Viable Gravity Mediation

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With Graham Kribs (U. Oregon, Fermilab) and Tuhin Roy (U. Washington)

The biggest question in SUSY

"Visible" sector

$Q \quad U^c \quad D^c \quad L \quad E^c$

$H_u \quad H_d$

$SU(3) \times SU(2) \times U(1)$

maybe $S?\ U(1)_{B-L}?$

$\cdots$

~~SUSY~~ sector

$\cdots\cdots$

$\langle X \rangle = \theta^2 F \quad \cdots$

$\langle W'_\alpha \rangle = \theta_\alpha D \quad \cdots$

$$\mathcal{L} \;=\; \mathcal{L}_{\text{vis.}}(Q, U^c, \cdots) \qquad + \mathcal{L}_{\text{S.B.}}(X, W', \cdots)$$

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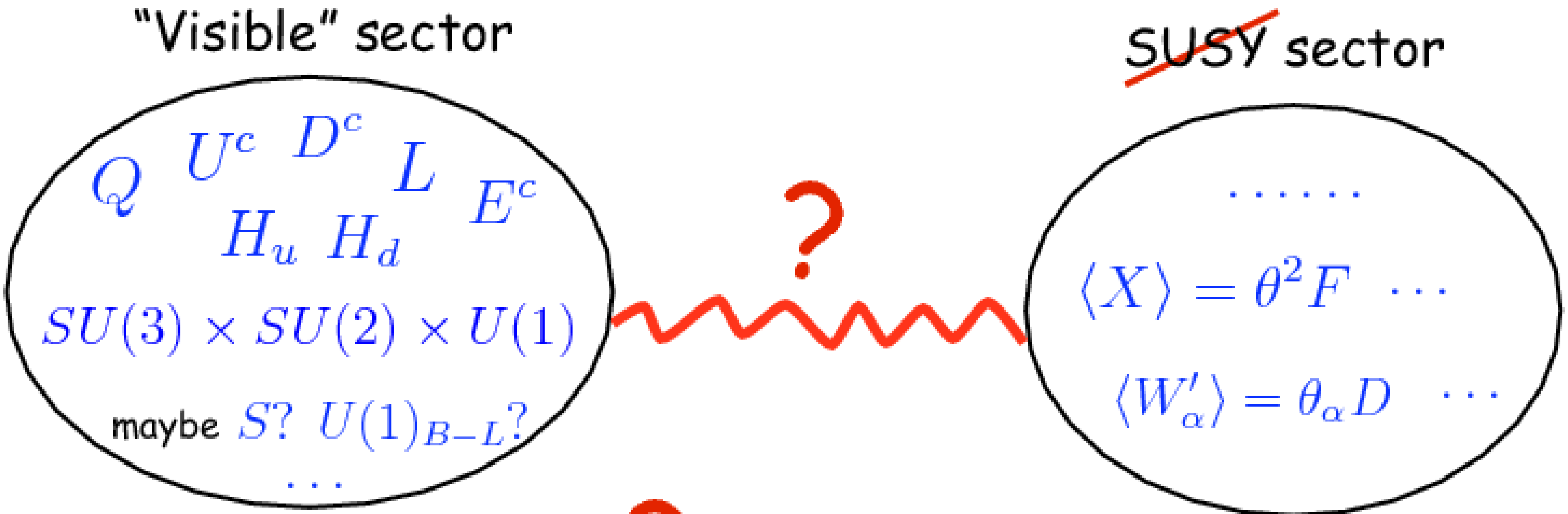

?

$$\mathcal{L} \;=\; \mathcal{L}_{\text{vis.}}(Q, U^c, \cdots) + \mathcal{L}_{\text{med.}}(Q, U^c, \cdots, X, W') + \mathcal{L}_{\text{S.B.}}(X, W', \cdots)$$

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At Planck scale, we always have

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The simplest scenario: this is it! "Gravity Mediation"

$\longrightarrow$ All mass scales right, no mu problem, neutralino DM, already unified...

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But flavor symmetry IS violated by Yukawas!

Then, WHY $c_{ij} \propto \delta_{ij}$? Any mechanism? "SUSY flavor problem"

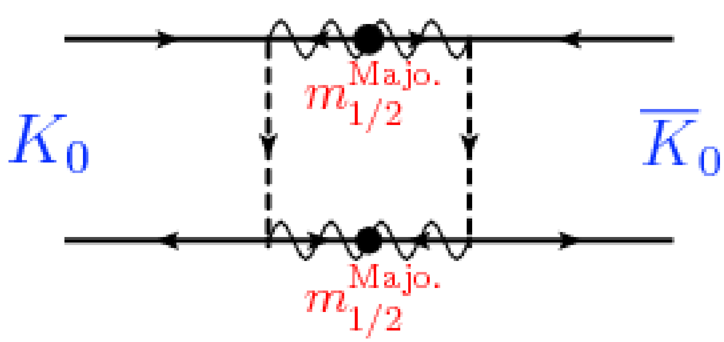
Solutions: gauge med., gaugino med., anomaly med., etc.

Is there a way to be flavor safe while $c_{ij} \not\propto \delta_{ij}$?

A closer look at SUSY flavor violations:

--- Excessive K_0-$\overline{K}_0$ mixing ---

-- MSSM (Majo. gaugino) --



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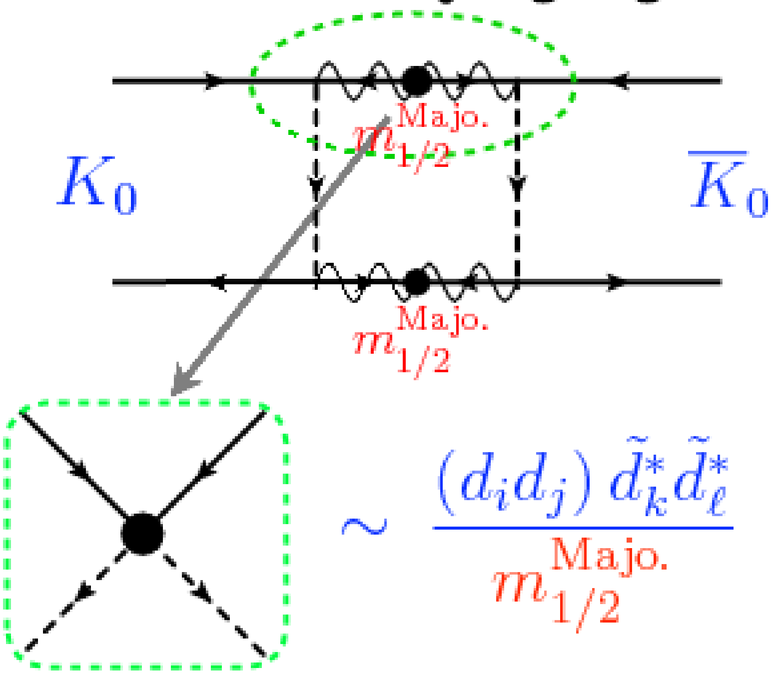

$$\sim \frac{(d_i d_j)\, \tilde{d}_k^* \tilde{d}_\ell^*}{m_{1/2}^{\text{Majo.}}}$$

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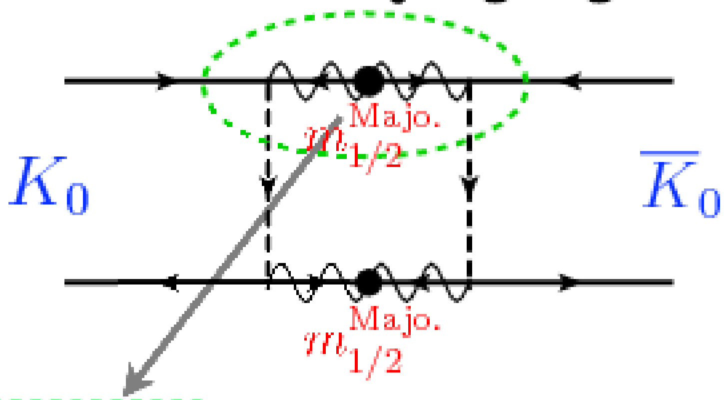

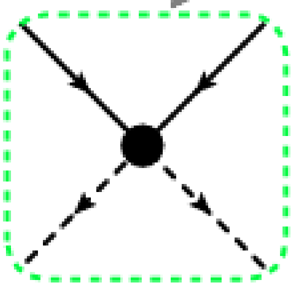

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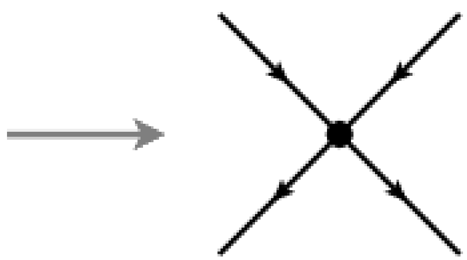

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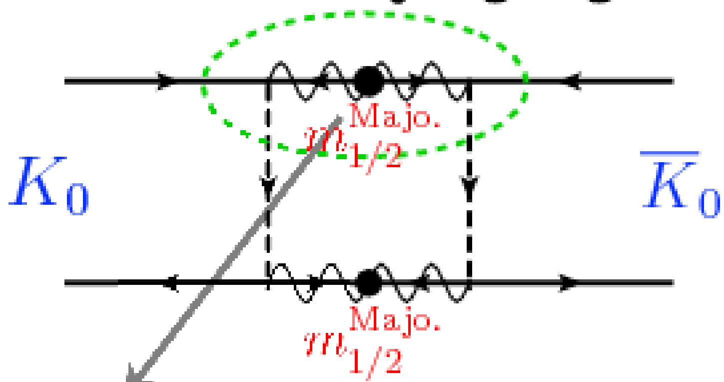

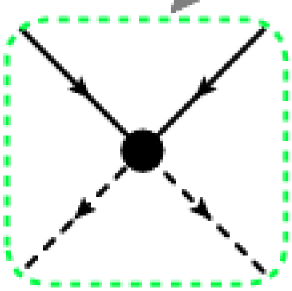

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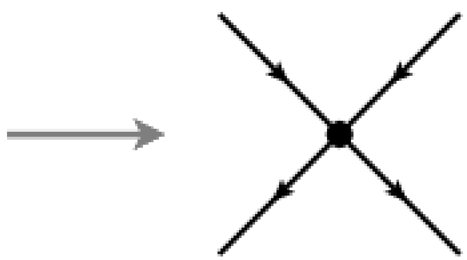

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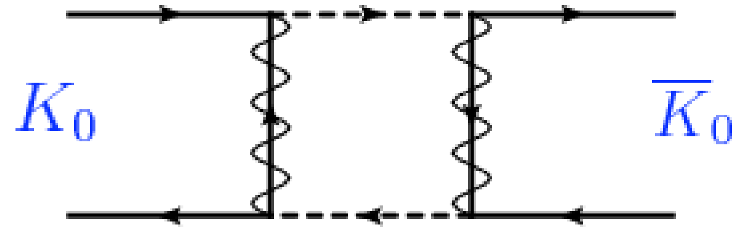

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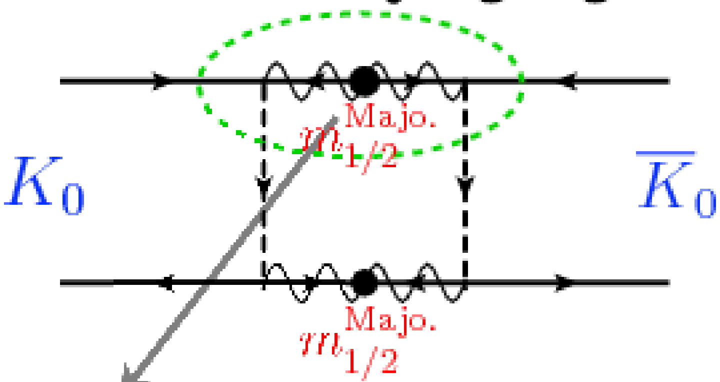

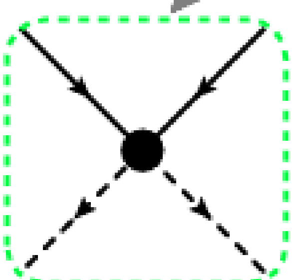

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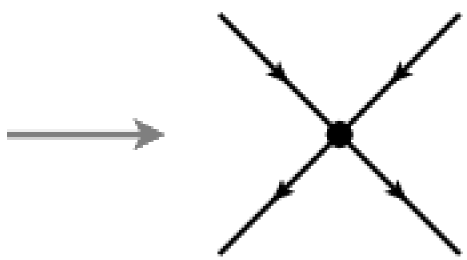

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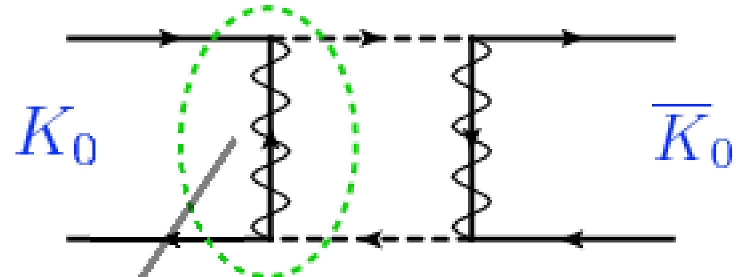

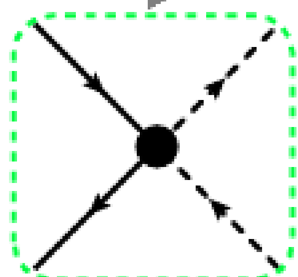

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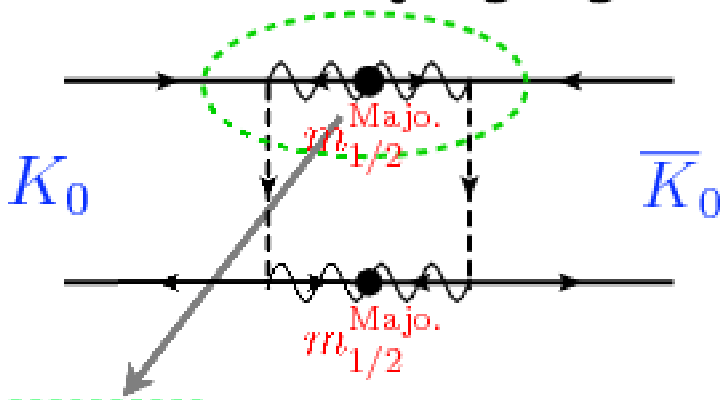

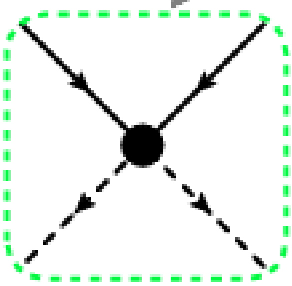

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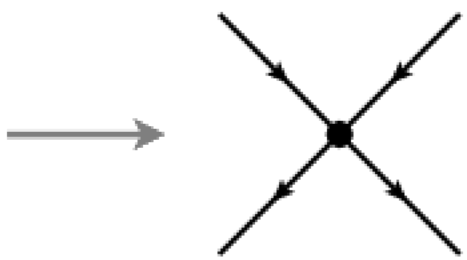

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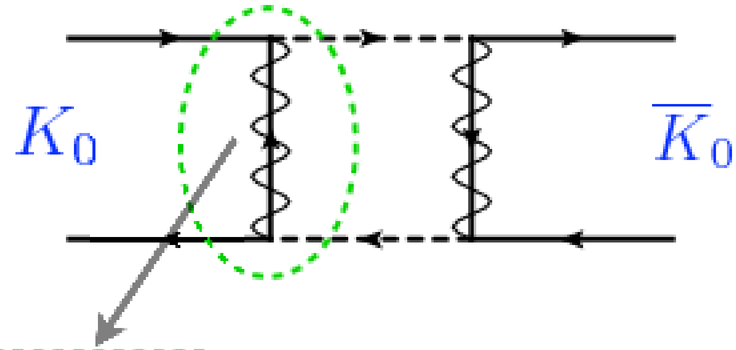

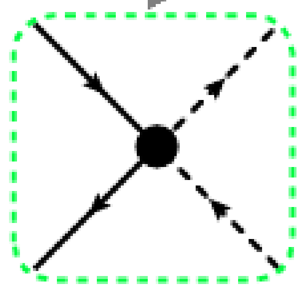

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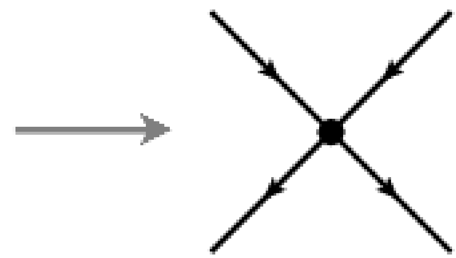

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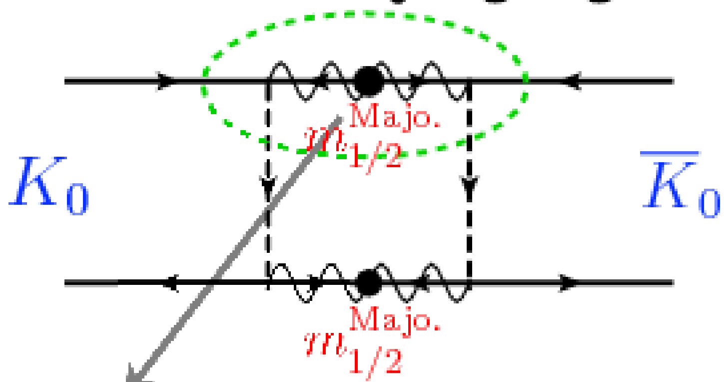

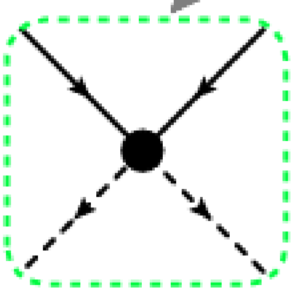

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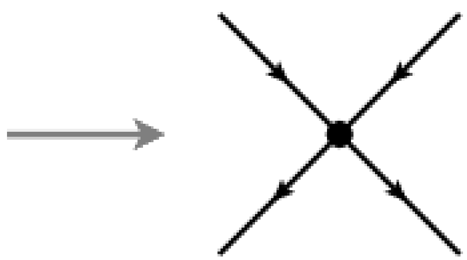

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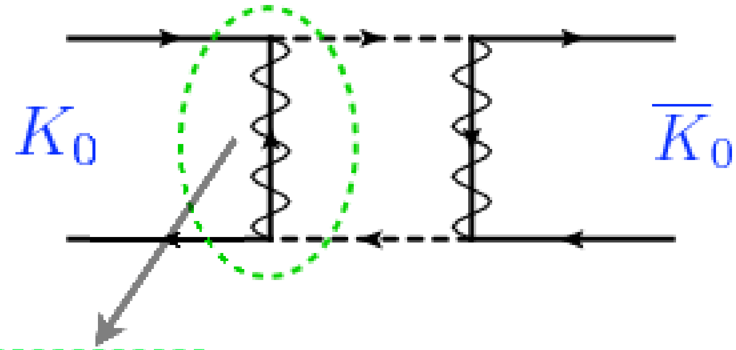

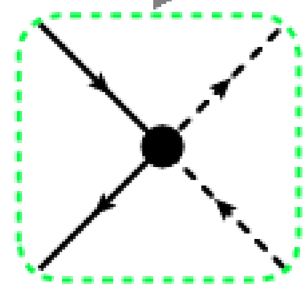

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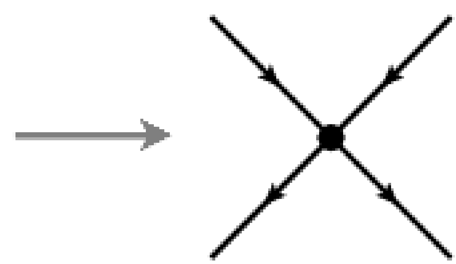

$$\propto \frac{m_{\tilde{q}}^2}{m_{1/2}^2 m_{1/2}^2}$$

Enough suppression if

$m_{1/2} \sim 10 m_{\tilde{q}}$, $c_{12} \sim c_{11}/10 \sim c_{22}/10$!

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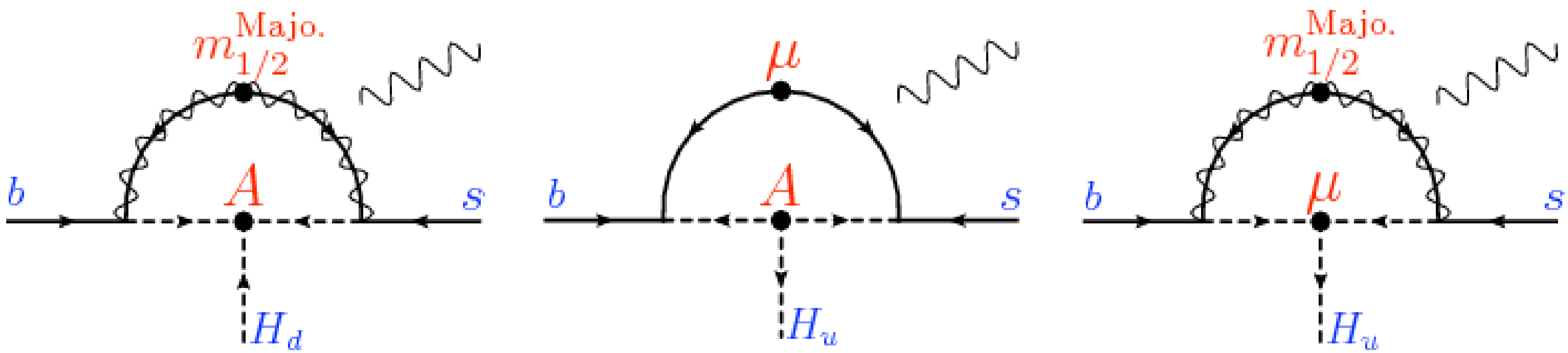
--- Excessive $\mu \to e\gamma\,,\ b \to s\gamma$ etc. ---



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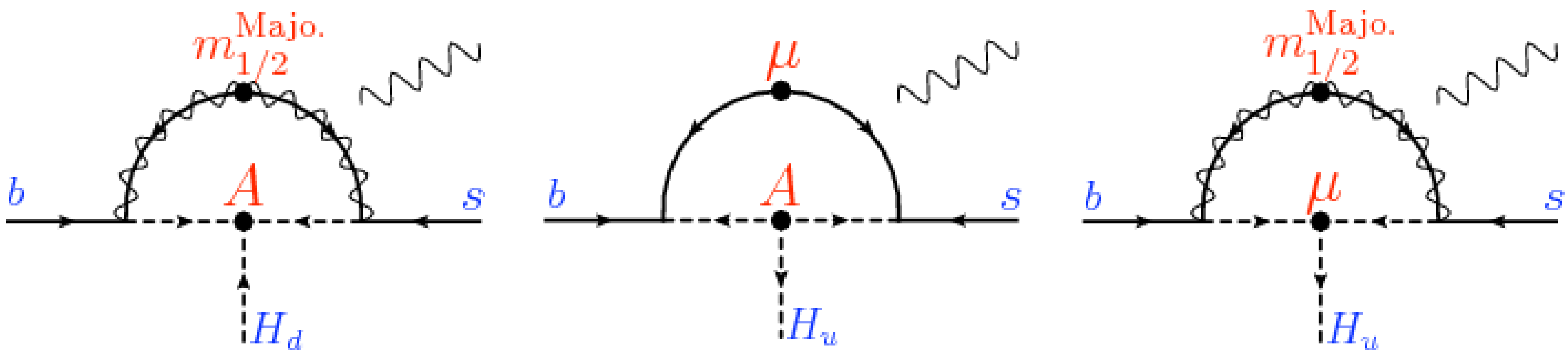

Will be doubly forbidden if $A = \mu = m_{1/2}^{\mathrm{Majo.}} = 0$!

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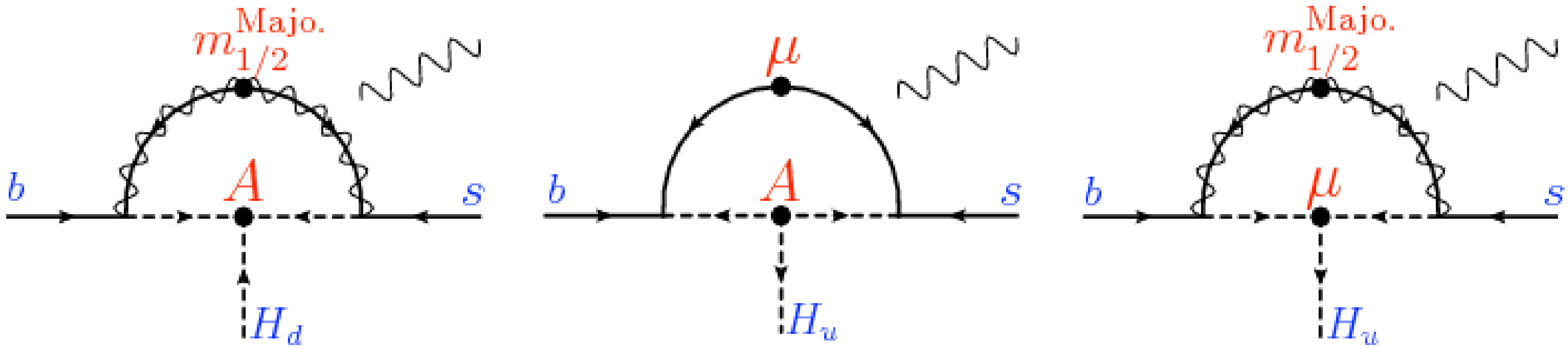

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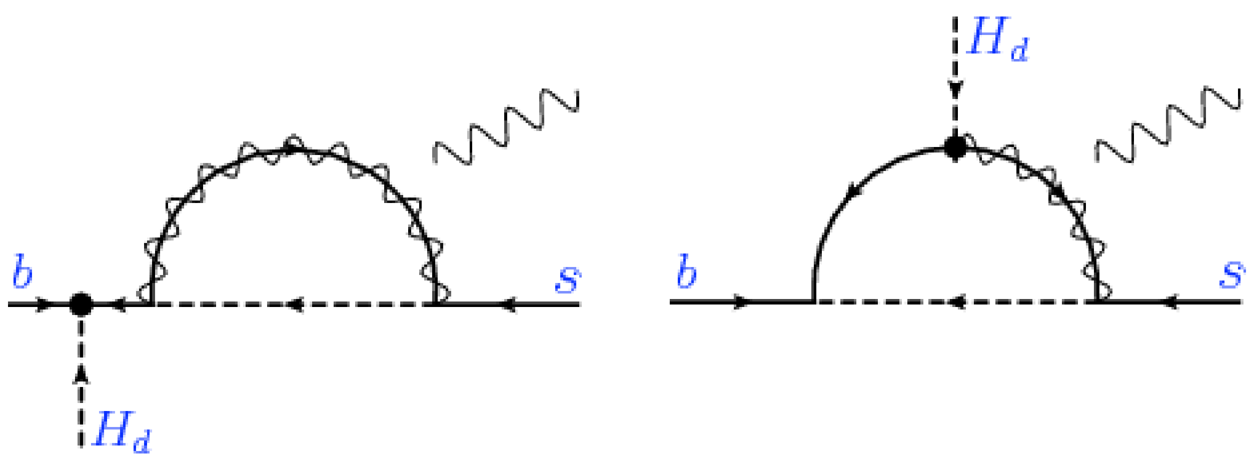

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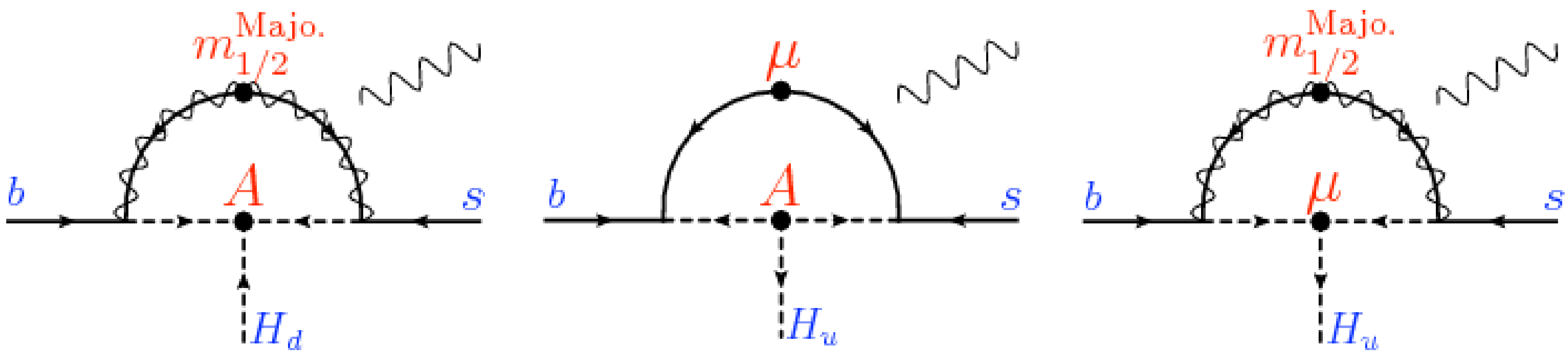

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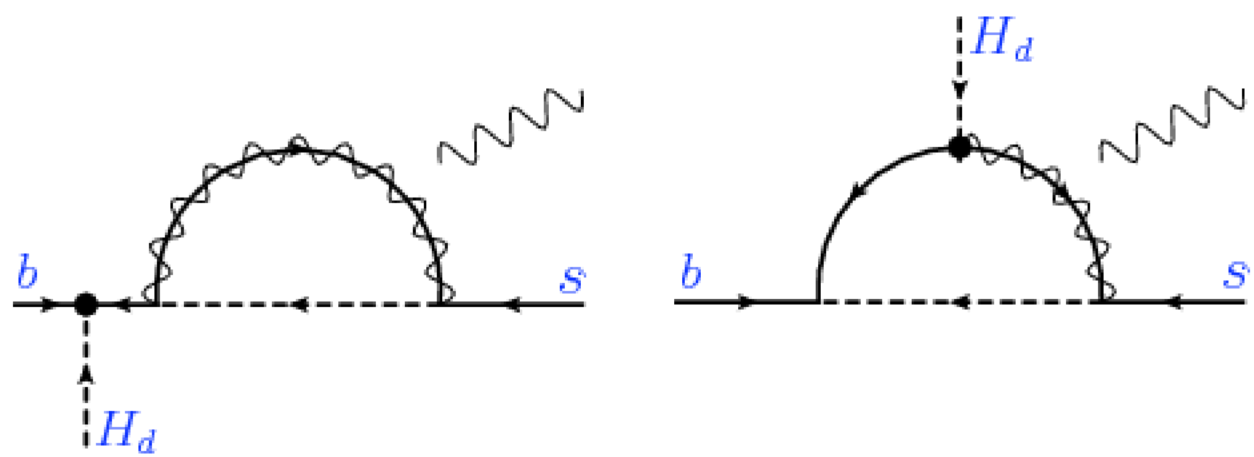

Will survive but small for $m_{1/2} \sim 10 m_{\tilde{q}}$, $c_{12} \sim c_{11}/10 \sim c_{22}/10$!

How do we get $A = \mu = m_{1/2}^{\text{Majo.}} = 0$?

Kribs, Poppitz, Weiner '07: "A $U(1)_R$ can do it!"

$\lambda\lambda^c$	$H_u Q U^c$	$h_u h_d$
$\lambda\lambda$	$h_u \tilde{q}\tilde{u}^c$	$H_u H_d$
$m_{1/2}^{\text{Majo.}}$	A	μ

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Where does it come from?

What about higgsino masses?

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$$\text{Introduce:} \begin{cases} \Sigma_3 \supset \tilde{g}^c \sim (\mathbf{8}, \mathbf{1})_0 \,, \; R[\Sigma_3] = 0 \\ \Sigma_2 \supset \widetilde{W}^c \sim (\mathbf{1}, \mathbf{3})_0 \,, \; R[\Sigma_2] = 0 \\ \Sigma_1 \supset \widetilde{B}^c \sim (\mathbf{1}, \mathbf{1})_0 \,, \; R[\Sigma_1] = 0 \end{cases} \longrightarrow \int d^2\theta \, \frac{W'}{M_{\text{Pl}}} W_3 \Sigma_3 \; \text{etc.}$$

with $\langle W'_\alpha \rangle = \theta_\alpha D$

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But $U(1)_R$ cannot be a fundamental symmetry!

* No global symmetry in quantum gravity.
* Gravitino mass requires $\cancel{U(1)_R}$!
* (cosmo. const.) = $(\cancel{\text{SUSY}})$ + (const. in superpotential)

$$0 = \left(10^{11}\ \mathrm{GeV}\right)^4 + \left(-(10^{14}\ \mathrm{GeV})^6/M_{\mathrm{Pl}}^2\right)$$

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A big explicit $U(1)_R$ breaking!

(Also gives "R-axion" mass)

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(Also gives "R-axion" mass)

[Traditional flavor prob.]	[New flavor prob.]
Sfermions: $U(3)^5$ (i.e. $c_{ij} \propto \delta_{ij}$)	"Normal" stuff: $U(1)_R$
Fermions: $\cancel{U(3)}^5$	Gravity stuff: $\cancel{U(1)}_R$
How?	How?

But $U(1)_R$ cannot be a fundamental symmetry!

* No global symmetry in quantum gravity.
* Gravitino mass requires $\cancel{U(1)_R}$!
* (cosmo. const.) = (~~SUSY~~) + $\boxed{\text{(const. in superpotential)}}$

$$0 = \left(10^{11}\ \mathrm{GeV}\right)^4 + \boxed{\left(-\left(10^{14}\ \mathrm{GeV}\right)^6 / M_{\mathrm{Pl}}^2\right)}$$

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Fermions: $\cancel{U(3)^5}$	Gravity stuff: $\cancel{U(1)_R}$
How?	How?
Gauge Med.: $U(3)^5$ "accidental"	$U(1)_R$ must be accidental!

Accidental $U(1)_R$ in visible sector

[What we want]

$$\int d^4\theta \, \frac{X^\dagger X}{M_{\rm Pl}^2} \Phi^\dagger \Phi \qquad (\Phi = Q, \cdots, H, R, \Sigma)$$

$$\int d^4\theta \, \frac{X^\dagger X}{M_{\rm Pl}^2} \Phi \Phi' \qquad (\Phi, \Phi' = H_{u,d}, R_{u,d}, \Sigma_{1,2,3})$$

$$\int d^2\theta \, \frac{W'}{M_{\rm Pl}} W_{1,2,3} \Sigma_{1,2,3} \qquad (\langle W'_\alpha \rangle = \theta_\alpha D)$$

[What we don't want]

$$\int d^2\theta \, \frac{X}{M_{\rm Pl}} WW$$

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$$\int d^4\theta \, \frac{X^\dagger}{M_{\rm Pl}} \Phi \Phi' \Phi'' \qquad (\Phi, \Phi', \Phi'' = Q, \cdots, H, R, \Sigma)$$

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[What we want]	[What we don't want]
$\int d^4\theta \, \frac{X^\dagger X}{M_{\rm Pl}^2} \Phi^\dagger \Phi$ $\quad (\Phi = Q, \cdots, H, R, \Sigma)$ $\longrightarrow \tilde{q}^\dagger \tilde{q}, \; h_u^\dagger h_u, \; \sigma_3^\dagger \sigma_3$ etc. (Scalar soft masses)	$\int d^2\theta \, \frac{X}{M_{\rm Pl}} WW$
$\int d^4\theta \, \frac{X^\dagger X}{M_{\rm Pl}^2} \Phi \Phi'$ $\quad (\Phi, \Phi' = H_{u,d}, R_{u,d}, \Sigma_{1,2,3})$	$\int d^4\theta \, \frac{X^\dagger}{M_{\rm Pl}} \Phi \Phi'$ $\quad (\Phi, \Phi' = H_{u,d}, R_{u,d}, \Sigma_{1,2,3})$
$\int d^2\theta \, \frac{W'}{M_{\rm Pl}} W_{1,2,3} \Sigma_{1,2,3}$ $\quad (\langle W'_\alpha \rangle = \theta_\alpha D)$	$\int d^4\theta \, \frac{X^\dagger}{M_{\rm Pl}} \Phi \Phi' \Phi''$ $\quad (\Phi, \Phi', \Phi'' = Q, \cdots, H, R, \Sigma)$

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$$\longrightarrow h_u h_d \, , \; r_u r_d \, , \; (\sigma_{1,2,3})^2$$

(B-type masses)

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$\int d^4\theta \, \frac{X^\dagger X}{M_{\rm Pl}^2} \Phi \Phi'$ $(\Phi, \Phi' = H_{u,d}, R_{u,d}, \Sigma_{1,2,3})$ $\longrightarrow h_u h_d, \; r_u r_d, \; (\sigma_{1,2,3})^2$ (B-type masses)	$\int d^4\theta \, \frac{X^\dagger}{M_{\rm Pl}} \Phi \Phi'$ $(\Phi, \Phi' = H_{u,d}, R_{u,d}, \Sigma_{1,2,3})$
$\int d^2\theta \, \frac{W'}{M_{\rm Pl}} W_{1,2,3} \Sigma_{1,2,3}$ $(\langle W'_\alpha \rangle = \theta_\alpha D)$ $\longrightarrow$ Dirac gaugino masses	$\int d^4\theta \, \frac{X^\dagger}{M_{\rm Pl}} \Phi \Phi' \Phi''$ $(\Phi, \Phi', \Phi'' = Q, \cdots, H, R, \Sigma)$

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$\longrightarrow$ $H_u H_d$, $R_u R_d$ etc.

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$\int d^4\theta \, \frac{X^\dagger X}{M_{\rm Pl}^2} \Phi^\dagger \Phi$ $(\Phi = Q, \cdots, H, R, \Sigma)$	$\int d^2\theta \, \frac{X}{M_{\rm Pl}} WW$
$\longrightarrow \tilde{q}^\dagger \tilde{q},\ h_u^\dagger h_u,\ \sigma_3^\dagger \sigma_3$ etc. (Scalar soft masses)	$\longrightarrow$ Majorana gaugino masses
$\int d^4\theta \, \frac{X^\dagger X}{M_{\rm Pl}^2} \Phi \Phi'$ $(\Phi, \Phi' = H_{u,d}, R_{u,d}, \Sigma_{1,2,3})$	$\int d^4\theta \, \frac{X^\dagger}{M_{\rm Pl}} \Phi \Phi'$ $(\Phi, \Phi' = H_{u,d}, R_{u,d}, \Sigma_{1,2,3})$
$\longrightarrow h_u h_d\,,\ r_u r_d\,,\ (\sigma_{1,2,3})^2$ (B-type masses)	$\longrightarrow H_u H_d\,,\ R_u R_d$ etc. (μ-type masses)
$\int d^2\theta \, \frac{W'}{M_{\rm Pl}} W_{1,2,3} \Sigma_{1,2,3}$ $(\langle W'_\alpha \rangle = \theta_\alpha D)$	$\int d^4\theta \, \frac{X^\dagger}{M_{\rm Pl}} \Phi \Phi' \Phi''$ $(\Phi, \Phi', \Phi'' = Q, \cdots, H, R, \Sigma)$
$\longrightarrow$ Dirac gaugino masses	$\longrightarrow h_u \tilde{q} \tilde{u}^c\,,\ \sigma_1 \sigma_3 \sigma_3\,,\ h_u \sigma_2 h_d$ etc. (A-type couplings)

Accidental $U(1)_R$ in visible sector

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Forbidden if X is not a singlet.

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$$\int d^4\theta \frac{X^\dagger}{M_{\rm Pl}}\Phi\Phi'\Phi''$$

Forbidden if X is not a singlet.

If no singlets in ~~SUSY~~ sector,

$\longrightarrow$ Accidental $U(1)_R$ in visible sector!

An Example Hidden Sector

Criteria:

* No gauge singlet for accidental R symm.
* $\langle D \rangle \sim \langle F \rangle$ for Dirac gauginos

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Very simple example — "4-1 model": (Dine, Nelson, Nir, Shirman, '95)

	$\overline{\Phi}$	S	A	Φ
$SU(4)$	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{6}$	$\mathbf{4}$
$U(1)$	-1	4	2	-3

$$\mathcal{W} = \lambda\, S \Phi \overline{\Phi}$$

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5bar 10

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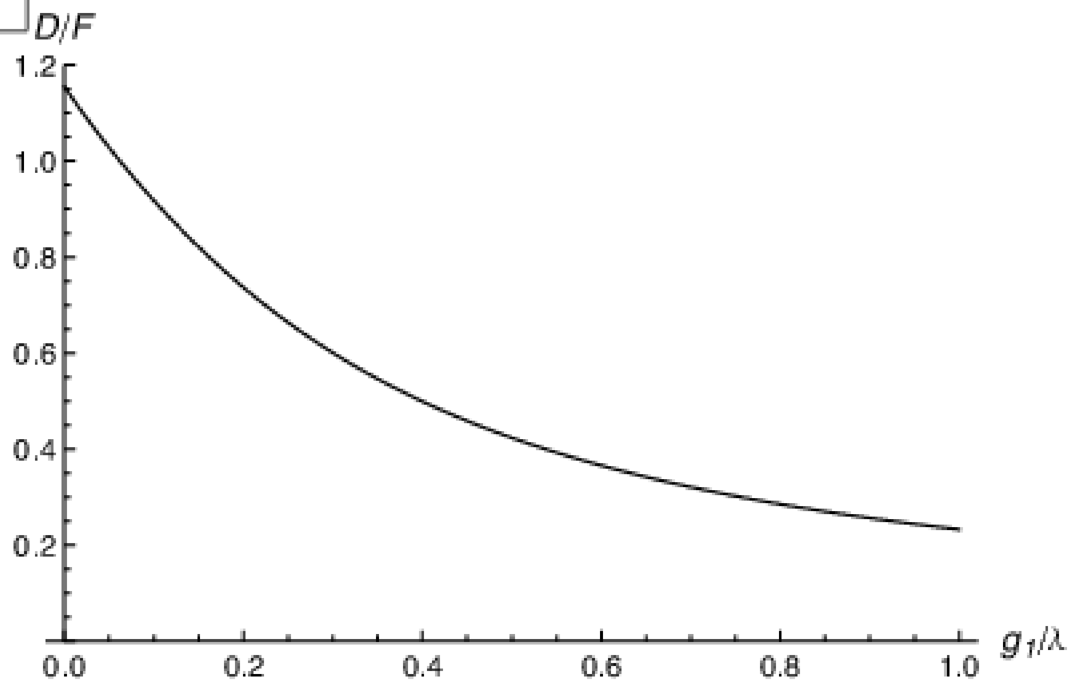
$g_4 \gg \lambda \gtrsim g_1$

$\longrightarrow \langle D_1 \rangle \sim \langle F \rangle$!

(Carpenter, Kaplan, Fox, '05;
Gregoire, Rattazzi, Scrucca, '05)



Simple existence proof!

Can we get the hierarchy $m_{\tilde{g}} \sim \underline{10} m_{\tilde{q}}$?

$$\int d^4\theta \, \frac{\theta^4 \langle F \rangle^2}{M_{\rm Pl}^2} Q^\dagger Q \quad + \quad \int d^2\theta \, \frac{\theta \langle D \rangle}{M_{\rm Pl}} W \Sigma$$

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$m_{\tilde{q}}^2$

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Look at RG effects:

$$\int d^4\theta \, \frac{\theta^4 \langle F \rangle^2}{M_{\rm Pl}^2} Q^\dagger Q \quad + \quad \int d^2\theta \, \frac{\theta \langle D \rangle}{M_{\rm Pl}} W \Sigma \qquad @ \, M_{\rm Pl}$$

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Look at RG effects:

$$\int d^4\theta \, \frac{\theta^4 \langle F \rangle^2}{M_{\rm Pl}^2} Q^\dagger Q \quad + 1 \int d^2\theta \, \frac{\theta \langle D \rangle}{M_{\rm Pl}} W\Sigma \qquad @ \, M_{\rm Pl}$$

$$\Big\updownarrow \text{RG}$$

$$\int d^4\theta \, \frac{\theta^4 \langle F \rangle^2}{M_{\rm Pl}^2} Q^\dagger Q \quad + \underset{!}{5.4} \int d^2\theta \, \frac{\theta \langle D \rangle}{M_{\rm Pl}} W\Sigma \qquad @ \, 1 \text{ TeV}$$

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(Dirac gauginos $\rightarrow$ 1-loop running only by Yukawa!) $\qquad$ RG

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The hierarchy arises naturally!

What about hierarchies inside $m_{\tilde{q}}^2$?

Flavor $\longrightarrow$ $m_{1/2} \sim 10 m_{\tilde{q}}\,,\, c_{12} \sim c_{11}/10 \sim c_{22}/10$

CP ($\mathrm{Im}\, K$-$\overline{K}$) $\longrightarrow$ $\theta_{\mathrm{CP}} \sim 1/10$ (Blechman, Ng, '08)

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But c_{ij} here is not the "fundamental" c_{ij}:

E

$$M_{\mathrm{Pl}} \quad (c_{ij}^{\mathrm{UV}}) = \mathcal{O}(0.1)\begin{pmatrix} \sim 1 & \sim 1 & \sim 1 \\ \sim 1 & \sim 1 & \sim 1 \\ \sim 1 & \sim 1 & \sim 1 \end{pmatrix} \quad \Delta\theta_{\mathrm{CP}} \sim 0.1$$

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$m_{\tilde{g}}$ 5 TeV

Integrate out gluino $\longrightarrow$ $(m^2_{\tilde{q}})_{ij} \sim (300\ \mathrm{GeV})^2 c^{\mathrm{UV}}_{ij} + (1\ \mathrm{TeV})^2 \delta_{ij}$

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$m_{\tilde{q}}$ — 1 TeV $\longrightarrow$ $c_{12}^{\rm IR} \sim \dfrac{0.1\ \mathrm{TeV}^2}{1\ \mathrm{TeV}^2} \sim 0.1$

"Fundamental" c_{ij} can be "anarchic"!

A new U(1) gauge symmetry

A serious problem:

$$\int d^4\theta \, \frac{X^\dagger X}{M_{\rm Pl}^2} R^\dagger_{d,u} H_{u,d}$$ would kill accidental $U(1)_R$!

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The new U(1) solves two additional problems!

(1) No singlets $\longrightarrow$ $\cancel{\int d^4\theta \, \frac{X^\dagger}{M_{\rm Pl}} \Phi\Phi'}$ $\longrightarrow$ $\cancel{\mu H_u H_d}$ good!

$\cancel{H_u R_u + H_d R_d}$ oops!

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$\longrightarrow$ Need a new gauge symmetry $U(1)_{\text{``N''}\,\rm ew}$! (No global symm with gravity)

$$N[R_u] = -N[R_d] = 1\,, \quad N[H, Q, U, D, L, E] = 0$$

Can be naturally broken at TeV: $\langle S \rangle \neq 0$ by ${m_s}^2 < 0$

(Naturally TeV)

The new U(1) solves two additional problems!

(1) No singlets $\longrightarrow$ $\cancel{\int d^4\theta \, \frac{X^\dagger}{M_{\rm Pl}} \Phi\Phi'}$ $\longrightarrow$ $\cancel{\mu H_u H_d}$ good!

$\cancel{H_u R_u + H_d R_d}$ oops!

But we have $\langle S \rangle \neq 0$! Just assign

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A new U(1) gauge symmetry

A serious problem:

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(2) LEP Higgs bound?

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(2) LEP Higgs bound? $\mathcal{O}(1)$ $\longrightarrow$ Large H quartic! $\longrightarrow$ $m_H > 114$ GeV!

Dirty Laundries...

* Neutralino masses

$$\begin{pmatrix} R[H] = R[S] = 0 \\ R[R] = 2 \end{pmatrix} \longrightarrow \quad H_u \to \begin{bmatrix} \tilde{h}_u^+ \\ \tilde{h}_u^0 \end{bmatrix} \qquad R_u \to \begin{bmatrix} \tilde{r}_u^0 \\ \tilde{r}_u^- \end{bmatrix} \qquad S_u \to \tilde{s}_u$$

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Need $T_{u,d}$ with $R[T_{u,d}]=2$. Then,

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(chiral "adjoints" for $U(1)_Y, U(1)_N$)

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Maybe trinification? $[SU(3)_C \otimes SU(3)_L \otimes SU(3)_R]/\mathbb{Z}_3$

$$(\mathbf{8},\mathbf{1},\mathbf{1}) \oplus (\mathbf{1},\mathbf{8},\mathbf{1}) \oplus (\mathbf{1},\mathbf{1},\mathbf{8}) \longrightarrow \Sigma_{1,2,3} \oplus R_{u,d} \oplus S_{u,d} \oplus 2\times[(\mathbf{1},\mathbf{1})_1 \oplus (\mathbf{1},\mathbf{1})_{-1}]$$

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But what about $U(1)_N$? $T_{u,d}$? Quartification $[SU(3)]^4$?

Collider Prospects

$U(1)_N$ will be very interesting!

$U(1)_N$-neutral

V, Σ

Q, U, D, L, E

$H_{u,d}$

$U(1)_N$-charged

$R_{u,d}$

$S_{u,d}$ $T_{u,d}$

Collider Prospects

$U(1)_N$ will be very interesting!

A Higgs-philic, fermi-phobic Z'!

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Q, U, D, L, E

$H_{u,d}$

Mix!

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$S_{u,d}$ $T_{u,d}$

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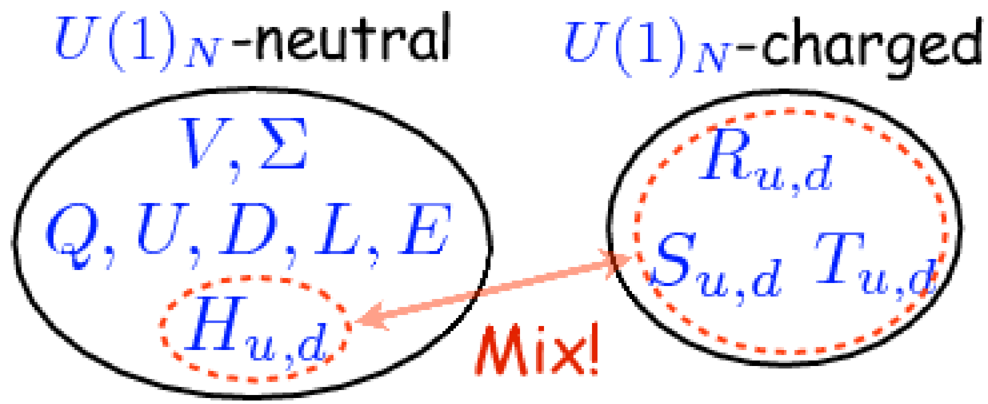
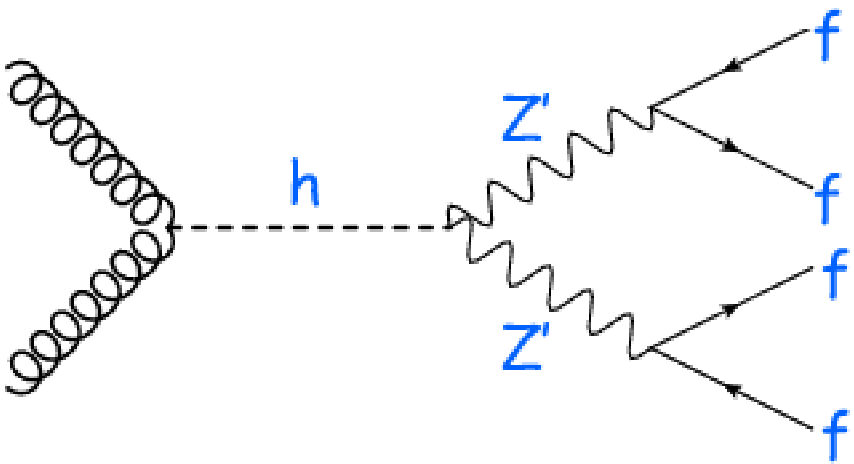


Production:



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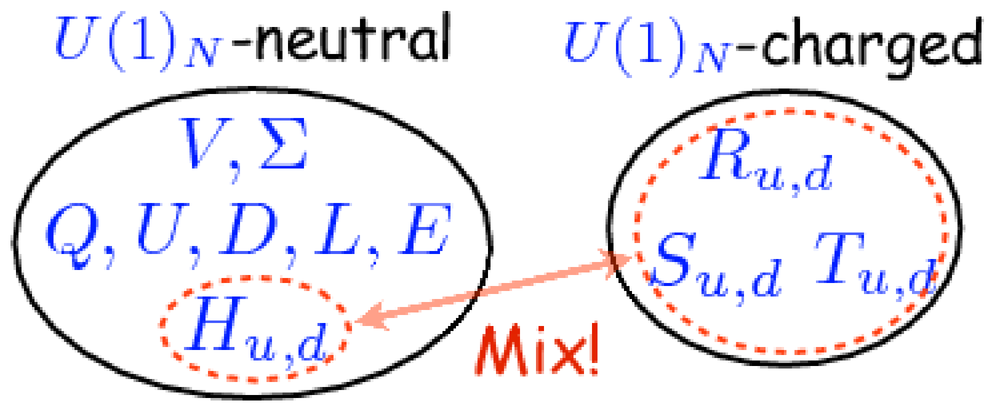

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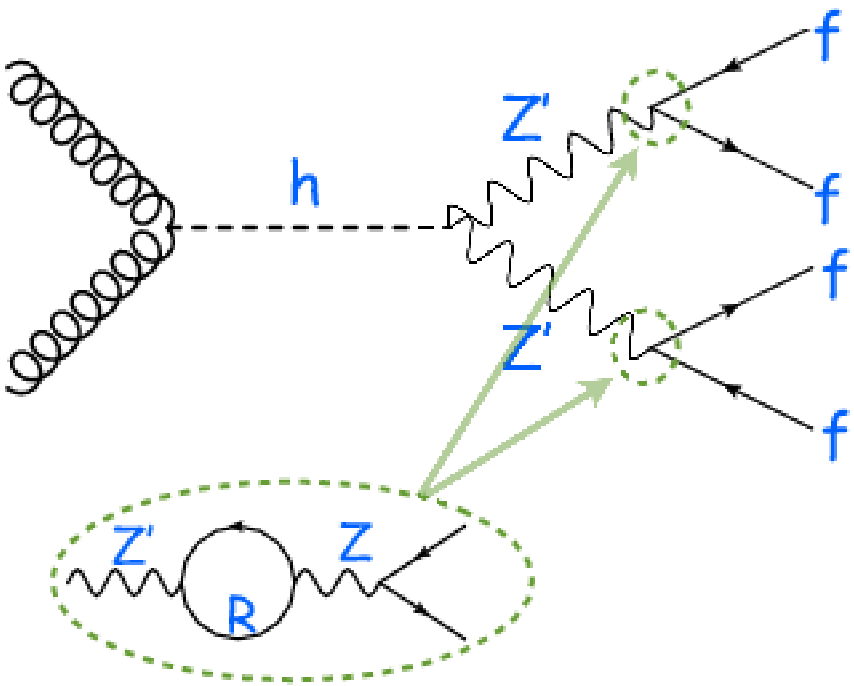

Tiny, only loop-induced

Collider Prospects

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$U(1)_N$-neutral: V, Σ; Q, U, D, L, E; $H_{u,d}$

$U(1)_N$-charged: $R_{u,d}$; $S_{u,d}$ $T_{u,d}$

Mix!

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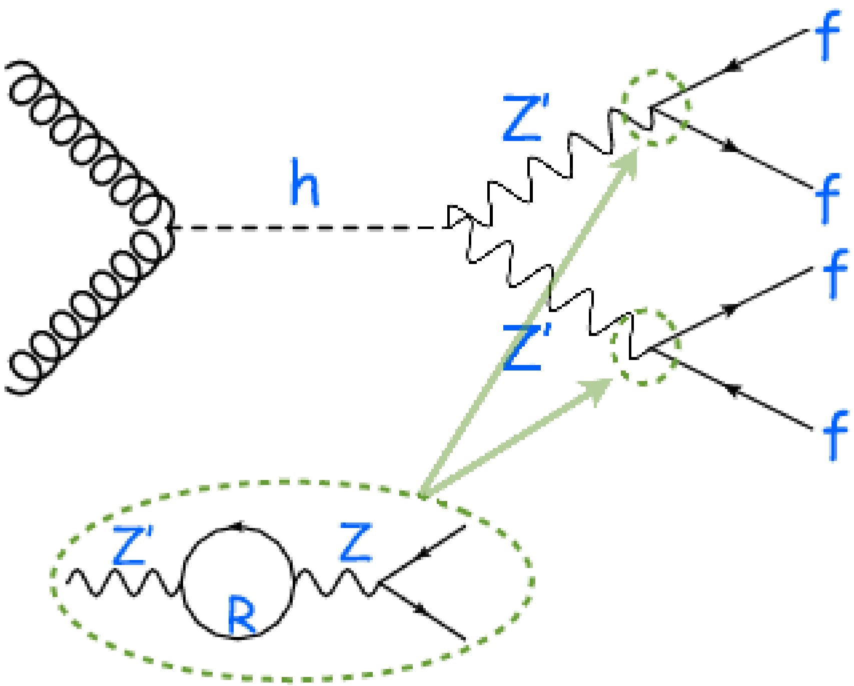

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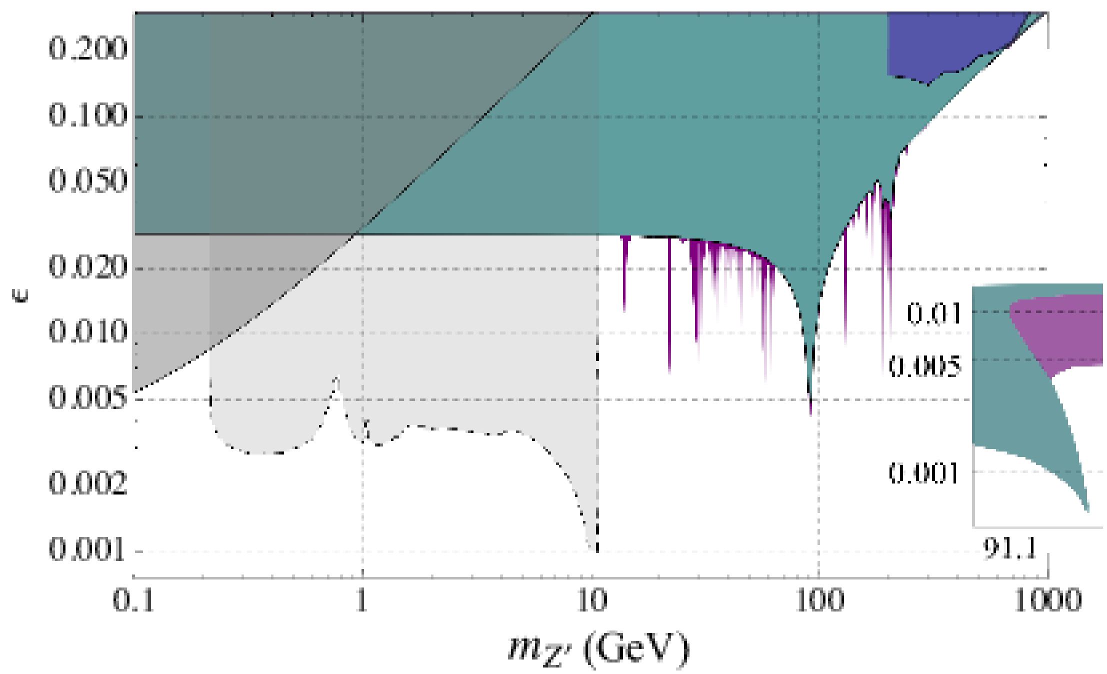
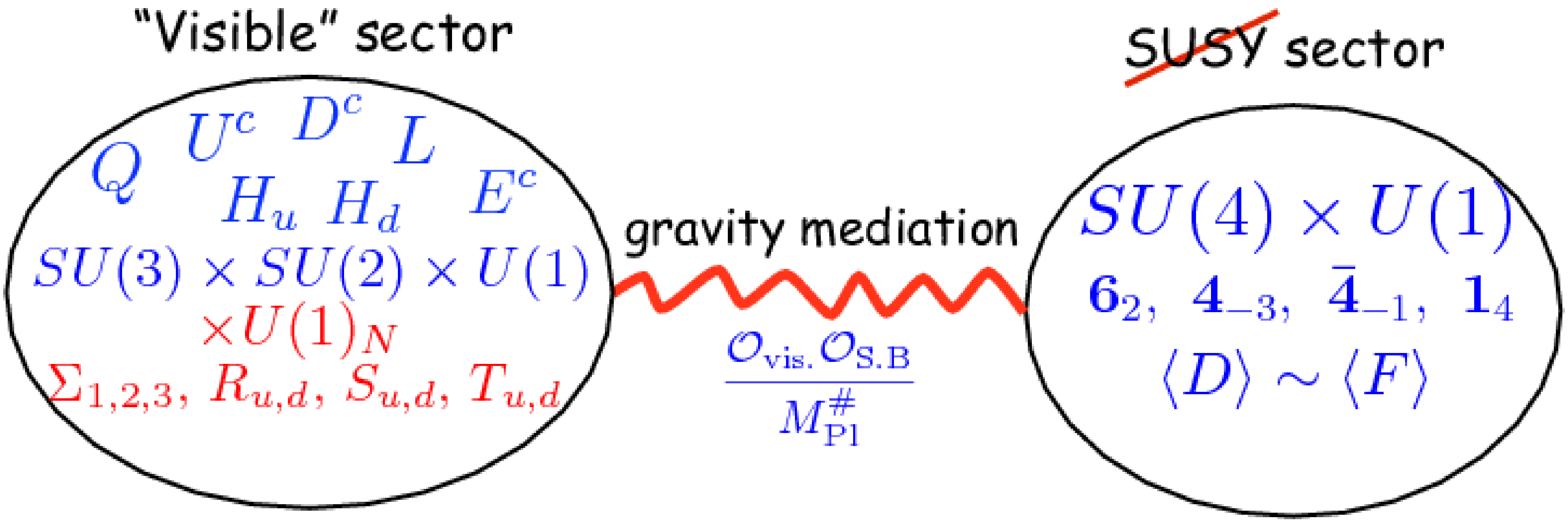


(Hook, Izaguirre, Wacker, 1006.0973)

Z' Can be very light!

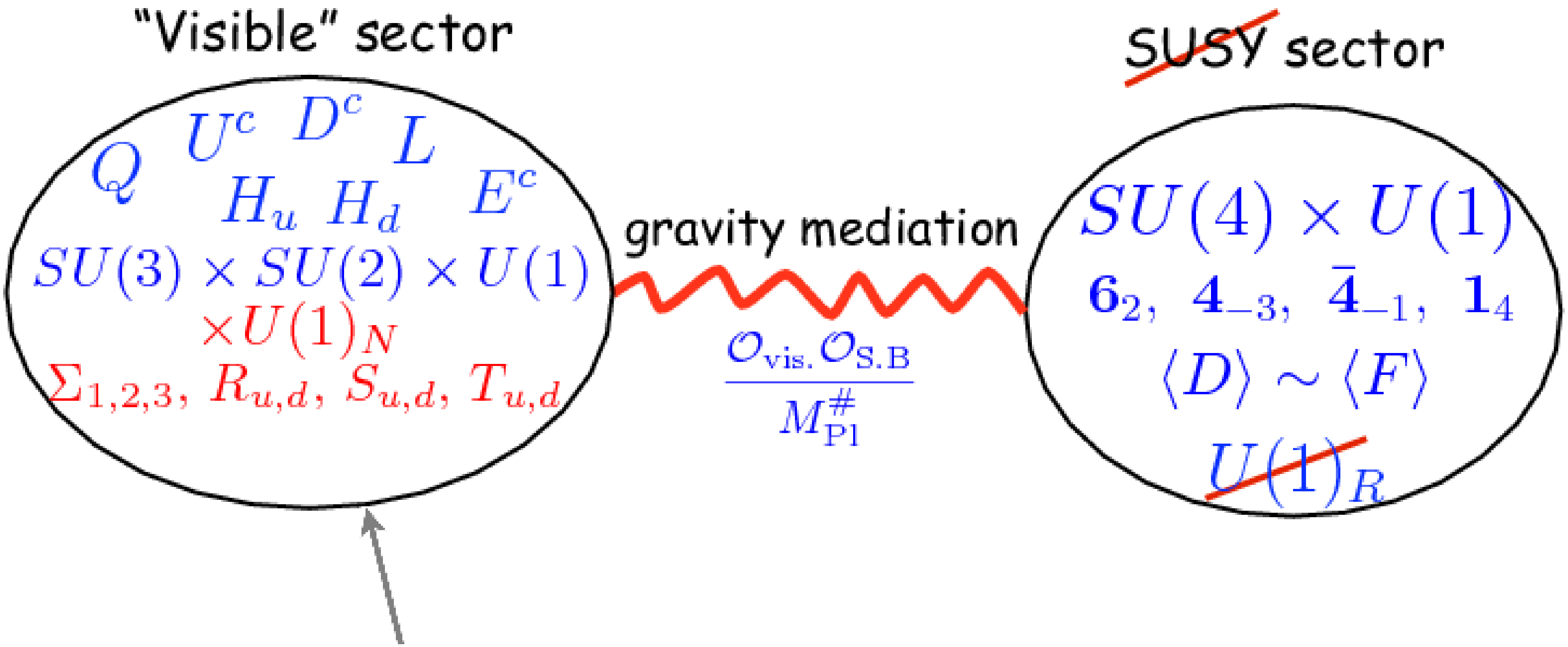
Possibly at early LHC!?

Summary



“Visible” sector
Q U^c D^c L
H_u H_d E^c
$SU(3) \times SU(2) \times U(1)$
$\times U(1)_N$
$\Sigma_{1,2,3},\ R_{u,d},\ S_{u,d},\ T_{u,d}$
gravity mediation
$\frac{\mathcal{O}_{\rm vis.}\mathcal{O}_{\rm S.B}}{M_{\rm Pl}^{\#}}$
$\cancel{\text{SUSY}}$ sector
$SU(4) \times U(1)$
$\mathbf{6}_2,\ \mathbf{4}_{-3},\ \bar{\mathbf{4}}_{-1},\ \mathbf{1}_4$
$\langle D \rangle \sim \langle F \rangle$

Summary



Accidental $U(1)_R$! (SUSY flavor problem solved!)

All mass scales right (esp. $m_{\tilde{g}} \sim 10 m_{\tilde{q}}$ from RG)
no mu-Bmu problem, neutralino DM.

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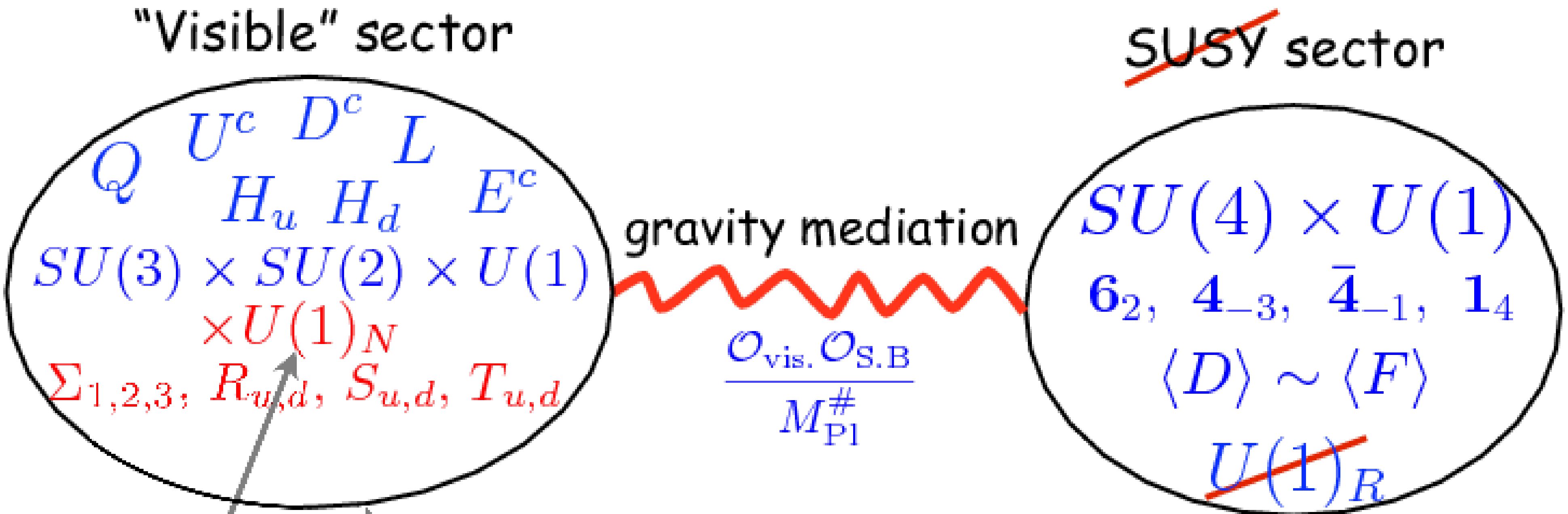

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Essential for accidental $U(1)_R$! Interesting LHC pheno!