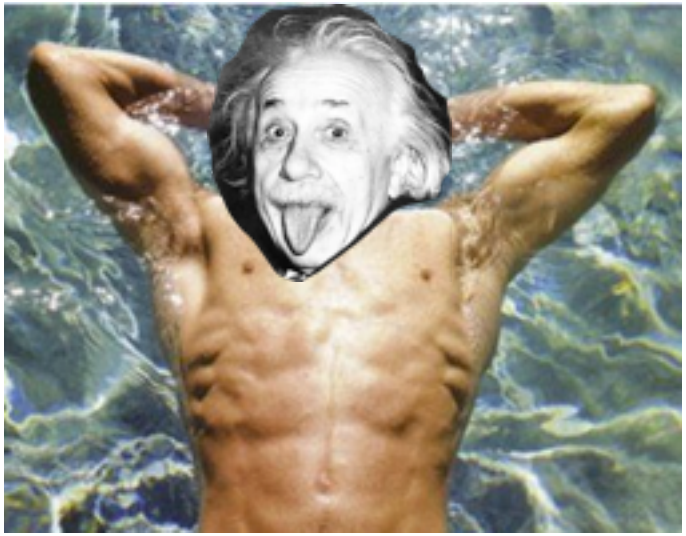


A Naturally Attractive Supermodel

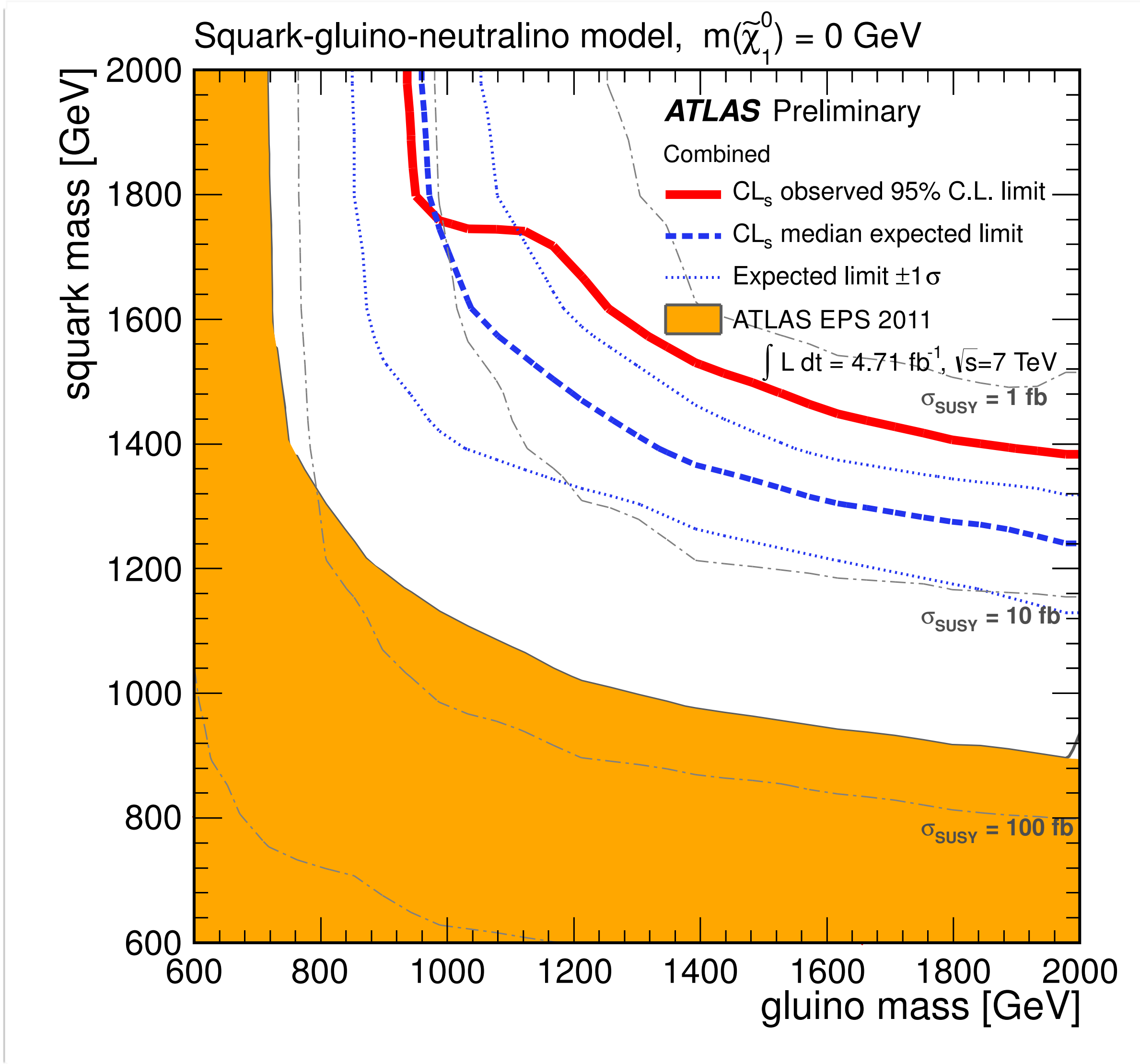
Timothy Cohen
(SLAC)

with Anson Hook and Gonzalo Torroba

arXiv:1204.1337

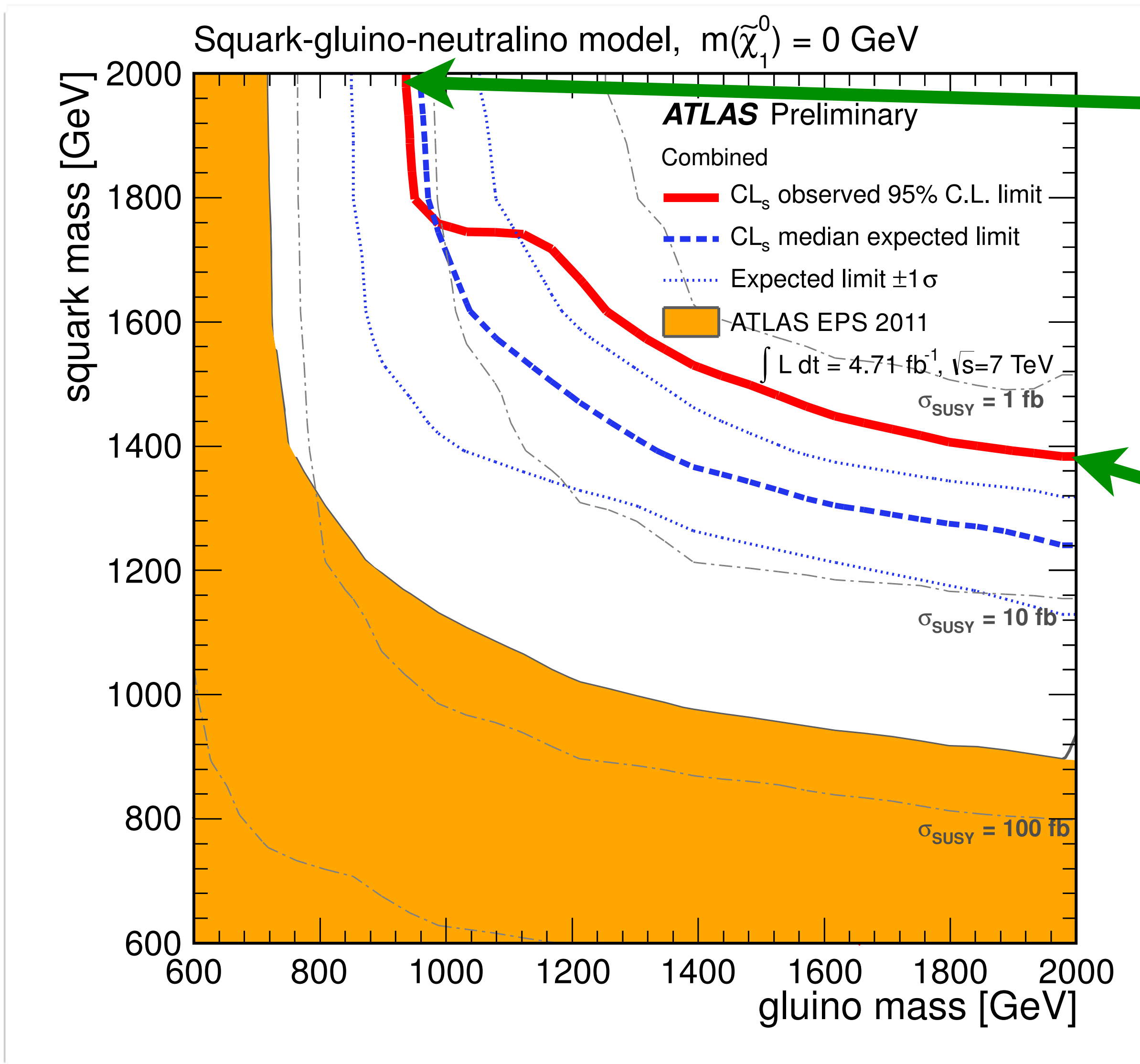
PHENO Symposium 2012
May 8, 2012

The Status of Weak Scale SUSY



ATLAS-CONF-2012-033

The Status of Weak Scale SUSY

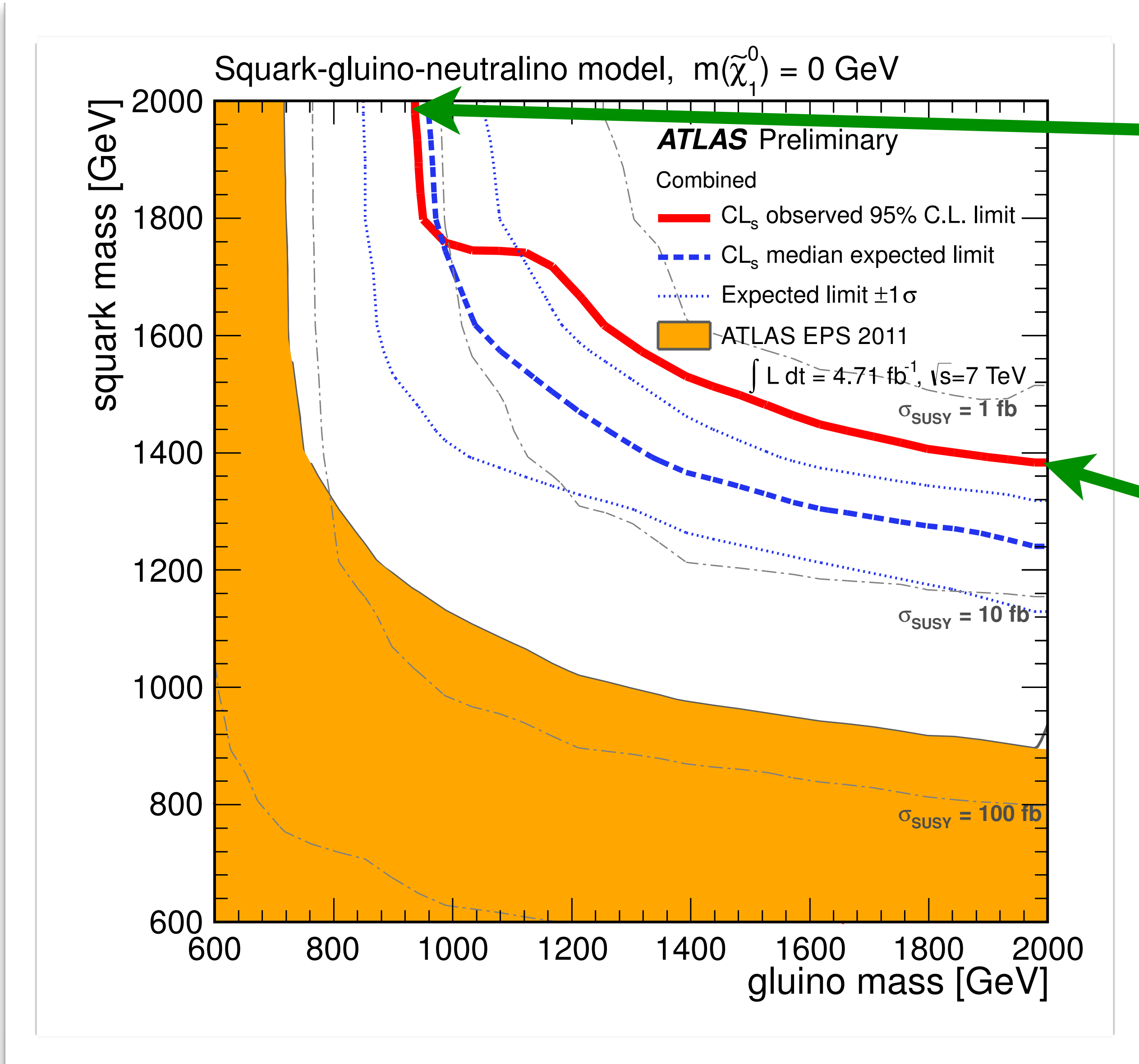


$m_{\tilde{g}} \gtrsim 1$ TeV

$m_{\tilde{q}} \gtrsim 1.5$ TeV

ATLAS-CONF-2012-033

The Status of Weak Scale SUSY



Does this tell us that the MSSM is unnatural?!?

ATLAS-CONF-2012-033

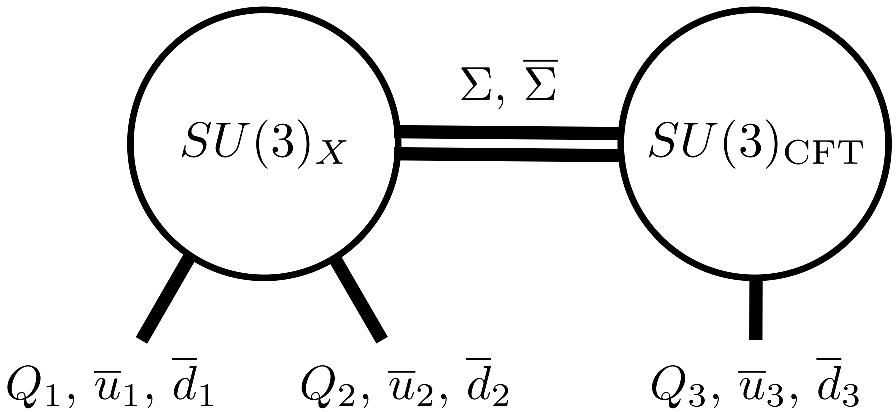
"Natural Supersymmetry"

- Fine tuning in the MSSM is due to canceling corrections to the up-type Higgs soft mass in order to solve
$$-m_Z^2 \simeq 2\left(|\mu|^2 + \widetilde{m}_{H_u}^2\right)$$
- The dominant contributions are from top-stop and gauge-gaugino loops.
$$\delta\widetilde{m}_{H_u}^2 \simeq -\frac{y_t^2}{16\pi^2}\left(12\,\widetilde{m}_t^2\,\log\Lambda + \frac{32}{\pi}\alpha_s|M_3|^2\log^2\Lambda\right) + \ldots$$
- A "natural" spectrum only requires that the 3rd generation squarks and gauginos are light. Dimopoulos, Giudice [1995]; Cohen, Kaplan Nelson [1996]
  - Also referred to as a "split-family" or "more-minimal SUSY" spectrum.
- LHC bounds on these particles are weaker then on the 1st and 2nd generation squarks. Papucci, Ruderman, Weiler [arXiv:1110:6926]
- Helps alleviate flavor problems.
- Known ways of mediating SUSY are flavor blind (e.g. gauge mediation); this spectrum requires novel model building.

THE MODEL

The Model

A quiver description:



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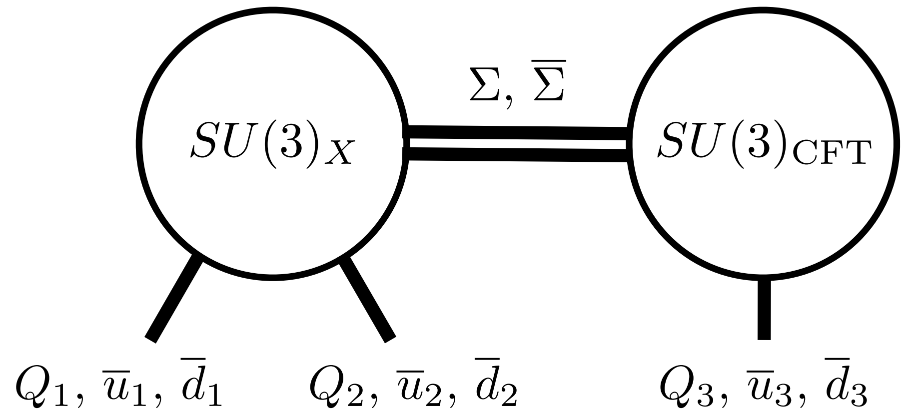

Relevant mass scales:

M	(the messenger scale)
Λ_{CFT}	(cross-over to the conformal regime)
v	(exit the conformal regime)
m_W	(the weak scale)

The matter content:

	$SU(3)_{\rm CFT}$	$SU(3)_X$	$SU(2)_W$	$U(1)_Y$
Q_3	$\Box$	1	$\Box$	$1/6$
$\overline{d}_3$	$\overline{\Box}$	1	1	$1/3$
$\overline{u}_3$	$\overline{\Box}$	1	1	$-2/3$
H_u	1	1	$\Box$	$1/2$
H_d	1	1	$\Box$	$-1/2$
Σ	$\Box$	$\overline{\Box}$	1	0
$\overline{\Sigma}$	$\overline{\Box}$	$\Box$	1	0
A	1	$1+\text{adj}$	1	0
$Q_{2,1}$	1	$\Box$	$\Box$	$1/6$
$\overline{d}_{2,1}$	1	$\overline{\Box}$	1	$1/3$
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The number of flavors associated with $SU(3)_{\rm CFT}$ is $N_f = 5$. This gauge group flows to a strongly interacting conformal fixed point in the IR.

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Marginal superpotential:

$$W \supset Q_3\, H_u\, \overline{u}_3 + Q_3\, H_d\, \overline{d}_3 + \Sigma\, A\, \overline{\Sigma} + W_{\cancel{U(1)}}$$

Relevant deformation:

$$W \supset -v^2\, \mathrm{Tr} A$$

This relevant deformation forces $\langle \Sigma\overline{\Sigma}\rangle = v^2$ which breaks $SU(3)_{\rm CFT} \times SU(3)_X \to SU(3)_C$.

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O(1) Top Yukawa

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CFTs and Soft masses

Nelson, Strassler [hep-ph/0104051]

- At the conformal fixed point, all physical couplings flow to their fixed point values.
- Promote couplings to superfields:
  - The higher theta components have mass dimension and thus flow to zero.
  - Since soft parameters are encoded as higher theta components of these superfields, certain combinations of soft parameters will flow to zero.

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- Since conserved currents are not renormalized, $\sum \mathrm{dim}(i)\, q_i\, \widetilde{m}_i^2$ does *not* flow to zero.
  - q_i is the charge under a non-anomalous global $U(1)$ symmetry.

Soft Masses

- Specify $W_{\cancel{U(1)}} = (Q_3\,\overline{u}_3)(Q_3\,\overline{d}_3)$.
- The remaining unbroken global $U(1)$ symmetries are given by:

	$U(1)_1$	$U(1)_2$	$U(1)_3$	$U(1)_R$
Q_3	1	0	0	$1/2$
$\overline{u}_3$	-1	-1	0	$1/2$
$\overline{d}_3$	-1	1	0	$1/2$
H_u	0	1	0	1
H_d	0	-1	0	1
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$\overline{\Sigma}$	0	0	-1	$1/3$
A	0	0	0	$4/3$

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- This implies that the following combinations of soft masses are unchanged by the CFT dynamics:

$$\widetilde{m}^2_{\Sigma} - \widetilde{m}^2_{\overline{\Sigma}}$$
$$2\,\widetilde{m}^2_{Q_3} - \widetilde{m}^2_{\overline{u}_3} - \widetilde{m}^2_{\overline{d}_3}$$
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Note the *R* charges, which can be computed simply from considering the superpotential and the mixed anomalies.

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Nelson, Strassler [hep-ph/0006251, hep-ph/0104051]

Yukawa Hierarchies

- Assume all Yukawa couplings are O(1) in the UV:

$$W \supset Y^u_{ij}\, Q_i\, H_u\, \overline{u}_j + Y^d_{ij}\, Q_i\, H_d\, \overline{d}_j + Y^u_{33}\, Q_3\, H_u\, \overline{u}_3 + Y^d_{33}\, Q_3\, H_d\, \overline{d}_3$$

- Recall that for a SCFT the anomalous dimension of fields is related to the *R* charge: $\gamma = 3R - 2$.
- Then we can compute the RG evolution of the Yukawa couplings:

$$Y^u_{ij}(E) = \left(\frac{E}{\Lambda_{\rm CFT}}\right)^{\frac{\gamma_{Q_i}+\gamma_{u_j}+\gamma_{H_u}}{2}} Y^u_{ij}(\Lambda_{\rm CFT})$$

- Below the exit scale, the Yukawa coupling is given by

$$Y_{ij}(v) = \epsilon^{\frac{\gamma_H}{2}}\, Y_{ij}(\Lambda_{\rm CFT}) \ll Y_{33}(v)$$

with $\epsilon \equiv \dfrac{v}{\Lambda_{\rm CFT}}$.

Yukawa Hierarchies

- Since the 3rd generation and 1st/2nd generation fields are charged under different gauge groups, there is no way to write down a renormalizable off-diagonal Yukawa coupling.
- However, the following higher dimensional operators are allowed by the symmetries:

$$W \supset \frac{1}{\Lambda_*} \overline{\Sigma}\, Q_3\, H_u\, \overline{u}_{1,2} + \frac{1}{\Lambda_*} Q_{1,2}\, H_u\, \Sigma\, \overline{u}_3 + \ldots$$

- Below the exit scale these couplings flow to

$$Y^u_{i3}(v) = \frac{v}{\Lambda_*} \epsilon^{\frac{\gamma_{H_u} + \gamma_{Q_3} + \gamma_{\overline{\Sigma}}}{2}} \; , \; Y^u_{3i}(v) = \frac{v}{\Lambda_*} \epsilon^{\frac{\gamma_{H_u} + \gamma_{u_3} + \gamma_{\Sigma}}{2}}$$

with $\epsilon \equiv \dfrac{v}{\Lambda_{\rm CFT}}$.

Flavor

- The resultant IR Yukawa matrix is given by

$$Y^u \sim \begin{pmatrix} \epsilon^{\frac{\gamma_{H_u}}{2}} & \epsilon^{\frac{\gamma_{H_u}}{2}} & \xi_Q\, \epsilon^{\frac{\gamma_{H_u}}{2}} \\ \epsilon^{\frac{\gamma_{H_u}}{2}} & \epsilon^{\frac{\gamma_{H_u}}{2}} & \xi_Q\, \epsilon^{\frac{\gamma_{H_u}}{2}} \\ \xi_u\, \epsilon^{\frac{\gamma_{H_u}}{2}} & \xi_u\, \epsilon^{\frac{\gamma_{H_u}}{2}} & 1 \end{pmatrix}$$

with $\xi_Q \equiv \frac{v}{\Lambda_*}\,\epsilon^{\frac{\gamma_\Sigma + \gamma_{Q_3}}{2}}$, $\xi_u \equiv \frac{v}{\Lambda_*}\,\epsilon^{\frac{\gamma_\Sigma + \gamma_{\bar{u}_3}}{2}}$ and $\epsilon \equiv \frac{v}{\Lambda_{\mathrm{CFT}}}$.

- This structure can reproduce the mass hierarchy and CKM matrix to a good approximation by varying the O(1) starting value for the Yukawa couplings in the UV and taking

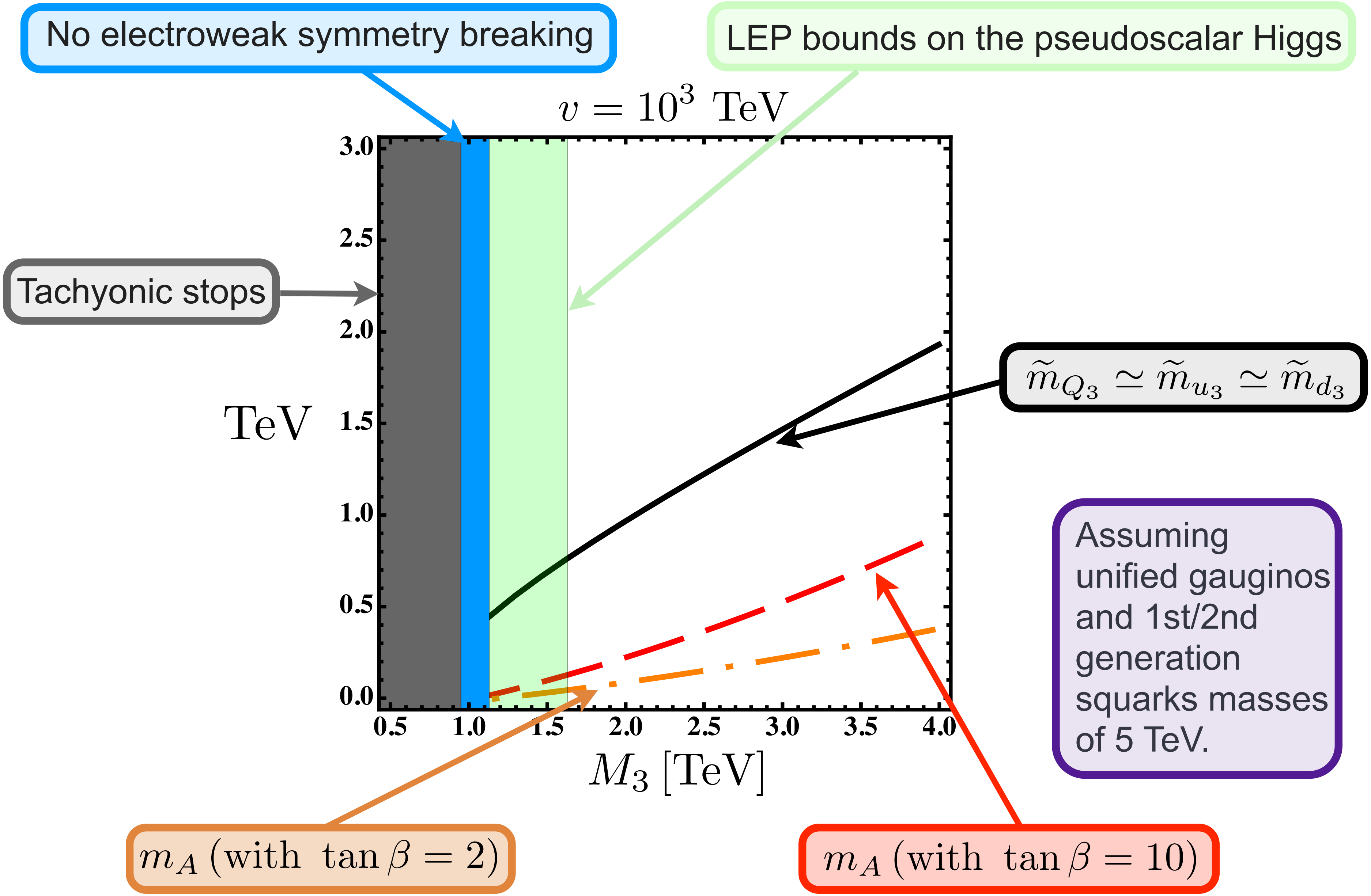
$$\frac{v}{\Lambda_{\mathrm{CFT}}} \sim 10^{-4}\,, \quad \frac{\Lambda_*}{\Lambda_{\mathrm{CFT}}} \sim 10^{-1} - 10^{-2}$$

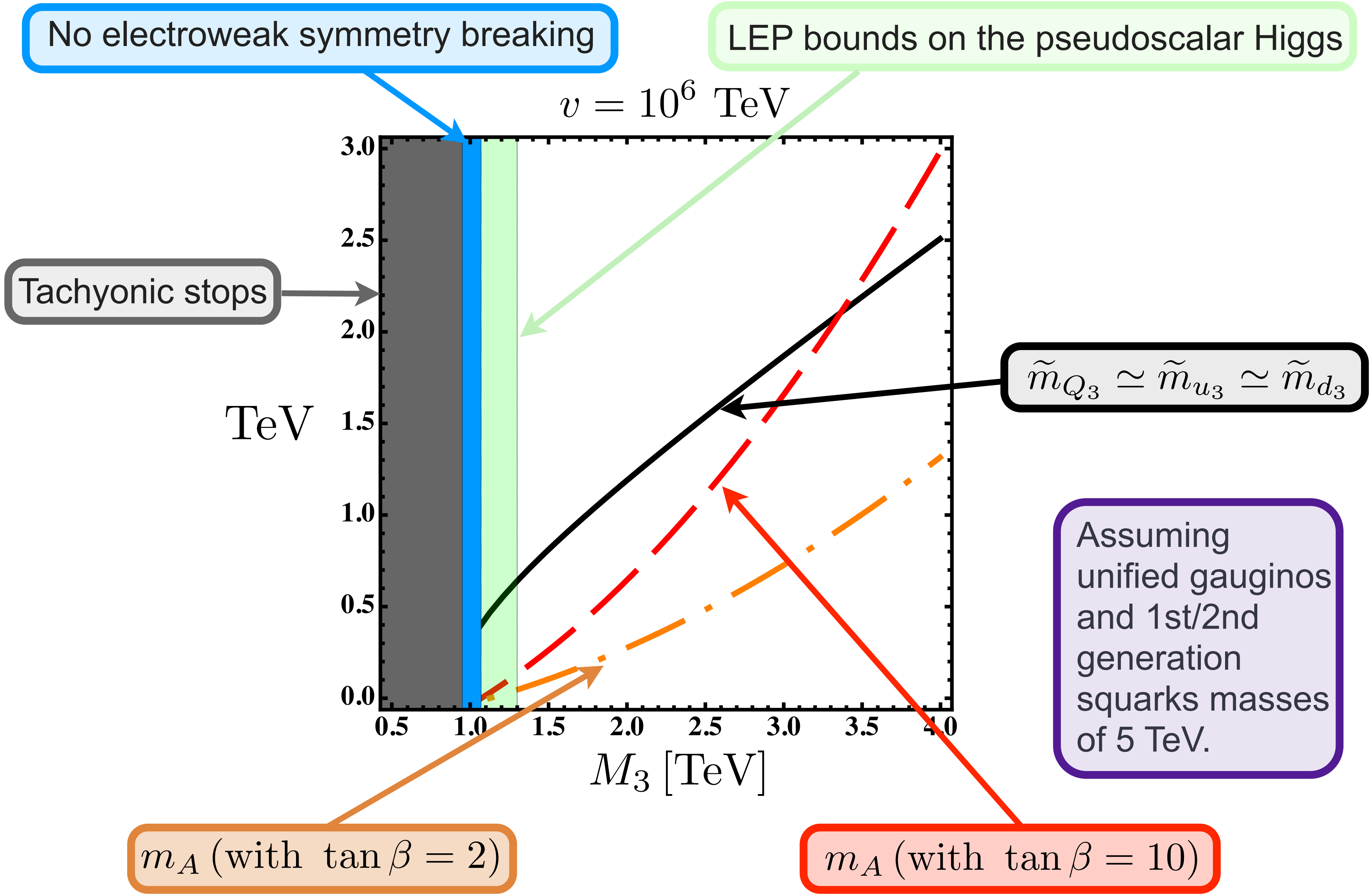
EXAMPLE SPECTRA

Example Spectra

- At the exit scale v, the soft masses for the 3rd generation squarks and the Higgs scalars are zero (up to a small correction proportional to the gluino mass).
- The soft masses for the gauginos and 1st/2nd generations are unchanged by the CFT dynamics.
- Choose a value of M_3 (assuming gaugino mass unification).
  - We then RG evolve the masses from the exit scale to the weak scale including the dominant 2-loop contributions.
  - The stop masses are generated via gaugino mediation.

    Kaplan, Kribs, Schmaltz [arXiv:hep-ph/9911293]; Chacko, Luty, Nelson, Ponton [arXiv:hep-ph/9911323]
  - This drives the up-type Higgs soft mass negative resulting in electroweak symmetry breaking.
- Choose a value of $\tan\beta$.
  - The weak scale value of μ is determined from $-m_Z^2 \simeq 2\left(|\mu|^2 + \widetilde{m}_{H_u}^2\right)$.
  - This fixes the weak scale value of b_μ using the electroweak symmetry breaking conditions (at tree level).


No electroweak symmetry breaking
LEP bounds on the pseudoscalar Higgs
$v = 10^3$ TeV
Tachyonic stops
TeV
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
M_3 [TeV]
$\widetilde{m}_{Q_3} \simeq \widetilde{m}_{u_3} \simeq \widetilde{m}_{d_3}$
Assuming unified gauginos and 1st/2nd generation squarks masses of 5 TeV.
m_A (with $\tan\beta = 2$)
m_A (with $\tan\beta = 10$)



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CONCLUSIONS

Conclusions

- Given bounds on light squark + gluino simplified models, we are being pushed to rethink the relationship between SUSY and naturalness.
  - Maybe SUSY is hidden
    - Compressed spectra
    - R-parity violation
    - Decays to hidden sectors
    - Something else?

  - Maybe there is a large hierarchy between the 3rd and 1st/2nd generations
- We have presented a model whose dynamics result in:
  - A split-family superpartner spectrum;
  - The hierarchical flavor structure of the quark Yukawa matrices.
- A given gluino mass implies the 3rd generation squark and Higgs sector masses.
- Currently, the strongest bounds on the spectrum are due to the non-observation of pseudo-scalar Higgs.

BACKUP SLIDES

Higgs Properties

- Our model does not explain a 125 GeV Higgs boson mass.
- Since the superpotential term $S H_u H_d$ is irrelevant while the CFT is strongly coupled, our model is incompatible with the NMSSM.
- To increase the Higgs mass, one can add a sector which results in non decoupling D-terms.

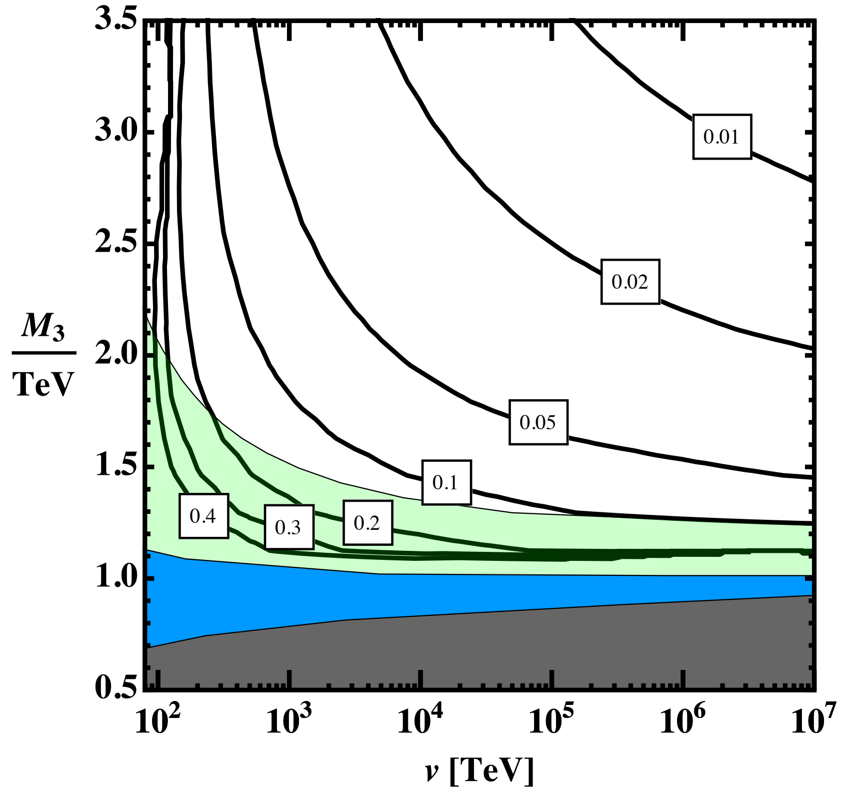
Batra, Delgado, Kaplan, Tait [arXiv:hep-ph/0309149]
Maloney, Pierce, Wacker [arXiv:hep-ph/049127]

- The results is to take all MSSM Higgs sector relationships and make the substitution:

$$m_Z^2 = \frac{g_Z^2}{2}\left(\langle {H_u}^2\rangle + \langle {H_d}^2\rangle\right) \quad \longrightarrow \quad \Xi^2 \equiv \frac{g_Z^2 + g_{\text{new}}^2}{2}\left(\langle {H_u}^2\rangle + \langle {H_d}^2\rangle\right).$$

  - In all presented plots we have assumed there is an additional D-term contribution to the Higgs quartic $\Xi = 150\ \text{GeV}$.

Fine-tuning



Exclusion contours are as in the spectrum plots.

- To get a sense of fine-tuning in this model we adopt a naive low-scale measure. Kitano, Nomura [arXiv:hep-ph/0509039]; Papucci, Ruderman, Weiler [arXiv:1110:6926]
- Plotted are contours of $\Delta^{-1} \equiv -2\frac{\delta m_H^2}{m_h^2} = -2\frac{\widetilde{m}_{H_u}^2}{m_h^2}$, with $\tan\beta = 2$.
- We see large regions with O(10%) fine-tuning are allowed.