Flavour Models with Dirac Gauginos

Pantelis Tziveloglou
VUB, Brussels

Based on work done with E. Dudas, M. Goodsell and L. Hurtier ph/1312.2011
E. Dudas, M. Goodsell ph/1406.XXXX

Dirac Gauginos in SUSY BSM

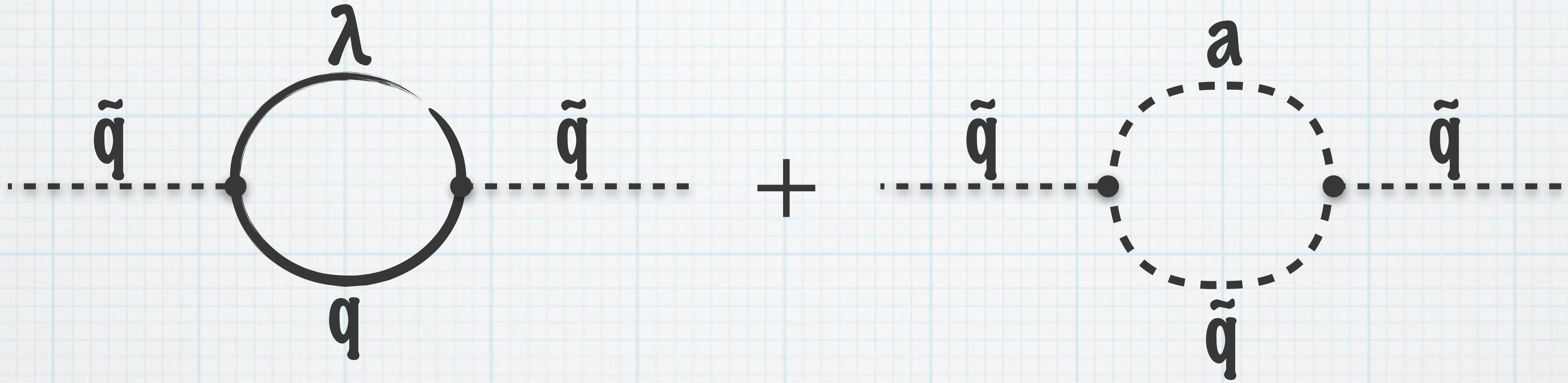
Why?

* Milder flavour constraints
  Kribs, Poppitz, Weiner '08
* Larger $\tilde{q}$-$\tilde{g}$ splitting allowed
* Suppressed $\tilde{q}$ production
* Finite stop correction to Higgs mass
* R-symmetry naturally from ~~SUSY~~
* Modified Higgs sector allows Higgs mass at 125 GeV even for light stops
* The scalar superpartners can be detectable

Why not?

* "Plurality is not to be posited without necessity"
  William of Ockham
* Gauge coupling unification is problematic
* Model building somewhat difficult

Finite correction to Higgs mass

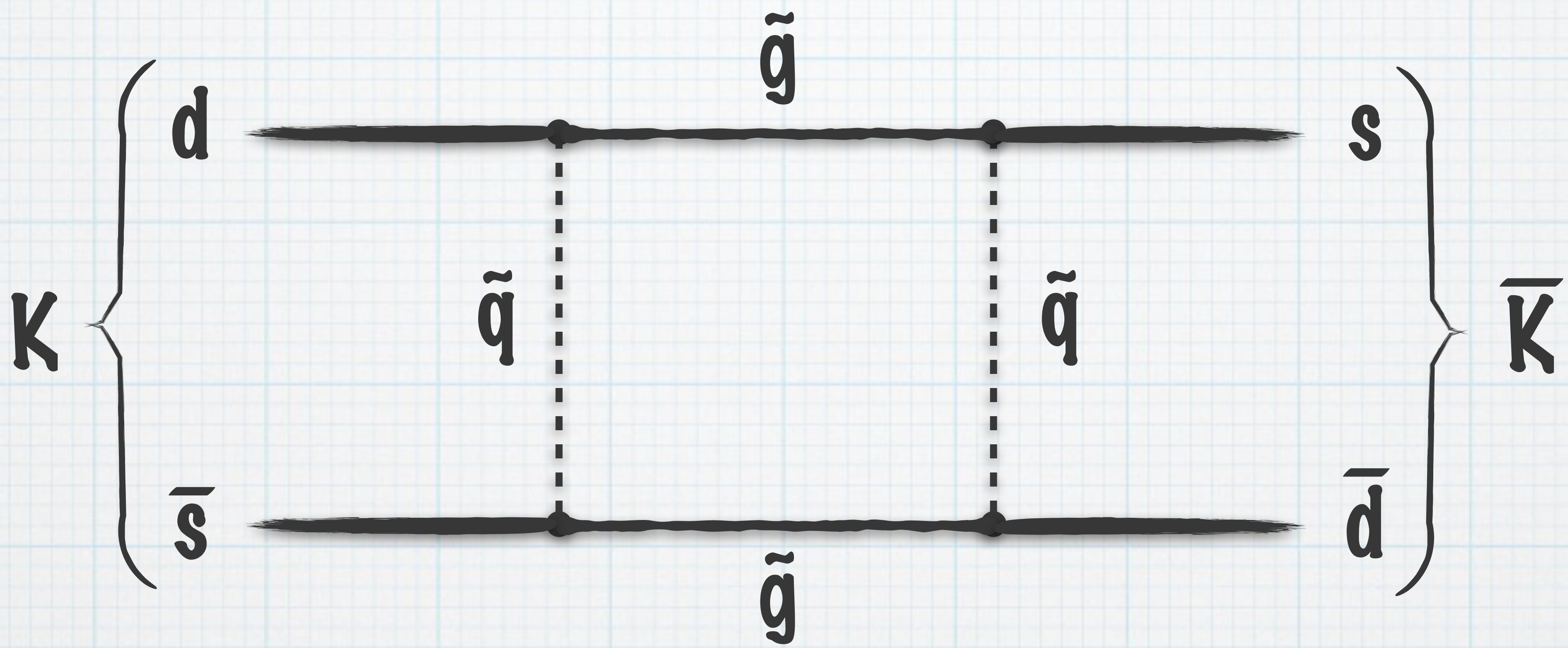


$$\Delta m_{\tilde{q}}^2 = \frac{C_i(r)\alpha_i m_{Di}^2}{\pi} \mathrm{Log}\left(\frac{m_{\mathrm{Re}(a_i)}^2}{m_{Di}^2}\right)$$

Fox, Nelson, Weiner '02

Neutral Meson Mixing in SUSY

(Neutral meson mixing in SUSY)



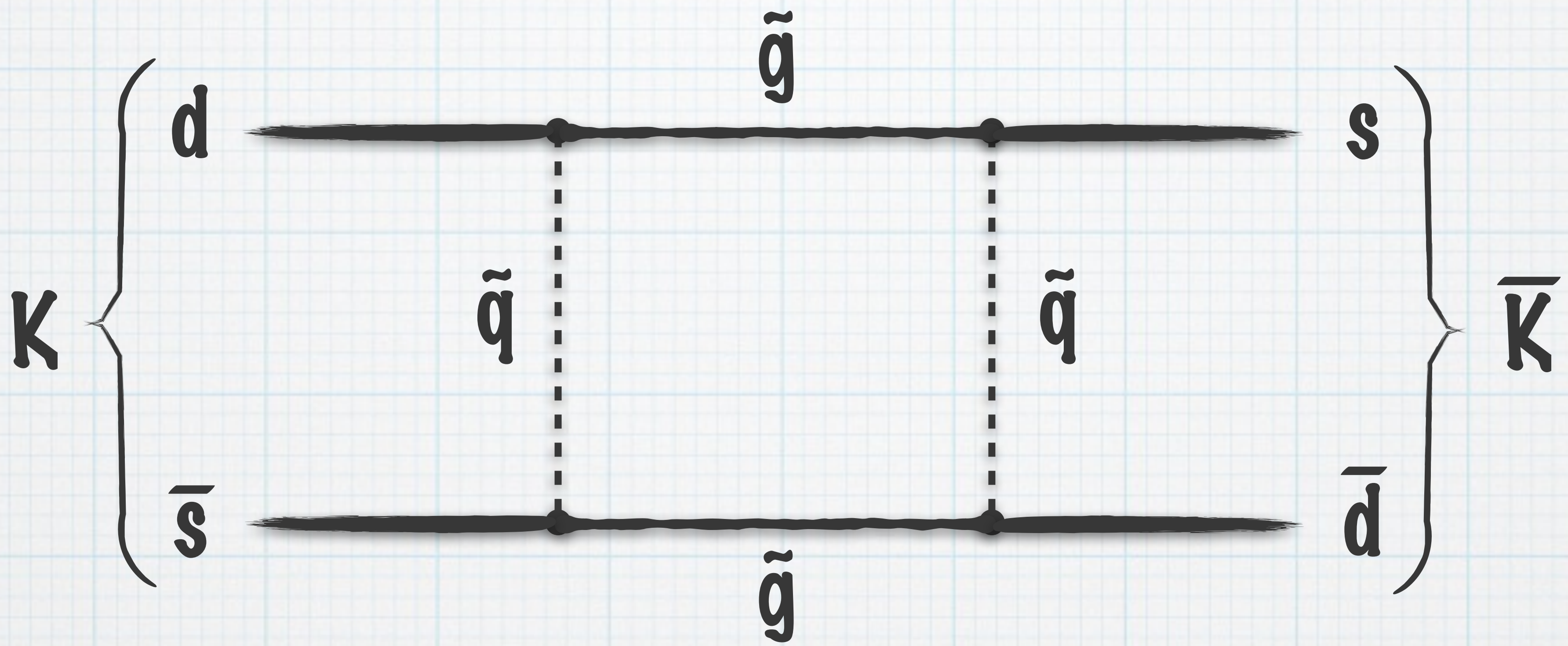
$$\mathrm{Re}\langle K|\mathcal{H}_K|\overline{K}\rangle \longrightarrow \Delta M_K = M_{K_L} - M_{K_S} = 3.484 \times 10^{-15}\,\mathrm{GeV}$$

$$\mathrm{Im}\langle K|\mathcal{H}_K|\overline{K}\rangle \longrightarrow \epsilon_K = 2.228 \times 10^{-3}$$

$\mathcal{H}_K$ = (Coefficients that depend on gluino couplings, masses etc) x (dimension 6 4-fermion operators)

Similar for: B_d - meson (b ⟷ d)
B_s - meson (b ⟷ s)
D - meson (u ⟷ c)

Neutral Meson Mixing in SUSY



$W^{\dagger}_{IJ}$ squark diagonalizing matrix in the basis where quarks are diagonal

$$g_s\,\tilde{q}^*_I\,\tilde{g}\,q_I \xrightarrow{\text{diagonalization}} g_s\,\tilde{q}^*_I\,(Z^{\dagger}_{IK}V_{KJ})\,\tilde{g}\,q_J$$

Flavour Patterns

$\mathcal{H}_K$ = (Coefficients that depend on gluino couplings, masses etc) x (dimension 6 4-fermion operators)

$\overline{d_L}\gamma^\mu s_L\,\overline{d_L}\gamma_\mu s_L$

$\overline{d_R}s_L\,\overline{d_L}s_R$

etc

Nir, Seiberg '93, ...

Dine, Kagan, Samuel '90
Dimopoulos, Giudice '95
Pomarol, Tommasini '96
Giudice, Nardecchia, Romanino '08

Alignment **Hierarchy**

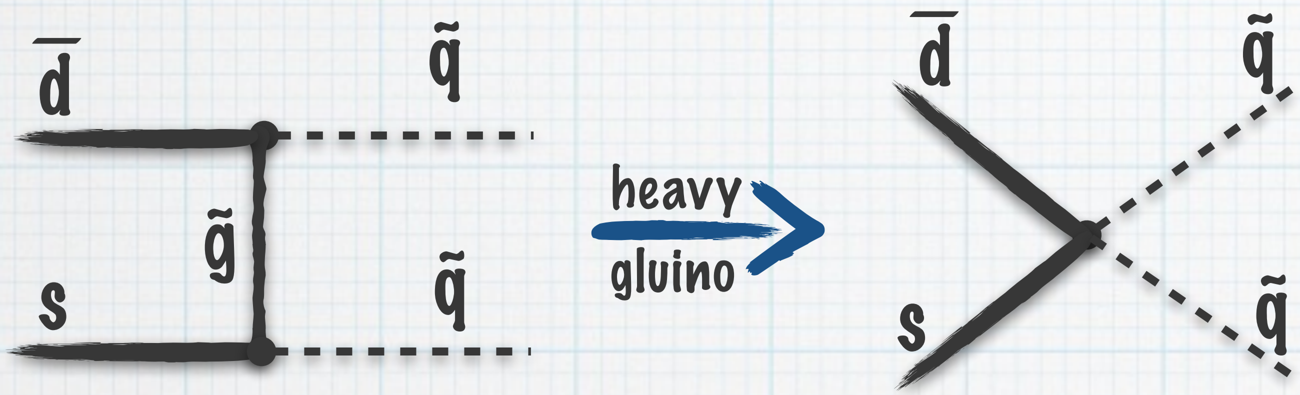
$$W_{IK}W_{LM}\,\mathrm{LOOP}(m^2_{\tilde g}, m^2_{\tilde g}, m^2_{\tilde q_K}, m^2_{\tilde q_M})\,W^\dagger_{KJ}W^\dagger_{MN}$$

DEGENERACY

aka **UNITARITY (à la GM)** aka **MASS INSERTION APPROXIMATION**

Dirac Gauginos and Flavour

If gauginos have Dirac mass, chirality flip transitions are forbidden



$$\sim \frac{1}{m_{\tilde{g}}} \tilde{d}_R \tilde{s}_L^* \bar{d}_R s_L$$ Majorana

$$\sim \frac{1}{m_{\tilde{g}}^2} \tilde{d}_L \partial_\mu \tilde{s}_L^* \bar{d}_L \gamma^\mu s_L$$ Dirac

$$\frac{\Delta M_K|_{Majorana}}{\Delta M_K|_{Dirac}} \sim \frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}$$

Dirac vs Majorana

Dudas, Goodsell, Heurtier, PT 1312.2011

If gauginos have Dirac mass, chirality flip transitions are forbidden

Naively, $$\frac{\Delta M_K|_{Majorana}}{\Delta M_K|_{Dirac}} \sim \frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}$$

However this is often **NOT** true

1) $$\frac{\Delta M_K|_{Majorana}}{\Delta M_K|_{Dirac}} \sim \mathrm{Log}\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right)$$ beyond mass insertion approximation

2) Same-chirality and chirality-flip transitions can partially cancel!

→ Bounds on Majorana **MILDER** than Dirac!

Dirac vs Majorana

Dudas, Goodsell, Heurtier, PT 1312.2011

$$C_{\bar{d}_L\gamma_\mu s_L \bar{d}_L\gamma^\mu s_L} = i g_s^4 W_{\tilde{d}_L k} W_{\tilde{d}_L m}\left(\frac{11}{36}\tilde{I}_4^{k,m} + \frac{m_{\tilde{g}}^2}{9} I_4^{k,m}\right) W^\dagger_{k\,\tilde{s}_L} W^\dagger_{m\,\tilde{s}_L}$$

$$\tilde{I}_4^{k,m} = \int \frac{d^4p}{(2\pi)^4}\frac{p^2}{(p^2-m_{\tilde{g}}^2)^2(p^2-m_{\tilde{q}_k}^2)(p^2-m_{\tilde{q}_m}^2)} \; ; \; I_4^{k,m} = \int \frac{d^4p}{(2\pi)^4}\frac{1}{(p^2-m_{\tilde{g}}^2)^2(p^2-m_{\tilde{q}_k}^2)(p^2-m_{\tilde{q}_m}^2)}$$

Nearly degenerate squarks: Expand integrals in squark mass difference.

$$C_{\bar{d}_L\gamma_\mu s_L \bar{d}_L\gamma^\mu s_L} = i g_s^4 \left(W_{\tilde{d}_L k}\delta m_{\tilde{q}_k}^2 W^\dagger_{k2}\right)^2 \left(\frac{11}{36}\tilde{I}_6 + \frac{m_{\tilde{g}}^2}{9} I_6\right) \underset{x \gg 1}{\rightarrow} \frac{g_s^4\left(W_{\tilde{d}_L k}\delta m_{\tilde{q}_k}^2 W^\dagger_{k2}\right)^2}{576\pi^2\, m_{\tilde{q}}^6}\left(\frac{11}{3x^2} - \frac{1}{x}\right), \qquad x = \frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}$$

$$\frac{\Delta M_K|_{Majorana}}{\Delta M_K|_{Dirac}} \sim \frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}$$

Otherwise (e.g. for a light “left” sbottom):

$$C_{\bar{d}_L\gamma_\mu s_L \bar{d}_L\gamma^\mu s_L} = i g_s^4 \left(W_{\tilde{d}_L \tilde{b}_L} W^\dagger_{\tilde{b}_L\,\tilde{s}_L}\right)^2 \left(\frac{11}{36}\tilde{I}_4 + \frac{m_{\tilde{g}}^2}{9} I_4\right) \underset{x \gg 1}{\rightarrow} \frac{g_s^4\left(W_{\tilde{d}_L \tilde{b}_L} W^\dagger_{\tilde{b}_L\,\tilde{s}_L}\right)^2}{144\pi^2 m_{\tilde{b}_L}^2}\left(\frac{11}{4x} - \frac{ln(x)}{x}\right)$$

$$\frac{\Delta M_K|_{Majorana}}{\Delta M_K|_{Dirac}} \sim \mathrm{Log}\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right)$$

Degeneracy (Majorana gluino)

* Bounds are not that stronger because of higher squarks' and gluinos' masses

* Bounds from ϵ_K around 25 times stronger than bounds from ΔM_K

$m_{\tilde{g}} = 1.5\,\text{TeV}$

$m_{\tilde{q}}$ [GeV]	$\delta^{LL} \neq 0$	$\delta^{LL} = \delta^{RR} \neq 0$	$\delta^{LR} = \delta^{RL} \neq 0$
750	0.211	0.002	0.004
1500	0.180	0.002	0.014
2000	0.157	0.003	0.008

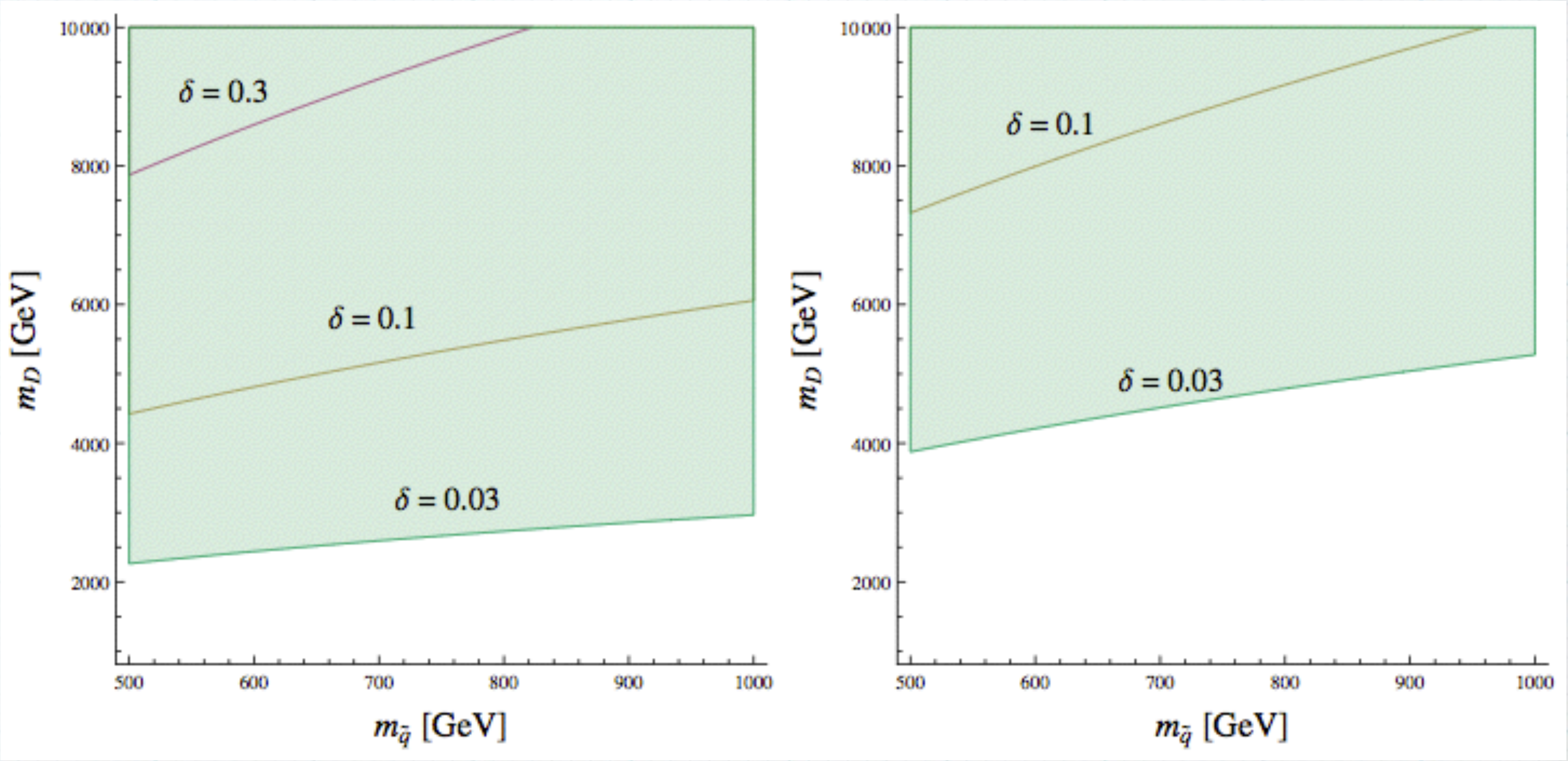
$m_{\tilde{g}} = 2\,\text{TeV}$

$m_{\tilde{q}}$ [GeV]	$\delta^{LL} \neq 0$	$\delta^{LL} = \delta^{RR} \neq 0$	$\delta^{LR} = \delta^{RL} \neq 0$
750	0.192	0.002	0.005
1500	0.374	0.003	0.011
2000	0.240	0.003	0.019

$$\delta^{AB} = \sqrt{|\mathrm{Re}(\delta_{12}^{AB})^2|} \simeq 25\sqrt{|\mathrm{Im}(\delta_{12}^{AB})^2|}$$

Degeneracy (Dirac gluino)

* ΔM_K "OK"
* ϵ_K Not OK



$\delta^{LL} = \delta^{RR} = \delta,\ \delta^{LR} = \delta^{RL} = 0$ $\qquad$ $\delta^{LL} = \delta^{RR} = \delta^{LR} = \delta^{RL} = \delta$

$$\delta^{AB} = \sqrt{|\mathrm{Re}(\delta_{12}^{AB})^2|} \simeq 25\sqrt{|\mathrm{Im}(\delta_{12}^{AB})^2|}$$

Alignment

* 2 U(1) symmetries

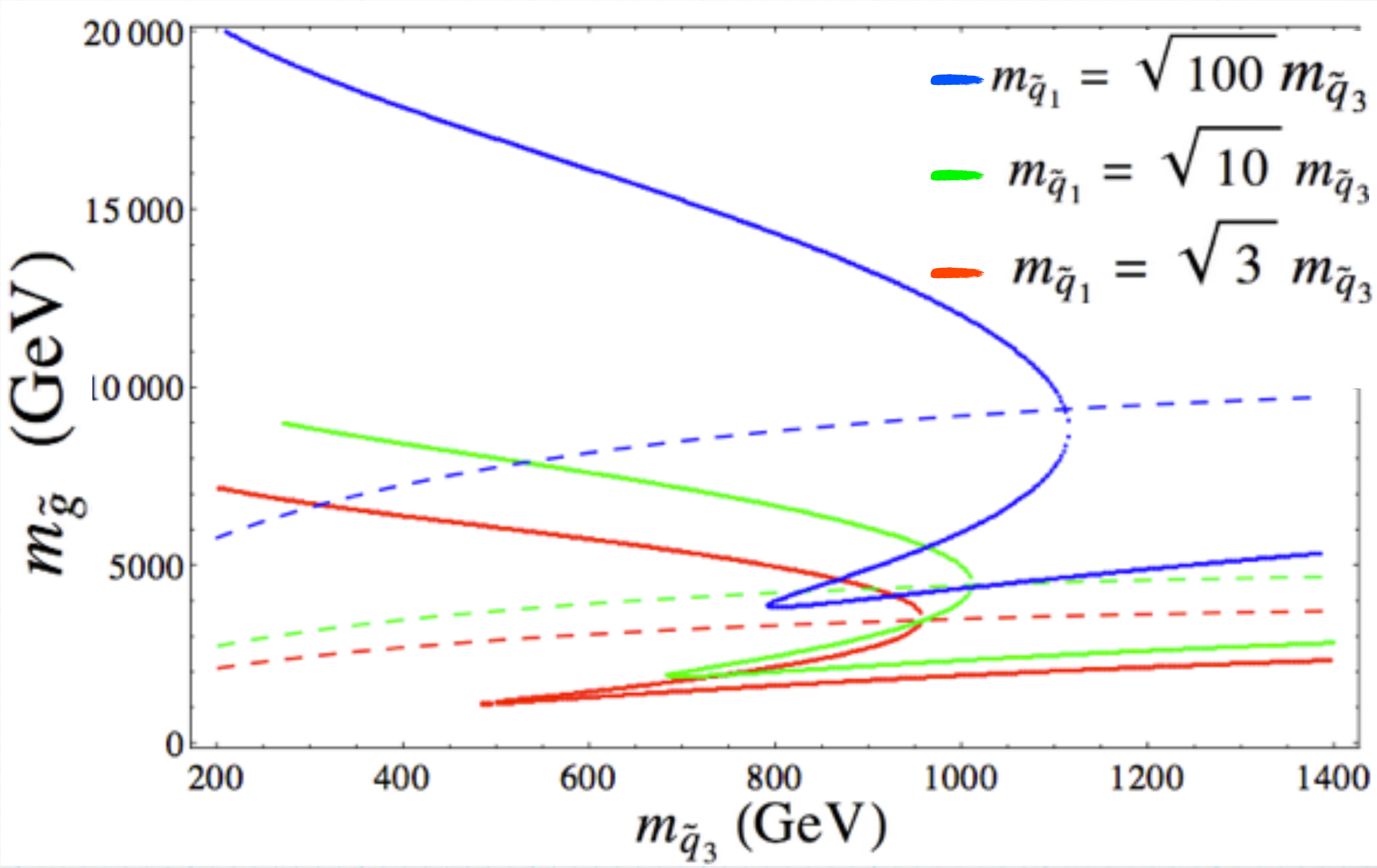
CHARGES		
Q	$\overline{D}$	$\overline{U}$
$(3,0)$	$(-1,2)$	$(-1,2)$
$(0,1)$	$(4,-1)$	$(1,0)$
$(0,0)$	$(0,1)$	$(0,0)$

$$W^{u_L} \sim \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \qquad W^{d_L} \sim \begin{pmatrix} 1 & \epsilon^5 & \epsilon^3 \\ \epsilon^5 & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

$$W^{u_R} \sim \begin{pmatrix} 1 & \epsilon^6 & \epsilon^5 \\ \epsilon^6 & 1 & \epsilon \\ \epsilon^5 & \epsilon & 1 \end{pmatrix} \qquad W^{d_R} \sim \begin{pmatrix} 1 & \epsilon^7 & \epsilon^3 \\ \epsilon^7 & 1 & \epsilon^4 \\ \epsilon^3 & \epsilon^4 & 1 \end{pmatrix}$$

* More freedom in mass hierarchies

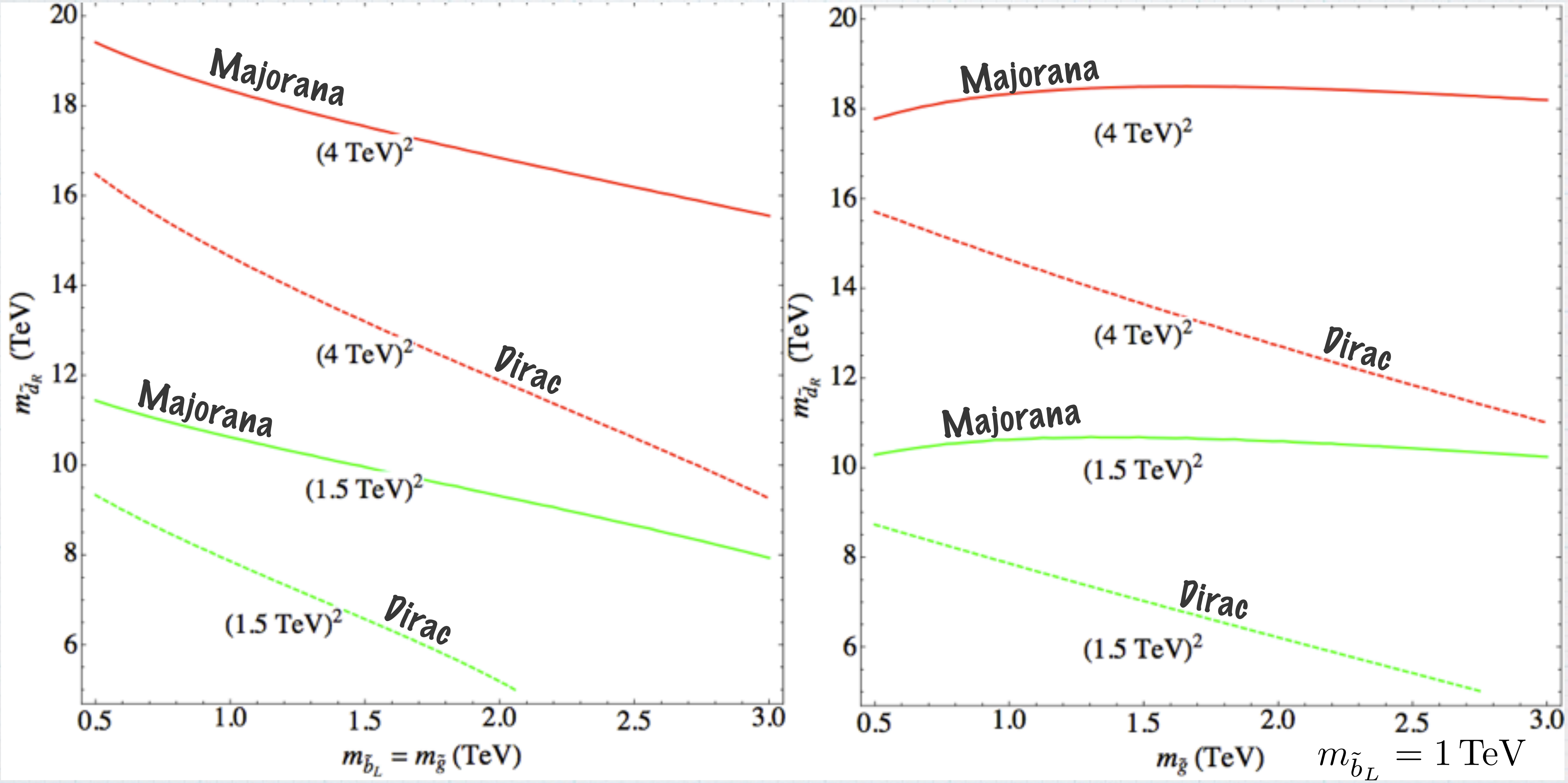
* **Majorana better than Dirac!**



Hierarchy

On the explicit model of Dudas, Gersdorff, Pokorski, Ziegler '13

Contour plots from bound on ϵ_K



$m_{\tilde{b}_L} = 1\,\mathrm{TeV}$

$$\left(|m^2_{\tilde{d}_R} - m^2_{\tilde{b}_R}| = (1.5\,\mathrm{TeV})^2\ ,\ (4\,\mathrm{TeV})^2\right)$$

Other directions - "Fake" gauginos

Dudas, Goodsell, Heurtier, PT 1312.2011

Majorana mass — adjoint mass — scalar partner of χ^α

$$\mathcal{L} \supset -\left(\frac{M}{2}\lambda^a\lambda^a + \frac{M_\chi}{2}\chi^a\chi^a + \frac{1}{2}B_\Sigma\Sigma^a\Sigma^a + i\sqrt{2}gf^{abc}\Sigma^{a\dagger}\lambda^b\chi^c + h.c.\right)$$
$$-(M_D\lambda^a\chi^a + h.c.) - m_\Sigma^2|\Sigma^a|^2 - (M_D\Sigma^a + h.c.)^2$$

Dirac mass

* **2** gluinos $\begin{cases} M_{\tilde{g}} \simeq M \text{ (heavy)} \\ M_{\tilde{g}_f} \simeq M_\chi \text{ (light)} \end{cases}$

$$R_{12} \simeq \frac{M_D}{M}$$

* $-\sqrt{2}g_s\tilde{d}^\dagger\lambda d \longrightarrow -\sqrt{2}g_s\tilde{d}^\dagger(R_{11}\,\tilde{g} + R_{12}\,\tilde{g}_f)d$

@ experiment

* Displaced gluino vertices with accessible squarks

(High Energy N=2 SUSY)

* Direct squark production with decay dominantly through higgsinos

(Unsuppressed only for 3rd generation squarks/sleptons)

Also: "Fake - Split SUSY" Dudas, Goodsell, Heurtier, PT 1312.2011
Benakli, Darmé, Goodsell, Slavich 1312.5220

Thank you