Flavor Mediation Delivers Natural SUSY

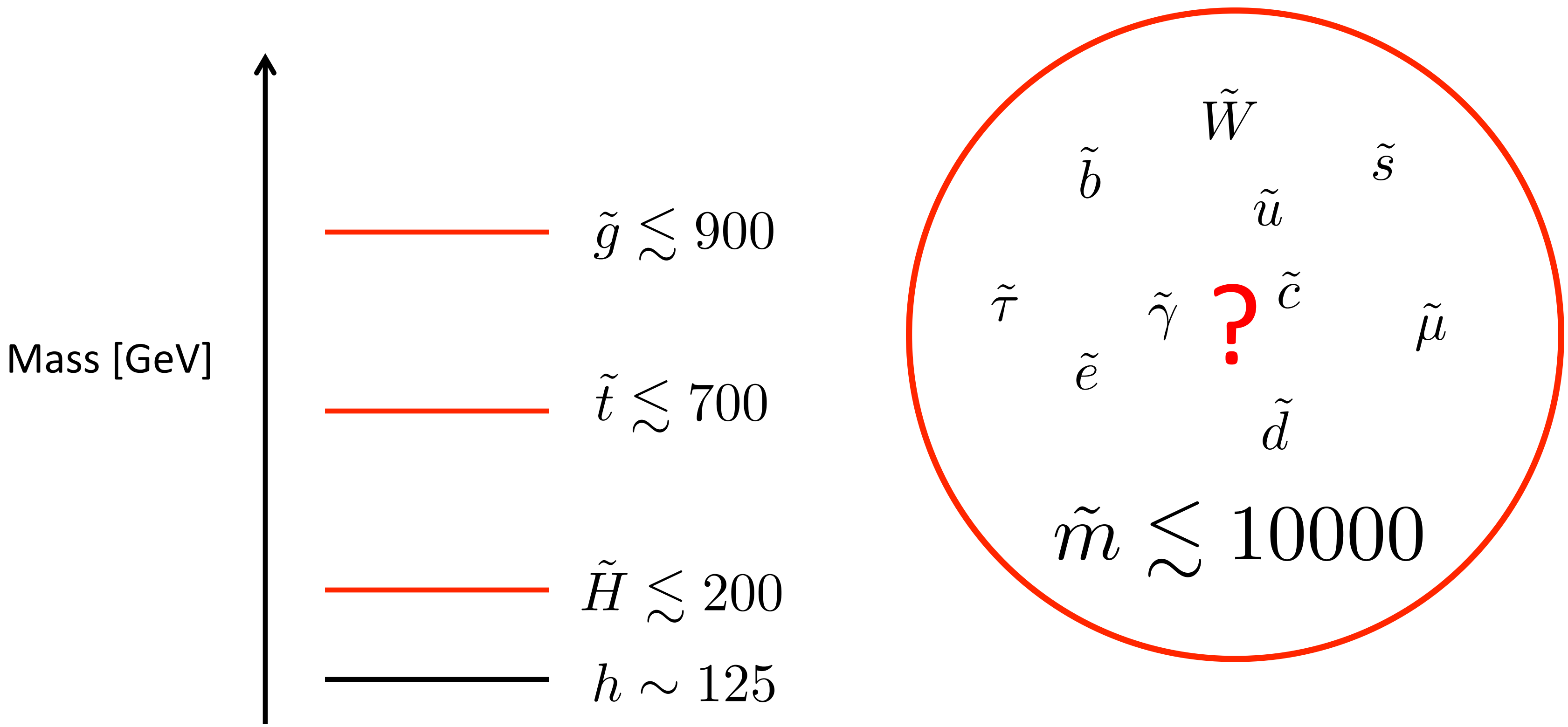
CERN BSM Institute
June 27th 2012

Based on Craig, MM, Thaler:
"The New Flavor of Higgsed Gauge Mediation" (JHEP)
"Flavor Mediation Delivers Natural SUSY" (JHEP)

Matthew McCullough, Simons Fellow, MIT

SUSY Naturalness

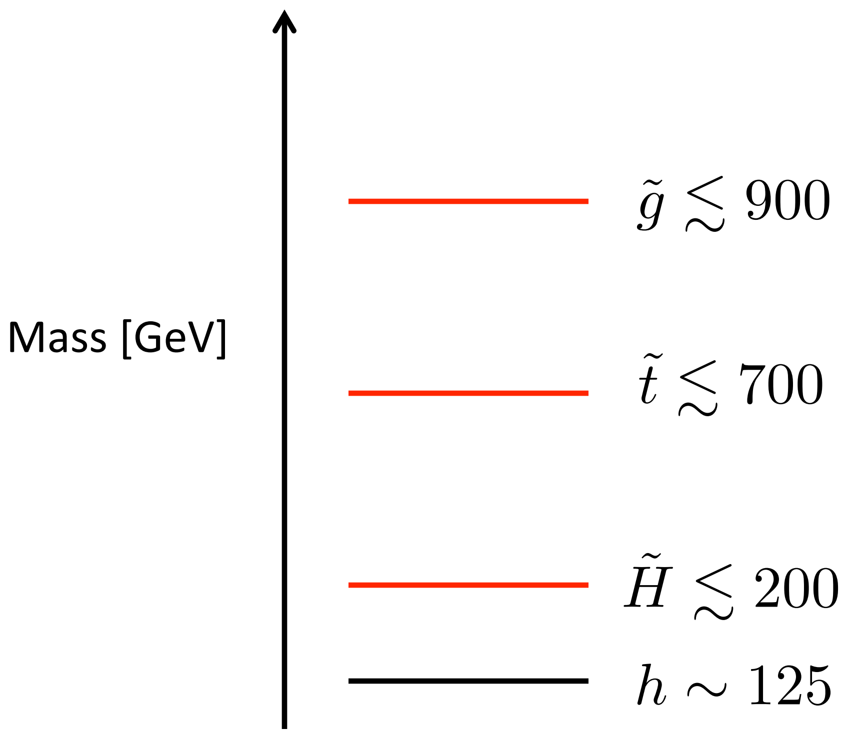
- If Higgs mass not fine-tuned, then at least require a spectrum of states like

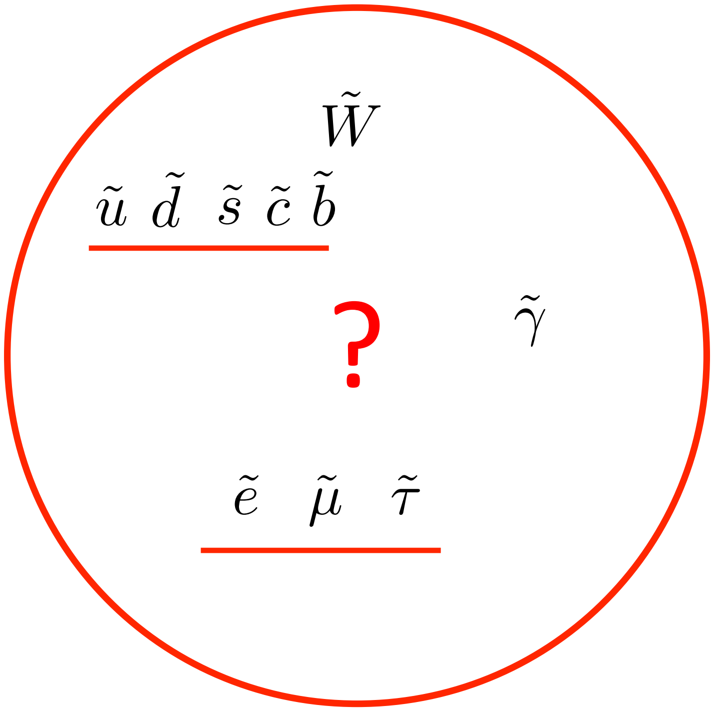


- Already need ()SSM for natural 125 GeV Higgs

Squark Degeneracy

- If Higgs mass not fine-tuned, and flavor measurements consistent, then





Squark Degeneracy

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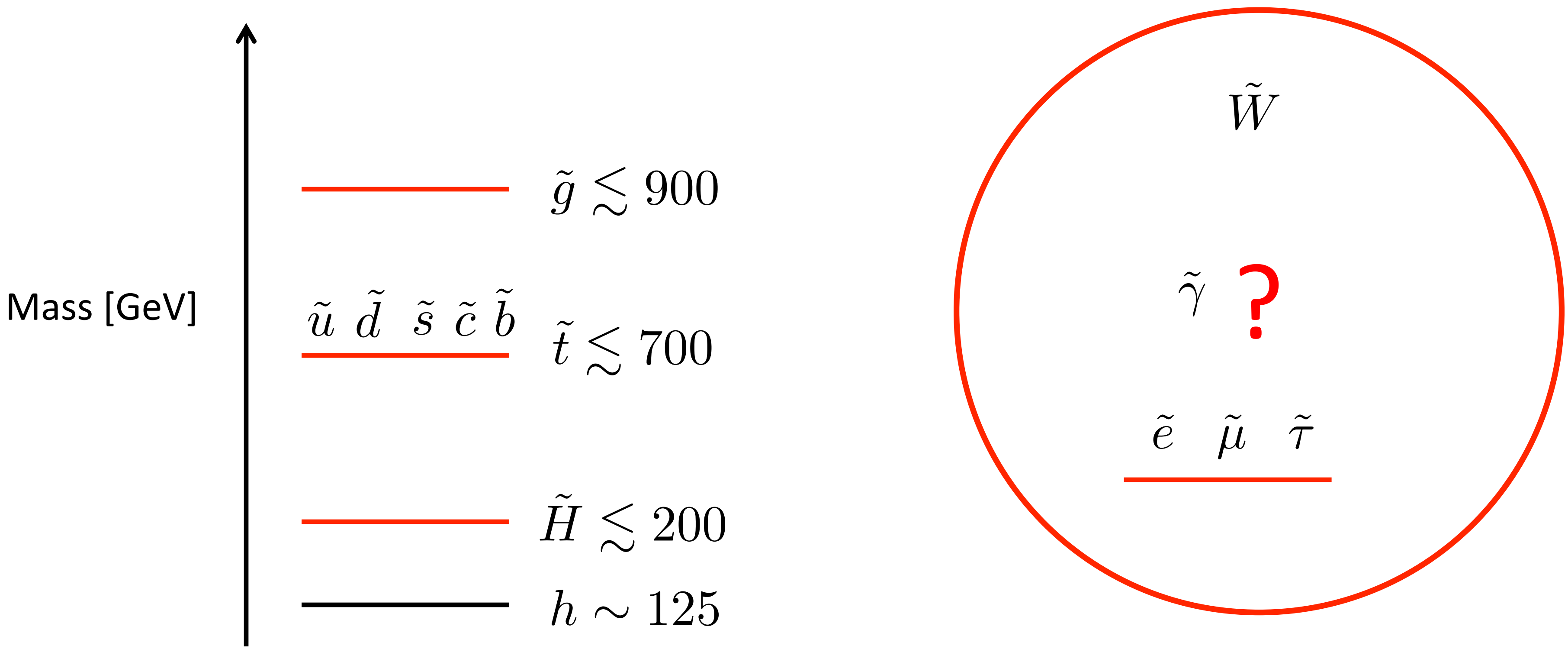
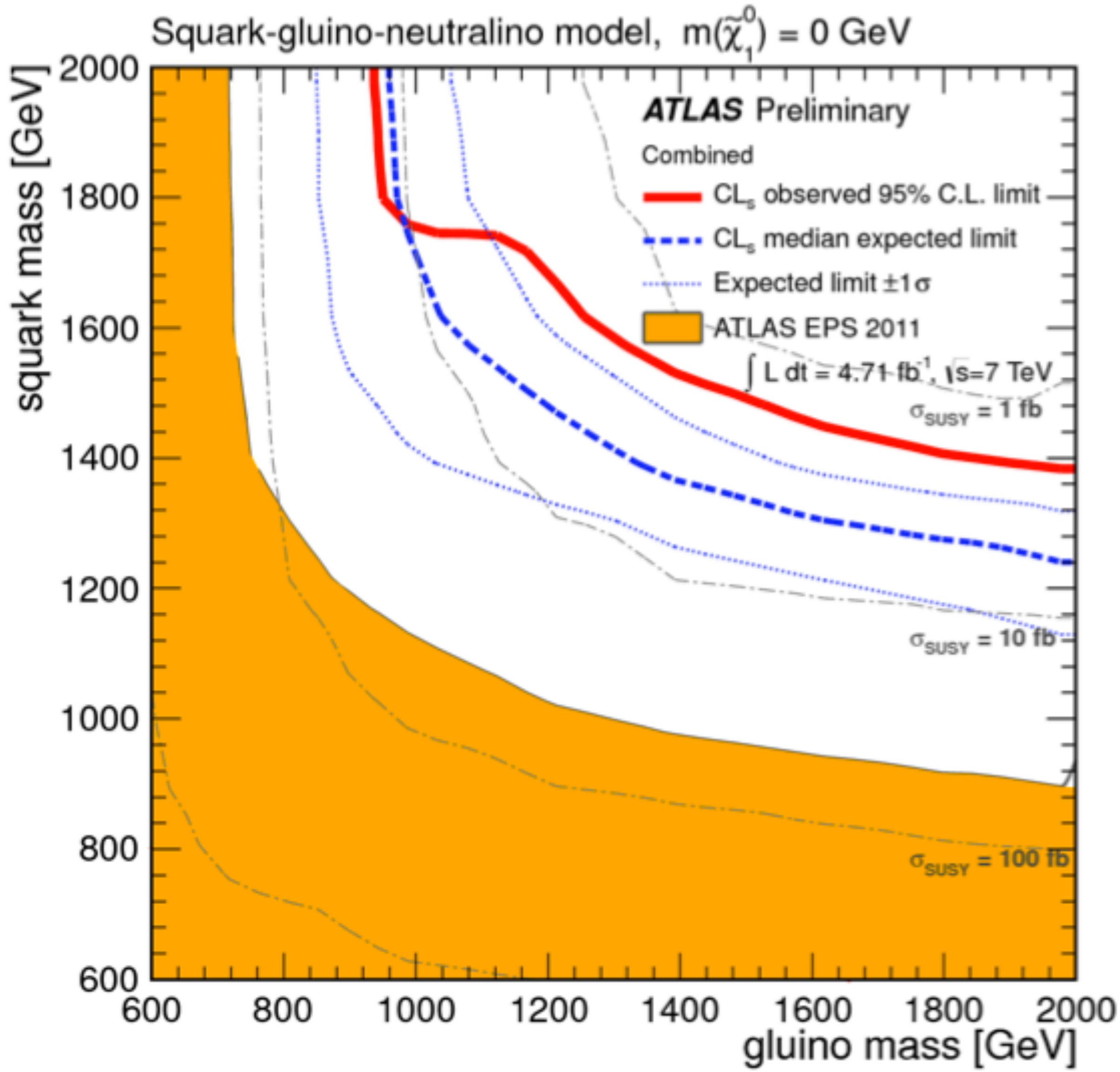


Easily observable at the LHC!

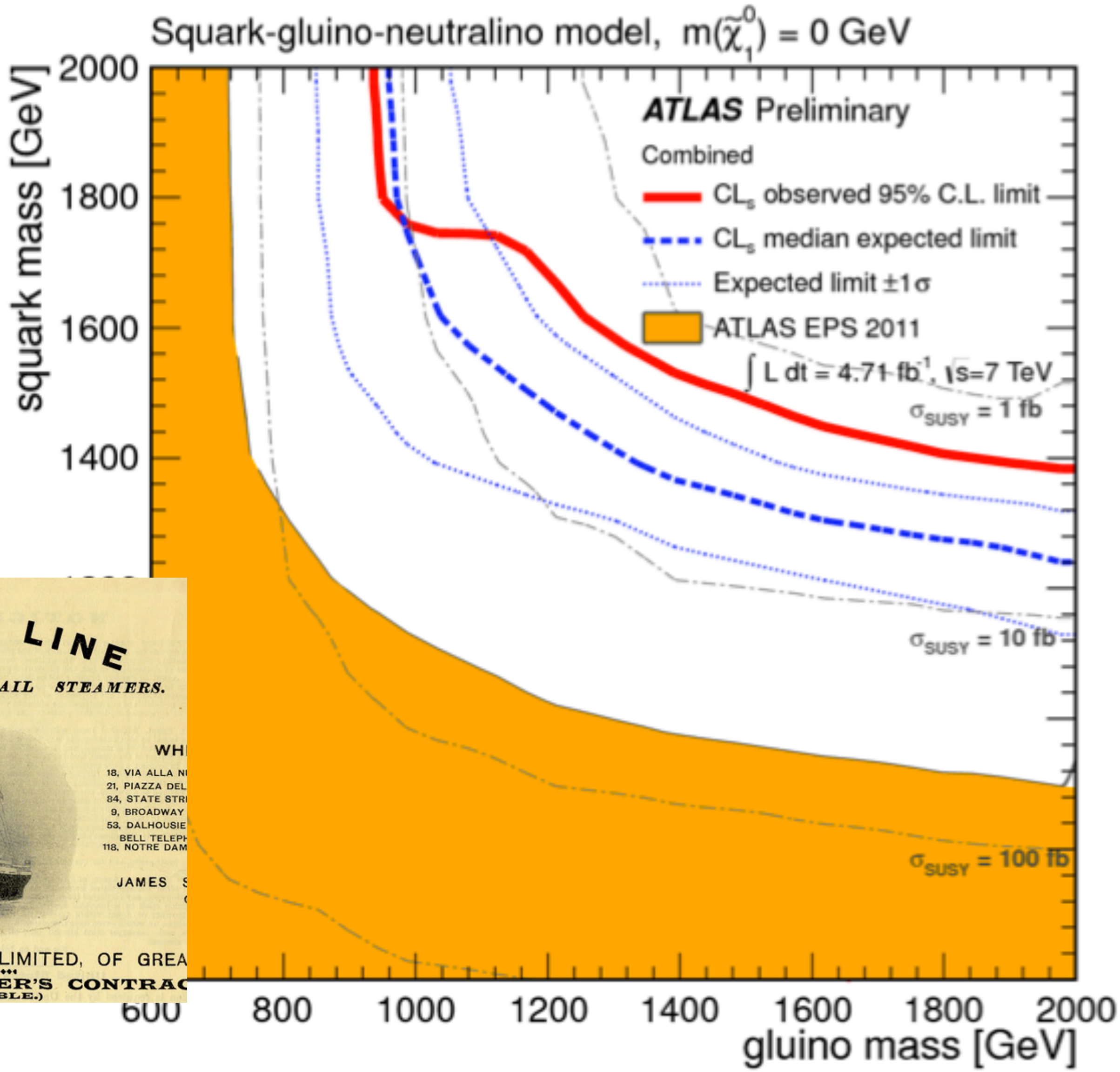
SUSY and the LHC

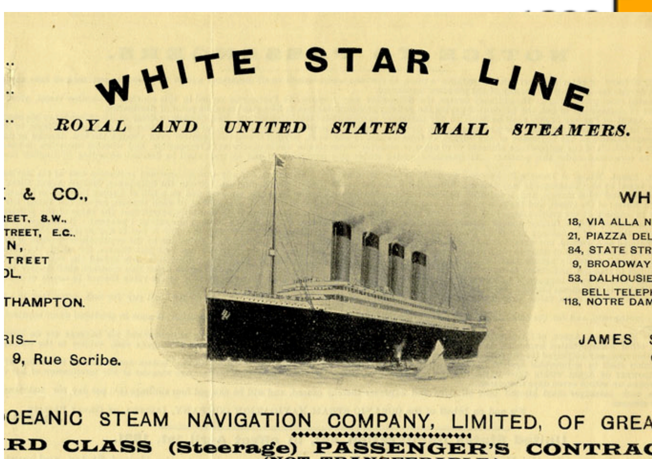
- Oops…



SUSY and the LHC

- Oops?





Natural SUSY

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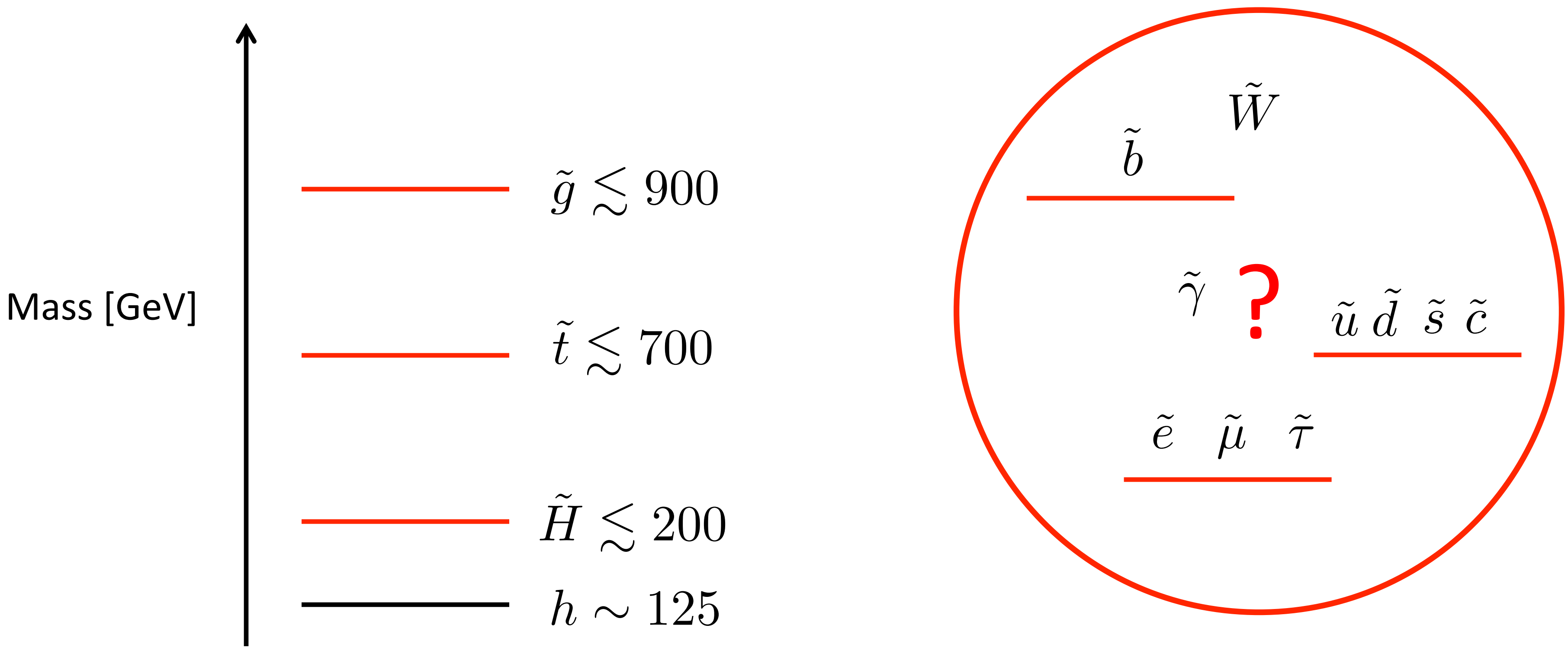

Natural SUSY

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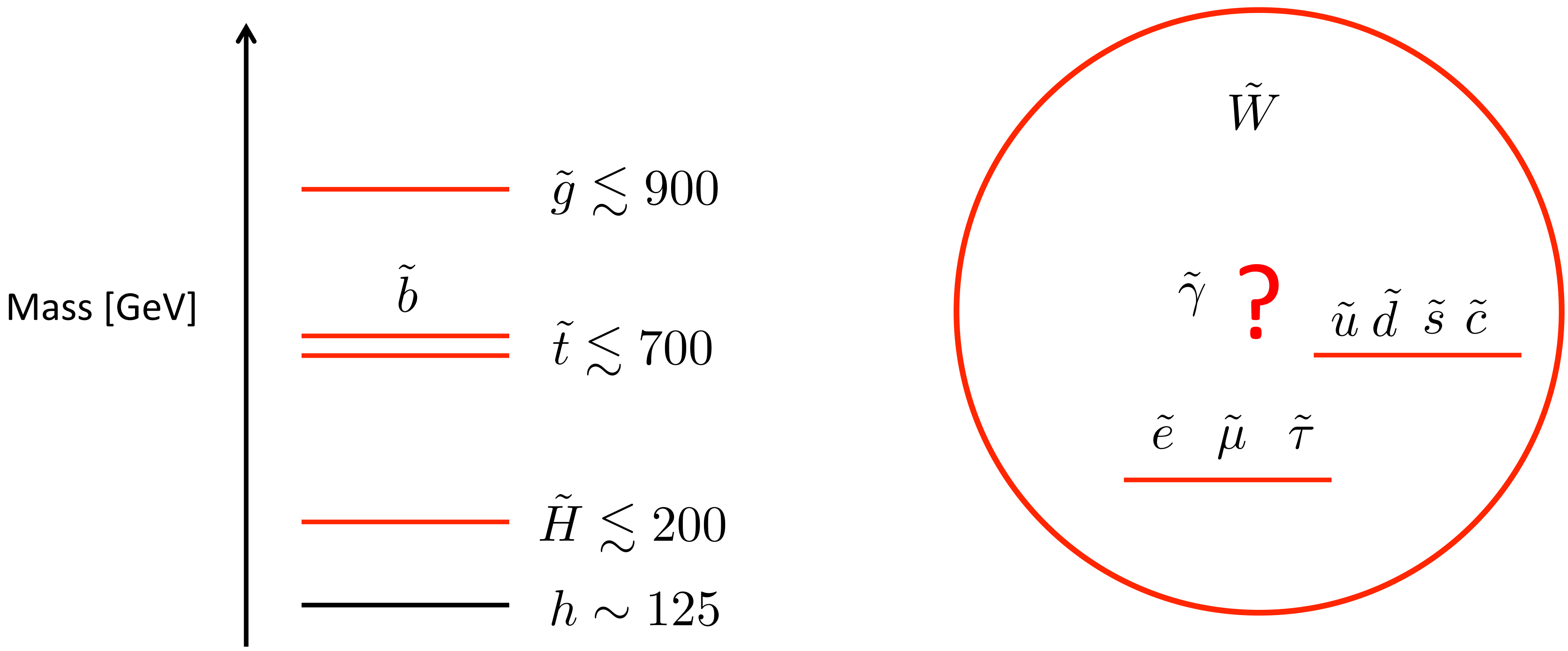
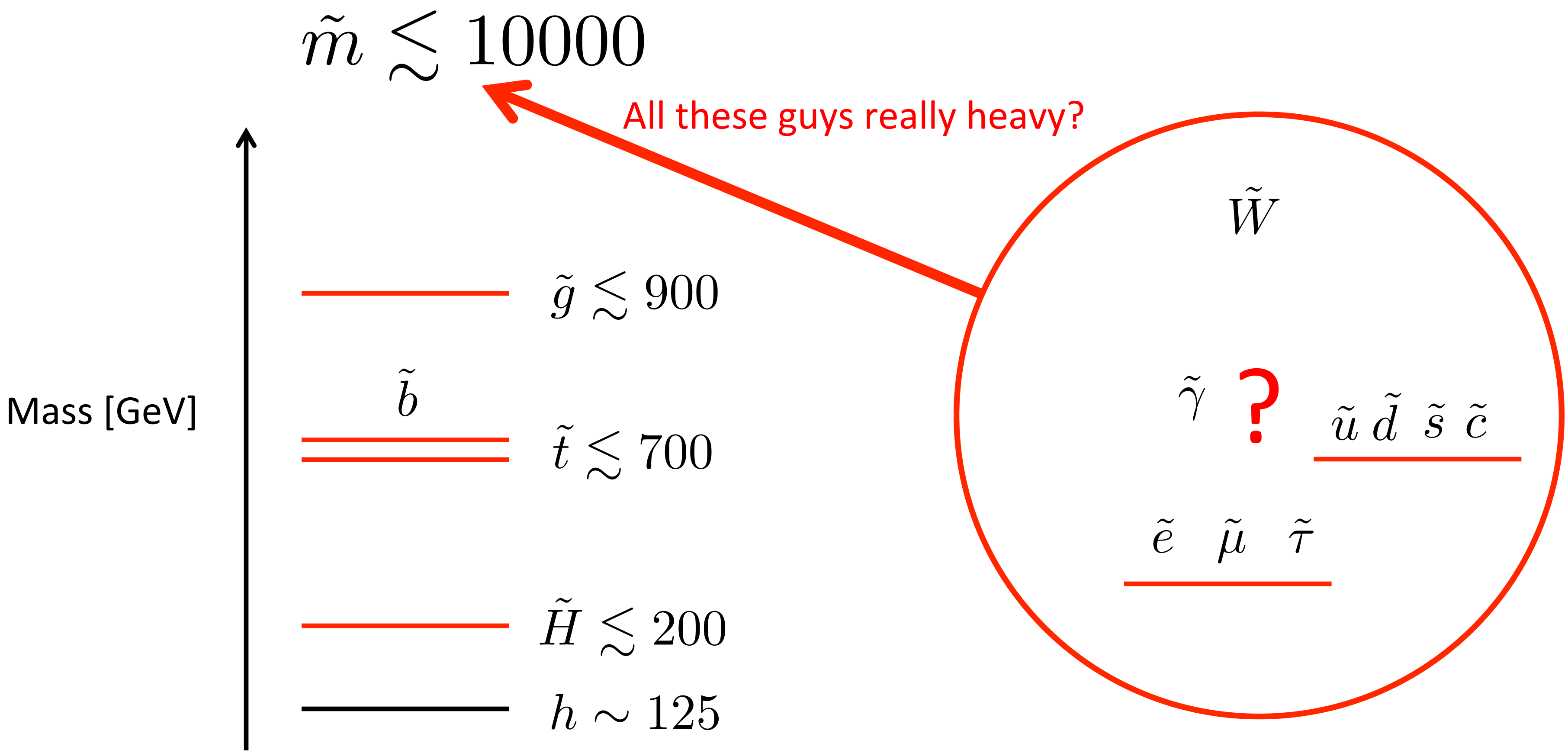


Natural SUSY

Dimopoulos, Giudice

- What if…



Natural SUSY

- Theorists should explain:
  - Why are top squarks lighter than others?
  - Why is the Higgs much lighter than other scalars?
  - Why are the first two generation squarks degenerate?

- and retain:
  - Unification
  - Other attractive features

Natural SUSY

- Theorists should explain:
  - Why are top squarks lighter than others?
  - Why is the Higgs much lighter than other scalars?
  - Why are the first two generation squarks highly mass-degenerate?

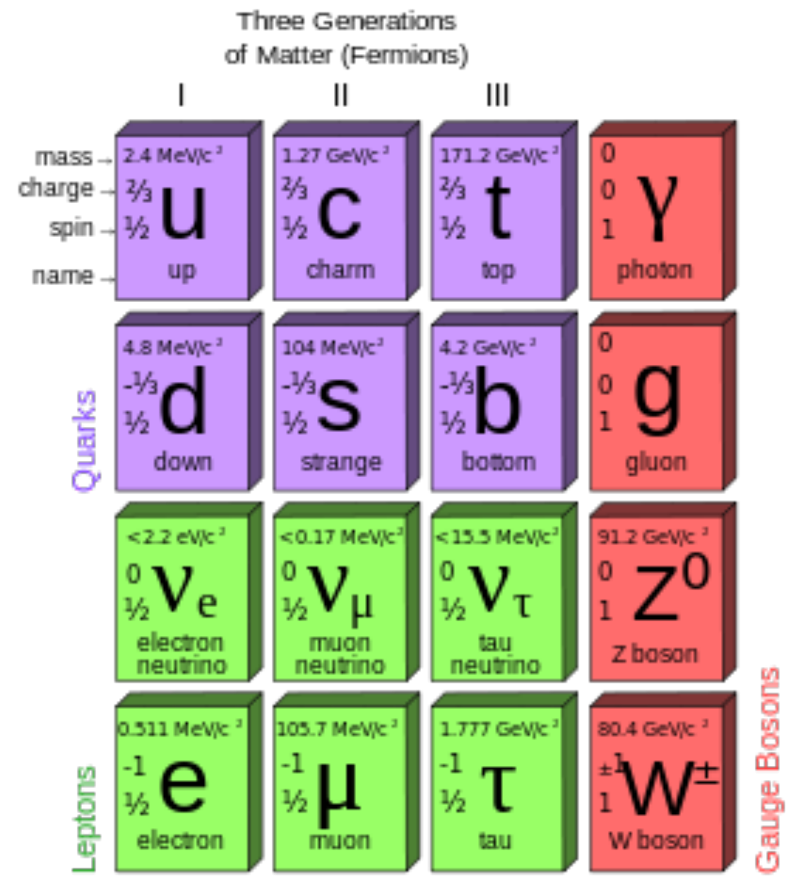
This is a "flavor" puzzle, relating different generations

- and retain:
  - Unification
  - Other attractive features
- A flavored explanation? A flavor force?

New Flavors of SUSY

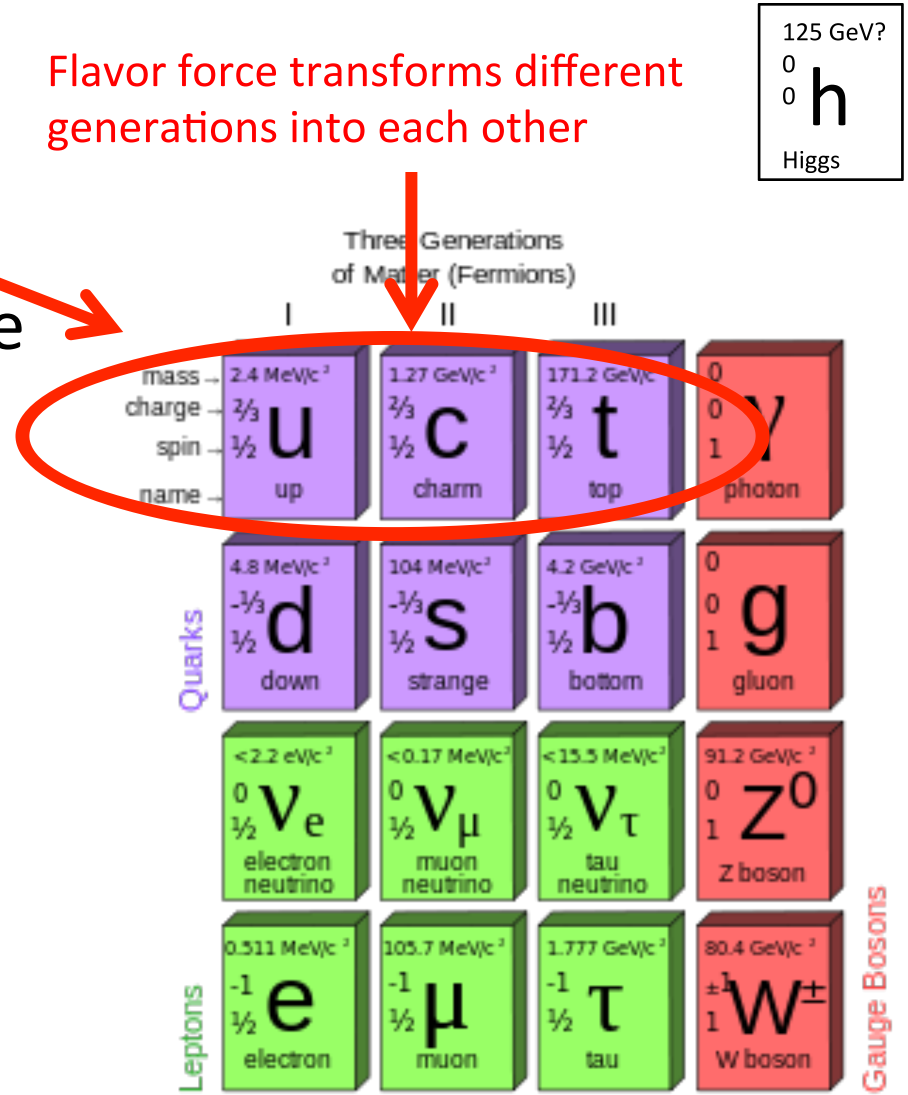
- A flavor force?

125 GeV?
0
0 h
Higgs



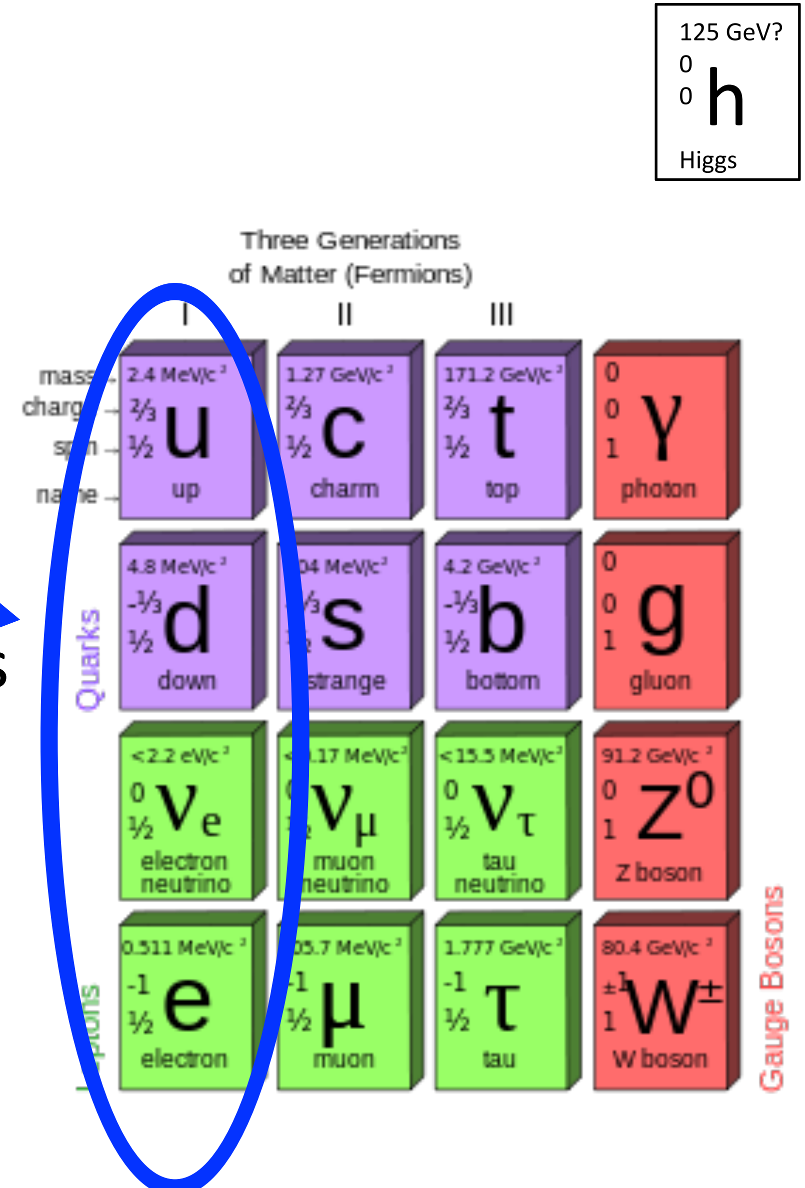
New Flavors of SUSY

- Which flavor force?
- No one is special
  - Should treat any three flavors equally



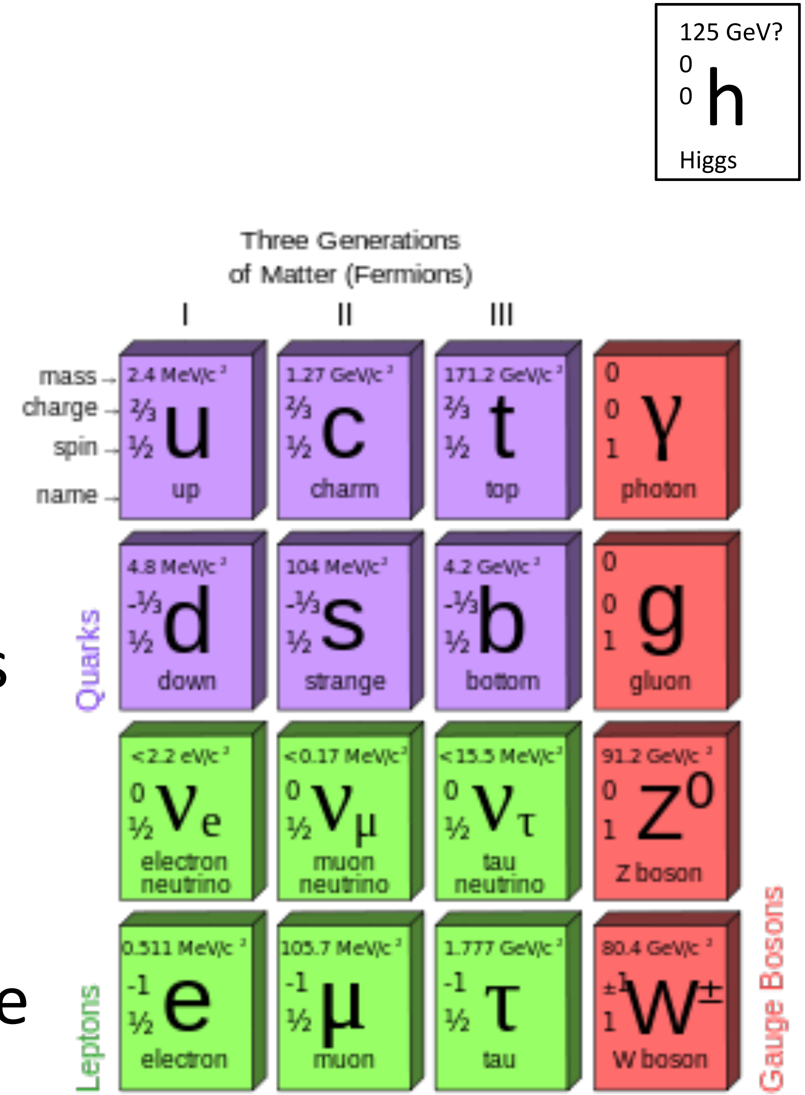
New Flavors of SUSY

- Which flavor force?
- No one is special
  - Should treat any three flavors equally
- Will it unify?
  - Different matter particles with same flavor charge



New Flavors of SUSY

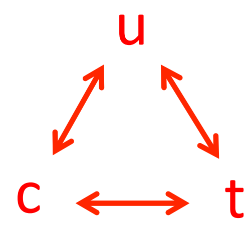
- Which flavor force?
- No one is special
  - Should treat any three flavors equally
- Will it unify?
  - Different matter particles with same flavor charge
- Is it consistent?
  - Must be SM anomaly-free



New Flavors of SUSY

- Candidate flavor force exists!
  - No SM anomalies
  - Consistent with unification
  - No need to add extra light charged particles
  - Like a "flavor QCD" $SU(3)_F$

- Flavor force rotates quark flavors



- Such processes very strongly constrained

New Flavors of SUSY

- Flavor forces not observed
  - Must be broken at high scales
  - Analogous to breaking of electroweak symmetry
  - Take flavor structure as input, i.e. spurions

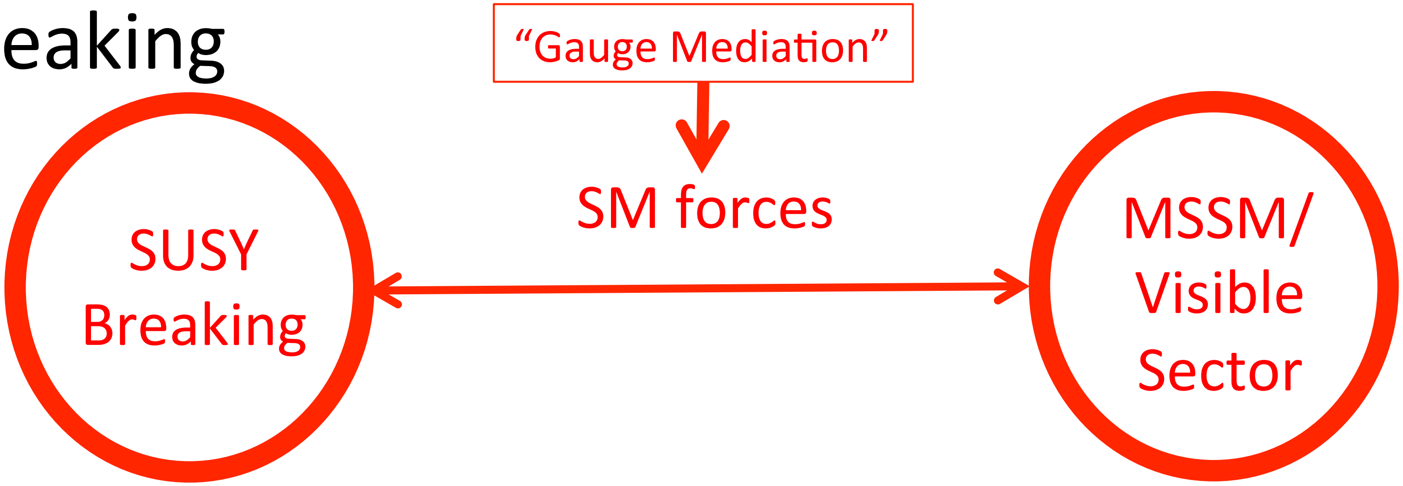
- "Flavor Higgs" proportional to quark masses

$$\langle \Phi_F \rangle \propto \begin{pmatrix} 172.9 & 0 & 0 \\ 0 & 1.29 & 0 \\ 0 & 0 & 0.0017 \end{pmatrix}$$

- More breaking = weaker force

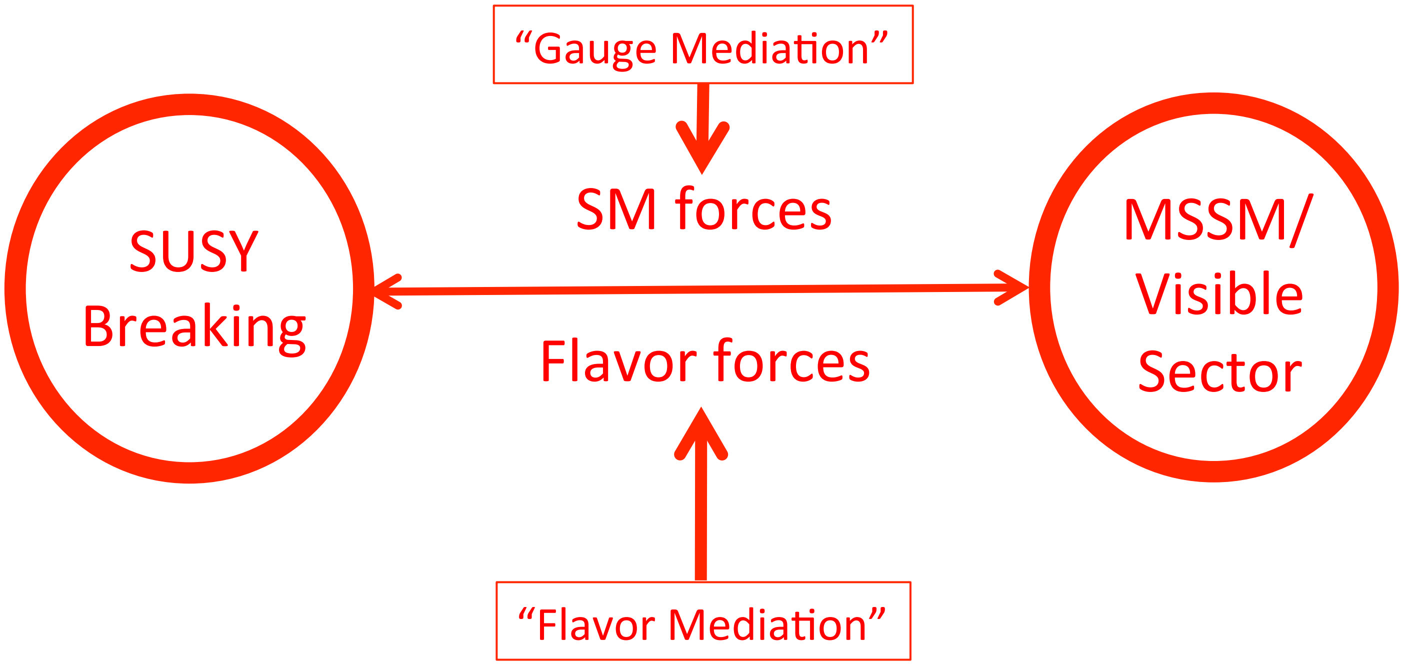
Flavor Mediation

- We know forces can communicate SUSY breaking



Flavor Mediation

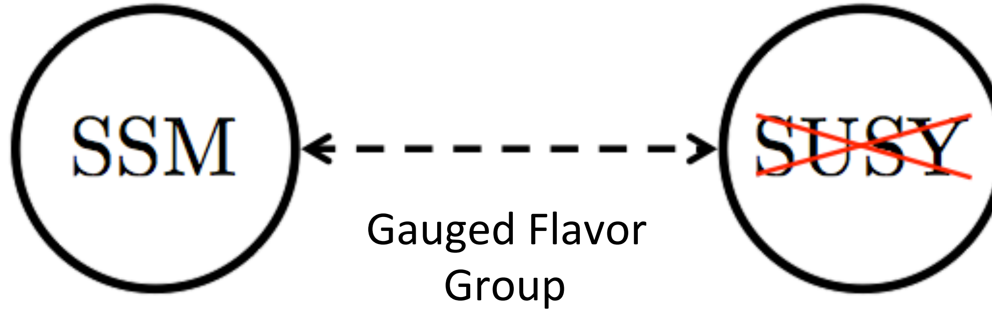
- We know forces can communicate SUSY breaking

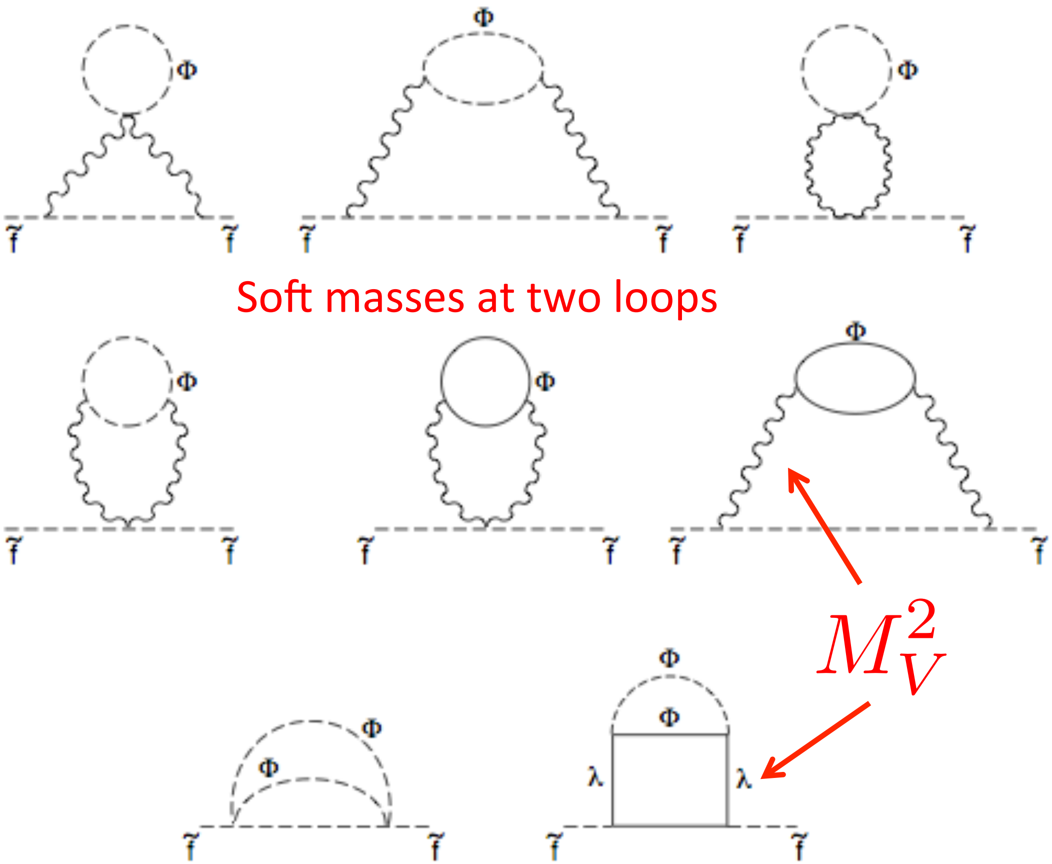


- Maybe flavor forces do too?
  - Kaplan & Kribs, 1999: U(1)
  - Craig, MM Thaler, 2012: Non-Abelian

Calculating

- Mediate via



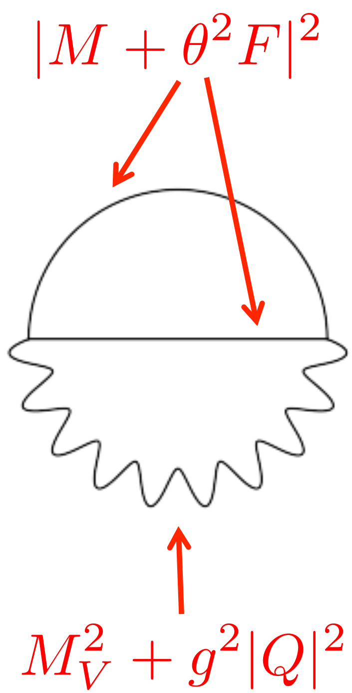


Flavor group broken: Massive gauge superfields complicates calculation

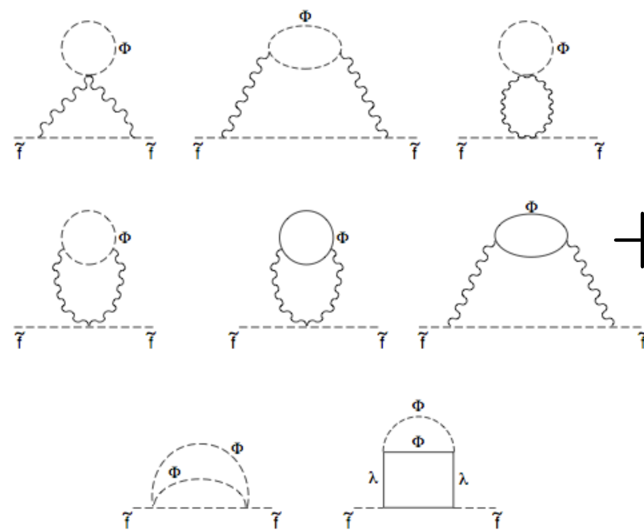
Calculating

- Or, to lowest order in F can find result from one supergraph (Craig, MM, Thaler)

$$\int d^4\theta$$



$$=$$



$$+\mathcal{O}\left(\frac{F}{M^2}\right)$$

Calculating

- Final result greatly simplified:

$$\left(\widetilde{m}_q^2\right)_{ij} = C(\Phi)\frac{\alpha'^2}{(2\pi)^2}\left|\frac{F}{M}\right|^2\sum_a f(\delta^a)\,(T_q^a T_q^a)_{ij}, \qquad \delta^a \equiv \frac{M_V^{a\,2}}{M^2},$$

Calculating

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where

$$f(\delta) = 2\frac{\delta(4-\delta)((4-\delta)+(\delta+2)\log(\delta)) + 2(\delta-1)\Omega(\delta)}{\delta(4-\delta)^3}$$

with

$$\Omega(\delta) = \sqrt{\delta(\delta-4)}\left(2\zeta(2)\log^2(\alpha) + 4\mathrm{Li}_2(\alpha)\right)$$

$$\alpha = \left(\sqrt{\frac{\delta}{4}} + \sqrt{\frac{\delta}{4} - 1}\right)$$

SUSY ♥ SU(3) Flavor

- Unique SM anomaly-free $SU(3)_F$ symmetry
- Superfields all fundamentals

$$Q, U^c, D^c, L, E^c$$

- Yukawa couplings from

$$W = \frac{1}{M_{S_u}} \boldsymbol{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \boldsymbol{S_d H_d Q D^c}$$

$\overline{\mathbf{6}}$ under $SU(3)_F$

- Plenty of ways to generate these couplings

SUSY ❤ SU(3) Flavor

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$\overline{\mathbf{6}}$ under $SU(3)_F$

- Break with

$$\langle \boldsymbol{S_u} \rangle = \begin{pmatrix} v_{u1} & 0 & 0 \\ 0 & v_{u2} & 0 \\ 0 & 0 & v_{u3} \end{pmatrix}, \qquad \langle \boldsymbol{S_d} \rangle = V_{\text{CKM}} \begin{pmatrix} v_{d1} & 0 & 0 \\ 0 & v_{d2} & 0 \\ 0 & 0 & v_{d3} \end{pmatrix} V_{\text{CKM}}^T$$

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Know these ratios

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Know these ratios

- Numerous models/possibilities for this exist. Focus on implications for SUSY.
- Future: Flavor breaking model

SUSY ❤ SU(3) Flavor

$$W = \frac{1}{M_{S_u}} \boldsymbol{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \boldsymbol{S_d H_d Q D^c}$$

- Don't know relative scales of both vevs.

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- Don't know relative scales of both vevs.

$$\frac{m_t}{m_b} = \frac{v_{u3}}{v_{d3}}\alpha, \qquad \alpha \equiv \frac{M_{S_d}}{M_{S_u}} \tan\beta.$$

SUSY ♥ SU(3) Flavor

$$W = \frac{1}{M_{S_u}} \boldsymbol{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \boldsymbol{S_d H_d Q D^c}$$

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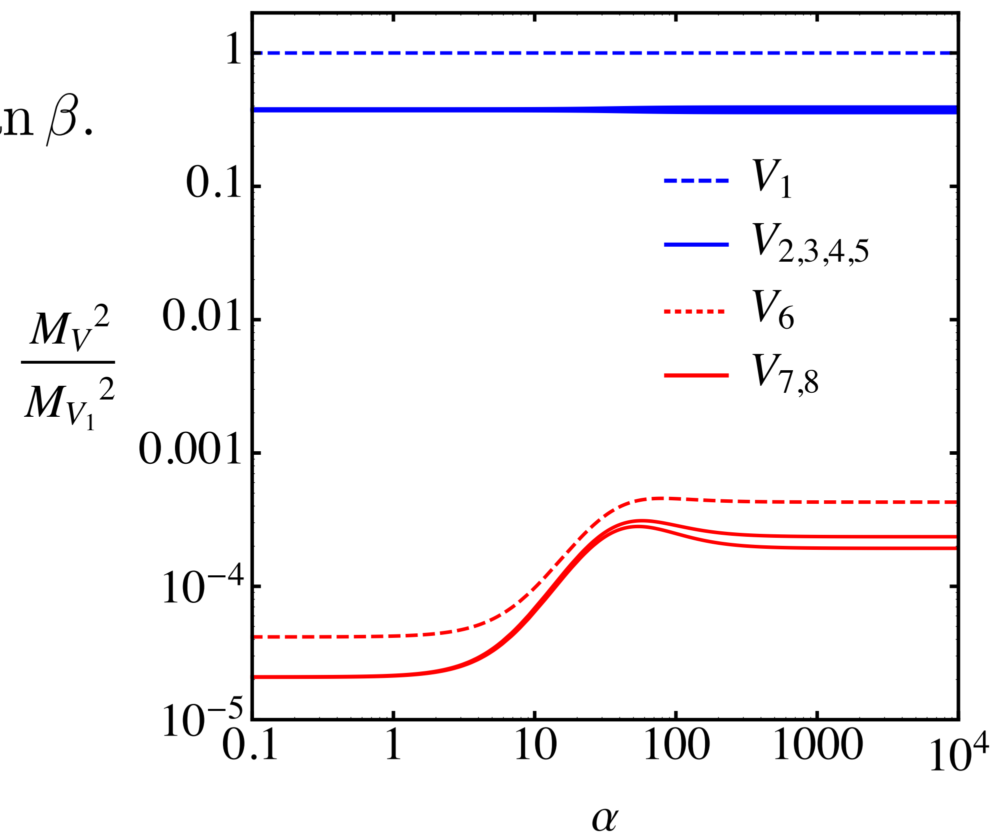
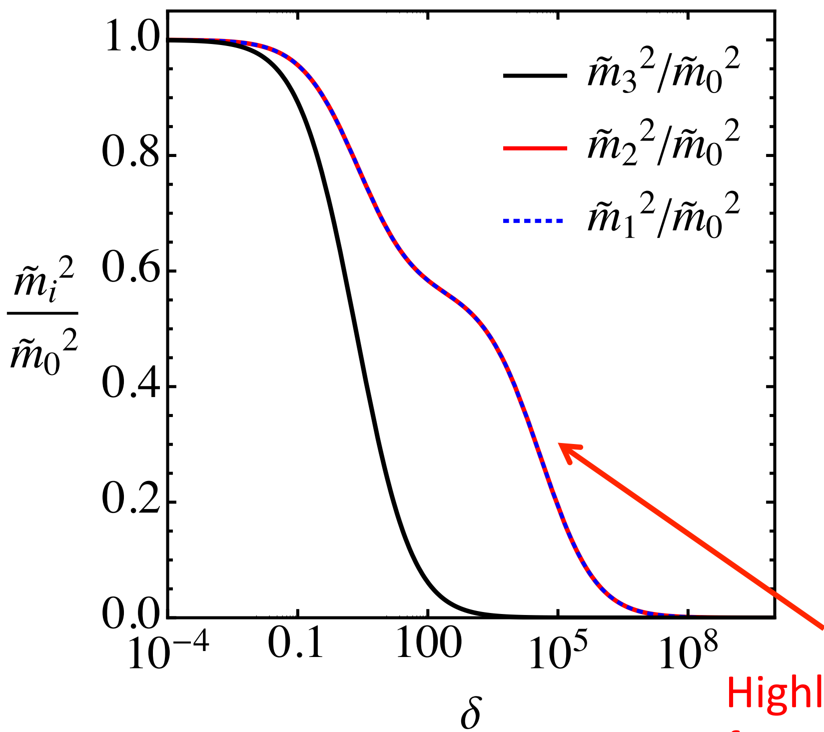
$$\frac{m_t}{m_b} = \frac{v_{u3}}{v_{d3}} \alpha, \qquad \alpha \equiv \frac{M_{S_d}}{M_{S_u}} \tan \beta.$$

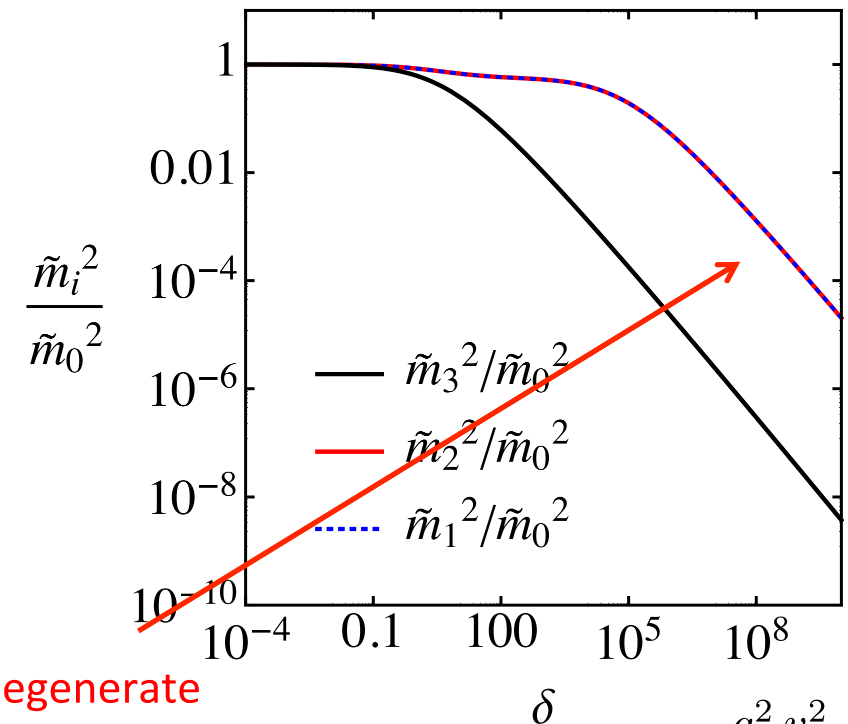
- Can now determine flavor boson spectrum



SUSY ❤ SU(3) Flavor

- Easy to calculate the squark spectrum!



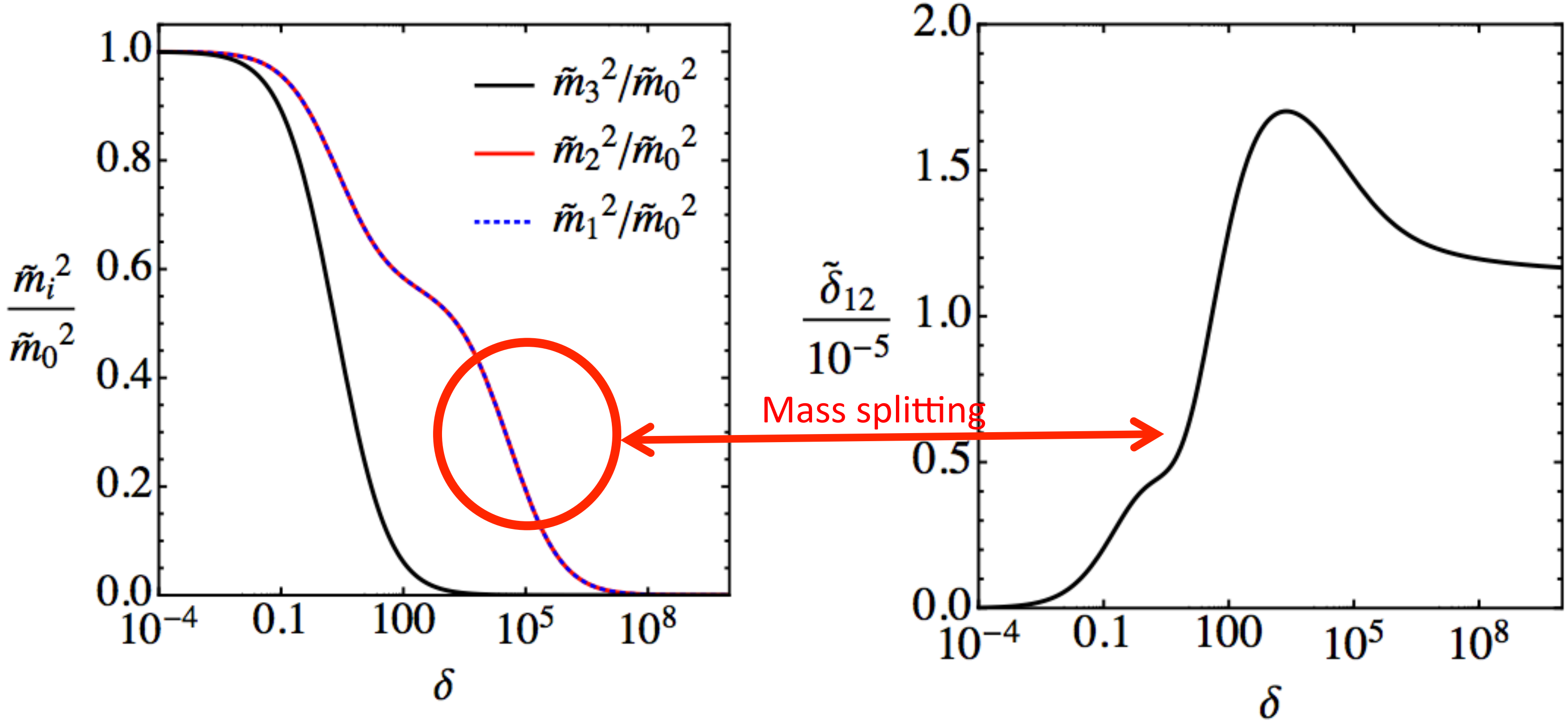


Highly degenerate
first two generations

$$\delta = \frac{g_F^2 v_F^2}{M^2}$$

SUSY ♥ SU(3) Flavor

- Zooming in…
- Flavor mediation makes first two generations highly degenerate!

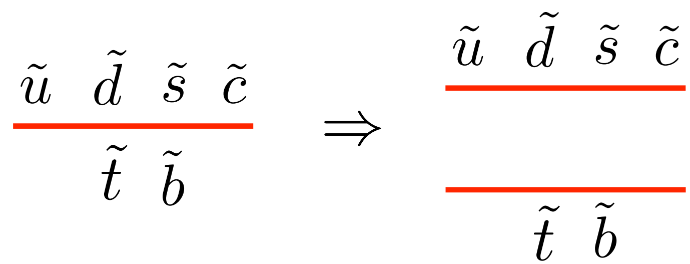


SUSY ♥ SU(3) Flavor

- Top Yukawa breaks flavor force, weaker interaction with third generation

$$SU(3)_F \rightarrow SU(2)_F$$

- Third generation split from first two

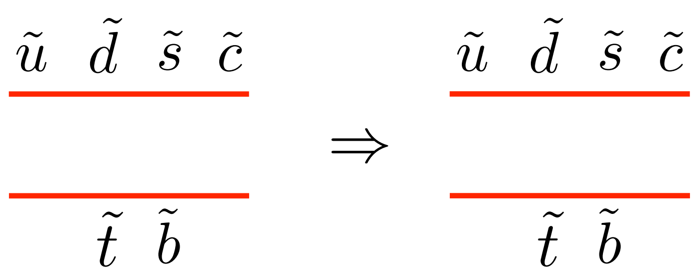


SUSY ♥ SU(3) Flavor

- Charm Yukawa breaks remaining flavor force

$$SU(2)_F \to \emptyset$$

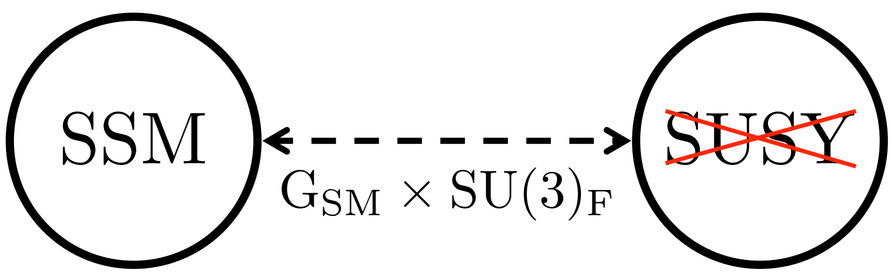
- Remaining flavor force broken
- No remaining flavor force to split off first generation



SUSY ♥ SU(3) Flavor

- So far, just squarks (and sleptons). Need a more complete model.

- Philosophy: Flavor group just another SM gauge group broken at high scales. If flavor mediation, then expect flavor + standard gauge mediation.



SUSY ♥ Flavor Mediation

- Now:
  - Gaugino masses: typical gauge-mediated
  - Higgs soft parameters: typical gauge-mediated
  - Squarks and sleptons: typical gauge-mediated + flavor-mediated contributions.

SUSY ♥ Flavor Mediation

- Now:
  - Gaugino masses: typical gauge-mediated
  - Higgs soft parameters: typical gauge-mediated
  - Squarks and sleptons: typical gauge-mediated + flavor-mediated contributions.

- Need explanation for 125 GeV Higgs mass. Choose SMSSM:

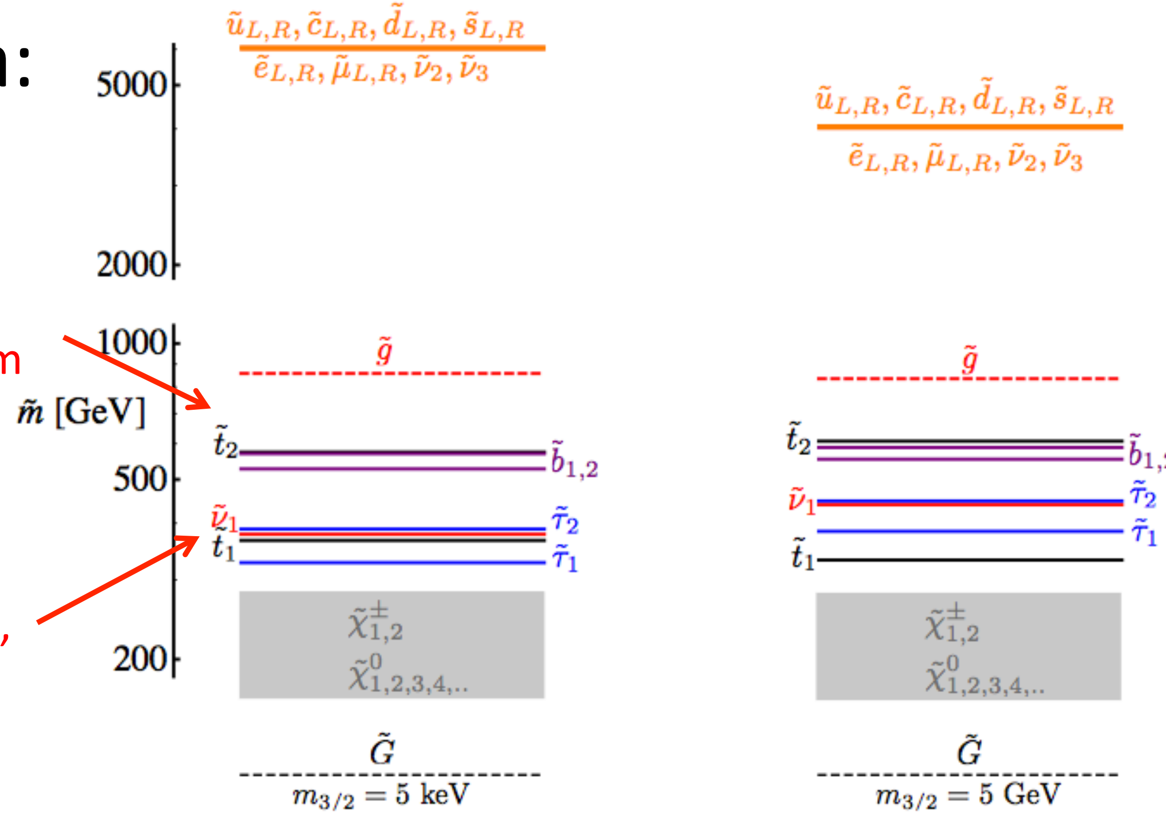
$$W_{\rm Higgs} = \mu_H H_u H_d + \mu_S S^2 + \lambda S H_u H_d + f S + \kappa S^3.$$

SUSY ♥ Flavor Mediation

- Typical spectra:

Another surprise: under RG heavy squarks drive stop masses down at two-loops, pushing them below gluinos.

Third generation sleptons and right-handed sbottoms also light, from anomaly cancellation.



Benchmark	M [GeV]	$\sqrt{C(\Phi)}\alpha_F(M)$	δ	$\tilde{m}^F_{1,2}$ [GeV]	$\tilde{m}^F_3$ [GeV]	$m_{\tilde{g}}$ [GeV]	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]
Low Scale	10^8	0.54	129^2	6000	300	859	367	575
High Scale	10^{14}	0.32	72^2	4000	300	836	332	608

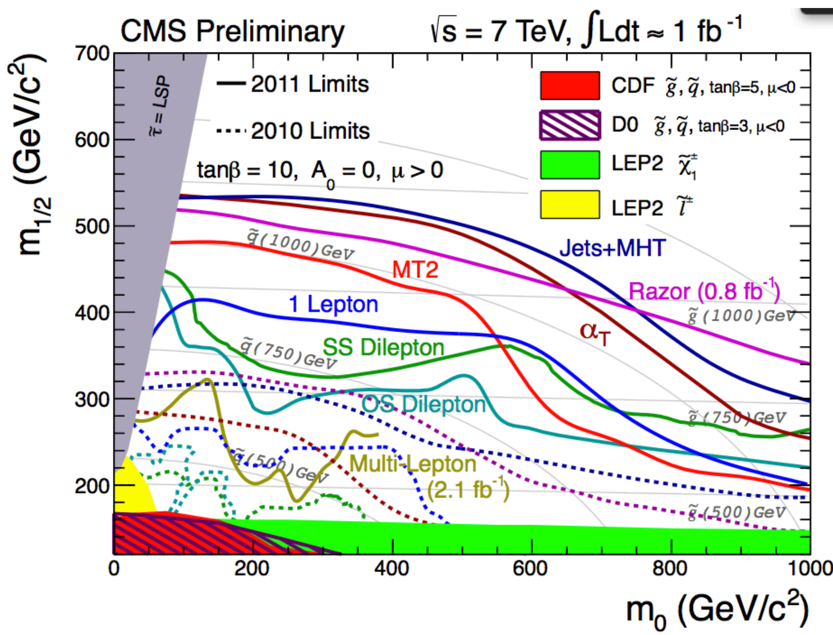
Flavor Mediation

- Force weakest when communicating to third generation
  - Stop squarks lighter than other squarks ✔
- Higgs not charged under flavor force
  - Higgs automatically lighter than squarks ✔
- Only allowed to have $SU(3)_F$ force
  - Explanation for degeneracy of first two generations ✔
- No new charged matter introduced at low scales
  - Unification ✔

Backup 1 hour talk slides

A New Age

- Veil over TeV-scale physics is lifting
- LHC data is pouring in



← What does all this information mean?

- Implications for ideas of unification of fundamental forces, new physics, etc?

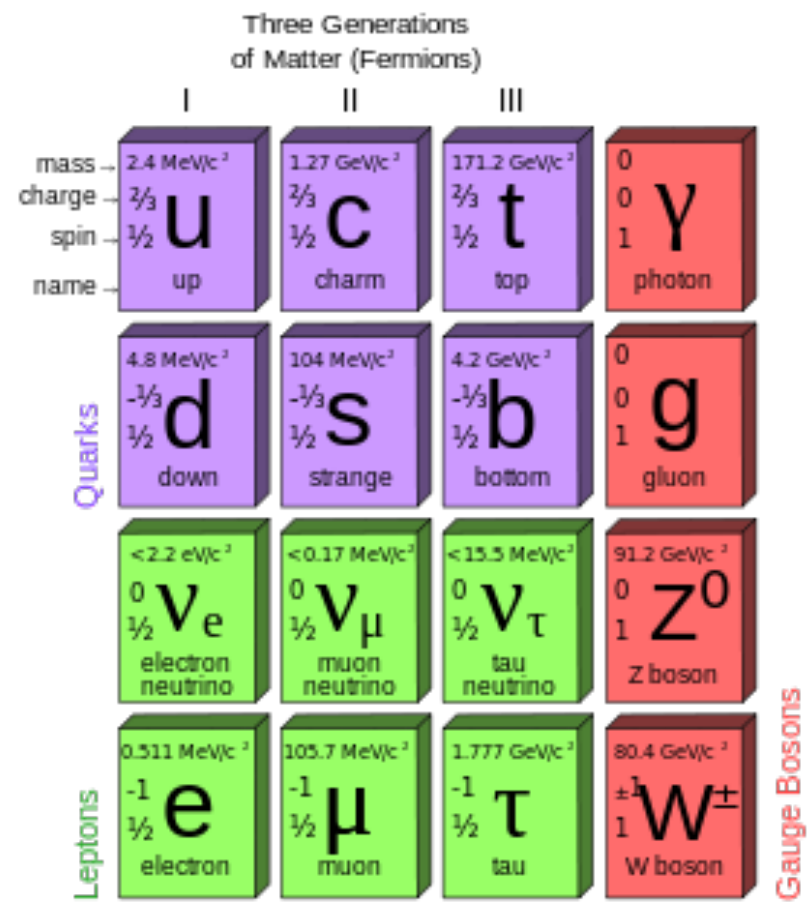
Plan

- Brief overview of Supersymmetry (SUSY)
  - Theoretical successes
  - Experimental puzzles
  - What we expected at LHC
- Implications of LHC results so far on SUSY
- New Flavors of Supersymmetry
  - Theoretical ideas
  - Experimental predictions

The Standard Model

125 GeV?
0
0 h
Higgs

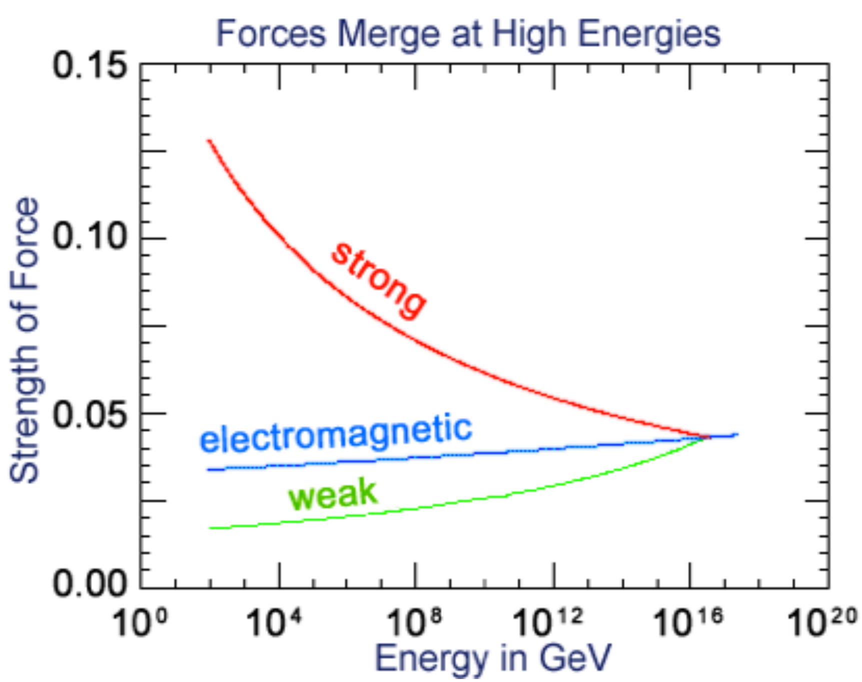
- Incredibly effective theory
- Is it an effective theory?
- Why anything else?
  - Dark Matter?
  - Neutrino masses?
  - Flavor structures?
  - Unification?



Wikipedia

Unification

- Perhaps the strength of known forces unites at high energies into one Grand Unified Force?



Particle Data Group

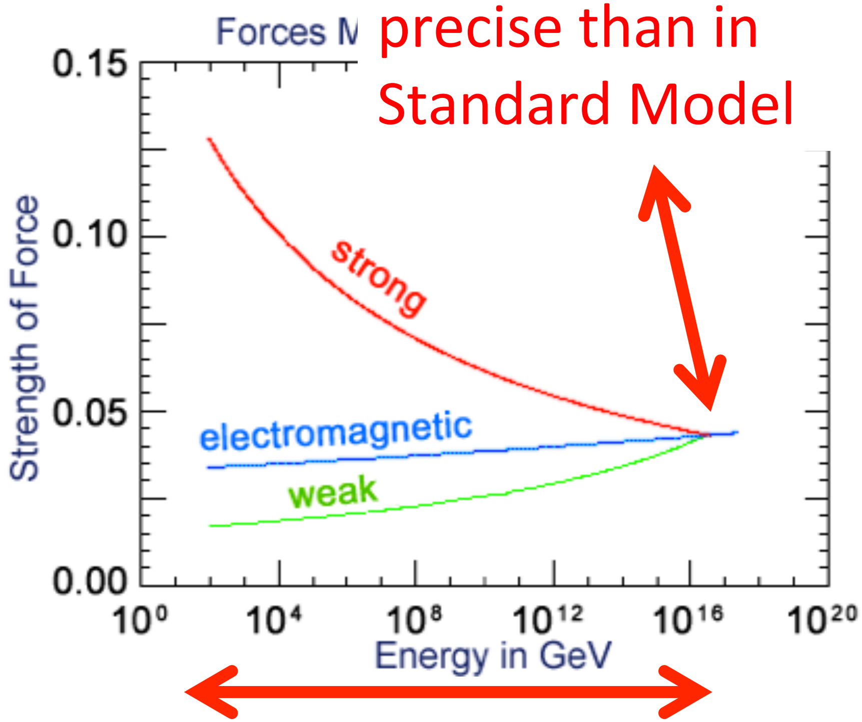
Higgs and Unification

- Higgs as fundamental particle
- Mass typically dragged up to scale of any heavier particles
- If forces unify, then why is the Higgs so light?
- "Hierarchy Problem"

Supersymmetry

- Theoretical framework offers answers

Unification more precise than in Standard Model



Higgs mass naturally lighter than physics at high energies

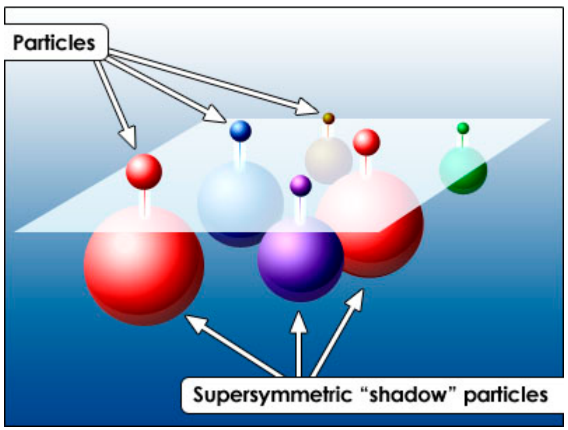
Higgs and SUSY

- Higgs is fundamental particle
- Quantum corrections cancel
- Higgs mass stable against physics at higher energies
- “Hierarchy Problem” solved

Dimopoulos, Georgi
Dimopoulos, Raby, Wilczek
…

Supersymmetry Redux

- No superpartners observed
- Supersymmetry broken, superpartners heavy:



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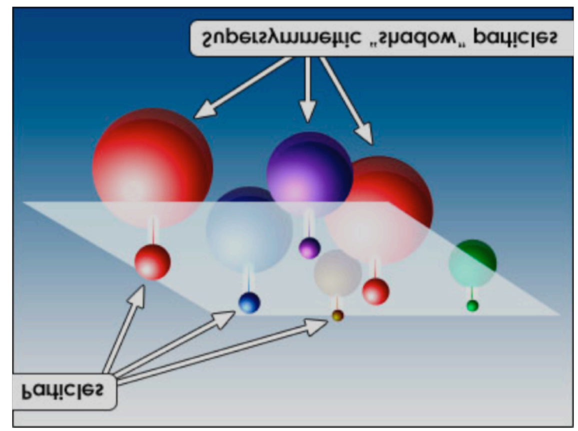


PDG

- Not too heavy, otherwise reintroduce hierarchy problem.
- (Unless you fine-tune corrections to cancel)

SUSY Naturalness

- SUSY removes $\delta(m^2) \sim \Lambda^2$ divergences
- Tree-level: $$-m_Z^2/2 = |\mu|^2 + m_{H_u}^2$$
- Higgsino masses from same superpotential term $$W = \mu H_u H_d$$
- 20% fine-tuning requires: $$m_{\tilde{H}} \lesssim 200 \text{ GeV}$$

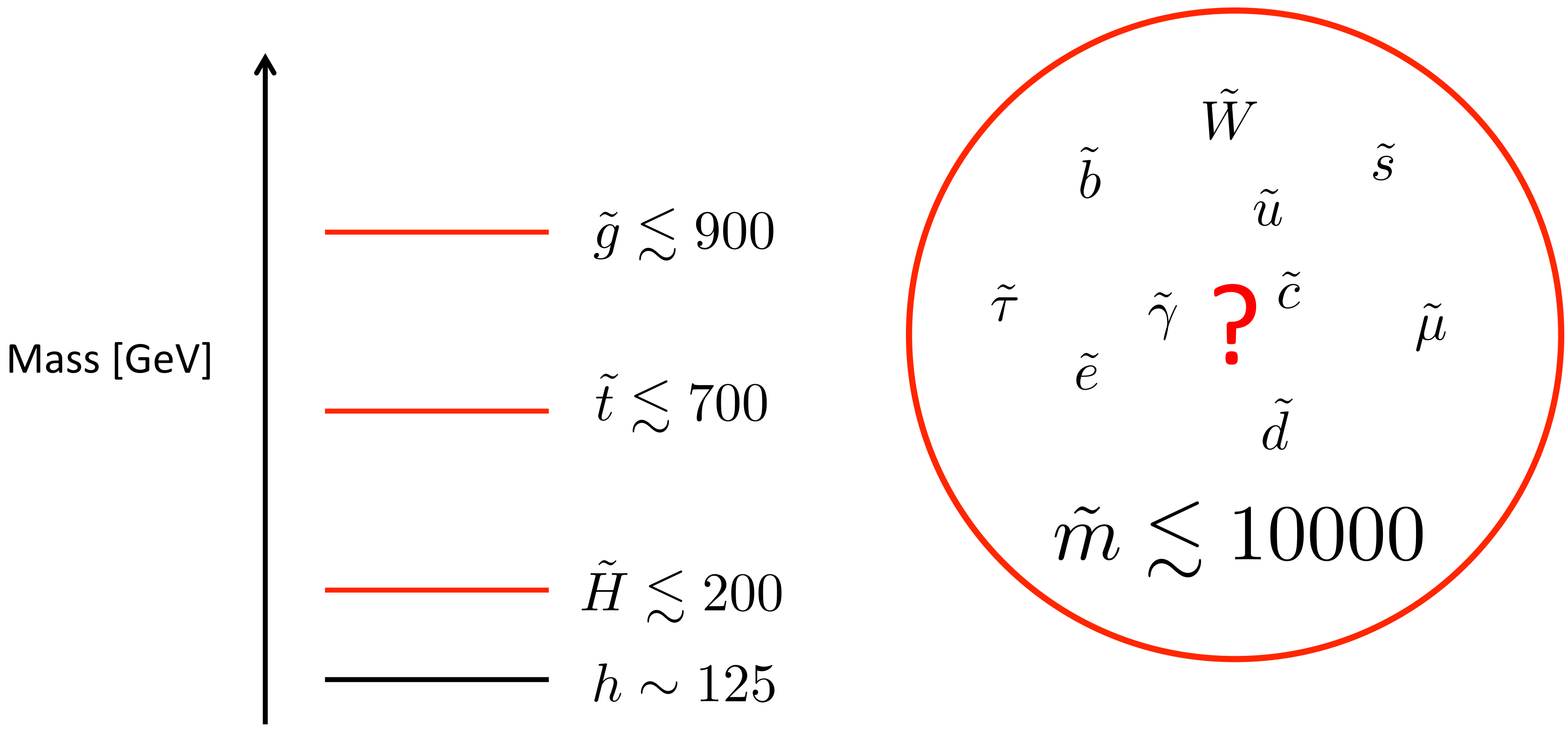
SUSY Naturalness

- SUSY removes $\delta(m^2) \sim \Lambda^2$ divergences
- Tree-level: $-m_Z^2/2 = |\mu|^2 + m_{H_u}^2$
- Stop: $-\frac{3y_t^2}{8\pi^2}(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2)\log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$
- Gluino: $\frac{2y_t^2}{\pi^2}\left(\frac{\alpha_s}{\pi}\right)|M_3|^2\log^2\left(\frac{\Lambda}{\mathrm{TeV}}\right)$
- For 20% fine-tuning: $m_{\tilde{t}} \lesssim 700\ \mathrm{GeV}$

$$m_{\tilde{G}} \lesssim 900\ \mathrm{GeV}$$

SUSY Naturalness

- If Higgs mass not fine-tuned, then at least require a spectrum of states like

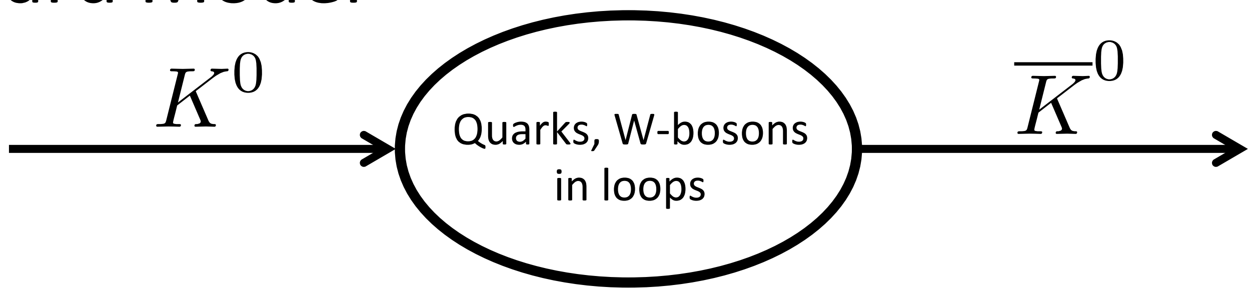


Supersymmetry

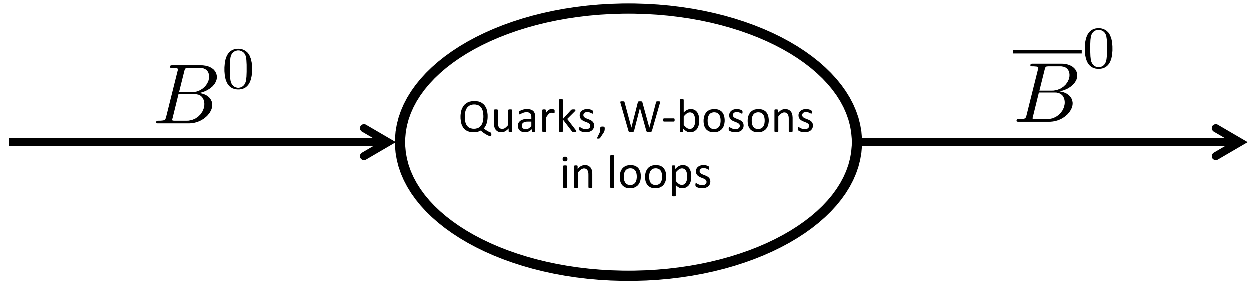
- Hierarchy problem solved (naturally) ✔
- Hopes for unification ✔
- Opportunity to solve other mysteries
  - Dark matter candidates ✔
  - Cosmological baryon asymmetry ?
  - ….
- What about the other consequences?

Flavor Physics

- Rate of meson oscillations predicted in Standard Model



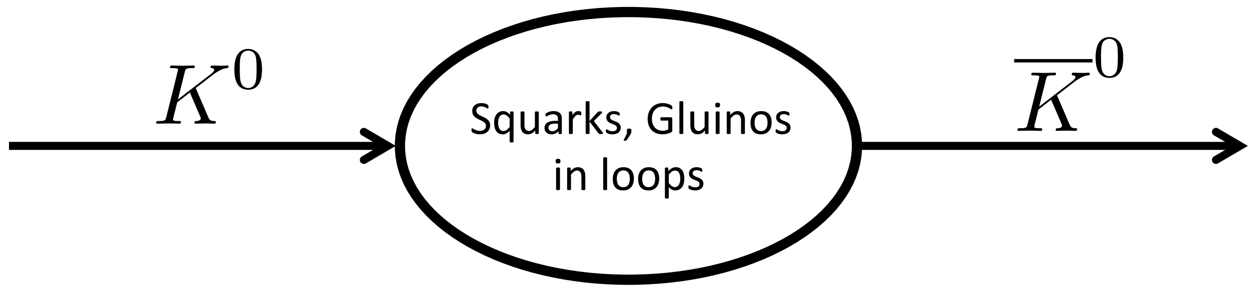
- Measured extremely accurately
- Also:



- Decent agreement with predictions

SUSY Flavlore

- New particles contribute to rates



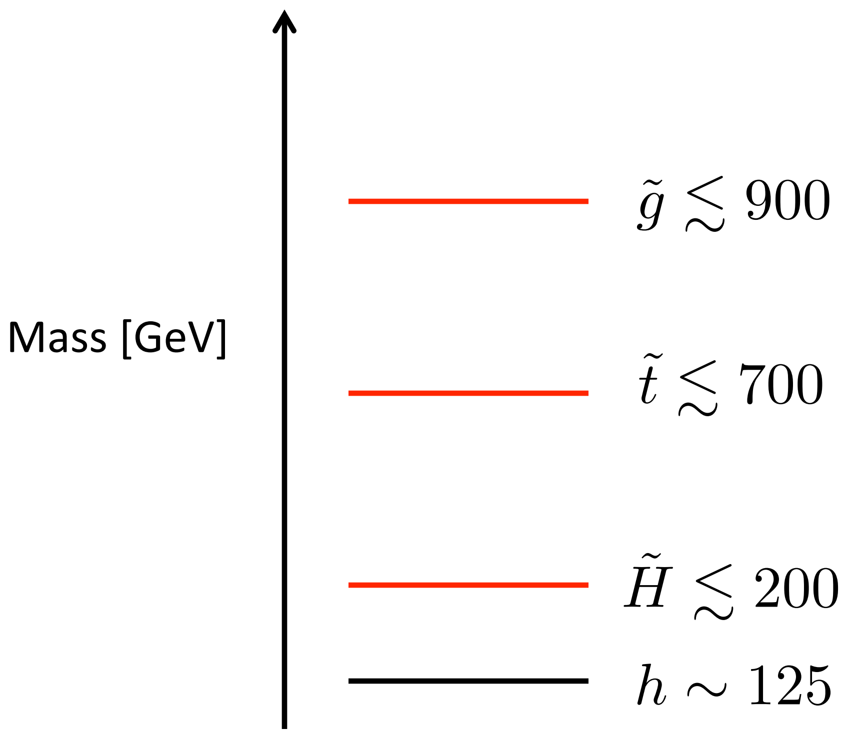
- Random spectrum of masses not viable
  - SUSY contributions far too great

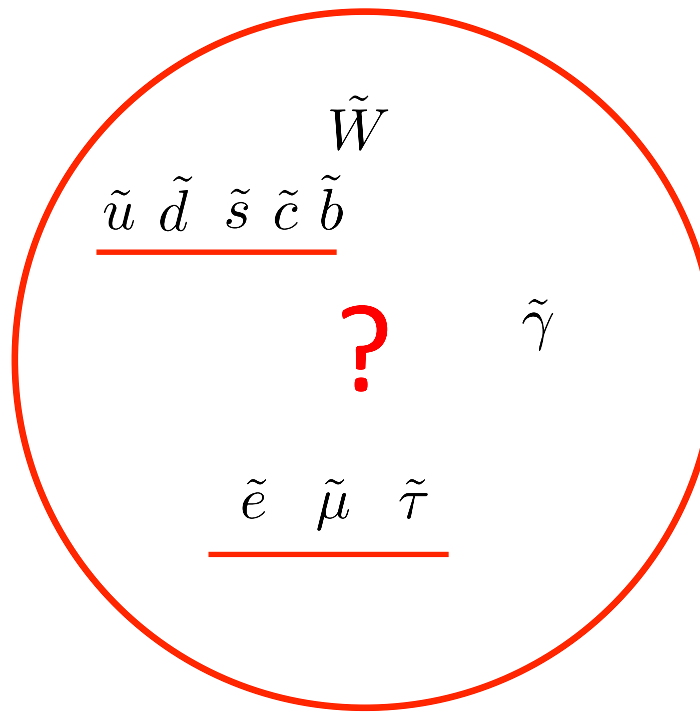
- If squarks in loop are mass-degenerate then extra contributions cancel

- Degeneracy: within measured rates

Squark Degeneracy

- If Higgs mass not fine-tuned, and flavor measurements consistent, then





Squark Degeneracy

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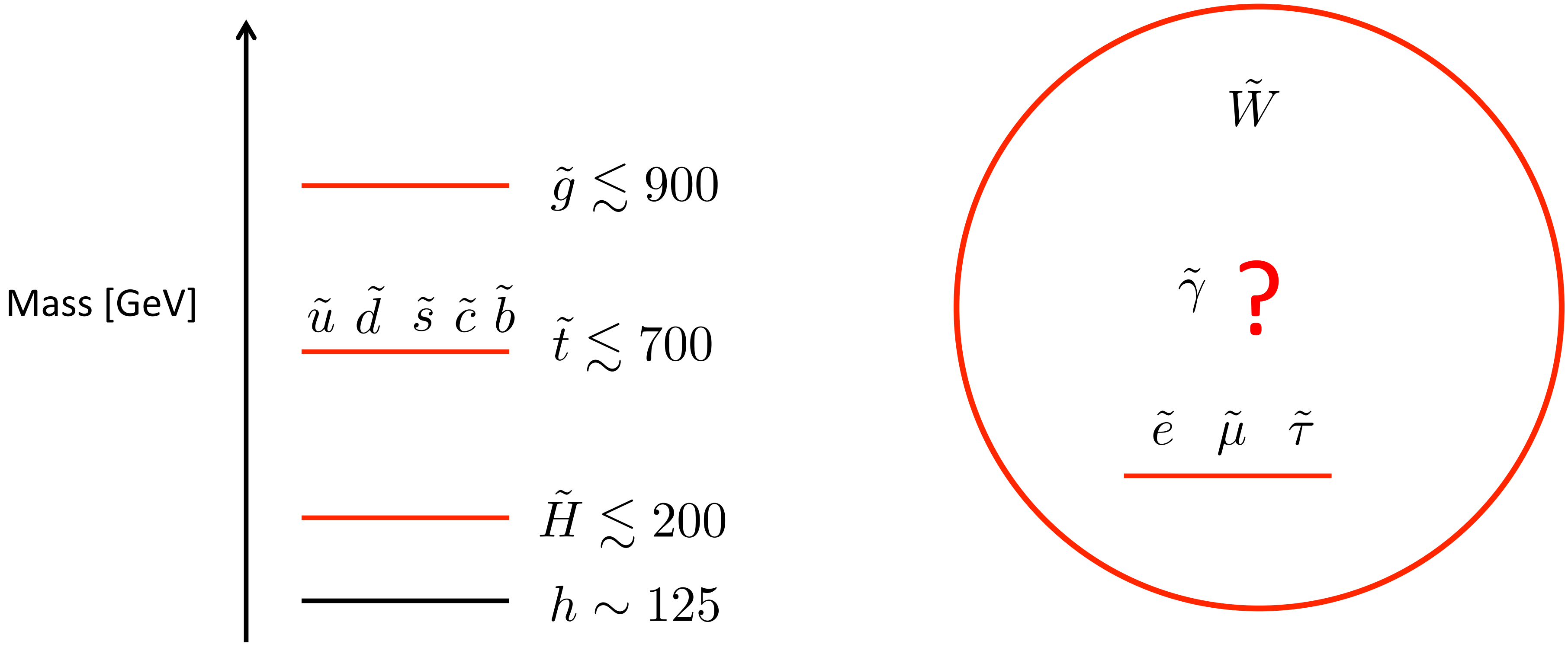
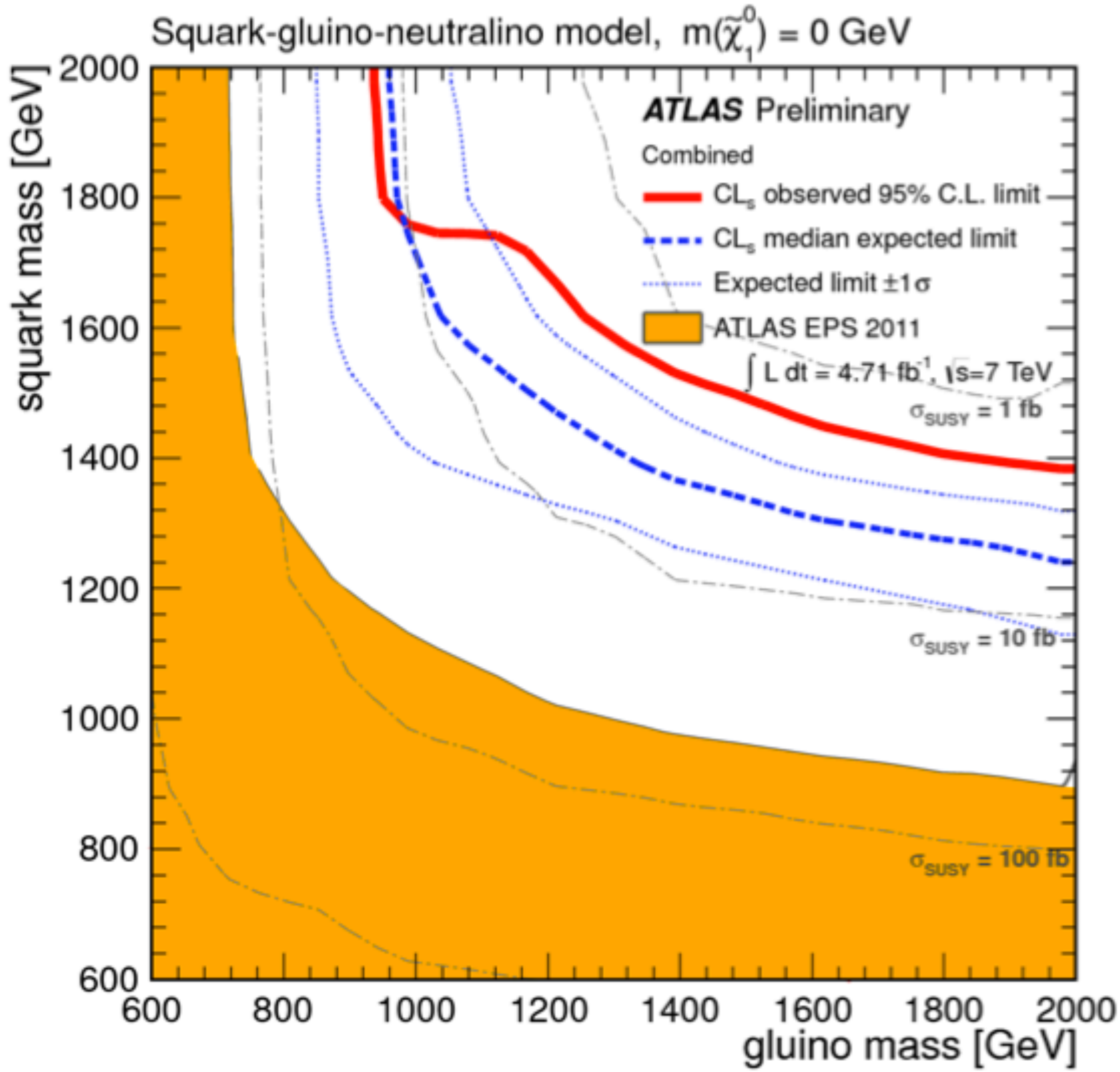


Easily observable at the LHC!

SUSY and the LHC

- Oops…

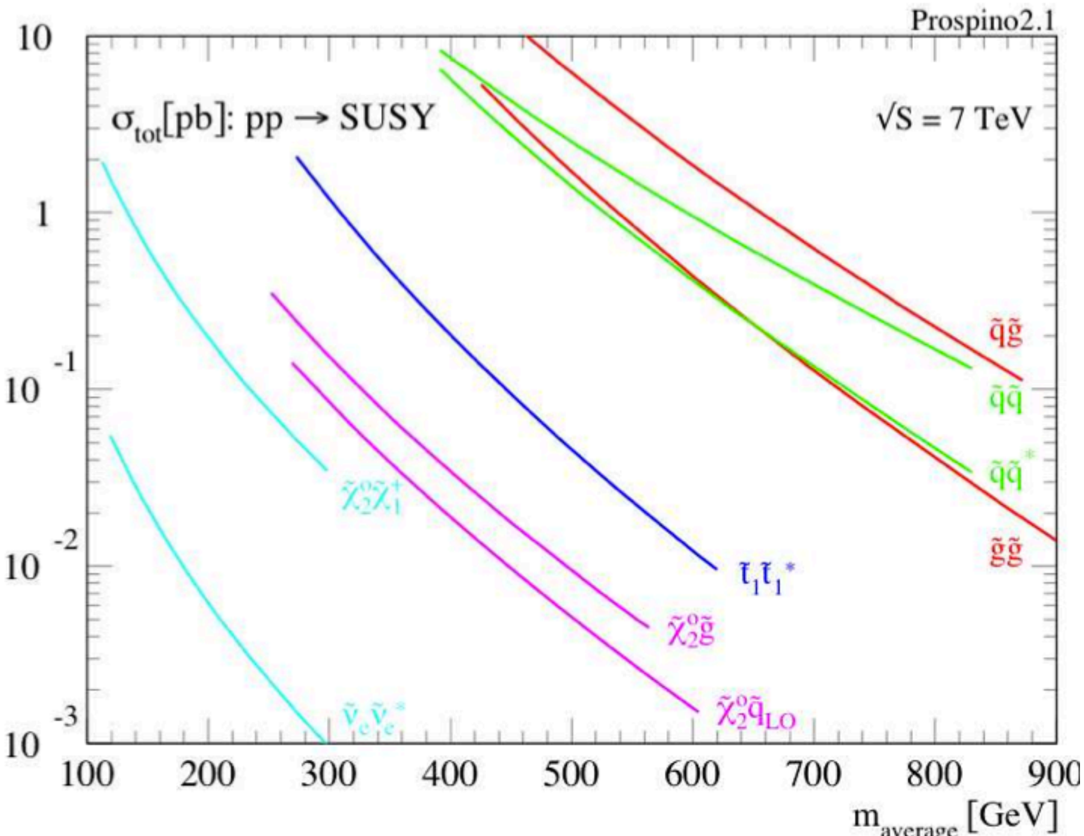


Whither Supersymmetry?

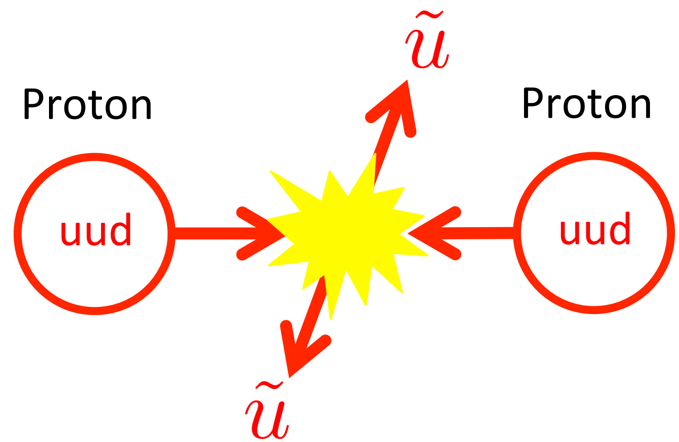
- Historical bias towards most easily discoverable (natural) models?
- Impression that simplest models, <u>are</u> SUSY?
- <u>Experimentalists</u> rapidly exploring possibilities
- Have <u>theorists</u> missed attractive possibilities?

Supersymmetry

- Other possibilities?
- Bounds driven by



Weiler



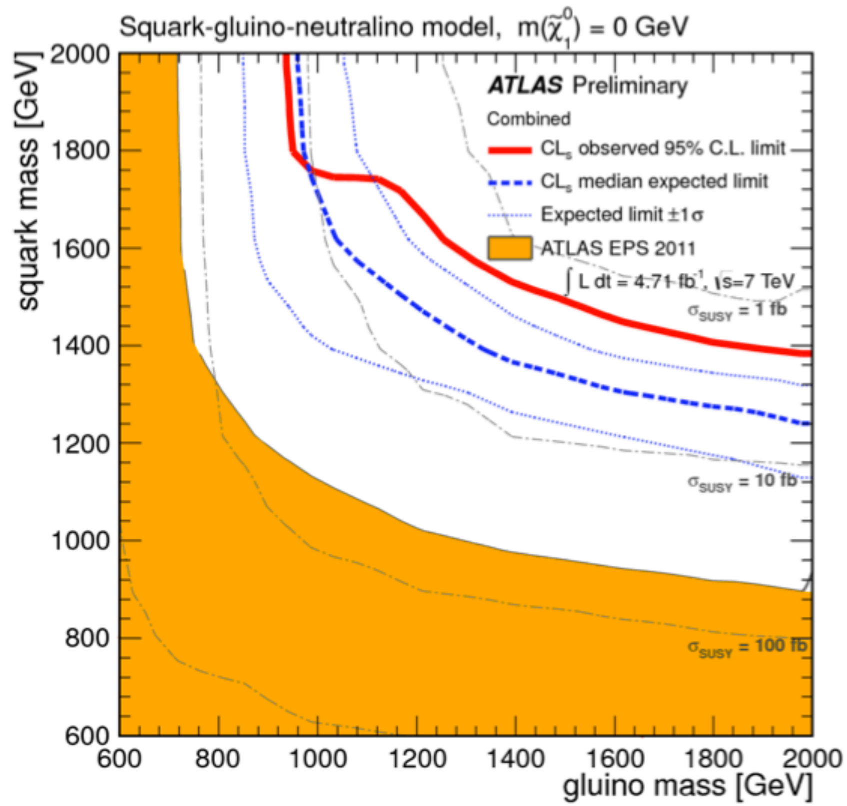
Proton made up of valence quarks

Produce "valence" squarks easily

Supersymmetry

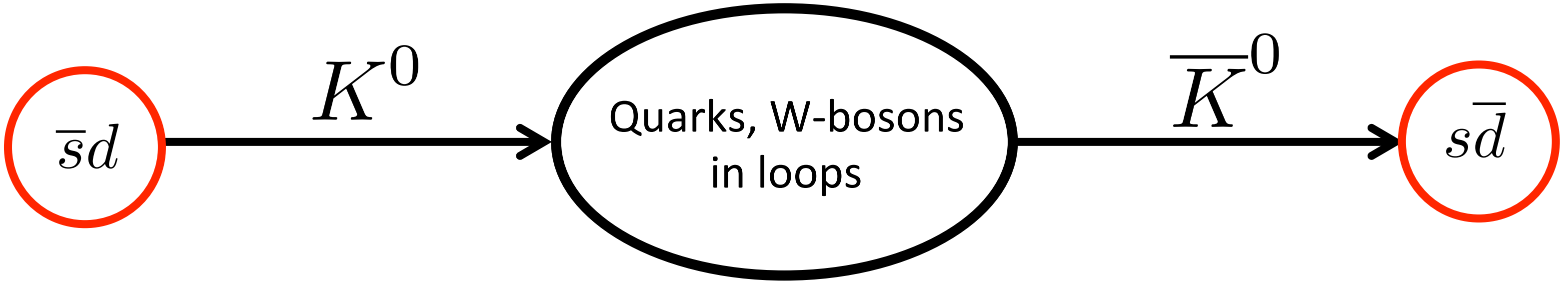
- Bounds on degenerate mass squarks <u>driven</u> by production of Up and Down squarks.

- Limits on other squarks <u>implied</u> by degeneracy.



Natural SUSY

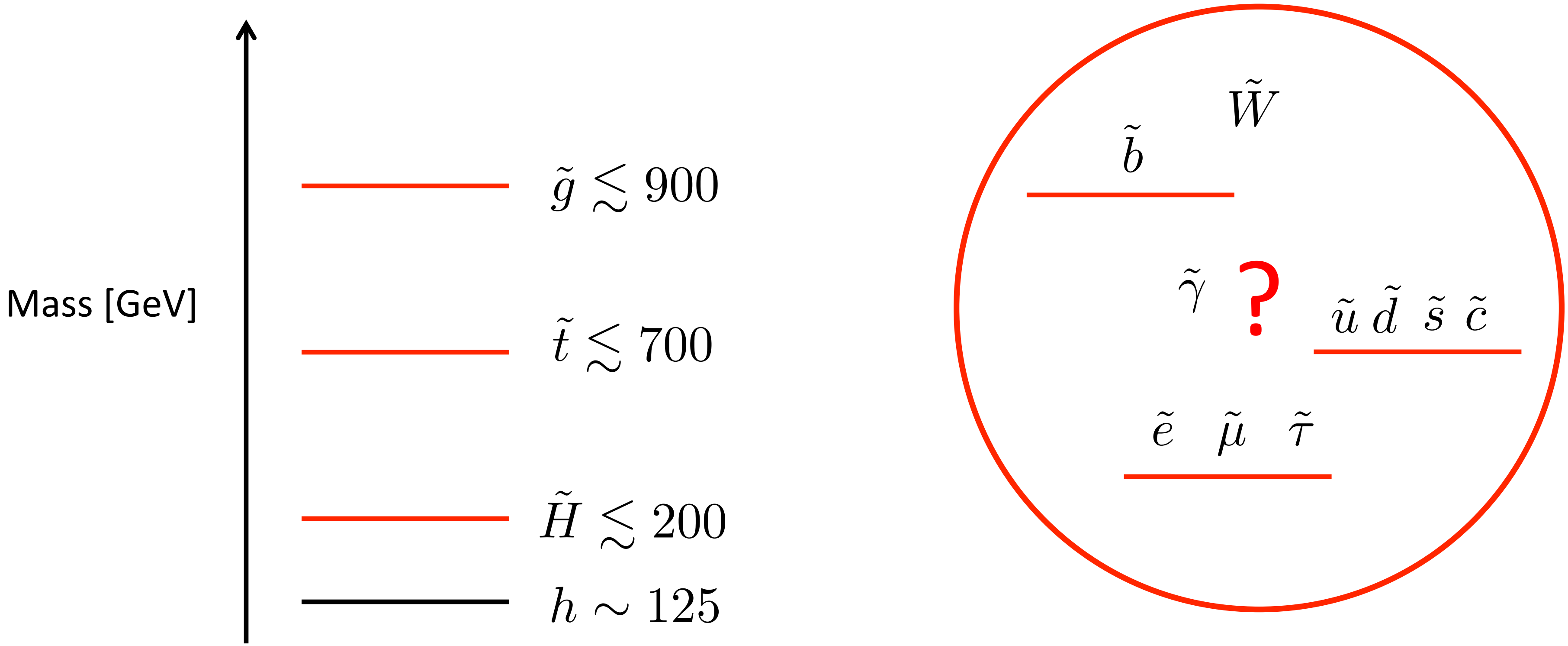
- Do we really need all squarks degenerate?



- Strongest bounds actually on up, down, strange, mesons.
- Only really need first two generations degenerate

Natural SUSY

- If Higgs mass not fine-tuned, then at least require a spectrum of states like



Natural SUSY

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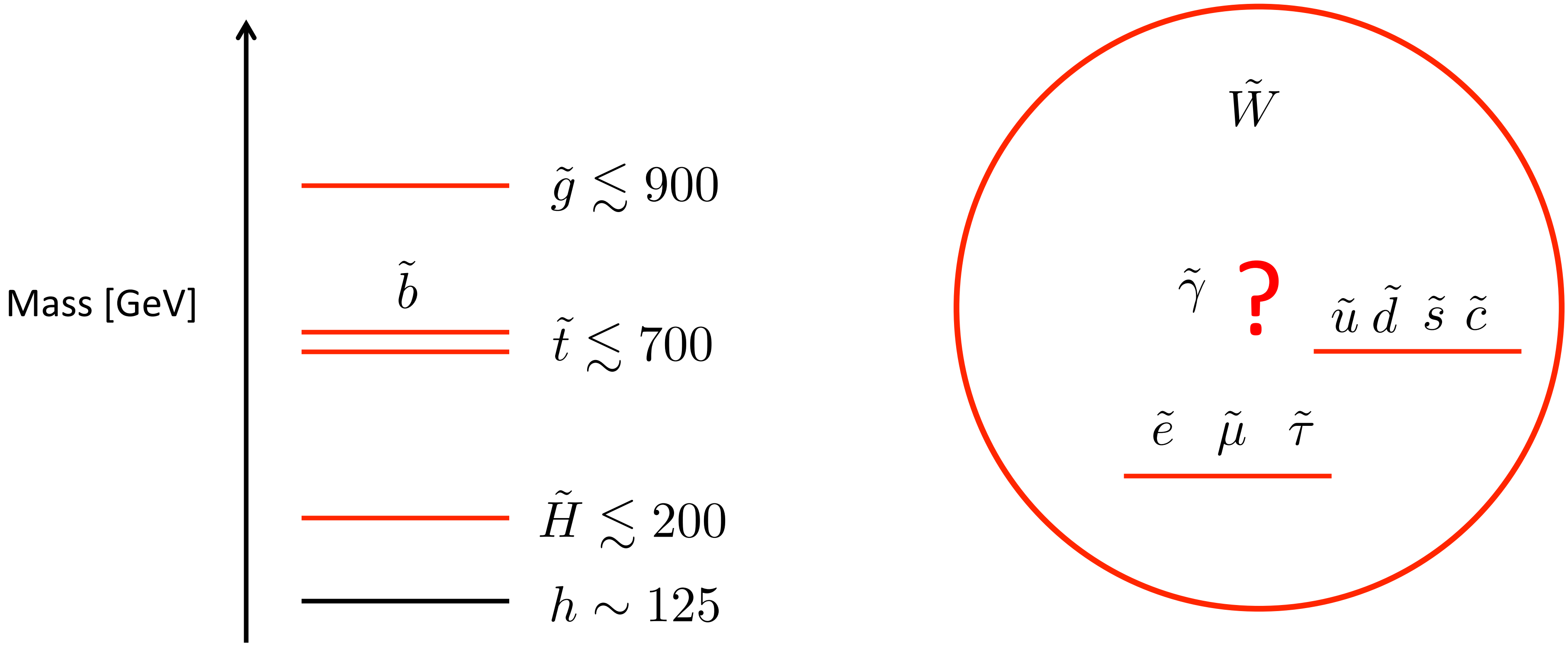
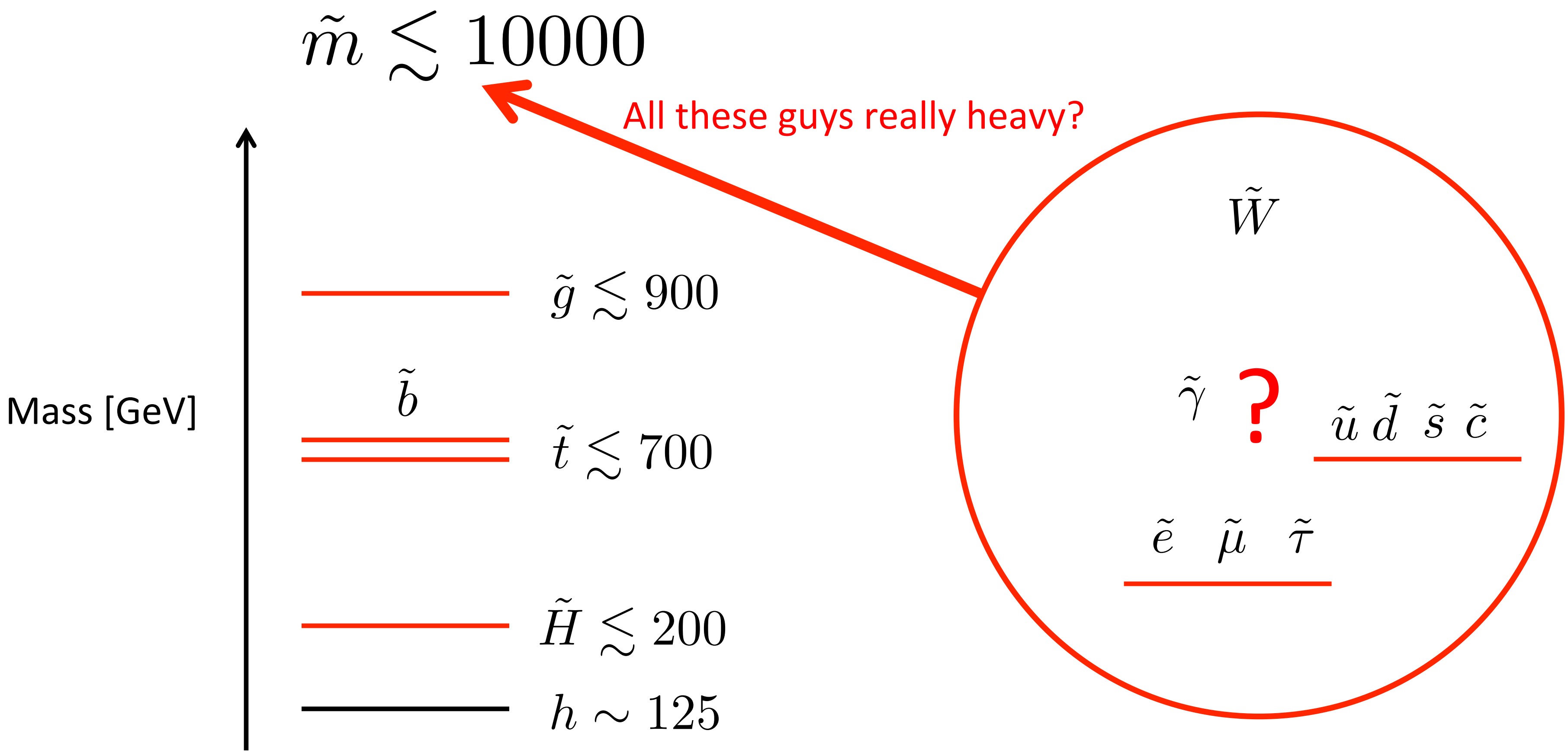


Natural SUSY

Dimopoulos, Giudice

- What if…



Alternatives…

- Just allow tuning:
  - Split SUSY (Arkani-Hamed, Dimopoulos)

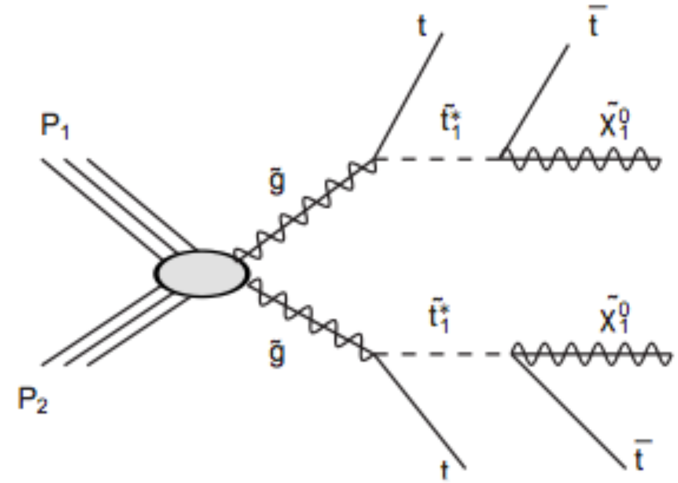
- Reason for delicate cancellation:
  - Focus Point (Feng, Matchev, Moroi)

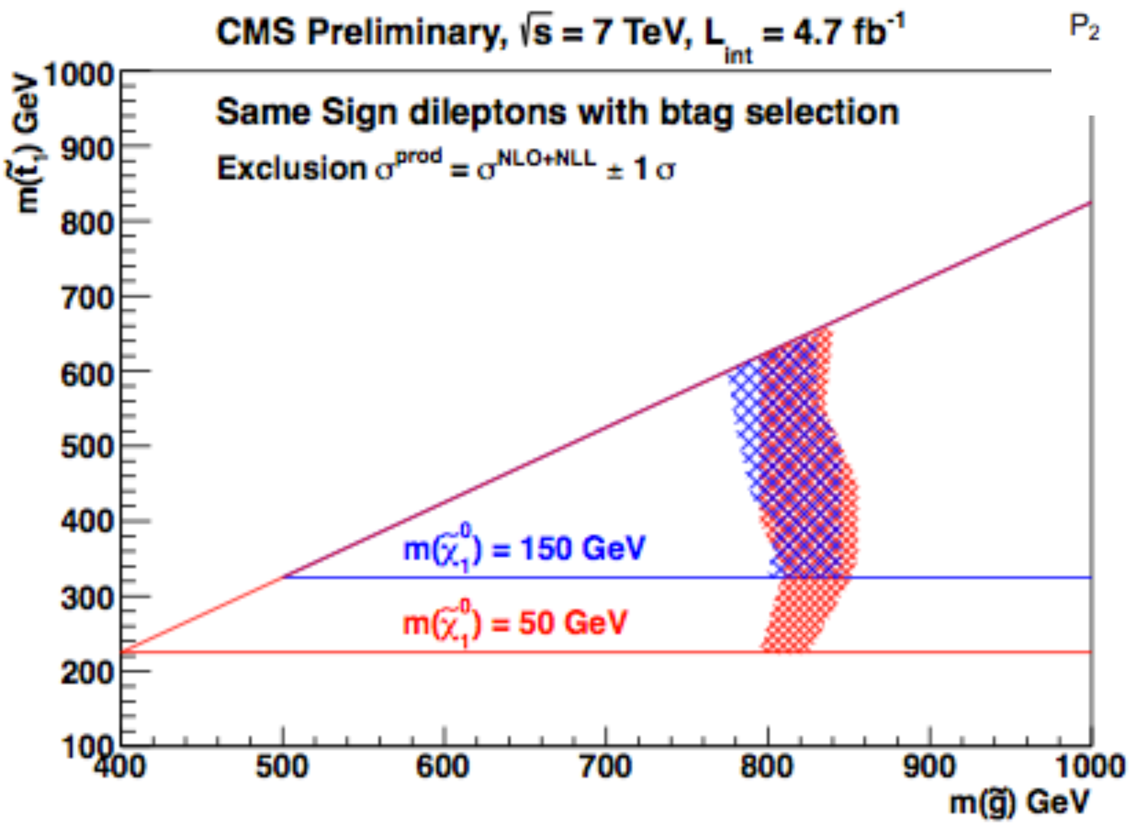
- Dirac Gauginos:
  - Heavier gauginos natural (Fox, Nelson, Weiner, Kribs, Martin)
  - Flavor constraints weakened (Kribs, Poppitz, Weiner)

- R-parity violation:
  - No missing energy (Lots of people)

Back to Natural SUSY

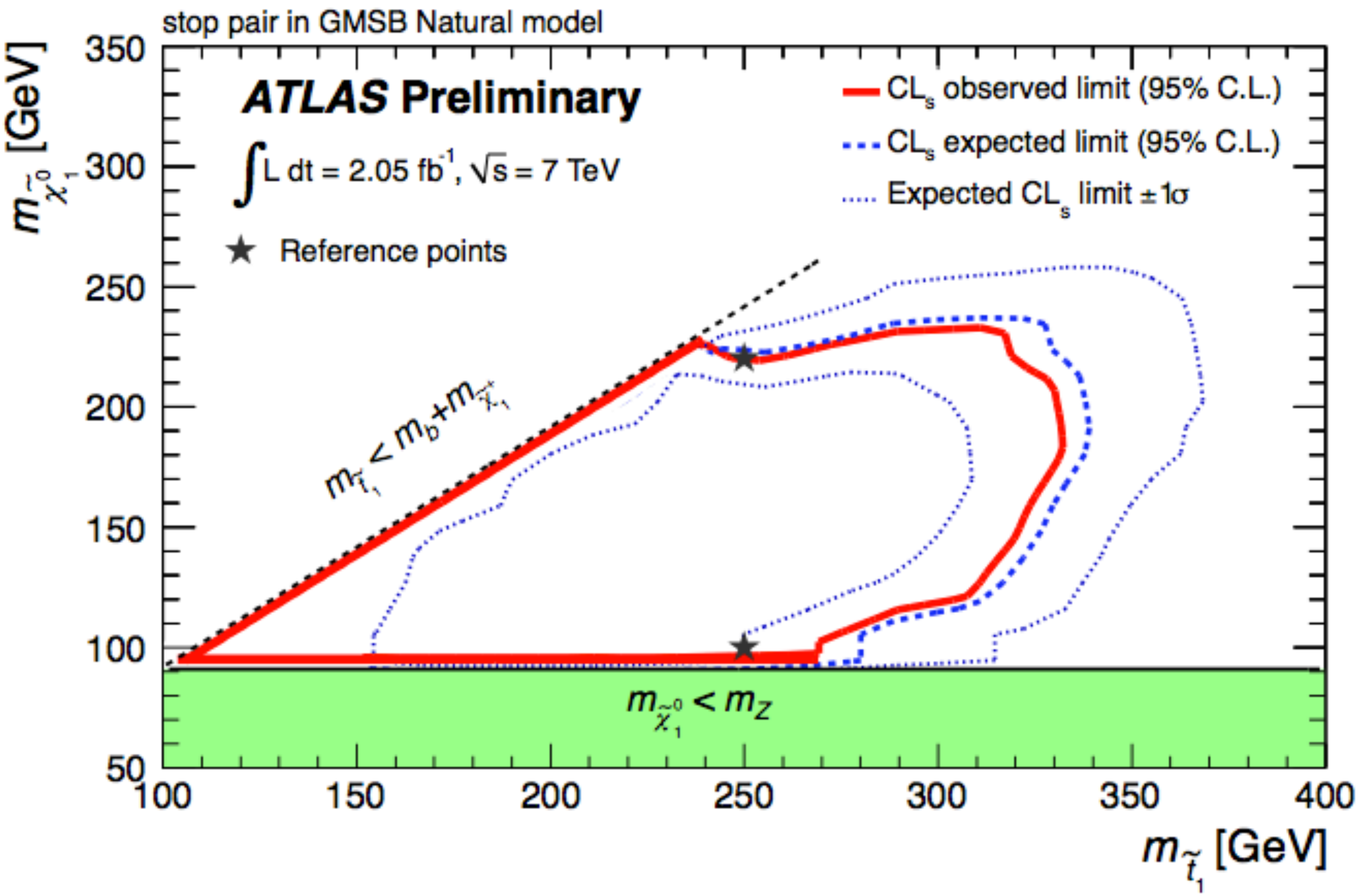
- LHC?
  - Gluino-production





Natural SUSY

- LHC?
  - Top squark production



Natural SUSY

- Theoretically looks contrived…
  - Why are top squarks lighter than others?
  - Why is the Higgs much lighter than other scalars?
  - Why are the first two generation squarks highly mass-degenerate?

- Known models/explanations
  - Often spoil unification
  - No explanation for high degree of degeneracy

Natural SUSY

- Theorists should explain:
  - Why are top squarks lighter than others?
  - Why is the Higgs much lighter than other scalars?
  - Why are the first two generation squarks highly mass-degenerate?

- and retain:
  - Unification
  - Other attractive features

Natural SUSY

- Theorists should explain:
  - Why are top squarks lighter than others?
  - Why is the Higgs much lighter than other scalars?
  - Why are the first two generation squarks highly mass-degenerate?

This is a "flavor" puzzle, relating different generations

- and retain:
  - Unification
  - Other attractive features

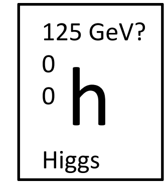
Natural SUSY

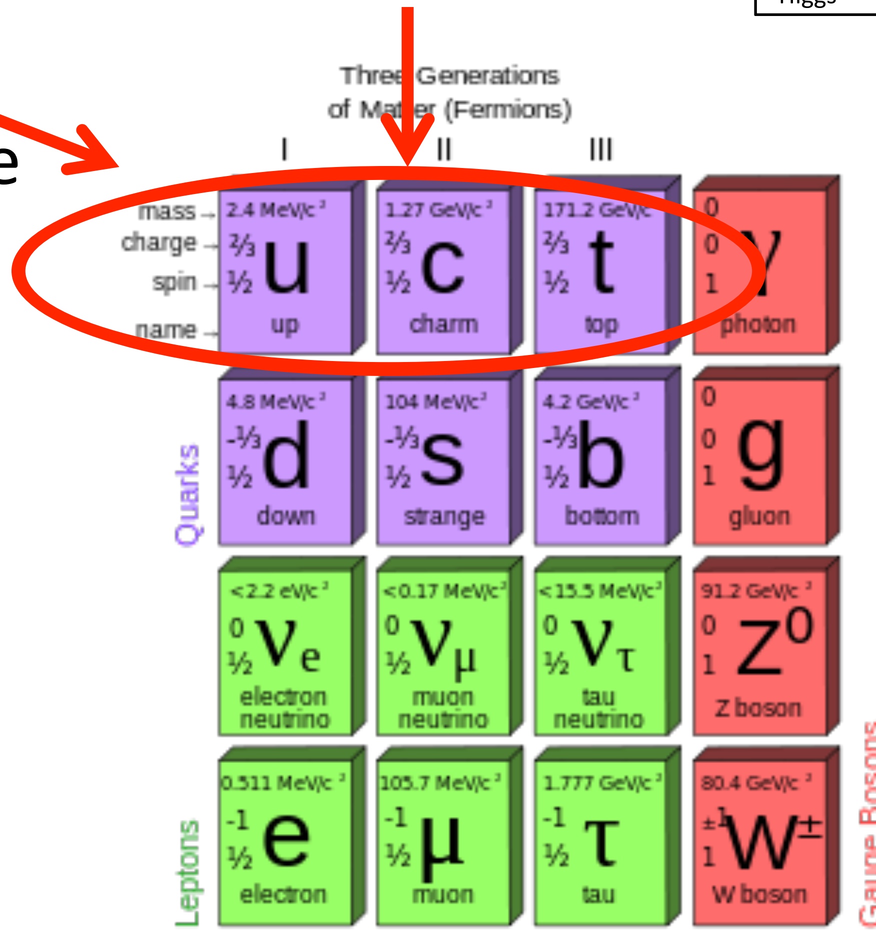
- Where to start?
  - Historically successful route map:
    - Look for remnants of symmetry structures
    - Perhaps those symmetries are gauged, i.e. become forces, at high energies
- Hints of symmetry in the SM
  - Approximate "flavor" symmetries in masses of quarks and leptons
  - Perhaps a flavor force could give insight to SUSY breaking?

New Flavors of SUSY

- Which flavor force?
- No one is special
  - Should treat any three flavors equally

Flavor force transforms different generations into each other





New Flavors of SUSY

- Which flavor force?
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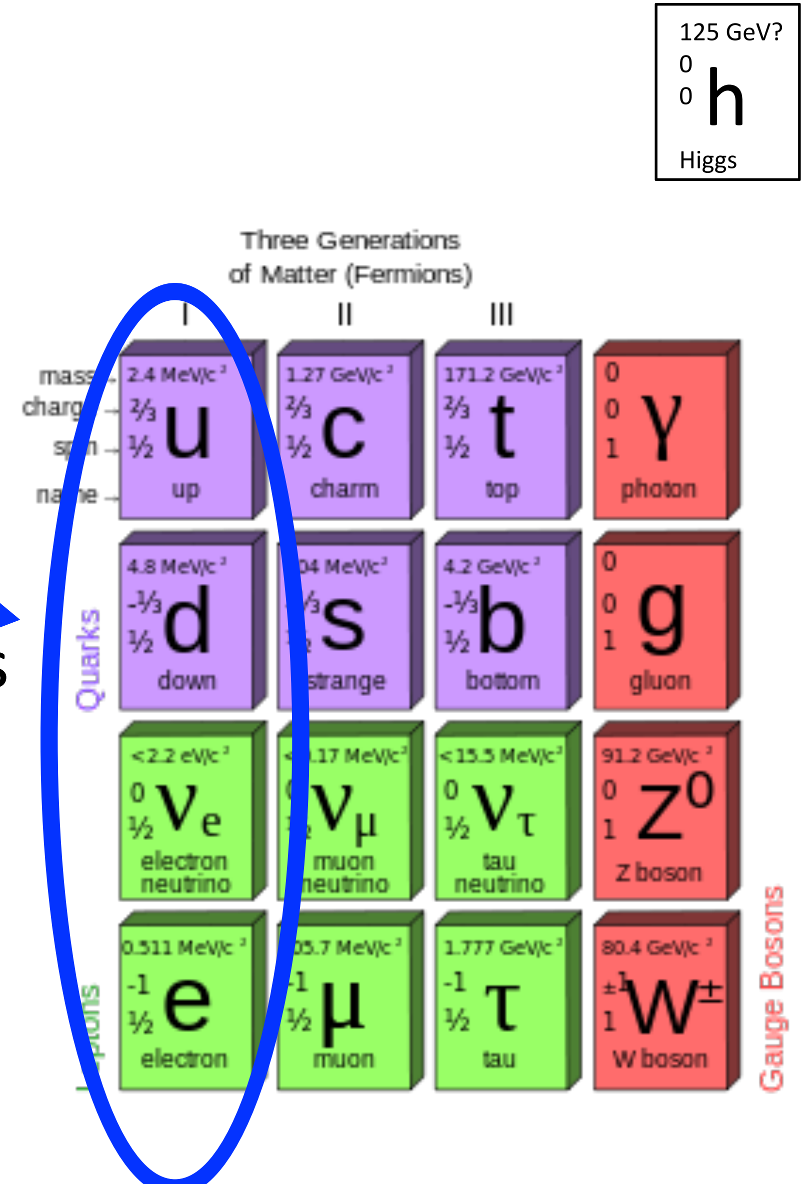
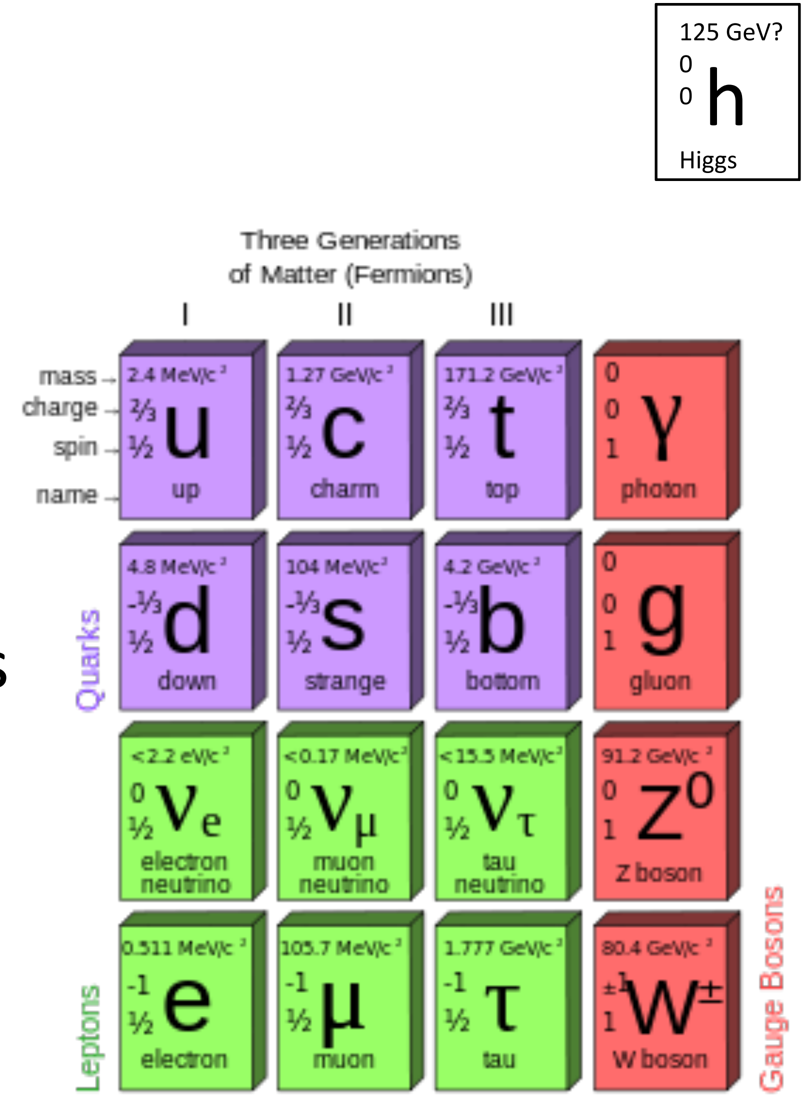
  - Should treat any three flavors equally
- Will it unify?
  - Different matter particles with same flavor charge



New Flavors of SUSY

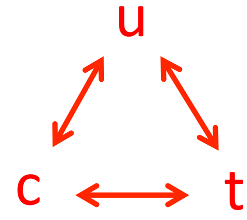
- Which flavor force?
- No one is special
  - Should treat any three flavors equally
- Will it unify?
  - Different matter particles with same flavor charge
- Is it consistent?
  - Must be anomaly-free



New Flavors of SUSY

- Candidate flavor force exists!
  - No anomalies
  - Consistent with unification
  - No need to add extra light charged particles
  - Like a "flavor QCD" $SU(3)_F$

- Flavor force rotates quark flavors



- Such processes very strongly constrained

New Flavors of SUSY

- Flavor forces not observed
  - Must be broken at high scales
  - Analogous to breaking of electroweak symmetry
  - Take flavor structure as <u>input</u>, i.e. spurions

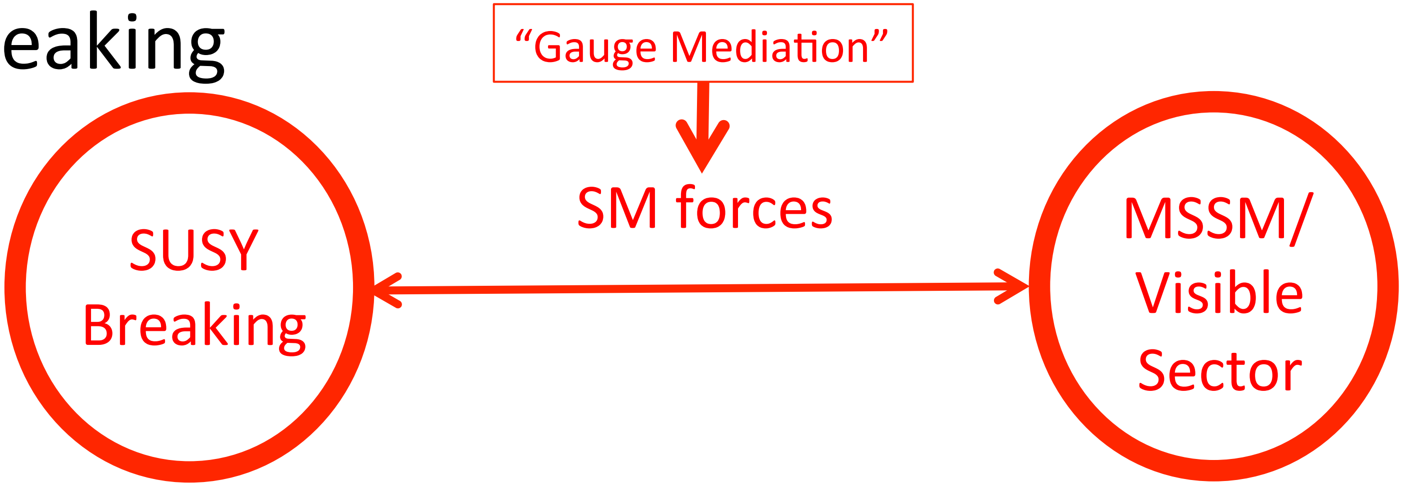
- "Flavor Higgs" <u>proportional</u> to quark masses

$$\langle \Phi_F \rangle \propto \begin{pmatrix} 172.9 & 0 & 0 \\ 0 & 1.29 & 0 \\ 0 & 0 & 0.0017 \end{pmatrix}$$

- More breaking = weaker force

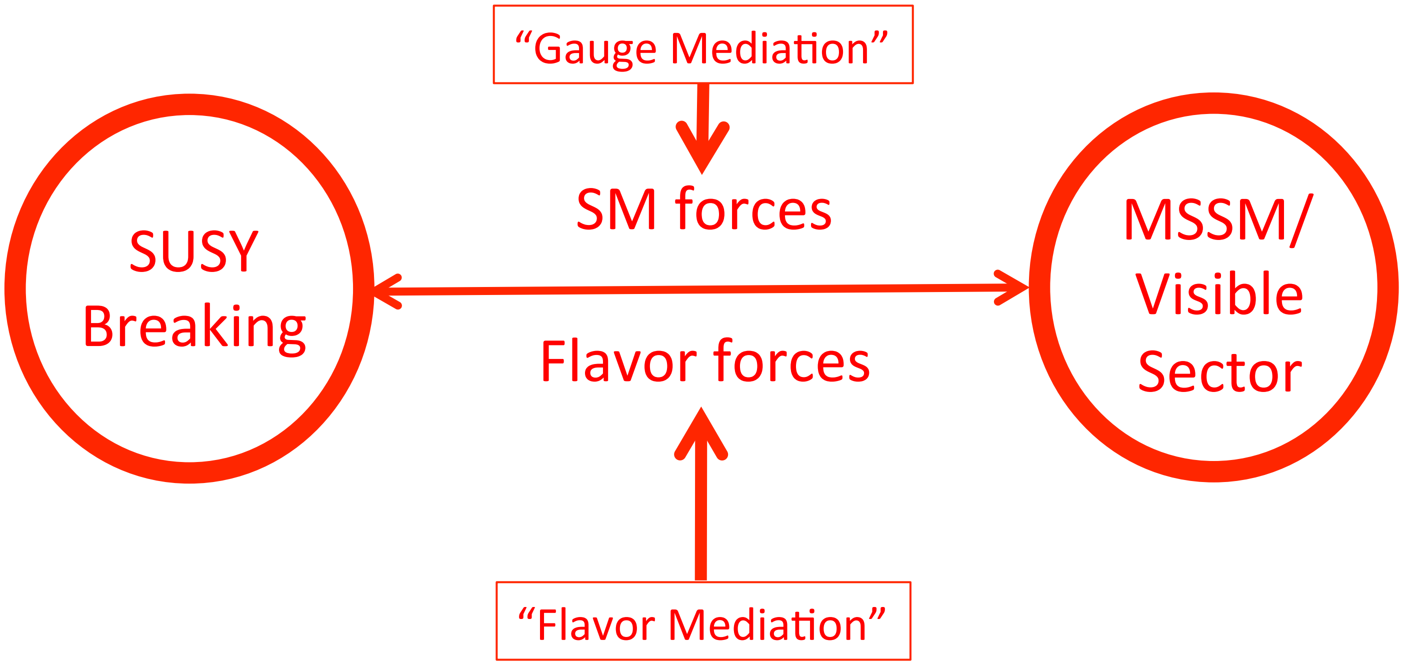
Flavor Mediation

- We know forces can communicate SUSY breaking



Flavor Mediation

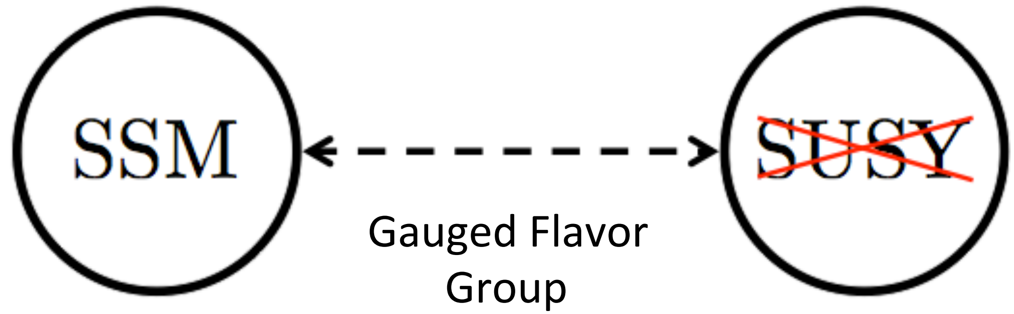
- We know forces can communicate SUSY breaking



- Maybe flavor forces do too?
  - Kaplan & Kribs, 1999: U(1)
  - Craig, MM Thaler, 2012: Non-Abelian

Calculating

- Mediate via



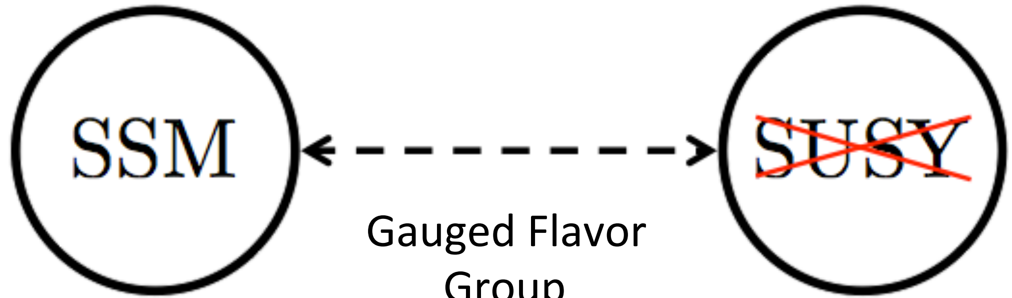
- MSSM fields charged under flavor symmetry

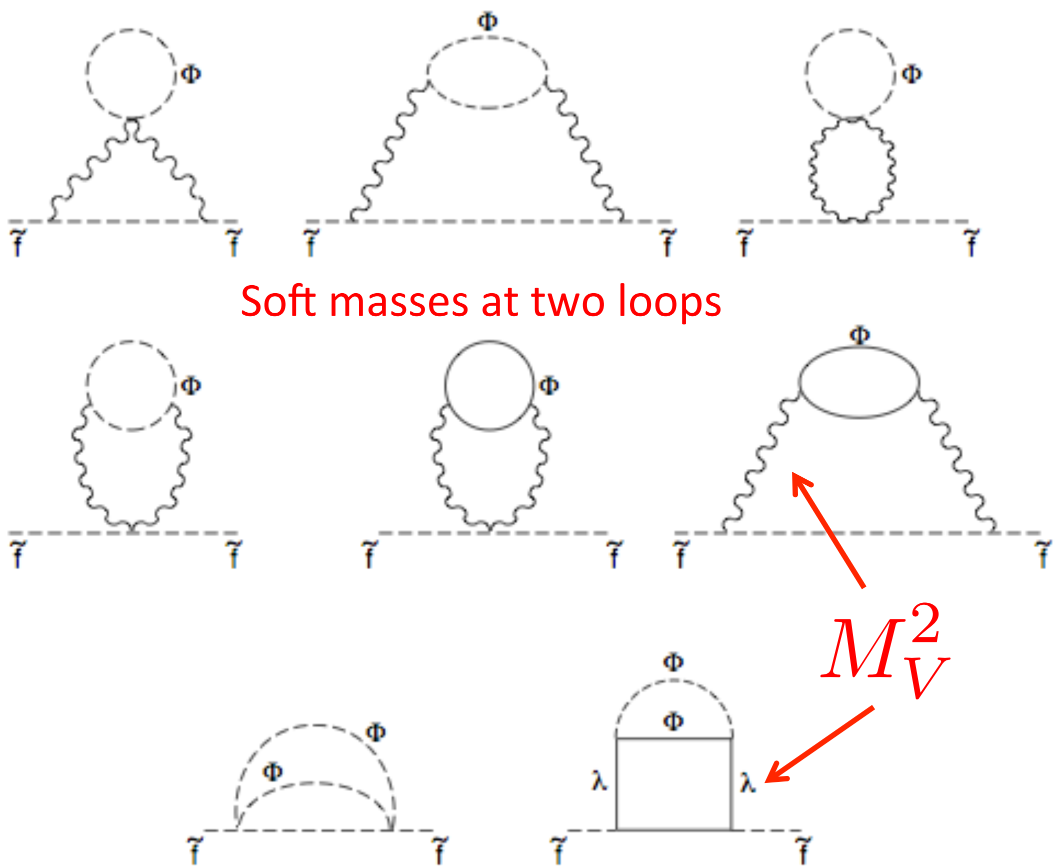
- Charge “messengers” under gauge symmetry and couple to SUSY breaking:

$$W = X\overline{\Phi}\Phi \qquad \langle X \rangle = M + \theta^2 F$$

Calculating

- Mediate via

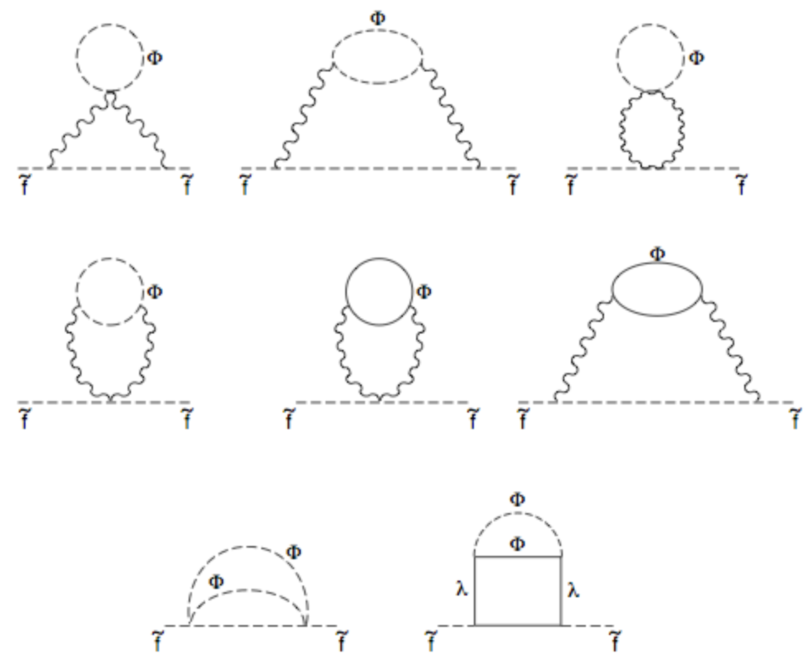




Flavor group broken: Massive gauge superfields complicates calculation

Calculating

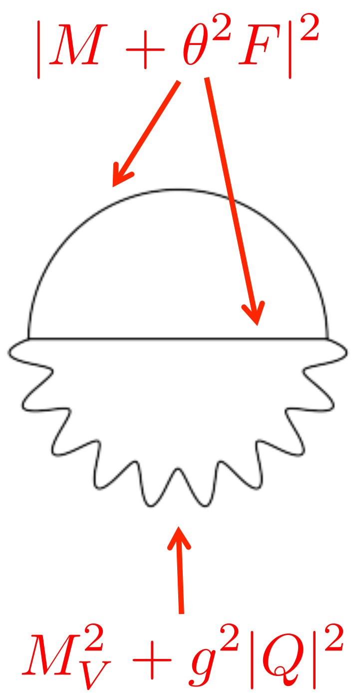
- Two thresholds: M and M_V, as well as SUSY breaking scale F
- Can sum all Feynman diagrams
- (Gorbatov & Sudano)
- Complicated



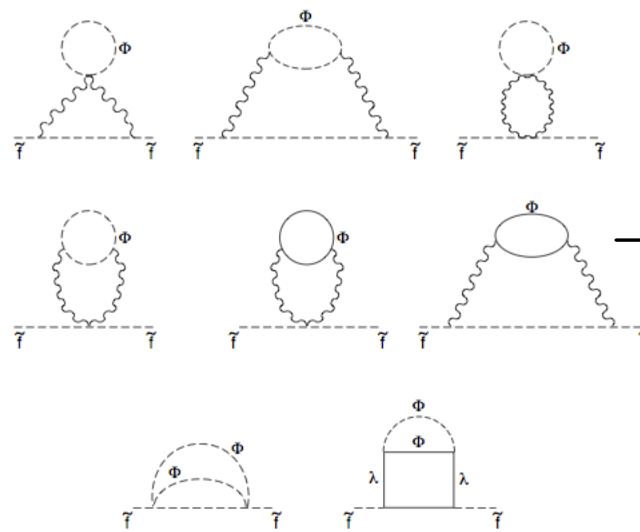
Calculating

- Or, to lowest order in F can find result from one supergraph (Craig, MM, Thaler)

$\int d^4\theta$



$=$



$+\mathcal{O}\left(\frac{F}{M^2}\right)$

Calculating

- Final result greatly simplified:

$$\left(\widetilde{m}_q^2\right)_{ij} = C(\Phi)\frac{\alpha'^2}{(2\pi)^2}\left|\frac{F}{M}\right|^2\sum_a f(\delta^a)\,(T_q^a T_q^a)_{ij}, \qquad \delta^a \equiv \frac{M_V^{a\,2}}{M^2},$$

Calculating

- Final result greatly simplified:

$$\left(\widetilde{m}_q^2\right)_{ij} = C(\Phi)\frac{\alpha'^2}{(2\pi)^2}\left|\frac{F}{M}\right|^2 \sum_a f(\delta^a)\,(T_q^a T_q^a)_{ij}, \qquad \delta^a \equiv \frac{M_V^{a\,2}}{M^2},$$

where

$$f(\delta) = 2\frac{\delta(4-\delta)((4-\delta)+(\delta+2)\log(\delta))+2(\delta-1)\Omega(\delta)}{\delta(4-\delta)^3}$$

with

$$\Omega(\delta) = \sqrt{\delta(\delta-4)}\left(2\zeta(2)\log^2(\alpha)+4\mathrm{Li}_2(\alpha)\right)$$

$$\alpha = \left(\sqrt{\frac{\delta}{4}}+\sqrt{\frac{\delta}{4}-1}\right)$$

SUSY ♥ SU(3) Flavor

- Unique anomaly-free $SU(3)_F$ symmetry
- Superfields all fundamentals

$$Q, U^c, D^c, L, E^c$$

- Yukawa couplings from

$$W = \frac{1}{M_{S_u}} \boldsymbol{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \boldsymbol{S_d H_d Q D^c}$$

$\overline{\mathbf{6}}$ under $SU(3)_F$

- Plenty of ways to generate these couplings

SUSY ❤ SU(3) Flavor

$$W = \frac{1}{M_{S_u}} \boldsymbol{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \boldsymbol{S_d H_d Q D^c}$$

$\overline{\mathbf{6}}$ under $SU(3)_F$

- Break with

$$\langle \boldsymbol{S_u} \rangle = \begin{pmatrix} v_{u1} & 0 & 0 \\ 0 & v_{u2} & 0 \\ 0 & 0 & v_{u3} \end{pmatrix}, \qquad \langle \boldsymbol{S_d} \rangle = V_{\mathrm{CKM}} \begin{pmatrix} v_{d1} & 0 & 0 \\ 0 & v_{d2} & 0 \\ 0 & 0 & v_{d3} \end{pmatrix} V_{\mathrm{CKM}}^T$$

SUSY ♥ SU(3) Flavor

$$W = \frac{1}{M_{S_u}} \boldsymbol{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \boldsymbol{S_d H_d Q D^c}$$

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Know these ratios

SUSY ♥ SU(3) Flavor

$$W = \frac{1}{M_{S_u}} \boldsymbol{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \boldsymbol{S_d H_d Q D^c}$$

$\overline{\mathbf{6}}$ under $SU(3)_F$

- Break with

$$\langle \boldsymbol{S_u} \rangle = \begin{pmatrix} v_{u1} & 0 & 0 \\ 0 & v_{u2} & 0 \\ 0 & 0 & v_{u3} \end{pmatrix}, \qquad \langle \boldsymbol{S_d} \rangle = V_{\rm CKM} \begin{pmatrix} v_{d1} & 0 & 0 \\ 0 & v_{d2} & 0 \\ 0 & 0 & v_{d3} \end{pmatrix} V_{\rm CKM}^T$$

Know these ratios

- Numerous models/possibilities for this exist. Focus on implications for SUSY.
- Future: Flavor breaking model

SUSY ❤ SU(3) Flavor

$$W = \frac{1}{M_{S_u}} \boldsymbol{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \boldsymbol{S_d H_d Q D^c}$$

- Don’t know relative scales of both vevs.

SUSY ♥ SU(3) Flavor

$$W = \frac{1}{M_{S_u}} \boldsymbol{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \boldsymbol{S_d H_d Q D^c}$$

- Don't know relative scales of both vevs.

$$\frac{m_t}{m_b} = \frac{v_{u3}}{v_{d3}} \alpha, \qquad \alpha \equiv \frac{M_{S_d}}{M_{S_u}} \tan\beta.$$

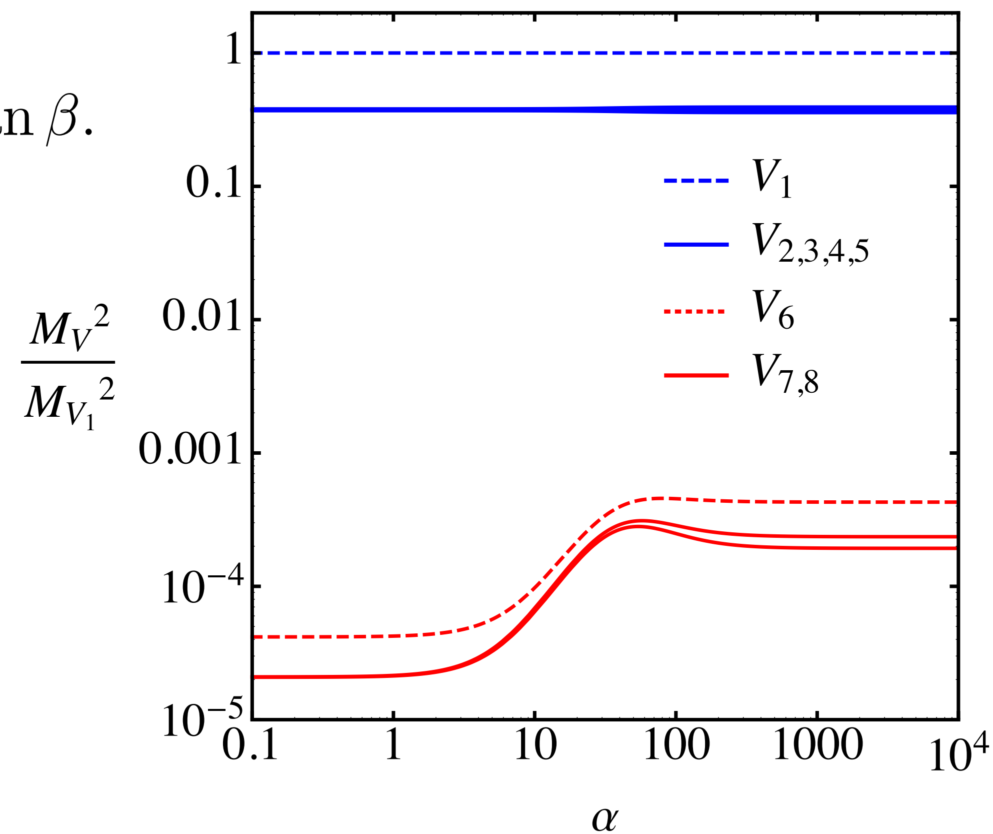
SUSY ♥ SU(3) Flavor

$$W = \frac{1}{M_{S_u}} \boldsymbol{S_u H_u Q U^c} + \frac{1}{M_{S_d}} \boldsymbol{S_d H_d Q D^c}$$

- Don't know relative scales of both vevs.

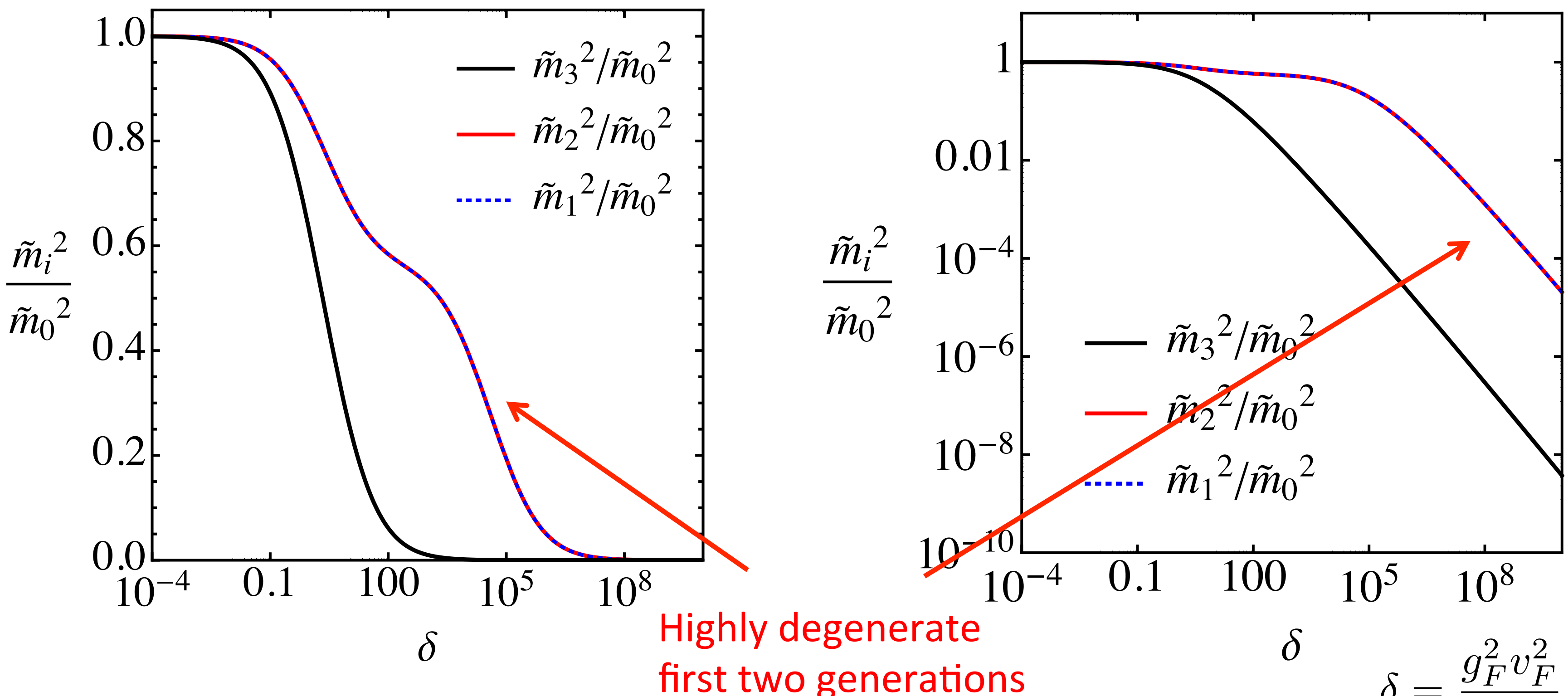
$$\frac{m_t}{m_b} = \frac{v_{u3}}{v_{d3}}\alpha, \qquad \alpha \equiv \frac{M_{S_d}}{M_{S_u}} \tan\beta.$$

- Can now determine flavor boson spectrum



SUSY ♥ SU(3) Flavor

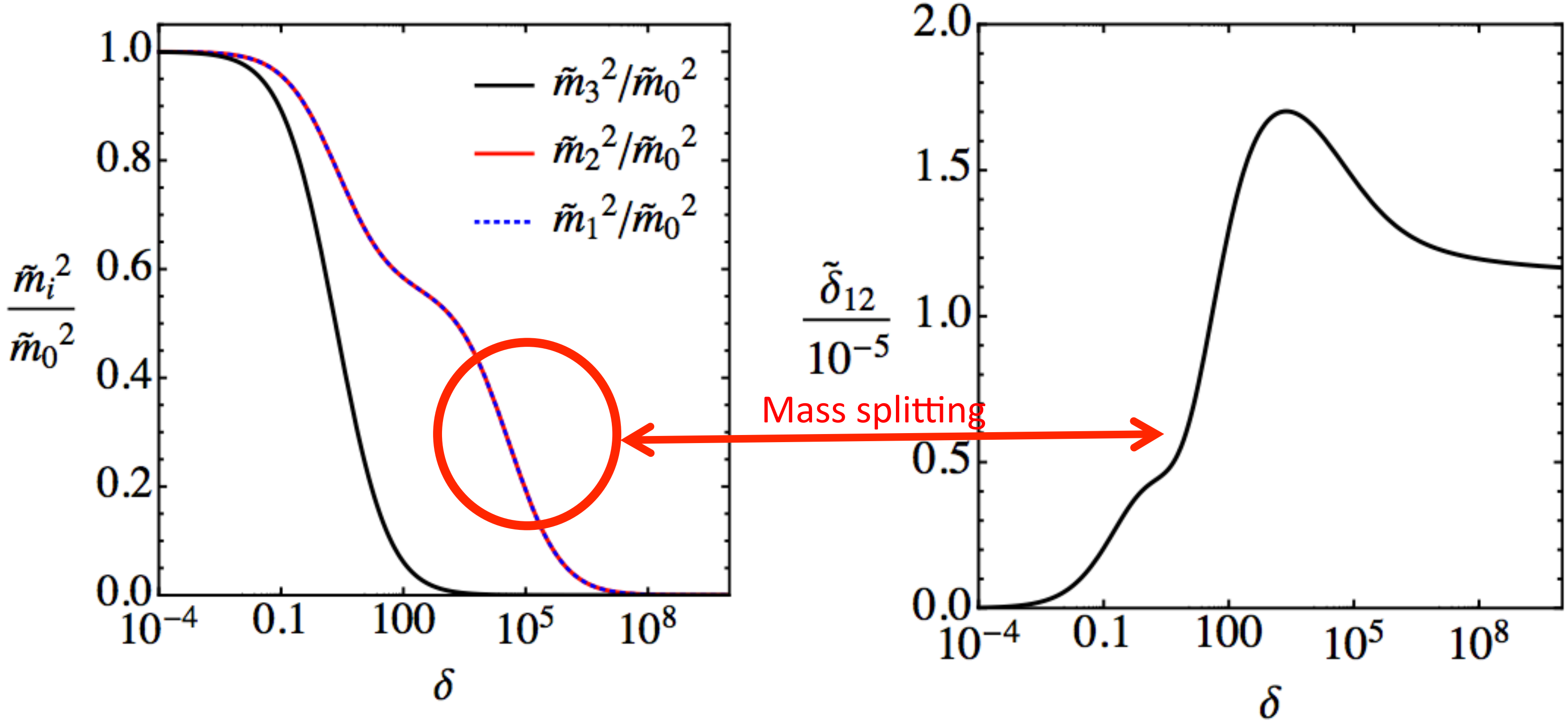
- Easy to calculate the squark spectrum!



$$\delta = \frac{g_F^2 v_F^2}{M^2}$$

SUSY ♥ SU(3) Flavor

- Zooming in…
- Flavor mediation makes first two generations highly degenerate!

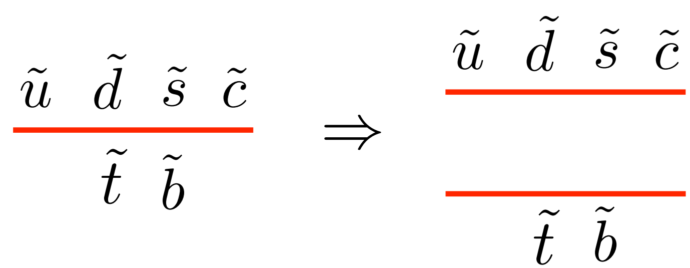


SUSY ♥ SU(3) Flavor

- Top mass breaks flavor force, weaker interaction with third generation

$$SU(3)_F \rightarrow SU(2)_F$$

- Third generation split from first two

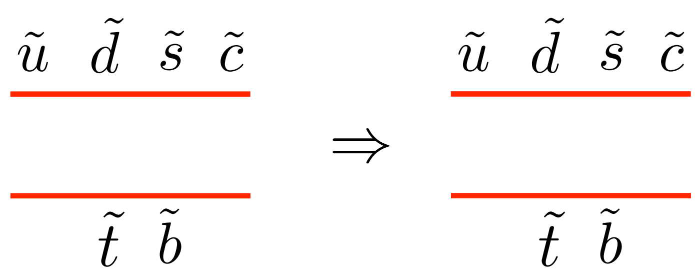


SUSY ♥ SU(3) Flavor

- Charm mass breaks remaining flavor force

$$SU(2)_F \to \emptyset$$

- Remaining flavor force broken
- No remaining flavor force to split off first generation



SUSY ♥ SU(3) Flavor

- What about off-diagonal terms?
- Calculate using same formalism

$$\tilde{m}^2 \approx \begin{pmatrix} \tilde{m}_2^2 & 0 & 0 \\ 0 & \tilde{m}_2^2 & 0 \\ 0 & 0 & \tilde{m}_3^2 \end{pmatrix} + (\tilde{m}_2^2 - \tilde{m}_3^2)\frac{v_{d3}^2}{v_{u3}^2 + v_{d3}^2} \begin{pmatrix} 0 & 0 & \cos(\delta_{\rm CKM})|V_{13}| \\ 0 & 0 & |V_{23}| \\ \cos(\delta_{\rm CKM})|V_{13}| & |V_{23}| & 0 \end{pmatrix}$$

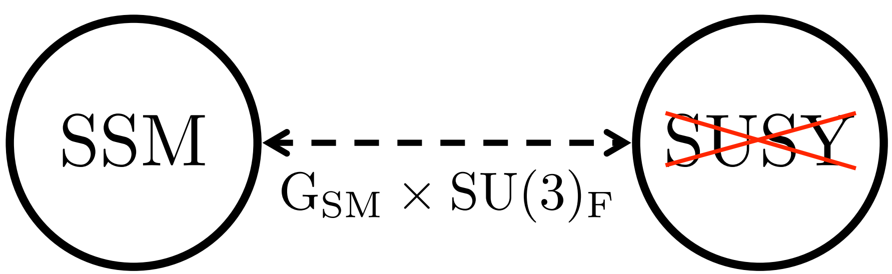
- Intuitive understanding of this.

- Dominant terms from mismatch with down-quark mass eigenstates.

SUSY ♥ SU(3) Flavor

- So far, just squarks (and sleptons). Need a more complete model.

- Philosophy: Flavor group just another SM gauge group broken at high scales. If flavor mediation, then expect flavor + standard gauge mediation.



SUSY ♥ Flavor Mediation

- Now:
  - Gaugino masses: typical gauge-mediated
  - Higgs soft parameters: typical gauge-mediated
  - Squarks and sleptons: typical gauge-mediated + flavor-mediated contributions.

SUSY ♥ Flavor Mediation

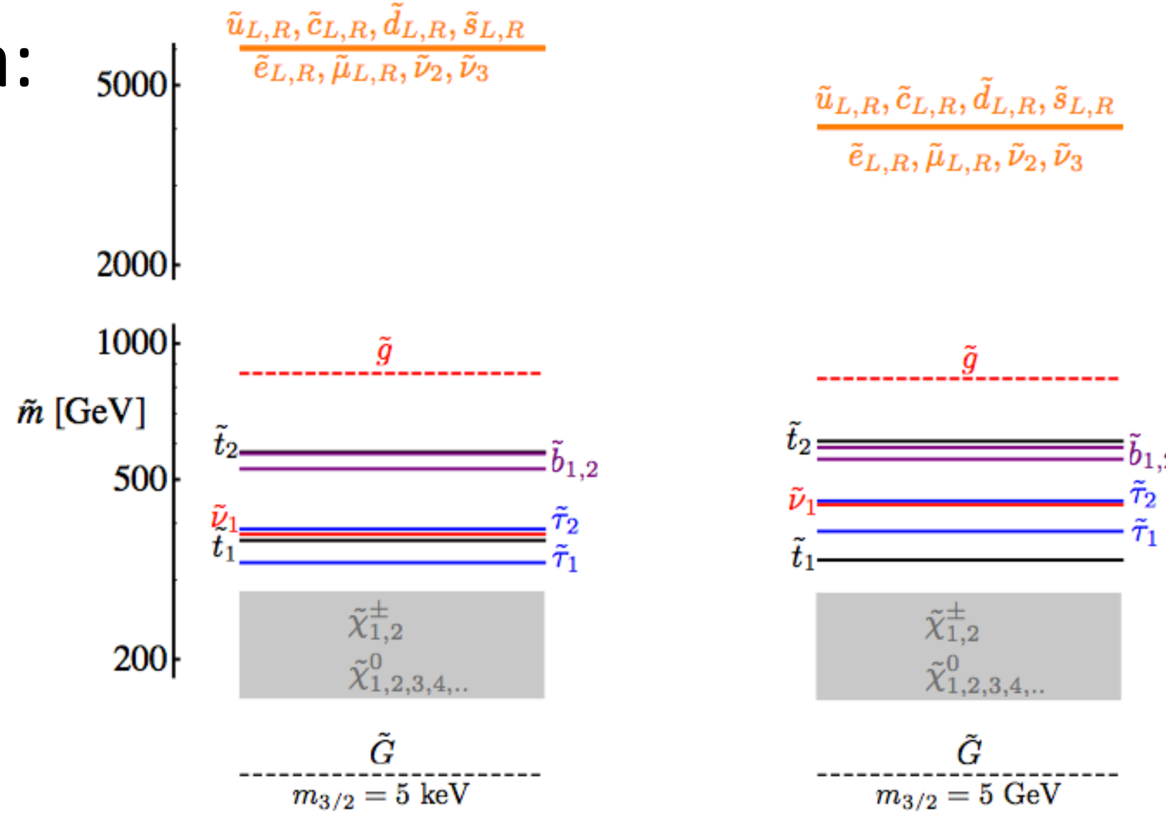
- Now:
  - Gaugino masses: typical gauge-mediated
  - Higgs soft parameters: typical gauge-mediated
  - Squarks and sleptons: typical gauge-mediated + flavor-mediated contributions.

- Need explanation for 125 GeV Higgs mass. Choose SMSSM:

$$W_{\rm Higgs} = \mu_H H_u H_d + \mu_S S^2 + \lambda S H_u H_d + f S + \kappa S^3.$$

SUSY ♥ Flavor Mediation

- Typical spectra:



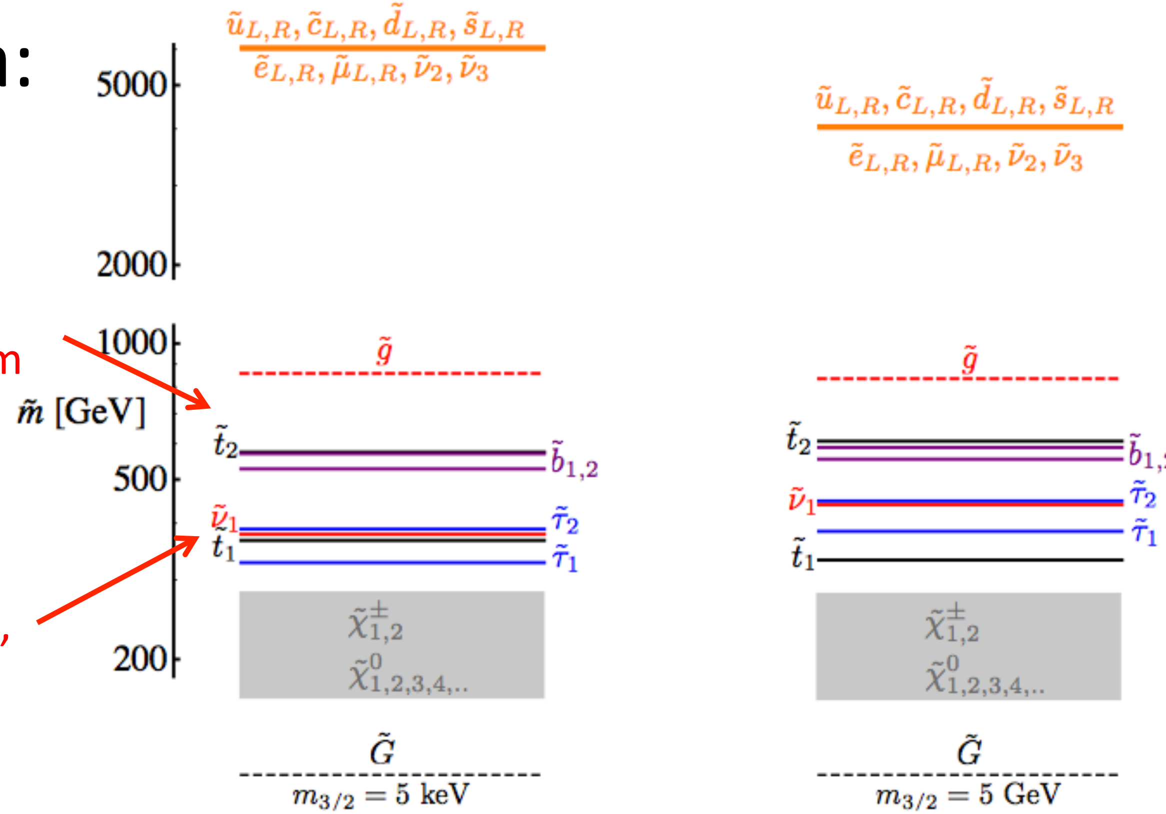
Benchmark	M [GeV]	$\sqrt{C(\Phi)}\alpha_F(M)$	δ	$\tilde{m}^F_{1,2}$ [GeV]	$\tilde{m}^F_3$ [GeV]	$m_{\tilde{g}}$ [GeV]	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]
Low Scale	10^8	0.54	129^2	6000	300	859	367	575
High Scale	10^{14}	0.32	72^2	4000	300	836	332	608

SUSY ❤ Flavor Mediation

- Typical spectra:

Another surprise: under RG heavy squarks drive stop masses down at two-loops, pushing them below gluinos.

Third generation sleptons and right-handed sbottoms also light, from anomaly cancellation.



Benchmark	M [GeV]	$\sqrt{C(\Phi)}\alpha_F(M)$	δ	$\tilde m^F_{1,2}$ [GeV]	$\tilde m^F_3$ [GeV]	$m_{\tilde g}$ [GeV]	$m_{\tilde t_1}$ [GeV]	$m_{\tilde t_2}$ [GeV]
Low Scale	10^8	0.54	129^2	6000	300	859	367	575
High Scale	10^{14}	0.32	72^2	4000	300	836	332	608

SUSY ♥ Flavor Mediation

- Is this really flavor safe?
- Gauged flavor generates:

$$\mathcal{L} \supset -\frac{g_F^2}{2M_{V_a}^2}(\bar{f}_M^i \gamma^\mu T_{ij}^a f_M^j)(\bar{f}_N^k \gamma_\mu T_{kl}^a f_N^l)$$

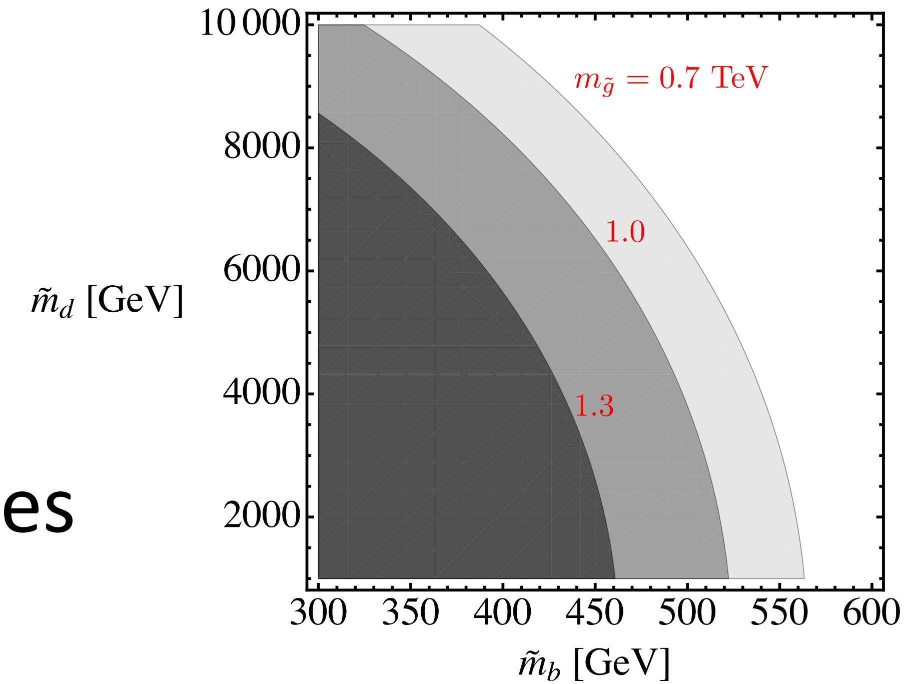
- Strongly constrained, requiring

$$M_V \gtrsim 10^5 \text{ TeV}$$

- Just tells us that $M \gtrsim 10^5 \text{ TeV}$, preferring SUSY breaking to be at, or above, this scale

SUSY ♥ Flavor Mediation

- FCNCs from gluino-squark box diagrams.
  - $K^0 \leftrightarrow \overline{K}^0$ below current limits, require CP phases to be small
  - $D^0 \leftrightarrow \overline{D}^0$ well below limits
  - $B_d^0 \leftrightarrow \overline{B}_d^0$ at current bounds
- Reach for B-factories



SUSY ❤ Flavor Mediation

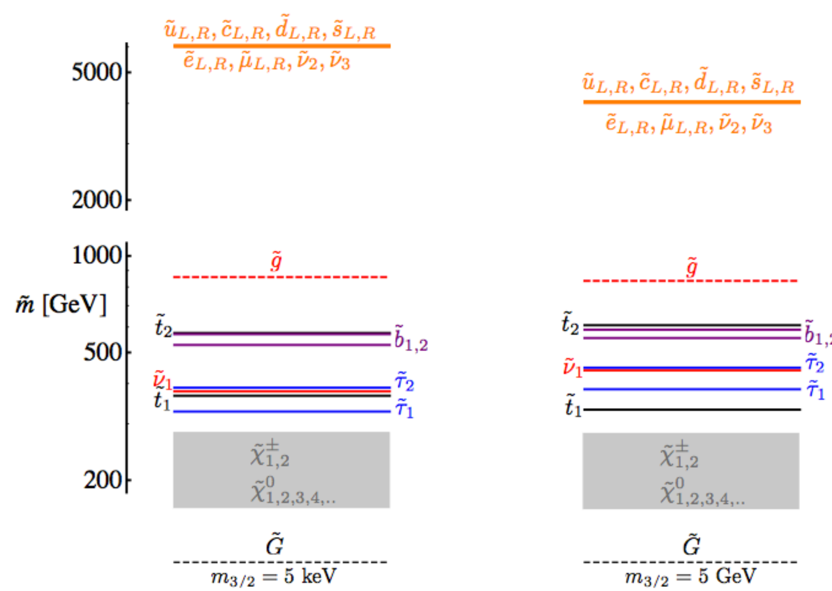
- Force weakest when communicating to third generation
  - Stop squarks lighter than other squarks ✔
- Higgs not charged under flavor force
  - Higgs automatically lighter than squarks ✔
- Only allowed to have $SU(3)_F$ force
  - Explanation for degeneracy of first two generations ✔
- No new charged matter introduced at low scales
  - Unification ✔

SUSY ♥ Flavor Mediation

- Current work:
  - Build a model for flavor-breaking sector
  - To what degree is “custodial” SU(2) symmetry preserved?
  - Generic spectrum

Predictions?

  - RG analysis



Conclusions

- LHC already excludes many supersymmetric models
- But natural SUSY still viable experimentally…
  - See e.g. Papucci, Ruderman, Weiler
- And theoretically in good shape too.
- "Flavor Mediation": a perturbative, unified model that explains natural SUSY spectrum
  - Alternatives:
    - Light stops from Seiberg duality (Csaki, Randall, Terning)
    - Split Families Unified (Craig, Dimopoulos, Gherghetta)
    - …