Relatively Heavy Higgs Boson From More Generic Gauge Mediation

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JLE, Ibe, Yanagida, arXiv:1108.3437

Outline

The Standard Model

- Fermilab has discovered the top
  - Completing the third quark family
  - Along time ago (1995) !!!!!!
- Flavor constraints consistent with CKM matrix
  - Cutoff scale for new physics in $K - \bar{K}$ mixing $\gtrsim$ 1000 TeV

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- SM can easily accommodate cosmology
- Neutrino masses and mixing are also possible
- LHC has pushed the scale of new physics to be quite high
- Is it time to give up?

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  - Dark Matter: Add new matter
  - Right handed neutrino: simple Dirac neutrinos will due
- More complicated gauge symmetries
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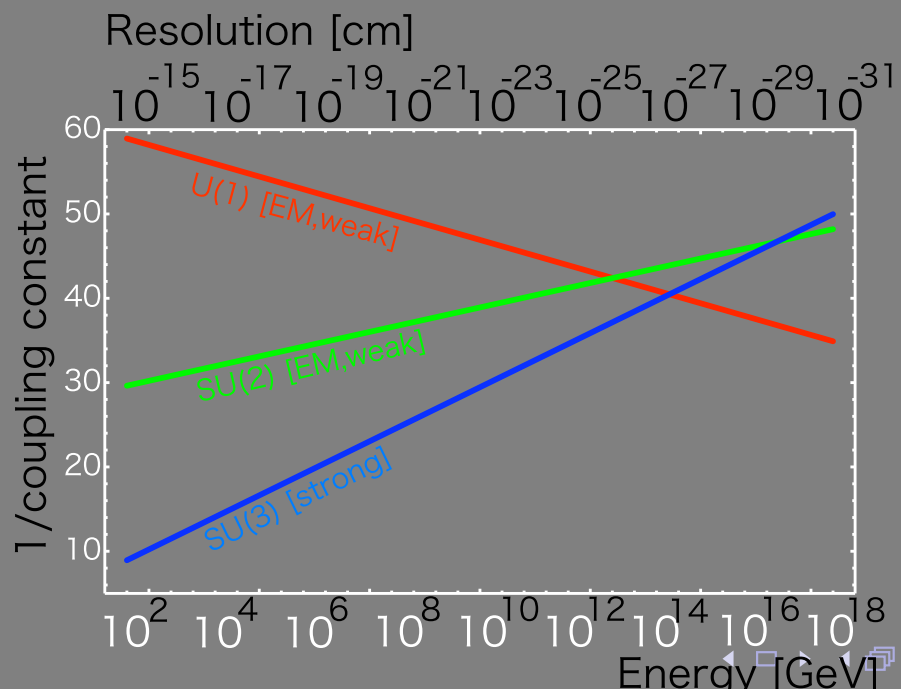

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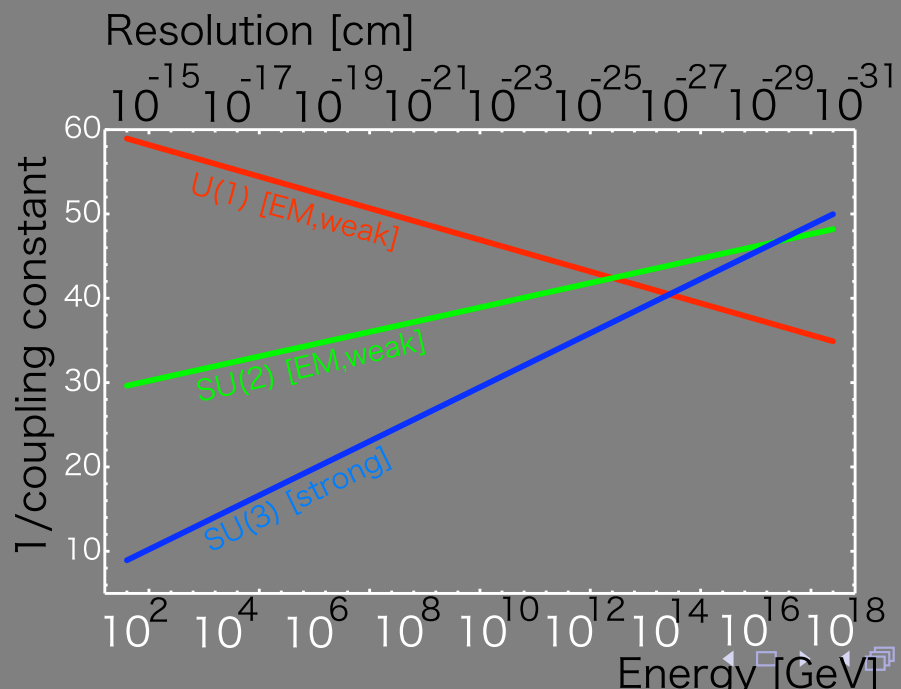
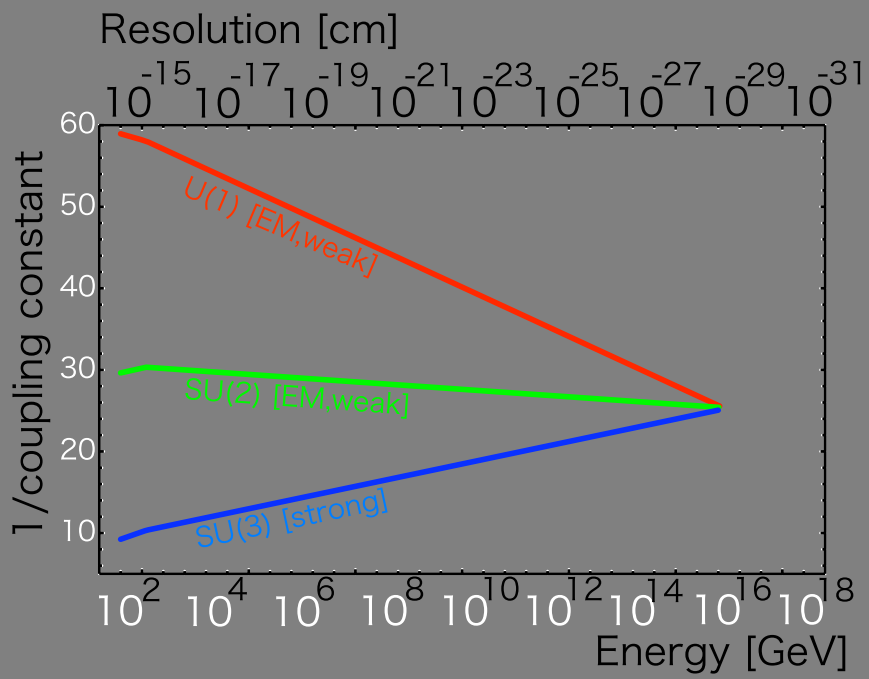


Higgs Boson and Grand Unification

- SM gauge couplings are suggestive, but not definitive
- If we take gauge coupling unification seriously in SM
  - Higgs boson mass is fine tuned to many orders of magnitude
    $$m_H^2 = m_0^2 + \mathcal{O}(M_{unif}^2/16/\pi^2)$$
  - Additional matter content needed for unification
  - If a scalar, can exasperate the hierarchy problem.
- My criteria for Interesting Unification
  - Gauge coupling unification, of course
  - Unification discernable at the LHC
  - Additional matter justified

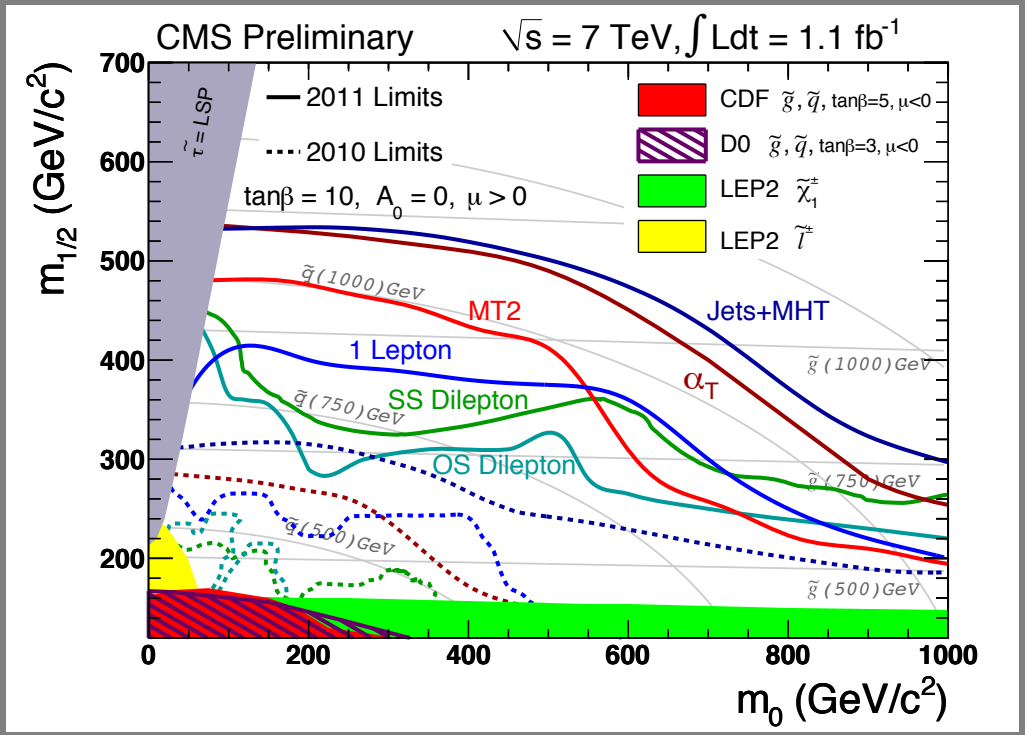
Grand Unification Suggestive of SUSY

- The beauty of SUSY Grand unification
  - Matter content justified by symmetry
  - Necessary matter visible at the LHC
  - Shields the SM Higgs from GUT scale physics



It Was the Best of Times, It Was the Worst of Times

- Best of Times: LHC is running collecting data
- Worst of Times: LHC hasn't seen anything



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- Higgs mass light even for $M_{SUSY} = 10^{16}$ GeV
- Additional matter does not help much
  - $5, \bar{5}$ couple to H_d, do not enhance lightest Higgs
    - Adding a singlet, possible to enhance Higgs mass
  - $10, \bar{10}$ couple to H_u, does enhance lightest Higgs
  - Can only add one set of $10, \bar{10}$
- These only contribute logarithmically to Higgs mass
- SUGRA additional $10, \bar{10}$ give max $m_H \simeq 140$ GeV (Asano, Moroi, Yanagida ... arXiv:1108.2402v1)

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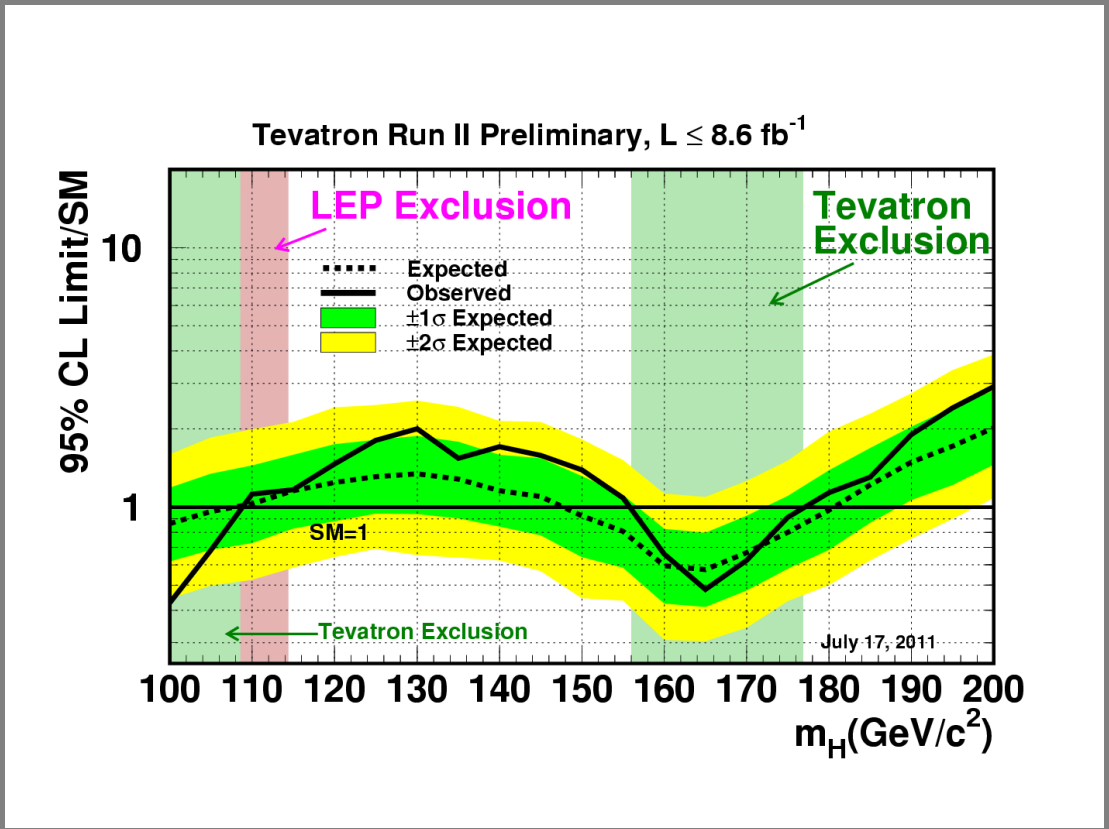
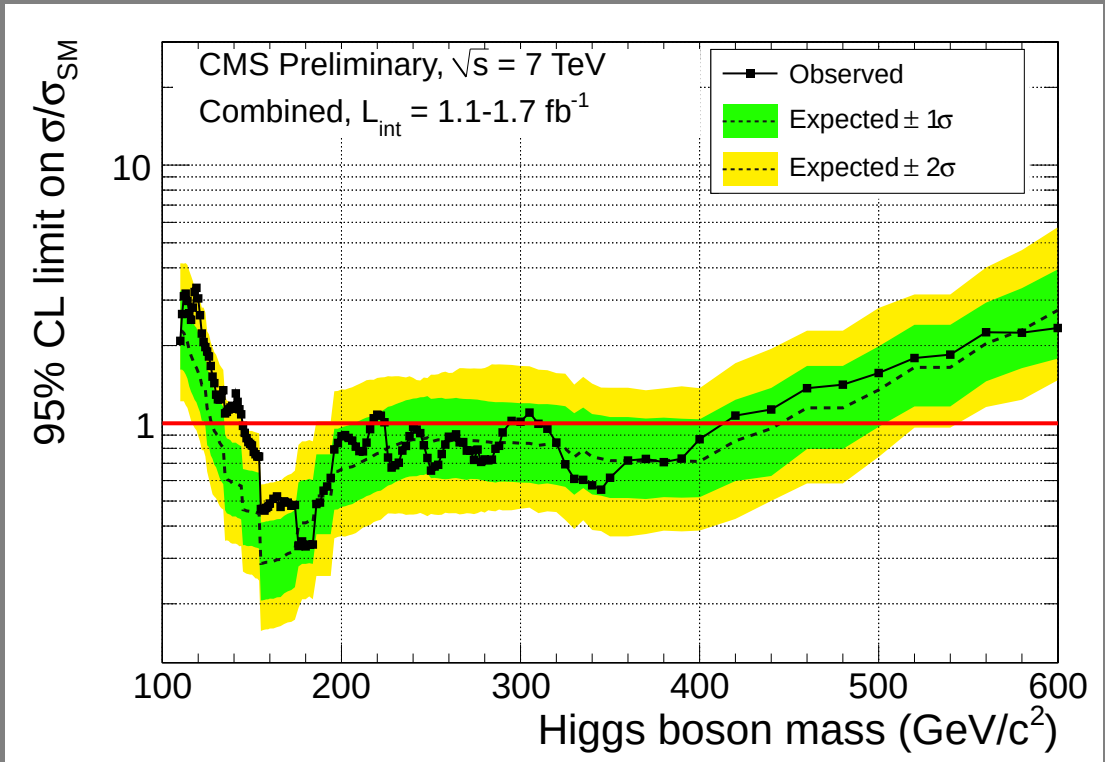
Higgs Searches: Pre LHC

- Pre LHC Higgs: Rougly $m_H > 114$GeV and $m_H \lesssim 600$ GeV
- Pre LHC Supersymmetric Higgs: $m_H \lesssim 135$ GeV



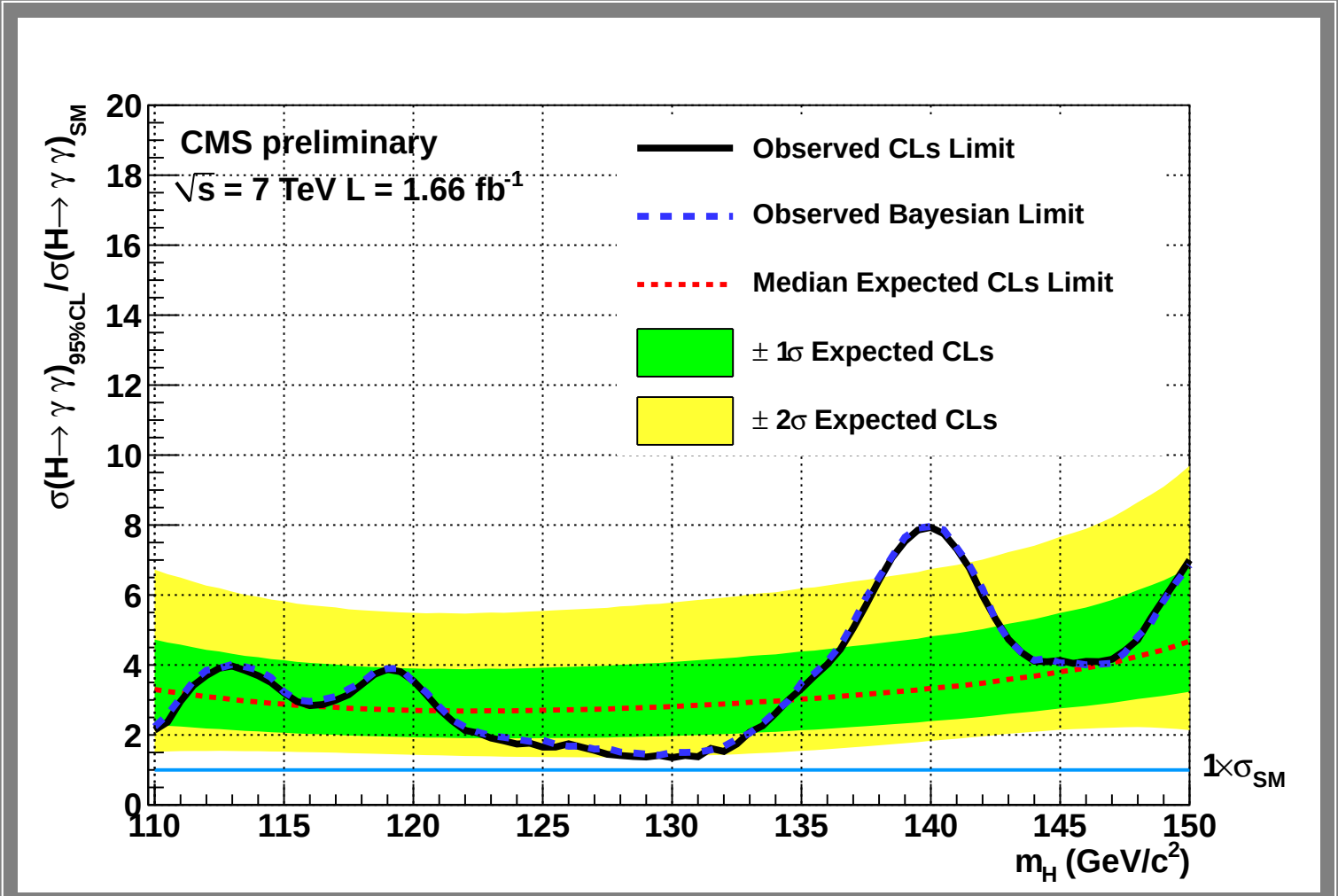
Higgs Searches at LHC

- LHC is making significant progress
- The Higgs is either Very Heavy or close to LEP bound
- Peak at 140 GeV the Higgs?



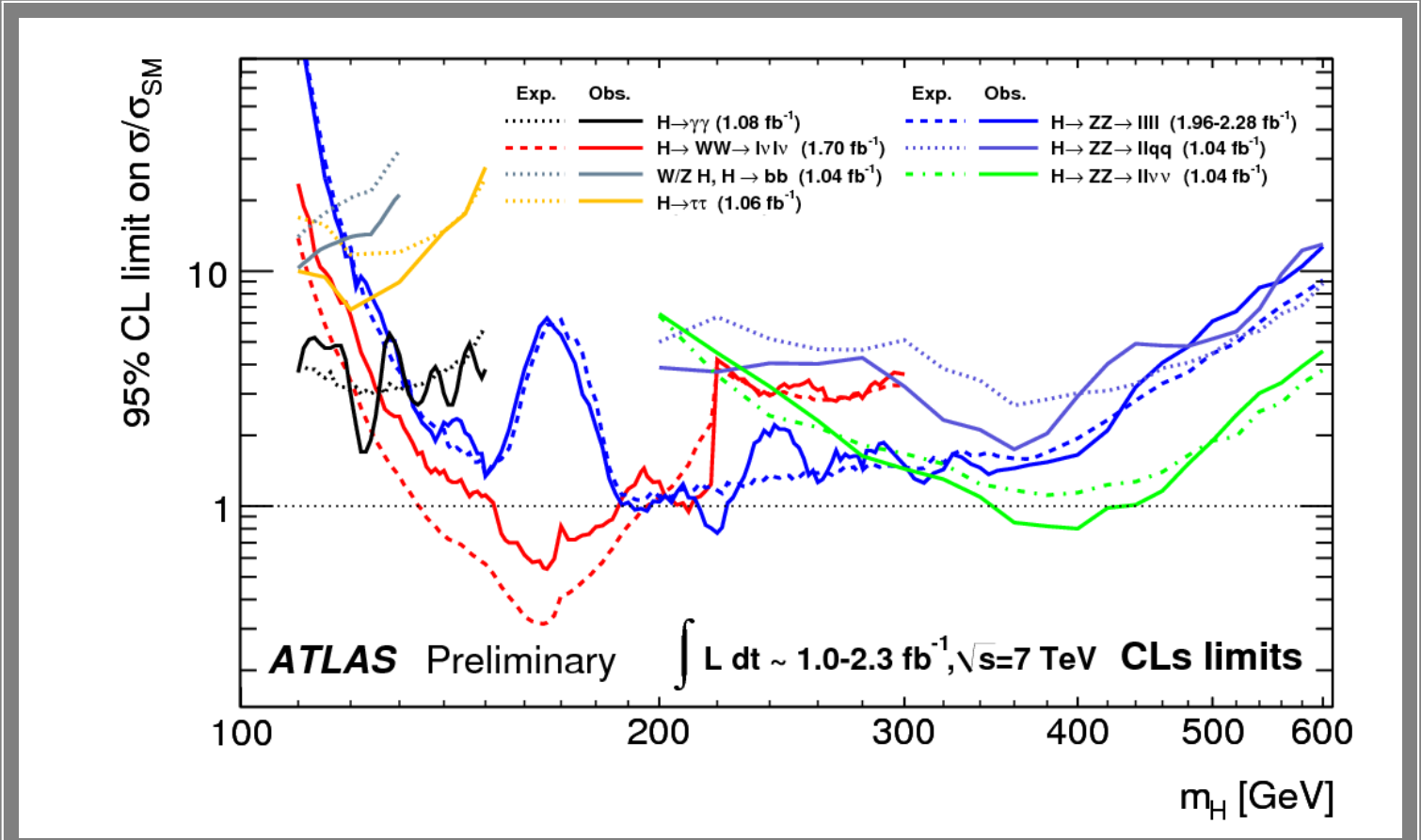
CMS Higgs Excess

- CMS sees prominent peek at 140 GeV, mostly in H$\rightarrow \gamma\gamma$



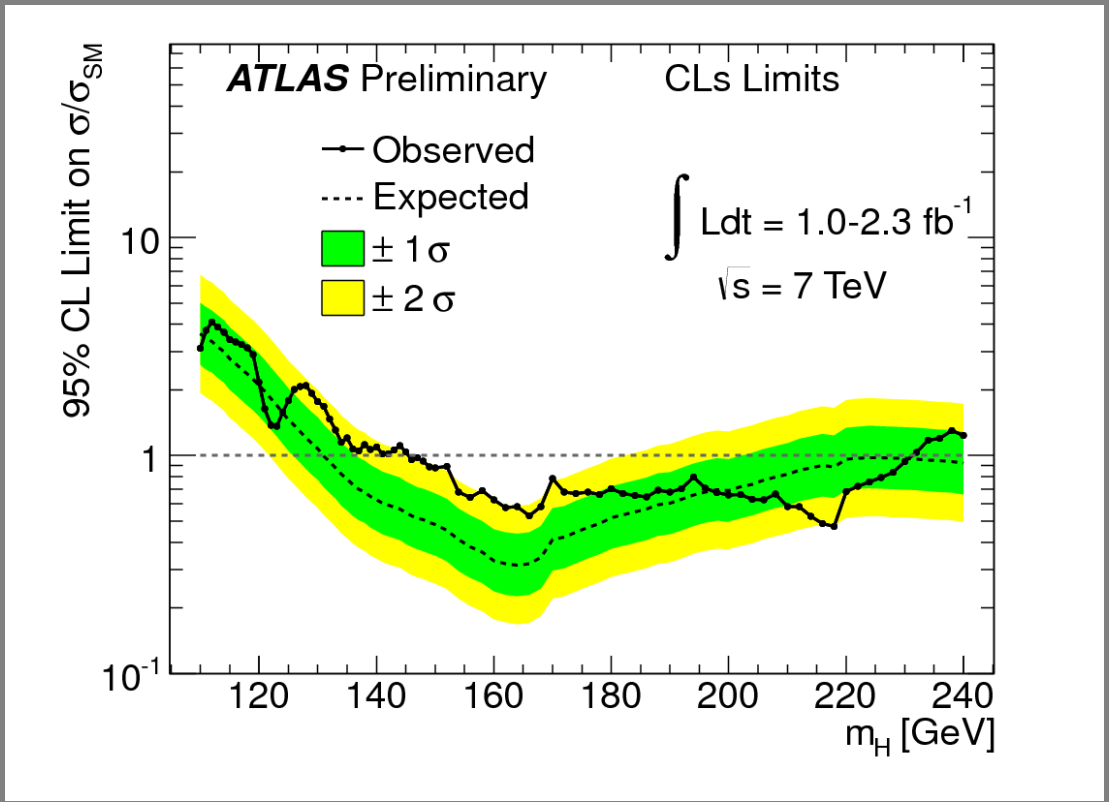
CMS Higgs Excess

- Atlas sees no 140 GeV peek in H$\rightarrow \gamma\gamma$



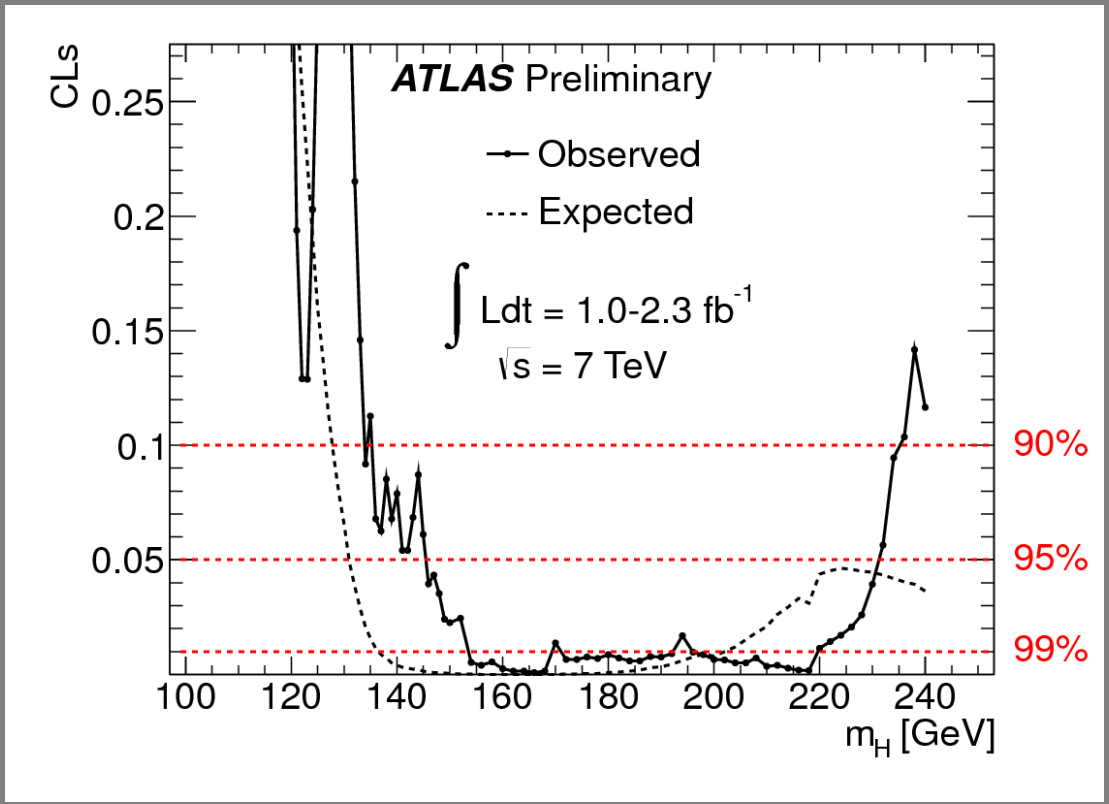
Higgs Searches at LHC: Continued

- Atlas Low Mass exclusion plot
- Atlas believes $m_H = 128$ GeV (Private Conversation)



Higgs Searches at LHC: Continued

- Exclusion Confidence Levels

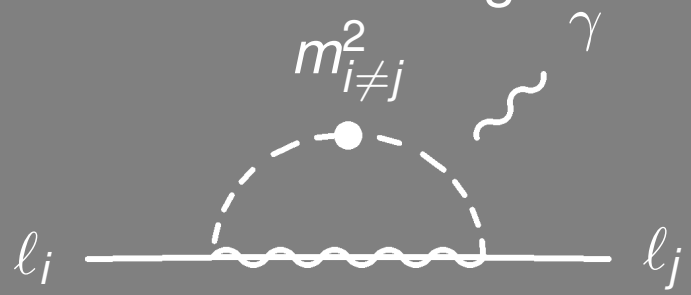


Why Gauge Mediation?

- Softly broken MSSM has many parameters(109 PILAFTSIS)

$$m^2_{\tilde{f}}, M_i, A_{ij}, B_{ij}$$

- Generic Soft Masses and A terms give FV



- Phenomenology requires

$$m^2_{\tilde{f}_{ij}} \simeq M_{f_i}\delta_{ij} \quad \text{etc.}$$

- Need a well motivated model with no FV
- Minimal gauge mediation also has no CP problem

Conventional Gauge Mediated SUSY Breaking

- Messengers are in GUT consistent representations
- Simplest representation, $5 + \bar{5}$

$$\Phi = (\Phi_L \;\; \Phi_C) \qquad \bar{\Phi} = (\bar{\Phi}_L \;\; \bar{\Phi}_C)$$

- Messenger parity sequesters the messenger sector

$$\Phi \to -\Phi \qquad \bar{\Phi} \to -\bar{\Phi}$$

- Messenger sector couples to a gauge singlet spurion

$$W_M = Z\bar{\Phi}\Phi \qquad Z = M + \theta^2 F$$

Without Messenger Parity

- Messengers quantum numbers identical to SM fields
- Flavor violating interactions not forbidden

$$W = \rho_1 \Phi_{\bar{L}} Q_L \bar{U}_R + \rho_2 \bar{\Phi}_{\bar{L}} Q_L \bar{D}_R + \rho_3 \bar{\Phi}_{\bar{L}} L_L \bar{E}_R \ ,$$

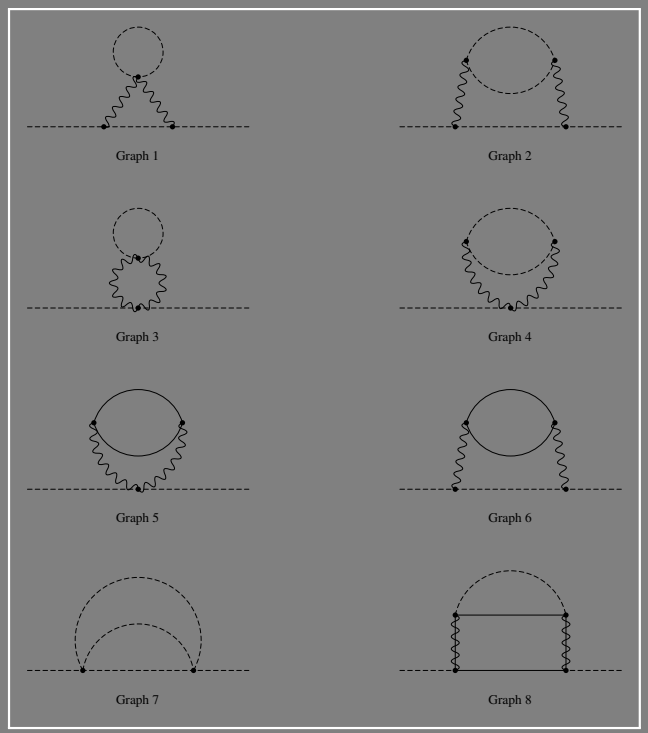
- Generic soft masses are generated
- Operators contributing to Proton decay

$$W = \lambda_1 \Phi_D Q_L Q_L + \lambda_2 \bar{\Phi}_D Q_L L_L \ ,$$

- Messenger parity seems quite necessary

Mass Generation in Gauge Mediation

- Scalar masses generated at two loops



$$m_{\tilde{f}}^2 \simeq \left(\frac{g^2}{16\pi^2}\right)^2 \frac{F^2}{M^2}$$

Mass Generation in Gauge Mediation

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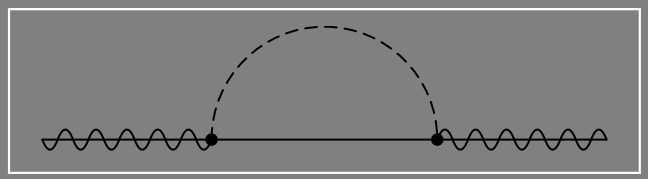
$$m_{\tilde{f}}^2 \simeq \left(\frac{g^2}{16\pi^2}\right)^2 \frac{F^2}{M^2}$$

- Gaugino masses generated at one loops



$$m_{\tilde{\chi}} \simeq \left(\frac{g^2}{16\pi^2}\right) \frac{F}{M} \simeq m_{\tilde{f}}$$

Mass Generation in Gauge Mediation

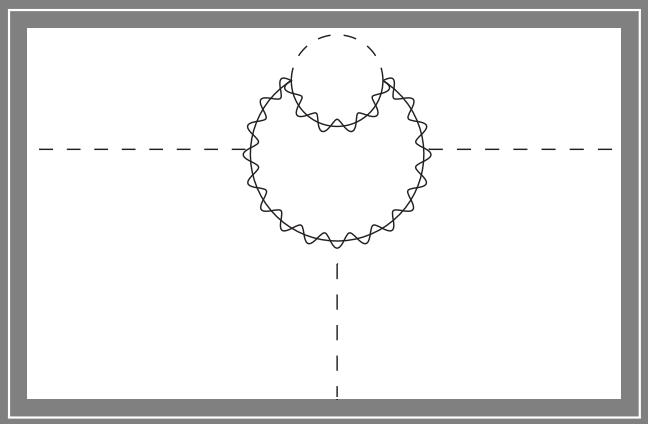
- Scalar masses generated at two loops

$$m_{\tilde{f}}^2 \simeq \left(\frac{g^2}{16\pi^2}\right)^2 \frac{F^2}{M^2}$$

- Gaugino masses generated at one loops

$$m_{\tilde{\chi}} \simeq \left(\frac{g^2}{16\pi^2}\right) \frac{F}{M}$$

- Trilinears at two loops



$$\frac{A_t^2}{m_{\tilde{f}}^2} \sim \left(\frac{g^2}{16\pi^2}\right)^2 \ll 1$$

Higgs Boson of mGMSB

- $A_t \simeq 0$ minimal gauge mediation
- One-loop Higgs mass

$$m_{h^0}^2 \lesssim m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} y_t^2 m_t^2 \sin^2 \beta \left(\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2} - \frac{A_t^4}{12 m_{\tilde{t}}^4} \right) .$$

- Larger log enhance term still present
- A_t contribute very little
- $m_H < 120$ GeV even for $m_{\tilde{g}} = 2.5$ TeV

More Generic Gauge Mediation

- Are large A-terms possible in gauge mediation?
  - Messenger parity$\rightarrow$ the Yukawa sector and messegner sector interact only at the loop level
  - SUSY breaking only communicated through gauge fields
  - A_t not possible at one-loop

- Wish list for more generic gauge mediation
  - Messenger Higgs mixing allowed $\rightarrow$ A-terms
  - No flavor violation
  - No proton decay problems

SUSY-zero and Messenger Higgs Mixing

- Gauge mediation without messenger parity

	ϕ_+	H_u	H_d	**10**	$\mathbf{5}^*$	$\bar{N}_R$	Φ	$\bar{\Phi}$	Z
$U(1)$	$+1$	-2	-3	$+1$	$+2$	0	0	0	0

$$W = gZ\bar{\Phi}\Phi + \langle\phi_+\rangle^2 Z\bar{\Phi}H_u = gZ\bar{\Phi}\Phi + g'Z\bar{\Phi}H_u$$

- ϕ_+ is some spurion of charge 1
- Holomorphy forbids negatively charged couplings
- Only two additional interaction allowed

Proton Decay and Flavor Violation

- Charge Assignments

	ϕ_+	H_u	H_d	**10**	$\mathbf{5}^*$	$\bar{N}_R$	Φ	$\bar{\Phi}$	Z
$U(1)$	$+1$	-2	-3	$+1$	$+2$	0	0	0	0

- Flavor Violation

$$W = \subset \underset{0}{\rho_1 \Phi_{\bar{L}}} \underset{+1}{Q_L} \underset{+1}{\bar{U}_R} + \underset{0+1+2}{\rho_2 \bar{\Phi}_{\bar{L}}} \underset{+1}{Q_L} \underset{+2}{\bar{D}_R} + \underset{0+2}{\rho_3 \bar{\Phi}_{\bar{L}}} \underset{+1}{L_L} \underset{+1}{\bar{E}_R} ,$$

- Proton Decay

$$W = \underset{0}{\lambda_1 \Phi_D} \underset{+1+1}{Q_L Q_L} + \underset{0+1+2}{\lambda_2 \bar{\Phi}_D} \underset{+1+2}{Q_L L_L} ,$$

- ϕ_+ does not help because of holomorphy

Four Types of More Generic Gauge Mediation

- **Four realizations of Gauge Mediation**

- No mixings between the messengers and the Higgs pair
- The messenger $\Phi_{\bar{L}}$ mixes with H_u with the help of a “charged" coupling constant
- The messenger $\bar{\Phi}_{\bar{L}}$ mixes with H_d with the help of a “charged" coupling constant
- The messengers $\Phi_{\bar{L}}$ and $\bar{\Phi}_{\bar{L}}$ mix with H_u and H_d, respectively, with the help of “charged" coupling constants.

Type-II Gauge Mediation

- Type-II gauge mediation, H_u mixes with messengers

$$W = gZ\bar{\Phi}\tilde{\Phi} + g'Z\bar{\Phi}_{\bar{L}}\tilde{H}_u + \tilde{\mu}\tilde{H}_u H_d + \tilde{y}_{Uij}\tilde{H}_u Q_{Li}\bar{U}_{Rj} \ ,$$

- Rotating, a messenger Yukawa interaction emerges

$$W = \bar{g}Z\bar{\Phi}\Phi + \mu H_u H_d + \mu'\Phi_{\bar{L}}H_d + y_{Uij}H_u Q_{Li}\bar{U}_{Rj} + y'_{Uij}\Phi_{\bar{L}}Q_{Li}\bar{U}_{Rj} \ ,$$

$$y_{Uij} = \frac{g}{\sqrt{g^2+g'^2}}\tilde{y}_{Uij} \ , \quad y'_{Uij} = \frac{g'}{\sqrt{g^2+g'^2}}\tilde{y}_{Uij} \ .$$

- Messenger Higgs mixing suppressed by μ'/M

Flavor in More Generic Gauge Mediation

- Messenger-Yukawa sector interactions

$$W = y_{Uij} H_u Q_{Li} \bar{U}_{Rj} + y'_{Uij} \Phi_{\bar{L}} Q_{Li} \bar{U}_{Rj} \ ,$$

- Yukawa couplings proportional

$$y_{Uij} = \frac{g}{g'} y'_{Uij}$$

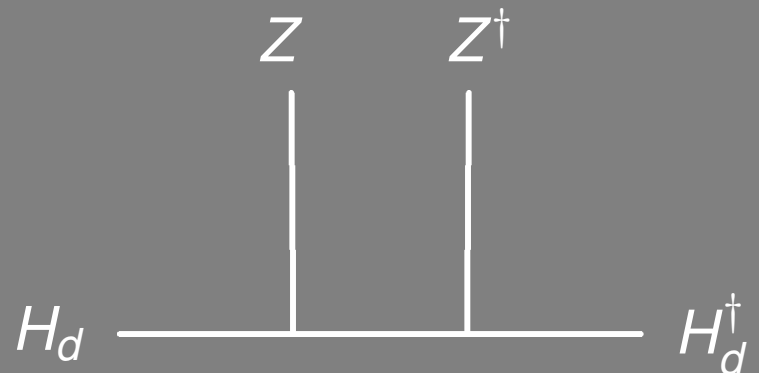
- Minimal Flavor violation!!!
- y_{Uij} and y'_{Uij} diagonalized simultaneously

Tree Level Effects

- Interactions

$$W = \bar{g} Z \bar{\Phi} \Phi + \mu' \Phi_{\bar{L}} H_d$$

- Higgs messenger mixing gives tree level Higgs mass

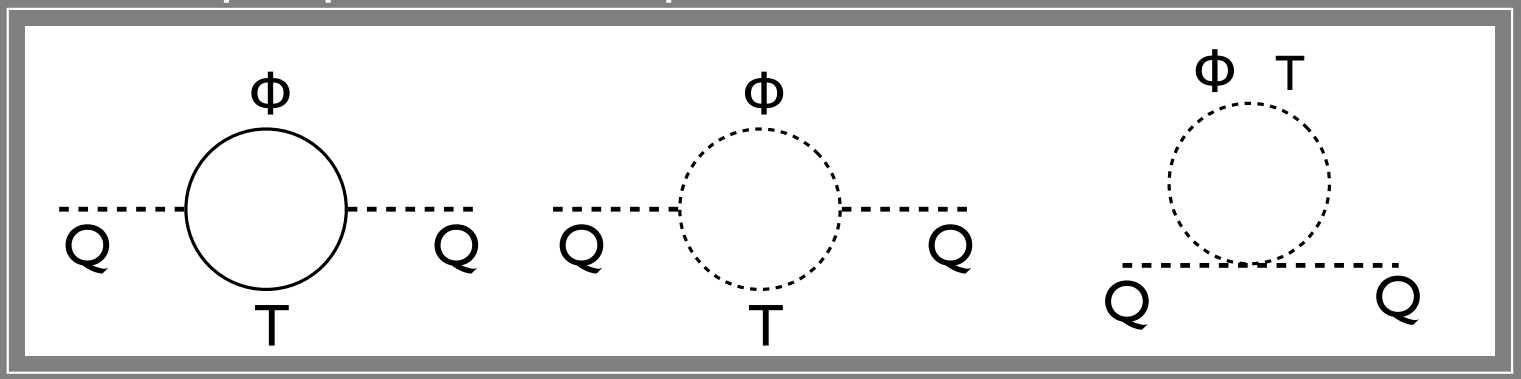


- Tree level diagram controlled by μ'
- Tree level effects suppressed by messenger scale

$$m_{H_d}^2 = -\mu'^2 \frac{F^2}{M^4 - F^2} \simeq -\mu'^2 \frac{F^2}{M^4}$$

One-Loop Scalar Masses

- One-loop squark and slepton masses



- One-loop contribution is negative

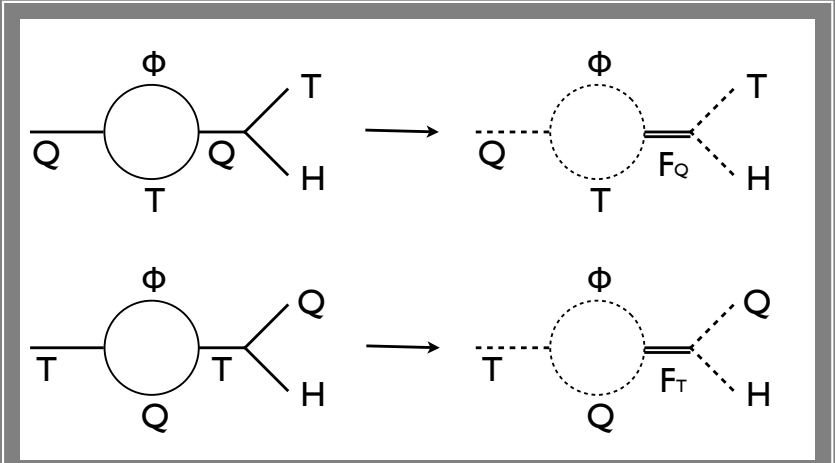
$$\delta m_{Q_3}^2 = \frac{1}{2}\delta m_{U_3}^2 \simeq \frac{8}{3}\left(\frac{\alpha_3}{4\pi}\right)^2 \frac{F^2}{M^2} - \frac{y_t'^2}{48\pi^2}\frac{F^2}{M^2}\frac{F^2}{M^4}, \quad (x \ll 1)$$

- Positive stop mass constraints

$$\frac{F}{M^2} \ll 2\sqrt{2} \times \frac{\alpha_3}{y_t'}.$$

A-Terms in Gauge Mediation

- A-terms from wave function renormalization



$$K \propto Q^\dagger Q Z^\dagger Z = F_Q^\dagger Q F_Z M \theta^2 \bar{\theta}^2 + \ldots.$$

$$F_Q^\dagger = H\bar{U} + \ldots$$

- A-term not suppressed by F/M^2 (can be large)

$$A_t = -\frac{3}{32\pi^2} y_t'^2 \frac{F}{M} \frac{1}{x} \log\left(\frac{1+x}{1-x}\right) \simeq -\frac{3y_t'^2}{16\pi^2} \frac{F}{M}$$

Two-Loop Scalar Masses

- Two-loop contribution from wave function renormalization

$$\mathcal{L} \supset \int d^4\theta \Phi^\dagger Z_\Phi(|Z|)\Phi \qquad Z = M + \theta^2 F$$

$$Z_\Phi(|Z|) = Z_\Phi(M) + \frac{1}{2}\frac{\partial Z_\Phi(M)}{\partial M}\left(F\theta^2 + F^\dagger\bar{\theta}^2\right) + \frac{1}{4}\frac{\partial^2 Z_\Phi(M)}{\partial M^2} F^\dagger F \theta^2\bar{\theta}^2$$

- Redefine the Q to go to the canonical basis

$$\Phi = Z^{1/2}\left(1 + \frac{1}{Z}\frac{\partial Z}{\partial M}F\theta^2\right)$$

- This gives two-loop mass contribution

$$M_Q^2 = -\frac{1}{4}\frac{\partial^2 \ln Z}{\partial^2 \ln |M|}\frac{FF^\dagger}{M^\dagger M}$$

- Sfermion masses are proportional to discontinuities in anomalous dimension and beta functions

Two-Loop: Messenger Higgs Mixing

- Messenger-Higgs wave functions mix ($\delta Z_{H\Phi} \neq 0$)
- Need to choose a rotation that keeps $g' = 0$

$$gZ\bar{\Phi}_L\Phi_L \to gZ\bar{\Phi}_L(\Phi_L - \delta Z_{HQ}H_u)$$

- Wave function mixing absorbed by H_u only

$$\Phi_L \simeq \Phi'_L$$
$$H_u \simeq H'_u - \delta Z_{H\Phi}\Phi'_L$$

- Only beta function of y'_t affected by mixing

Two-Loop Sfermion Masses

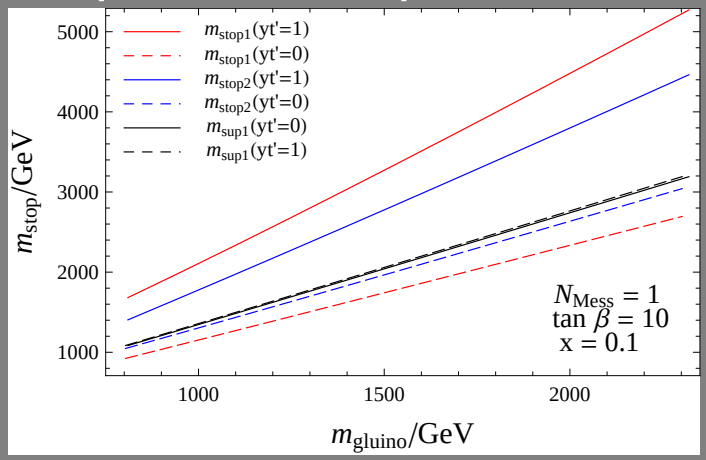
- Two loop contributions to the scalar masses

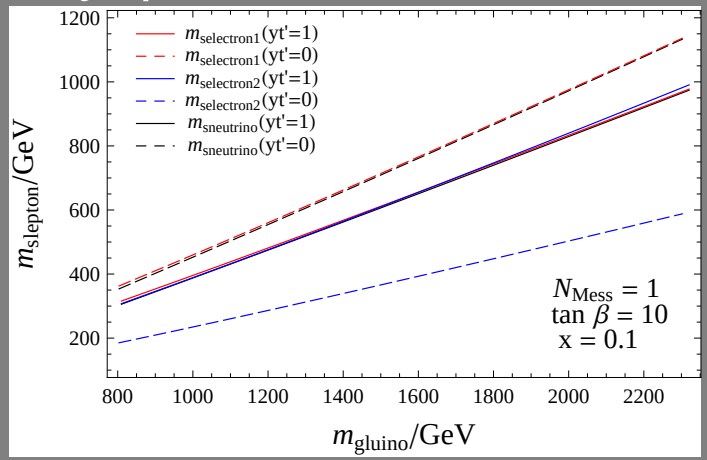
$$\begin{aligned}
\delta m^2_{Q_3} &= \frac{y_t'^2}{128\pi^4}\left(3y_t'^2 + 3y_t^2 - \frac{8}{3}g_3^2 - \frac{3}{2}g_2^2 - \frac{13}{30}g_1^2\right)\frac{F^2}{M^2}\,, \\
\delta m^2_{\bar{T}} &= \frac{y_t'^2}{128\pi^4}\left(6y_t'^2 + 6y_t^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right)\frac{F^2}{M^2}\,, \\
\delta m^2_{H_u} &= -9\frac{y_t^2 y_t'^2}{256\pi^4}\frac{F^2}{M^2}\,.
\end{aligned}$$

- Two loop contribution important, not suppressed by F/M^2.
- Two loop contribution to squarks POSITIVE for most y_t'
- Two-loop $>$ One-loop contribution unless $F/M^2 \simeq 1$

Mass Spectrum of Type-II

- Slepton and squark masses in Tyep-II





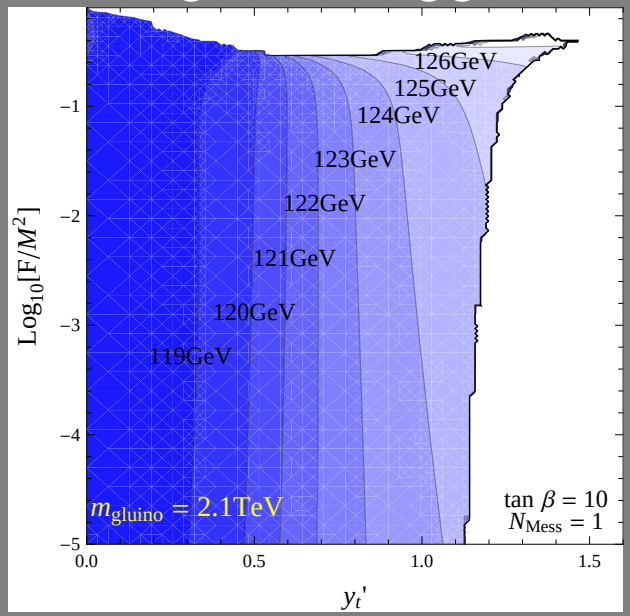
- Third generation squark masses significantly increased
- Right-handed slepton masses decreased
- Left-handed slepton masses increased

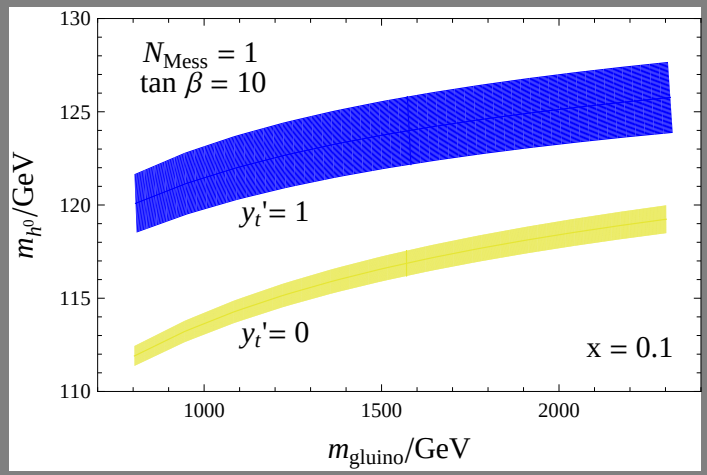
$$\delta\beta_{m_{\tilde{i}}^2} \simeq \frac{1}{8\pi^2}\frac{3}{5} Y g_1^2 \mathcal{S}_{new} \propto m_{Q_3}^2 - 2m_{U_3}^2$$

- $\mathcal{S}$ is large and negative because of two-loop contribution

Lightest Higgs Boson Mass

- The Lightest Higgs boson mass in Type-II





- Upper bound on F/M^2 from tachyonic stop mas
- Upper bound on y_t' from tachyonic slepton

$$\delta\beta_{m_{\tilde{l}}^2} \simeq \frac{1}{8\pi^2}\frac{3}{5} Y g_1^2 \mathcal{S}_{new} \propto m_{Q_3}^2 - 2m_{U_3}^2$$

- $\mathcal{S}$ is large and negative because of two-loop contribution

Conclusion

- Past years of experiment have rigorously tested the SM
- Final piece (Higgs) to be unveiled soon
- LHC excluded Higgs mass in most of 145$\sim$ 400 GeV (95%)
- Some prominent features are emerging
- Vanilla SUSY models have very light Higgs mass
- Using SUSY-zero, Higgs-Messenger mixing possible
- Higgs-Messenger mixing enhances A-terms
- Large A-terms Give larger Higgs mass