Gauging the way to MFV

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Overview

- **Preliminaries: SM & SUSY**

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- **SUSY survival guide : “what’s left ?”**

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- MFV SUSY : philosophy vs. tradition
- Gauged flavor: inverted hierarchy
- “MFV” SUSY : gauged, inverted scenario

Standard Model

SM describes all short distance phenomena down to ~ 10^{-18} cm.

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$$ **Gauge bosons**

$$+\, i\bar{\psi}_i \not{D} \psi_i$$ **Fermions**

$$+\, \psi_i \mathbf{y}_{ij} \psi_j \phi + \text{ h.c.}$$ **Yukawa couplings**

$$+\, |D_\mu \phi|^2 - V(\phi)$$ **Higgs**

Standard Model

$$\mathcal{L}_{quark} = i\bar{Q}_i \not{D} Q_i + i\bar{u}_i \not{D} u_i + i\bar{d}_i \not{D} d_i$$
$$+ \mathcal{Y}^u_{ij} Q_i \phi^\dagger u_j + \mathcal{Y}^d_{ij} Q_i \phi d_j + h.c.$$

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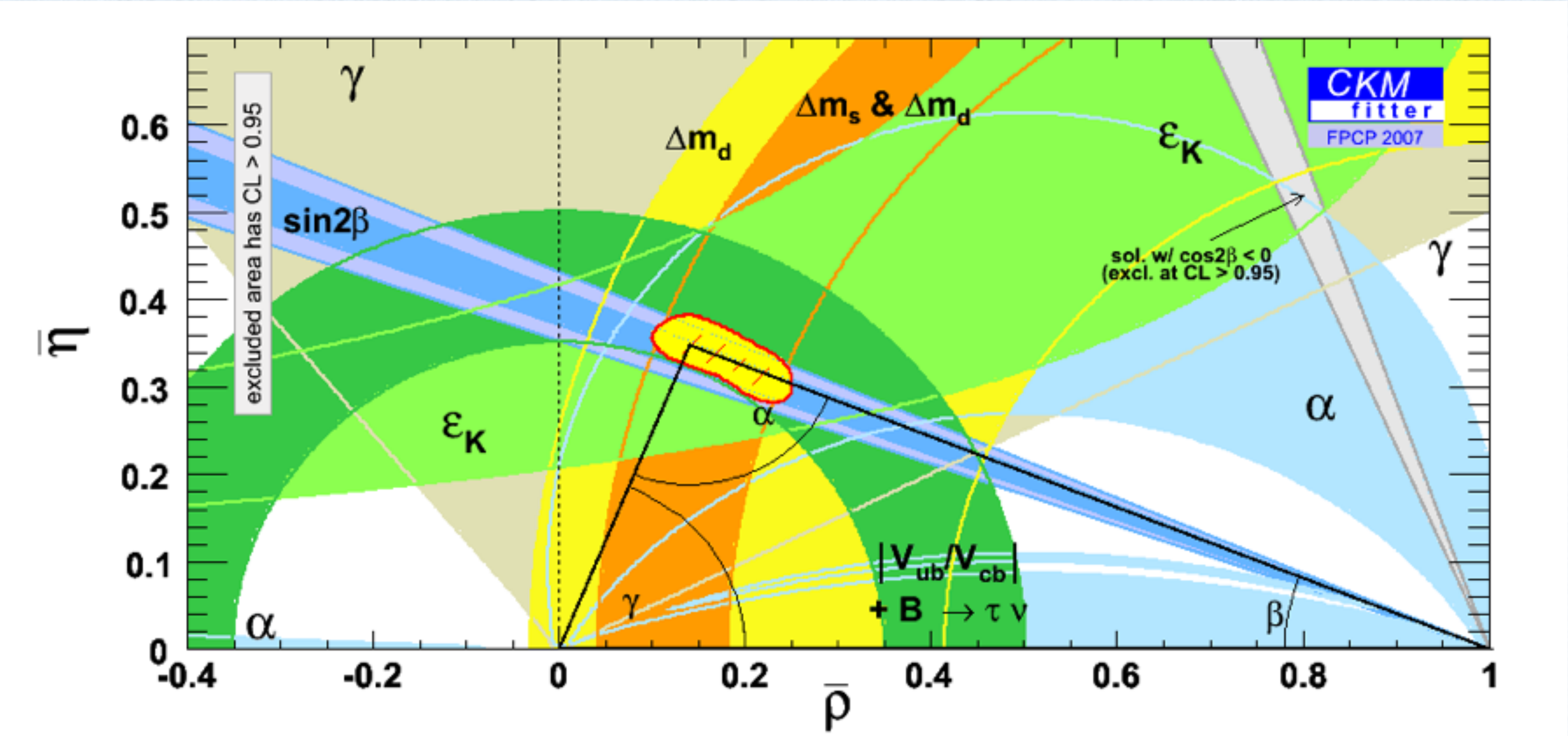
Without Yukawa couplings, SM possesses a large global flavor symmetry $SU(3)_Q \times SU(3)_u \times SU(3)_d$

With Yukawa couplings, flavor structure still very predicative, supressed FCNC's, small CP violation, lepton and baryon number conservation, etc.

Standard Model



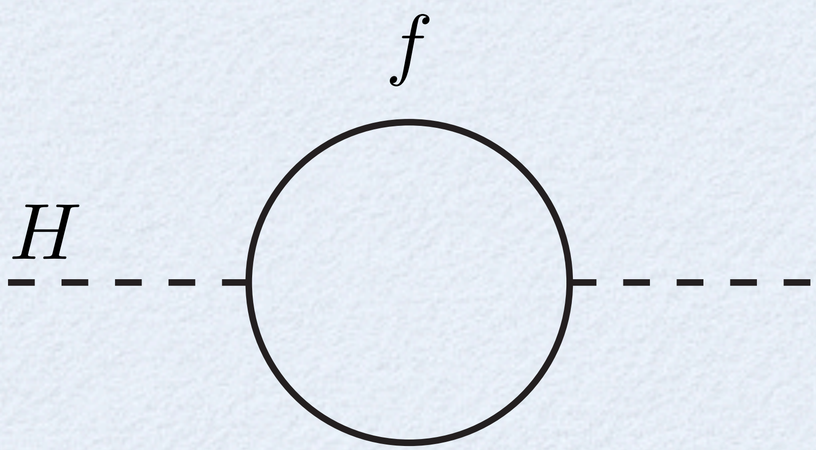
Tremendous experimental support for CKM flavor picture (2008 Nobel Prize)

Tightly constrains "new physics" that doesn't feature the same structure

Why New Physics? 

$$\mathcal{L}_{\text{Higgs}} = |D_\mu \phi|^2 - m^2 \phi^\dagger \phi - \frac{\lambda}{4}(\phi^\dagger \phi)^2$$

Higgs potential has only dimensionful parameter in SM



$$\sim \Lambda_{UV}^2$$

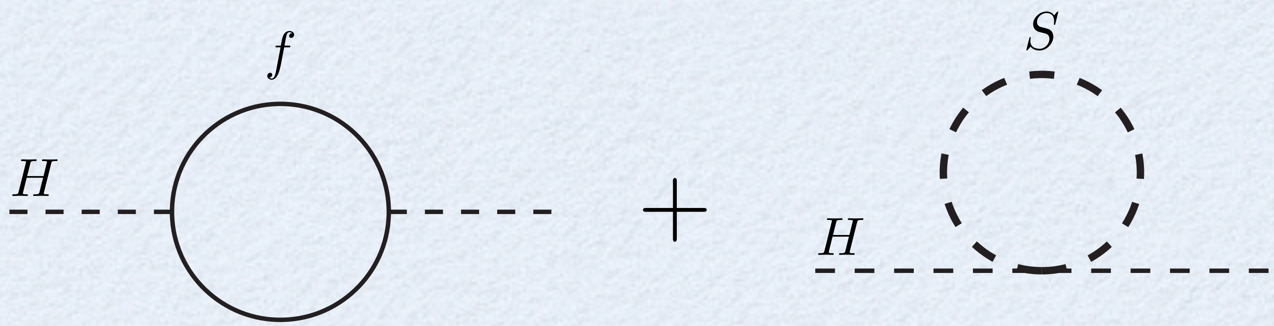
Quantum corrections make the mass parameter unstable

Fine tuning ~ 16 decimals for weak scale Higgs

Motivates searches for new particles to cancel bad stuff

Why SUSY?

Quadratic divergences cancel with superpartner loops



$$\sim m_S^2 \log \frac{\Lambda_{UV}^2}{m_S^2}$$

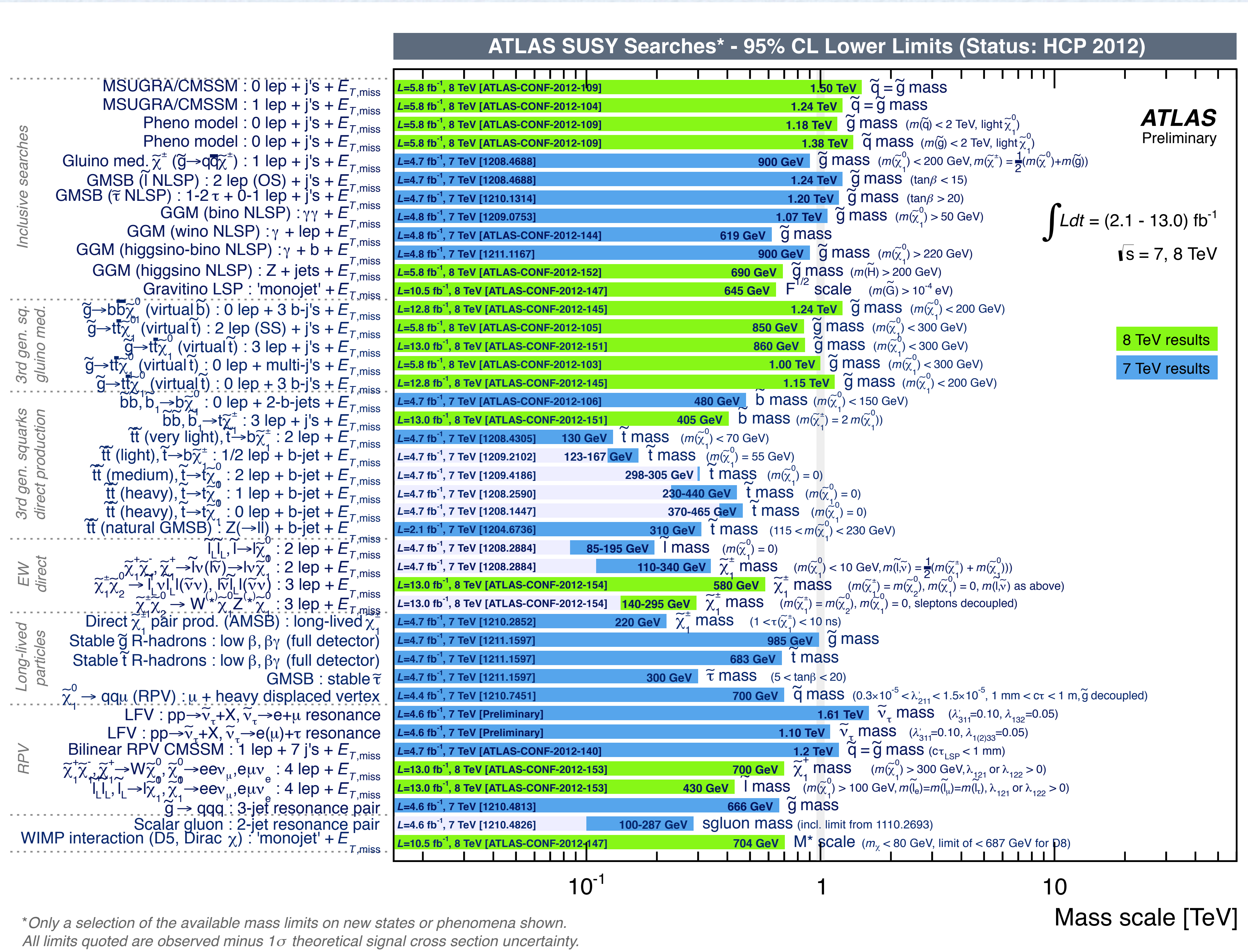
Gauge couplings unify better than SM w/ SU(5) or SO(10)

Dark matter for free (if R-parity is imposed)

Important ingredient in UV physics

In short: a highly motivated scenario

Not So Fast!



Bounds ~ TeV

Weakens naturalness motivation

Generic* problem for weak scale SUSY

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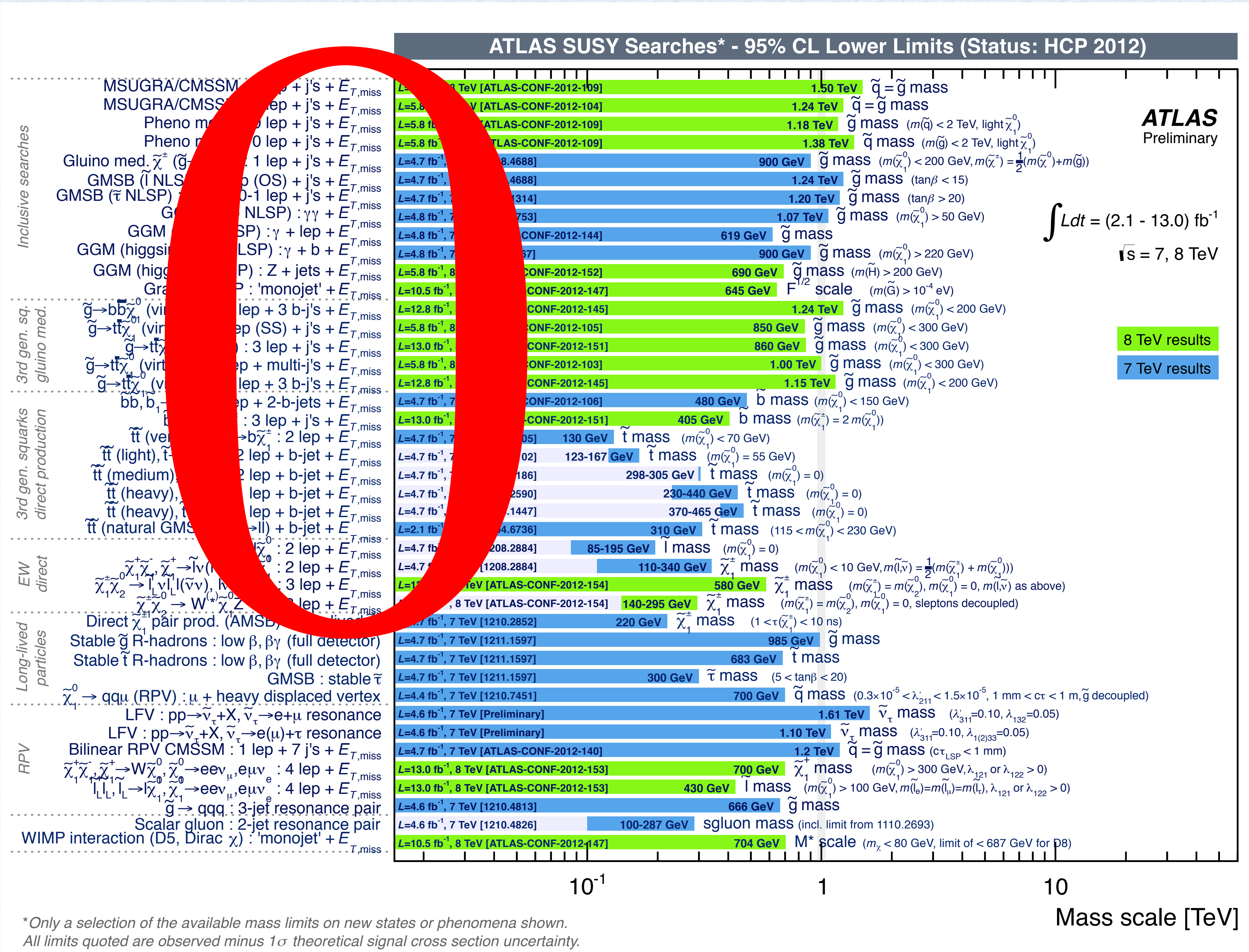

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*** Almost!**

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- Light 3rd generation (heavy 1st & 2nd)
  - Reduces number of predicted signal events
  - Stops/sbottoms still solve hierarchy problem
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RPV = Trouble

$$W_{\rm RPV} = \frac{1}{2}\lambda^{ijk} L_i L_j e_k + \lambda'^{ijk} L_i Q_j d_k + \mu'^{i} L_i H_u$$
$$+ \frac{1}{2}\lambda''^{ijk} u_i d_j d_k \; \Big\} \; \Delta B = 1$$

Saves you from MET searches, but flavor problem is worse!

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Totally ruled out unless there's structure in couplings

MFV SUSY

Nikolidakis and Smith (arXiv:0710.3129)

Csaki, Grossman, Hedenreich (arXiv:111.1239)

Motivation: SUSY models usually assume:

1) R-Parity conservation
2) Flavor blind mediation

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- **holomorphic in superpotential**

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Yukawa *matrices* $\mathcal{Y}_{u,d,e}$

- only source of flavor violation
- holomorphic in superpotential
- suppress baryon & lepton violation

MFV SUSY

$$G_F \equiv SU(3)_Q \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

	$\mathrm{SU}(3)_Q$	$\mathrm{SU}(3)_u$	$\mathrm{SU}(3)_d$	$\mathrm{SU}(3)_L$	$\mathrm{SU}(3)_e$	$\mathrm{U}(1)_{B-L}$	$\mathrm{U}(1)_H$
Q	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$1/3$	0
$\bar{u}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	0
$\bar{d}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	0
L	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	-1	0
$\bar{e}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	1	0
H_u	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	1
H_d	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
Y_u	$\square$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
Y_d	$\square$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	0	1
Y_e	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\overline{\square}$	0	1

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$\bar{d}$	$\mathbf{1}$	$\mathbf{1}$	$\Box$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	0
L	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\Box}$	$\mathbf{1}$	-1	0
$\bar{e}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\Box$	1	0
H_u	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	1
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Y_u	$\Box$	$\bar{\Box}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
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In massless neutrino limit, a $\mathbb{Z}_3^L \in \mathrm{SU}(3)_L \times \mathrm{SU}(3)_e$ **symmetry**

$$L \to \omega L \;,\; \bar{e} \to \omega^{-1}\bar{e} \;,\; Y_e \to Y_e \qquad \omega \equiv e^{2\pi i/3}$$

forbids dangerous lepton violating terms

$$LL\bar{e},\, QL\bar{d},\, LH_u$$

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Baryon violation highly yukawa suppressed

$$W_{\rm BNV} \propto (\mathcal{Y}_u \bar{u})(\mathcal{Y}_d \bar{d})(\mathcal{Y}_d \bar{d})$$

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Soft masses flavor diagonal up to yukawa insertions

$$\mathcal{L}_{\mathcal{S}} \supset m^2_{\mathcal{S}} \tilde{Q}^* \left(\mathcal{Y}_u {\mathcal{Y}_u}^\dagger + \mathcal{Y}_d {\mathcal{Y}_d}^\dagger \right) Q + \cdots$$

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Typical SUSY flavor constraints ameliorated by MFV

Strongest constraints from Δ B = 2 processes

- **Dinucleon decay** $pp \to K^+ K^+$
- **Neutron-antineutron oscillations** $n - \bar{n}$

MFV SUSY

Features

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Is there a plausible UV story?

Gauged Flavor (non-SUSY)

Digression: General Considerations

The SM enjoys a large global symmetry w/o Yukawas

$$G_F \equiv SU(3)_Q \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

Q: why not a global UV group?

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Naive gauging has a similar problem:

If yukawas $\propto$ <*y*> VEV of a scalar, gauge boson masses $\propto$ g <*y*> $\Longrightarrow$ unsuppressed FCNCs for light quarks

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Inverted hierarchy : *Grinstein, Redi, Villadoro (*arXiv: 1009.2049)

– **Gauge flavor group** $SU(3)_Q \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$

– **Add minimal field content to cancel flavor anomalies**

– ***Displace* the flavor breaking fields**

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$$\mathcal{L} \supset \lambda_u \tilde{H} \bar{Q} \psi_{uR} + \lambda'_u Y_u \bar{\psi}_u \psi_{uR} + M_u \bar{\psi}_u \bar{U}_R + (u \leftrightarrow d)$$

		$\mathrm{SU(3)}_{Q_L}$	$\mathrm{SU(3)}_{U_R}$	$\mathrm{SU(3)}_{D_R}$	$\mathrm{SU(3)}_c$	$\mathrm{SU(2)}_L$	$\mathrm{U(1)}_Y$
Quarks	Q_L	3	1	1	3	2	1/6
	U_R	1	3	1	3	1	2/3
	D_R	1	1	3	3	1	-1/3
Exotics	Ψ_{uR}	3	1	1	3	1	2/3
	Ψ_{dR}	3	1	1	3	1	-1/3
	Ψ_u	1	3	1	3	1	2/3
	Ψ_d	1	1	3	3	1	-1/3
Flavons	Y_u	$\bar{3}$	3	1	1	1	0
	Y_d	$\bar{3}$	1	3	1	1	0
	H	1	1	1	1	2	1/2

(awful notation)

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Integrate out (diagonalize) fermions after SSB:

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Gauge boson masses feature inverse-yukawa hierarchy

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$$\rightarrow M_A^2 \sim g^2 \langle Y_u \rangle^2 = \left(\frac{g\lambda M_u}{\lambda'}\right)^2 \frac{1}{y_u^2}$$

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$$\to M_A^2 \sim g^2 \langle Y_u \rangle^2 = \left(\frac{g \lambda M_u}{\lambda'} \right)^2 \frac{1}{y_u^2}$$

Strongly suppresses FCNCs for light flavors $\sim \frac{1}{\langle Y_u^2 \rangle} (\overline{Q} \gamma^\mu Q)^2$

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Some Features

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– **Strongest bounds from modified Zbb coupling, 4th gen searches**

Lightest exotics > 400-500 GeV

Finally Add SUSY

Let's Supersymmetrize the gauged model

	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$+1/6$
$\overline{u}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$
$\overline{d}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$+1/3$
ψ_{u^c}	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$
ψ_{d^c}	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$+1/3$
ψ_u	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$+2/3$
ψ_d	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
Y_u	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0
Y_u^c	$\overline{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0
Y_d	$\mathbf{3}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	0
Y_d^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	0

Note: $Y^c_{u,d}$ **superfields added to cancel flavor anomalies**

As before : flavor spurions are *not* the yukawas, despite the notation

Generating Yukawas

Superpotential

$$W \supset H_u Q \psi_{u^c} + Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} + Y_u Y_u Y_u + \mu_Y Y_u Y_u^c$$

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Flavor "Higgses" get VEVs $\langle Y_u \rangle = \langle Y_u^c \rangle \neq 0$

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and a *massless* MSSM triplet $\bar{U}$

$$\Longrightarrow \; H_u Q(\mathcal{V}\bar{U}) + H_u Q(\mathcal{W}\Psi_{u^c})$$

with Yukawa couplings $\mathcal{Y}_u \propto \mathcal{V} \sim \mathcal{O}\left(M_u / \langle Y_u \rangle\right)$

“Exotic” BNV

R-Parity is not imposed by hand, but $\bar{u}\bar{d}\bar{d}$ **is forbidden**

since $\bar{u} \sim (3,1), \bar{d} \sim (1,3)$ **under** $SU(3)_U \times SU(3)_D$

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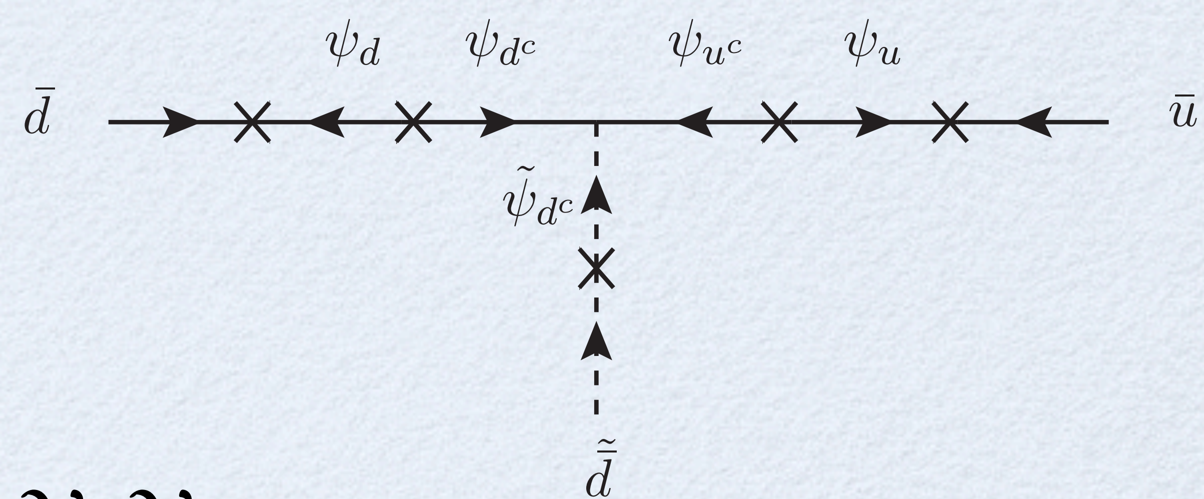

$$W_{BNV} \to (\mathcal{V}_u \bar{U})(\mathcal{V}_d \bar{D})(\mathcal{V}_d \bar{D})$$

Consistent with MFV $\lambda'' \propto \mathcal{Y}_u \mathcal{Y}_d \mathcal{Y}_d$

Deviations From MFV

Before breaking SUSY, we also have flavor violation from

$$\left|\frac{\partial W}{\partial Y_u}\right|^2 \supset \mu_Y^* \langle Y_u^c \rangle^* \tilde{\psi}_u \tilde{\psi}_{u^c} + (u \to d) + c.c.$$

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D-terms are also not of Yukawa form

$$\frac{g_Q^2}{2}\left|\tilde{Q}^* T_Q^a \tilde{Q} - \tilde{\psi}_{u^c}^* T_Q^a \tilde{\psi}_{u^c} + Y_u^* T_Q^a Y_u - Y_u^{c*} T_Q^a Y_u^c + (u \to d)\right|^2$$

and similar terms for $SU(3)_{U,D}$ **which will constrain the gauge couplings later...**

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However, if the flavor scale satisfies $\langle Y \rangle \gg m_{\mathcal{S}}$

these problems are tamed

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Now let's break SUSY ...

Finally Break SUSY

SUSY Breaking spurion : $X = F\theta^2$

$$\mathcal{L}_{\mathcal{S}} \supset \int d^4\theta \frac{X^\dagger X}{M_*^2} \left(\Phi^\dagger \Phi + \cdots\right) + \int d^2\theta \frac{X}{M_*} \left(H_u Q \psi_{u^c} + Y_u \psi_u \psi_{u^c} + M_u \psi_u \bar{u} + \cdots\right)$$

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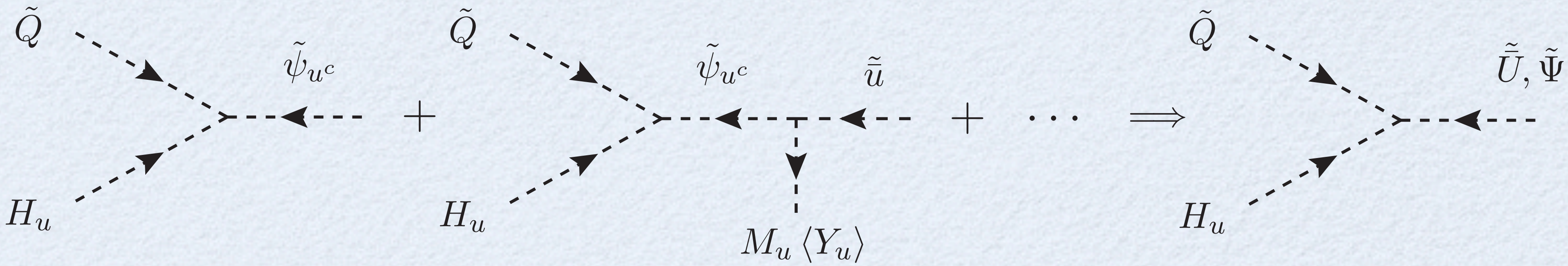
MSSM *scalar* flavor violation is proportional to Yukawa *matrices*

$$\Longrightarrow \tilde{\psi}_{u^c} \to \mathcal{V}\tilde{\bar{U}} + \mathcal{W}\,\tilde{\Psi}_{u^c} \quad , \quad \mathcal{V} \propto \mathcal{Y}_u$$

A Terms

Leading diagrams exactly MFV in degenerate mass limit



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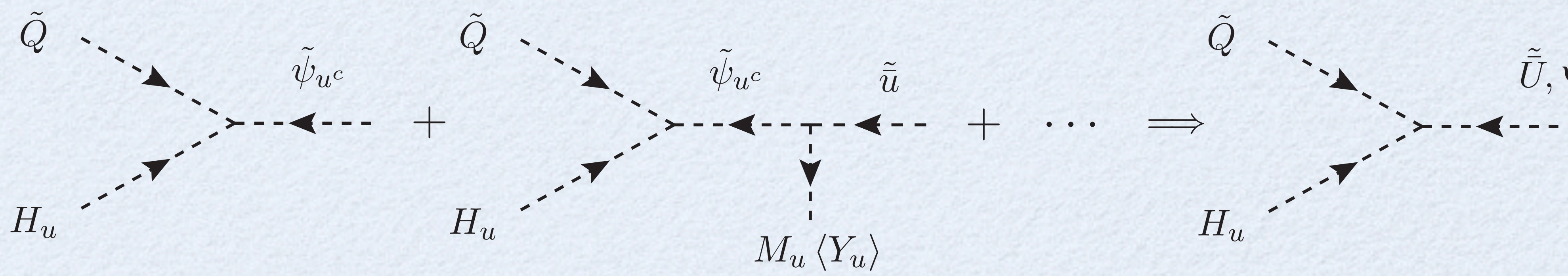

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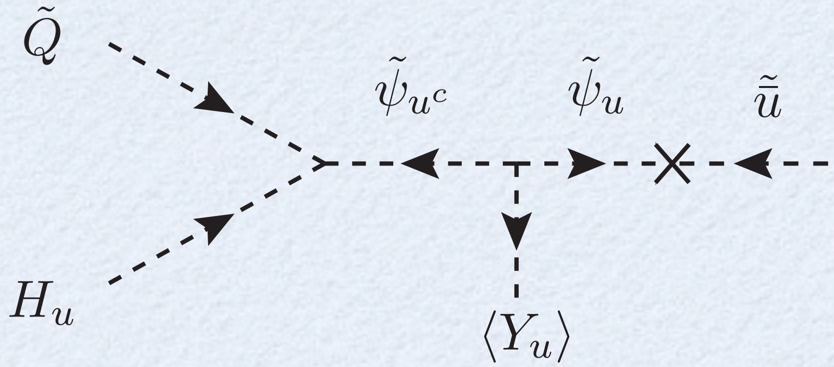

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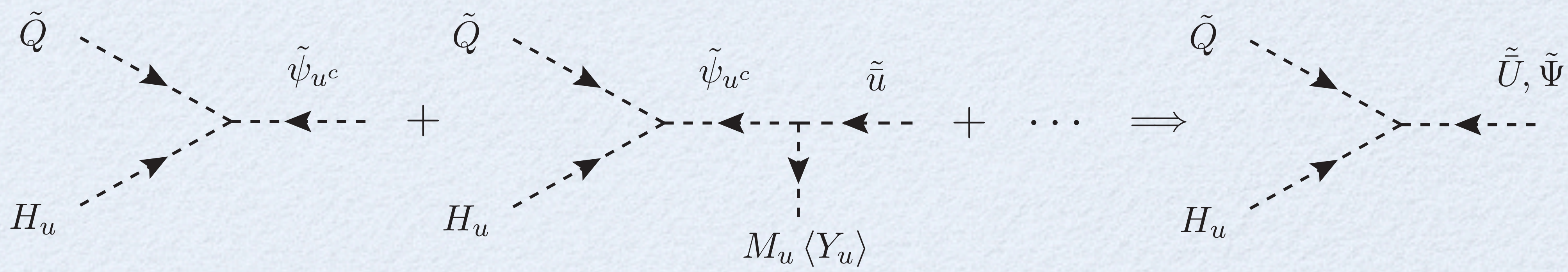

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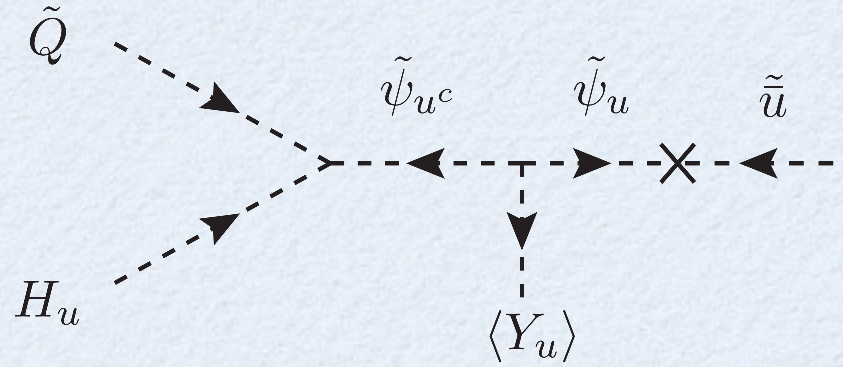

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- **Deviations under theoretical control**
- **Similar corrections from MSSM Higgs VEVs**

Soft Masses

Similar story for other soft parameters

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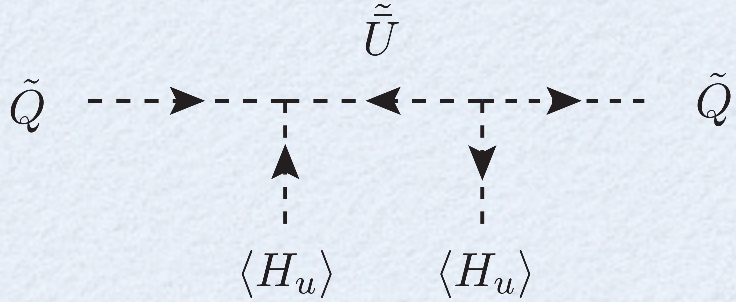

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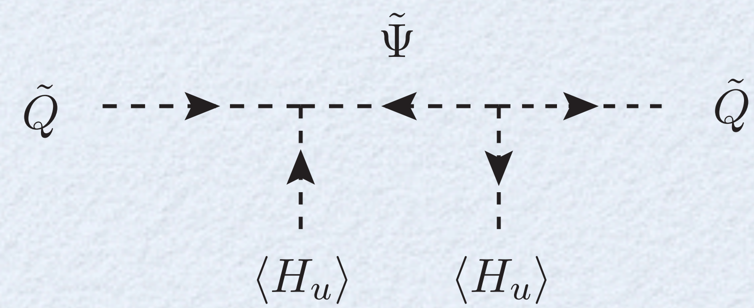

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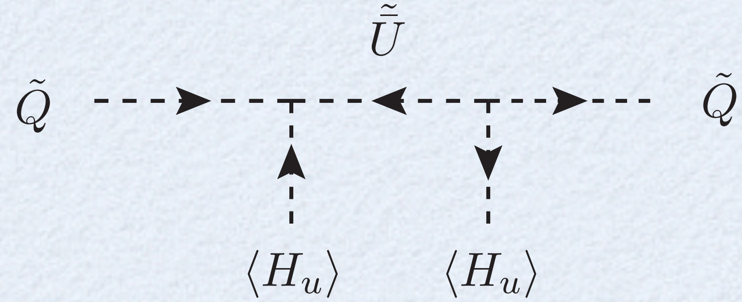

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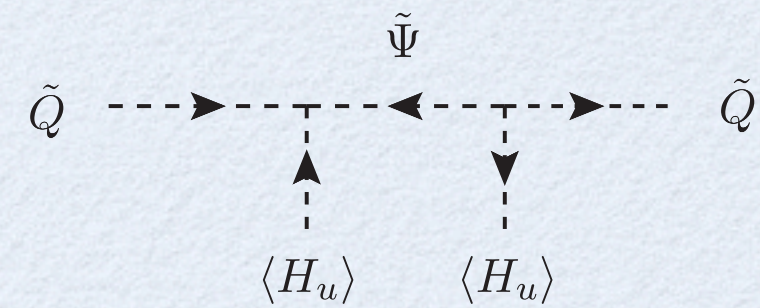

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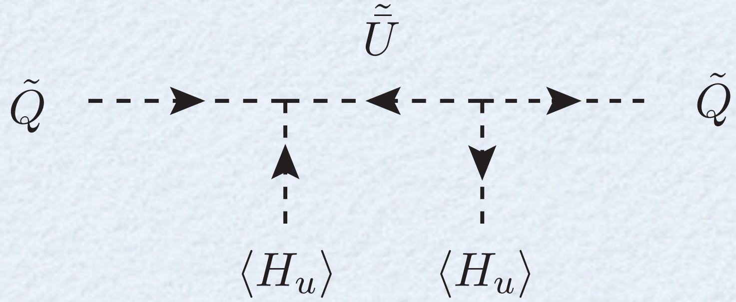

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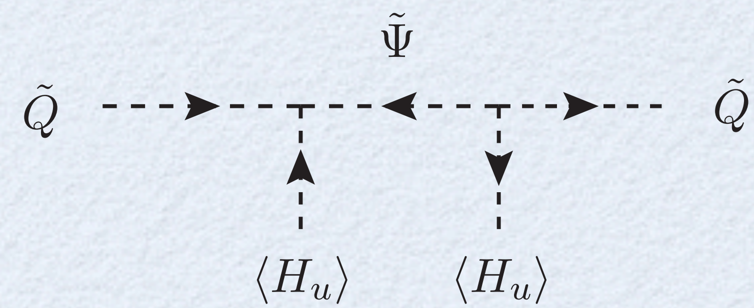

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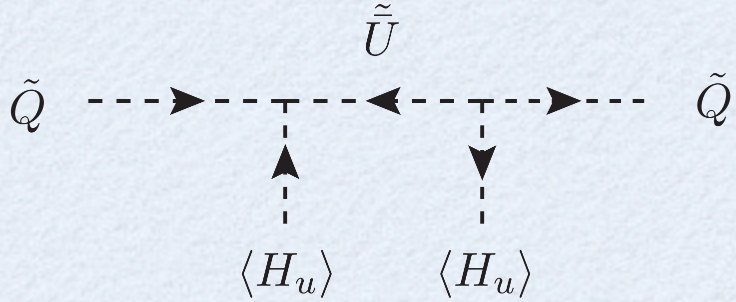

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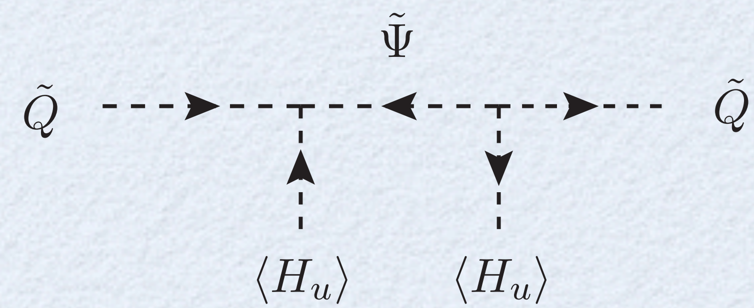

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- **For weak-scale soft masses, this automatically satisfies LR bounds**

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Like *Grinstein et. al.* getting right textures requires multiple fields

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Flavor VEVs

The simplest way to get VEVs :

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Equality of VEVs at leading order ensures D-term squark masses vanish up to corrections from Y's soft masses

$$g_F^2 \left| \tilde{Q}^* T \tilde{Q} + \tilde{Y}_u^* T \tilde{Y}_u - \tilde{Y}_u^c T \tilde{Y}_u^{c*} + \cdots \right|^2 \supset g_F^2 m_{\mathcal{S}}^2 \, Q^* T Q$$