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 $\Lambda^2_{UV} \gg 1\,\mathrm{TeV}$

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

d=4

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d=4

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

d>4

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$$+ \ldots$$

d>4

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

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

d=4

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

d=4

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

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

$$+ \quad \ldots$$

d>4

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

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

d=2

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

d=4

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

d=4

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

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

$$+ \quad \ldots$$

d>4

$\Lambda_{UV} \gg$ 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

$$\mathcal{L}_{SM} \;=\; \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda (H^\dagger H)^2$$ d=4

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

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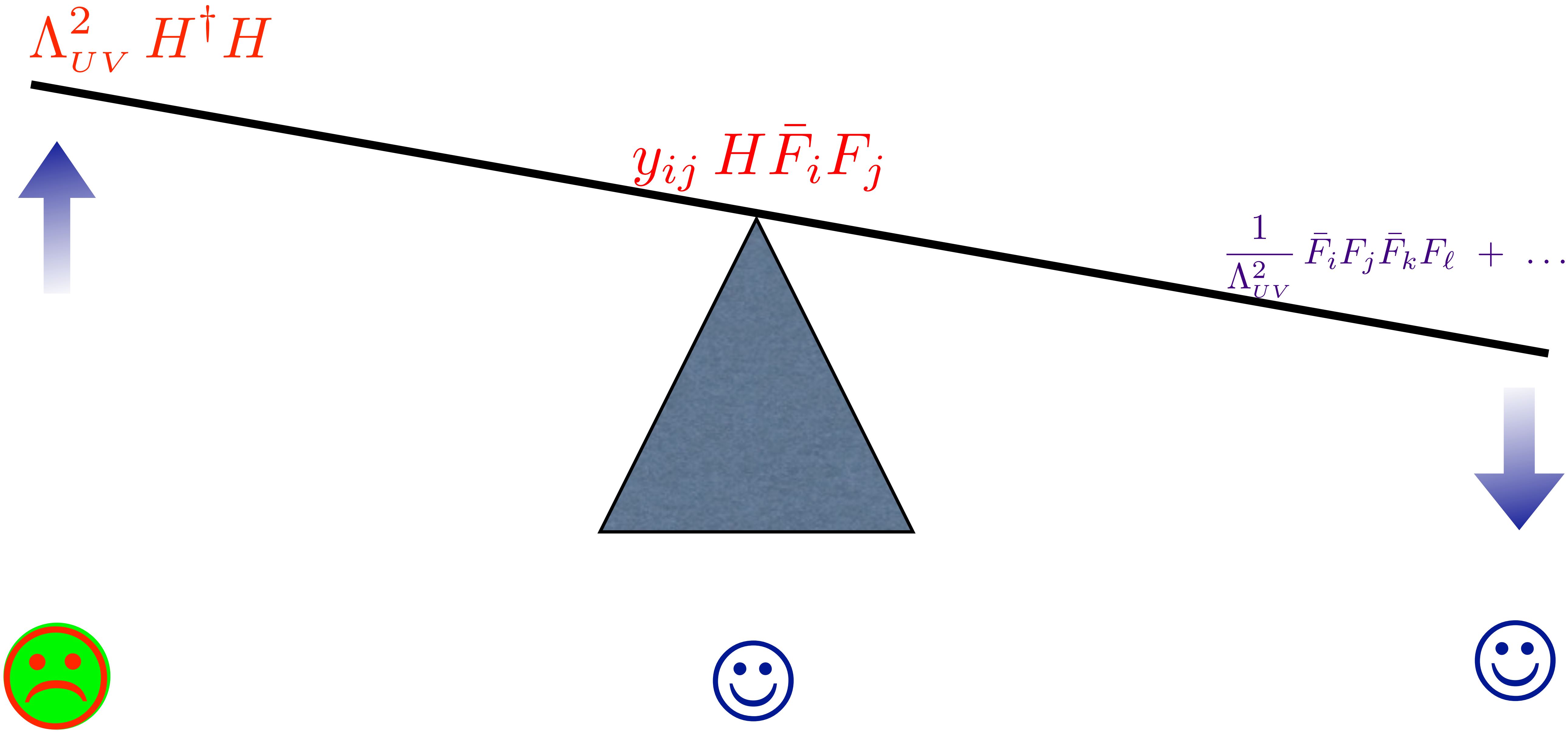
$$+ \quad \ldots$$

d>4

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

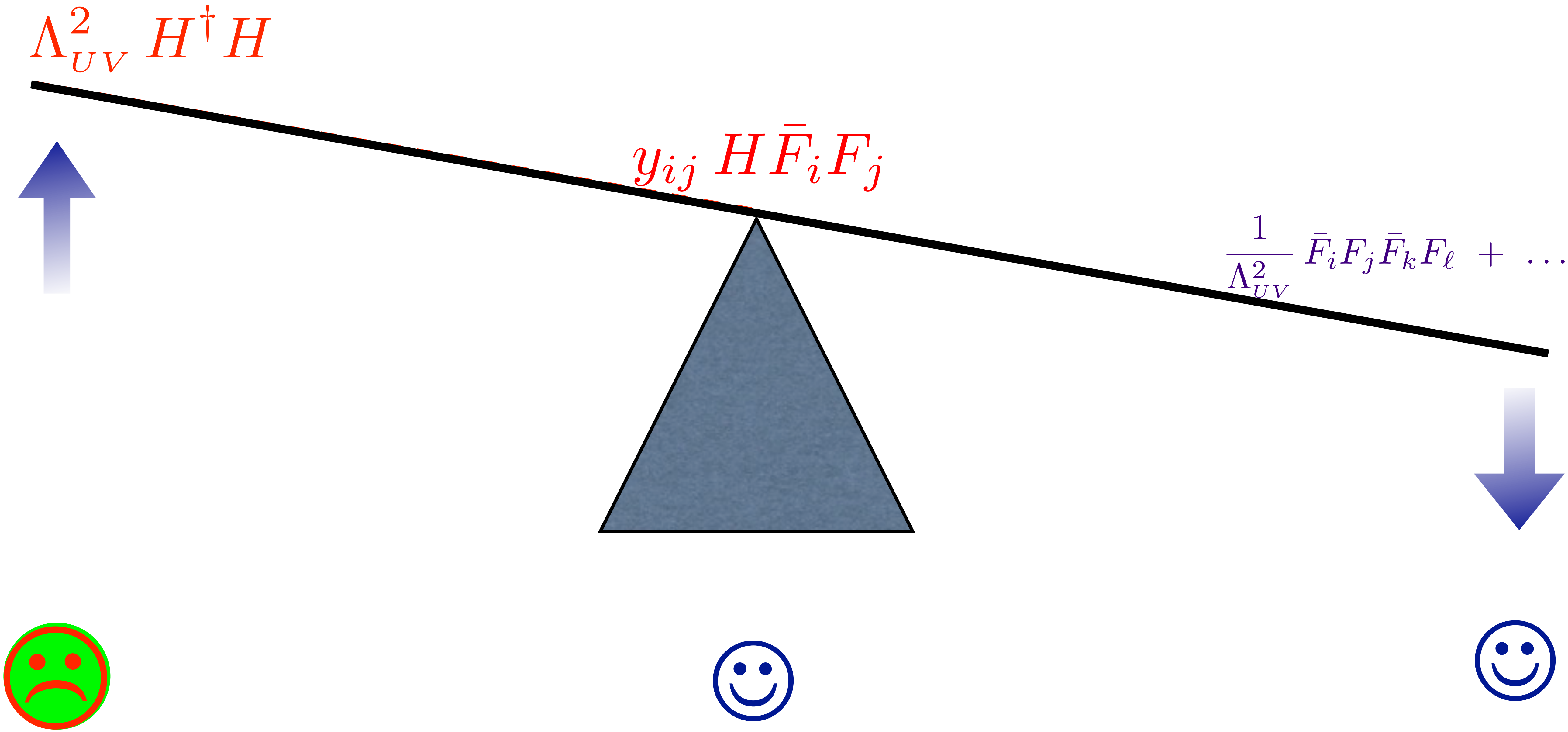
Hierarchy see-saw

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



Hierarchy see-saw

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



Hierarchy see-saw

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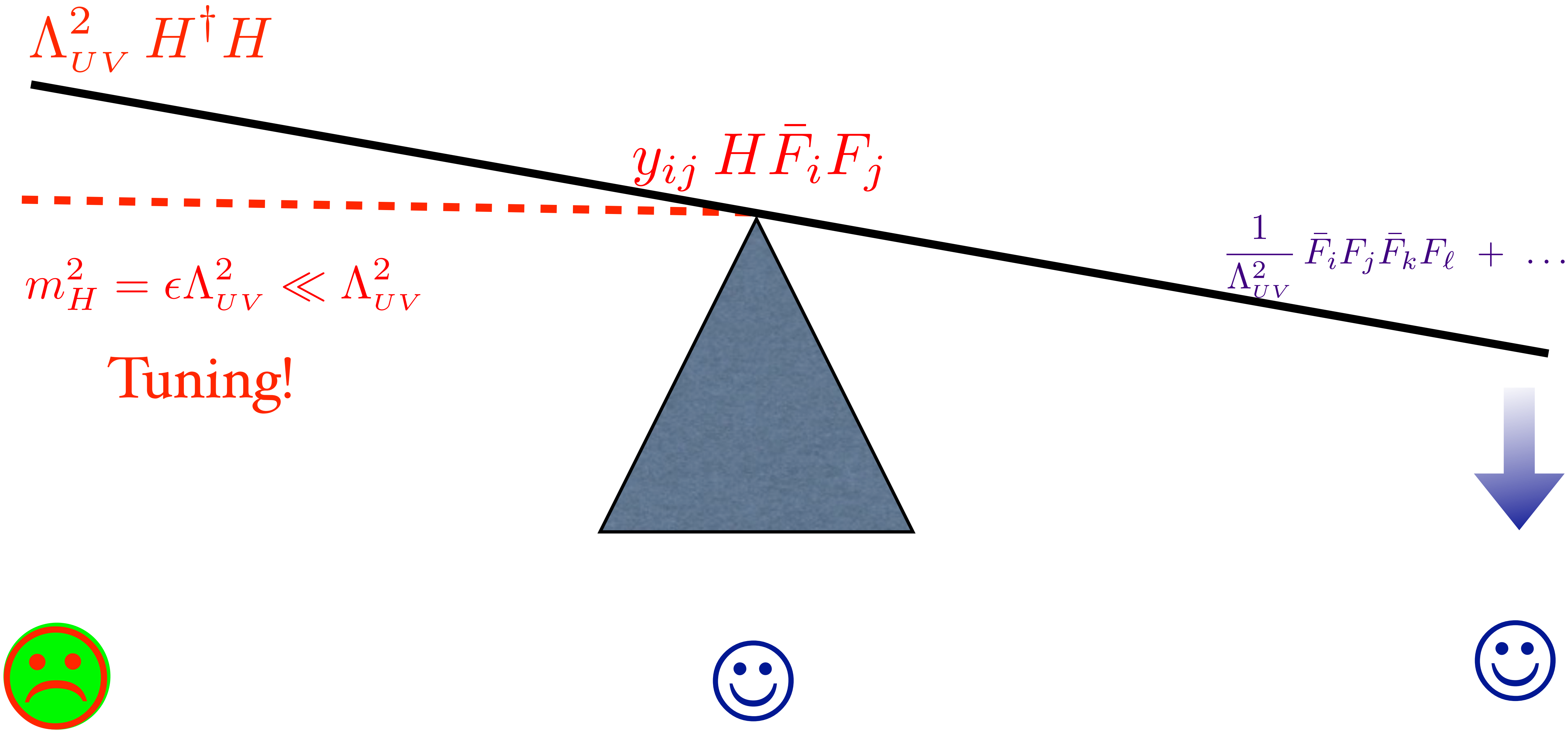
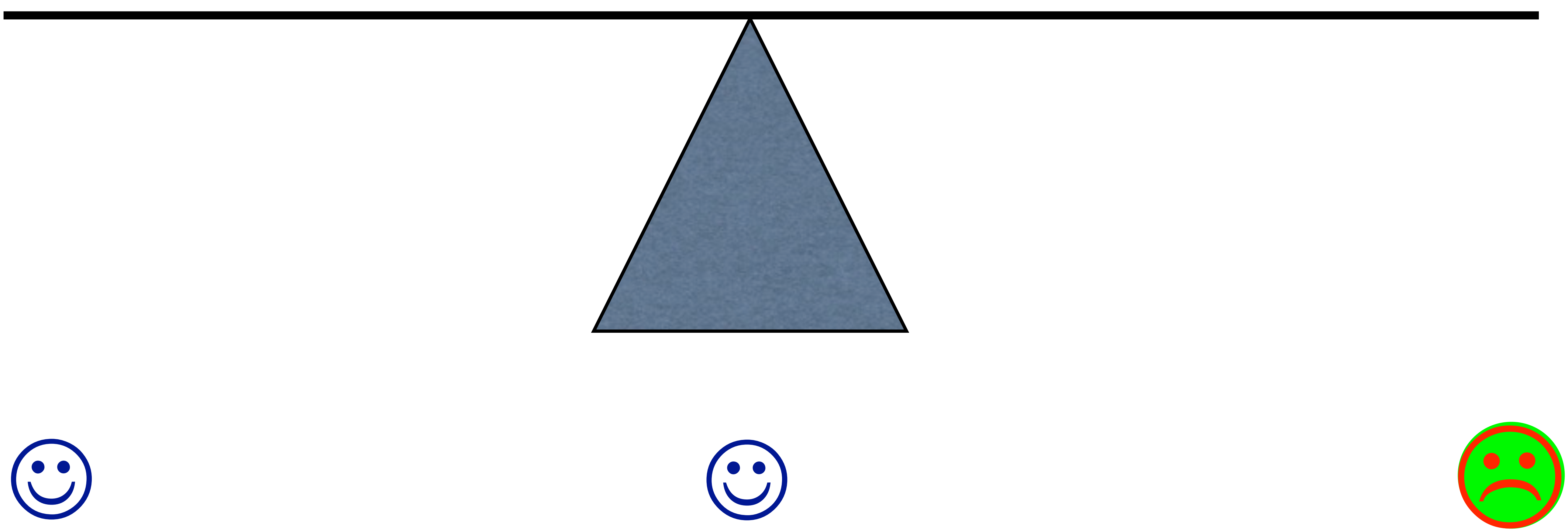


Natural SM : $\Lambda_{UV}^2 \lesssim 1\,\mathrm{TeV}$

$\Lambda_{UV}^2\, H^\dagger H$ $\qquad$ $y_{ij}\, H \bar{F}_i F_j$ $\qquad$ $\frac{1}{\Lambda_{UV}^2} \bar{F}_i F_j \bar{F}_k F_\ell + \ldots$



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 $\Lambda_{UV} \sim 1\,\mathrm{TeV}$

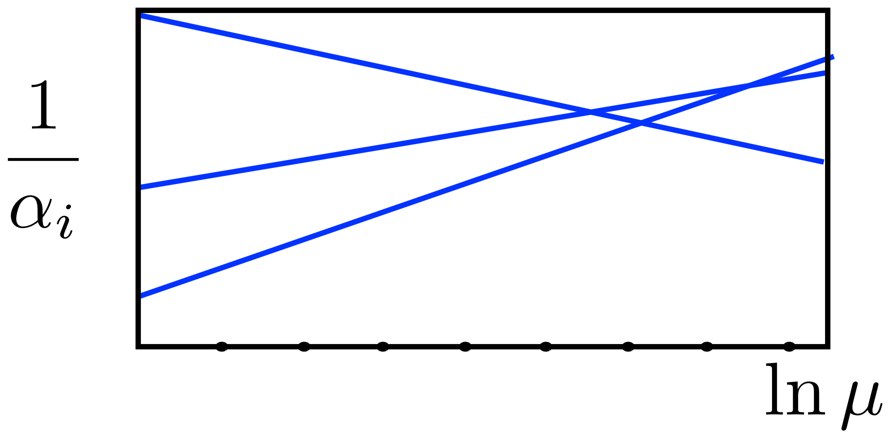
- In the correct theory the hierarchy problem does not even arise (naturalness)
- What about B, L and Flavor? In all models not nearly as nice as in SM

A high scale scenario

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

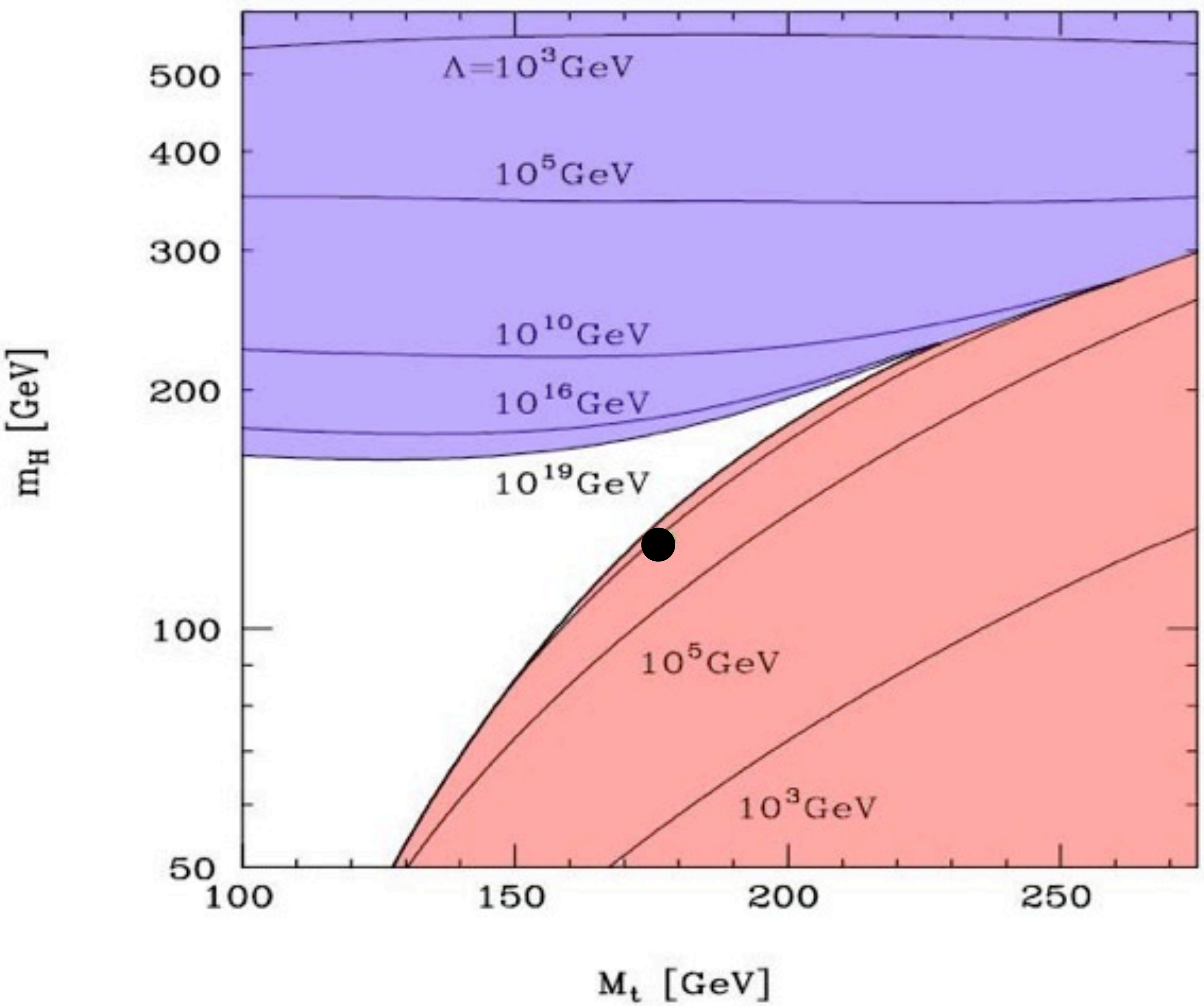
- Θ-QCD and Dark Matter ➔ high scale axion $f_a \sim 10^{12}$ GeV

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

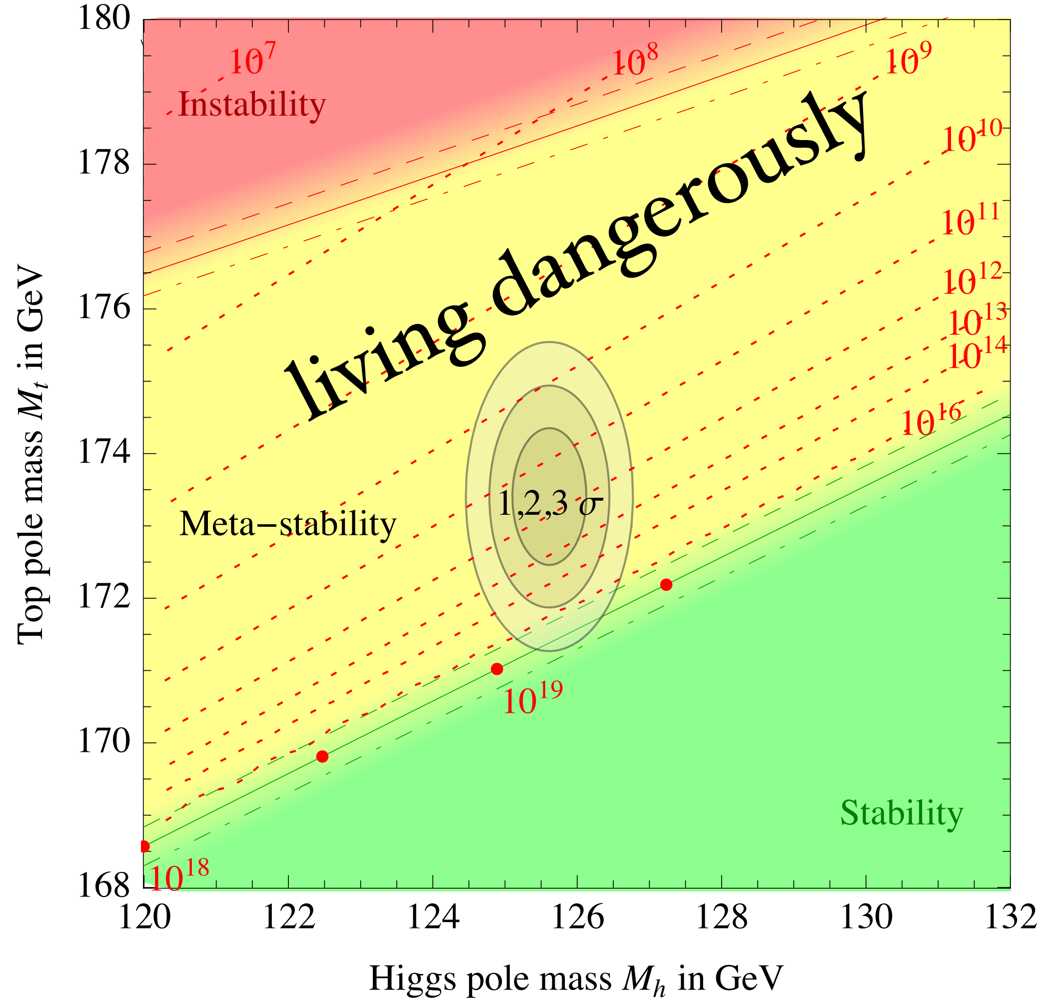


- neutrino masses $\frac{\ell\ell H H}{\Lambda}$ ➔ $m_\nu \sim \frac{v^2}{\Lambda}$ $\Lambda \sim 10^{14}$ GeV

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

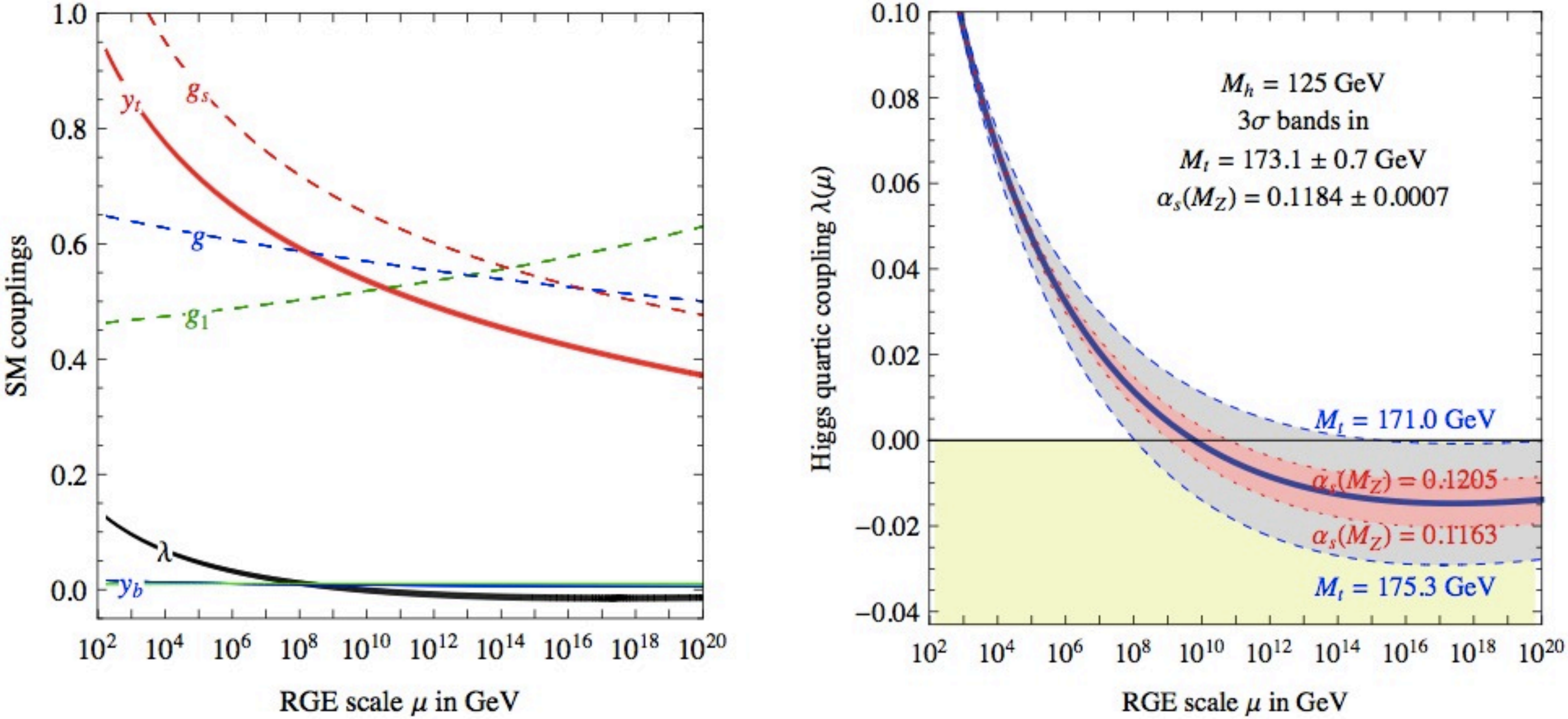


Elias-Miro, Espinosa, Giudice, Isidori, Riotto, Strumia '11



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

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



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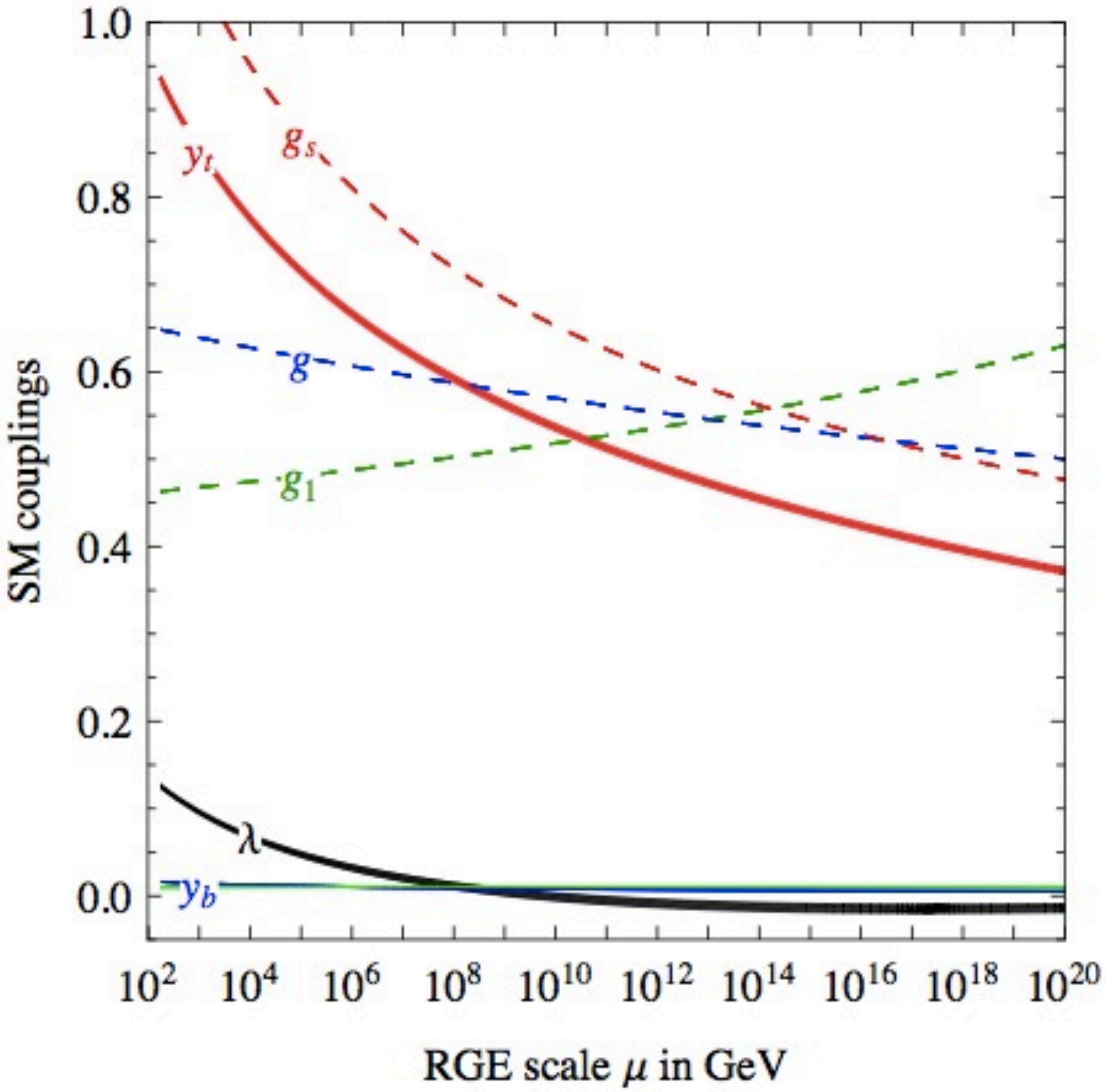
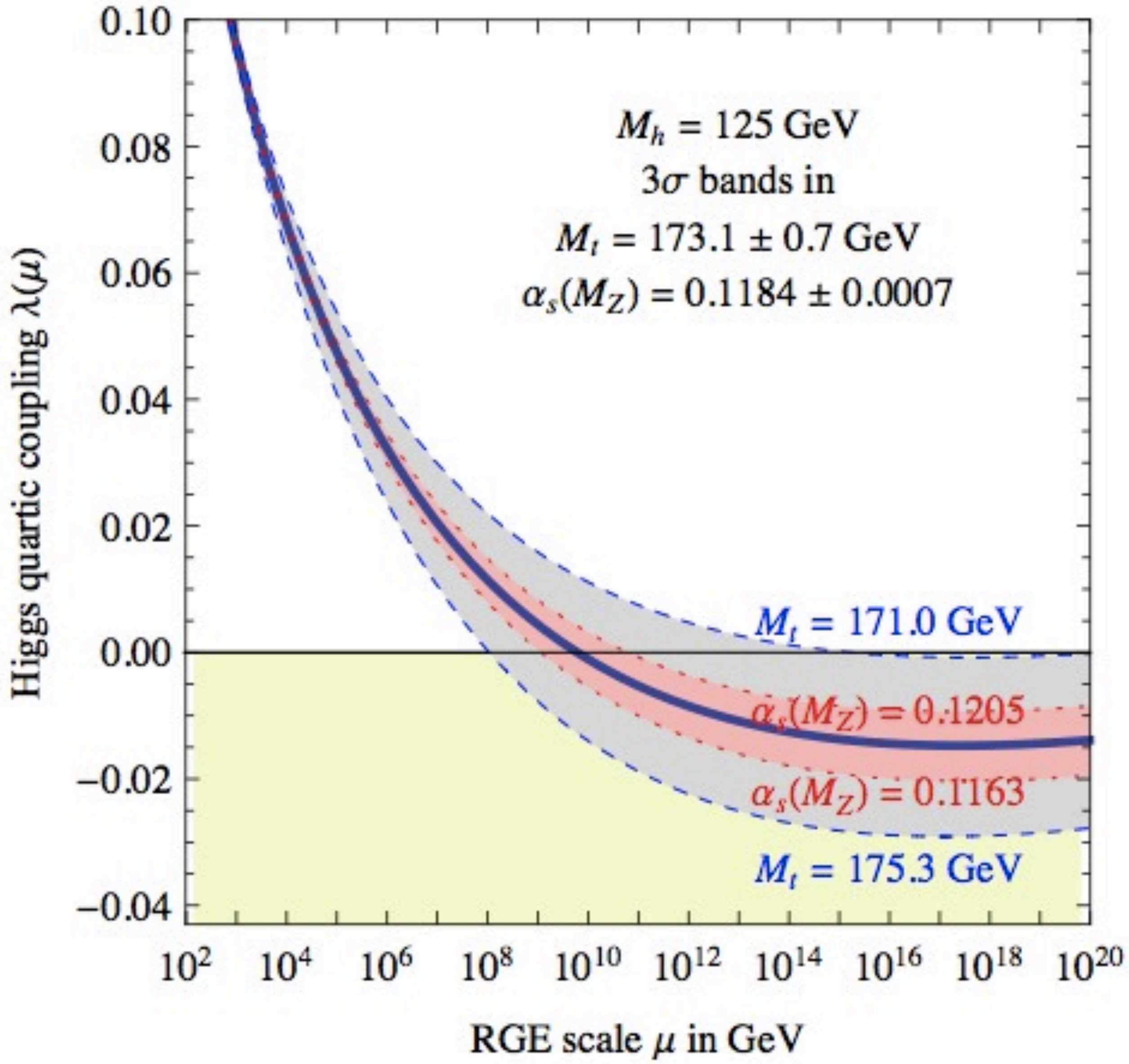
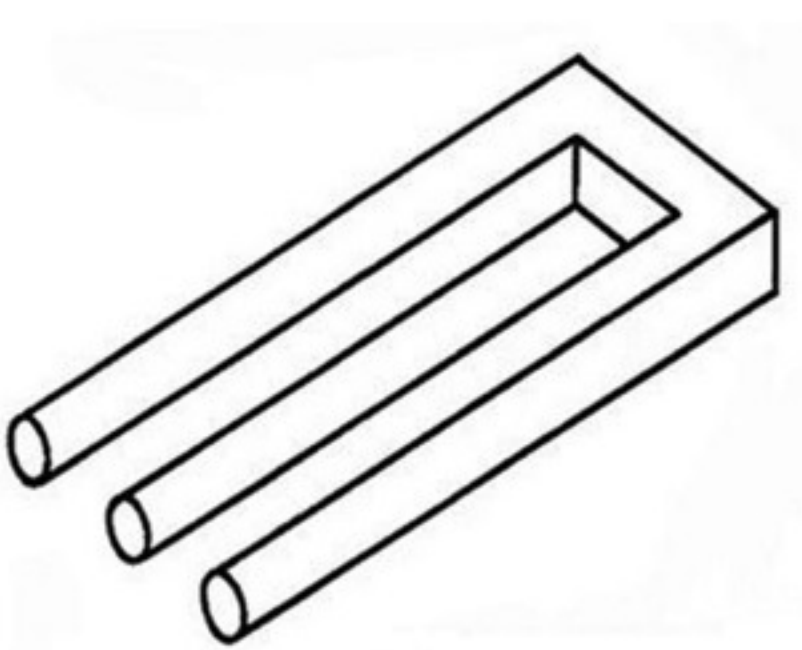
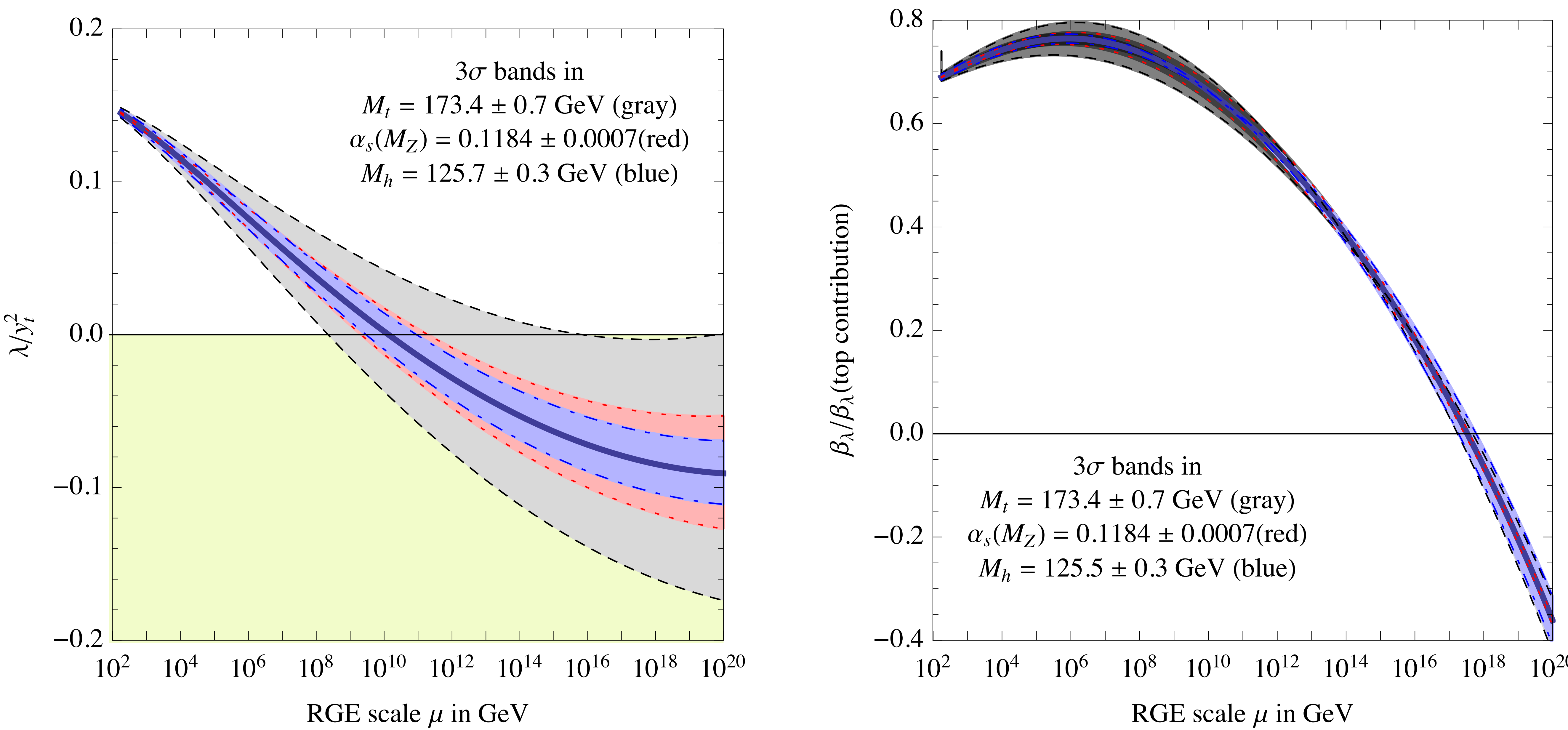




but watch your eyes





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 $d \leq 4$ terms violating F, B and L

$$\mathcal{L}^{d\leq 4} = m^2_{ij}\tilde{Q}^\dagger_i\tilde{Q}_j + A_{ij}Y^D_{ij}\tilde{Q}_i\tilde{D}_jH_d + \lambda_{ijk}\tilde{U}_iD_jD_k + \ldots$$

Naive Composite Higgs (TC) : the Yukawa themselves are $d > 4$

$$Y_{ij}\,H\,\bar{Q}^i_L Q^j_R \;\rightarrow\; Y_{ij}\,\frac{1}{\Lambda^2_F}\,(\bar{\Psi}\Psi)Q^i_L Q^j_R \qquad\qquad m_{ij} = Y_{ij}\,\frac{v^3_F}{\Lambda^2_F}$$

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 ↕ holography
- flavor from partial compositeness

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Dynamics

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

holography

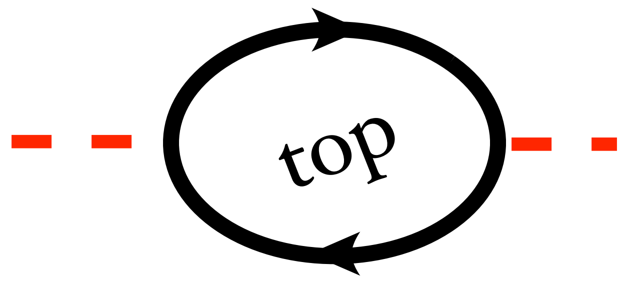
unfortunately disfavored in natural theories

What naturalness demands

supersoft models: Higgs mass parameter fully saturated by IR physics

- dirac gauginos in supersymmetry
- general composite Higgs

$\delta m_H^2 =$



$\sim \dfrac{3\lambda_t^2}{8\pi^2} M^2$

$\Rightarrow$ $m_h = 125\,\text{GeV}$

tuning $\left(\dfrac{400\,\text{GeV}}{M}\right)^2$

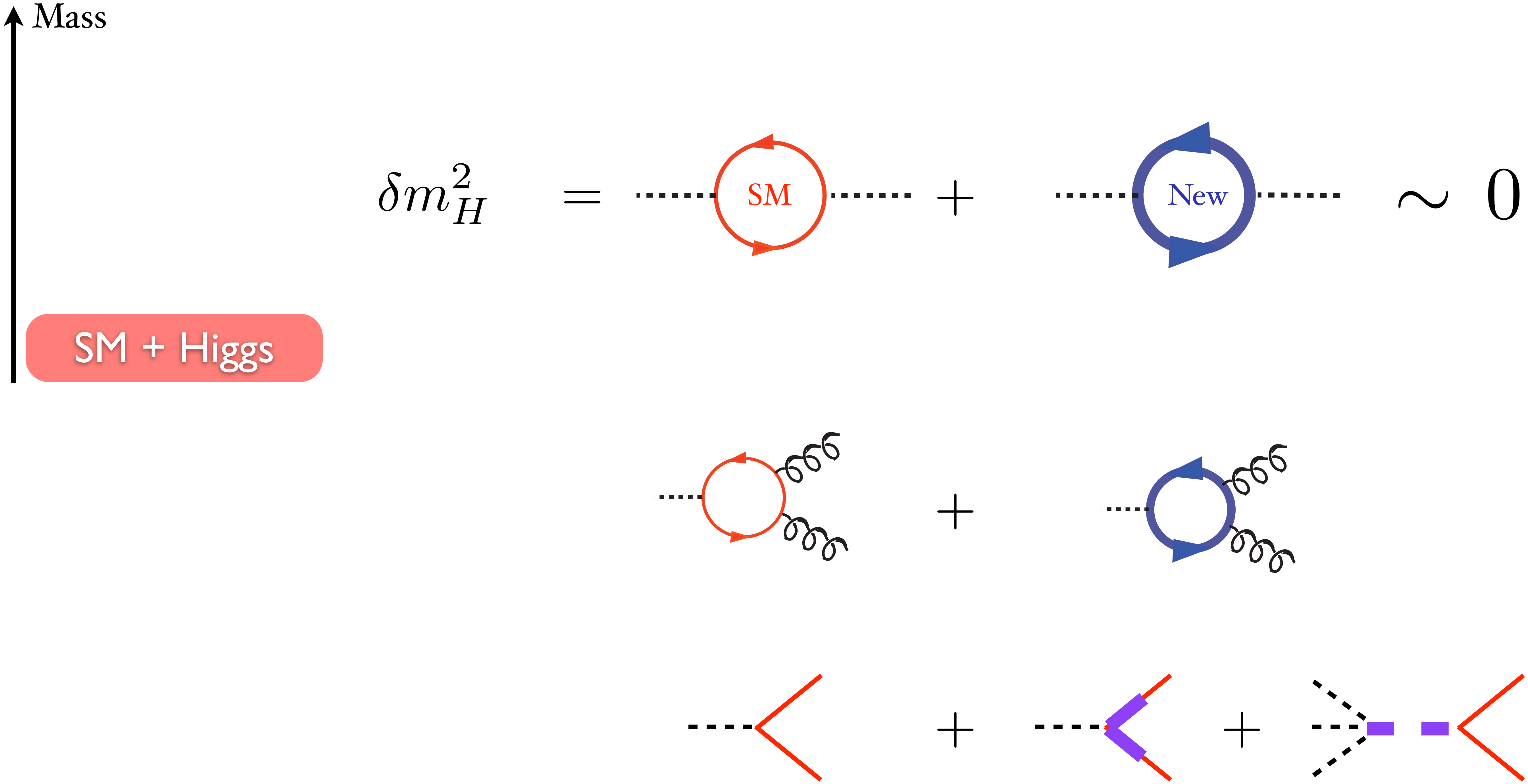
soft models: Higgs mass logarithmically sensitive to UV

- MSSM and its extensions with high scale mediation

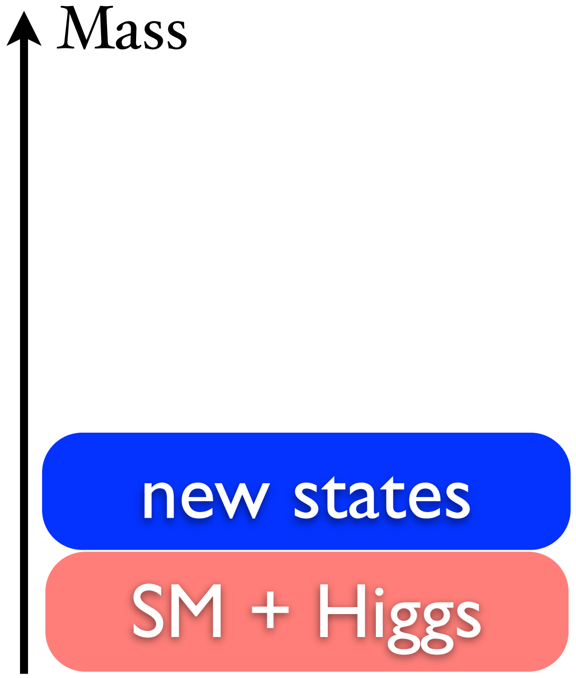
$m_h^2 \sim m_Z^2 \sim m_{\tilde{t}}^2$

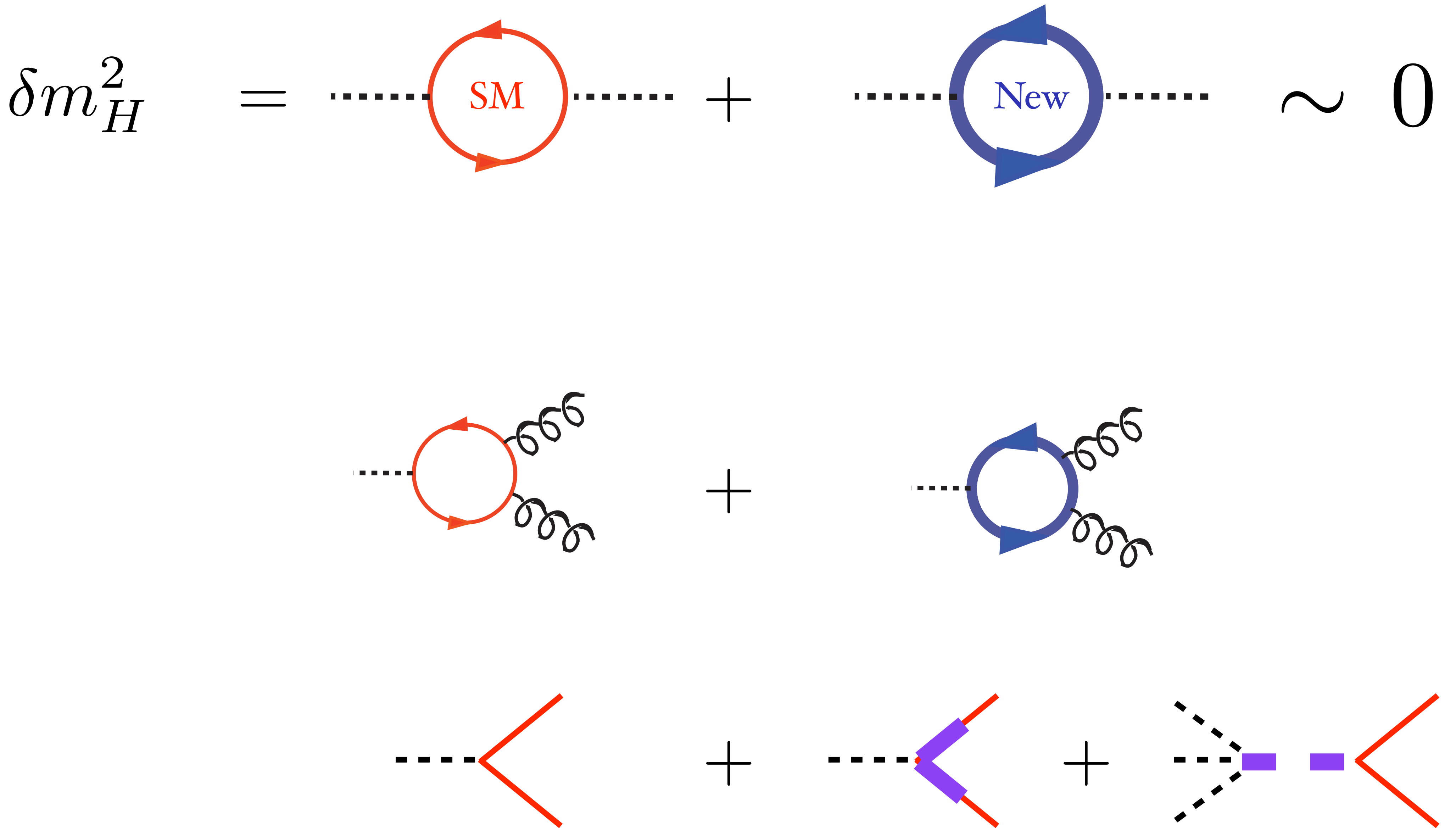
$\Rightarrow$ $m_h = 125\,\text{GeV}$

tuning $\left(\dfrac{125\,\text{GeV}}{\tilde{m}}\right)^2$



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





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Supersymmetry

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

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

soft $\rightarrow$ $O(1)$

super-soft $\rightarrow$ $O(\alpha_t/4\pi)$

Compositeness

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

minimal $\rightarrow$ $O(1)$

Little Higgs with T-parity $\rightarrow$ $O(\alpha_t/4\pi)$

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

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

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

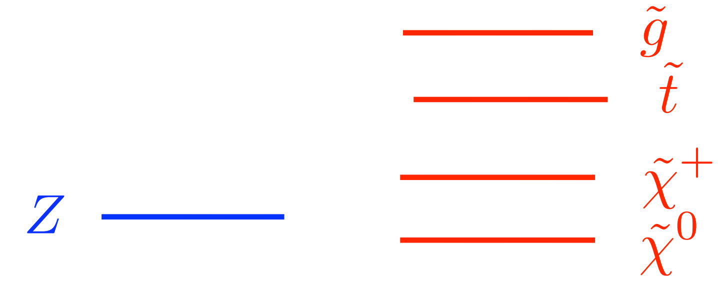
Perspective on Supersymmetry before and after LHC 7/8

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

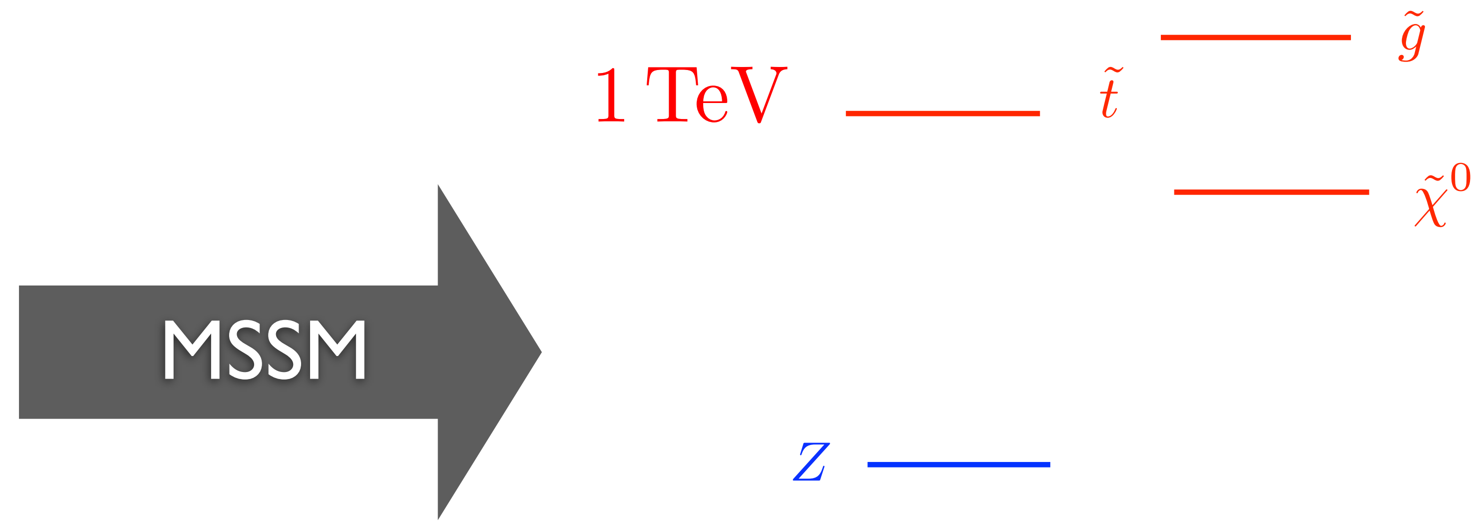
LEP/Tevatron

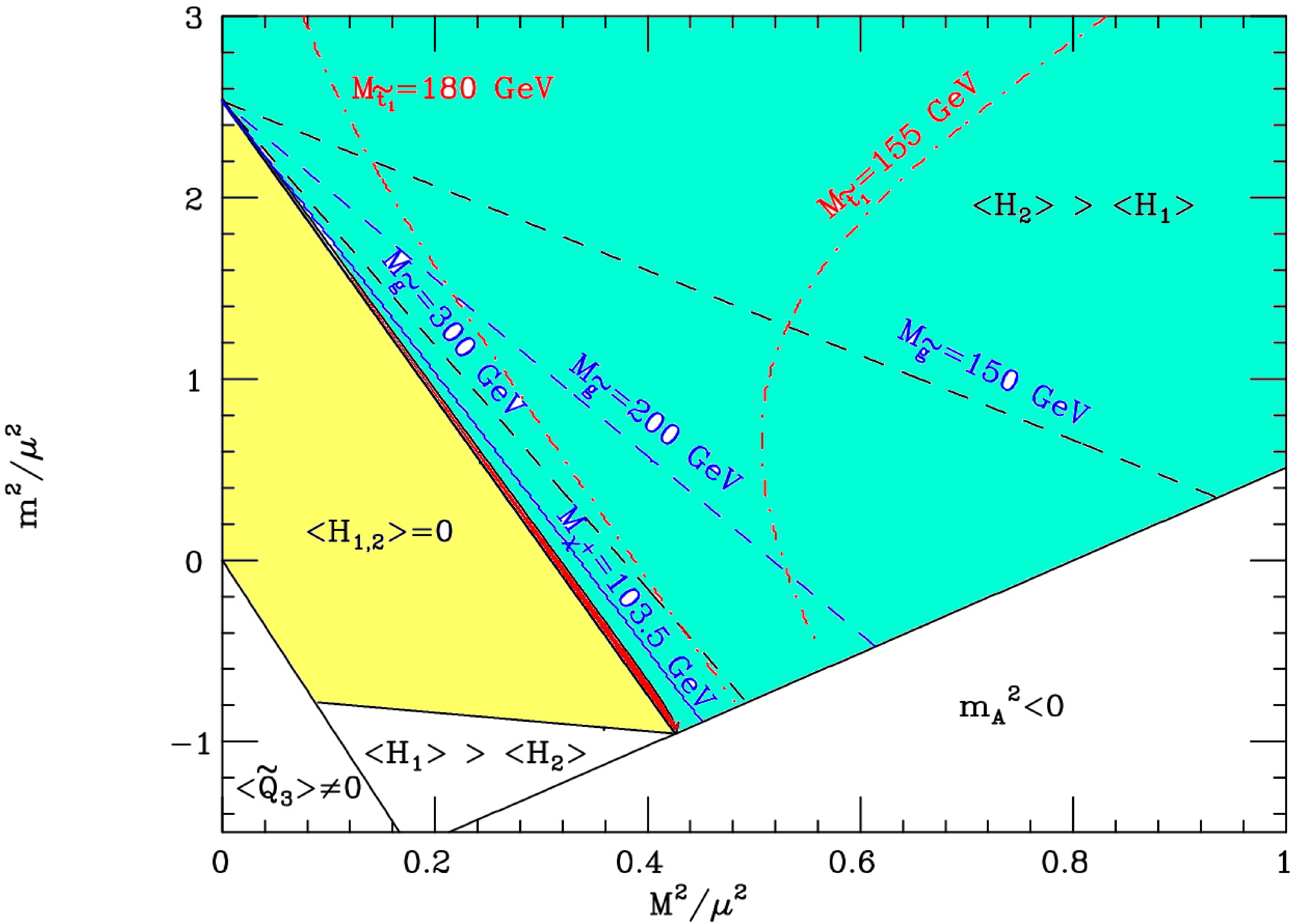
$$m_{\tilde{l}},\, m_{\chi^+} \gtrsim 100\,\mathrm{GeV}$$

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



$$m_h > 114.4\,\mathrm{GeV}$$





Giudice, Rattazzi '06

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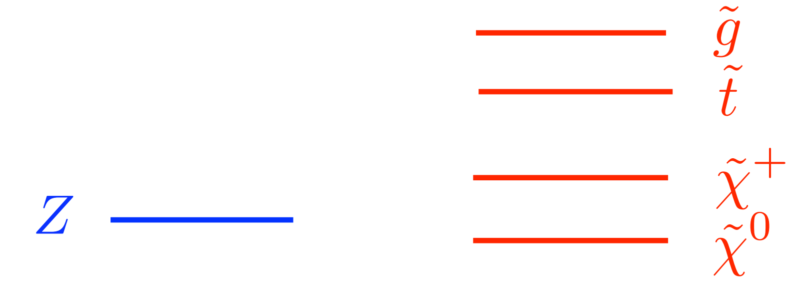

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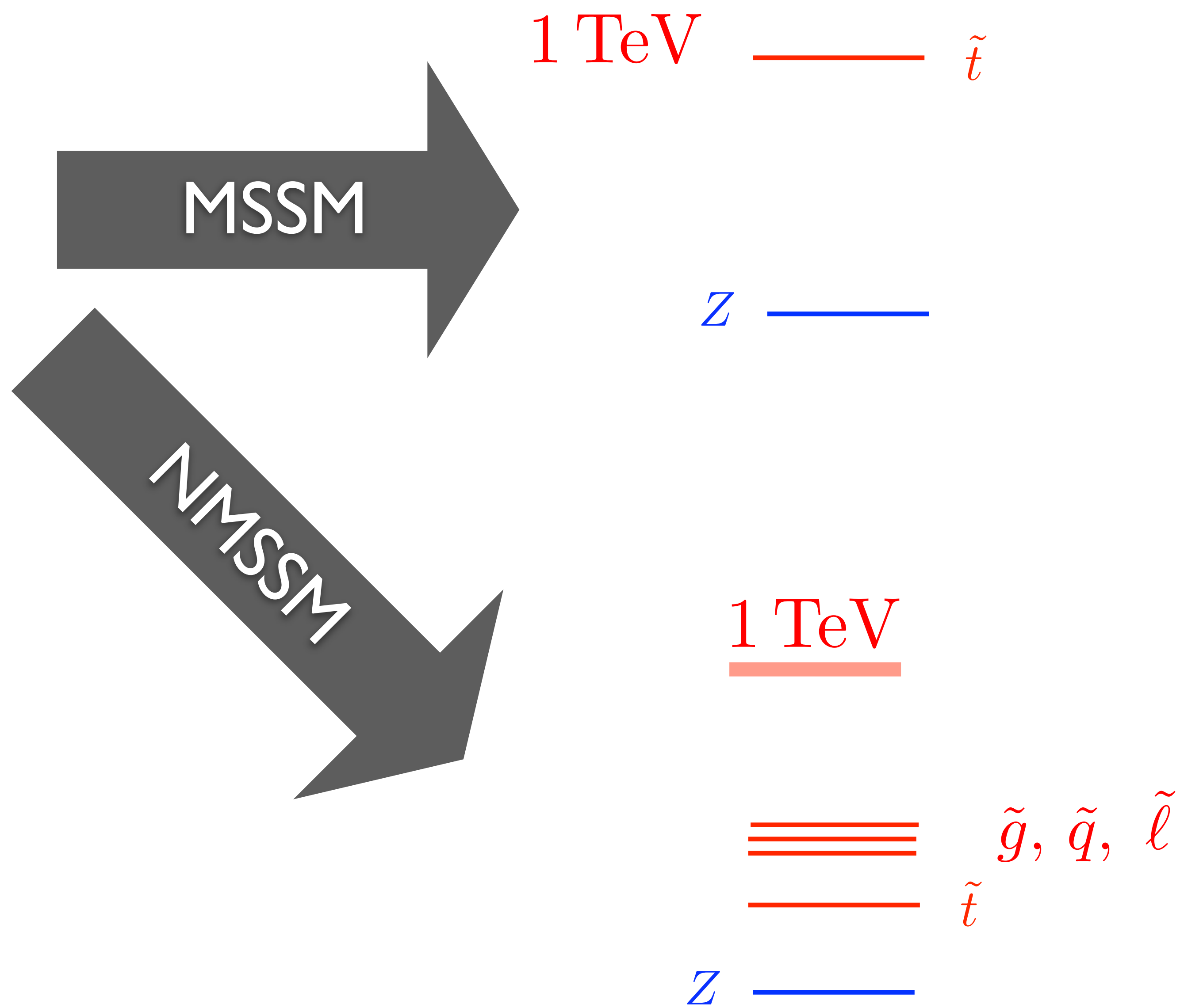


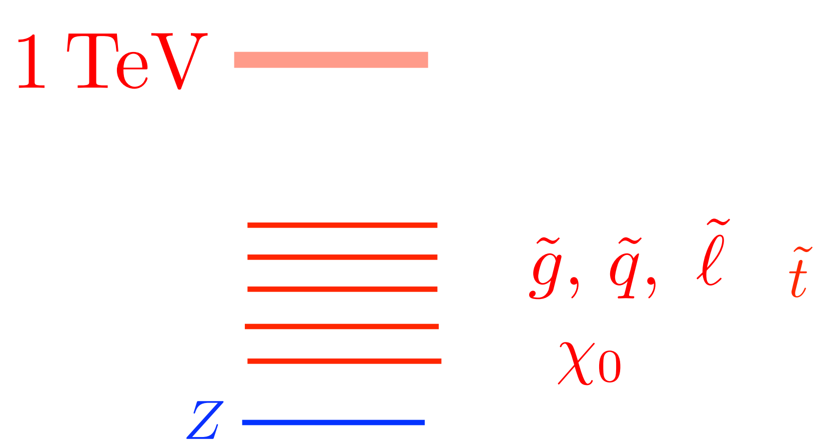
Before LHC: *natural* and *simple* spectrum possible within NMSSM

After LHC

- situation only slightly worse with $m_h \simeq 125\,\mathrm{GeV}$ 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 straighforward NMSSM scenario (in particular flavor universal sfermion masses)



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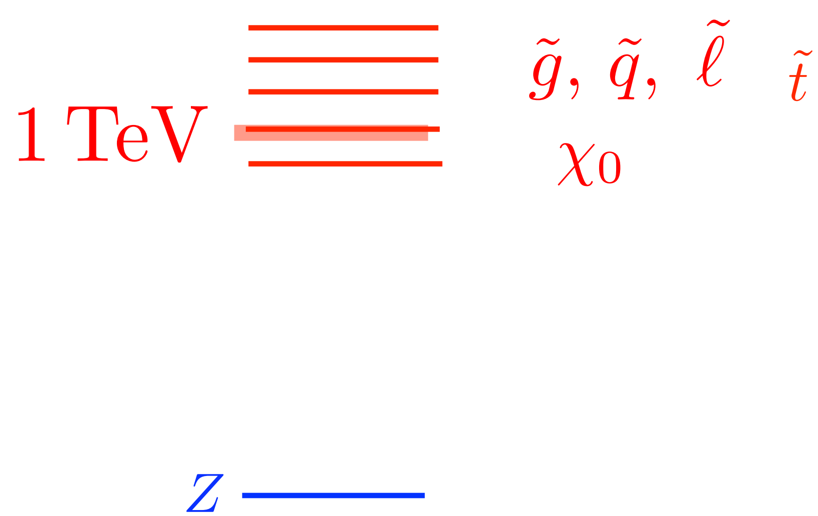
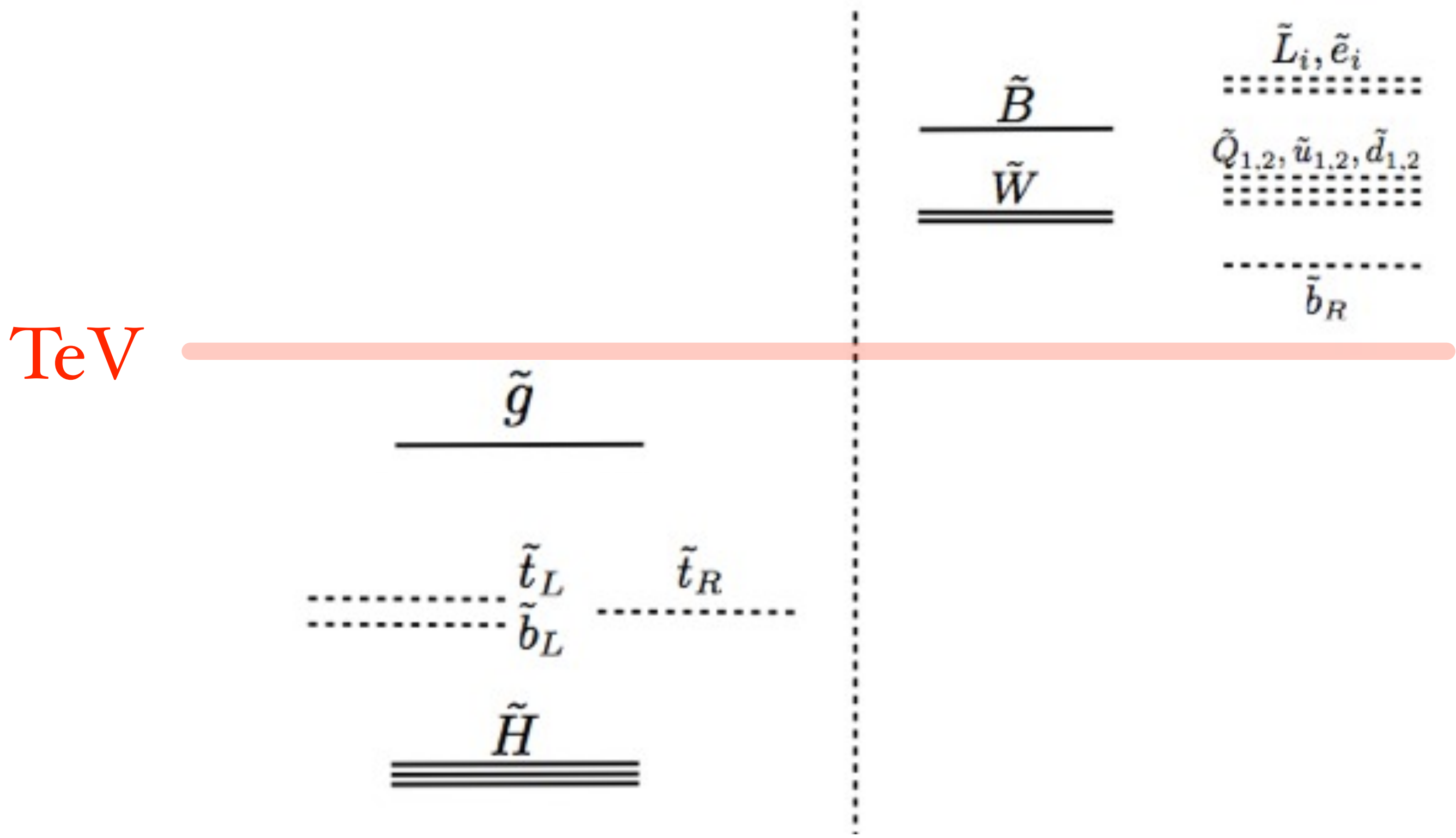


MSSM: simplest scenarios were under pressure already before LHC

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

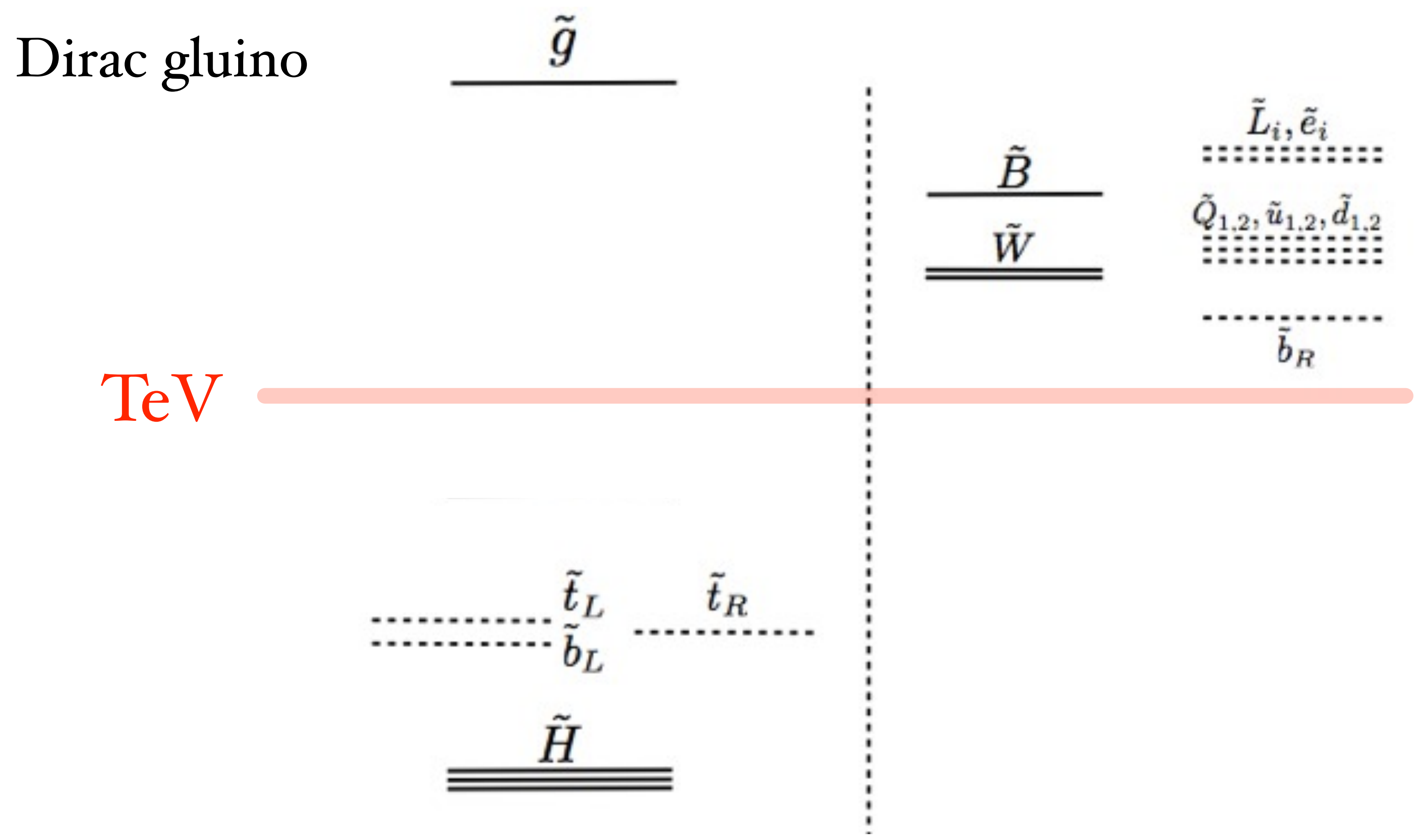


$m_{\tilde{t}} \lesssim 500\,\mathrm{GeV}$ some other physics (ex NMSSM) takes care of m_h

consider all possible ways to suppress the signal:

Dirac gluino, RPV, compressed spectrum,...

not-so-un-Natural SUSY



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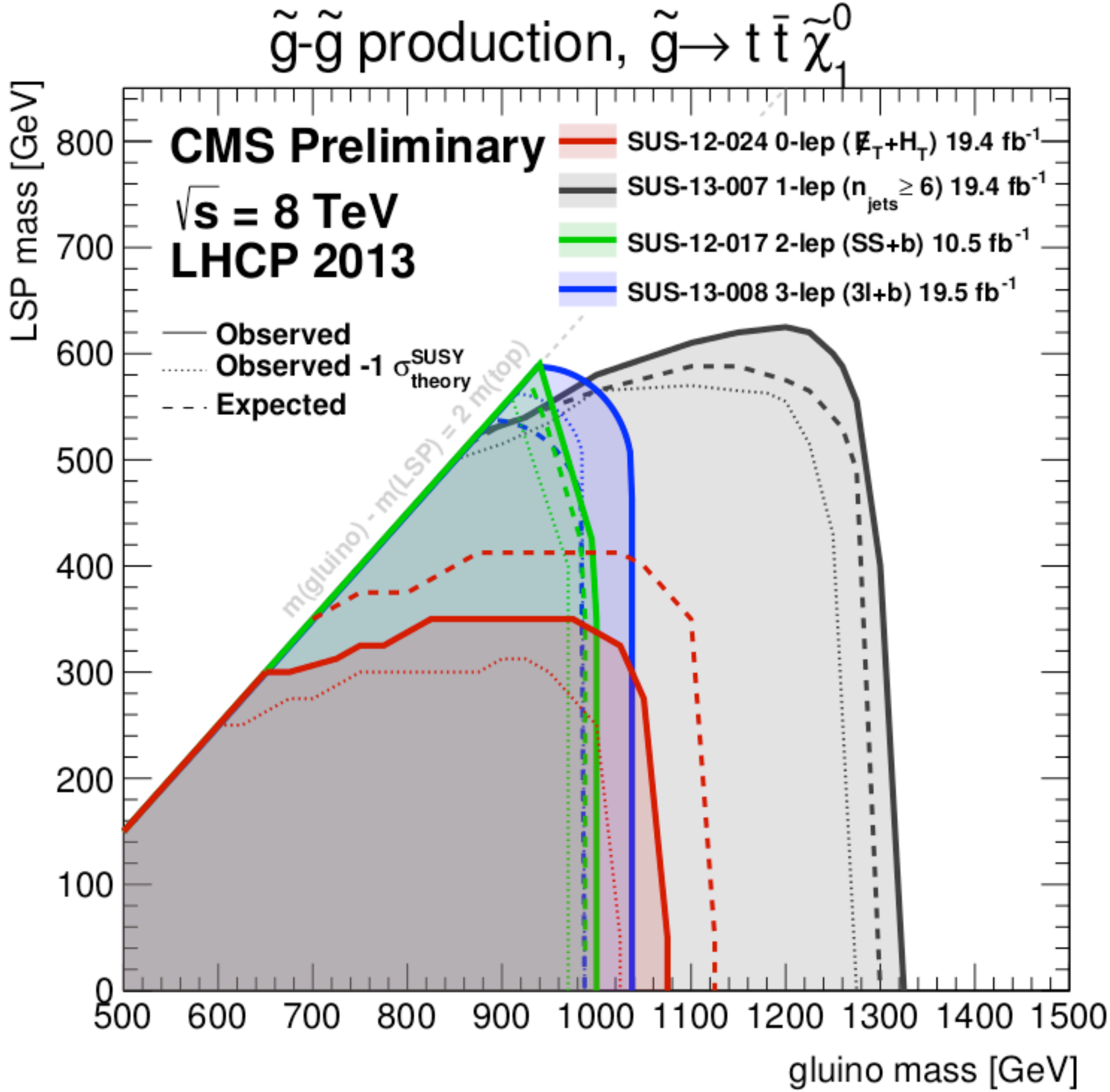
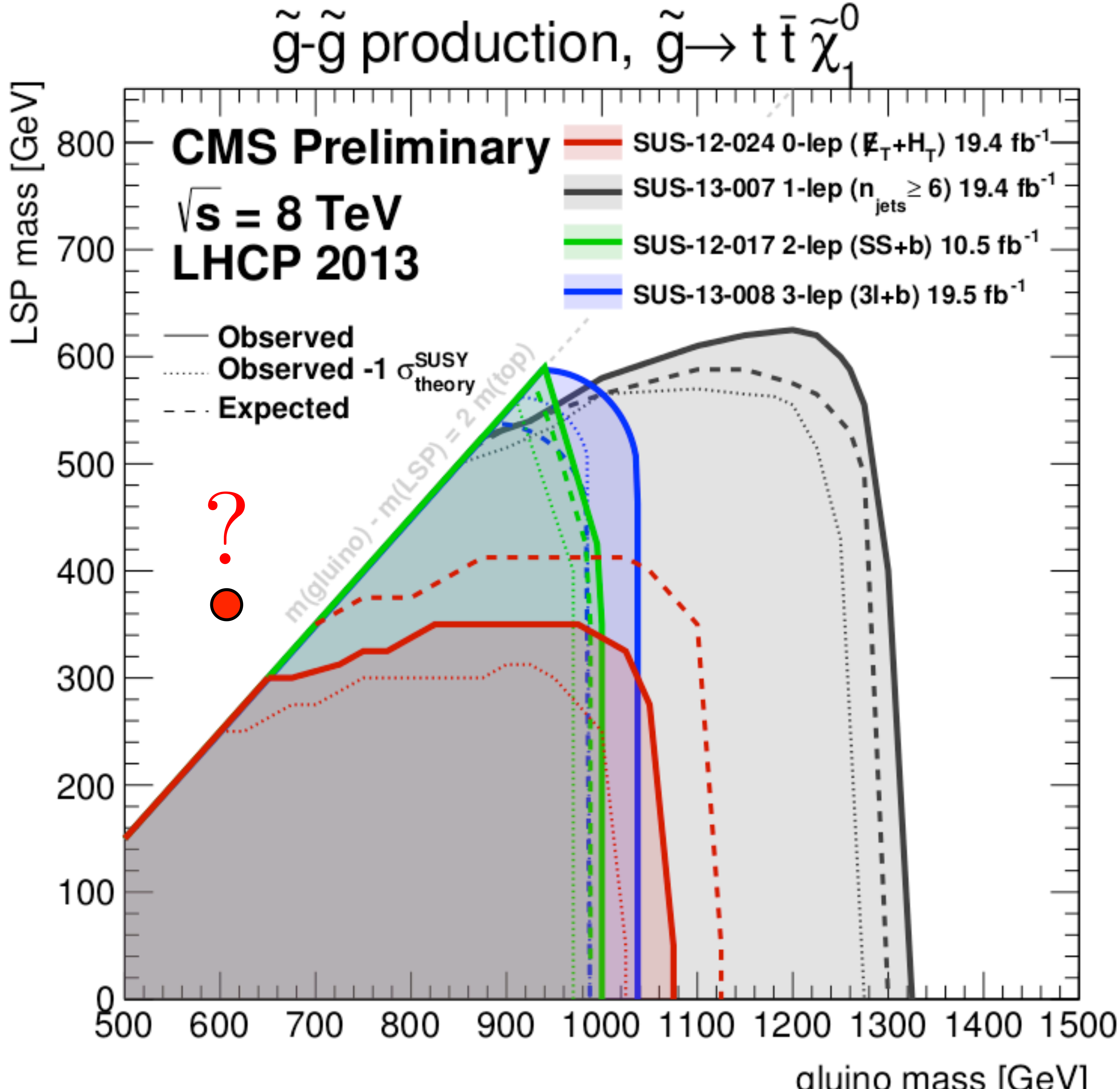


$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}^0_1$
CMS Preliminary
$\sqrt{s}$ = 8 TeV
LHCP 2013
SUS-12-024 0-lep ($\not{E}_T$+H_T) 19.4 fb^{-1}
SUS-13-007 1-lep ($n_{jets} \geq 6$) 19.4 fb^{-1}
SUS-12-017 2-lep (SS+b) 10.5 fb^{-1}
SUS-13-008 3-lep (3l+b) 19.5 fb^{-1}
Observed
Observed -1 σ^{SUSY}_{theory}
Expected
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
gluino mass [GeV]
0
100
200
300
400
500
600
700
800
500
600
700
800
900
1000
1100
1200
1300
1400
1500



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?
LSP mass [GeV]
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0
100
200
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400
500
600
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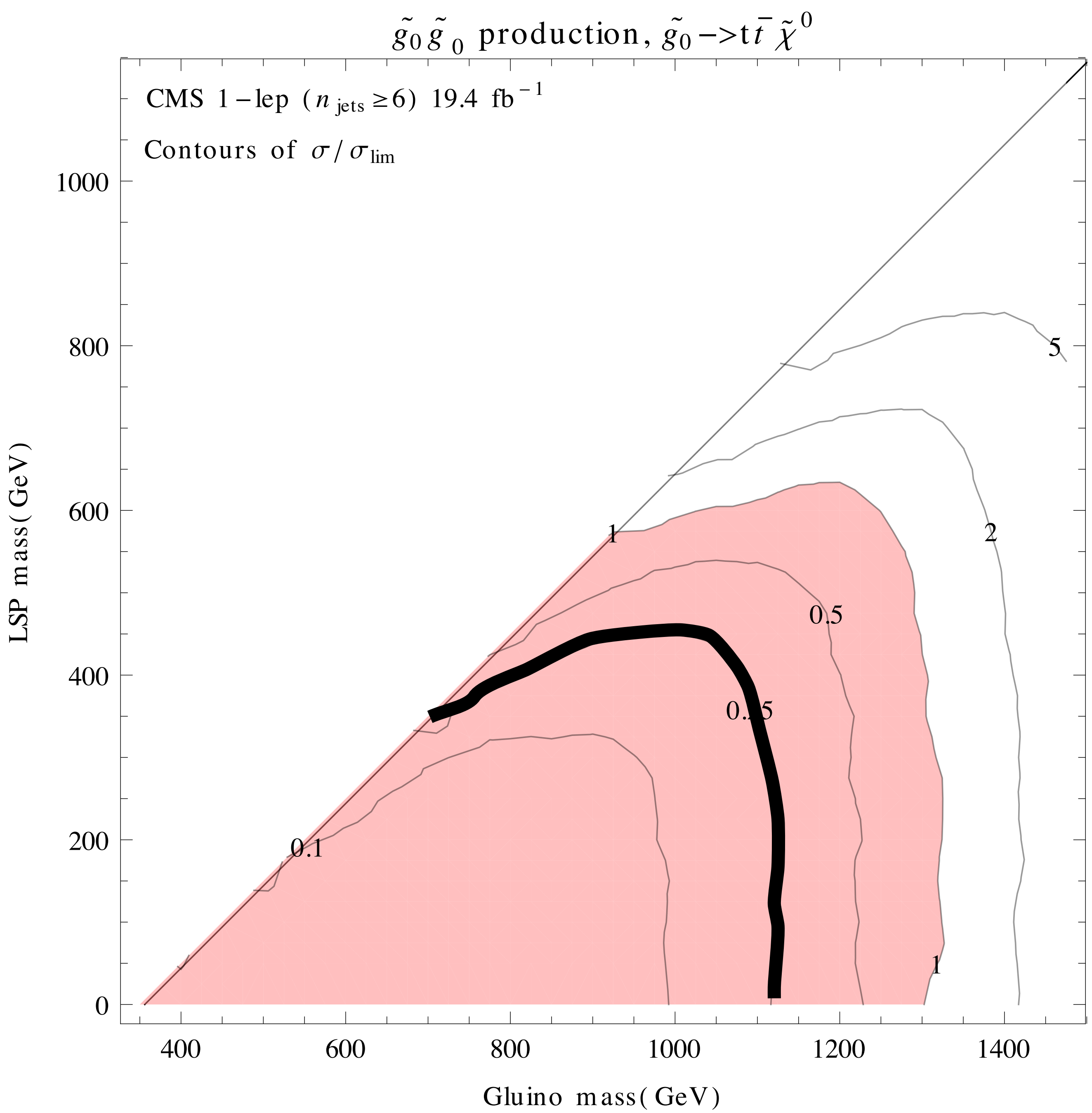
800
500
600
700
800
900
1000
1100
1200
1300
1400
1500

notice Br(4t) < 0.25 in relevant scenario:
15-20% reduction of bound

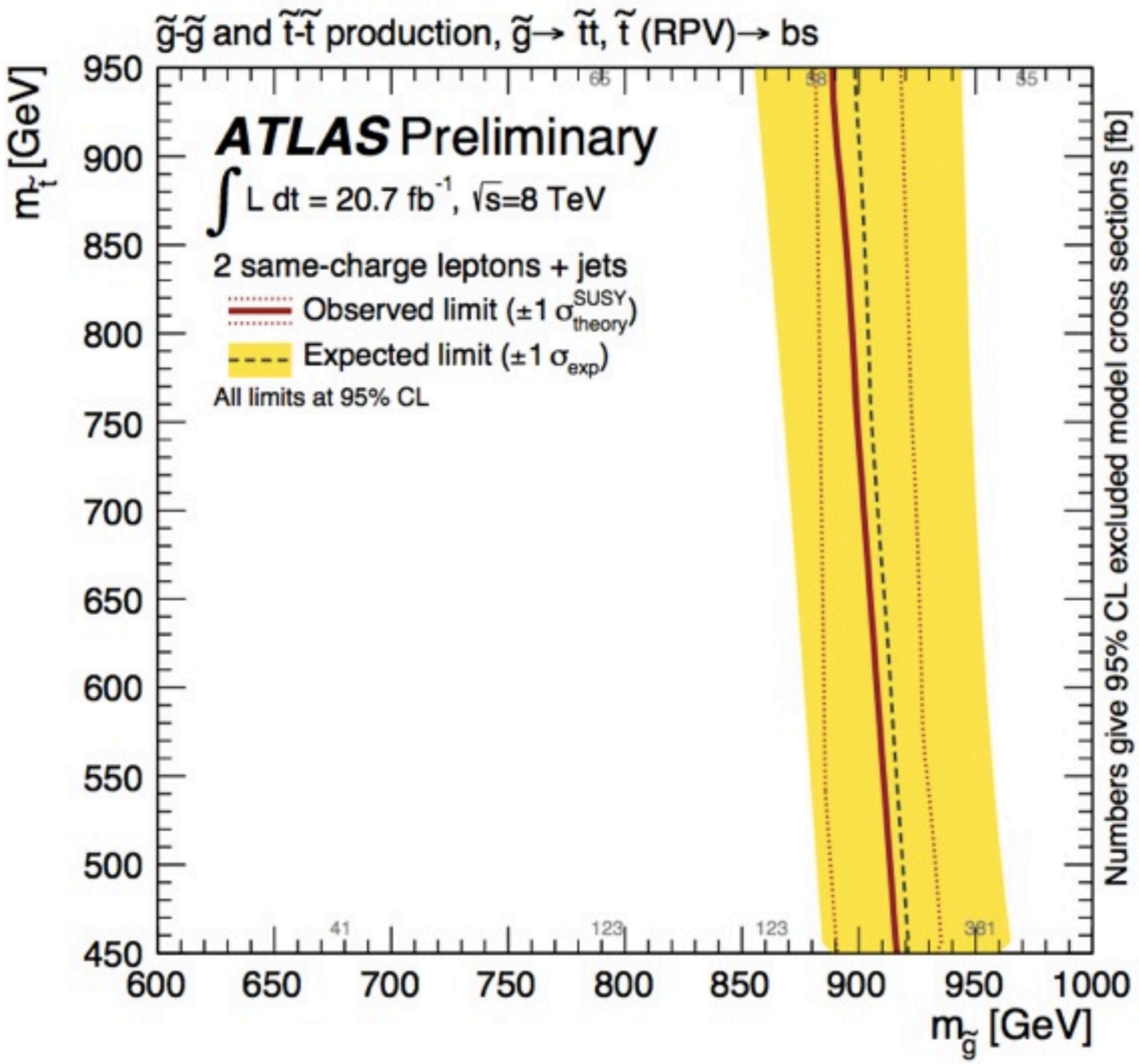
Barbieri, Pappadopulo '09



Mahbubani '13

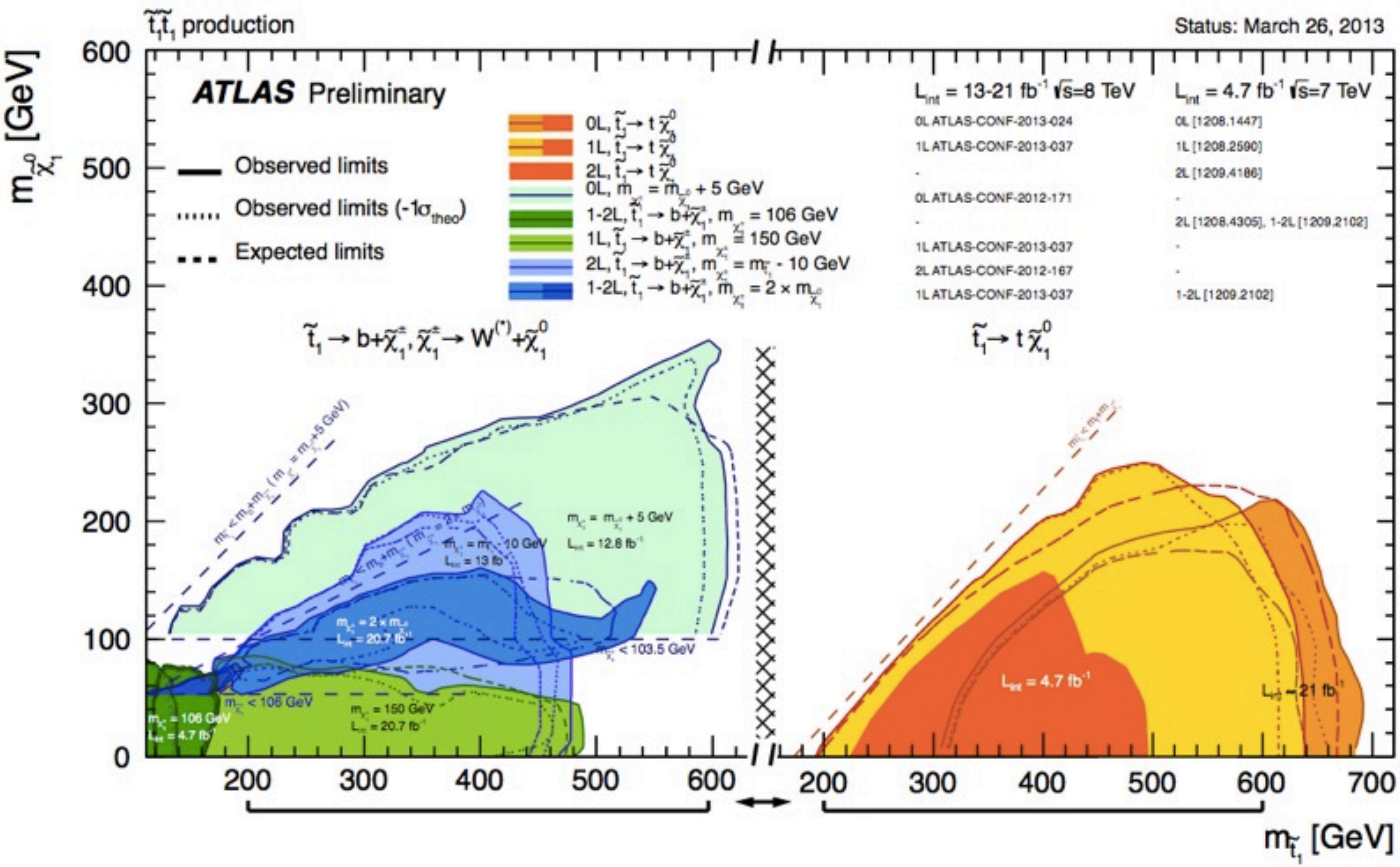
however the other channels (tttb, ttbb) add to same signal
expect compensation, in the end bound should not change much

what about some help from baryonic RPV?



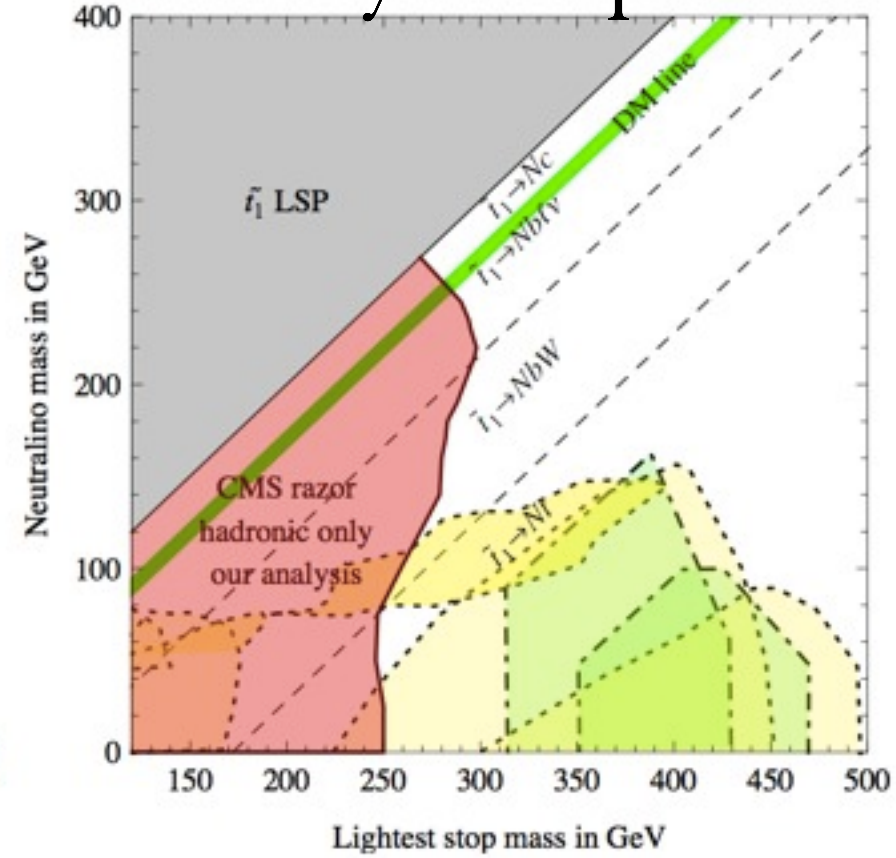
some relaxation but not much

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



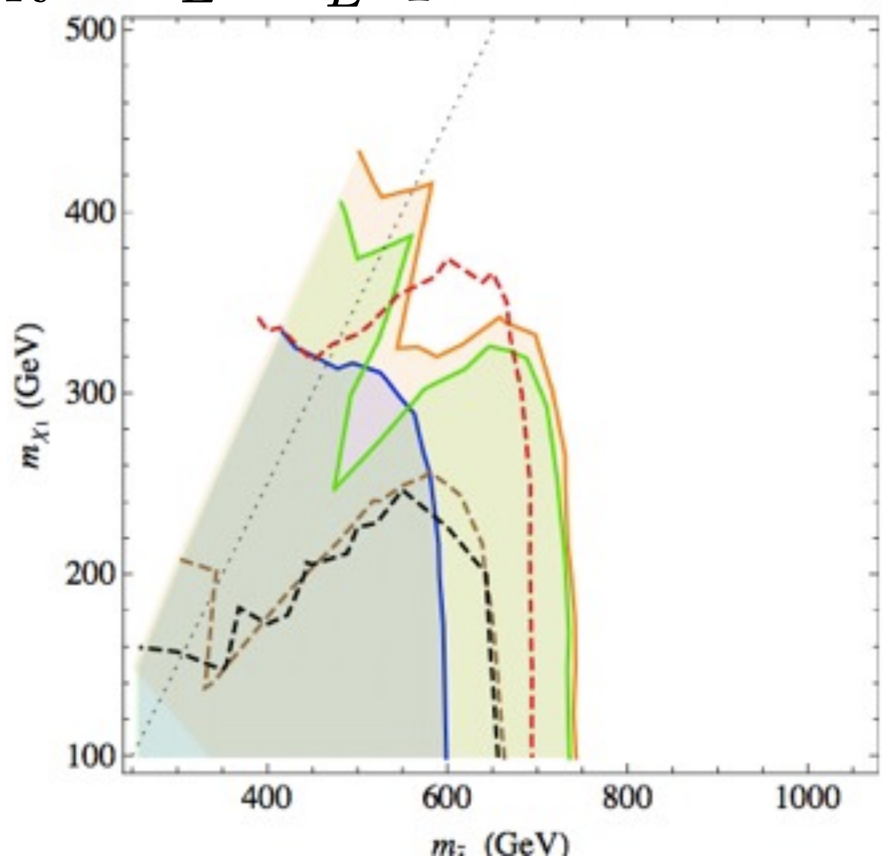
impressive but significant natural regions with squashed
spectra remain

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



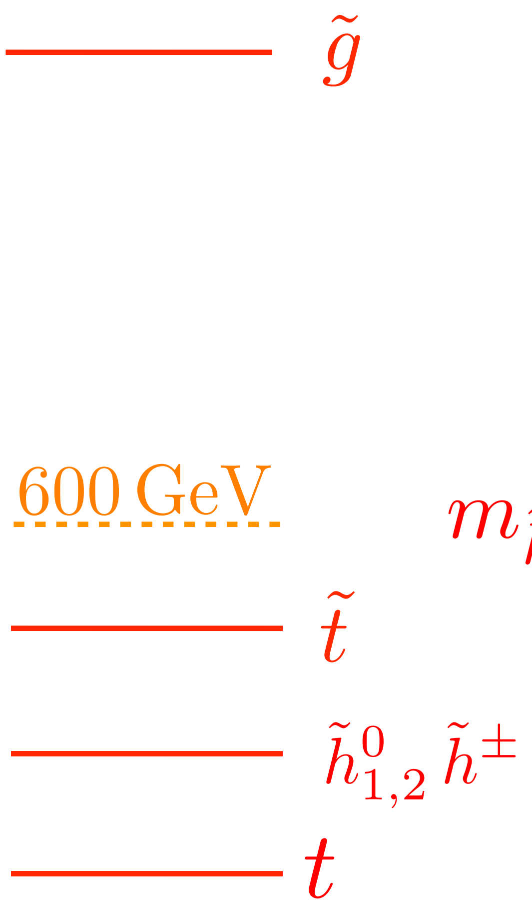
Delgado, Giudice, Isidori, Pierini, Strumia '13

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

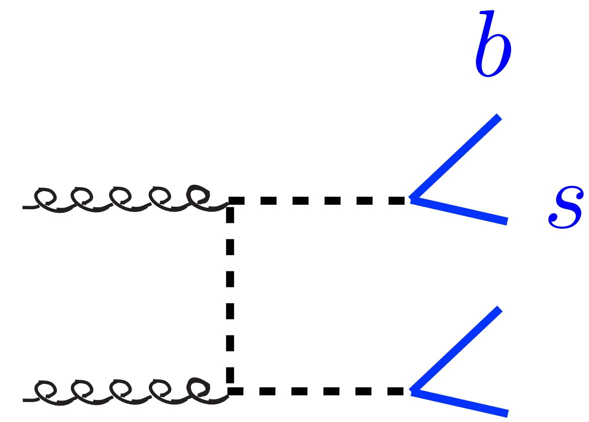


Kribs, Martin, Menon '13

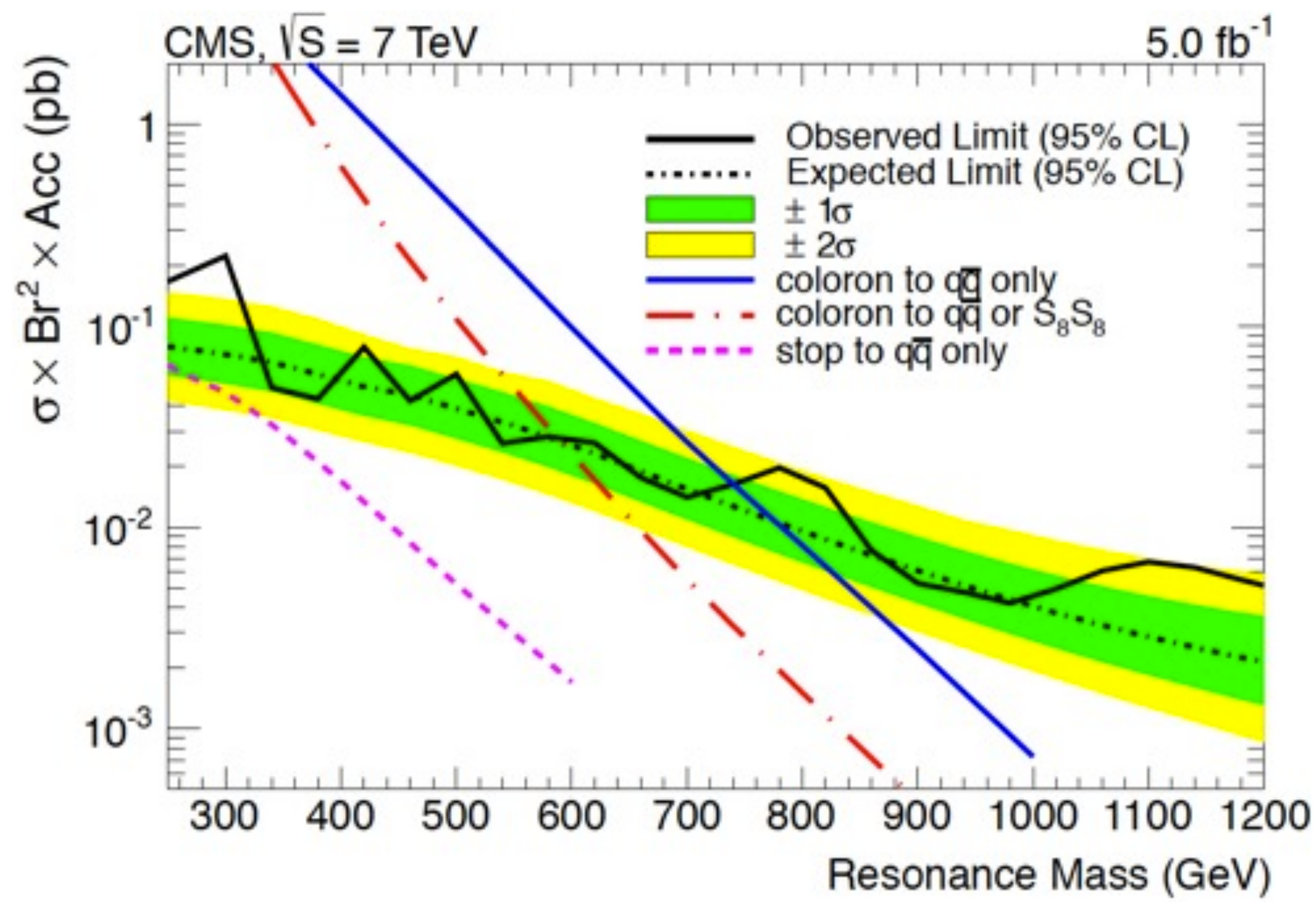
what about RPV decaying $\tilde{t}_R$, $\tilde{t}_L$, $\tilde{b}_L$?



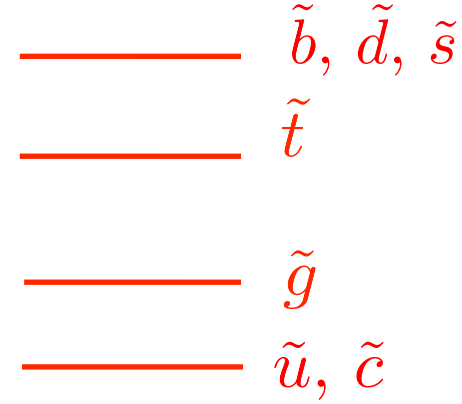
$$m_{\tilde{h}} + m_t > m_{\tilde{t}}$$

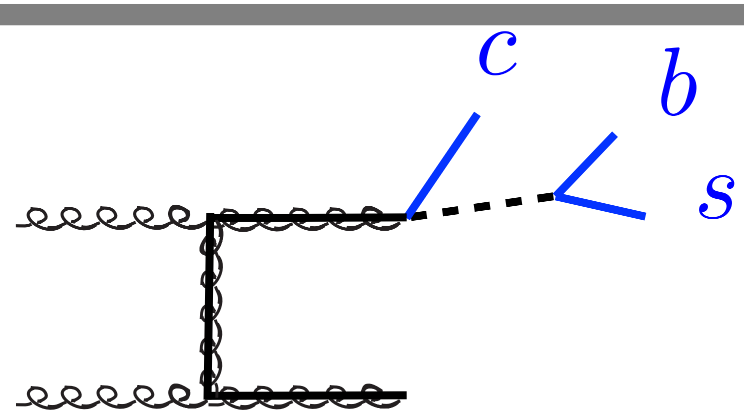


CMS 7 TeV data below
250 Gev
wait for upcoming 8 TeV



what about topless gluino decays?





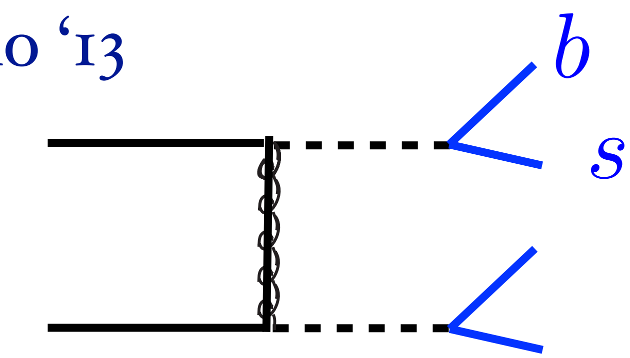
ATLAS, 7 TeV 4.6 fb-1

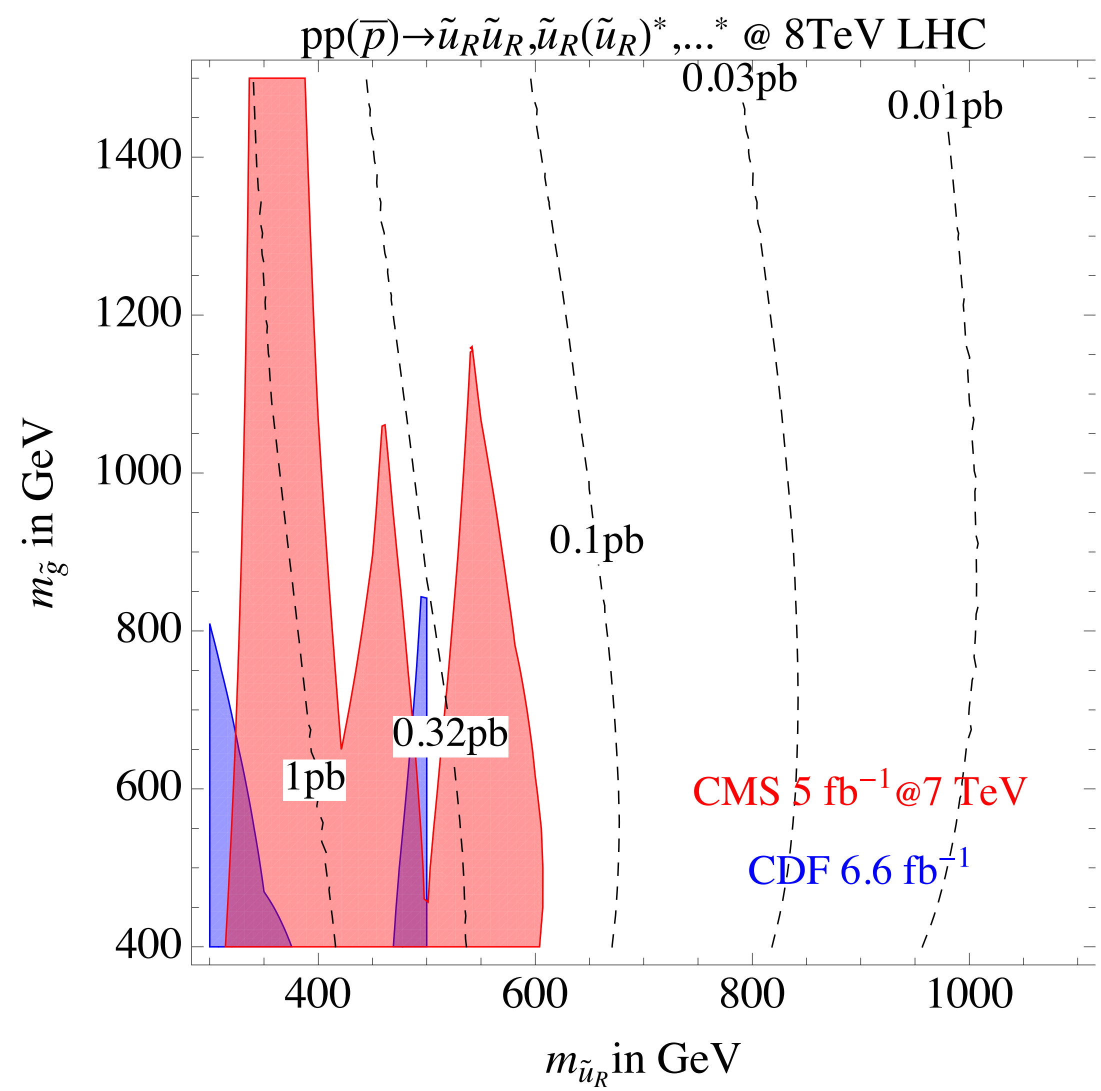
$m_{\tilde{g}} > 666$ GeV

but bound relaxed if bino enters decays chain

$\tilde{g}\tilde{g} \to 10$jets

Pappadopulo '13





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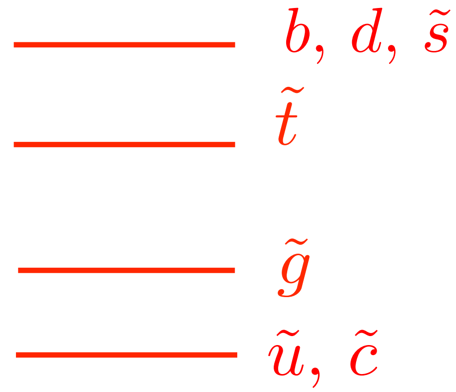

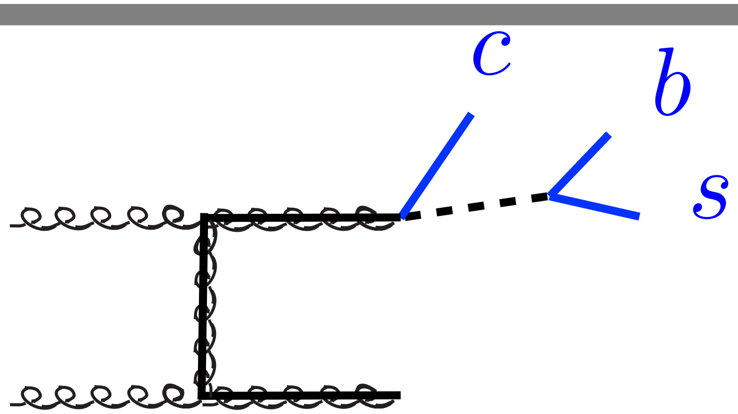

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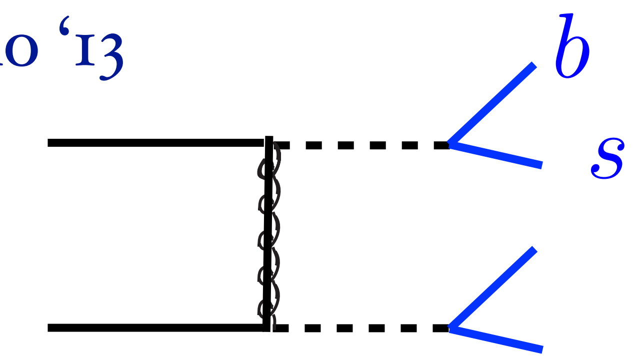
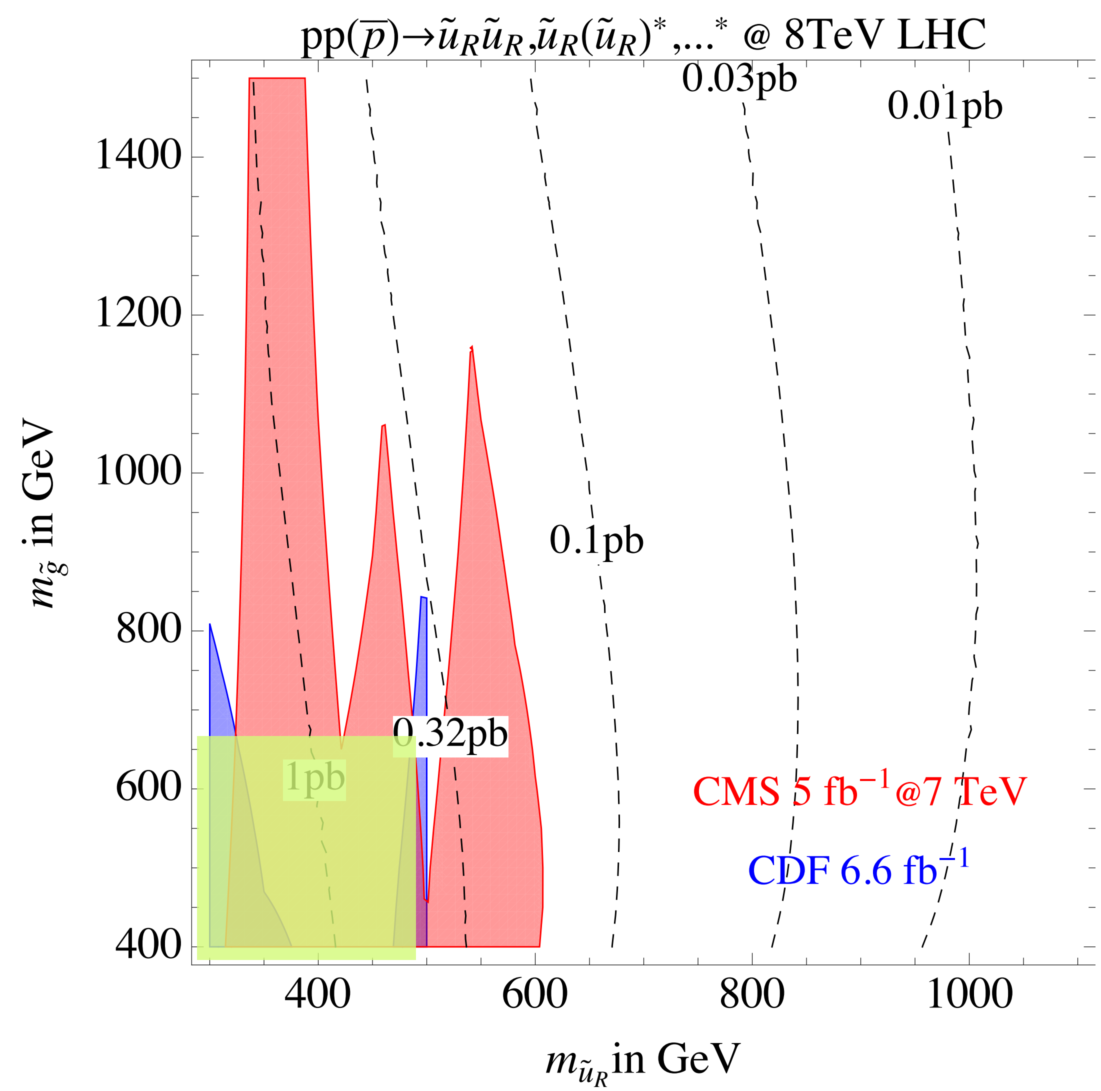




ATLAS & CMS are hunting down Supersymmetry in nooks and crannies

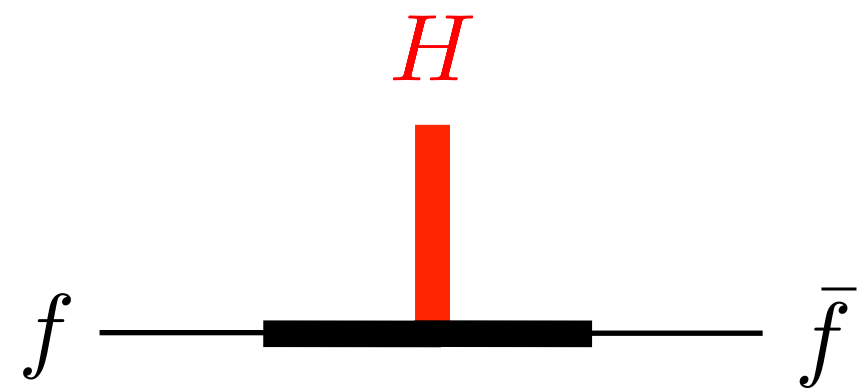
Looking forward to next run and to even more clever analyses

Too early tough 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



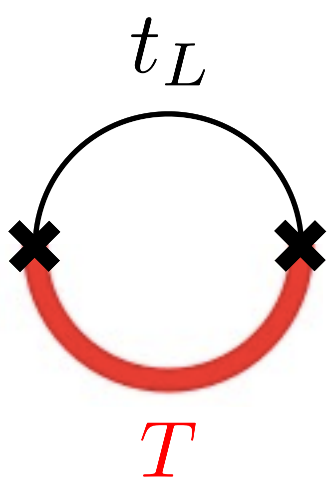
without any additional symmetry

FCNC	$m_* \gtrsim 10-20\,\text{TeV}$
edms	$m_* \gtrsim 40\,\text{TeV}$
$\mu \to e\gamma$	$m_* \gtrsim 150\,\text{TeV}$

with combination of SU(2)'s and SU(3) can bring scale down to ~TeV

Redi '12
Babrbieri, Buttazzo, Sala, Straub, Tesi '12

$V(H) =$



top partners $\longleftrightarrow$ $(B_{-1/3}, \quad T_{2/3}, \quad X_{5/3}, \quad \Xi_{8/3}, \ldots)$

expectations from naturalness

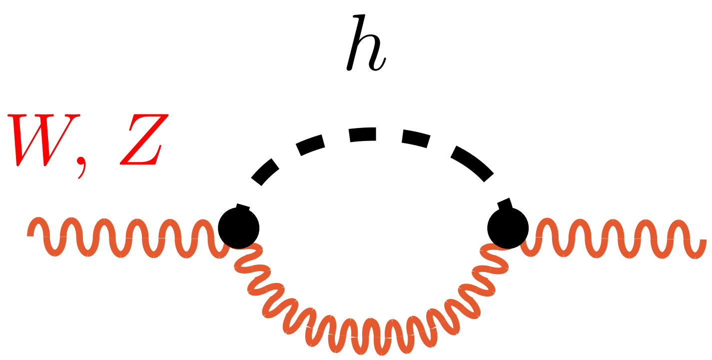
generic $\quad V \equiv V(H/f)$

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

$m_h \simeq 125\,\text{GeV}$

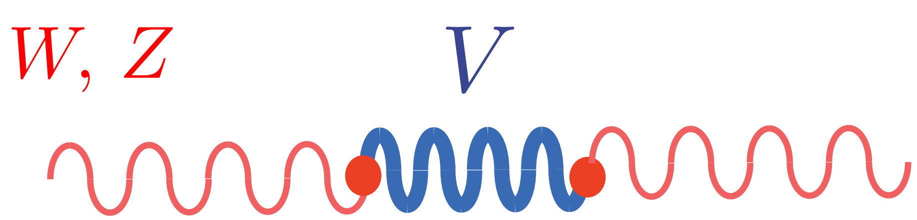
$$\left(\frac{400\,\text{GeV}}{m_T}\right)^2 = O(1)$$

Electroweak Precision Tests



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

$$\frac{v^2}{f^2} \lesssim 0.05 \quad \text{(pessimist)} \qquad (0.2) \quad \text{(optimist)}$$



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

$$m_V^2 \gtrsim 2 - 3\,\mathrm{TeV}$$

EWPT already imply some tuning

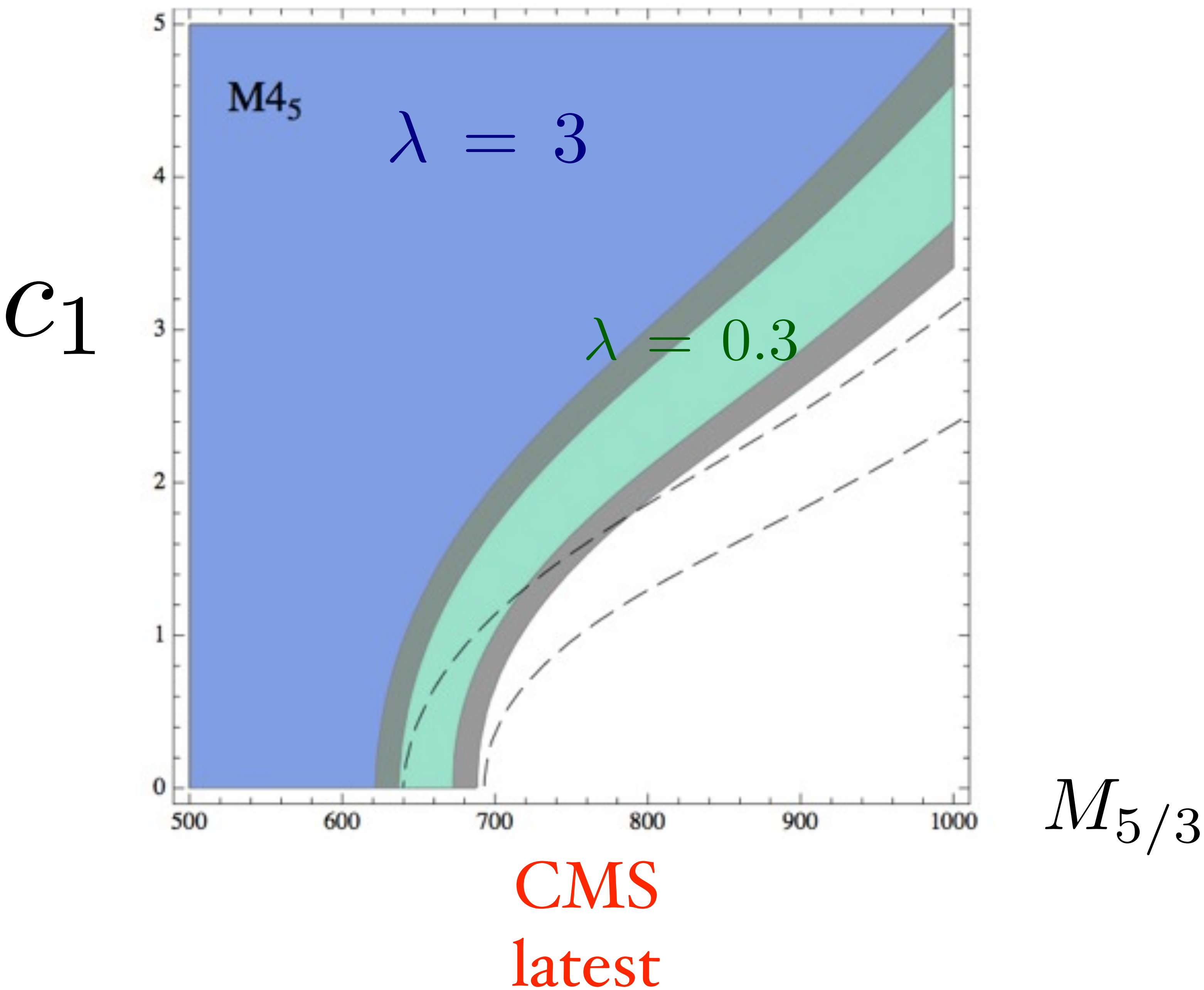
technical naturalness demands structural complexity $(\,m_V \gg m_T\,)$

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

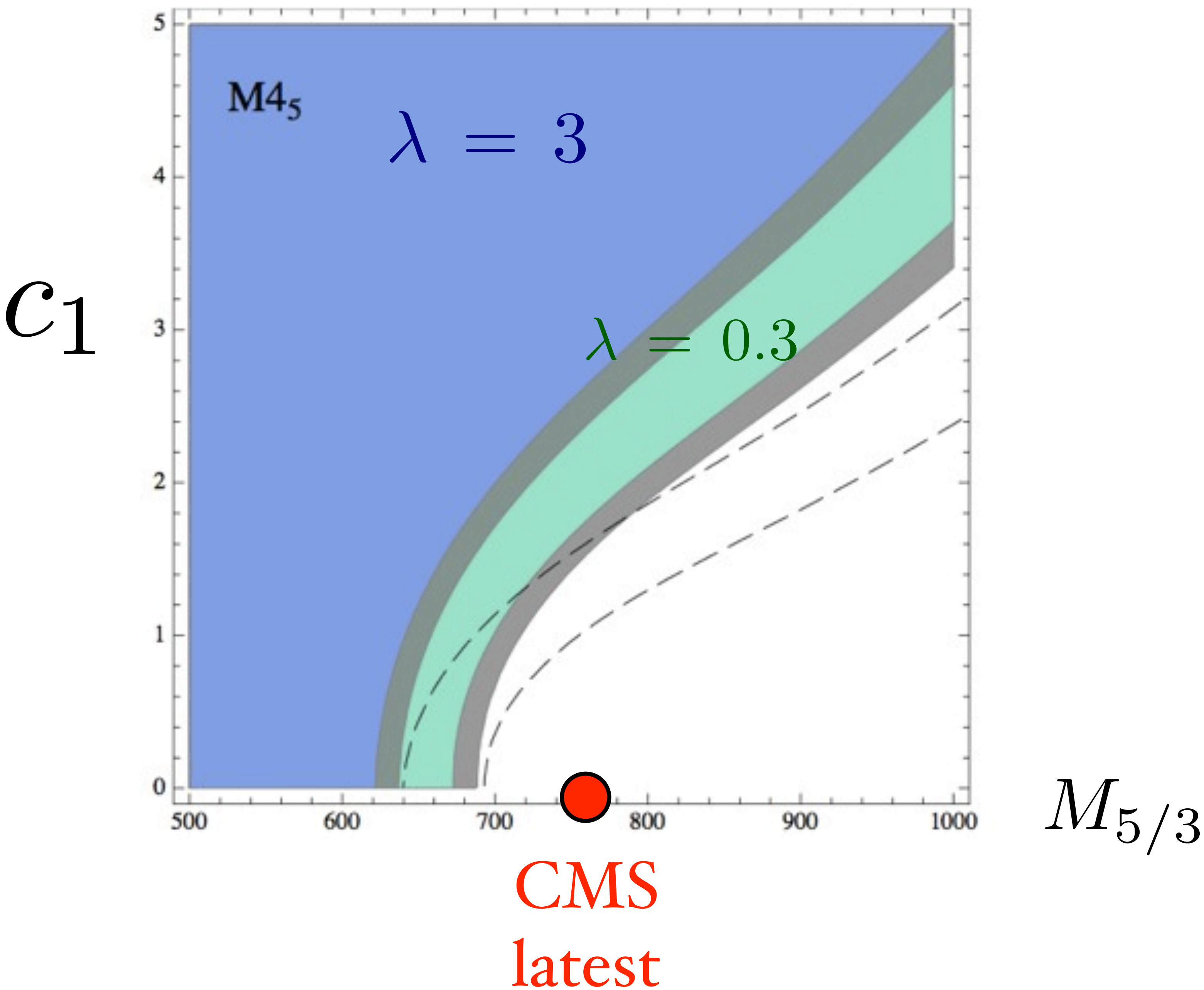
De Simone, Matsedonkyi, Rattazzi , Wulzer '12



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

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

De Simone, Matsedonkyi, Rattazzi , Wulzer '12



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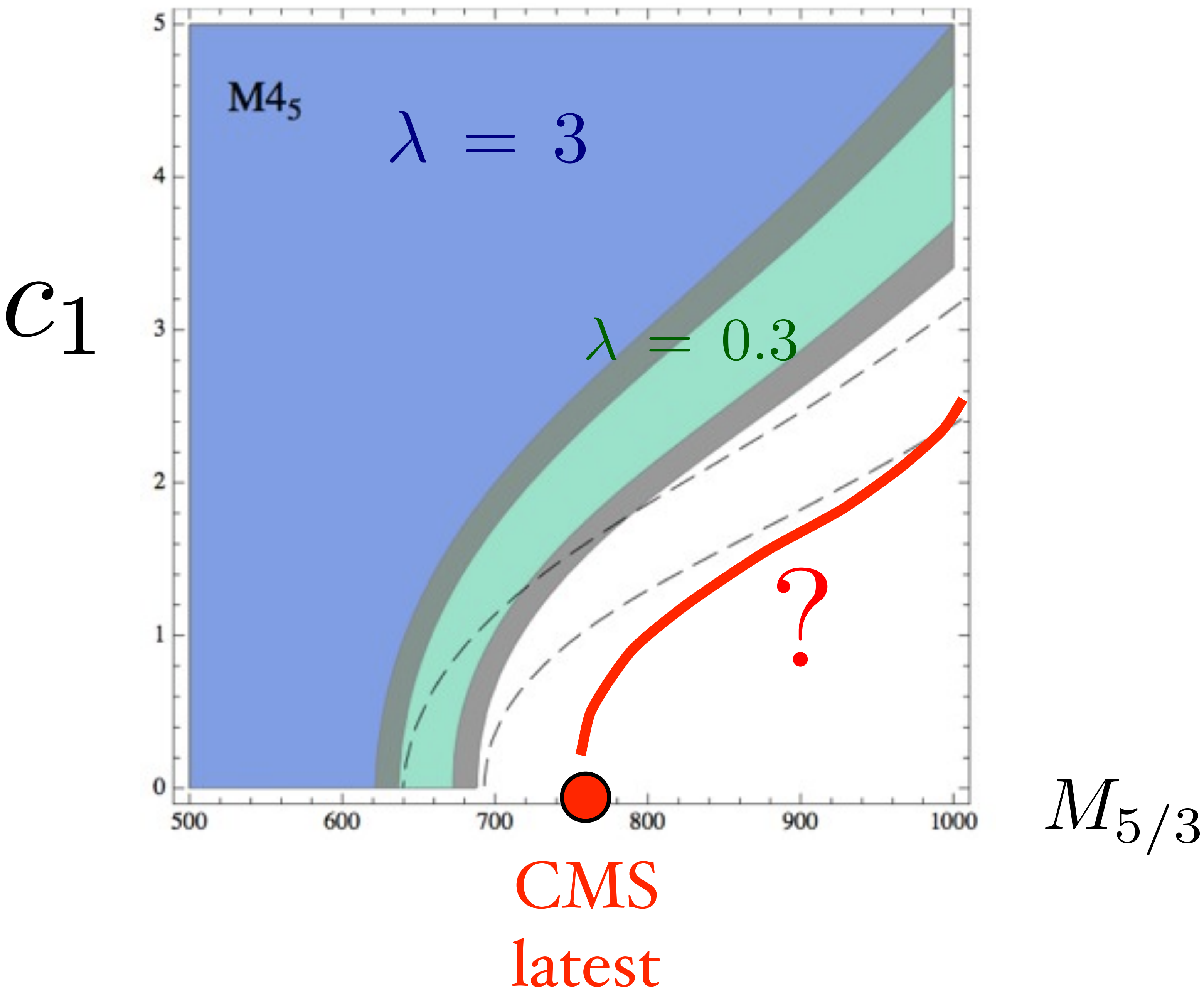

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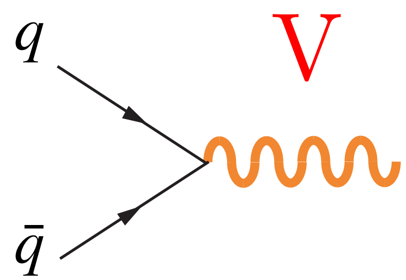
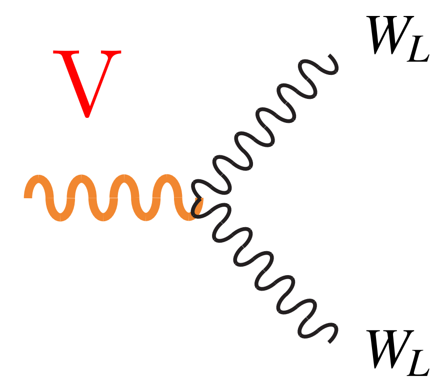
Vector Resonances



$$= \frac{g_W^2}{g_V} \ll g_W$$



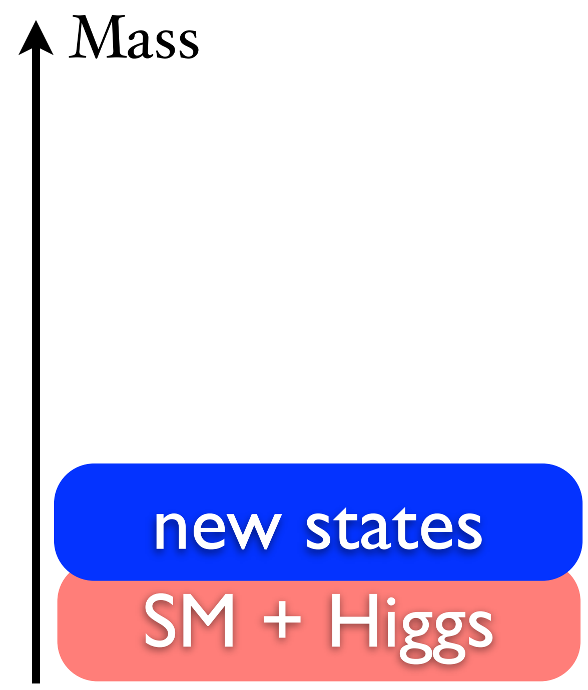
$$= g_V$$

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

- 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

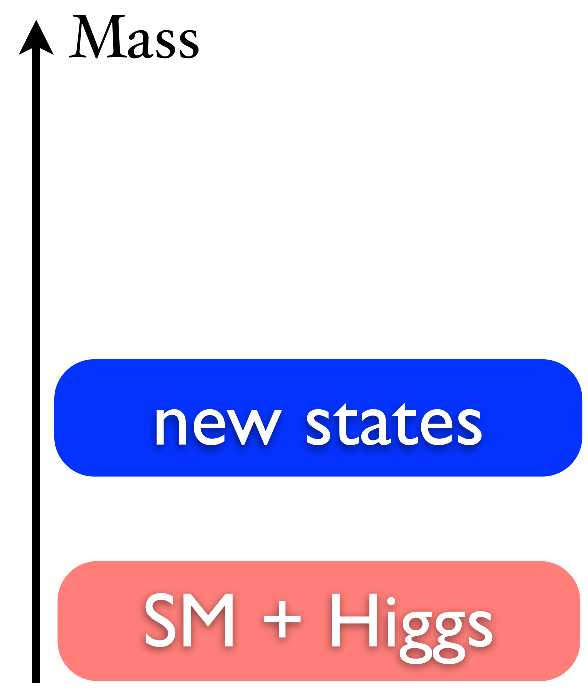
upcoming ‘theorists analysis’ : Contino, Grojean, Pappadopulo, Thamm, Torre, Wulzer

Higgzoology



Can use effective lagrangian to describe deviations from SM

= simple parametrization encompassing a large class of models



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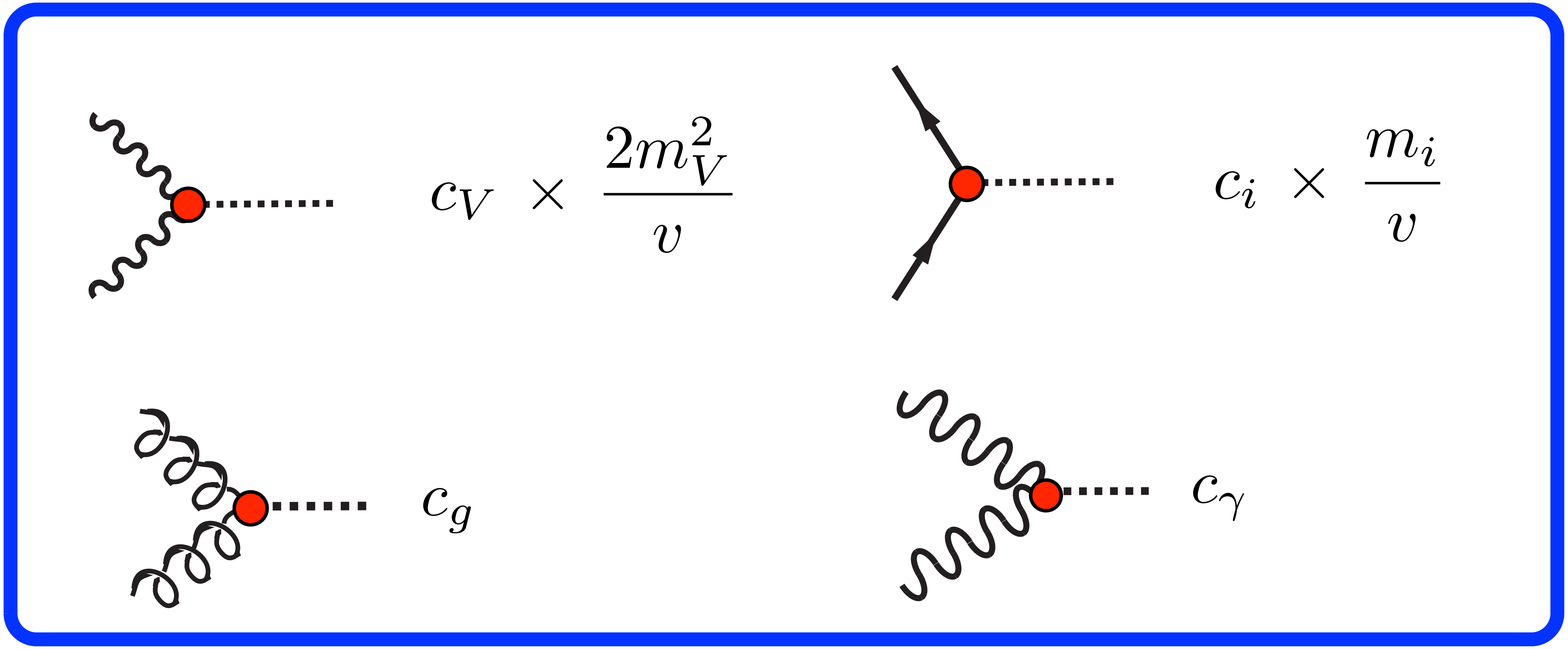
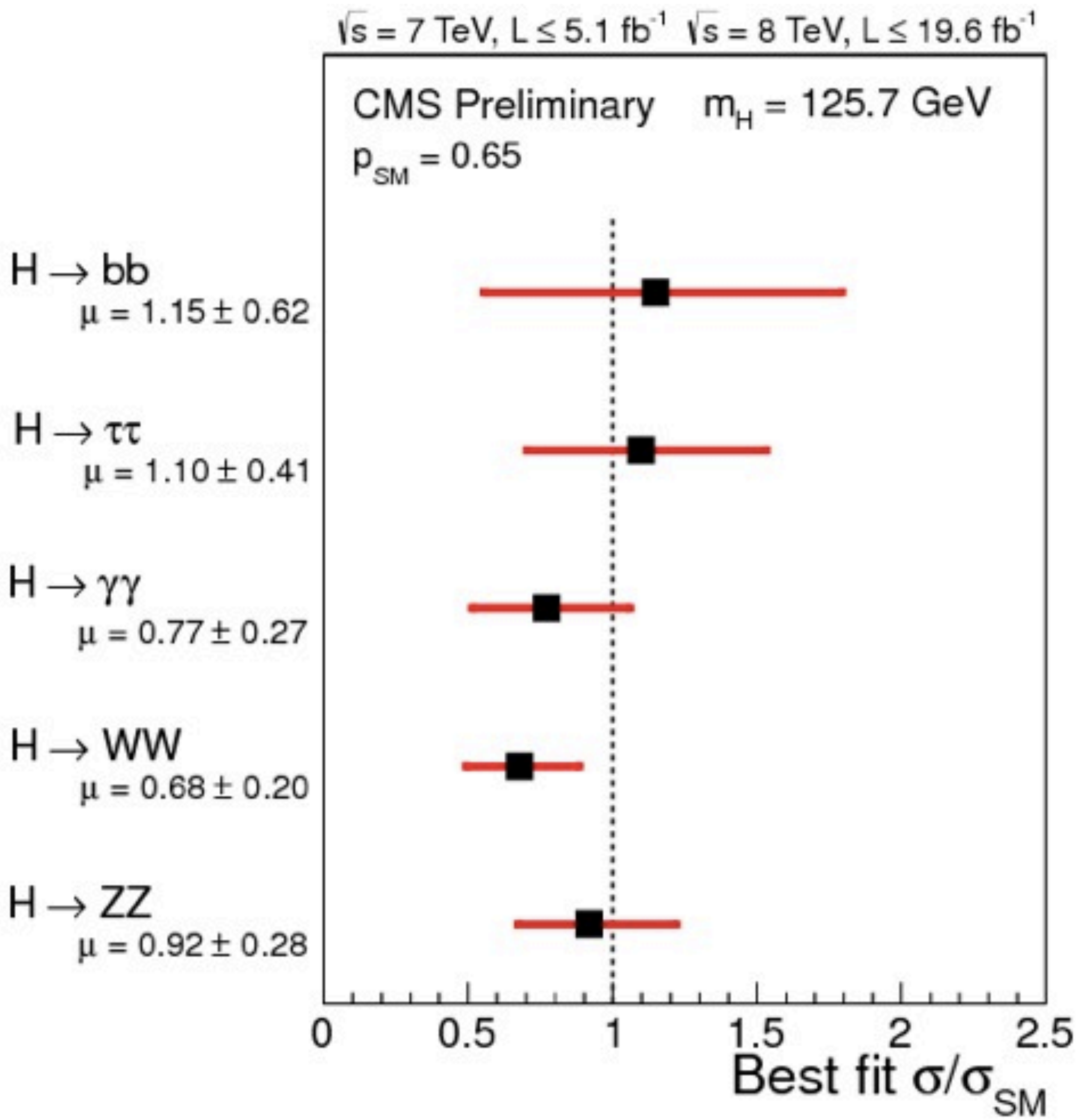


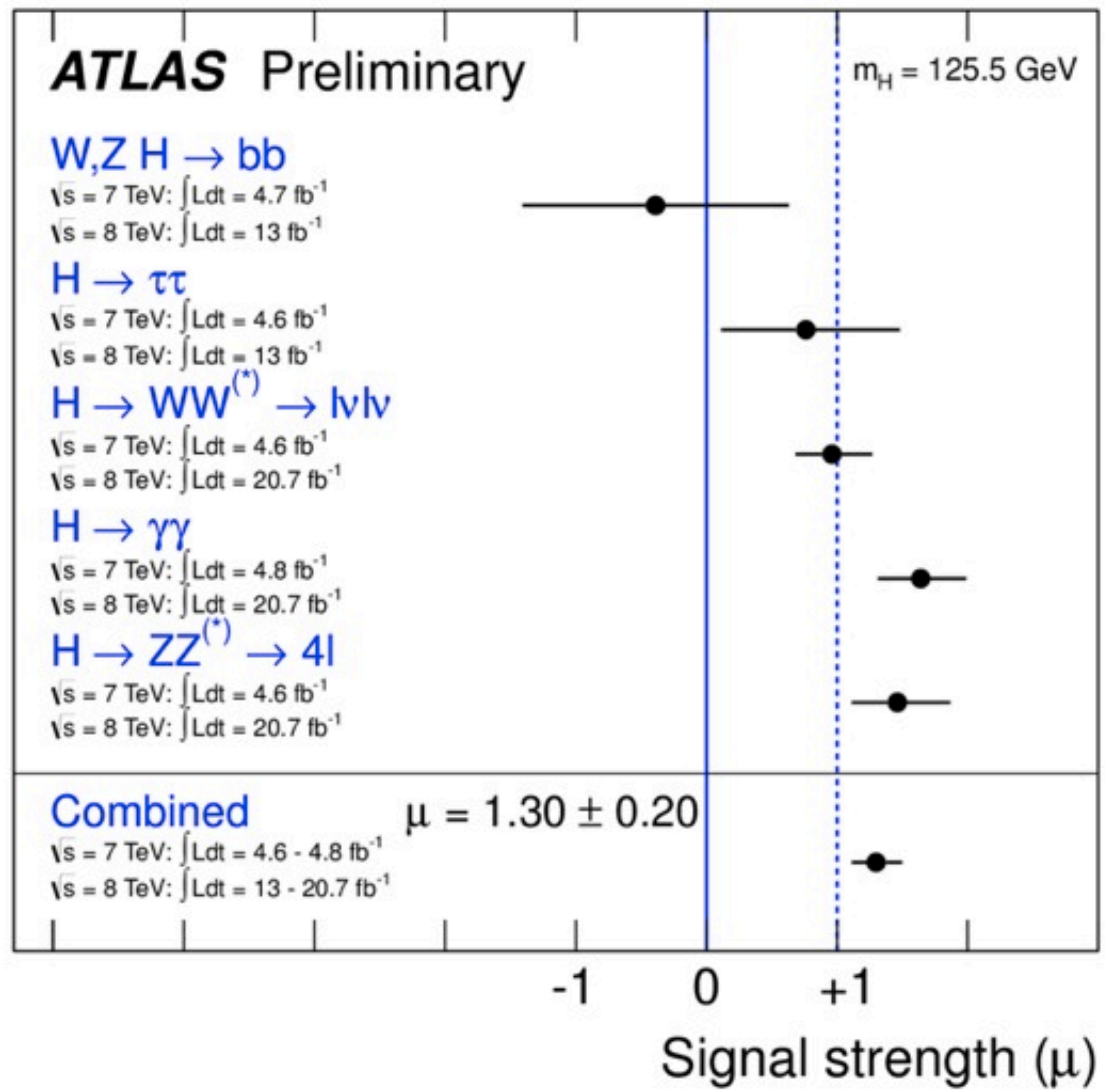
$c_V > 1$ ⟷ only if ∃ scalar of electric charge 2

$c_b > 1,\ c_t < 1$ ⟷ MSSM

$c_b < 1,\ c_t > 1$ ⟷ NMSSM dominated quartic

$c_V, c_f < 1$ $c_g, c_\gamma \sim 0$ ⟷ Composite Higgs





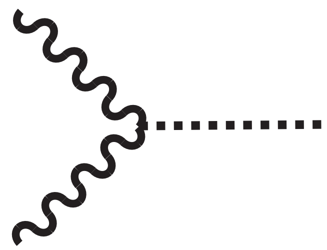
No clear trend of deviation from SM

Compatible with SM within 30%


Higgs comin' !!

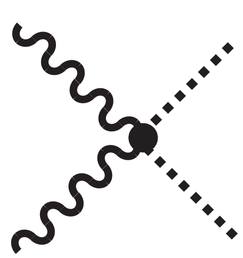

Welcome Higgs !!
WELCOME
HOME
Please
WELCOME BACK

The precision frontier

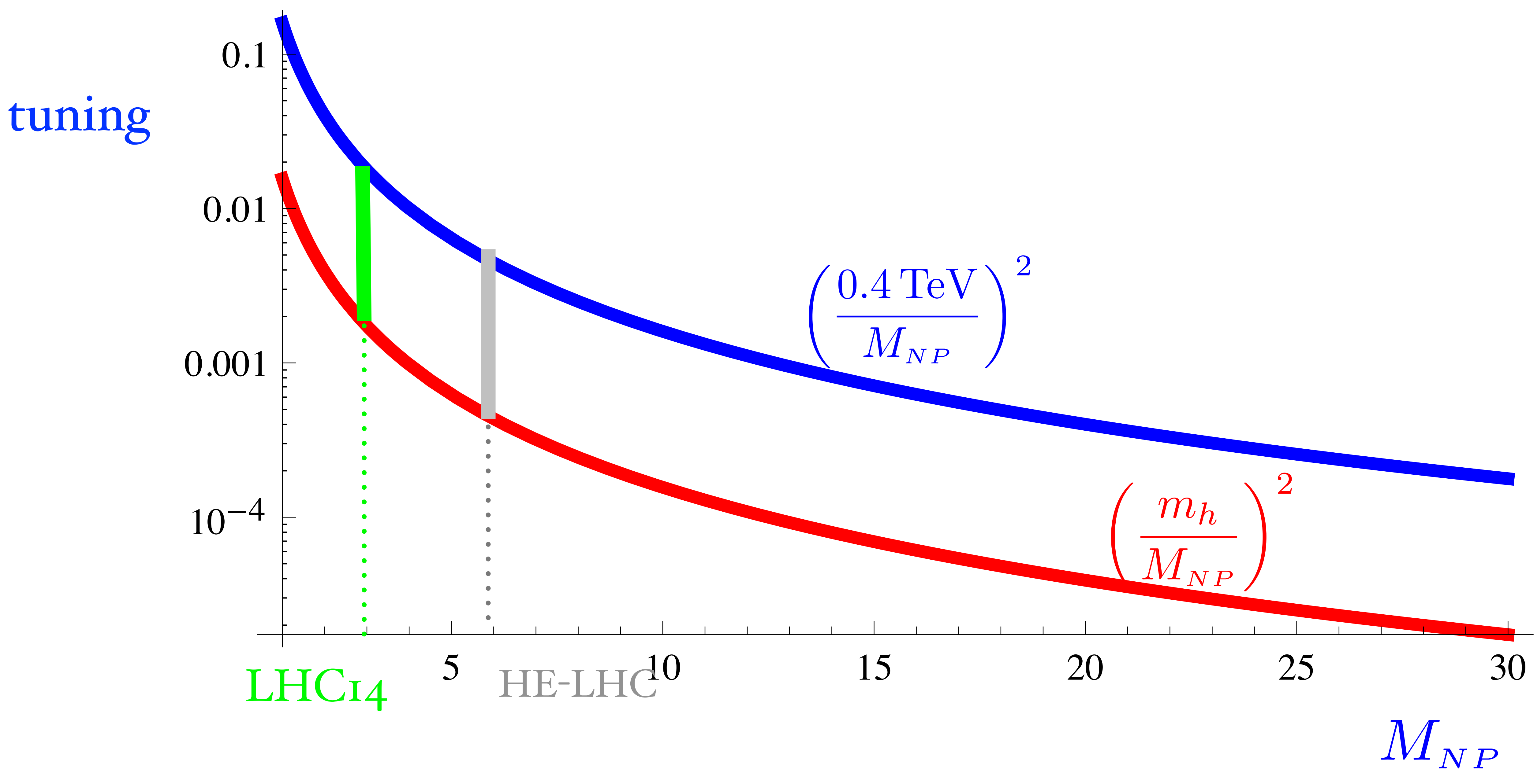
single Higgs physics  measures $\frac{g_{NP}^2 v^2}{M_{NP}^2} \lesssim$ fine tuning

EWPT	HL-LHC	ILC-LEPpone
10%	5%	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 ~1%

The energy frontier



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 were 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%