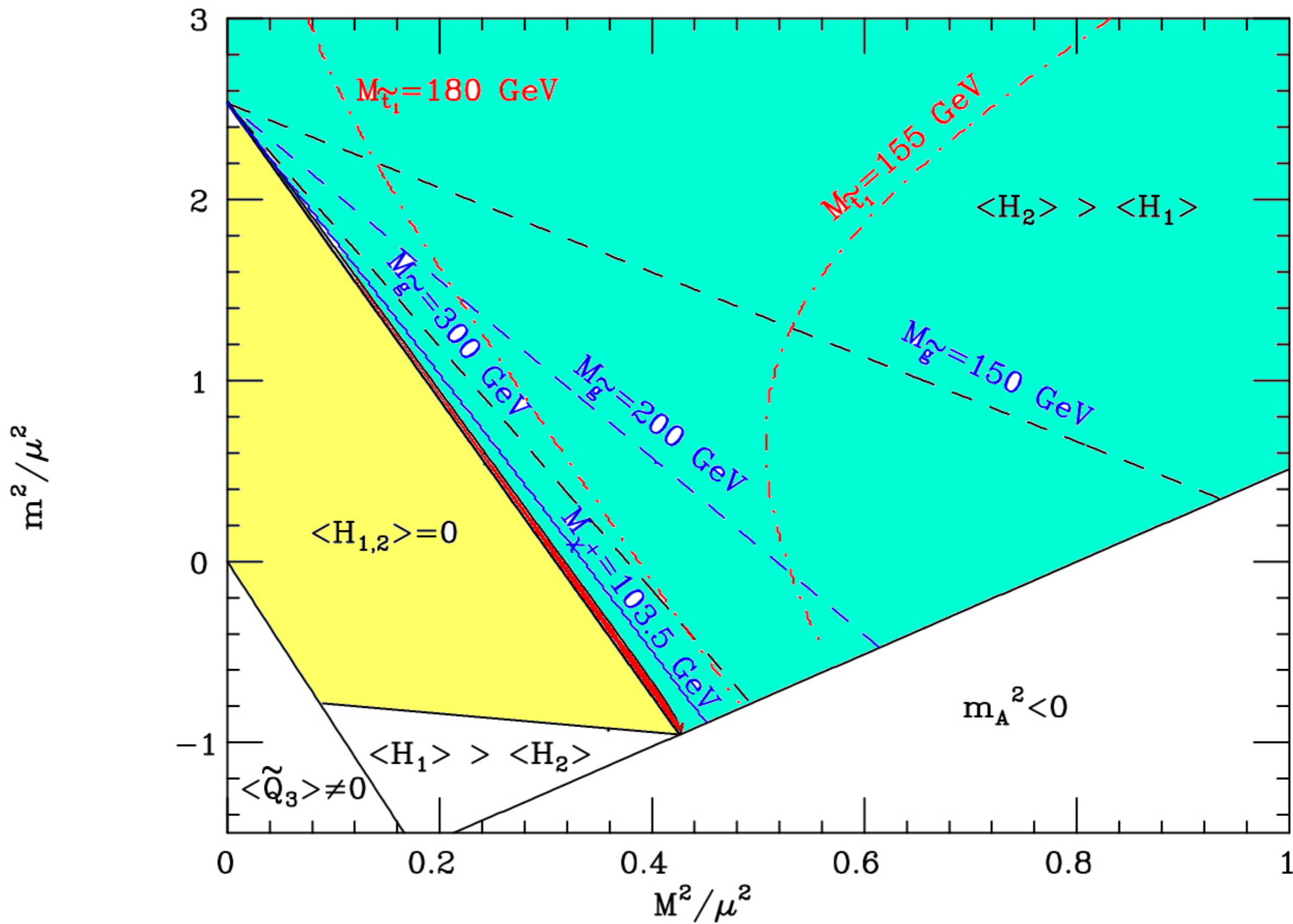
$$m_{\tilde{l}}, m_{\chi^+} \gtrsim 100 \text{ GeV}$$

$$m_{\tilde{q}}, m_{\tilde{g}} \gtrsim 300 \text{ GeV}$$



$$m_h > 114.4 \text{ GeV}$$





LEP/Tevatron

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Z ———

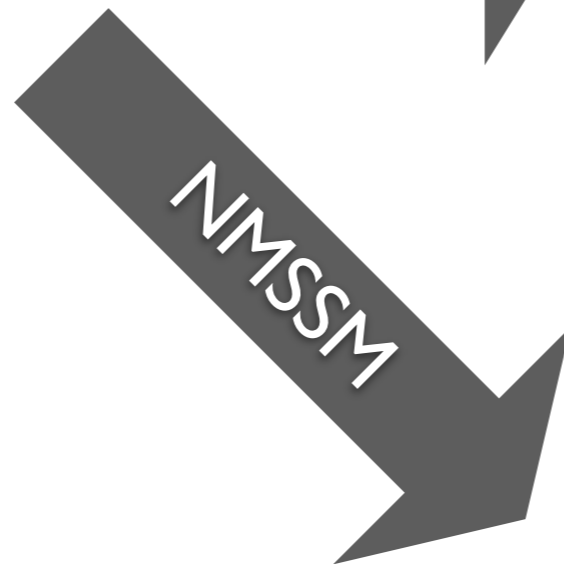
———— \tilde{g}
———— \tilde{t}
———— $\tilde{\chi}^+$
———— $\tilde{\chi}^0$

$$m_h > 114.4 \text{ GeV}$$



1 TeV ——— \tilde{t}

Z ———



1 TeV

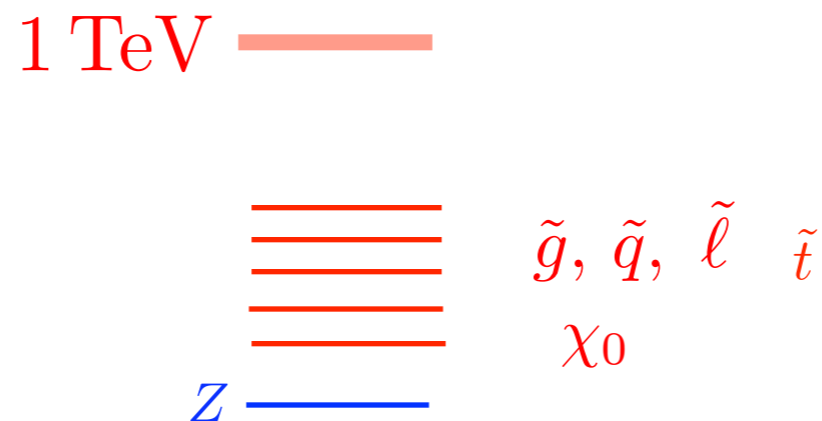
==== $\tilde{g}, \tilde{q}, \tilde{l}$
—— \tilde{t}

Z ———

Before LHC: *natural* and *simple* spectrum possible within NMSSM


After LHC

- situation only slightly worse with $m_h \simeq 125 \text{ GeV}$ [Hall, Pinner, Ruderman '11](#)
- GUT perturbativity borderline, but needn't worry too much
[see Barbieri et al 2013](#)
- direct searches have however eliminated the natural region of the most straightforward NMSSM scenario (in particular flavor universal sfermion masses)



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1 TeV  $\tilde{g}, \tilde{q}, \tilde{\ell}, \tilde{t}$
 χ_0

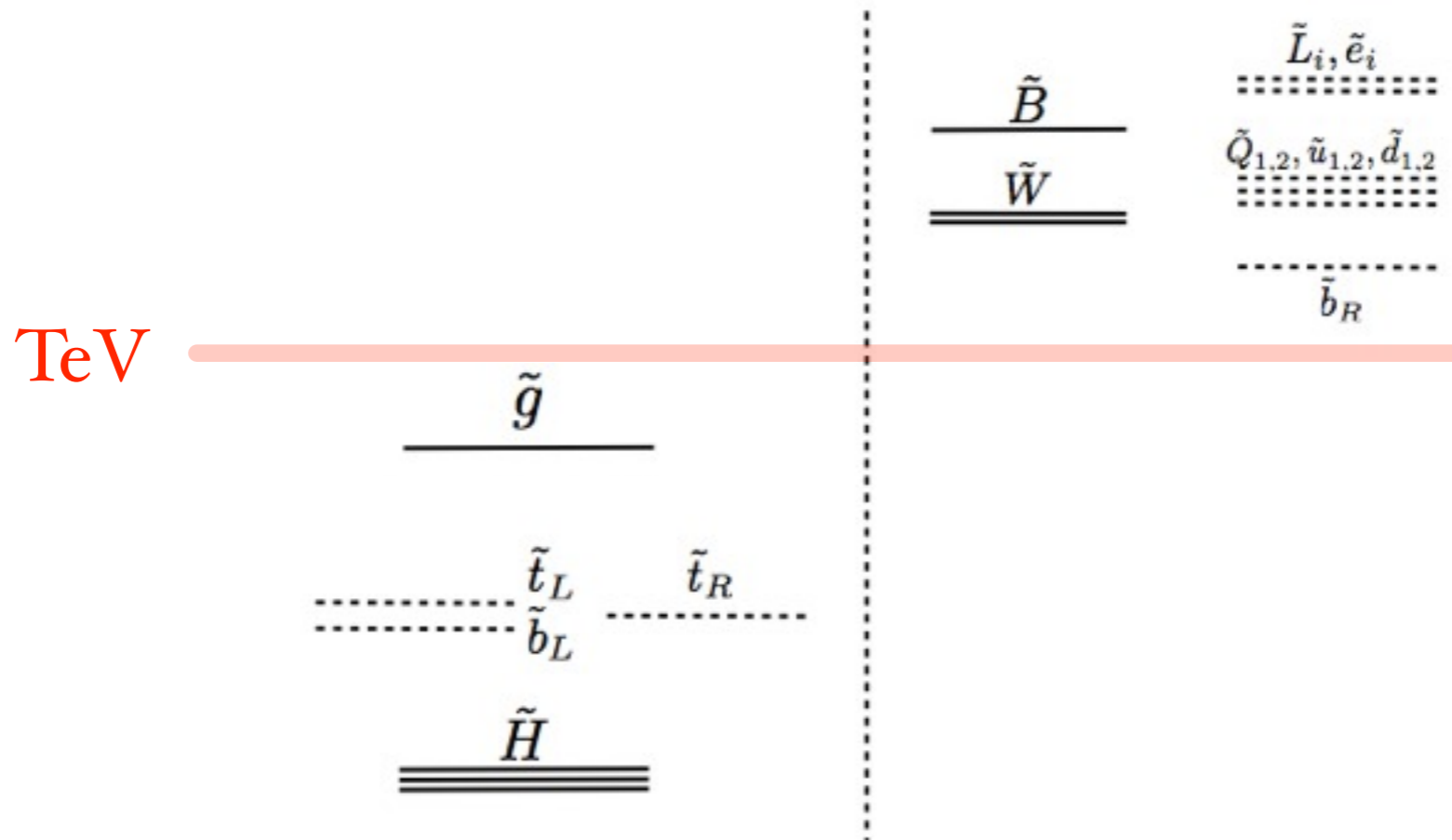
Z 

MSSM: simplest scenarios were under pressure already before LHC

NMSSM: simplest scenarios came under pressure with LHC

What about more 'structured' models, those that stick to naturalness like a mussel to her reef?

not-so-un-Natural SUSY

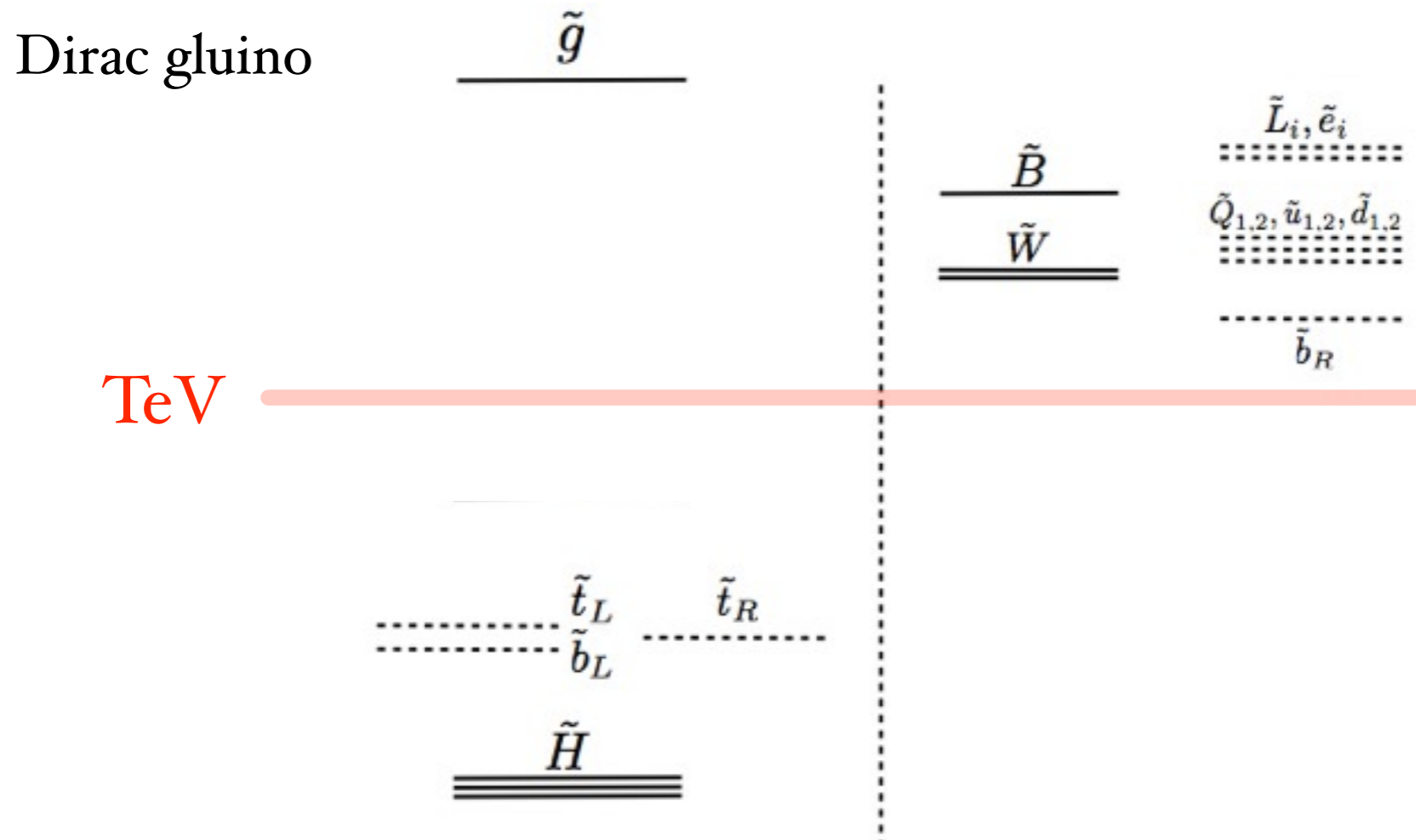


$m_{\tilde{t}} \lesssim 500 \text{ GeV}$ some other physics (ex NMSSM) takes care of m_h

consider all possible ways to suppress the signal:

Dirac gluino, RPV, compressed spectrum,...

not-so-un-Natural SUSY

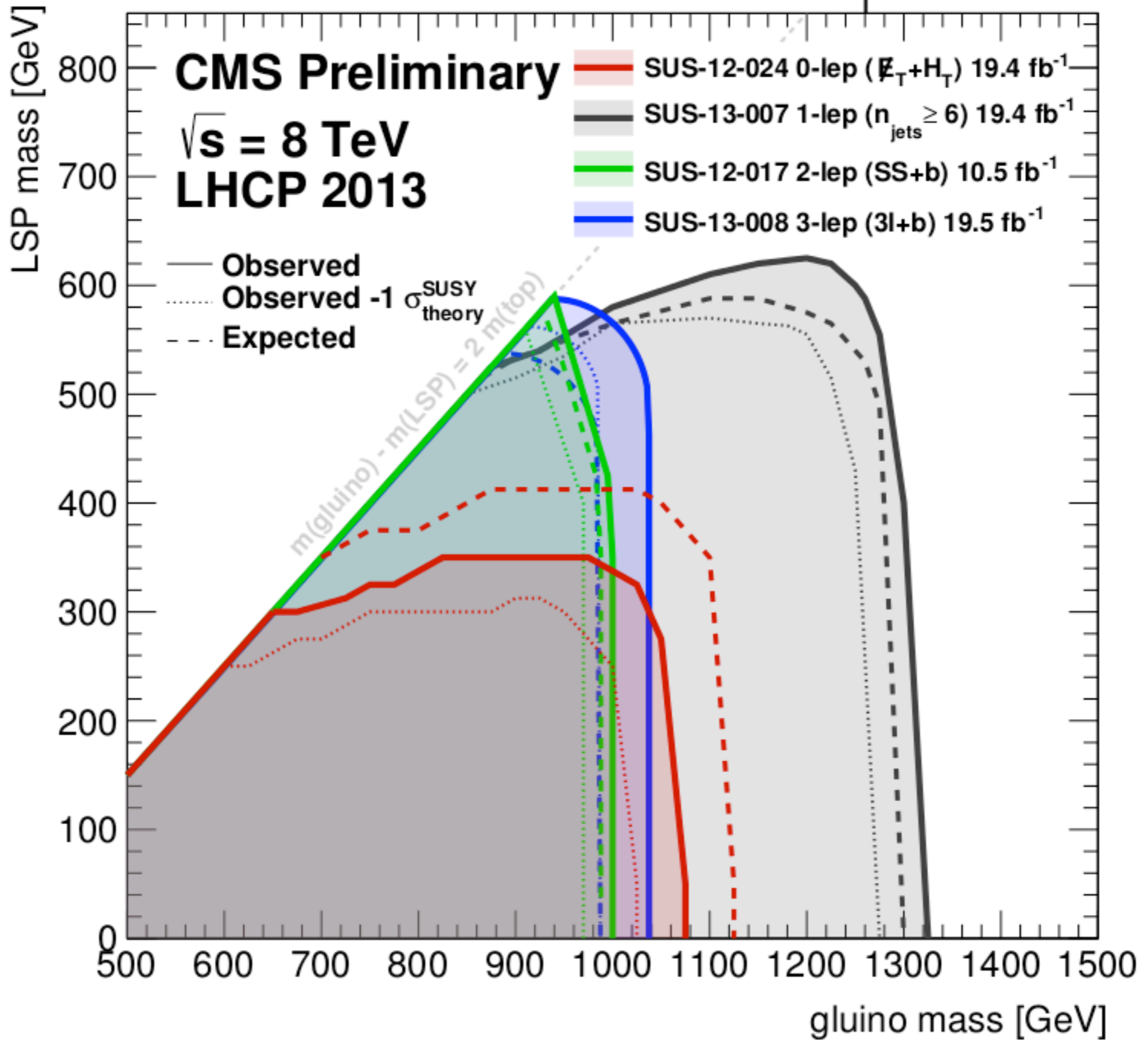


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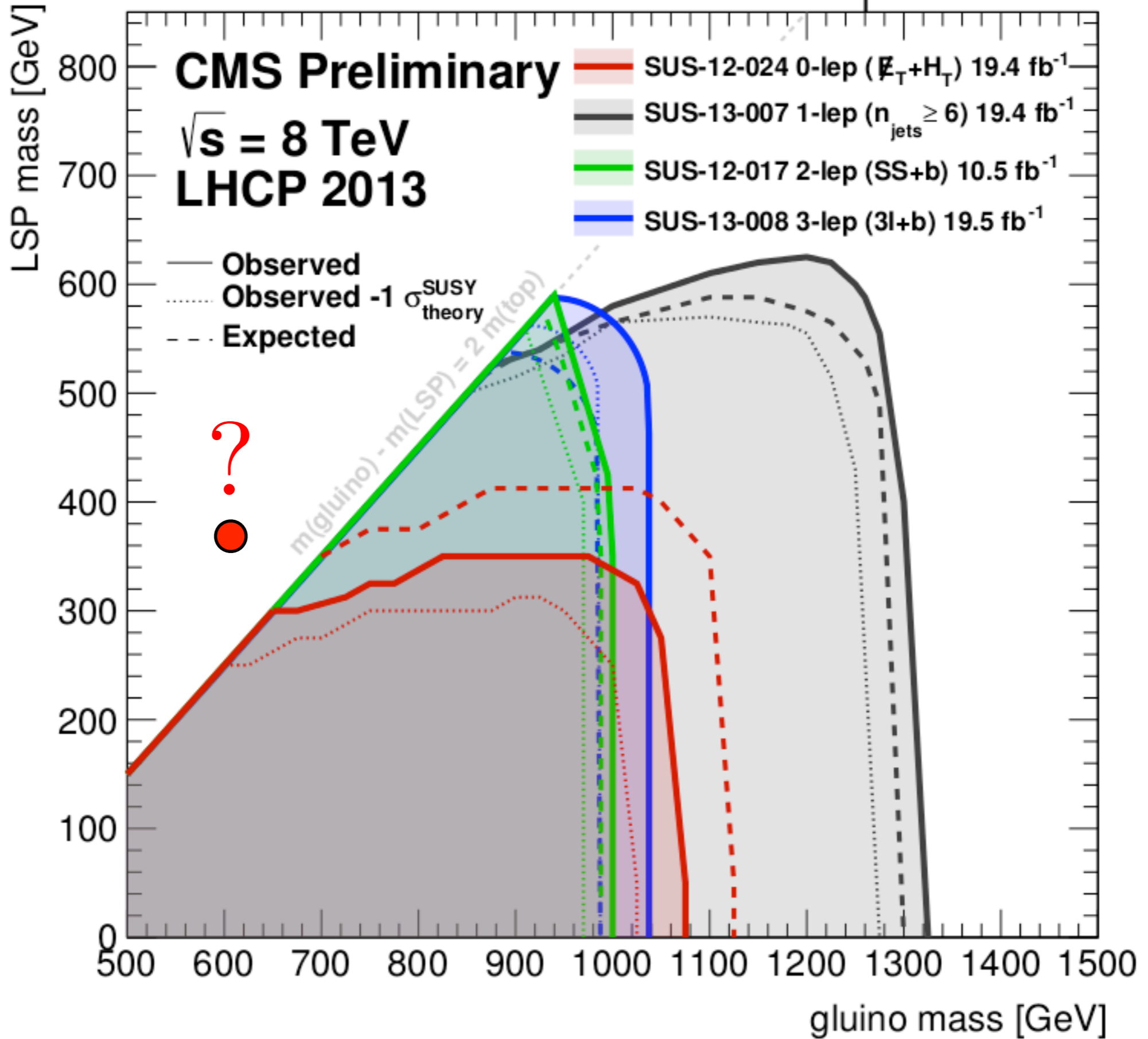
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$\tilde{g}\text{-}\tilde{g}$ production, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$

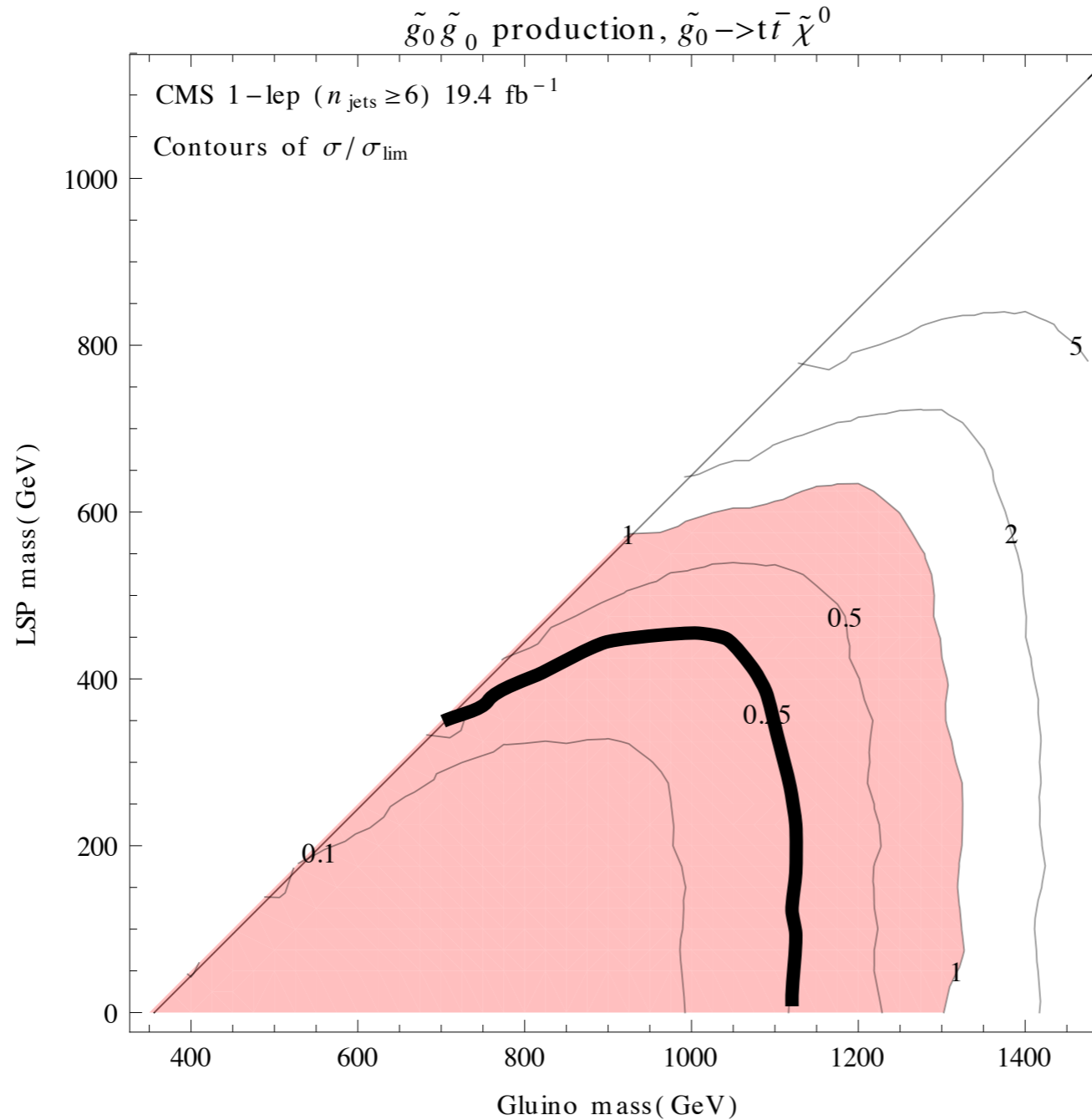


$\tilde{g}\text{-}\tilde{g}$ production, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$



notice $\text{Br}(4t) < 0.25$ in relevant scenario:
15-20% reduction of bound

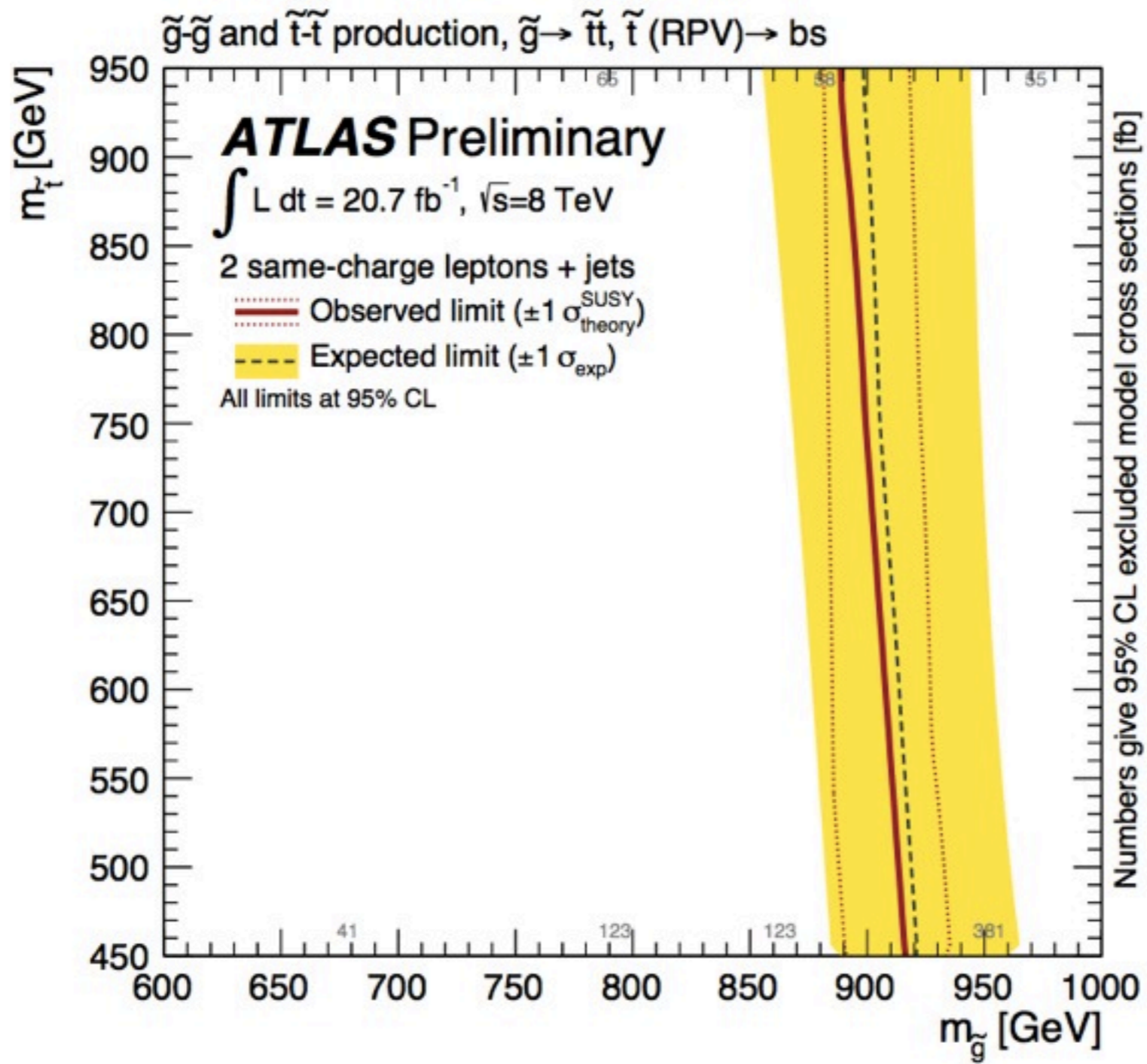
Barbieri, Pappadopulo '09



Mahbubani '13

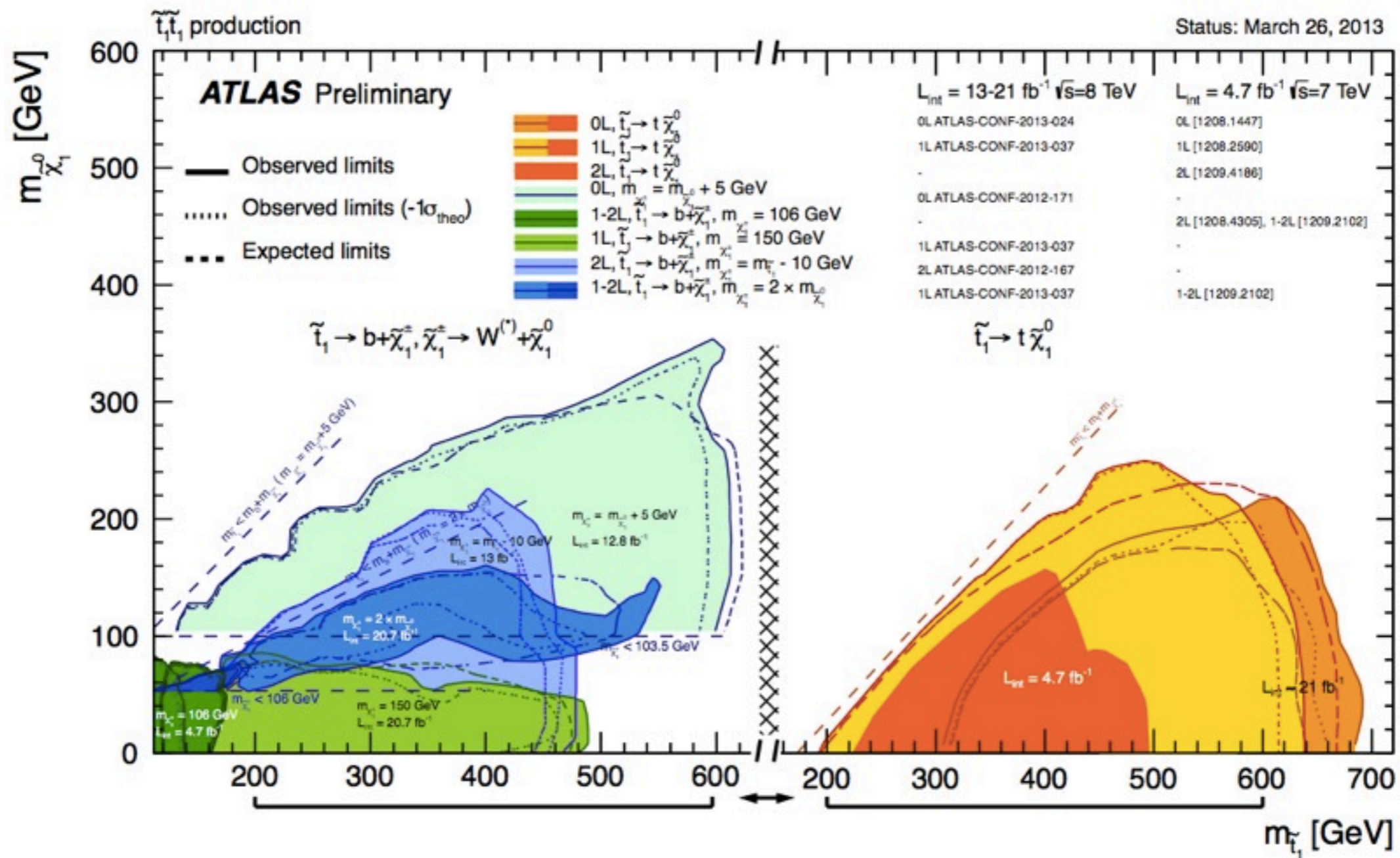
however the other channels ($t\bar{t}b\bar{b}$, $t\bar{t}b\bar{b}$) add to same signal
expect compensation, in the end bound should not change much

what about some help from baryonic RPV?



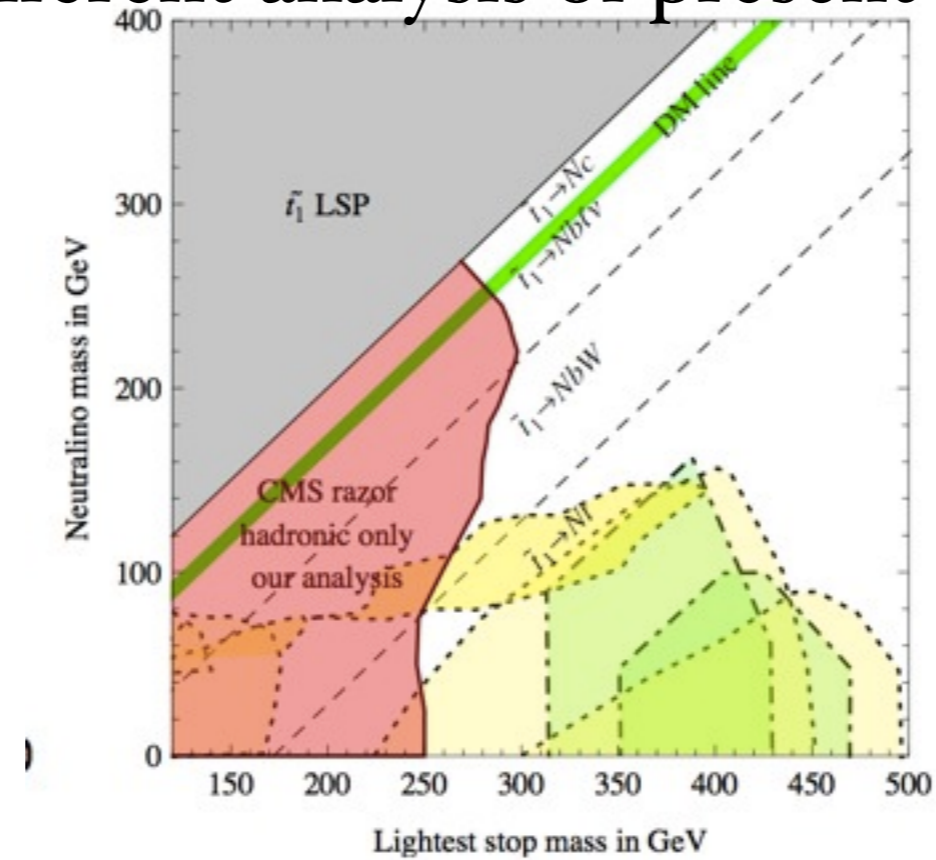
some relaxation but not much

forget about majorana gluino and go to dirac: supersoft stop masses
 zoom on stops and higgsinos



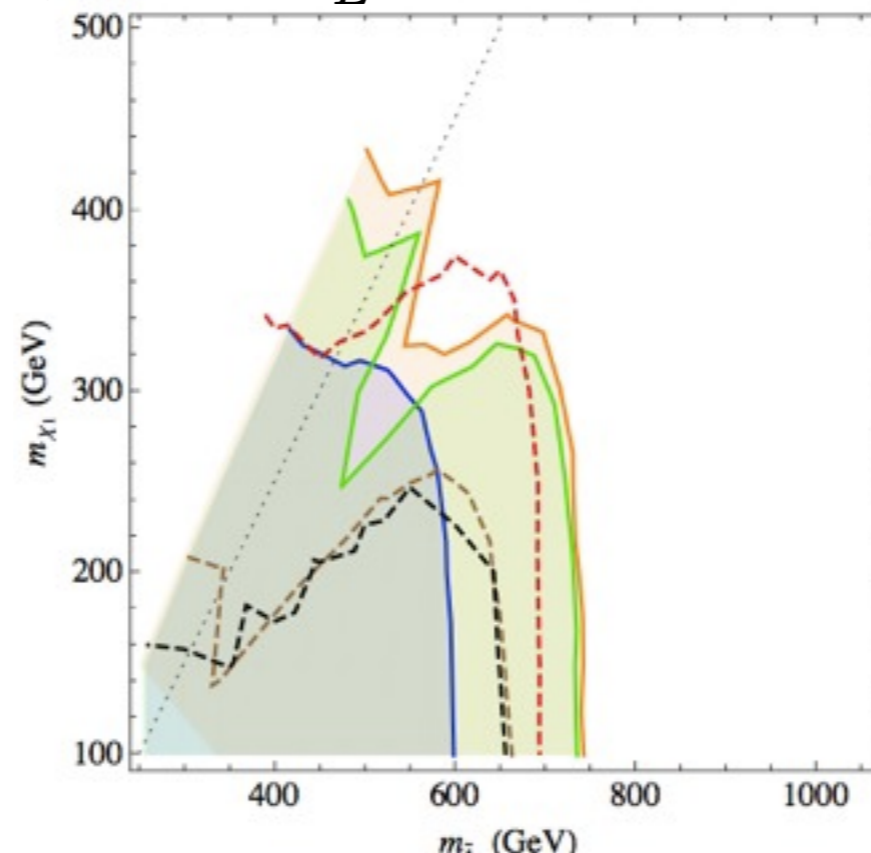
impressive but significant natural regions with squashed
 spectra remain

probably these regions can already be more significantly constrained by different analysis of present data



Delgado, Giudice, Isidori, Pierini, Strumia '13

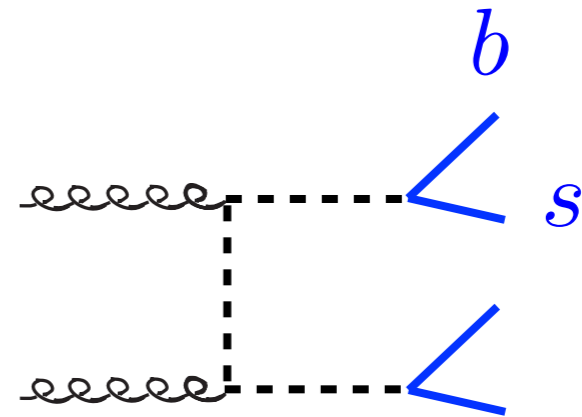
also addition of \tilde{t}_R , \tilde{t}_L , \tilde{b}_L production should be considered



Kribs, Martin, Menon '13

what about RPV decaying $\tilde{t}_R, \tilde{t}_L, \tilde{b}_L$?

— \tilde{g}



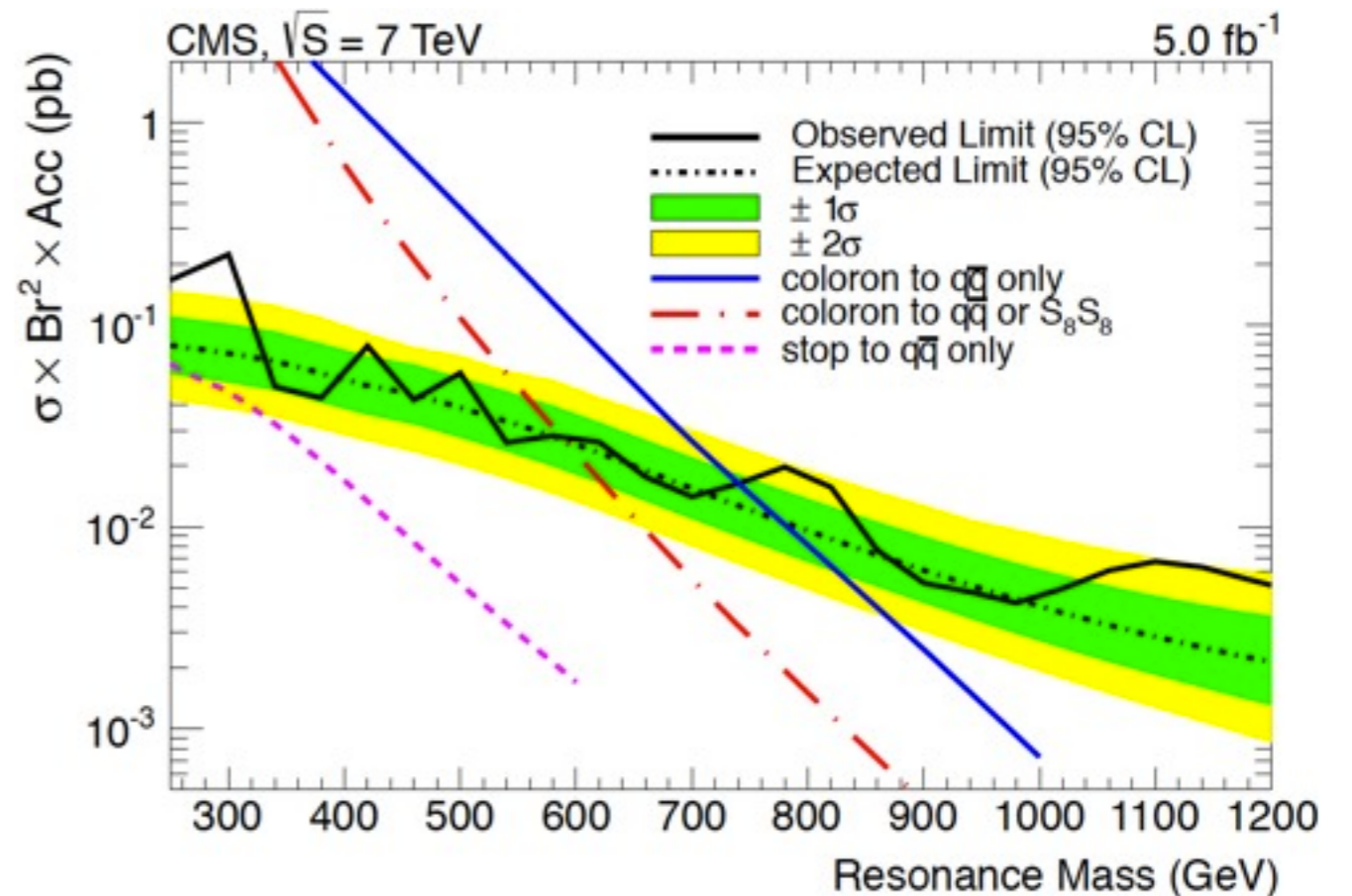
600 GeV

$$m_{\tilde{h}} + m_t > m_{\tilde{t}}$$

— \tilde{t}

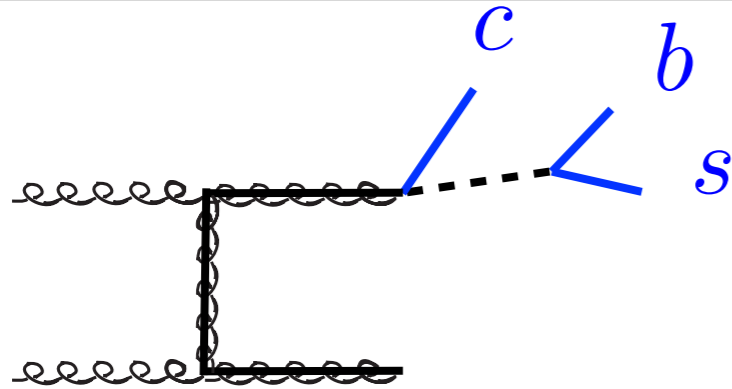
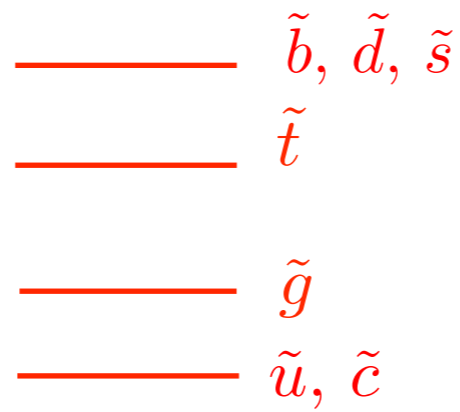
— $\tilde{h}_{1,2}^0, \tilde{h}^\pm$

— t



CMS 7 TeV data below
250 GeV
wait for upcoming 8 TeV

what about topless
gluino decays?

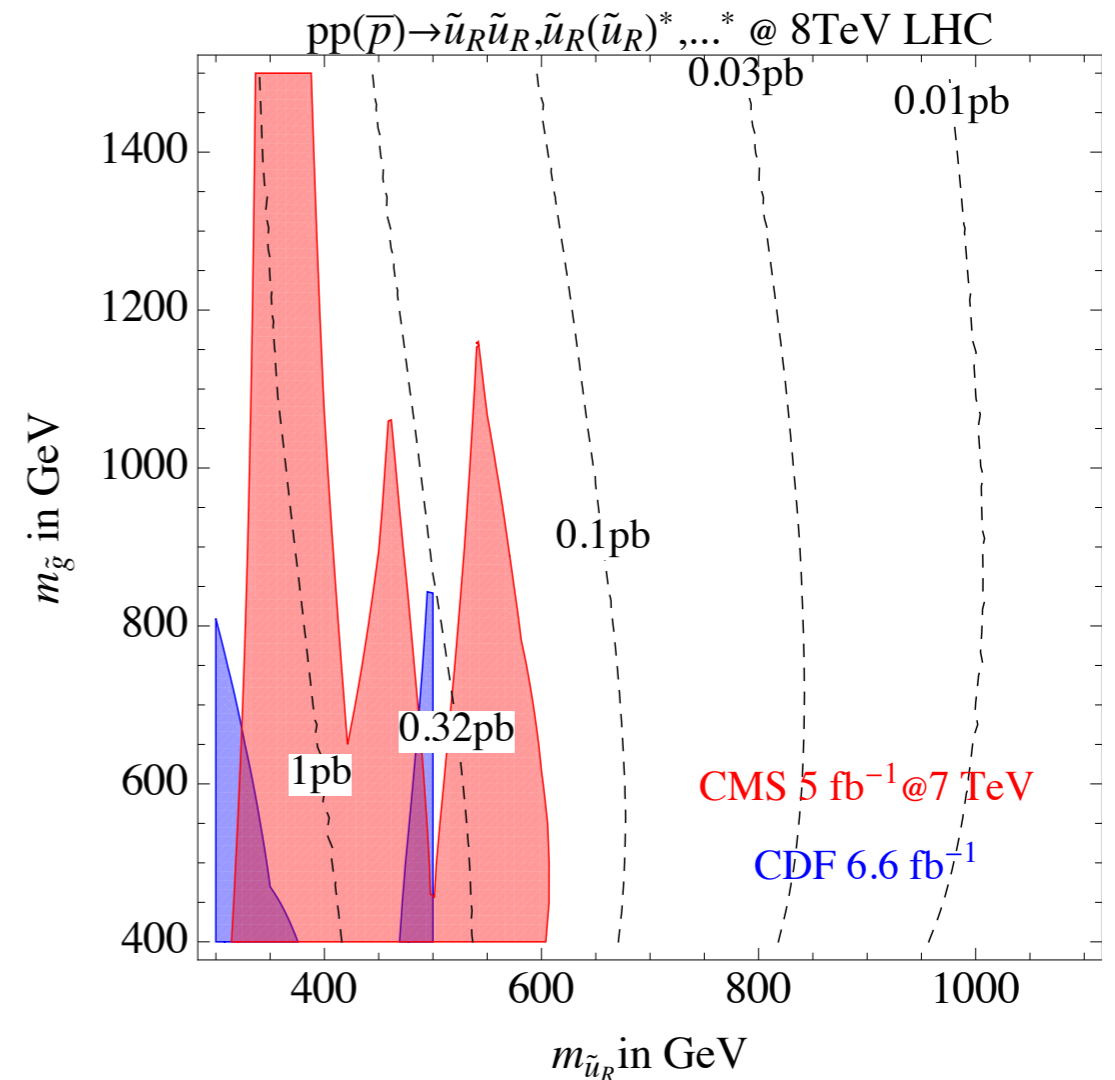
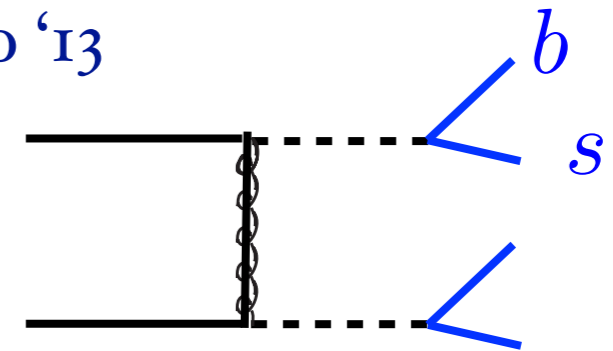


ATLAS, 7 TeV 4.6 fb^{-1}
 $m_{\tilde{g}} > 666 \text{ GeV}$

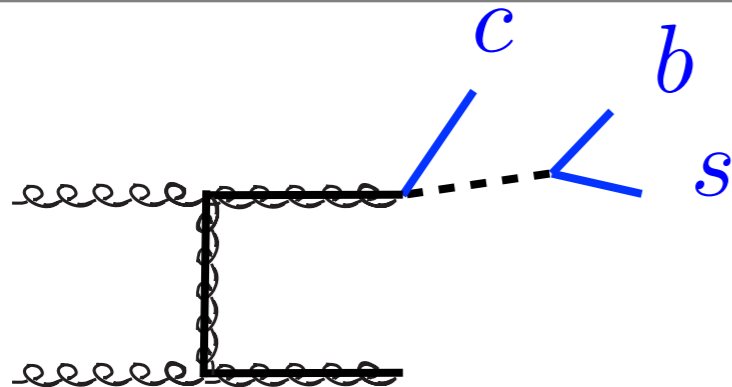
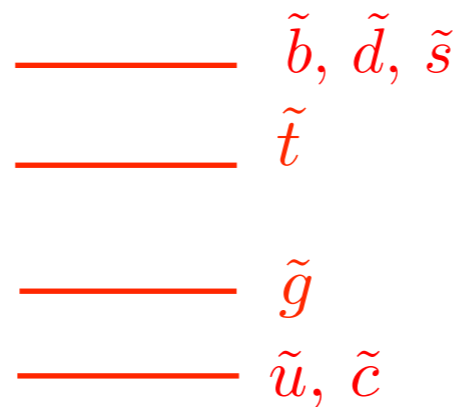
but bound relaxed if bino
enters decays chain

$\tilde{g}\tilde{g} \rightarrow 10\text{jets}$

Pappadopulo '13



what about topless
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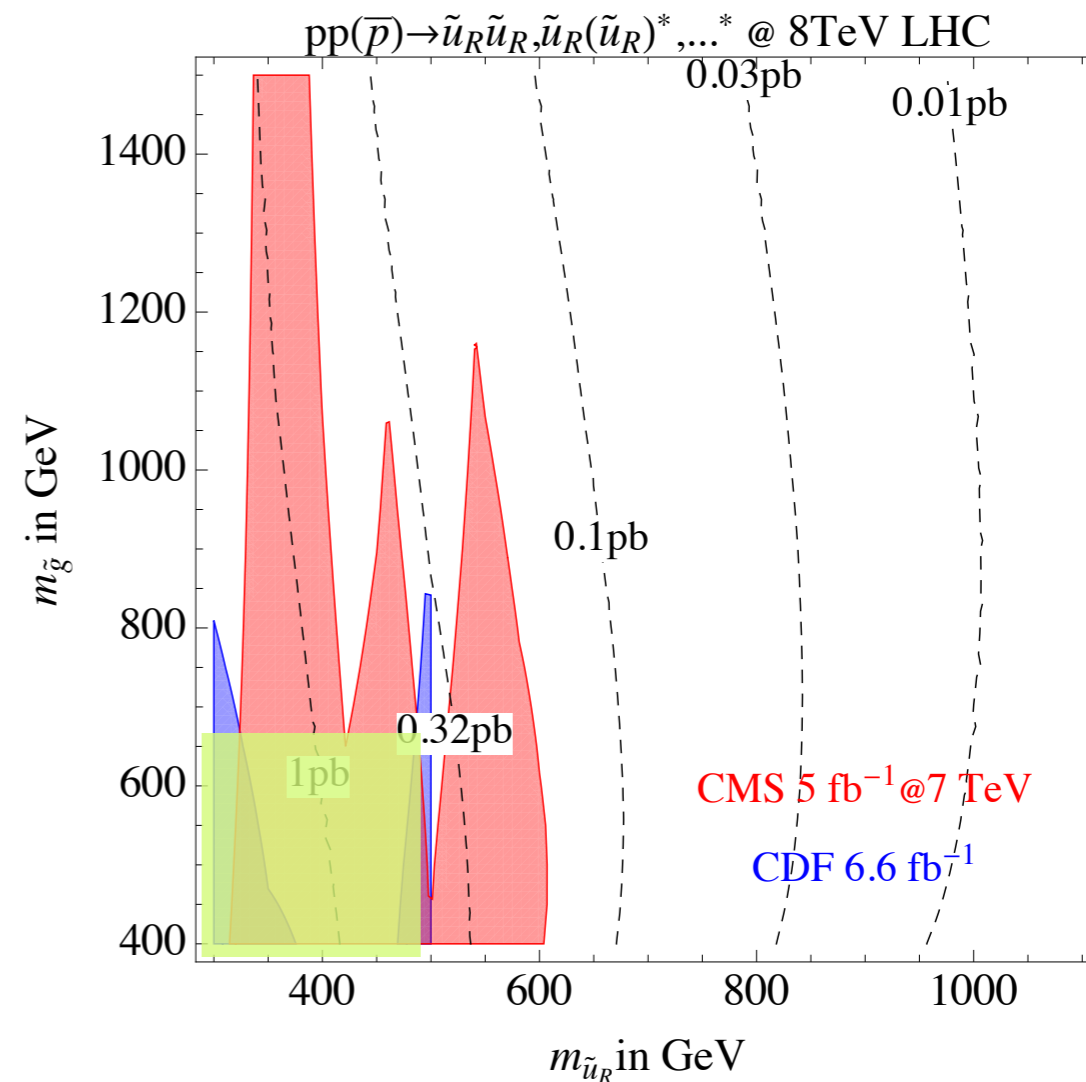
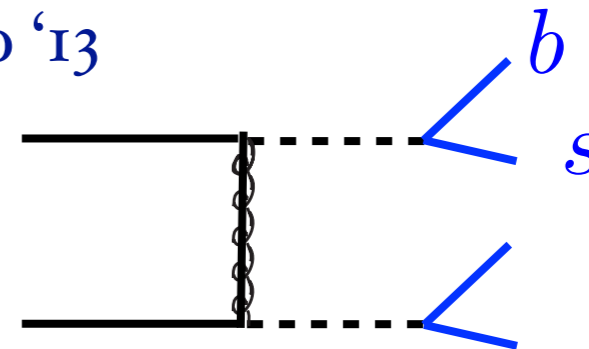


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Pappadopulo '13



ATLAS & CMS are hunting down Supersymmetry in nooks and crannies

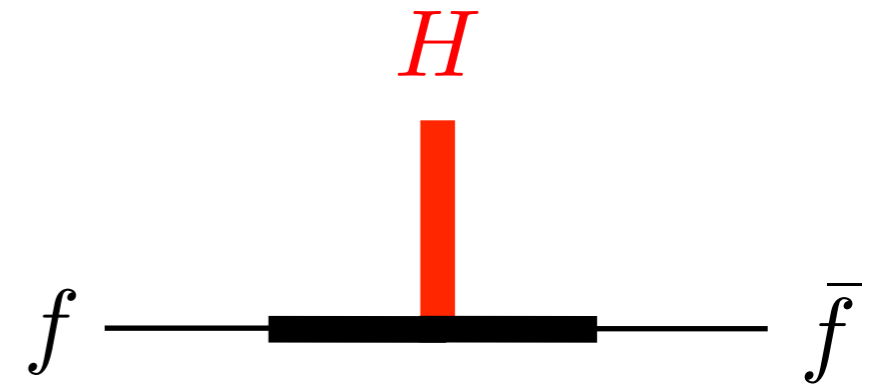
Looking forward to next run and to even more clever analyses

Too early though to fully overthrow naturalness in favor
of scenarios like, for instance, mini-split SUSY
but pressure is clearly building up

anyway, wait to hear Nima

Compositeness

Flavor: only option is partial compositeness



without any additional symmetry

FCNC

$$m_* \gtrsim 10 - 20 \text{ TeV}$$

edms

$$m_* \gtrsim 40 \text{ TeV}$$

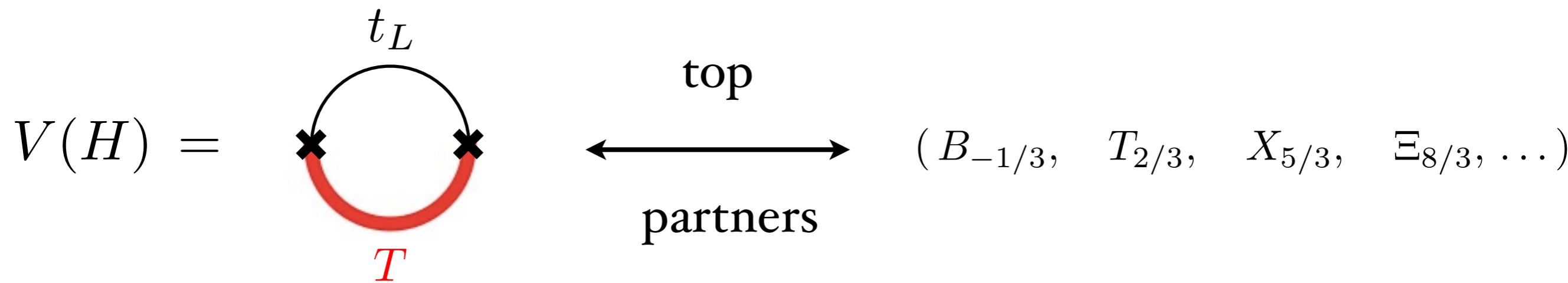
$\mu \rightarrow e\gamma$

$$m_* \gtrsim 150 \text{ TeV}$$

with combination of $SU(2)$'s and $SU(3)$ can bring scale down to $\sim \text{TeV}$

Redi '12

Babrbieri, Buttazzo, Sala, Straub, Tesi '12



expectations from naturalness

generic $V \equiv V(H/f)$

$m_h \simeq 125 \text{ GeV}$

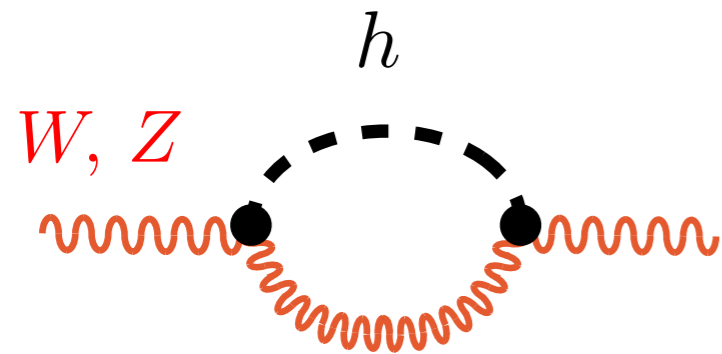


$\frac{v^2}{f^2} = O(1)$



$\left(\frac{400 \text{ GeV}}{m_T}\right)^2 = O(1)$

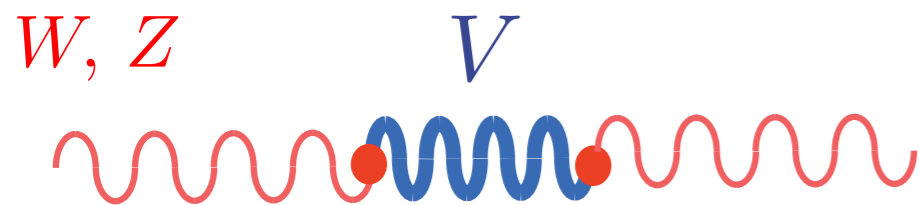
Electroweak Precision Tests



$$\Delta\hat{S}, \Delta\hat{T}$$

$$\frac{v^2}{f^2} \lesssim 0.05 \quad \begin{array}{l} \text{optimist} \\ (0.2) \end{array}$$

pessimist



$$\Delta\hat{S} \sim \frac{m_W^2}{m_V^2}$$

$$m_V^2 \gtrsim 2 - 3 \text{ TeV}^2$$

EWPT already imply some tuning

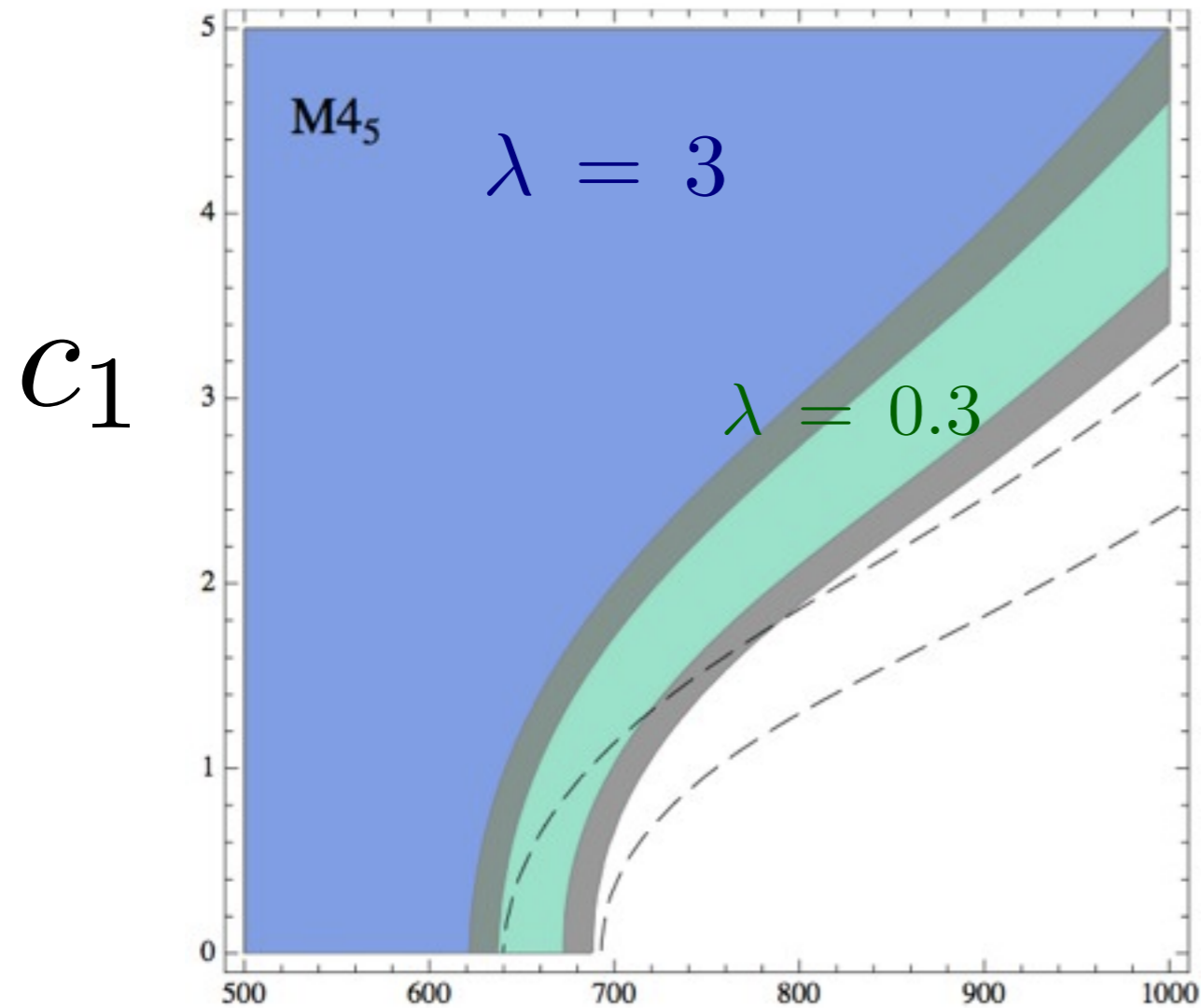
technical naturalness demands structural complexity $(m_V \gg m_T)$

Higgs couplings

$$\frac{\delta g}{g_{SM}} \sim \frac{v^2}{f^2} \lesssim 0.2$$

from EWPT

wait for more integrated luminosity to break new grounds

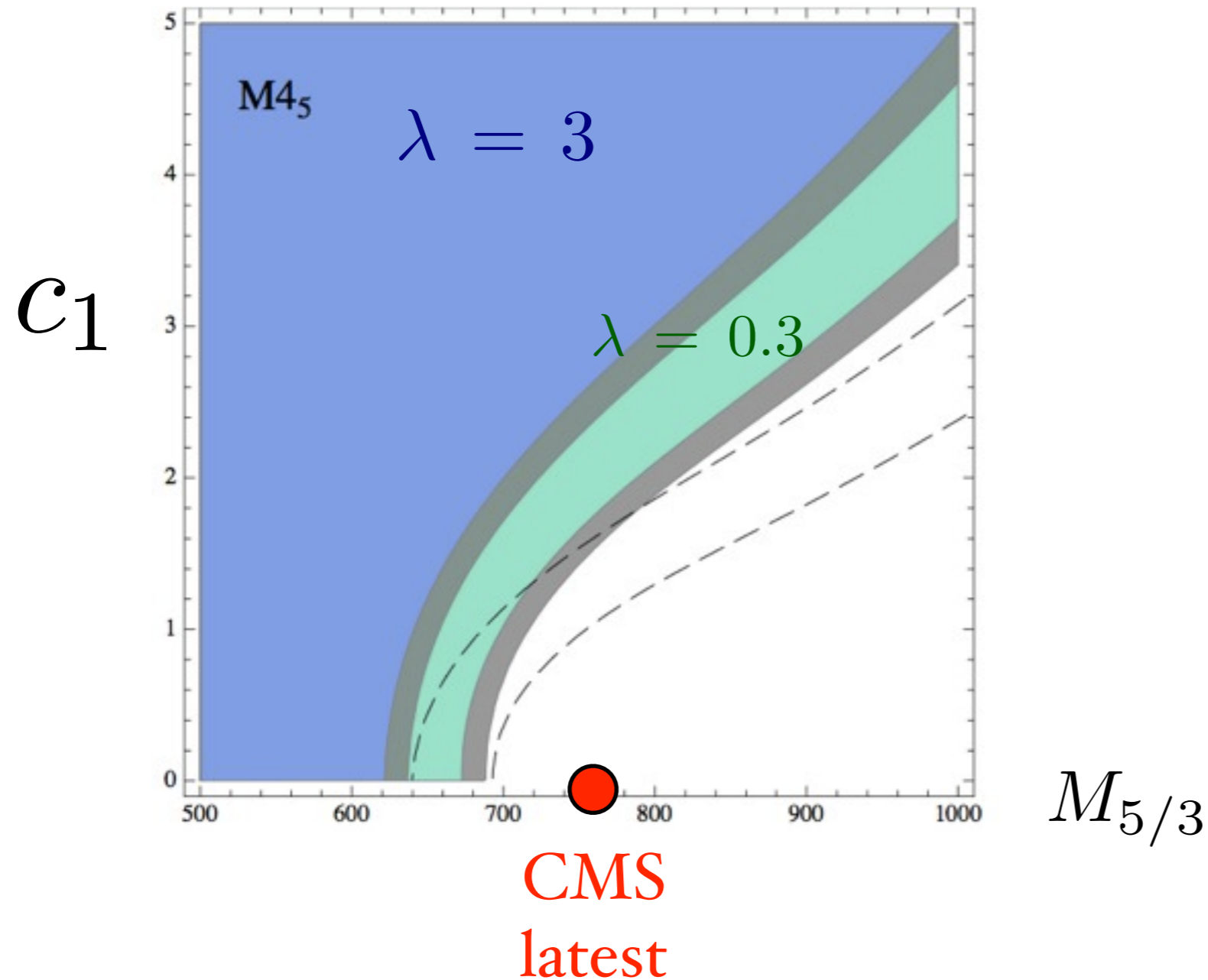


CMS
latest

$M_{5/3}$

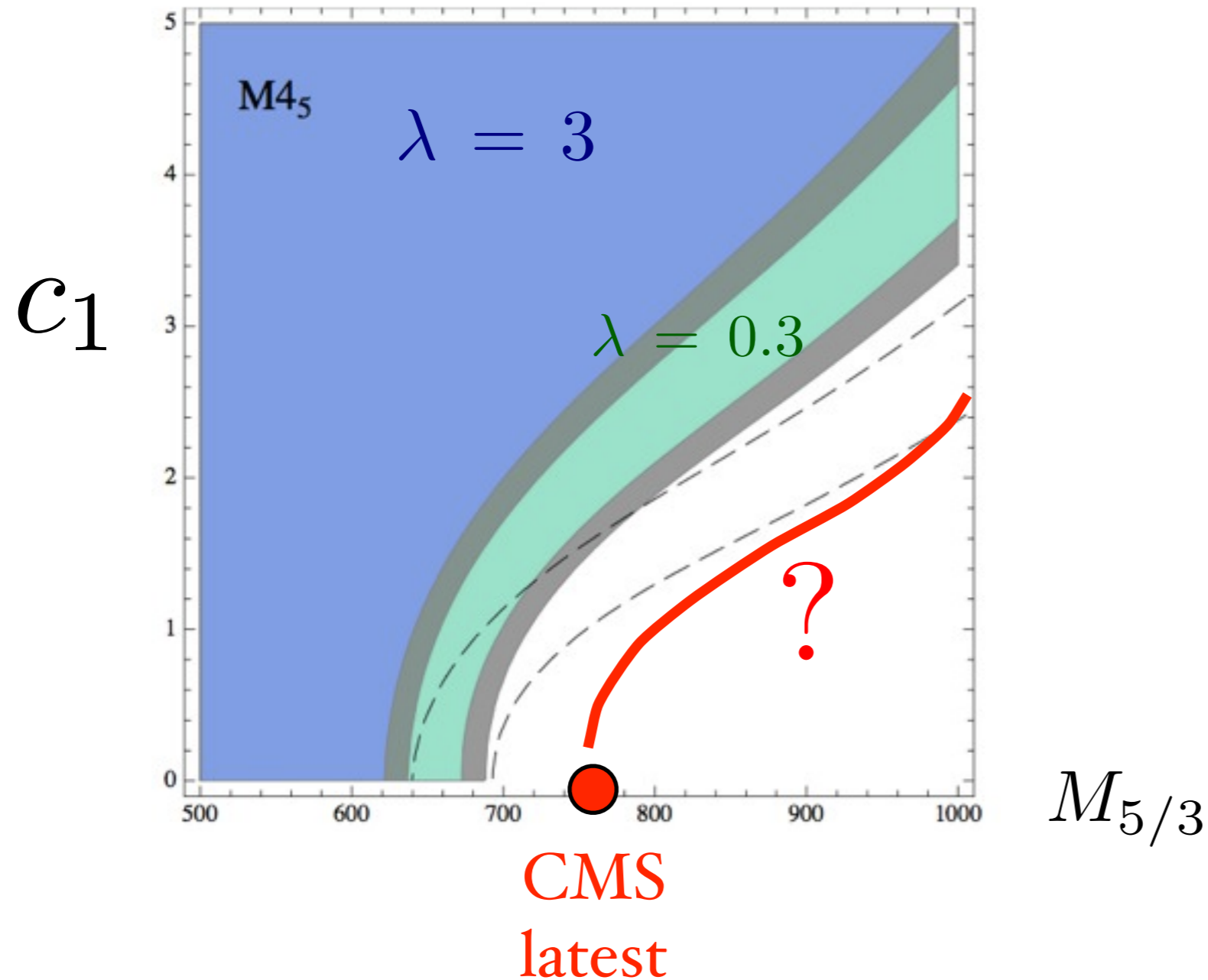
$$\xi \equiv \frac{v^2}{f^2} = 0.2$$

this is a very significant direct 'test' of naturalness
but result not fully unexpected in view of LEP/etc...



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Vector Resonances

$$q \text{ and } \bar{q} \text{ merging into } V = \frac{g_w^2}{g_V} \ll g_w$$

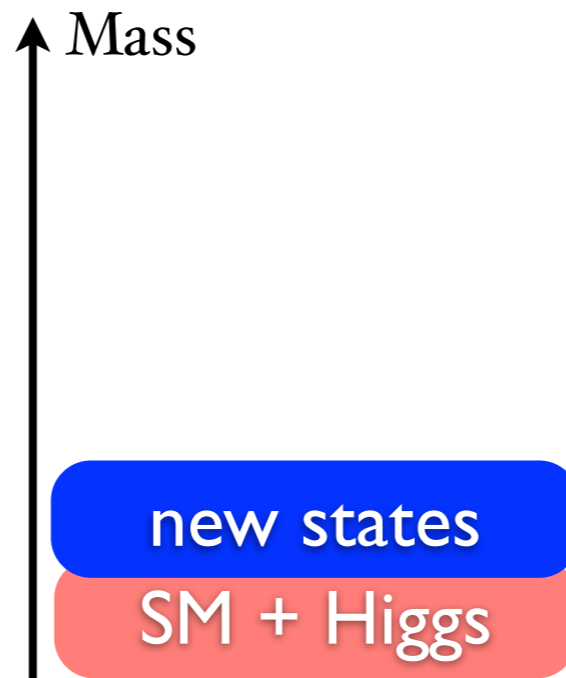
$$V \text{ decaying into } W_L \text{ and } W_L = g_V$$

$$\sigma \sim 10 \text{ fb} \left(\frac{3}{g_V} \right)^2 \left(\frac{2 \text{ TeV}}{m_V} \right)^6$$

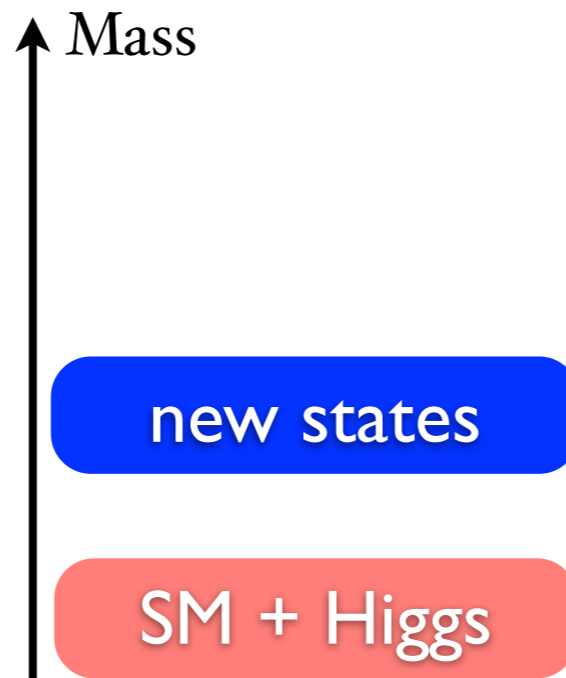
- resonances couple ‘superweakly’ to light fermions
- significantly different from weakly coupled W’ and Z’
- LHC bound still below 2 TeV for $g_V > 3$
- wait for LHC13 to break new ground

upcoming ‘theorists analysis’: Contino, Grojean, Pappadopulo, Thamm, Torre, Wulzer

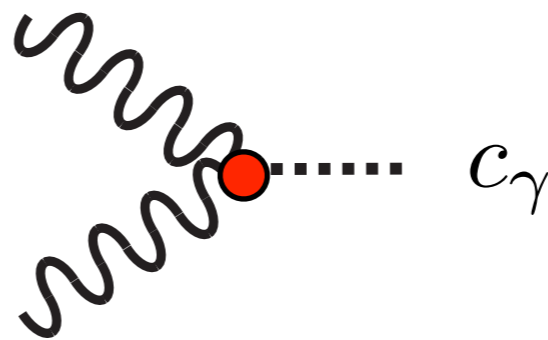
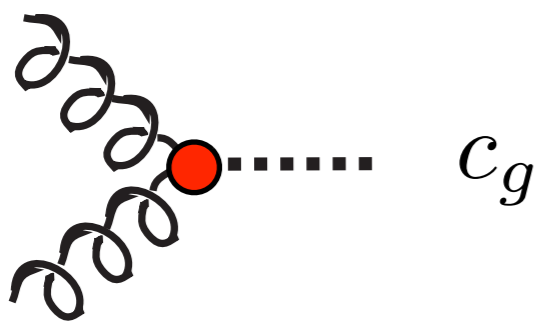
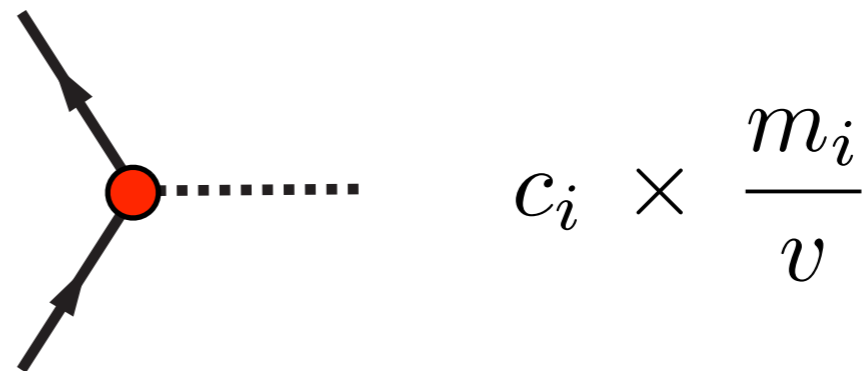
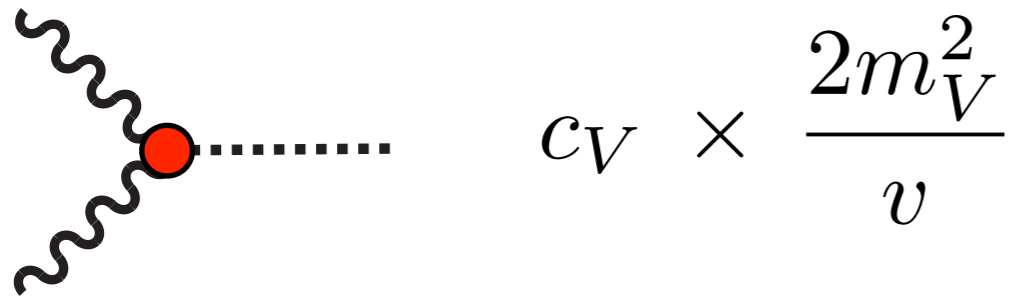
Higgzology



Can use effective lagrangian to describe deviations from SM
= simple parametrization encompassing a large class of models



Can use effective lagrangian to describe deviations from SM
= simple parametrization encompassing a large class of models



$$c_V > 1$$



only if \exists scalar of electric charge 2

$$c_b > 1, c_t < 1$$



MSSM

$$c_b < 1, c_t > 1$$



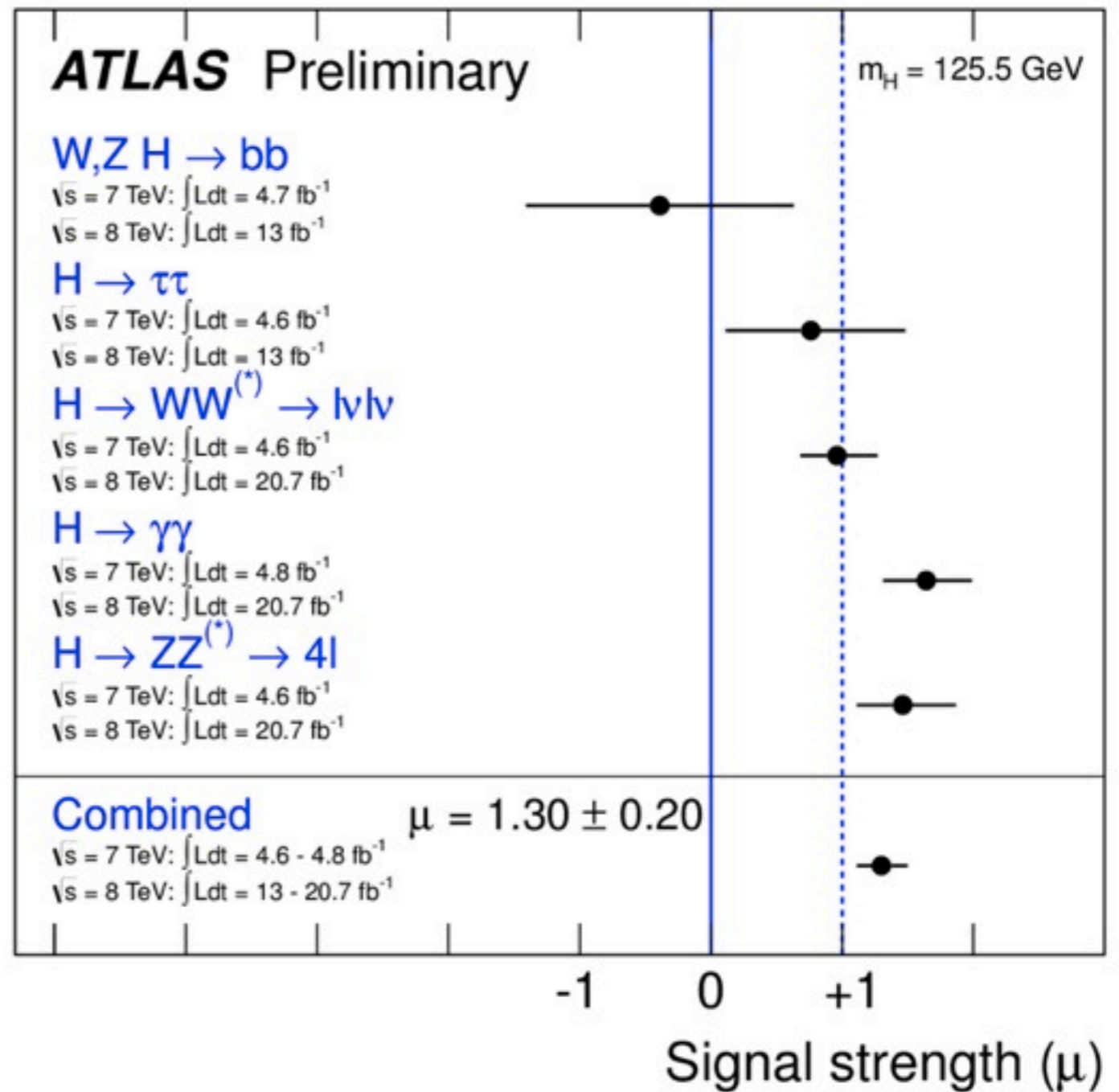
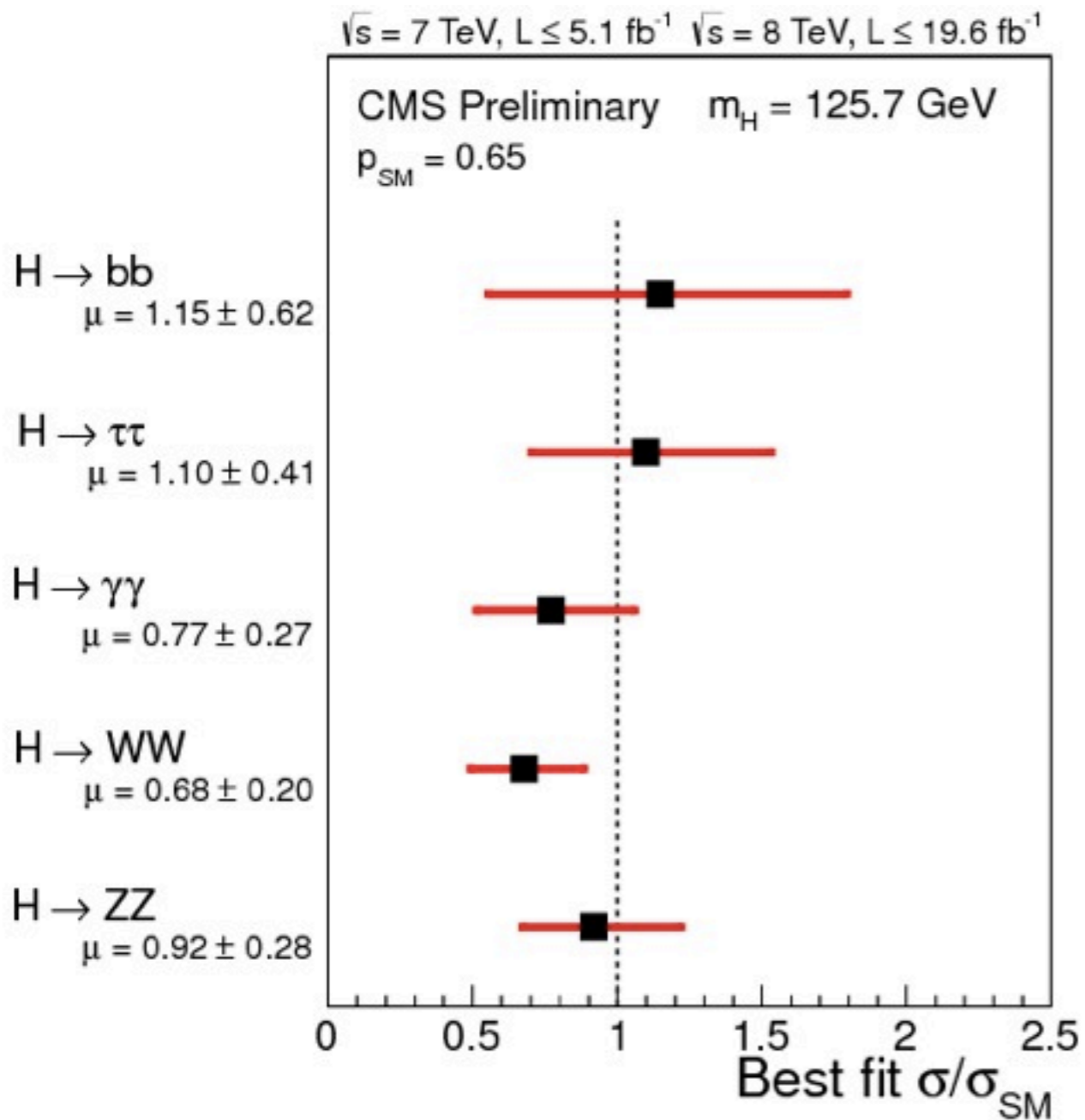
NMSSM dominated quartic

$$c_V, c_f < 1$$

$$c_g, c_\gamma \sim 0$$



Composite Higgs



No clear trend of deviation from SM

Compatible with SM within 30%

Higgs comin' !!

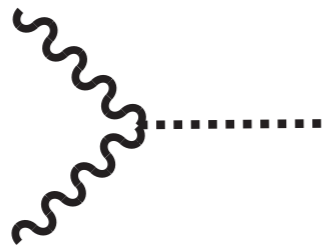




Welcome Higgs !!

The precision frontier

single
Higgs
physics



measures

$$\frac{g_{NP}^2 v^2}{M_{NP}^2} \lesssim$$

fine tuning

EWPT

10%

HL-LHC

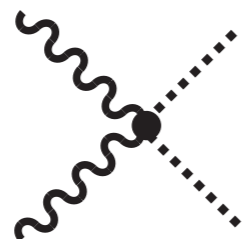
5%

ILC-LEPpone

1%

precision Higgs physics breaks ground in the test of naturalness
though it can only give us indirect clues

semidirect
clues

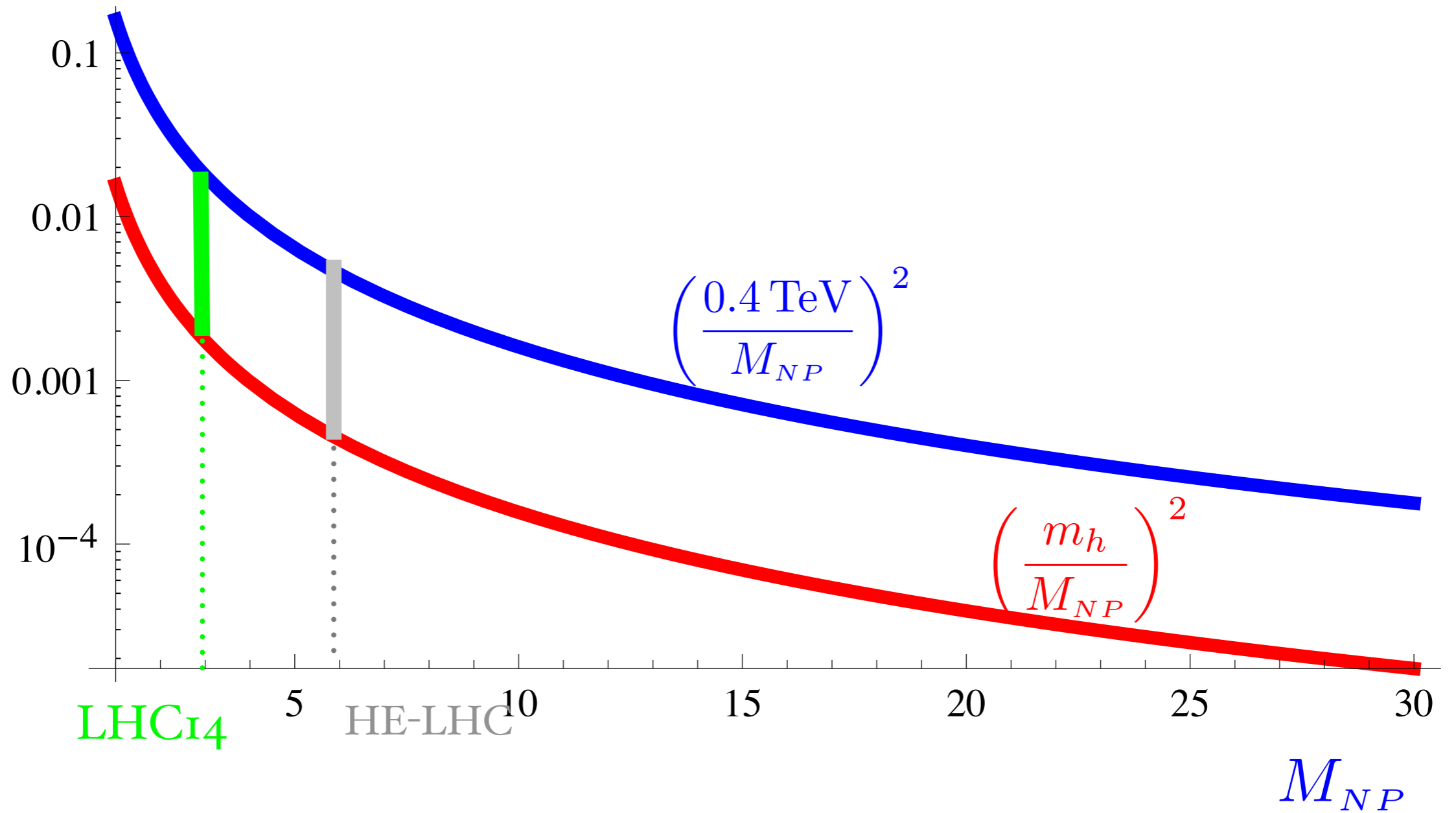


at CLIC

sensitive to tuning of $\sim 1\%$

The energy frontier

tuning



Summary

- discovery of Higgs boson with rates in agreement with SM within the present precision of 30% is far from unexpected: it is basically a corollary of results of LEP/Tevatron/B-factories
- direct searches are directly pushing several scenarios (especially in SUSY) into 1% tuning grounds, though that is basically where the simplest (and maybe nicest) models were already expected by indirect reasoning (ex, MSSM with flavor universal soft terms)
- LHC searches are now also putting significant pressure on cleverly natural models, though regions with moderate tuning are not ruled out yet
- Refined analyses & LHC13 can break grounds on those regions and perform a comprehensive test of naturalness
- HL-LHC will break grounds in EW physics by testing Higgs rates at, so it seems, 5%