Partially Composite Supersymmetry

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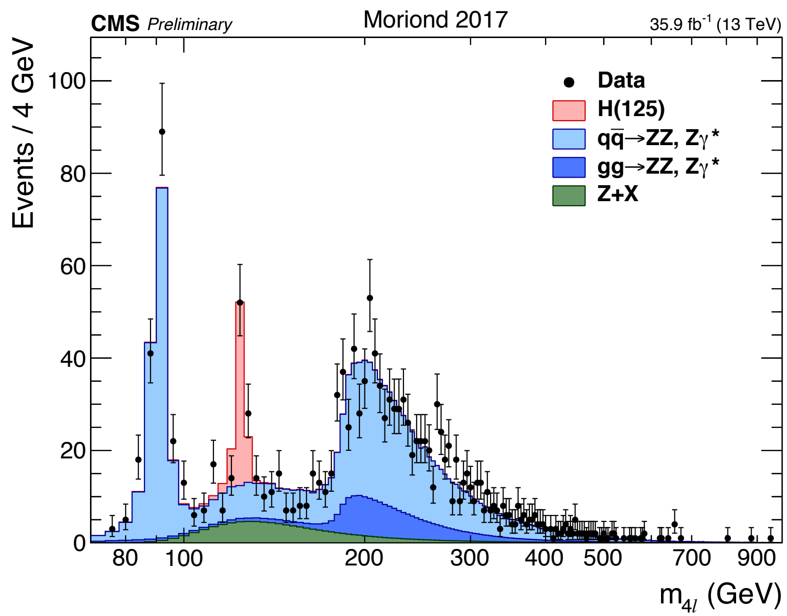
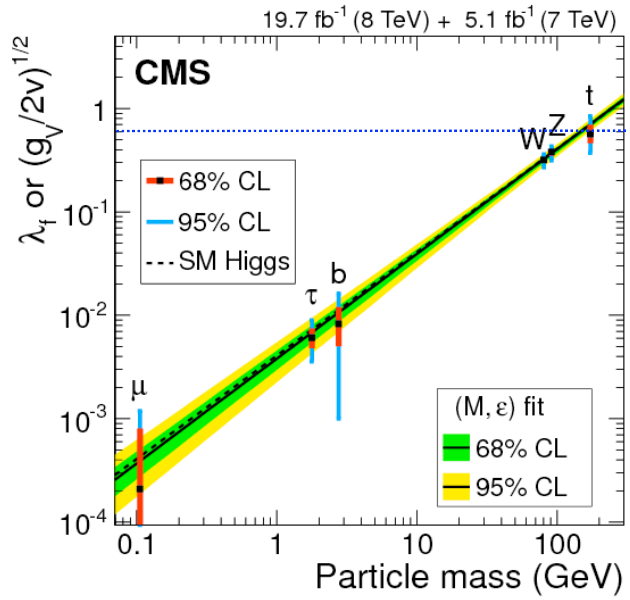
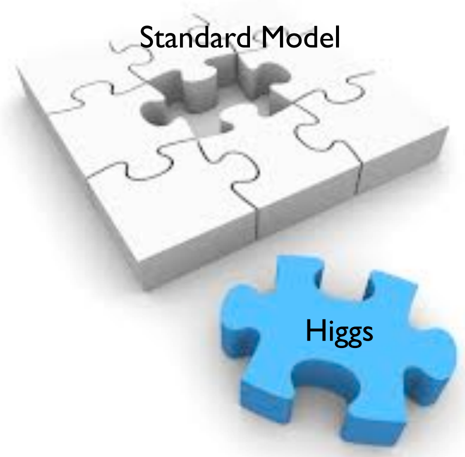
[Yusuf Buyukdag, TG, Andrew Miller: 1811.12388]

Higgs discovery - LHC Run I







Higgs potential: $V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4$

$$v^2 = \frac{\mu_h^2}{\lambda_h} \simeq (246\ \mathrm{GeV})^2 \qquad m_h^2 = 2\lambda_h v^2 \simeq (125\,\mathrm{GeV})^2$$

$$\boxed{\mu_h^2 \simeq (89\ \mathrm{GeV})^2} \qquad \boxed{\lambda_h \simeq 0.13}$$

"Completes" the Standard Model

However, SM is ***not*** a complete theory of Nature!

Questions:

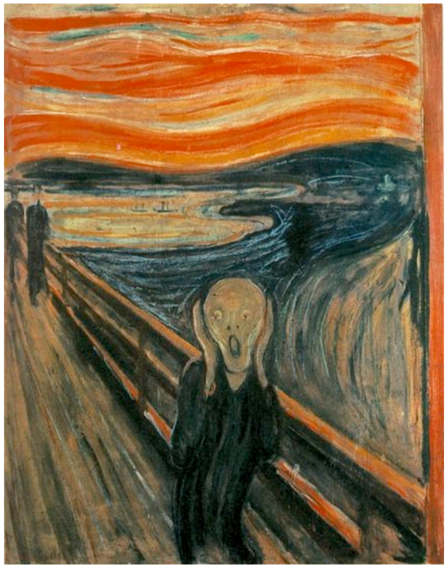
- Planck/weak scale hierarchy? $(m_h \ll M_p)$
- Fermion mass hierarchy? Neutrino masses?
- GUTS? 3 fermion generations?
- Dark matter?
- Baryon asymmetry?
- Strong CP problem?
- Inflaton? Cosmological constant?
- UV completion of gravity?

Clearly requires new physics...beyond the Standard Model

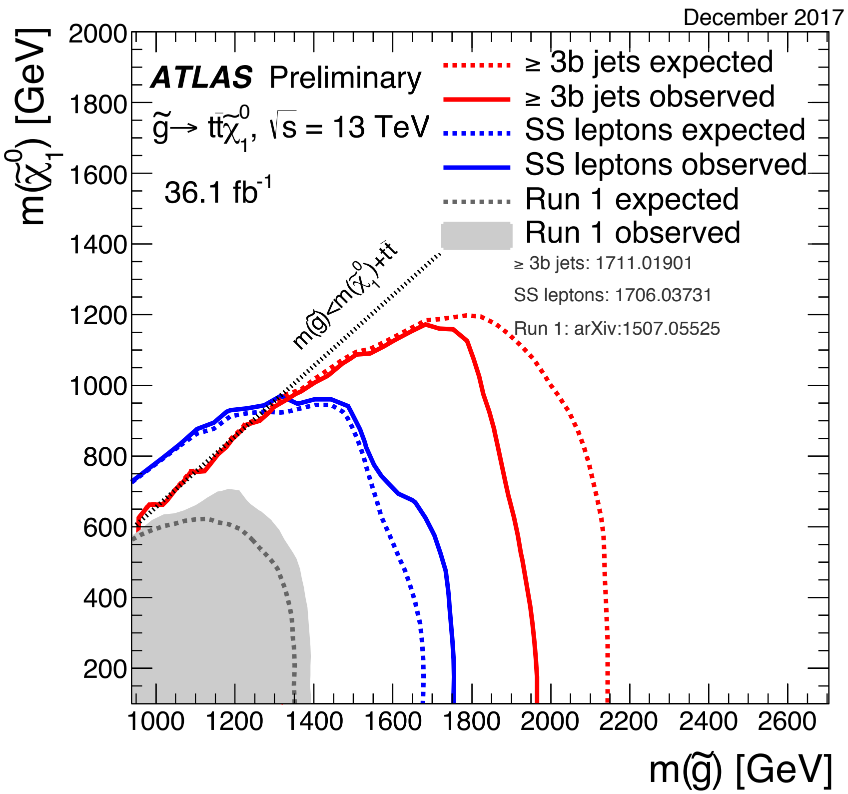
SUPERSYMMETRY provides a complete theoretical framework for Beyond the Standard Model

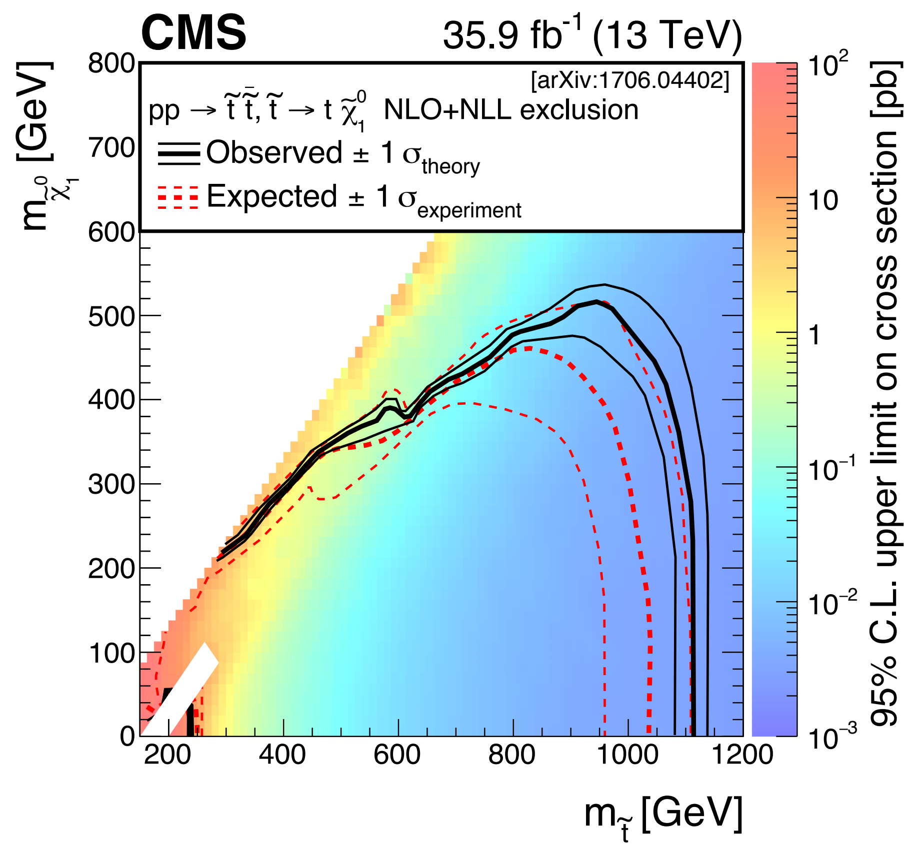
- Stabilizes Planck/weak scale hierarchy
- Dark matter
- Gauge coupling unification
- Low-energy limit of string theory

BUT where are the superpartners?!?



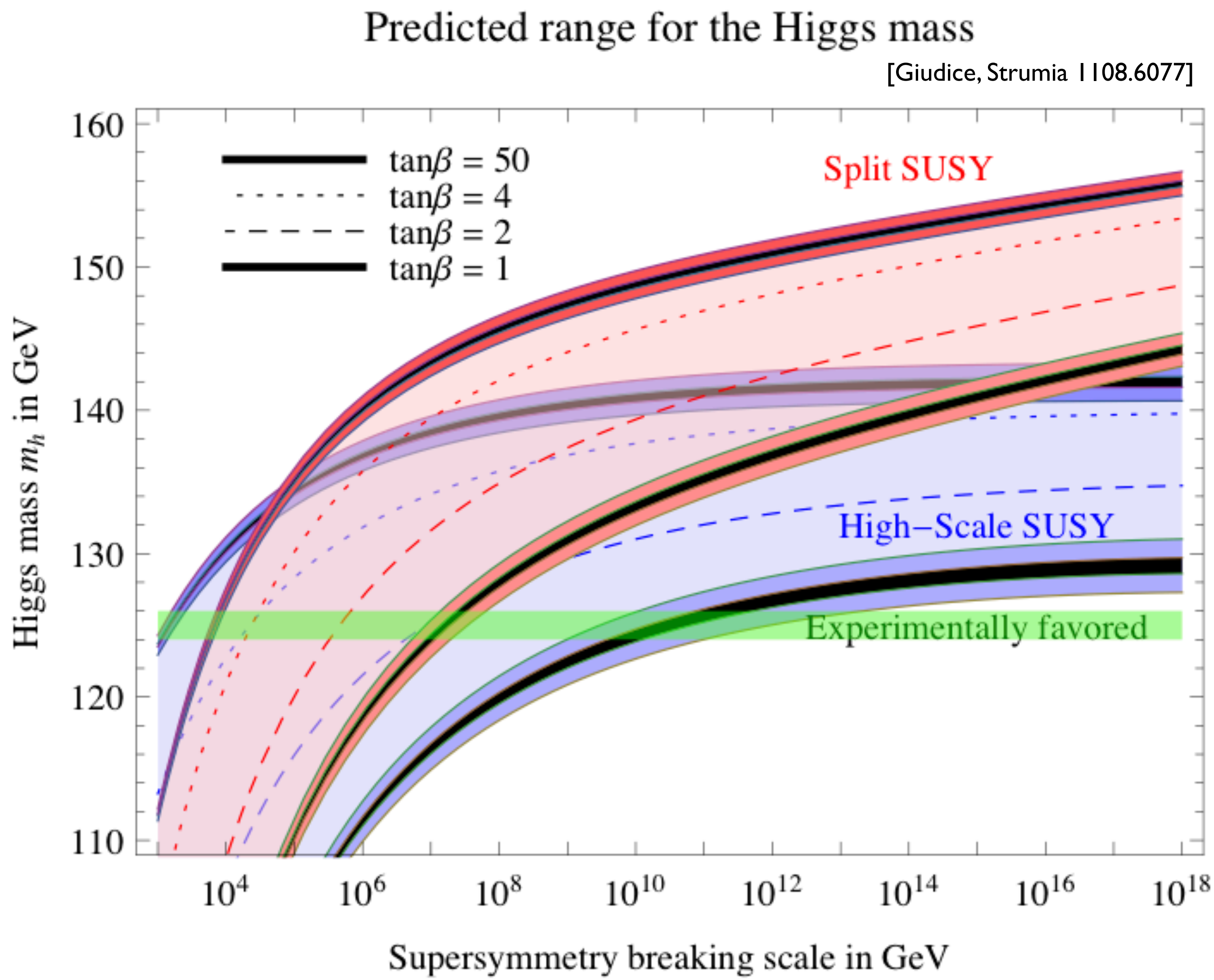
LHC Run 2 limits:





$$m_{\tilde{g}} \gtrsim 1970 \text{ GeV}$$

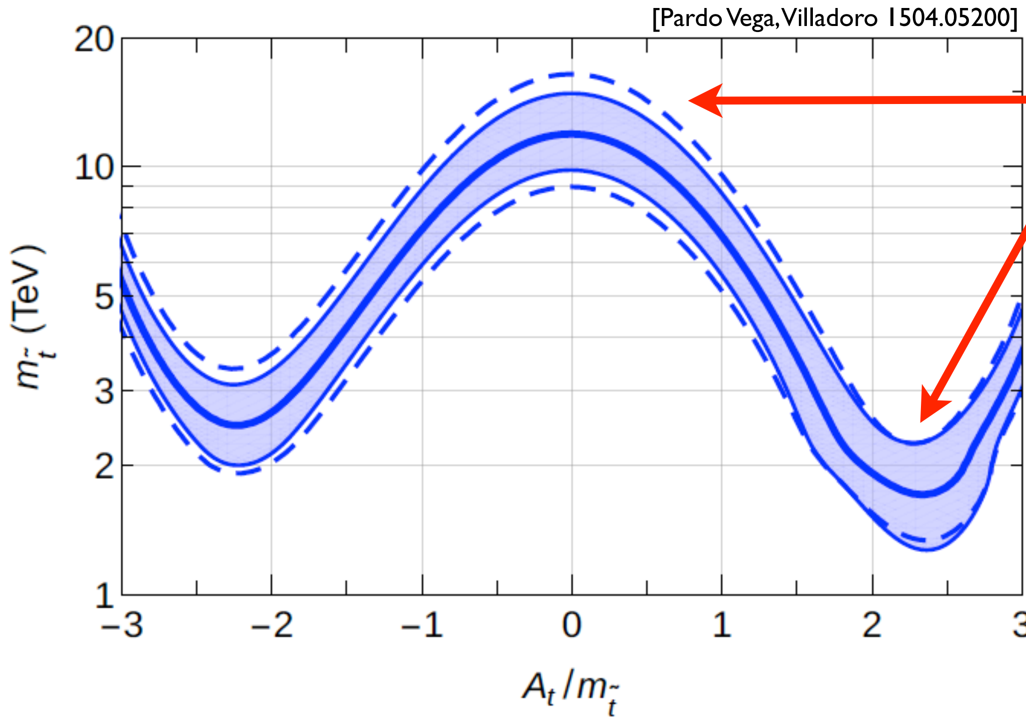
$$m_{\tilde{t}} \gtrsim 1120 \,\text{GeV}$$



SUSY breaking scale $\lesssim 10^7$ GeV

Minimal SUSY

- Higgs mass



Requires ~10 TeV stop masses or large A-terms

- Supersymmetric flavor problem

e.g. K-K mixing: $$\frac{\delta\tilde{m}^2_{ds}}{(10\ \mathrm{TeV})^2} \lesssim 10^{-2}\frac{(F/M)^3}{(10\ \mathrm{TeV})^3}$$

Requires heavy sfermions $\tilde{m}_{1,2} \gtrsim 100\ \mathrm{TeV}$

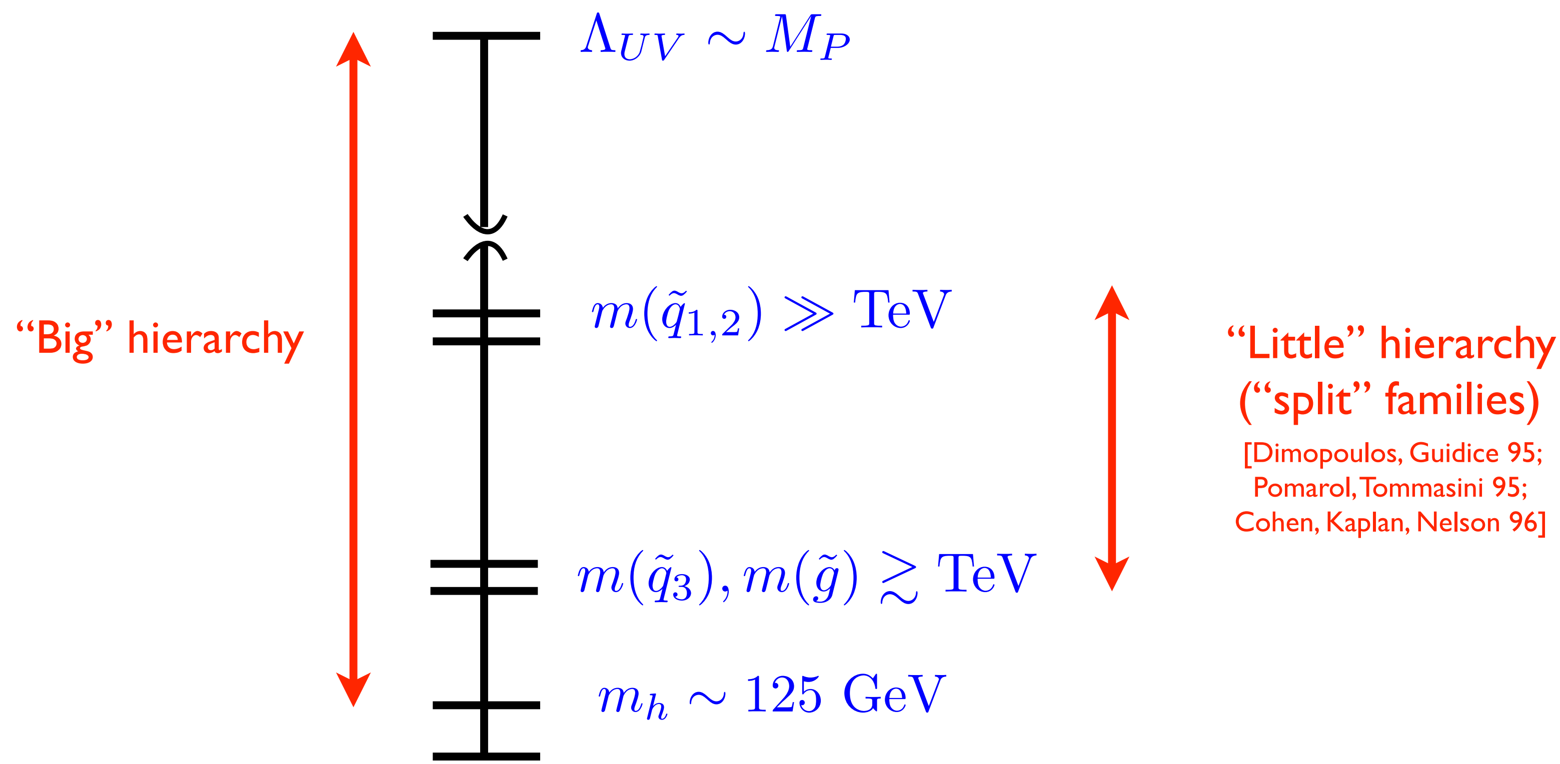
- Fermion masses

Yukawa coupling hierarchy not explained

A possible SUSY scenario:

(i) weakly-coupled Higgs (~125 GeV)

(ii) $m(\tilde{q}_{1,2}) \gg m(\tilde{g}), m(\tilde{q}_3)$ SUSY breaking is ***flavour dependent***!



Can ***sfermion*** mass hierarchy be related to
fermion mass hierarchy? *Yes!*

Partial Compositeness [Kaplan 91]

SM gauge field, Higgs and matter

$$A_\mu, H, \Psi_i$$

$$\mathcal{L}_{mix} = \lambda_{L,R} \Psi_{L,R} \mathcal{O}_\Psi + g_V A^\mu J_\mu$$

strongly-coupled sector

$$\mathcal{O}_i$$

relative admixture controlled by dim $\mathcal{O}_i$

$$|\psi\rangle \sim a_e |\text{elementary}\rangle + a_c |\text{composite}\rangle$$

elementary Higgs couples to elementary component

New strong dynamics breaks supersymmetry

Cases:

$a_e \gg a_c \longrightarrow \dim(\Psi \mathcal{O}_\psi) > 4$ "irrelevant" mixing

$a_e \ll a_c \longrightarrow \dim(\Psi \mathcal{O}_\psi) < 4$ "relevant" mixing

[Similar to $\gamma - \rho$ mixing which explains $\rho \to \mathrm{e}^+\mathrm{e}^-$ in QCD!]

Example: Fermion mixing

$$\mathcal{L}_\psi = i\psi^\dagger \bar\sigma^\mu \partial_\mu \psi - \frac{1}{\Lambda_{\rm UV}^{\delta-1}}\left(\psi \mathcal{O}_\psi^c + h.c.\right)$$

anomalous dimension

$$(\dim\, \mathcal{O}_\psi^c = \frac{3}{2} + \delta)$$

$\Lambda_{IR} \ll \Lambda_{UV}$

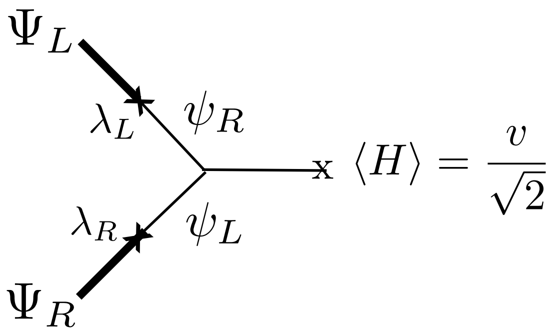
$$\mathcal{L}_\psi = i\psi^\dagger \bar\sigma^\mu \partial_\mu \psi + i\psi^{\dagger(1)} \bar\sigma^\mu \partial_\mu \psi^{(1)} + i\psi^{\dagger c(1)} \bar\sigma^\mu \partial_\mu \psi^{c(1)}$$
$$- \underbrace{\varepsilon_\psi}_{\text{Depends on } \delta} \Lambda_{\rm IR}\left(\psi\psi^{c(1)} + h.c.\right) - \underbrace{m_\psi^{(1)}}_{= g_\psi^{(1)}\Lambda_{\rm IR}}\left(\psi^{(1)}\psi^{c(1)} + h.c.\right)$$

mass mixing!

$$|\psi_0\rangle \simeq \mathcal{N}_\psi \left\{ |\psi\rangle - \frac{\varepsilon_\psi}{g_\psi^{(1)}}|\psi^{(1)}\rangle \right\}$$

Mass eigenstate is partially composite!

Explains the fermion mass hierarchy [TG, Pomarol 00]



$$m_f \sim \lambda_L \lambda_R v$$

where $\lambda_{L,R} \sim \left(\frac{\Lambda_{\mathrm{IR}}}{\Lambda_{\mathrm{UV}}}\right)^{\dim\mathcal{O}_{L,R}-\frac{5}{2}}$

- Light fermions are mostly composite!

⇨ $\frac{3}{2} \leq \dim\,\mathcal{O}_{L,R} < \frac{5}{2}$ (or $0 \leq \delta_{L,R} < 1$) $\left(\dim\,\mathcal{O}_{L,R} = \frac{3}{2} + \delta_{L,R}\right)$

- Top quark is elementary

⇨ $\dim\,\mathcal{O}_{L.R} > \frac{5}{2}$ (or $\delta_{L,R} > 1$)

Supersymmetry breaking

Assume strong sector breaks supersymmetry: $\mathcal{X} = \theta\theta F_X$

Gaugino:

linear supermultiplet $D^2\mathcal{J} = D^{\dagger 2}\mathcal{J} = 0$

$$\mathcal{L}_V = \left(\frac{1}{4}\left[W^\alpha W_\alpha\right]_F + h.c.\right) + 2\tilde{\varepsilon}_V \left[V\mathcal{J}\right]_D$$

$$\Rightarrow \quad |\lambda_0\rangle \simeq \mathcal{N}_V \left\{ |\lambda\rangle - \frac{1}{g_V^{(1)}\sqrt{2\zeta_V \log\left(\frac{\Lambda_{\rm UV}}{\Lambda_{\rm IR}}\right)}} |\lambda^{(1)}\rangle \right\} \quad \longleftarrow \text{partially composite gaugino}$$

SUSY breaking mass: $$\frac{\xi_3}{2}\frac{g_V^{(1)2}}{\Lambda_{\rm IR}}\left(\left[\mathcal{X} W^{\alpha(1)} W_\alpha^{(1)}\right]_F + h.c.\right)$$

$$\Rightarrow \quad M_\lambda \simeq \underbrace{g^2}_{\text{4D gauge coupling}} \xi_3 \frac{F_{\mathcal{X}}}{\Lambda_{\rm IR}}$$

Sfermion:

$$\mathcal{L}_\Phi = \left[\Phi^\dagger\Phi\right]_D + \frac{1}{\Lambda_{\rm UV}^{\delta-1}}\left(\left[\Phi\mathcal{O}^c\right]_F + h.c.\right) \qquad (\dim\, \mathcal{O}^c = 1+\delta)$$

$$\Rightarrow \quad |\phi_0\rangle \simeq \mathcal{N}_\Phi \left\{ |\phi\rangle - \frac{1}{g_\Phi^{(1)}\sqrt{\zeta_\Phi}}\sqrt{\frac{\delta-1}{\left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{2(1-\delta)}-1}}\,|\phi^{(1)}\rangle \right\}$$

partially composite sfermion

SUSY breaking: $\xi_4\frac{g_\Phi^{(1)2}}{\Lambda_{\rm IR}^2}\left[\mathcal{X}^\dagger\mathcal{X}\Phi^{(1)\dagger}\Phi^{(1)}\right]_D = \xi_4 g_\Phi^{(1)2}\frac{|F_\mathcal{X}|^2}{\Lambda_{\rm IR}^2}\phi^{(1)\dagger}\phi^{(1)}$

$$\Rightarrow \quad \widetilde{m}^2 \simeq \begin{cases} \frac{(\delta-1)}{\zeta_\Phi}\left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{2(\delta-1)}\xi_4\frac{|F_\mathcal{X}|^2}{\Lambda_{\rm IR}^2} & \delta\geq 1 \\ \frac{(1-\delta)}{\zeta_\Phi}\xi_4\frac{|F_\mathcal{X}|^2}{\Lambda_{\rm IR}^2} & 0\leq\delta<1 \end{cases}$$

Hierarchical sfermion masses!

However for sufficiently large δ $\qquad \delta\widetilde{m}^2 \simeq \frac{g_i^2}{16\pi^2}M_{\lambda_i}^2$ $\qquad$ i.e. radiative corrections dominate

Critical value $(\delta\widetilde{m}^2 \simeq \widetilde{m}^2)$ $\qquad \delta^* \simeq 1 + \frac{\log\left(\frac{4\pi}{g_i}\log\left(\frac{\Lambda_{\rm UV}}{\Lambda_{\rm IR}}\right)\right)}{\log\left(\frac{\Lambda_{\rm UV}}{\Lambda_{\rm IR}}\right)}$

Gravitino mass:

$$-\frac{1}{4}\frac{W}{M_P^2}\,\psi_\rho\,[\sigma^\mu,\bar{\sigma}^\rho]\,\psi_\mu + h.c.$$

W = constant superpotential

$$\Rightarrow \quad m_{3/2} \simeq \xi_3 \frac{F_\chi}{\sqrt{3}M_P}$$

where $|F_\chi|^2 \frac{N}{16\pi^2} \simeq 3\frac{|W|^2}{M_P^2}$

Higgsino mass:

[Kim, Nilles 84]

$$W_{KN} = \frac{\kappa_\mu}{2M_P} S^2 H_u H_d \quad \Rightarrow \quad \mu \simeq \frac{\kappa_\mu f^2}{2M_P}$$

where $\langle S \rangle \sim f$

Sfermion mass hierarchy:

$m_e \ll v$ ⇨ "relevant" mixing $(0 < \delta_e < 1)$ → "composite" electron

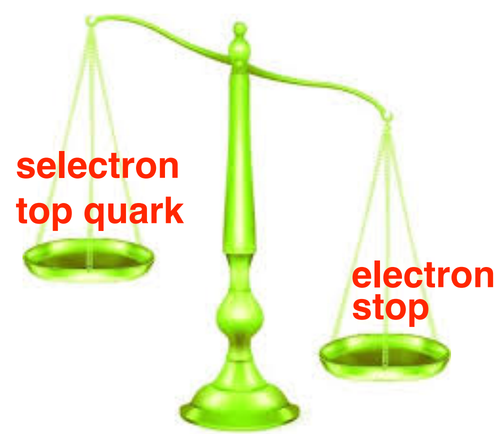
$m_t \sim v$ ⇨ "irrelevant" mixing $(\delta_t > 1)$ → "elementary" top quark

Yukawa couplings at IR scale: $$\frac{y_e}{y_t} \simeq \frac{1-\delta_e}{\delta_t - 1}\left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{2(1-\delta_e)}$$

Partial compositeness explains Yukawa coupling hierarchy!

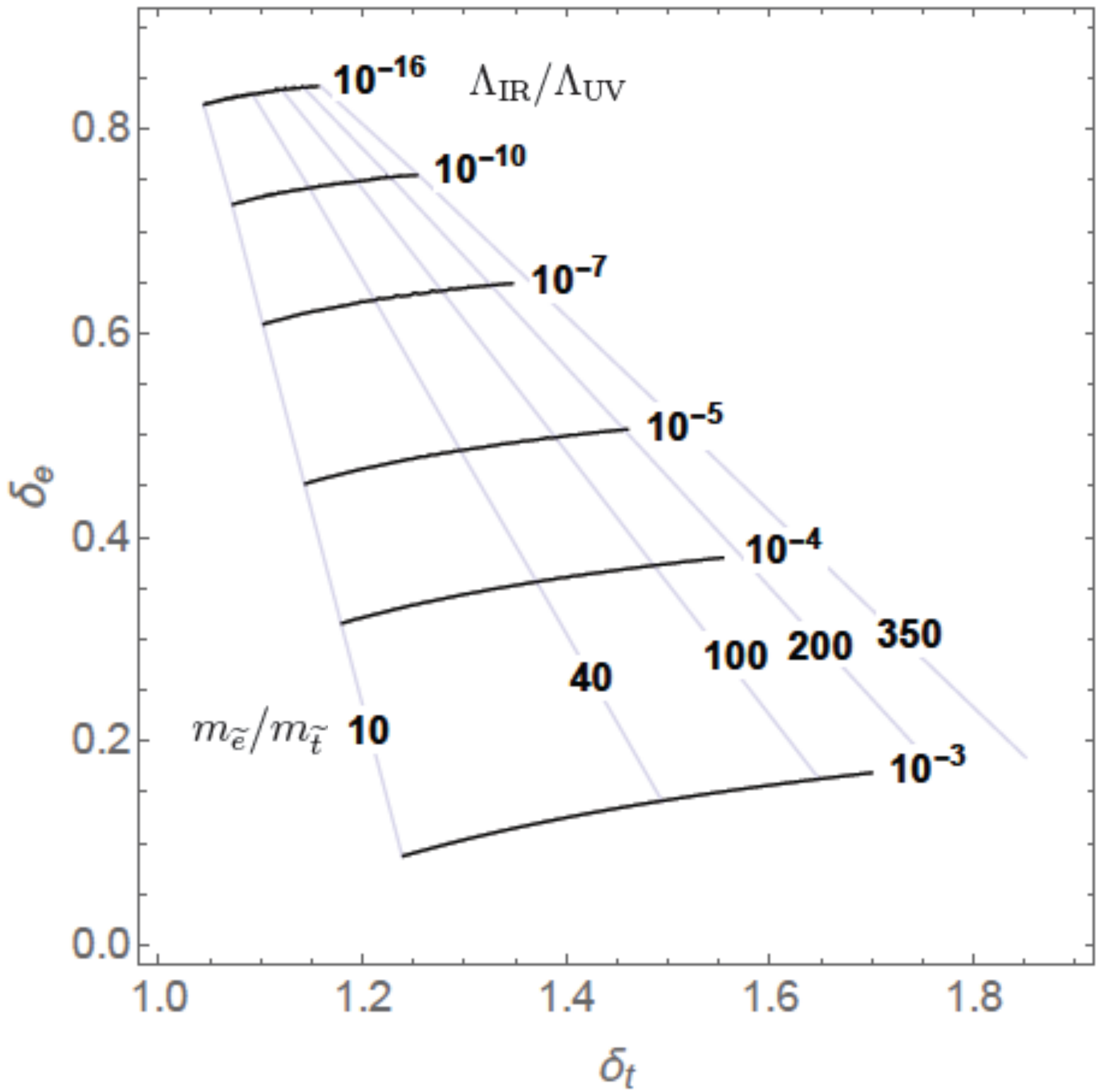
⇨ $$\frac{m^2_{\tilde e}}{m^2_{\tilde t}} = \begin{cases} \frac{1-\delta_e}{\delta_t-1}\left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{2(1-\delta_t)} & \delta_t < \delta_t^* \,, \\ \frac{4\pi}{\alpha_3}(1-\delta_e)\log^2\left(\frac{\Lambda_{\rm UV}}{\Lambda_{\rm IR}}\right) & \delta_t \geq \delta_t^* \end{cases}$$

Partial compositeness predicts ***inverted*** sfermion mass hierarchy!



Anomalous dimension contours

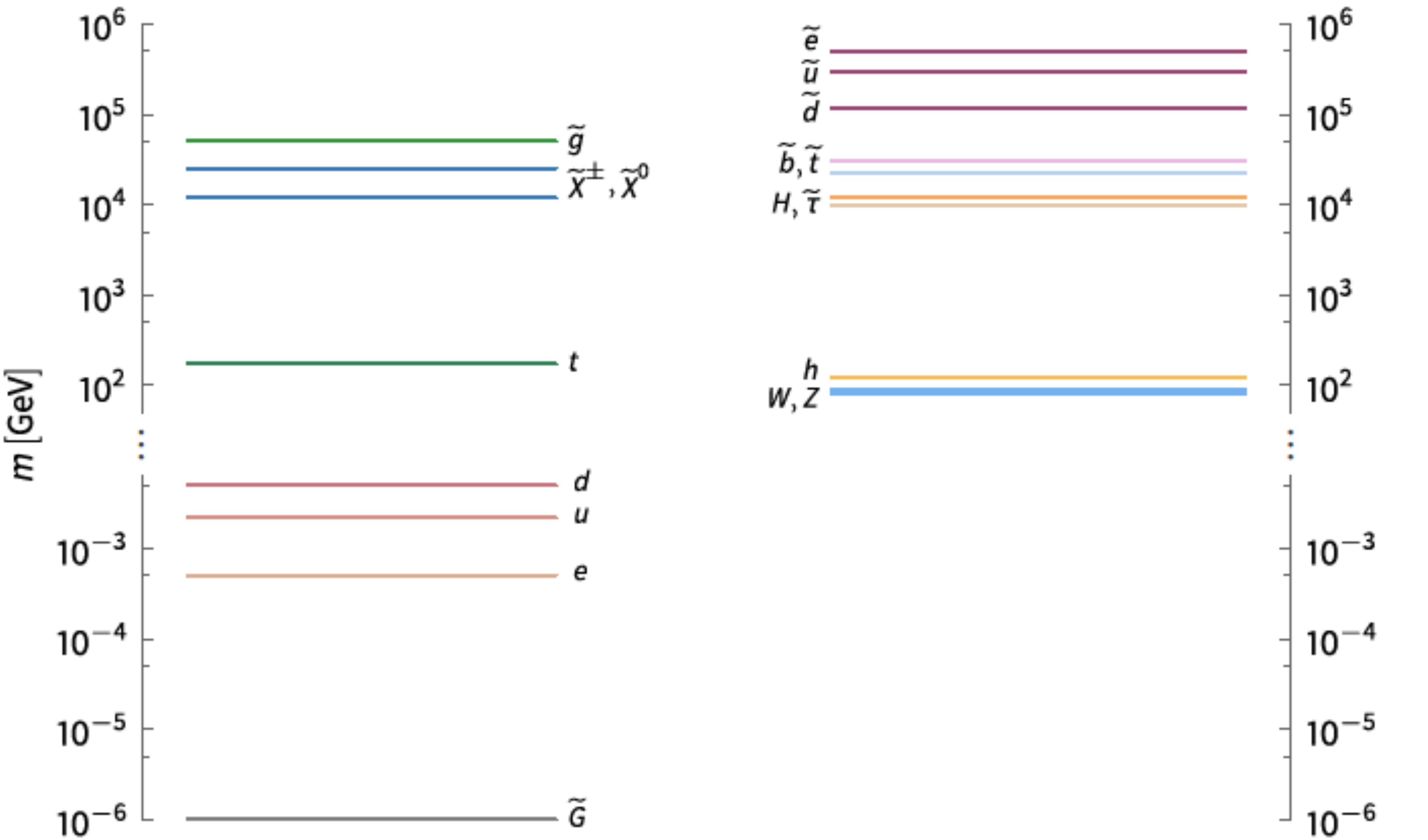
[Buyukdag, TG, Miller: 1812.12388]



$$\Lambda_{\rm UV} = 10^{18}\ {\rm GeV},\ \ \tan\beta = 3$$

$$M_{\rm SUSY} = 50\ {\rm TeV}$$

Partially Composite Spectrum [Buyukdag, TG, Miller: 1811.12388]



Fermions **Bosons**

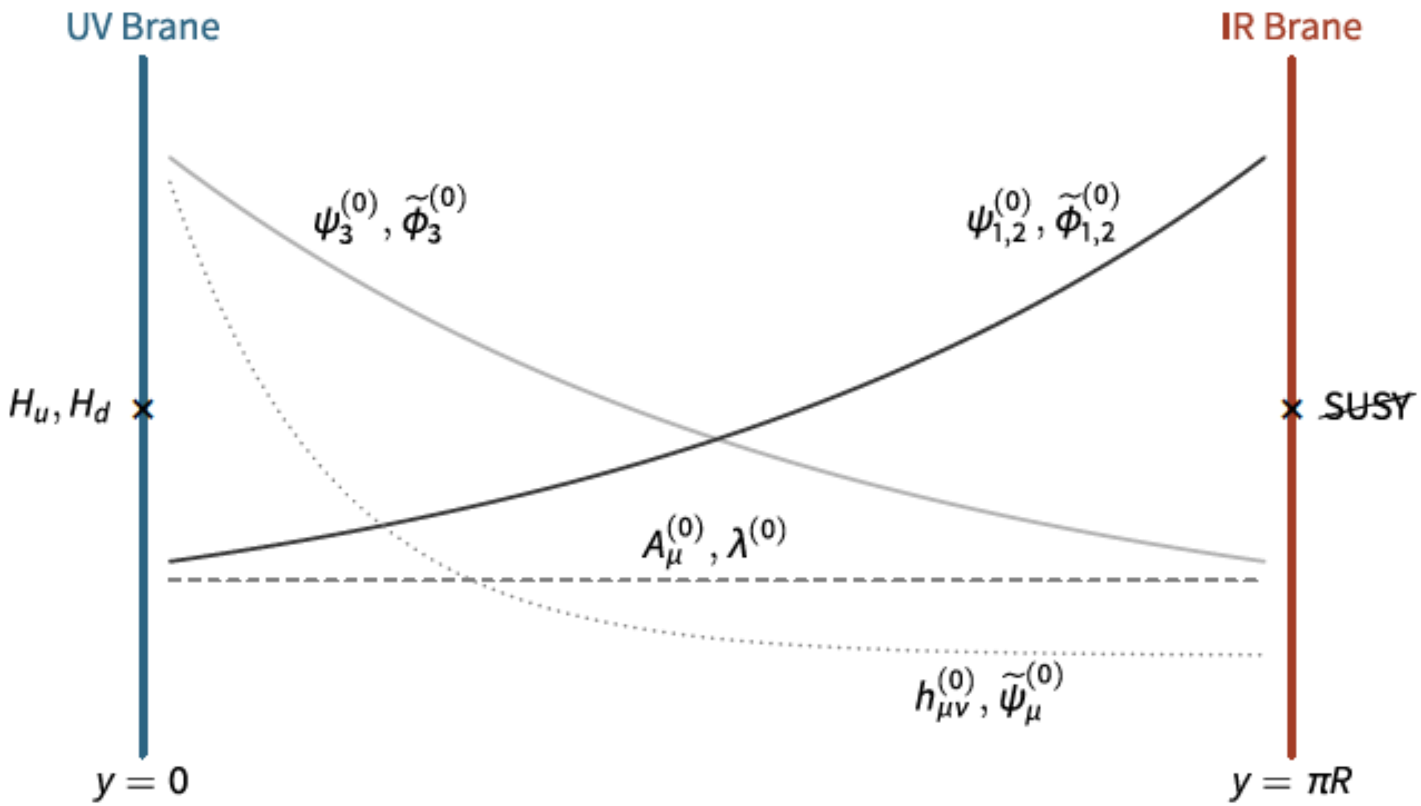
AdS/CFT

Partial Compositeness ⟺ 5D Localization in a slice of AdS

5D Model:

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}\, dx^\mu\, dx^\nu + dy^2 \equiv g_{MN}\, dx^M\, dx^N$$

(k = AdS curvature)



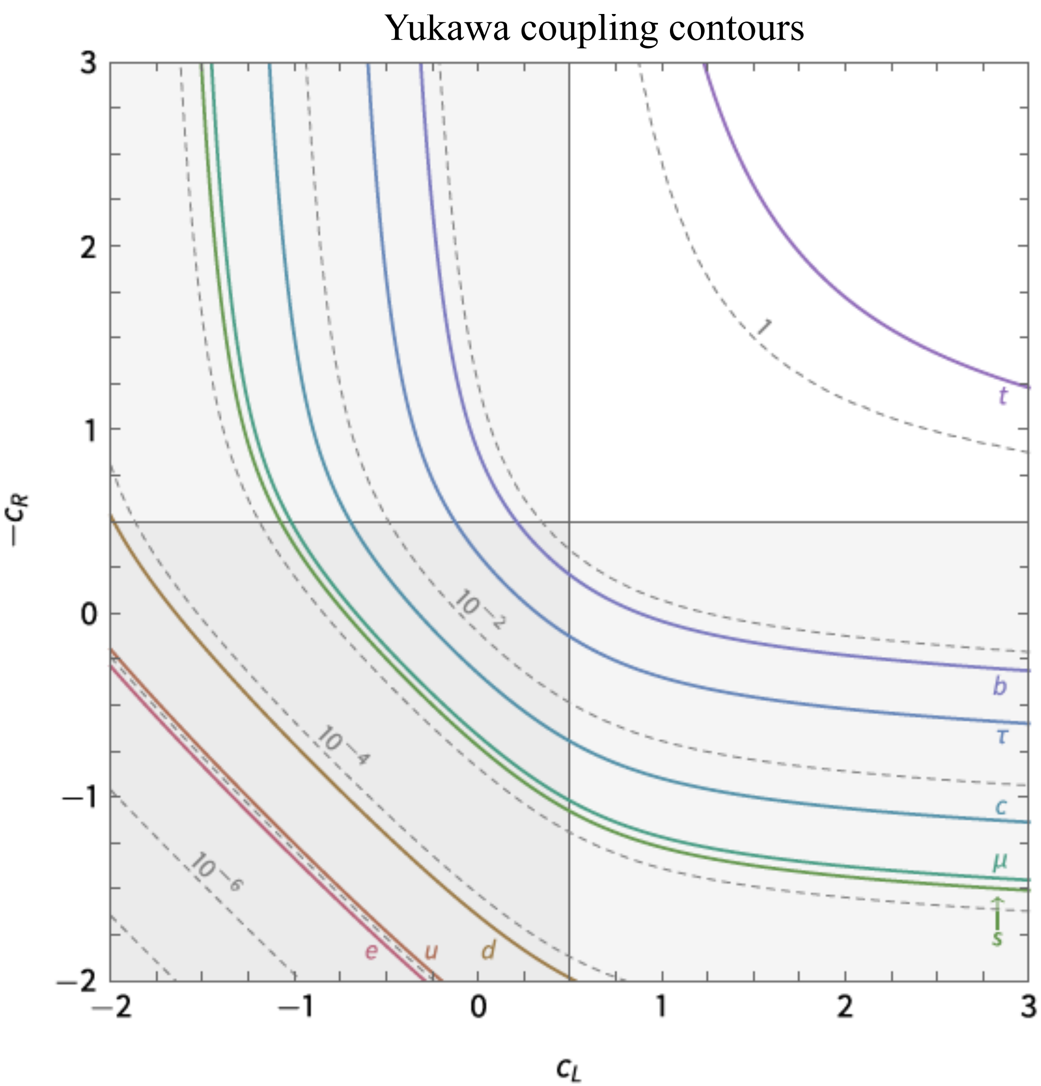
Fermion mass hierarchy:

UV brane localized Higgs

$$S_5 = \int d^5x \sqrt{-g}\, Y_{ij}^{(5)} \left[\bar{\Psi}_{iL}(x^\mu, y)\, \Psi_{jR}(x^\mu, y) + h.c.\right] H\underbrace{(x^\mu)\,\delta(y)} \equiv \int d^4x \left[y_{ij}\, \bar{\psi}_{iL}^{(0)}(x^\mu)\, \psi_{jR}^{(0)}(x^\mu)\, H(x^\mu) + h.c + \cdots \right]$$

$$\Rightarrow \quad y_{ij} = Y_{ij}^{(5)} \tilde{f}_{iL}^{(0)}(0)\, \tilde{f}_{jR}^{(0)}(0) = Y_{ij}^{(5)} k \sqrt{\frac{\frac{1}{2} - c_{iL}}{e^{2(\frac{1}{2} - c_{iL})\pi k R} - 1}} \sqrt{\frac{\frac{1}{2} + c_{jR}}{e^{2(\frac{1}{2} + c_{jR})\pi k R} - 1}}$$

cL,cR = bulk mass parameters



$$\Lambda_{\mathrm{IR}} = 2 \times 10^{16}\ \mathrm{GeV}$$
$$\tan\beta = 3$$
$$Y_{ij}^{(5)} k = 1$$

Supersymmetry breaking

IR brane spurion superfield: $X = \theta\theta F_X$ $\Rightarrow$ SUSY breaking scale: $F = F_X e^{-2\pi kR}$

Gaugino masses:

$X = \text{singlet}$

$$\int d^5x \sqrt{-g} \int d^2\theta \left[\frac{1}{2} \frac{X}{\Lambda_{\rm UV} k} W^{\alpha a} W^a_\alpha + h.c. \right] \delta(y - \pi R)$$

$$\Rightarrow \quad M_\lambda \simeq \frac{g_5^2 k}{2\pi k R} \frac{F}{\Lambda_{\rm IR}} = \underbrace{g^2}_{\text{4D gauge coupling}} \frac{F}{\Lambda_{\rm IR}}$$

$X = \text{non singlet}$

$$\int d^5x \sqrt{-g} \int d^2\theta \left[\frac{1}{2} \frac{X^\dagger X}{\Lambda_{\rm UV}^3 k} W^{\alpha a} W^a_\alpha + h.c. \right] \delta(y - \pi R)$$

$$\Rightarrow \quad M_\lambda \simeq \frac{g_5^2 k}{2\pi k R} \frac{F^2}{\Lambda_{\rm IR}^3} = g^2 \frac{F^2}{\Lambda_{\rm IR}^3}$$

$\longleftarrow$ Extra suppression $\frac{F}{\Lambda_{\rm IR}^2}$

Gravitino mass:

$$\int d^5x \sqrt{-g} \left[\frac{1}{4} \frac{W}{M_5^3} \psi_\mu \left[\sigma^\mu, \bar{\sigma}^\nu\right] \psi_\nu + h.c. \right] \delta(y)$$

$$\Rightarrow \quad m_{3/2} \simeq \frac{F}{\sqrt{3} M_P}$$

where $|F|^2 \simeq 3 \frac{|W|^2}{M_P^2}$ for vanishing cosmological constant

Sfermion masses:

$$\int d^5x \sqrt{-g} \int d^4\theta \, \frac{X^\dagger X}{\Lambda_{UV}^2 k} \Phi^\dagger \Phi \, \delta(y - \pi R)$$

$$\Rightarrow \quad m_{\phi_{L,R}}^{\text{tree}} \simeq \begin{cases} (\pm c - \frac{1}{2})^{1/2} \frac{F}{\Lambda_{\text{IR}}} e^{(\frac{1}{2} \mp c)\pi k R} & \pm c > \frac{1}{2} \\ (\frac{1}{2} \mp c)^{1/2} \frac{F}{\Lambda_{\text{IR}}} & \pm c < \frac{1}{2} \end{cases}$$

Flavor-dependent masses

Matches partial composite result using AdS/CFT dictionary: $\delta_i = |c_i \pm \frac{1}{2}|$

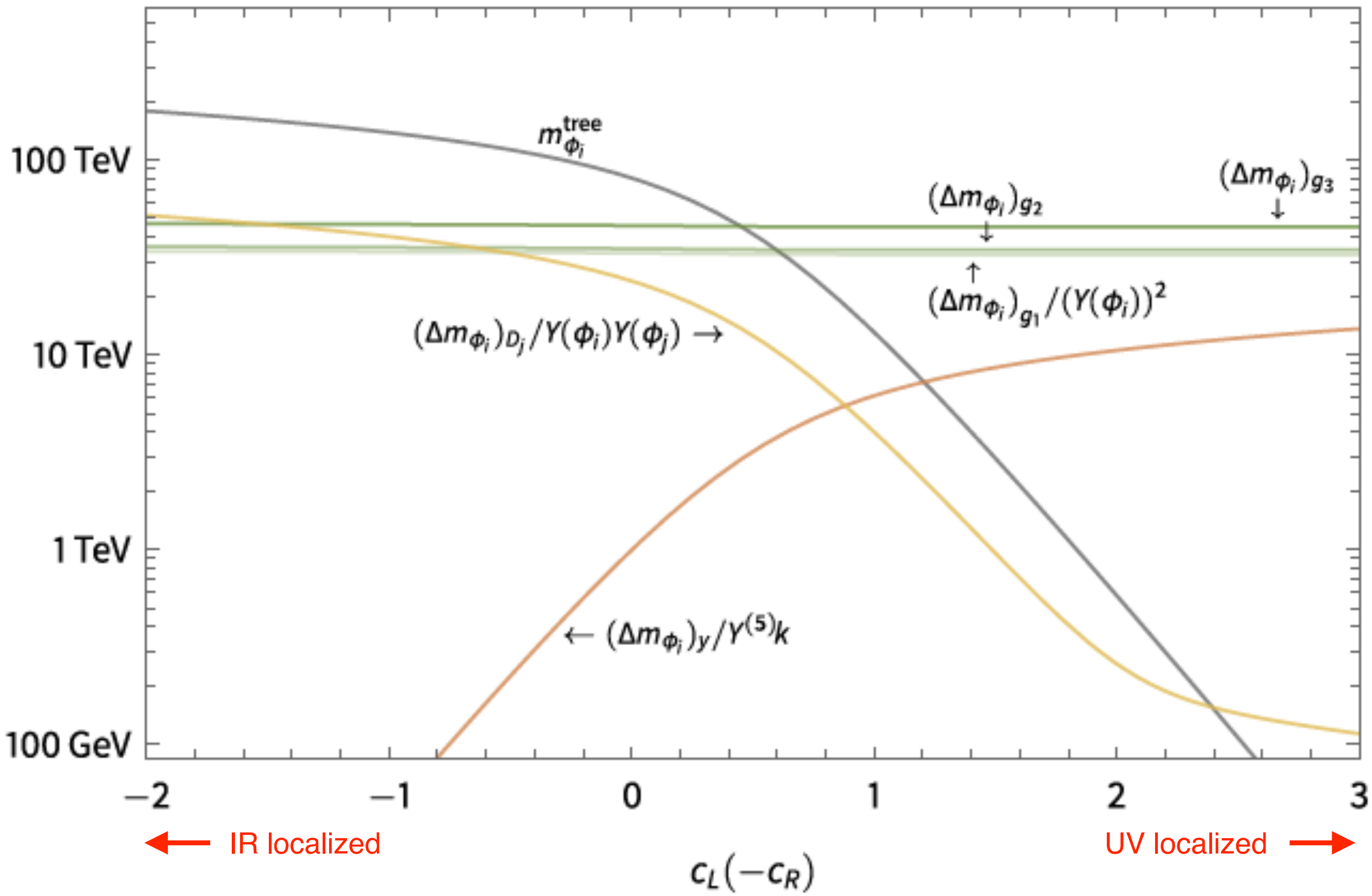
Sfermion radiative corrections

$$16\pi^2(\Delta m^2_{\widetilde{Q}_i})_{\text{1-loop}} = \frac{32}{3} r^{\widetilde{Q}_i}_{g_3} g_3^2 M_3^2 + 6\, r^{\widetilde{Q}_i}_{g_2} g_2^2 M_2^2 + \frac{2}{15} r^{\widetilde{Q}_i}_{g_1} g_1^2 M_1^2$$
$$- 2\, r^{\widetilde{Q}_i}_{y_{u_i}} y^2_{u_i} m^2_{\widetilde{u}_i} - 2\, r^{\widetilde{Q}_i}_{y_{d_i}} y^2_{d_i} m^2_{\widetilde{d}_i} - \frac{1}{5} g_1^2 \Delta_S\,,$$
$$16\pi^2(\Delta m^2_{\widetilde{u}_i})_{\text{1-loop}} = \frac{32}{3} r^{\widetilde{u}_i}_{g_3} g_3^2 M_3^2 + \frac{32}{15} r^{\widetilde{u}_i}_{g_1} g_1^2 M_1^2 - 4\, r^{\widetilde{u}_i}_{y_{u_i}} y^2_{u_i} m^2_{\widetilde{Q}_i} + \frac{4}{5} g_1^2 \Delta_S\,,$$
$$16\pi^2(\Delta m^2_{\widetilde{d}_i})_{\text{1-loop}} = \frac{32}{3} r^{\widetilde{d}_i}_{g_3} g_3^2 M_3^2 + \frac{8}{15} r^{\widetilde{d}_i}_{g_1} g_1^2 M_1^2 - 4\, r^{\widetilde{d}_i}_{y_{d_i}} y^2_{d_i} m^2_{\widetilde{Q}_i} - \frac{2}{5} g_1^2 \Delta_S\,,$$
$$16\pi^2(\Delta m^2_{\widetilde{L}_i})_{\text{1-loop}} = 6\, r^{\widetilde{L}_i}_{g_2} g_2^2 M_2^2 + \frac{6}{5} r^{\widetilde{L}_i}_{g_1} g_1^2 M_1^2 - r^{\widetilde{L}_i}_{y_{e_i}} y^2_{e_i} m^2_{\widetilde{e}_i} + \frac{3}{5} g_1^2 \Delta_S\,,$$
$$16\pi^2(\Delta m^2_{\widetilde{e}_i})_{\text{1-loop}} = \frac{24}{5} r^{\widetilde{e}_i}_{g_1} g_1^2 M_1^2 - 4\, r^{\widetilde{e}_i}_{y_{e_i}} y^2_{e_i} m^2_{\widetilde{L}_i} - \frac{6}{5} g_1^2 \Delta_S\,,$$

where $\Delta_S = \sum_i Y(\phi_i)\, r^D_{\phi_i}\, m^2_{\phi_i} = \mathrm{Tr}\left[r^D_{\widetilde{Q}_i} m^2_{\widetilde{Q}_i} - 2\, r^D_{\widetilde{u}_i} m^2_{\widetilde{u}_i} + r^D_{\widetilde{d}_i} m^2_{\widetilde{d}_i} - r^D_{\widetilde{L}_i} m^2_{\widetilde{L}_i} + r^D_{\widetilde{e}_i} m^2_{\widetilde{e}_i} \right]$

One-loop sfermion radiative corrections

[Buyukdag, TG, Miller: 1811.12388]



$\Lambda_{\text{IR}} = 2\times 10^{16}$ GeV,

$\sqrt{F} = 4.75\times 10^{10}$ GeV

$\tan\beta = 3$.

UV localized sfermions dominated by radiative corrections

Soft trilinear couplings (a-terms)

a-terms generated at one-loop (since Higgs is UV localized):

$$
\begin{aligned}
16\pi^2 a_{u_i} &= -y_{u_i}\left(\frac{32}{3}(r^a_{\lambda_3})_{Q_i u_i}\, g_3^2 M_3 + 6\,(r^a_{\lambda_2})_{Q_i}\, g_2^2\, M_2\right.\\
&\qquad\qquad \left. + \left[-\frac{2}{5}(r^a_{\lambda_1})_{Q_i} + \frac{8}{5}(r^a_{\lambda_1})_{u_i} + \frac{8}{15}(r^a_{\lambda_1})_{Q_i u_i}\right] g_1^2 M_1\right)\,,\\
16\pi^2 a_{d_i} &= -y_{d_i}\left(\frac{32}{3}(r^a_{\lambda_3})_{Q_i d_i}\, g_3^2 M_3 + 3\,(r^a_{\lambda_2})_{Q_i}\, g_2^2 M_2\right.\\
&\qquad\qquad \left. + \left[\frac{2}{5}(r^a_{\lambda_1})_{Q_i} + \frac{4}{5}(r^a_{\lambda_1})_{d_i} - \frac{4}{15}(r^a_{\lambda_1})_{Q_i d_i}\right] g_1^2 M_1\right)\,,\\
16\pi^2 a_{e_i} &= -y_{e_i}\left(6\,(r^a_{\lambda_2})_{L_i}\, g_2^2 M_2 + \left[-\frac{6}{5}(r^a_{\lambda_1})_{L_i} + \frac{12}{5}(r^a_{\lambda_1})_{e_i} + \frac{12}{5}(r^a_{\lambda_1})_{L_i e_i}\right] g_1^2 M_1\right)\,,
\end{aligned}
$$

Higgs sector: Soft terms generated at one-loop (since Higgs is UV localized)

$$16\pi^2 m_{H_u}^2 = 6\, r_{g_2}^H g_2^2 M_2^2 + \frac{6}{5} r_{g_1}^H g_1^2 M_1^2 - 6\,\mathrm{Tr}\left[r_{y_{u_i}}^H y_{u_i}^2 \left(m_{\widetilde{Q}_i}^2 + m_{\widetilde{u}_i}^2 \right) \right] - \frac{3}{5} g_1^2 \Delta_S \,,$$

$$\begin{aligned} 16\pi^2 m_{H_d}^2 = {} & 6\, r_{g_2}^H g_2^2 M_2^2 + \frac{6}{5} r_{g_1}^H g_1^2 M_1^2 - 6\,\mathrm{Tr}\left[r_{y_{d_i}}^H y_{d_i}^2 \left(m_{\widetilde{Q}_i}^2 + m_{\widetilde{d}_i}^2 \right) \right] \\ & - 2\,\mathrm{Tr}\left[r_{y_{e_i}}^H y_{e_i}^2 \left(m_{\widetilde{L}_i}^2 + m_{\widetilde{e}_i}^2 \right) \right] + \frac{3}{5} g_1^2 \Delta_S \,, \end{aligned}$$

$$16\pi^2 b = -\mu \left(6\, r_{\lambda_1}^b g_2^2 M_2 + \frac{6}{5} r_{\lambda_2}^b g_1^2 M_1 \right) \,,$$

EWSB:

$$m_{H_u}^2 + |\mu|^2 - b\cot\beta - \frac{1}{8}(g_1^2 + g_2^2) v^2 \cos 2\beta = 0$$

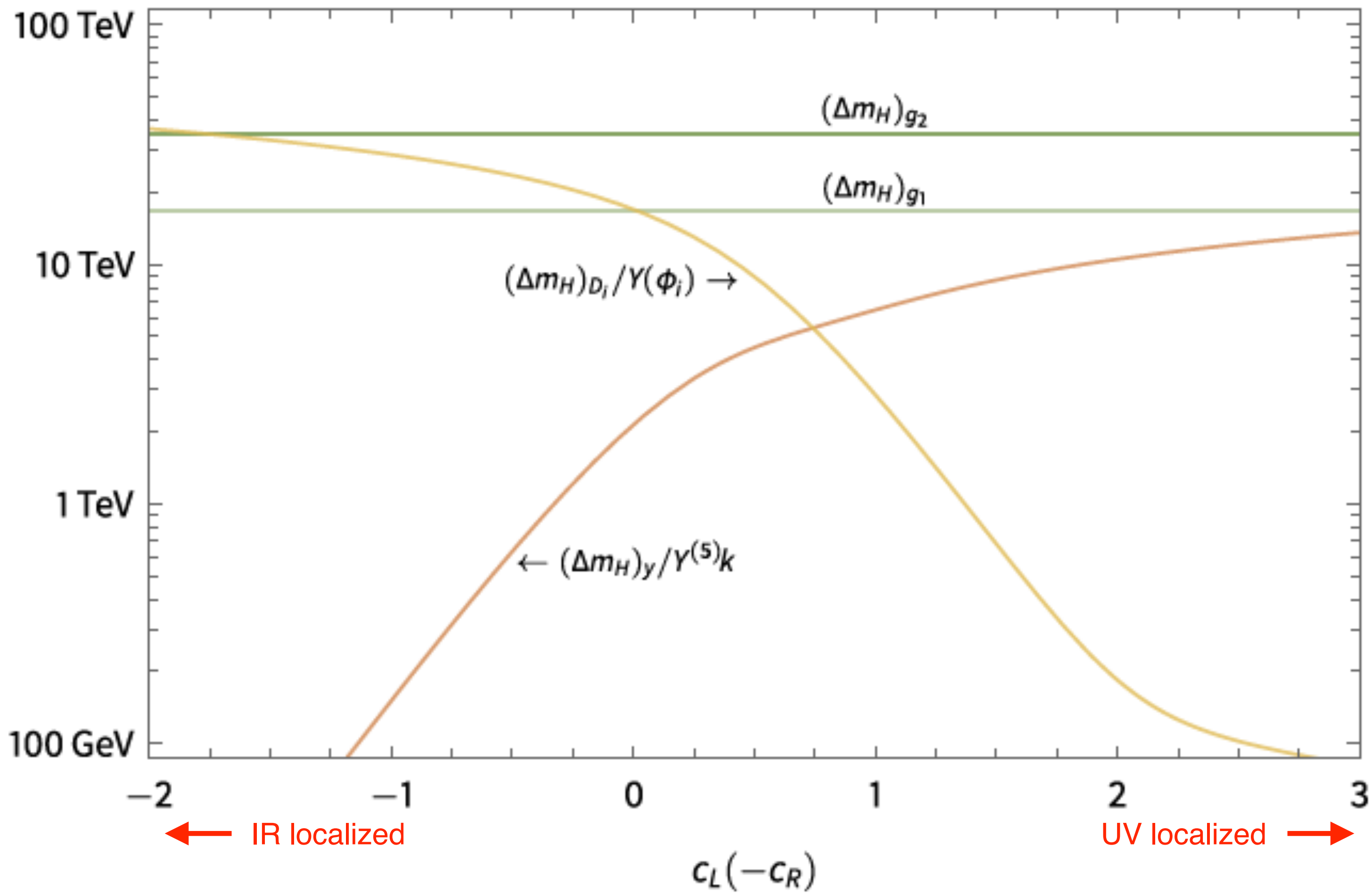
$$m_{H_d}^2 + |\mu|^2 - b\tan\beta + \frac{1}{8}(g_1^2 + g_2^2) v^2 \cos 2\beta = 0$$

$$\tan\beta \simeq \frac{(m_{H_d}^2 - m_{H_u}^2) + \sqrt{(m_{H_d}^2 - m_{H_u}^2)^2 + 4b^2}}{2b} + \mathcal{O}\left(\frac{v^2}{b}\right) \,,$$

$$|\mu|^2 \simeq \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} + \mathcal{O}(v^2) \,,$$

One-loop Higgs soft mass radiative corrections

[Buyukdag, TG, Miller: 1811.12388]

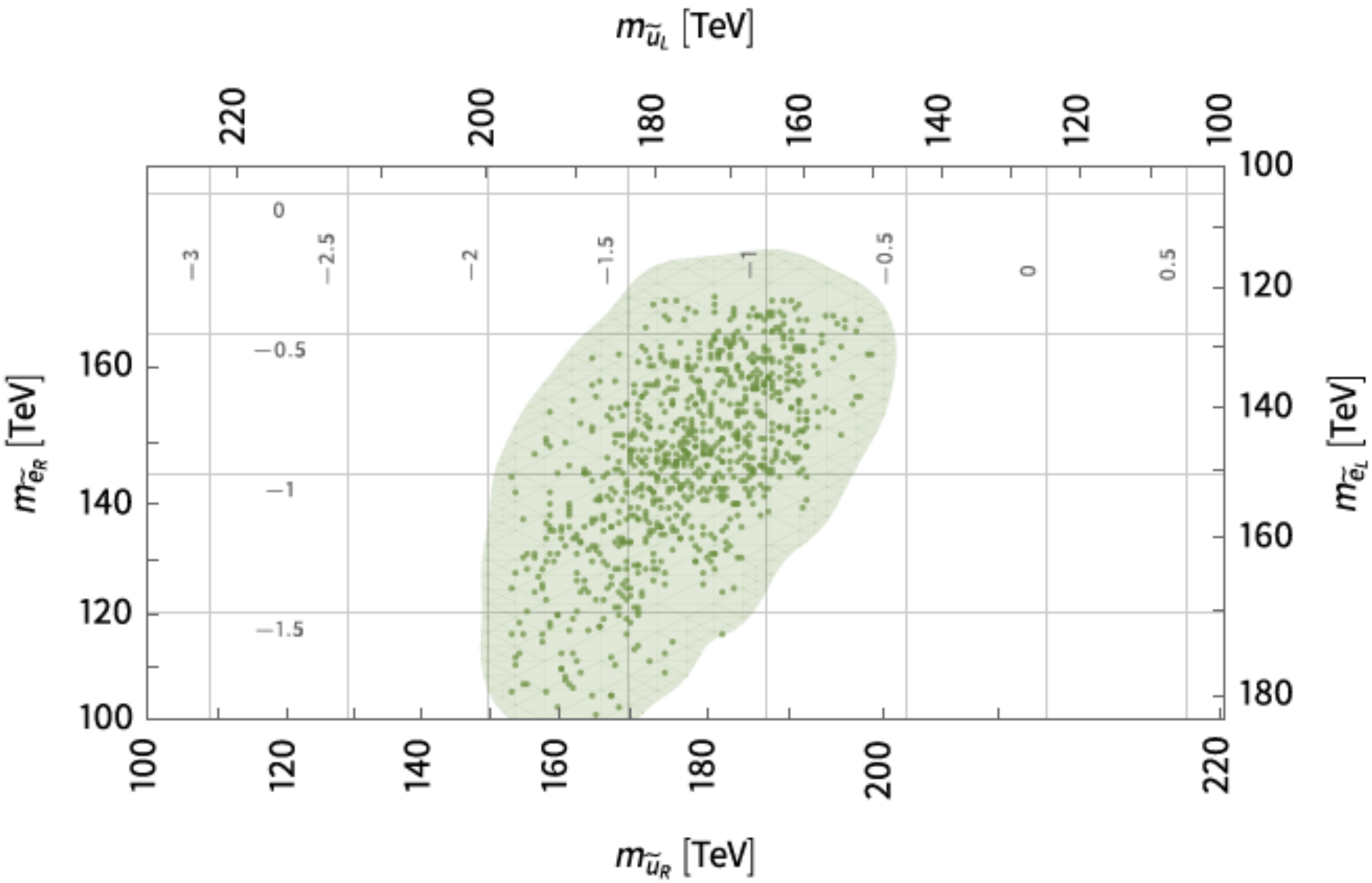


$\Lambda_{\rm IR} = 2\times 10^{16}$ GeV,

$\sqrt{F} = 4.75\times 10^{10}$ GeV

$\tan\beta = 3.$

D-term contributions ➡ Requires mild correlation between heaviest sfermions



Phenomenological constraints

- Higgs mass $m_h \simeq 125\ \mathrm{GeV}$
- Supersymmetric flavor problem $\tilde{m}_{1,2} \gtrsim 100\ \mathrm{TeV}$
- Gauge coupling unification $|\mu| \sim M_\lambda \lesssim 100\ \mathrm{TeV}$
- Gravitino Dark Matter $m_{3/2} \gtrsim \mathcal{O}(1)\,\mathrm{keV}$
- Charge and color breaking minima $m^2_{\tilde{\phi}} > 0$

⇨ constrains $\sqrt{F}, \Lambda_{\mathrm{IR}}$

Charge and Color breaking minima

Sfermions can receive negative mass-squared corrections from:

- Weak hypercharge D-term

$$16\pi^2(\beta_{m^2_{\phi_i}})_{\text{1-loop}} \supset \frac{6}{5}g_1^2\, Y(\phi_i)\, \mathrm{Tr}\left[Y(\phi_j)\, m^2_{\phi_j}\right] \equiv \frac{6}{5}g_1^2\, Y(\phi_i)\, \mathcal{S}$$

where $\mathcal{S} = m^2_{H_u} - m^2_{H_d} + \mathrm{Tr}\left[\mathbf{m}^2_{\tilde{\mathbf{Q}}} - \mathbf{m}^2_{\tilde{\mathbf{L}}} - 2\mathbf{m}^2_{\tilde{\mathbf{u}}} + \mathbf{m}^2_{\tilde{\mathbf{d}}} + \mathbf{m}^2_{\tilde{\mathbf{e}}}\right]$

- Bulk D-term (and Yukawa couplings)

$$(\Delta m^2_{\phi_i})_D = \frac{3}{5}g_1^2 Y(\phi_i) \sum_j Y(\phi_j)\, (\Pi_D^{\phi_i})_{\phi_j} \;\equiv -\frac{1}{8\pi^2}\frac{3}{5}g_1^2 Y(\phi_i)\, \Delta_{\mathcal{S}}$$

where $\Delta_{\mathcal{S}} = \sum_i Y(\phi_i)\, r^D_{\phi_i}\, m^2_{\phi_i} = \mathrm{Tr}\left[r^D_{\tilde{Q}_i} m^2_{\tilde{Q}_i} - 2\, r^D_{\tilde{u}_i} m^2_{\tilde{u}_i} + r^D_{\tilde{d}_i} m^2_{\tilde{d}_i} - r^D_{\tilde{L}_i} m^2_{\tilde{L}_i} + r^D_{\tilde{e}_i} m^2_{\tilde{e}_i}\right]$

- 2-loop gauge boson [Arkani-Hamed, Murayama '97]

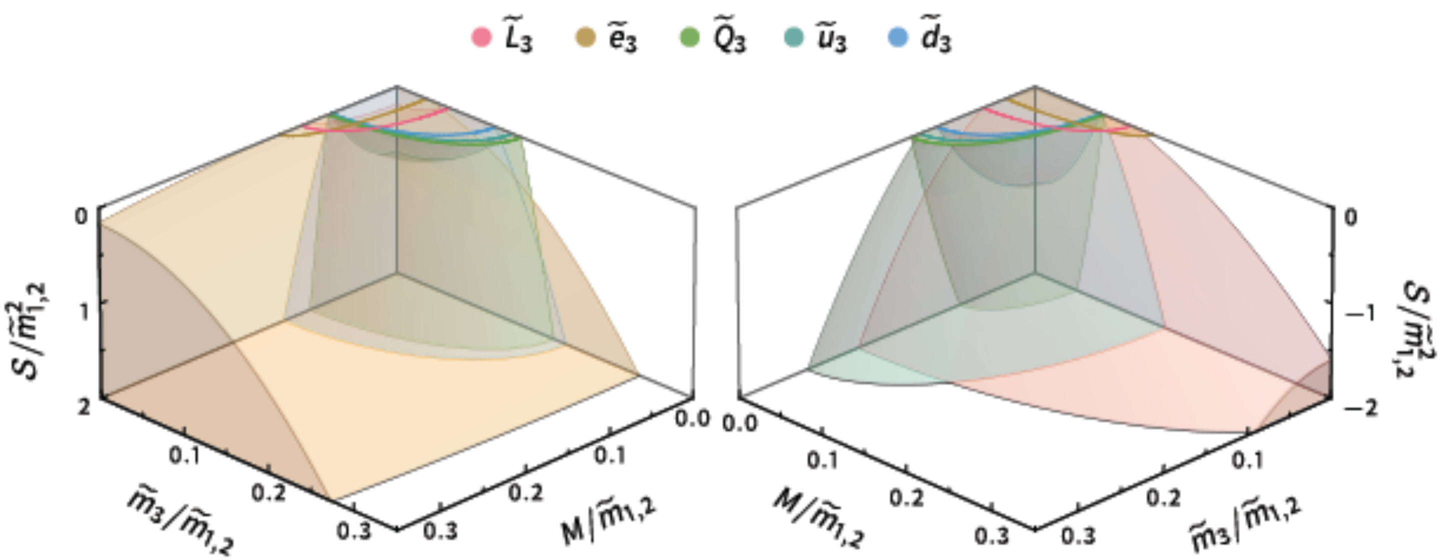
$$(16\pi^2)^2(\beta_{m^2_{\phi_i}})_{\text{2-loop}} \supset 4\sum_a g_a^4\, C_a(R_{\phi_i})\, \sigma_a\,;$$

where
$$\sigma_1 = \frac{1}{5}\left(3m^2_{H_u} + 3m^2_{H_d} + \mathrm{Tr}\left[\mathbf{m}^2_{\tilde{\mathbf{Q}}} + 3\mathbf{m}^2_{\tilde{\mathbf{L}}} + 8\mathbf{m}^2_{\tilde{\mathbf{u}}} + 2\mathbf{m}^2_{\tilde{\mathbf{d}}} + 6\mathbf{m}^2_{\tilde{\mathbf{e}}}\right]\right),$$
$$\sigma_2 = m^2_{H_u} + m^2_{H_d} + \mathrm{Tr}\left[3\mathbf{m}^2_{\tilde{\mathbf{Q}}} + \mathbf{m}^2_{\tilde{\mathbf{L}}}\right],$$
$$\sigma_3 = \mathrm{Tr}\left[2\mathbf{m}^2_{\tilde{\mathbf{Q}}} + \mathbf{m}^2_{\tilde{\mathbf{u}}} + \mathbf{m}^2_{\tilde{\mathbf{d}}}\right].$$

Tachyonic constraints

$$\frac{d}{dt}m^2_{\tilde{\phi}} = -\frac{2}{\pi}\sum_a \alpha_a C_a^\phi M_a^2 + \frac{2}{\pi^2}\sum_a \overbrace{\alpha_a^2 C_a^\phi \widetilde{m}^2_{1,2}}^{\text{two-loop}} + \frac{6}{5}\overbrace{Y_\phi \mathcal{S}}^{\text{D-term}}\,\frac{\alpha_1}{4\pi}$$

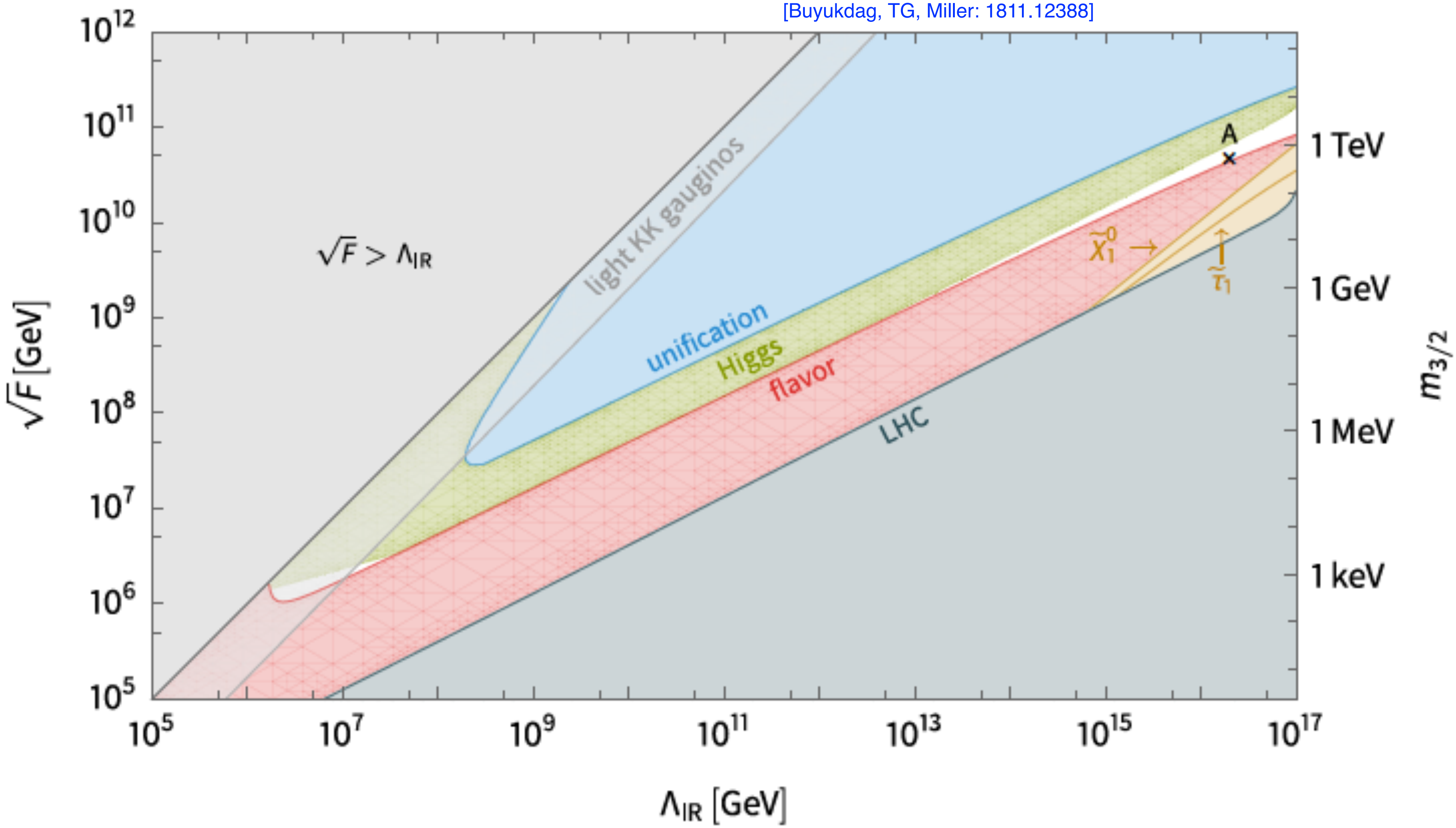
where $\mathcal{S} = m^2_{H_u} - m^2_{H_d} + \mathrm{Tr}\left[\mathbf{m^2_Q} - \mathbf{m^2_L} - 2\mathbf{m^2_u} + \mathbf{m^2_d} + \mathbf{m^2_e}\right]$



The shaded regions are excluded

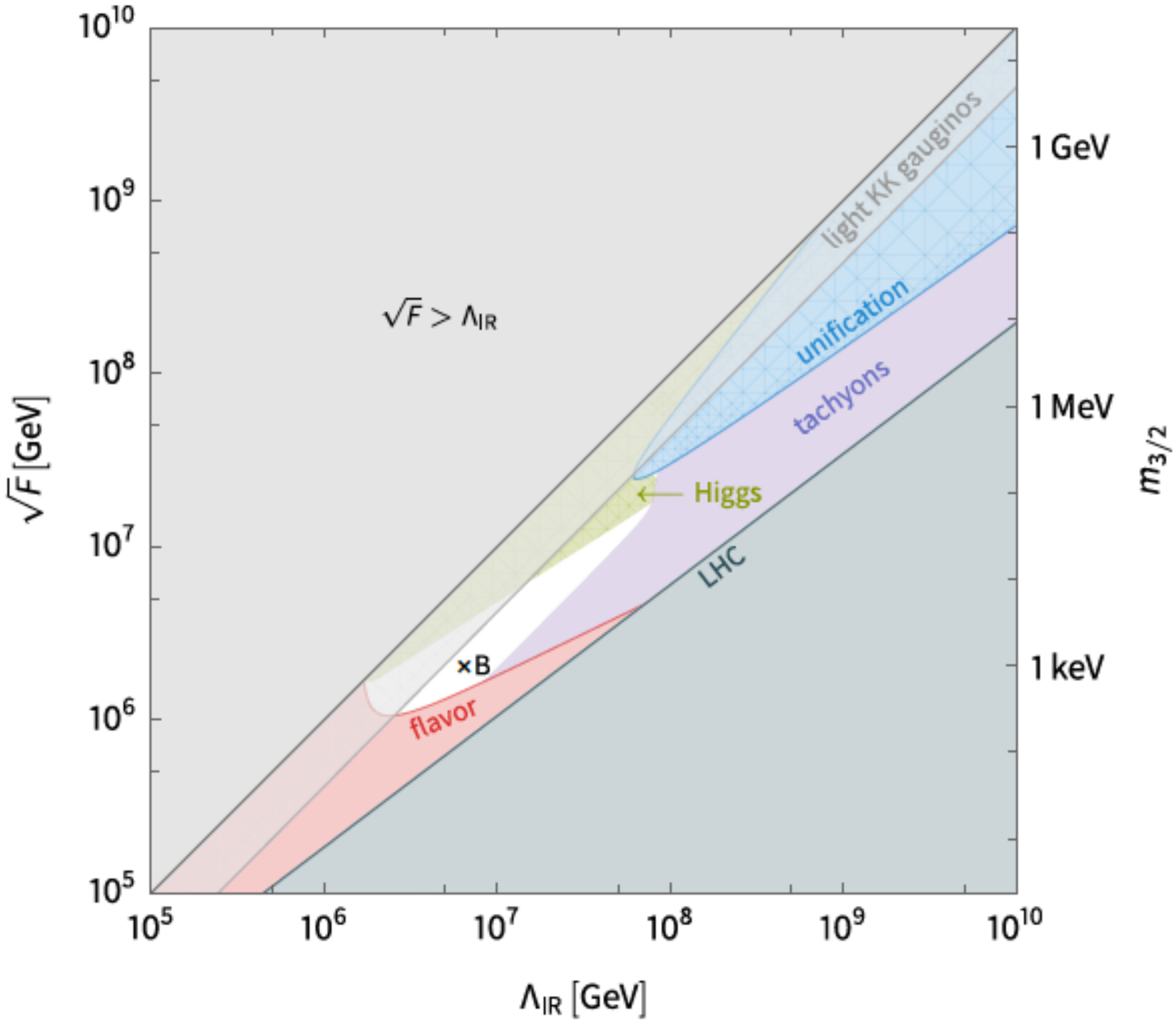
Parameter space constraints (singlet X spurion)

[Buyukdag, TG, Miller: 1811.12388]



Parameter space constraints (non-singlet X spurion)

[Buyukdag, TG, Miller: 1811.12388]

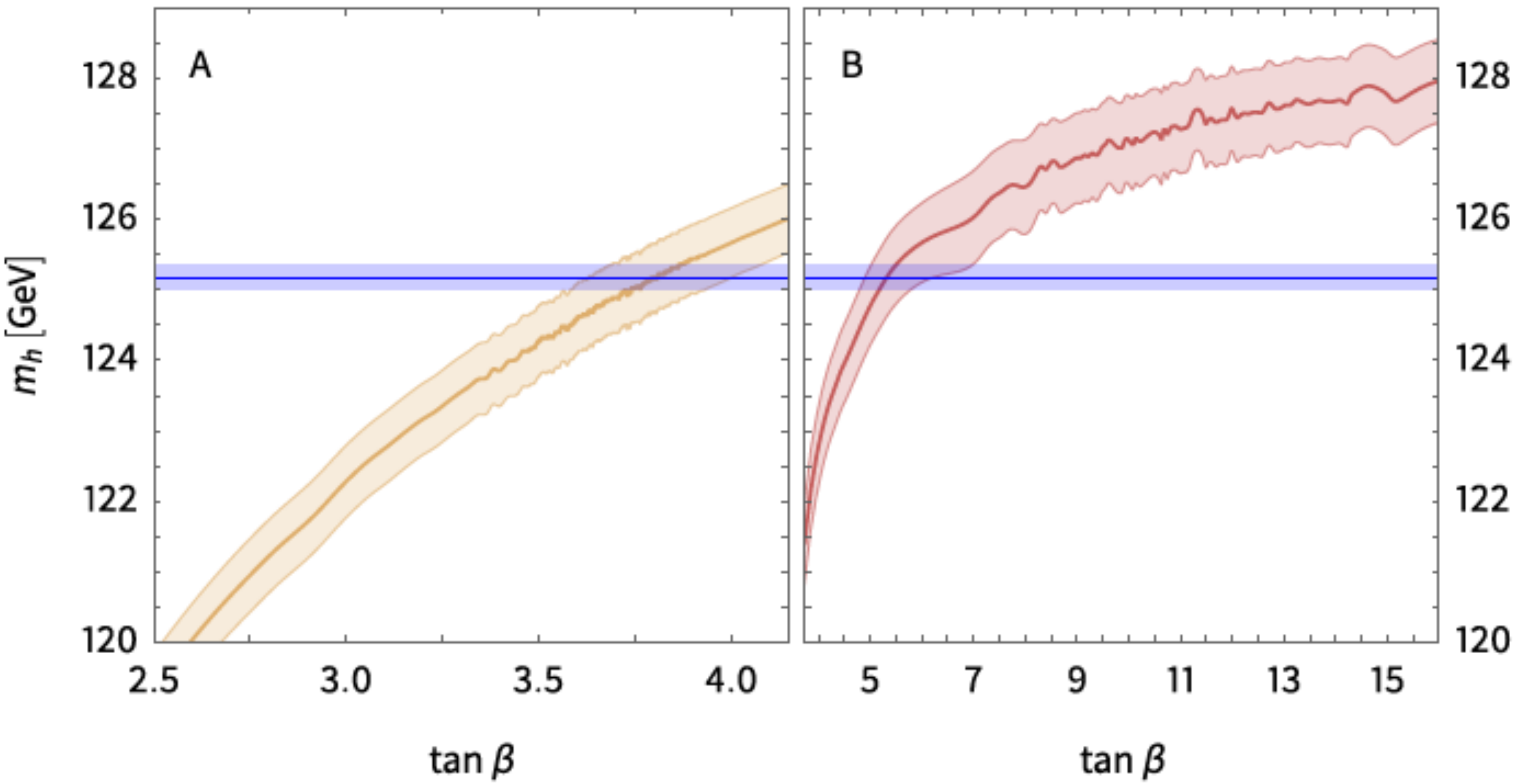


Two benchmark scenarios

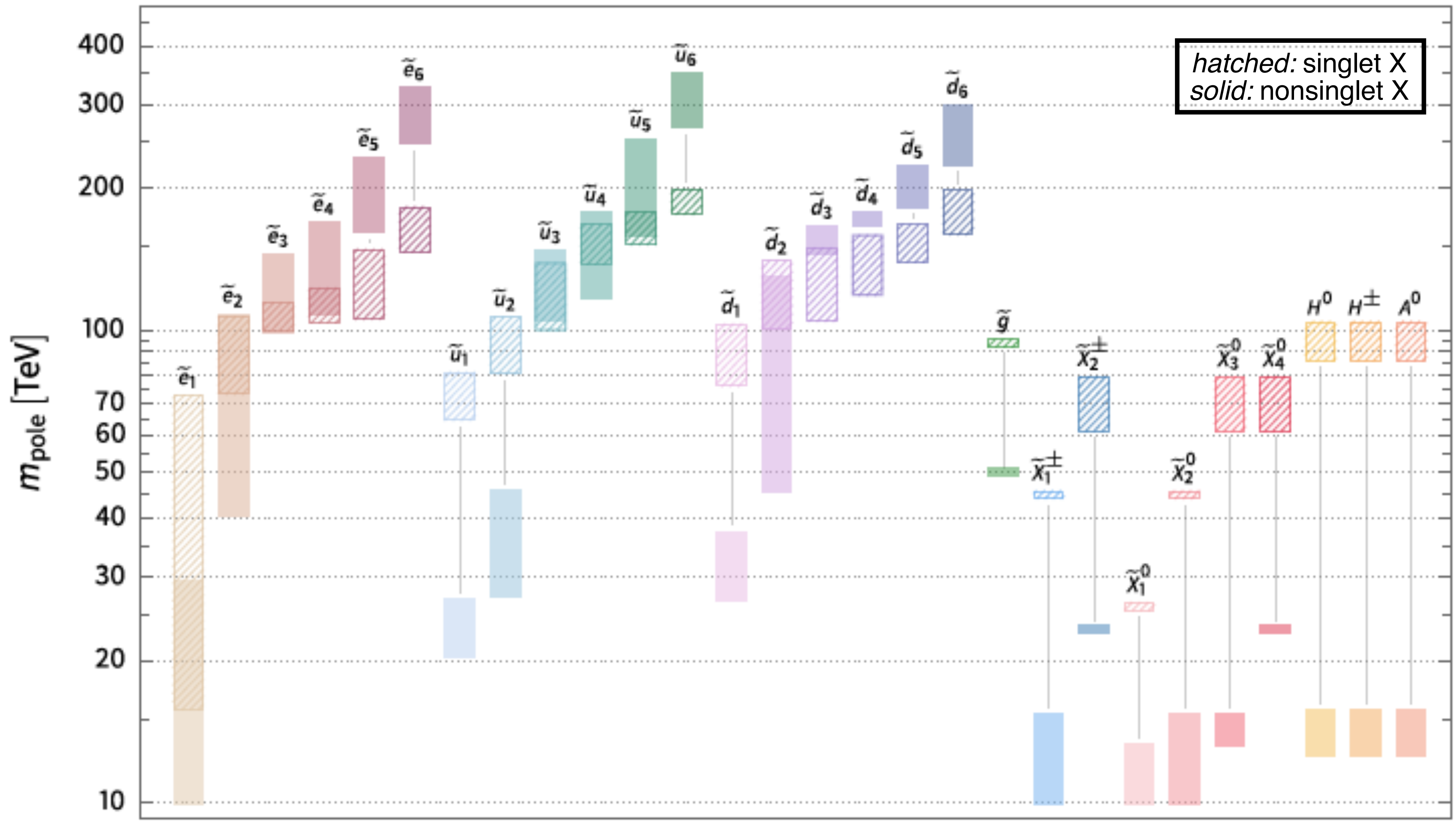
	A	B
$\Lambda_{\rm IR}$	2×10^{16} GeV	6.5×10^{6} GeV
$\sqrt{F}$	4.75×10^{10} GeV	2×10^{6} GeV
$\tan\beta$	$\sim$3	$\sim$5
$\text{sign}\,\mu$	-1	-1
$Y^{(5)}k$	1	1
Spurion	singlet	non-singlet
$M_1(\Lambda_{\rm IR})$	52.9 TeV	14.60 TeV
$M_2(\Lambda_{\rm IR})$	50.7 TeV	22.9 TeV
$M_3(\Lambda_{\rm IR})$	49.85 TeV	38.94 TeV
$m_{3/2}$	535 GeV	1 keV

Numerical Results

Higgs mass [Buyukdag, TG, Miller: 1811.12388]



Superpartner pole masses [Buyukdag, TG, Miller: 1811.12388]



$$m_{\tilde{u}_6}/m_{\tilde{t}_1} \sim 3\ (18) \qquad m_{\tilde{u}_6}/m_{\tilde{\tau}_1} \sim 13\ (35)$$ for singlet (non-singlet)

Summary

- Partial compositeness relates fermion and sfermion mass spectrum

  --- Higgs/top quark = elementary

  --- First two generations = partly composite

  --- Hierarchies arise from order one anomalous dimensions

- Predicts inverted sparticle spectrum

  --- $20(65)\ \text{TeV} \lesssim m_{\tilde{t}_1} \lesssim 27(80)\ \text{TeV}$ or $150(250)\ \text{TeV} \lesssim m_{\tilde{e}_6} \lesssim 180(330)\ \text{TeV}$

  --- gravitino = dark matter

  --- long-lived (stau or neutralino) NLSP decay

- Sfermion flavor structure leads to specific flavor-violation processes (e.g Mu2e) or EDM

  --- work in progress