Chiral Flavor Violation from Extended Gauge Mediation

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arxiv:1303.0228 – JAE, D. Shih
arxiv:1411.XXXX – JAE, D. Shih, A. Thalapillil
More In Progress – JAE, D. Shih, A. Thalapillil

Higgs at 125 GeV

A problem for the MSSM

A Higgs at ~ 125 GeV is a *big* problem for the MSSM

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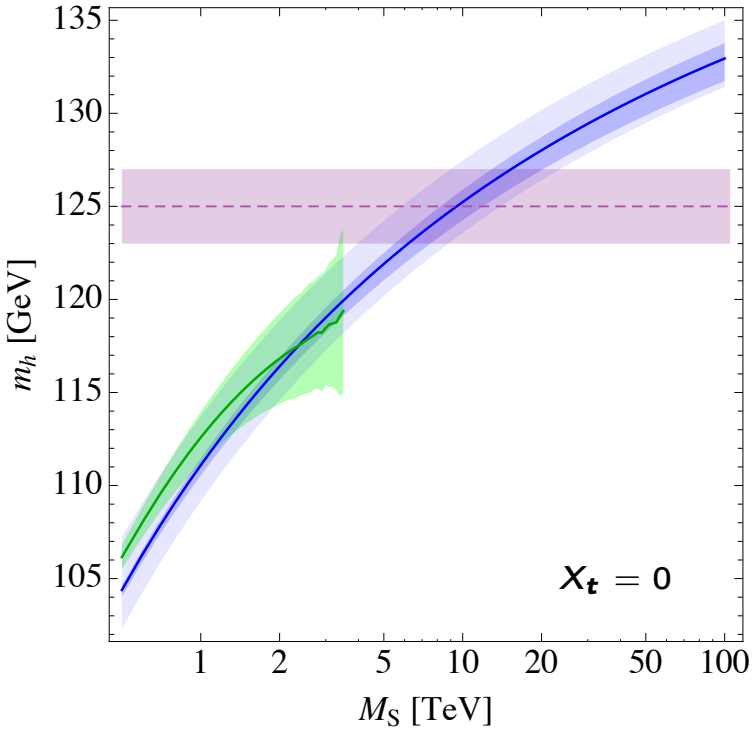
A Higgs at $\sim$ 125 GeV is a *big* problem for the MSSM

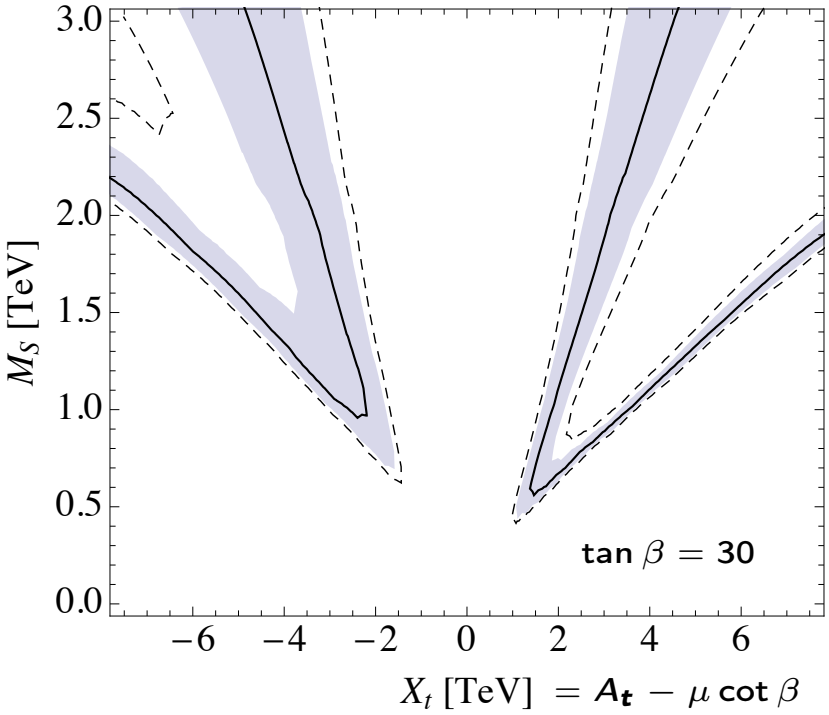
To accommodate, we need either: (Draper, Meade, Reece, Shih 2011)

Heavy Stops



Large tuning: $\Delta \sim 5000$

Large A-terms $\sim \sqrt{6} M_S$



Smaller tuning: $\Delta \sim 500$

Higgs at 125 GeV

A *HUGE* problem for GMSB

Gauge mediated SUSY breaking (GMSB) $\Rightarrow$ no A-terms at M_{mess}

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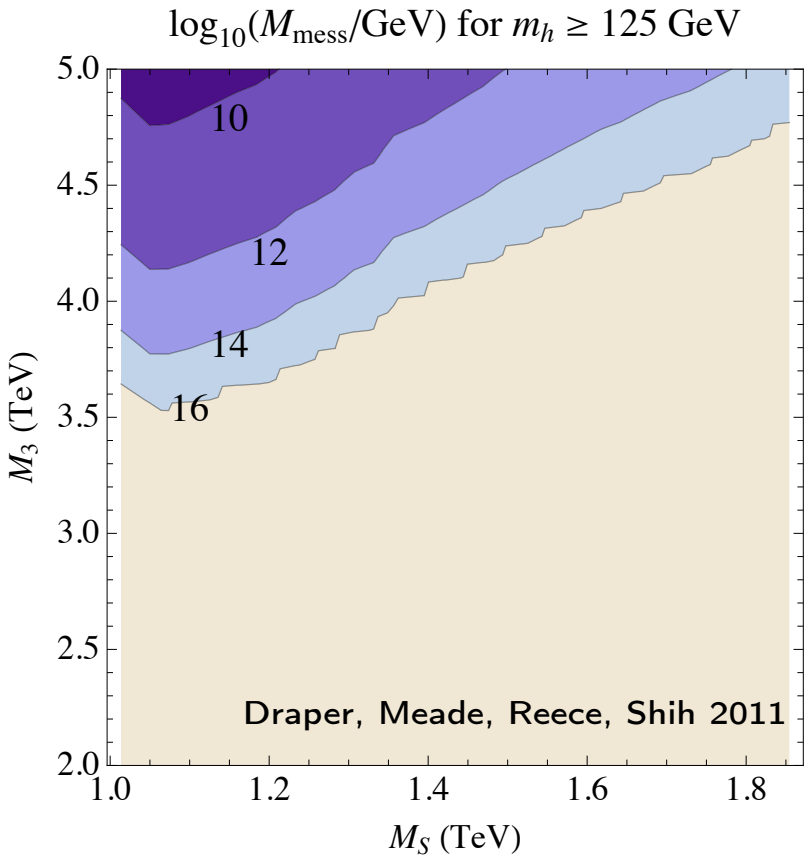

Can be generated through running, but need $M_{mess} \gg M_{SUSY}$

$\Rightarrow$ huge tuning $\Delta \sim 5000$

Higgs at 125 GeV

Better in EGMSB!

Extended GMSB has MSSM-messenger terms in the superpotential

$$W \supset \lambda H_u \Phi \Psi + y_t H_u Q_3 U_3 + X(\Phi\bar{\Phi} + \Psi\bar{\Psi}) + \text{h.c.}$$

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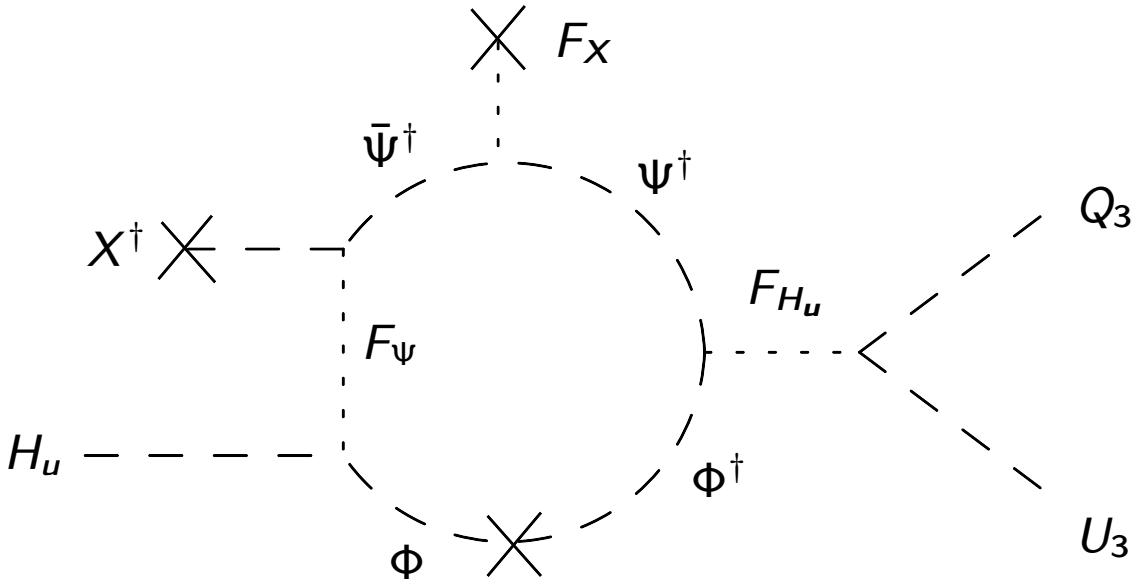

A-terms are *bilinear* terms: $A_t = y_t \left(A^{H_u} F^\dagger_{H_u} H_u + A^Q F^\dagger_{Q_3} Q_3 + A^U F^\dagger_{U_3} U_3 \right)$

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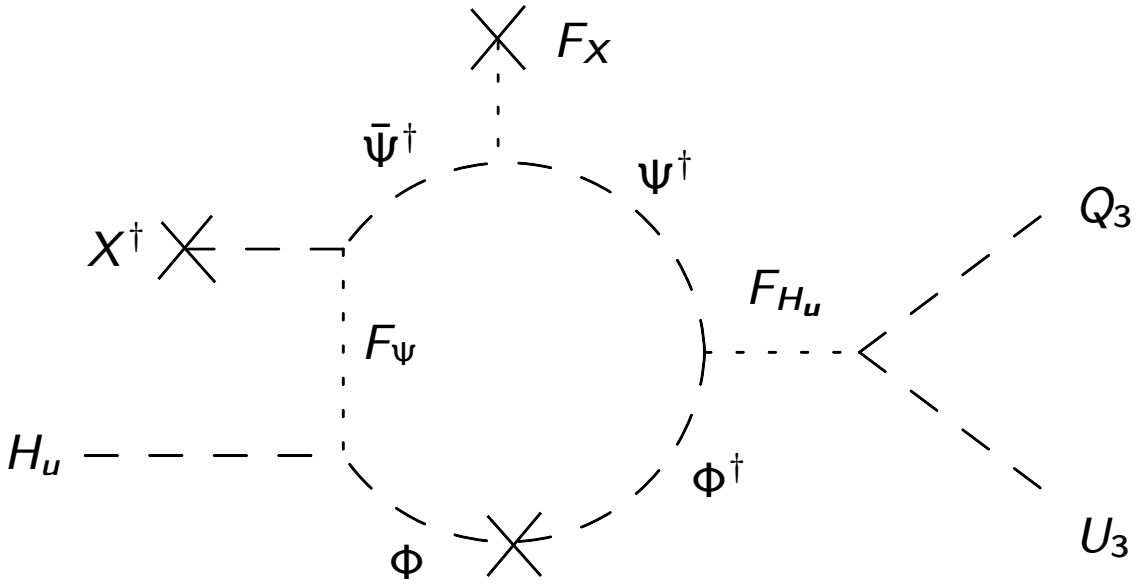

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With a low messenger scale and large A-terms, tuning is reduced!

Tuning: $\Delta \sim 1000$, i.e., $2\times$ the best the MSSM can get!

Outline

$$A_t = y_t \left(A^{H_u} F^\dagger_{H_u} H_u + A^Q F^\dagger_{Q_3} Q_3 + A^U F^\dagger_{U_3} U_3 \right)$$

Discuss Tuning in EGMSB Models with a 125 GeV Higgs

Survey Flavor in EGMSB Models with Lower Tuning

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- Need EGMSB couplings that contain H_u, Q_3 or U_3 ($Q \equiv Q_3$)
- Write all couplings compatible with $SU(5)$ unification ($N_{eff} \leq 6$)
- Define each model by ONE EGMSB coupling (31 models total)
- Scan each model to determine smallest tuning possible

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Survey Flavor in EGMSB Models with Lower Tuning

- Relax flavor alignment, i.e., $\kappa_3 Q_3 \Phi \tilde{\Phi} \rightarrow \kappa_i Q_i \Phi \tilde{\Phi}$
- How much misalignment allowed before flavor constraints?
- What does the future hold?

Lightning GMSB Review

$$W \sim X\Phi\tilde{\Phi} + \{\text{MSSM yukawas}\}$$

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$$\langle X \rangle = M + \theta^2 F, \qquad \Lambda = F/M, \qquad \tilde{\Lambda} = \frac{\Lambda}{16\pi^2}$$

$$M_r \sim N_{eff}\, g_r^2 \tilde{\Lambda} \qquad m_{soft}^2 \sim 2 N_{eff}\, C_r g_r^4 \tilde{\Lambda}^2 \qquad (C_r \text{ quadratic Casimirs})$$

$$A\text{-terms} = 0$$

EGMSB

EGMSB adds superpotential interactions between MSSM and Messengers

Two types of models

Type I			Type II	
MSSM-Messenger-Messenger			MSSM-MSSM-Messenger	
Higgs	Q-class	U-class	w/ mixing	w/o mixing
$\lambda H_u \Phi \tilde{\Phi}$	$\lambda Q \Phi \tilde{\Phi}$	$\lambda U \Phi \tilde{\Phi}$	$\lambda H_u Q \Phi_U$	$\lambda U E \Phi_{\bar{D}}$

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	$\lambda H_u \Phi \tilde{\Phi}$	$\lambda Q \Phi \tilde{\Phi}$	$\lambda U \Phi \tilde{\Phi}$	$\lambda H_u Q \Phi_U$	$\lambda U E \Phi_{\bar{D}}$
Tuning:	???	???	???	???	???
Flavor:	???	???	???	???	???

Type I Higgs

EGMSB Soft Formulas

#	Model	d_H	d_ϕ	C_r
I.1	$H_u \phi_{\bar{5},H_d} \phi_{1,S}$	N_m	3	$\left(\frac{3}{10}, \frac{3}{2}, 0\right)$
I.2	$H_u \phi_{10,Q} \phi_{10,U}$	$3N_m$	3	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
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I.4	$H_u \phi_{5,\bar{L}} \phi_{\bar{10},\bar{E}}$	1	3	$\left(\frac{9}{10}, \frac{3}{2}, 0\right)$
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I.6	$H_u \phi_{\bar{5},L} \phi_{24,W}$	$\frac{3}{2}$	$\frac{5}{2}$	$\left(\frac{3}{10}, \frac{7}{2}, 0\right)$
I.7	$H_u \phi_{\bar{5},D} \phi_{24,X}$	3	3	$\left(\frac{19}{30}, \frac{3}{2}, \frac{8}{3}\right)$

$$W \sim \kappa H_u \sum^{N_m} \Phi_i \tilde{\Phi}_i$$

$$A_{H_u} = -d_H \kappa^2 \tilde{\Lambda}$$

$$\delta m_{H_u}^2 = d_H \kappa^2 \left(\left(d_H + d_\phi \right) \kappa^2 - 2 C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right) \frac{\Lambda^2}{M^2} \right) \tilde{\Lambda}^2$$

$$\delta m_Q^2 = -d_H y_t^2 \kappa^2 \tilde{\Lambda}^2$$

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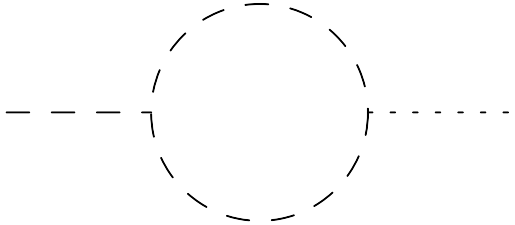
bilinear A

bilinear A^2

$$W \sim \kappa H_u \sum^{N_m} \Phi_i \tilde{\Phi}_i$$



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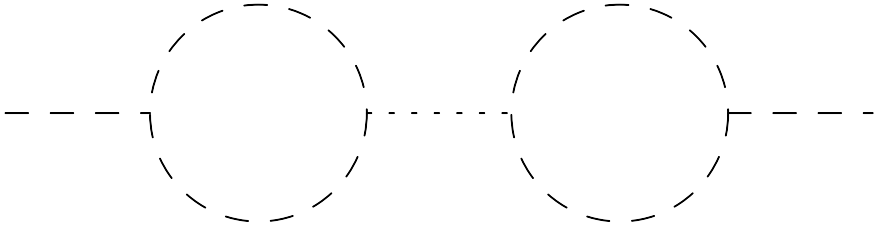

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other κ^4

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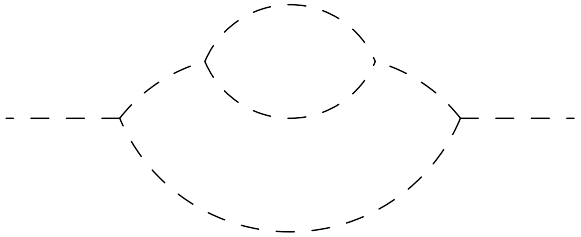

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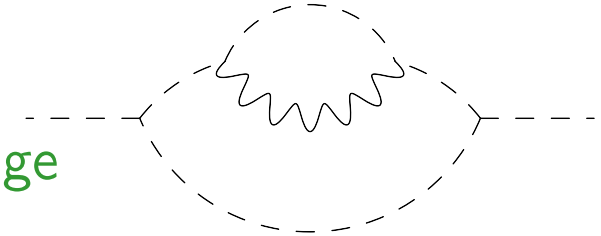

other κ^4

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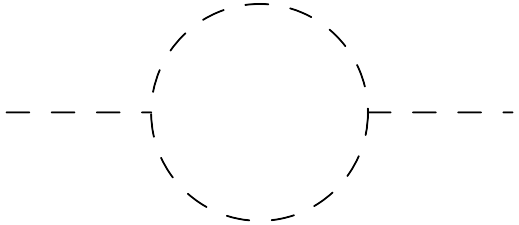

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one-loop term

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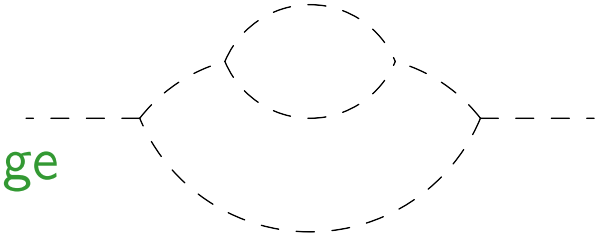

bilinear A

bilinear A^2

other κ^4

gauge

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$$\delta m_Q^2 = -d_H y_t^2 \kappa^2 \tilde{\Lambda}^2$$

$$\delta m_U^2 = -2 d_H y_t^2 \kappa^2 \tilde{\Lambda}^2$$

through yukawa

one-loop term

Type I Squark Models

EGMSB Soft Formulas

#	Model	d_Q	d_ϕ	C_r
I.8	$Q\phi_{\bar{10},\bar{Q}}\phi_{1,S}$	N_m	7	$\left(\frac{1}{30}, \frac{3}{2}, \frac{8}{3}\right)$
I.9	$Q\phi_{\bar{5},D}\phi_{\bar{5},L}$	N_m	5	$\left(\frac{7}{30}, \frac{3}{2}, \frac{8}{3}\right)$
I.10	$Q\phi_{10,U}\phi_{5,H_u}$	1	5	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
I.11	$Q\phi_{10,Q}\phi_{5,\bar{D}}$	2	6	$\left(\frac{1}{10}, \frac{3}{2}, 4\right)$

#	Model	d_U	d_ϕ	C_r
I.12	$U\phi_{\bar{10},\bar{U}}\phi_{1,S}$	N_m	4	$\left(\frac{8}{15}, 0, \frac{8}{3}\right)$
I.13	$U\phi_{\bar{5},D}\phi_{\bar{5},D}$	$2N_m$	4	$\left(\frac{2}{5}, 0, 4\right)$
I.14	$U\phi_{10,Q}\phi_{5,H_u}$	2	4	$\left(\frac{13}{30}, \frac{3}{2}, \frac{8}{3}\right)$
I.15	$U\phi_{10,E}\phi_{5,\bar{D}}$	1	4	$\left(\frac{14}{15}, 0, \frac{8}{3}\right)$

$$W \sim \kappa Q \sum^{N_m} \Phi_i \tilde{\Phi}_i \qquad A_Q = -d_Q \kappa^2 \tilde{\Lambda}$$

$$\delta m_Q^2 = d_Q \kappa^2 \left(\left(d_Q + d_\phi\right) \kappa^2 - 2 C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right) \frac{\Lambda^2}{M^2} \right) \tilde{\Lambda}^2$$

$$\delta m_{H_u}^2 = -3 d_Q y_t^2 \kappa^2 \tilde{\Lambda}^2 \qquad \delta m_{H_d}^2 = -3 d_Q y_b^2 \kappa^2 \tilde{\Lambda}^2$$

$$\delta m_U^2 = -2 d_Q y_t^2 \kappa^2 \tilde{\Lambda}^2 \qquad \delta m_D^2 = -2 d_Q y_b^2 \kappa^2 \tilde{\Lambda}^2$$

$$W \sim \kappa U \sum^{N_m} \Phi_i \tilde{\Phi}_i \qquad A_U = -d_U \kappa^2 \tilde{\Lambda}$$

$$\delta m_U^2 = d_U \kappa^2 \left(\left(d_U + d_\phi\right) \kappa^2 - 2 C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right) \frac{\Lambda^2}{M^2} \right) \tilde{\Lambda}^2$$

$$\delta m_Q^2 = -d_U y_t^2 \kappa^2 \tilde{\Lambda}^2 \qquad \delta m_{H_u}^2 = -3 d_U y_t^2 \kappa^2 \tilde{\Lambda}^2$$

Solving for $m_h = 125$ GeV

$A_{H_u} = -d_H \kappa^2 \tilde{\Lambda}$ Note: $A_t = y_t \left(A_{H_u} + A_{Q_3} + A_{U_3}\right)$

$$\delta m_{H_u}^2 = d_H \kappa^2 \left(\left(d_H + d_\phi\right) \kappa^2 - 2 C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right) \frac{\Lambda^2}{M^2} \right) \tilde{\Lambda}^2$$

$$\delta m_Q^2 = -d_H y_t^2 \kappa^2 \tilde{\Lambda}^2$$

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Given an EGMSB model, κ, F, and M: spectra completely determined

Moreover, given $\left(\kappa, \frac{\Lambda}{M}\right)$, increasing M increases m_h monotonically

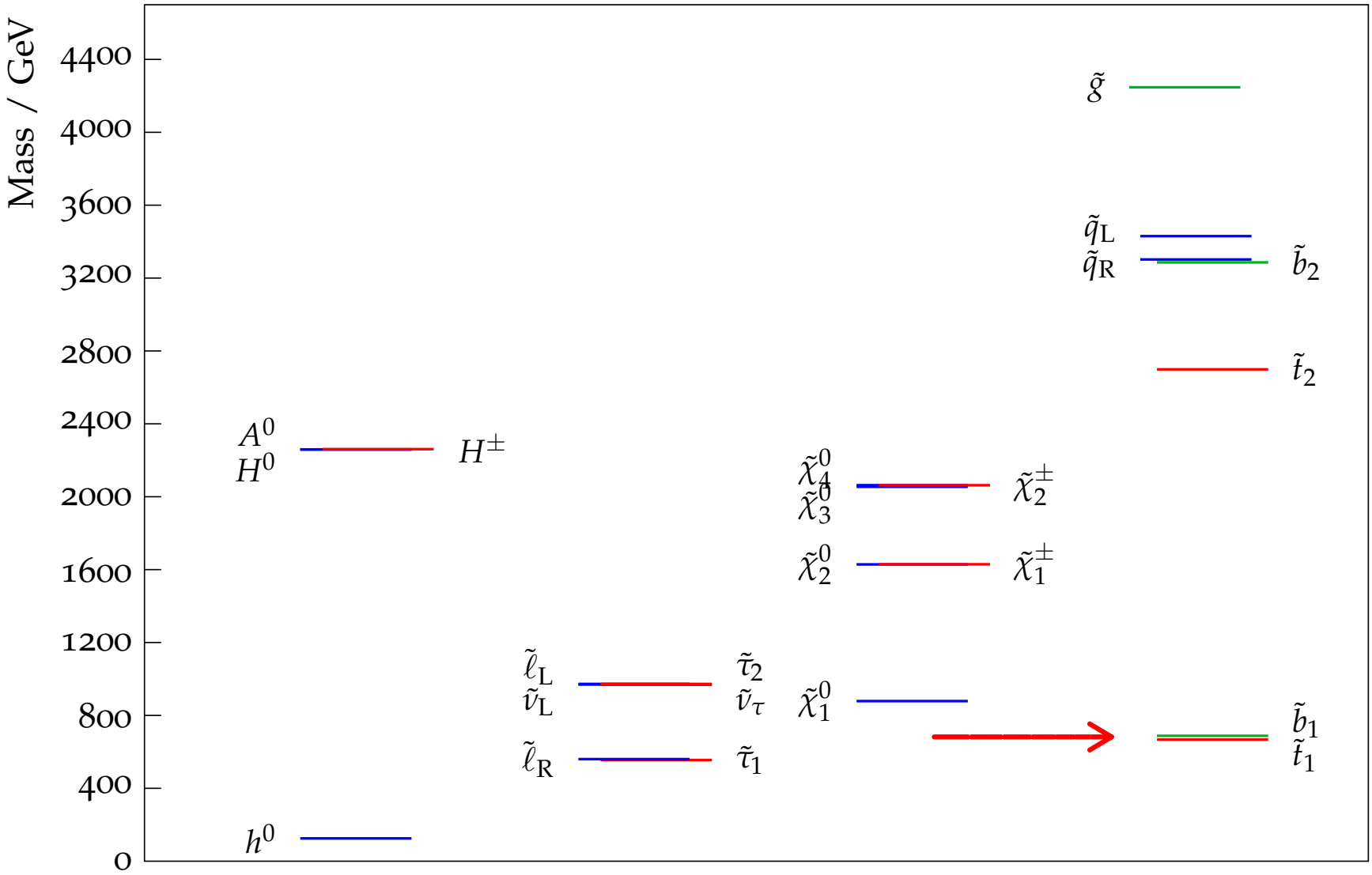
(Evans, Shih 2013)

1. **For each model, scan over $\left(\kappa, \frac{\Lambda}{M}\right)$**
2. **Dial M to solve for $m_h = 125$**
3. **Quantify how finely-tuned that point is**

#	Coupling	$\lvert\Delta b\rvert$	Best Point $\{\frac{\Lambda}{M}, \lambda\}$	$\lvert A_t\rvert / M_S$	$M_{\tilde{g}}$	M_S	$\lvert\mu\rvert$	Tuning
I.1	$H_u \phi_{\bar{5},L} \phi_{1,S}$	N_m	$\{0.375, 1.075\}$	1.98	3222	1842	777	3400
I.2	$H_u \phi_{10,Q} \phi_{10,U}$	$3N_m$	$\{0.25, 1.075\}$	1.99	3178	1828	789	2450
I.3	$H_u \phi_{5,\bar{D}} \phi_{\bar{10},\bar{Q}}$	4	$\{0.25, 1.3\}$	2.05	2899	1709	668	3200
I.4	$H_u \phi_{5,\bar{L}} \phi_{\bar{10},\bar{E}}$	4	$\{0.125, 0.95\}$	0.58	11134	8993	2264	4050
I.5	$H_u \phi_{\bar{5},L} \phi_{24,S}$	6	$\{0.225, 1.000\}$	0.54	13290	9785	3408	3850
I.6	$H_u \phi_{\bar{5},L} \phi_{24,W}$	6	$\{0.15, 1.025\}$	0.67	11835	8637	3259	3410
I.7	$H_u \phi_{\bar{5},D} \phi_{24,X}$	6	$\{0.3, 1.425\}$	2.04	3020	1743	576	3500
I.8	$Q \phi_{\bar{10},\bar{Q}} \phi_{1,S}$	$3N_m$	$\{0.534, 1.5\}$	2.82	4336	1274	2056	1015
I.9	$Q \phi_{\bar{5},D} \phi_{\bar{5},L}$	N_m	$\{0.353, 0.858\}$	2.67	4247	1342	2058	1015
I.10	$Q \phi_{10,U} \phi_{5,H_u}$	4	$\{0.51, 1.788\}$	2.65	4040	1318	2301	1275
I.11	$Q \phi_{10,Q} \phi_{5,\bar{D}}$	4	$\{0.378, 1.245\}$	2.76	4020	1257	2292	1260
I.12	$U \phi_{\bar{10},\bar{U}} \phi_{1,S}$	$3N_m$	$\{0.476, 1.622\}$	2.62	3815	1347	2070	1030
I.13	$U \phi_{\bar{5},D} \phi_{\bar{5},D}$	$2N_m$	$\{0.301, 0.908\}$	2.91	3829	1199	2061	1020
I.14	$U \phi_{10,Q} \phi_{5,H_u}$	4	$\{0.37, 1.352\}$	2.81	3575	1220	2312	1285
I.15	$U \phi_{10,E} \phi_{5,\bar{D}}$	4	$\{0.51, 1.972\}$	2.63	3526	1312	2310	1280
II.1	$QU \phi_{5,H_u}$	1	$\{0.55, 1.64\}$	2.02	769	1965	2738	1800
II.2	$U H_u \phi_{10,Q}$	3	$\{0.009, 1.067\}$	2.14	2203	1628	543	850
II.3	$Q H_u \phi_{10,U}$	3	$\{0.269, 1.05\}$	2.27	2514	1458	439	1500
II.4	$QD \phi_{\bar{5},H_d}$	1	$\{0.37, 1.2\}$	1.78	2597	1829	3553	3020
II.5	$Q H_d \phi_{\bar{5},D}$	1	$\{0.15, 1.19\}$	1.45	2497	2108	3773	6050
II.6	$QQ \phi_{5,\bar{D}}$	1	$\{0.45, 0.1\}$	0.22	7943	9870	3610	5000
II.7	$UD \phi_{\bar{5},D}$	1	$\{0.21, 1.26\}$	2.34	1374	1334	2998	2150
II.8	$QL \phi_{\bar{5},D}$	1	$\{0.14, 1.2\}$	1.51	1501	1204	2203	3700
II.9	$UE \phi_{5,\bar{D}}$	1	$\{0.445, 1.46\}$	1.89	2004	1750	3373	2730
II.10	$H_u D \phi_{24,X}$	5	$\{0.42, 1.45\}$	2.13	2943	1649	282	3500
II.11	$H_u L \phi_{1,S}$	1^*	$\{0.15, 0.675\}$	0.54	7103	8166	3714	4930
II.12	$H_u L \phi_{24,S}$	5	$\{0.296, 0.96\}$	0.53	12629	9660	3333	3780
II.13	$H_u L \phi_{24,W}$	5	$\{0.212, 0.96\}$	0.65	11487	8710	3687	3380
II.14	$H_u H_d \phi_{1,S}$	1^*	$\{0.125, 0.675\}$	0.55	7049	8051	3255	5000
II.15	$H_u H_d \phi_{24,S}$	5	$\{0.20, 1.00\}$	0.57	12047	9213	1628	4220
II.16	$H_u H_d \phi_{24,W}$	5	$\{0.2, 0.946\}$	0.64	11571	8789	3665	3460

Sample Spectra

$\kappa_3 Q_3 \phi_{\bar{5},D} \phi_{\bar{5},L}$



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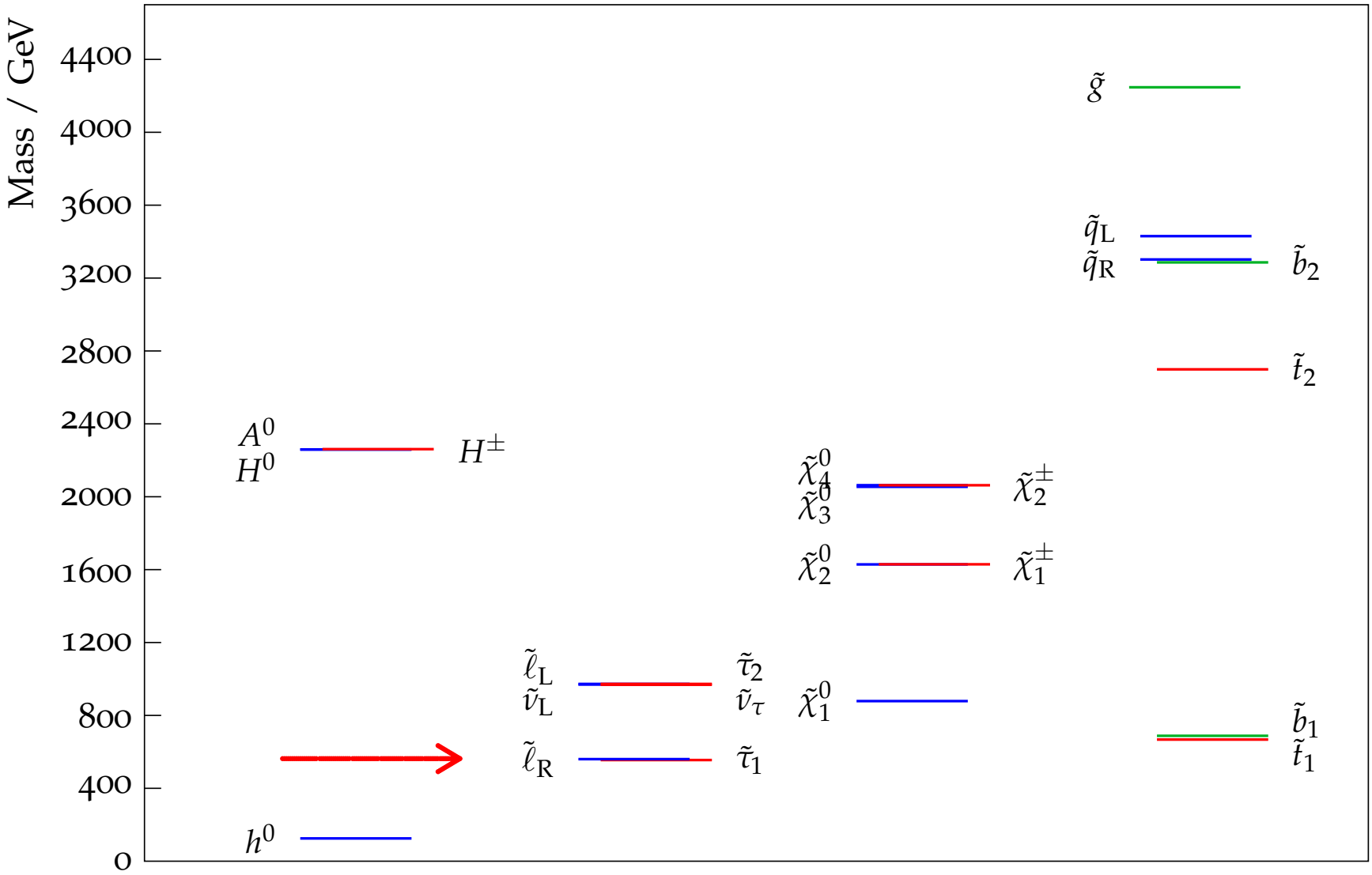

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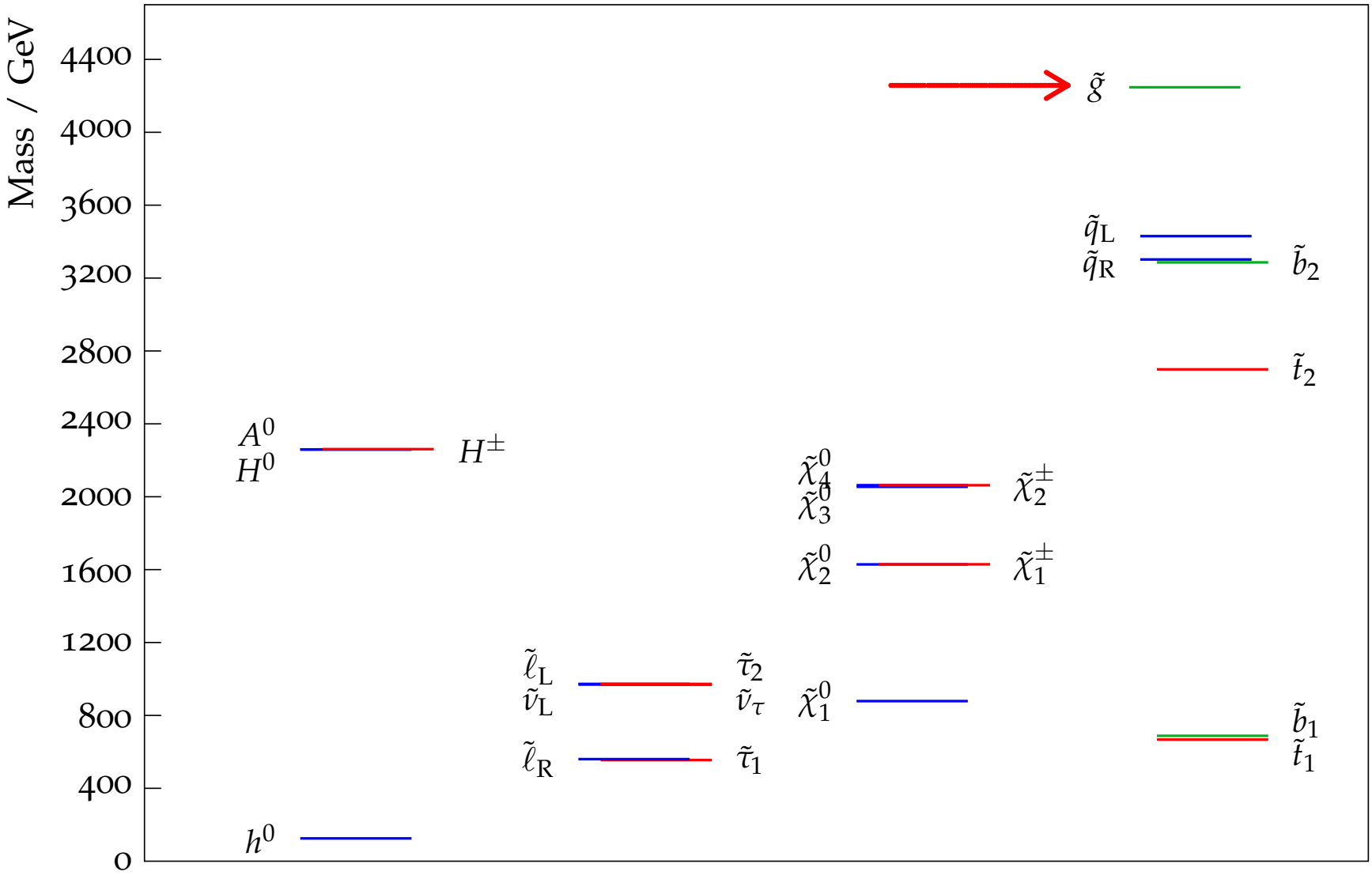

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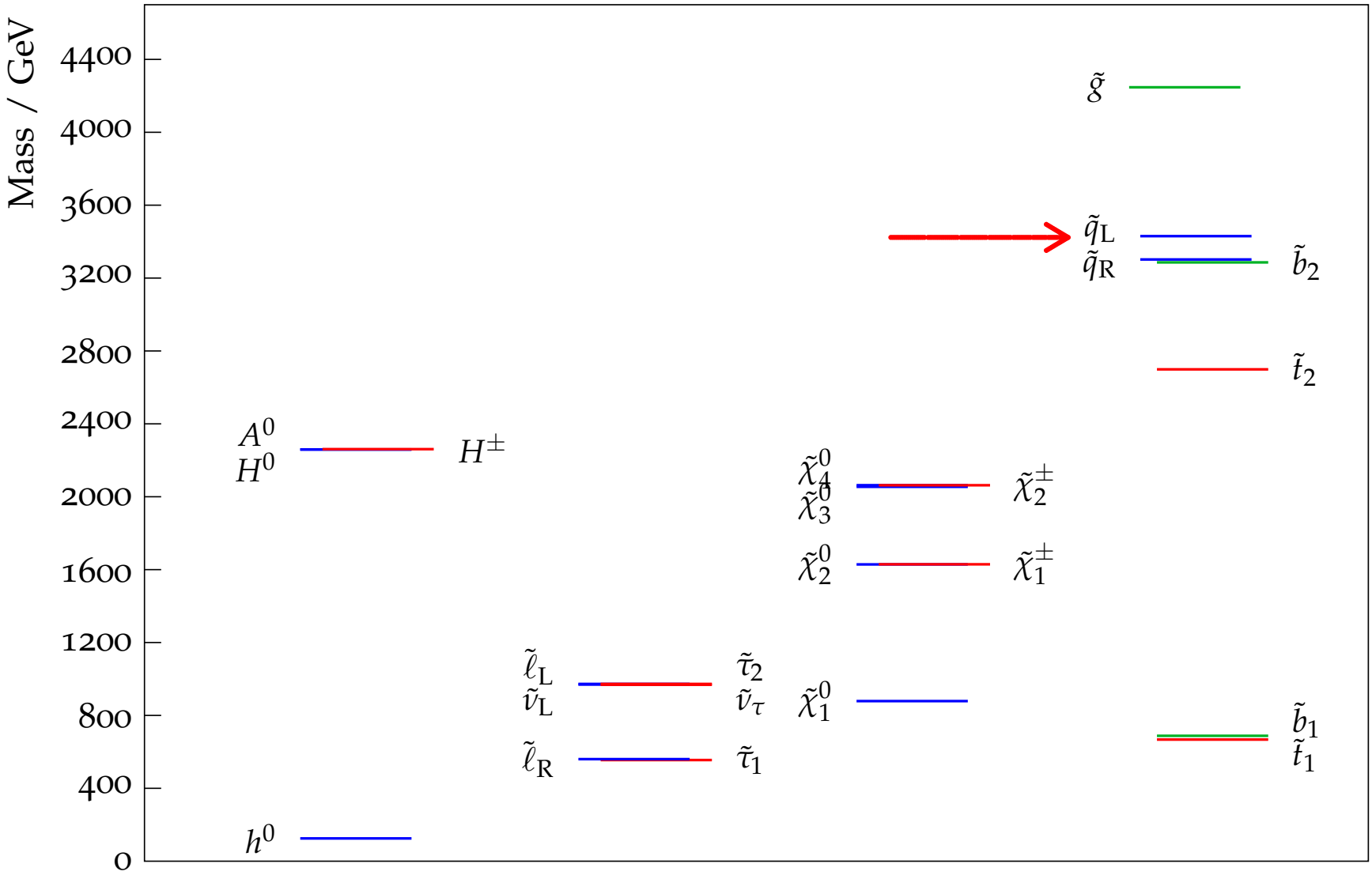

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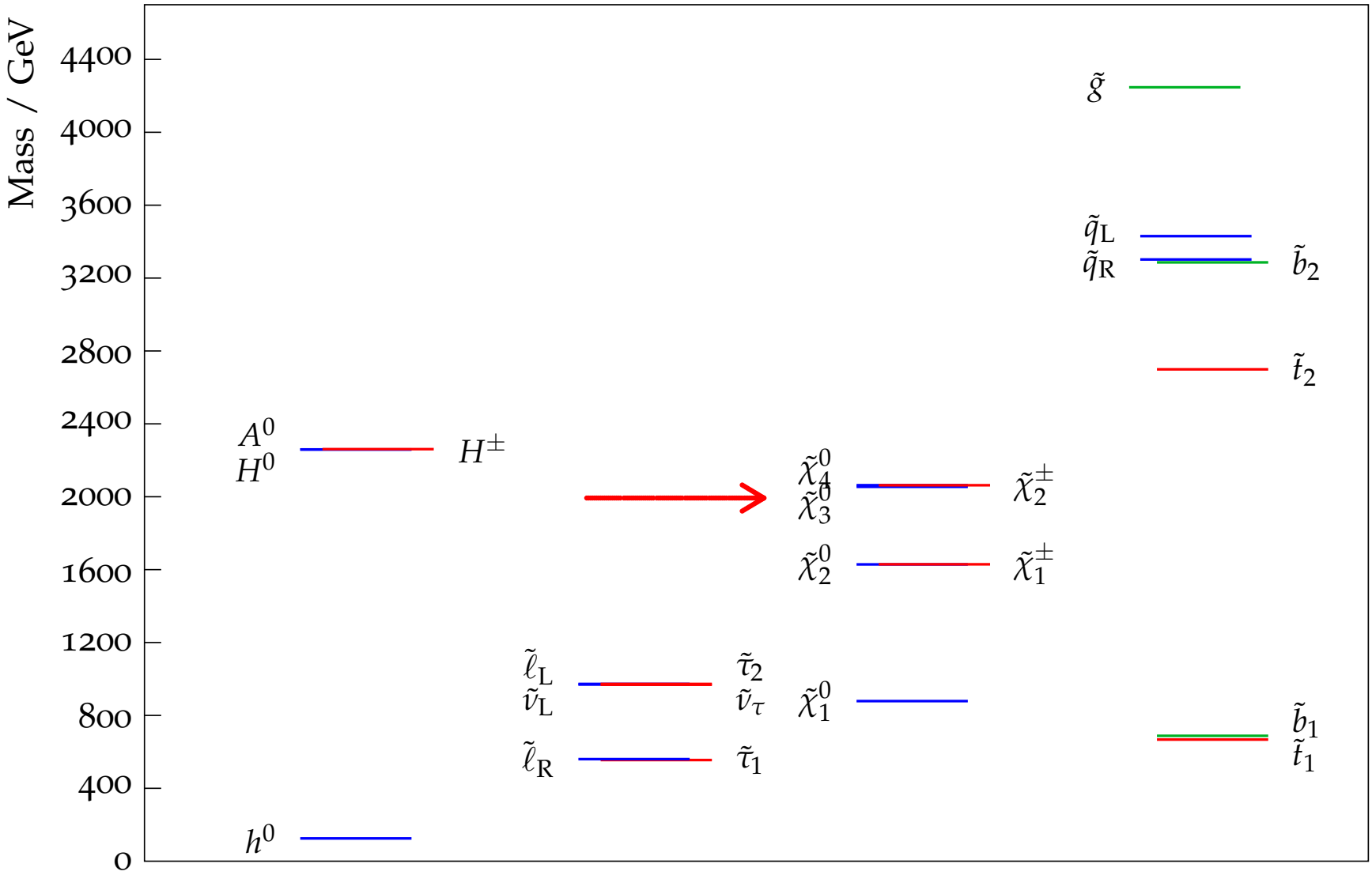

Types of models

Tuning & Flavor

	Type I			Type II	
	Higgs	Q-class	U-class	w/ mixing	w/o mixing
	$\lambda H_u \Phi \tilde{\Phi}$	$\lambda Q \Phi \tilde{\Phi}$	$\lambda U \Phi \tilde{\Phi}$	$\lambda H_u Q \Phi_U$	$\lambda U E \Phi_{\bar{D}}$
Tuning:	BAD	GOOD	GOOD	GOOD	BAD
Flavor:	MFV	???	???	???	???

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Tuning:	BAD	GOOD	GOOD	GOOD	BAD
Flavor:	MFV	???	???	???	DON'T CARE!

Lightning Flavor Review

The SM

In the SM, flavor is only violated by the CKM – W charged current

To constrain NP, flavor observables that vanish at tree level in SM are best

Small CKM and GIM suppress many further

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Observable	Experiment	SM prediction
Δm_K	$(3.484 \pm 0.006) \times 10^{-15}$ GeV	$-^*$
Δm_{B_d}	$(3.36 \pm 0.02) \times 10^{-13}$ GeV	$(3.56 \pm 0.60) \times 10^{-13}$ GeV
Δm_{B_s}	$(1.169 \pm 0.0014) \times 10^{-11}$ GeV	$(1.13 \pm 0.17) \times 10^{-11}$ GeV
Δm_D	$(6.2^{+2.7}_{-2.8}) \times 10^{-15}$ GeV	$-$
$Br(K^+ \to \pi^+ \nu\bar{\nu})$	$(1.7 \pm 1.1) \times 10^{-10}$	$(7.8 \pm 0.8) \times 10^{-11}$
$Br(B \to X_s \gamma)$	$(3.40 \pm 0.21) \times 10^{-4}$	$(3.15 \pm 0.23) \times 10^{-4}$
$Br(B \to X_d \gamma)$	$(1.41 \pm 0.57) \times 10^{-5}$	$(1.54^{+0.26}_{-0.31}) \times 10^{-5}$
$Br(B_s \to \mu^+\mu^-)$	$(2.9 \pm 0.7) \times 10^{-9}$	$(3.65 \pm 0.23) \times 10^{-9}$
$Br(B_d \to \mu^+\mu^-)$	$(3.6^{+1.6}_{-1.4}) \times 10^{-10}$	$(1.06 \pm 0.09) \times 10^{-10}$

Lightning Flavor Review

Wilson Operators

Flavor violation can be parameterized by dimension 5 & 6 operators

- Dimension 5: $\frac{1}{\Lambda}\bar{q}_1\sigma^{\mu\nu}q_2F_{\mu\nu}$, $\frac{1}{\Lambda}\bar{q}_1\sigma^{\mu\nu}q_2G_{\mu\nu}$
  - Radiative $\Delta F = 1$: $b \to s\gamma$, $b \to d\gamma$

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- Hadronic Dimension 6: $\frac{1}{\Lambda^2}\left(\bar{q}_1q_2\right)\left(\bar{q}_3q_4\right)$, $\frac{1}{\Lambda^2}\left(\bar{q}_1\gamma_\mu q_2\right)\left(\bar{q}_3\gamma^\mu q_4\right)$, etc.
  - Meson Mixing $\Delta F = 2$: Δm_K, Δm_D, Δm_{B_s}, Δm_{B_d}

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  - Meson Mixing $\Delta F = 2$: Δm_K, Δm_D, Δm_{B_s}, Δm_{B_d}
- Leptonic Dimension 6: $\frac{1}{\Lambda^2}\left(\bar{q}_1q_2\right)\left(\mu^+\mu^-\right)$, $\frac{1}{\Lambda^2}\left(\bar{q}_1\gamma_\mu q_2\right)\left(\bar{\nu}\gamma^\mu\nu\right)$, etc.
  - Semi-leptonic $\Delta F = 1$: $K \to \pi\nu\nu$, $B_s \to \mu\mu$, $B_d \to \mu\mu$

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Bounds on some operators *much* stronger than others, even for the same observable:

$$\begin{aligned} \text{OpA} — \Delta m_K &: \left(\bar{s}_L\gamma^\mu d_L\right)^2 \quad \Rightarrow \Lambda > 9.8 \times 10^2 \text{ TeV} \\ \text{OpB} — \Delta m_K &: \left(\bar{s}_R d_L\right)\left(\bar{s}_L d_R\right) \Rightarrow \Lambda > 1.8 \times 10^4 \text{ TeV} \end{aligned}$$

(Isidori, Nir, Perez 2010)

Lightning Flavor Review

SUSY: The Mass Matrix and the MIA

$$M_d^2 = \left(\begin{array}{ccc|ccc} m^2_{Q,11} & m^2_{Q,12} & m^2_{Q,13} & A^\dagger_{d,11} v_d & A^\dagger_{d,12} v_d & A^\dagger_{d,13} v_d \\ m^2_{Q,21} & m^2_{Q,22} & m^2_{Q,23} & A^\dagger_{d,21} v_d & A^\dagger_{d,22} v_d & A^\dagger_{d,23} v_d \\ m^2_{Q,31} & m^2_{Q,32} & m^2_{Q,33} & A^\dagger_{d,31} v_d & A^\dagger_{d,32} v_d & A^\dagger_{d,33} v_d \\ \hline A_{d,11} v_d & A_{d,12} v_d & A_{d,13} v_d & m^2_{D,11} & m^2_{D,12} & m^2_{D,13} \\ A_{d,21} v_d & A_{d,22} v_d & A_{d,23} v_d & m^2_{D,11} & m^2_{D,12} & m^2_{D,13} \\ A_{d,31} v_d & A_{d,32} v_d & A_{d,33} v_d & m^2_{D,11} & m^2_{D,12} & m^2_{D,13} \end{array}\right)$$

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$$M_d^2 = \tilde{m}^2_{d,0}(\mathbf{1} + \delta^{XY}), \qquad \text{where } \tilde{m}^2_{d,0} = \frac{1}{6}\,\mathrm{Tr}(M_d^2)$$

$$\delta^{XY} = \left(\begin{array}{c|c} \delta^{LL}_{ij} & \delta^{RL}_{ij} \\ \hline \delta^{LR}_{ij} & \delta^{RR}_{ij} \end{array}\right)$$

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LL RL LR RR

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$$\delta^{LL}_{ij} = \frac{m^2_{Q,ij}}{\tilde{m}^2_{d,0}} - \mathbf{1} \qquad \delta^{LR}_{ij} = \frac{v_d A_{d,ij}}{\tilde{m}^2_{d,0}}$$

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Toward a Flavor Story

The Task at Hand

$$W = \kappa_3 Q_3 \Phi \tilde{\Phi} \rightarrow W = \kappa_i Q_i \Phi \tilde{\Phi}$$

We want to compute bounds on couplings κ_i from flavor observables

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To do this we need the following:

- Compute general non-MFV soft masses at the messenger scale
- Run them down to the SUSY scale, including full 3x3 CKM & CPV
- Compute 1-loop Wilson coefficients for all operators of interest
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We could not find a suitable public code to do all of this, so we wrote it!

FormFlavor

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- Mathematica package based on FeynArts and FormCalc

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  - ϵ_K, neutron EDM
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(Now, FlavorKit exists which does similar things with SARAH and Spheno)

Toward a Flavor Story

Our EGMSB Mass Matrix: Chiral Flavor Violation

In the third-generation dominant limit ($y_i = 0$ for $i \neq t, b$)

Q-class:

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Toward a Flavor Story

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General χFV arises simply from symmetries, e.g anarchic Q, vanilla $U, D \Rightarrow Q\chi$FV

Toward a Flavor Story

The Deformation

At best tuned point, for $(\kappa_1, \kappa_2) = (0, 0)$, $\delta m^2_{Q,33} < 0$

$$\delta m^2_{Q,ab} = d_Q \left((d_\phi + d_Q)\kappa^2 - 2C_r g_r^2 - \frac{16\pi^2}{3} h\left(\frac{\Lambda}{M}\right)\frac{\Lambda^2}{M^2} \right) \kappa_a^* \kappa_b \tilde{\Lambda}^2$$

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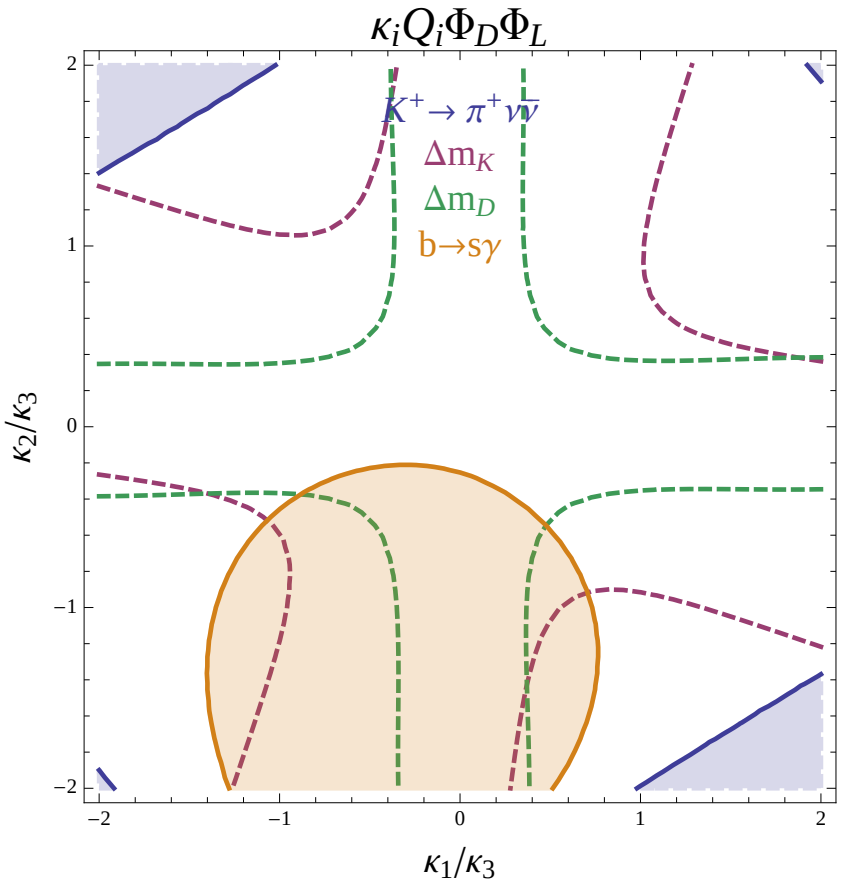
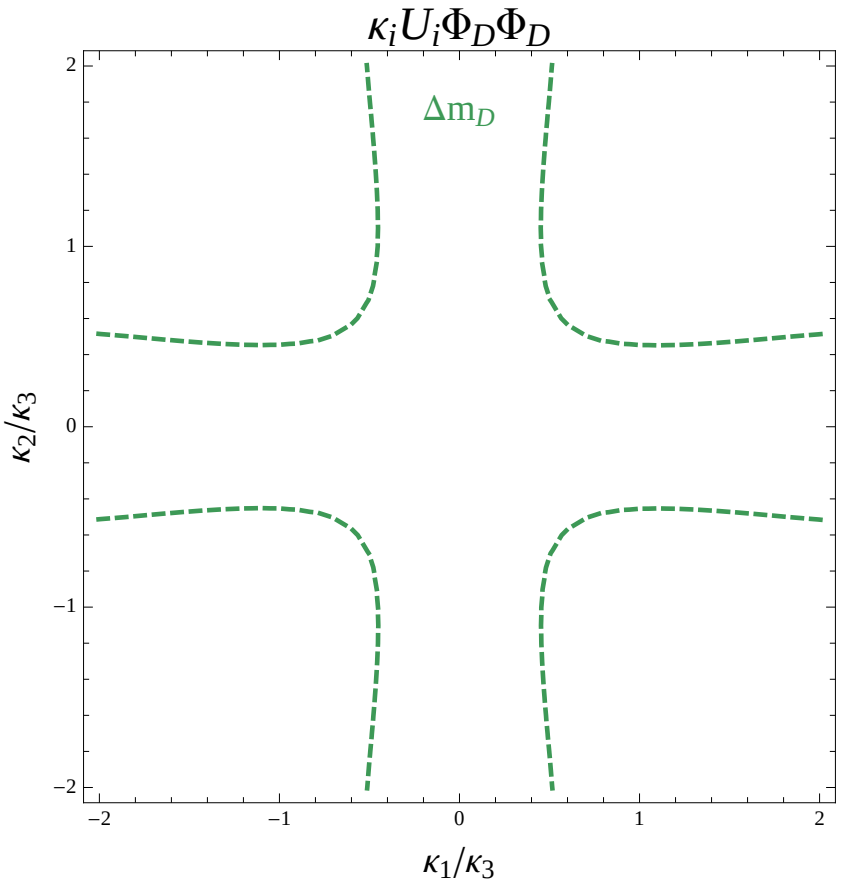
Instead, we fix Λ, but vary M to fix the lightest eigenvalue in the m_Q^2 block

Note: Eigenvalues$[c\tilde{\Lambda}^2 \mathbf{1}_3 - F\left(\kappa, \frac{\Lambda}{M}\right)\tilde{\Lambda}^2 \kappa_i^* \kappa_j] = \{c, c, c - F\left(\kappa, \frac{\Lambda}{M}\right)\kappa^2\}\tilde{\Lambda}^2$

Type I Q-class and U-class Constraints

2σ Constraints





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2. $m_h = 125$ GeV $\Rightarrow$ most squarks at ~ 3 TeV
3. Effective operator bounds can exaggerate the problem
4. Flavor violation is from rank 1 tensor, suppresses FV a bit
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From SUSY MIA:

$$\frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu d_L\right)^2 = \frac{\alpha_s^2}{216\tilde{m}^2}\left(\delta_{12}^{LL}\right)^2\left(\bar{s}_L\gamma^\mu d_L\right)^2 : \ \Lambda > 10^3\,\text{TeV} \Rightarrow \tilde{m} > 5\,\text{TeV}$$

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We fix lightest e.value: $M^2_{Q,ij} \sim M^2 \mathbf{1} - X\kappa_i\kappa_j \Rightarrow \{M^2, M^2, M^2 - X\kappa^2\}$

$X\kappa^2 \sim M^2 \Rightarrow \delta^{LL}_{ij} \sim \frac{3\kappa_i\kappa_j}{2(\kappa_1^2+\kappa_2^2+\kappa_3^2)}$ for $\kappa_1 = \kappa_2 = \kappa_3$, $\delta^{LL}_{ij} \sim \frac{1}{2}$

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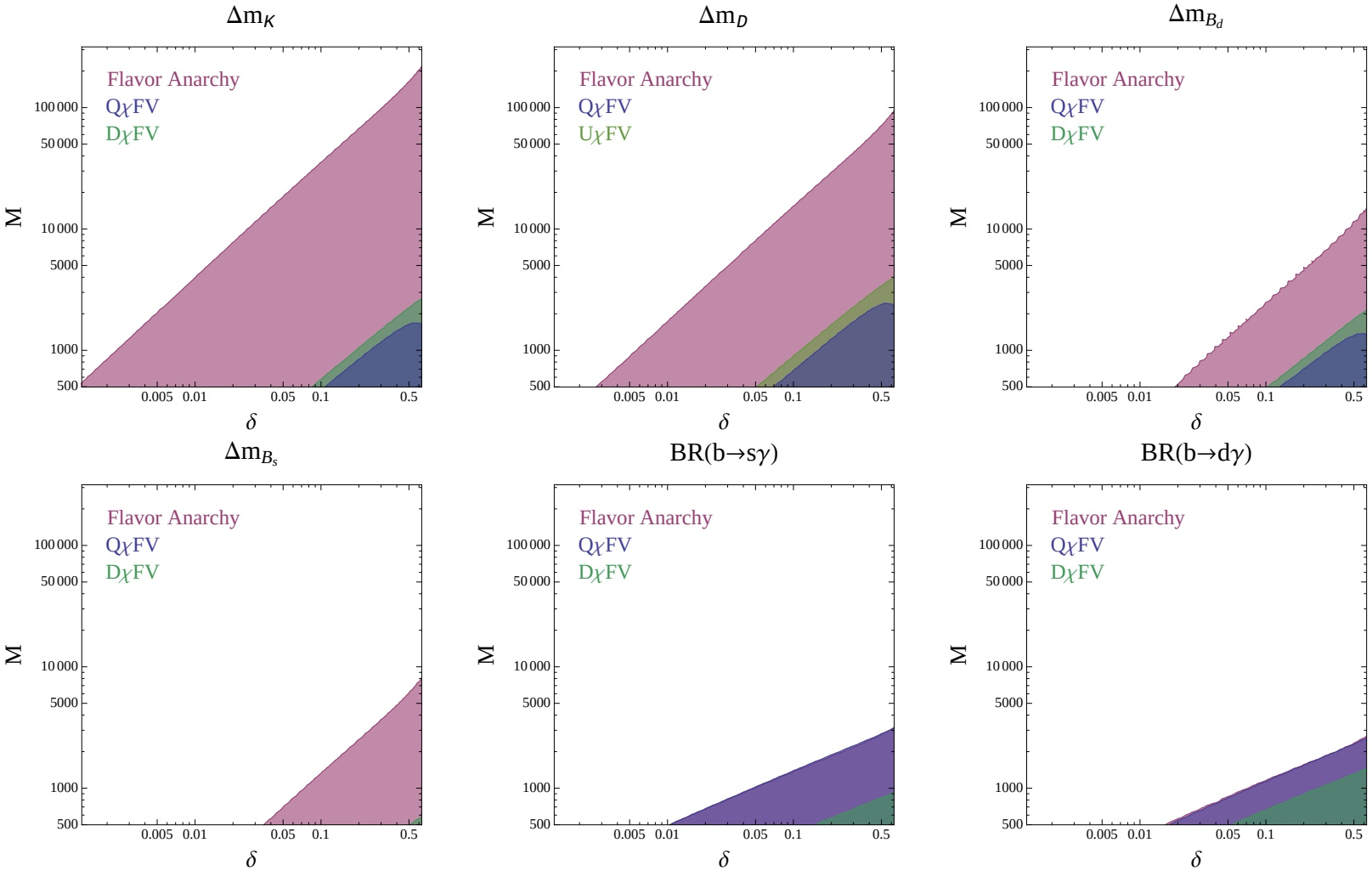
Type I Q-class and U-class Constraints

χFV Texture

Q-class EGMSB mass matrix has FV in LL and select LR/RL elements



Why is Δm_K so weak??? (Compared to Flavor Anarchy)

Several factors work in the same direction: $\frac{\Delta m_K(\text{Anarchy})}{\Delta m_K(\chi\text{FV})} \sim$

χFV: Contributes to O_V^{LL} ONLY

$$O_V^{LL} = (\bar{s}\gamma^\mu P_L d)^2$$

Anarchy: All wilson operators

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Work together to make Δm_X constraints weak!

Future Constraints / Discovery

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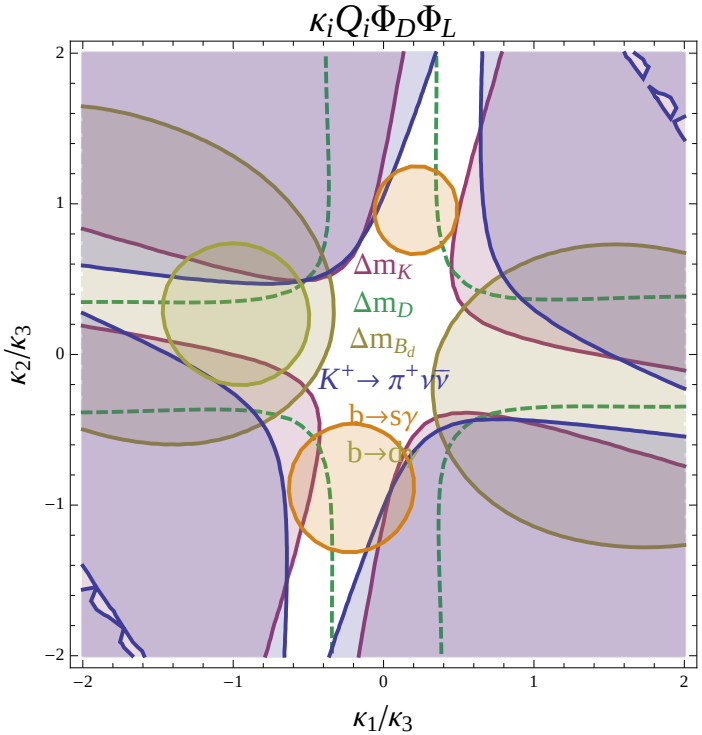

Observable	Improvement	Projected
Δm_K	Theory	10%
Δm_{B_d}	Theory	$\sim$10%
Δm_{B_s}	Theory	5%
Δm_D	None	–
$Br(K^+ \to \pi^+ \nu\bar{\nu})$	Experiment	10%
$Br(B \to X_s \gamma)$	Experiment	7%
$Br(B \to X_d \gamma)$	Experiment	24%
$Br(B_s \to \mu^+ \mu^-)$	Experiment	15%
$Br(B_d \to \mu^+ \mu^-)$	Experiment	$\sim$35%

Flavor in Type II models

Especially UH_u and QH_u

Turning on small κ_1, κ_2 makes these models encounter tachyons:

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(Note: flavor is fine in narrow window of validity)

Types of models

Tuning & Flavor

	Type I			Type II	
	Higgs	Q-class	U-class	w/ mixing	w/o mixing
	$\lambda H_u \Phi \tilde{\Phi}$	$\lambda Q \Phi \tilde{\Phi}$	$\lambda U \Phi \tilde{\Phi}$	$\lambda H_u Q \Phi_U$	$\lambda U E \Phi_{\bar{D}}$
Tuning:	BAD	GOOD	GOOD	GOOD	BAD
Flavor:	MFV	OKAY	OKAY	TACHYONS	DON'T CARE!

Summary & Future Directions

- We examined tuning in EGMSB models that get $m_h = 125$ GeV
- Wrote FormFlavor to investigate flavor in this non-MFV model
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Future directions

- We only focused on flavor observables, we want to look at CP as well
- The χFV texture deserves further study on its own (like MFV)
- We plan to make FormFlavor public
- Collider phenomenology is very interesting, especially in the FV case
  – Complete model for Flavored Naturalness (Blanke, Giudice, Paradisi, Perez, Zupan)