SUSY breaking and the nature of *.inos

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Outline

SUSY is a space-time (ST) symmetry

$$\left.\begin{array}{rcl} Q|\text{Fermion}\rangle & = & |\text{Boson}\rangle \\ Q|\text{Boson}\rangle & = & |\text{Fermion}\rangle \end{array}\right\} Q\text{s generate a ST symmetry}$$

$$\{Q, Q^\dagger\} = P \Longleftrightarrow [\theta Q, \theta^\dagger Q^\dagger] = \theta\theta^\dagger P$$

An Introduction to Superspace

$$x \longrightarrow (x, \theta, \theta^\dagger)$$
$$s(x) \longrightarrow S(x, \theta, \theta^\dagger)$$

$$\Phi = \phi + \theta\psi + \theta^2 F + \dots$$
$$\mathbf{V} = \theta\theta^\dagger A + \theta^{\dagger 2}\theta\lambda + \theta^2\theta^{\dagger 2} D + \dots$$
$$\mathbf{W}_\alpha = \lambda_\alpha + \theta_\alpha D + \dots$$

Solving the Higgs Hierarchy Problem

Quick Higgs revision

Standard Model Higgs potential

$$V(H) \sim \mu^2 |H|^2 + \lambda |H|^4$$

Higgs vacuum expectation value (VEV)

$$\langle H \rangle = \sqrt{-\mu^2/2\lambda} \sim 174\,\mathrm{GeV}$$

Implies a Higgs mass

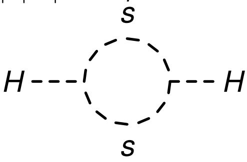
$$m_H^2 = -\mu^2 \sim 100\,\mathrm{GeV}$$

Solving the Higgs Hierarchy Problem

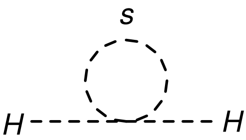
Higgs self-energy at one-loop

$$-\mathcal{L} \subset \lambda_s |s|^2 |H|^2 + \lambda_f H \bar{f} f$$

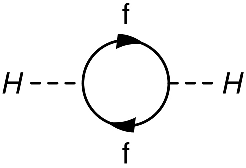
s = scalars
f = fermions



$$\sim -\lambda_s m_S^2 \ln\left(\frac{\Lambda}{m_S}\right)$$



$$\sim \lambda_s \Lambda^2$$



$$\sim -\lambda_f^2 \Lambda^2$$

Solving the Higgs Hierarchy Problem

UV cut-off at one-loop

At one-loop

$$m_H^2 \longrightarrow m_H^2 + \Lambda^2 \left(\sum_{\text{scalars}} \lambda_s - \sum_{\text{fermions}} \lambda_f^2 \right) - \sum_{\text{scalars}} \lambda_s m_s^2 \ln \left(\frac{\Lambda}{m_s} \right)$$

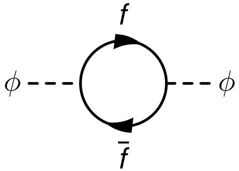
Natural Higgs mass

$$\Lambda \sim m_{\text{Pl}} \implies m_{\text{nat}} \sim m_{\text{Pl}}$$

Solving the Higgs Hierarchy Problem

Higgs self-energy at one-loop

$$-\mathcal{L} \supset \lambda_f \phi f \bar{f}$$



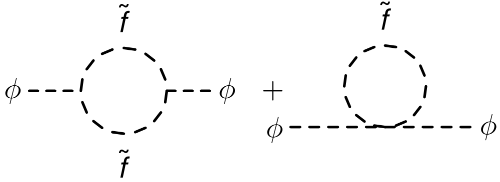
$$= \pi^f_{\phi\phi}(0)$$

$$\pi^f_{\phi\phi}(0) = -2N(f)\lambda_f^2 \int \frac{d^4k}{(2\pi)^4} \left[\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right]$$

Solving the Higgs Hierarchy Problem

Higgs self-energy at one-loop

$$-\mathcal{L} \supset A_f \lambda_f \phi \tilde{f}_L \tilde{f}_R^* + \tilde{\lambda}_f \phi^2 \left(|\tilde{f}_L|^2 + |\tilde{f}_R|^2 \right) + v \tilde{\lambda}_f \phi \left(|\tilde{f}_L|^2 + |\tilde{f}_R|^2 \right)$$



$$= \pi^{\tilde{f}}_{\phi\phi}(0)$$

$$\pi^{\tilde{f}}_{\phi\phi}(0) = -\tilde{\lambda}_f N(\tilde{f}) \int \frac{d^4k}{(2\pi)^4} \left[\frac{1}{k^2 - m^2_{\tilde{f}_L}} + (L \leftrightarrow R) \right] + \cdots$$

Solving the Higgs Hierarchy Problem

Higgs self-energy at one-loop

$$\pi^{f}_{\phi\phi}(0) = -2N(f)\lambda_f^2 \int \frac{d^4k}{(2\pi)^4}\left[\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2}\right]$$

$$\pi^{\tilde{f}}_{\phi\phi}(0) = -\tilde{\lambda}_f N(\tilde{f}) \int \frac{d^4k}{(2\pi)^4}\left[\frac{1}{k^2 - m_{\tilde{f}_L}^2} + (L \leftrightarrow R)\right]$$

$$+ \left(\tilde{\lambda}_f v\right)^2 N(\tilde{f}) \int \frac{d^4k}{(2\pi)^4}\left[\frac{1}{\left(k^2 - m_{\tilde{f}_L}^2\right)^2} + (L \leftrightarrow R)\right]$$

$$+ |\lambda_f A_f|^2 N(\tilde{f}) \int \frac{d^4k}{(2\pi)^4} \frac{1}{\left(k^2 - m_{\tilde{f}_L}^2\right)\left(k^2 - m_{\tilde{f}_R}^2\right)}$$

Solving the Higgs Hierarchy Problem

Higgs self-energy at one-loop

$$\tilde{\lambda}_f = -\lambda_f^2, \quad N(\tilde{f}) = N(f)$$

$$\pi_{\phi\phi}^{f+\tilde{f}}(0) = i\frac{\lambda_f^2 N(f)}{16\pi^2}\Bigg[-2m_f^2\left(1-\log\frac{m_f^2}{\mu^2}\right)+4m_f^2\log\frac{m_f^2}{\mu^2}$$
$$+2m_{\tilde{f}}^2\left(1-\log\frac{m_{\tilde{f}}^2}{\mu^2}\right)-4m_f^2\log\frac{m_{\tilde{f}}^2}{\mu^2}$$
$$-|A_f|^2\log\frac{m_{\tilde{f}}^2}{\mu^2}\Bigg]$$

Solving the Higgs Hierarchy Problem

Higgs self-energy at one-loop

$$\tilde{\lambda}_f = -\lambda_f^2, \quad N(\tilde{f}) = N(f), \quad m_{\tilde{f}} = m_f, \quad A_f = 0$$

$$\pi_{\phi\phi}^{f+\tilde{f}}(0) = 0$$

Solving the Higgs Hierarchy Problem

You saved us... thanks supersymmetry!

ψ/ϕ pairings

$+ \quad \tilde{\lambda}_f = -\lambda_f^2$

$+ \quad A_f = 0$

Unavoidable with supersymmetry

Gauge Coupling Unification

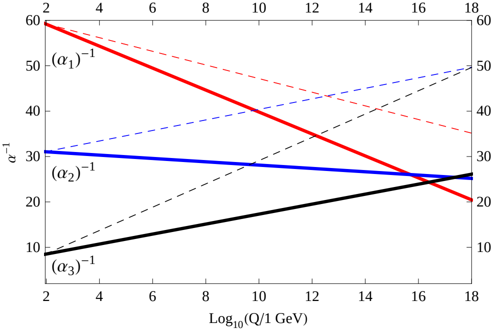
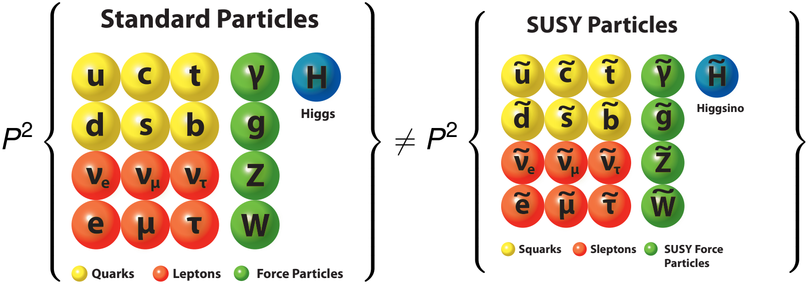


Figure: RGE of α_i^{-1} in SM (dashed) and MSSM (solid)

Evidence

- Degeneracy in (s)particle mass spectrum not observed

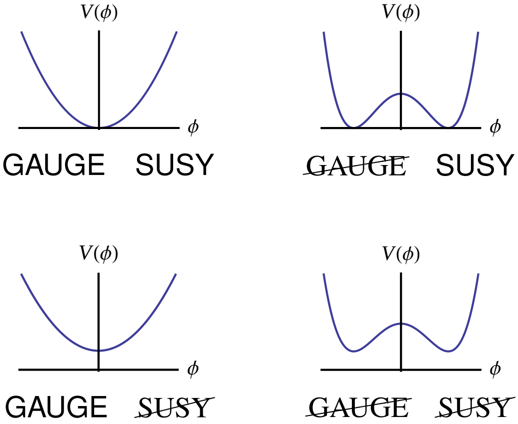


- If SUSY is realized, it is broken at low energies

Properties

- Theory is SUSY but scalar potential V admits ~~SUSY~~ vacua

$$Q|\mathrm{vacuum}\rangle \neq 0 \Longleftrightarrow V(\mathrm{vacuum}) > 0$$



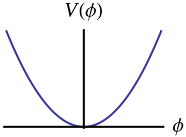
Recipe

- $U(1)$ VSF spurion $\langle \mathbf{W}_\alpha \rangle = \theta_\alpha D$
- Gauge-singlet χSF spurion $\langle \mathbf{X} \rangle = \theta^2 F$

How does this work?

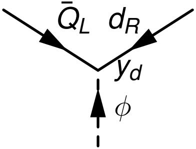
The Standard Model Higgs Mechanism

$$\Lambda > \Lambda_{\rm EWSB}$$



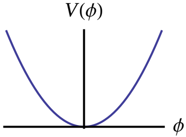
GAUGE

$$-\mathcal{L} \supset y_d \bar{Q}_L \phi d_R$$



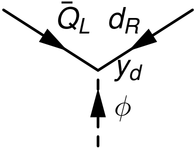
The Standard Model Higgs Mechanism

$$\Lambda > \Lambda_{\mathrm{EWSB}}$$



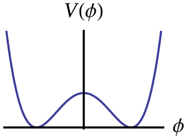
GAUGE

$$-\mathcal{L} \supset y_d \bar{Q}_L \phi d_R$$



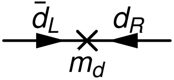
$$\Lambda < \Lambda_{\mathrm{EWSB}}$$

$$\phi \longrightarrow (0, \nu + H)$$



~~GAUGE~~

$$-\mathcal{L} \supset \underbrace{y_d \nu}_{m_d} \bar{d}_L d_R$$

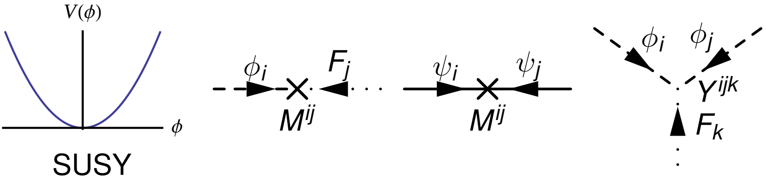


SUSY Breaking in Wess-Zumino Model

$$\Lambda > \Lambda_{\not{\text{SUSY}}}$$

$$\mathcal{L} = \int d^2\theta \underbrace{M^{ij}\Phi_i\Phi_j + Y^{ijk}\Phi_i\Phi_j\Phi_k}_{W(\Phi_i)} + \text{h.c.} + \int d^2\theta d^2\theta^\dagger \underbrace{\Phi^{*i}\Phi_i}_{K(\Phi^{*i},\Phi_i)}$$

$$\supset -M^{ij}\left(\phi_i F_j + \psi_i\psi_j\right) - Y^{ijk}\phi_i\phi_j F_k + \text{h.c.} + F^{*i}F_i$$



SUSY Breaking in Wess-Zumino Model

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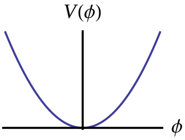
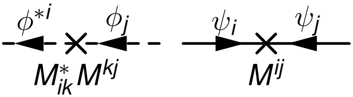
$$\mathcal{L} = \int d^2\theta \underbrace{M^{ij}\Phi_i\Phi_j + Y^{ijk}\Phi_i\Phi_j\Phi_k}_{W(\Phi_i)} + \text{h.c.} + \int d^2\theta d^2\theta^\dagger \underbrace{\Phi^{*i}\Phi_i}_{K(\Phi^{*i},\Phi_i)}$$

$$\supset -M^*_{ik}M^{kj}\phi^{*i}\phi_j - M^{ij}\psi_i\psi_j$$



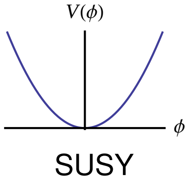
SUSY

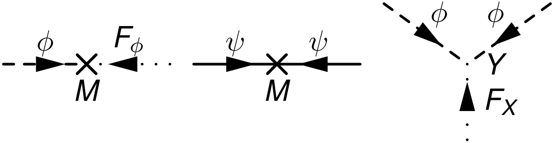


SUSY Breaking in Wess-Zumino Model

$$\Lambda > \Lambda_{\cancel{SUSY}}$$

$$\mathcal{L} = \int d^2\theta \left(M\Phi^2 + Y\Phi^2 X \right) + \text{h.c.} + \int d^2\theta d^2\theta^\dagger \Phi^* \Phi$$
$$\supset -M\left(\phi F_\phi + \psi\psi\right) - Y\phi\phi F_X + \text{h.c.} + |F_\phi|^2 + |F_X|^2$$

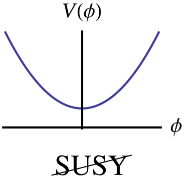


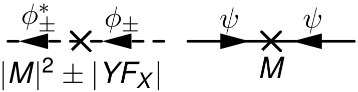


SUSY Breaking in Wess-Zumino Model

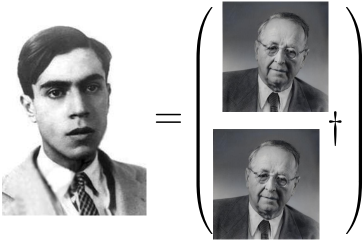
$$\Lambda < \Lambda_{\not{\mathrm{SUSY}}} \quad \langle X \rangle = \theta^2 F$$

$$\mathcal{L} = \int d^2\theta \left(M\Phi^2 + Y\Phi^2 X \right) + \text{h.c.} + \int d^2\theta d^2\theta^\dagger \Phi^* \Phi$$
$$\supset -M\psi\psi - (|M|^2 \pm |YF_X|)|\phi_\pm|^2$$

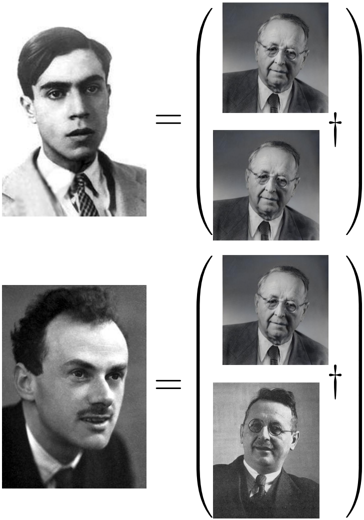




Dirac and Majorana particles



Dirac and Majorana particles



Mass terms

Majorana mass

$$-\mathcal{L}_{\text{Majorana}} \supset M_M \bar{\Psi}_M \Psi_M = M_M(\xi\xi + \xi^\dagger\xi^\dagger) \qquad \Psi_M = \begin{pmatrix} \xi \\ \xi^\dagger \end{pmatrix}$$

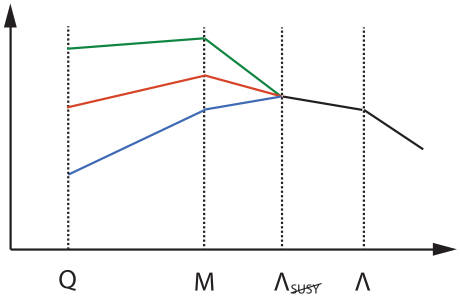
Dirac mass

$$-\mathcal{L}_{\text{Dirac}} \supset M_D \bar{\Psi}_D \Psi_D = M_D(\xi\chi + \xi^\dagger\chi^\dagger) \qquad \Psi_D = \begin{pmatrix} \xi \\ \chi^\dagger \end{pmatrix}$$

$$-\mathcal{L}^{\text{MSSM}}_{\text{soft}} \supset M_3\, \tilde{\text{g}}\tilde{\text{g}} + M_2\, \widetilde{\text{W}}\widetilde{\text{W}} + M_1\, \widetilde{\text{B}}\widetilde{\text{B}}$$

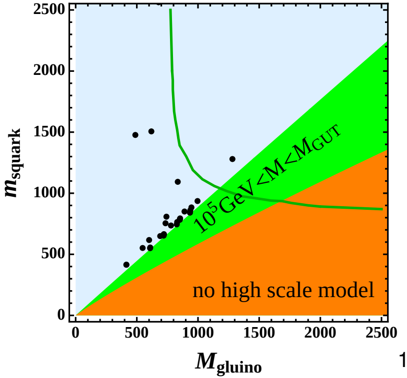
Approximate SQCD β Functions

$$\frac{d}{dt} m_{\tilde{q}}^2 \sim m_{\tilde{q}}^2 + M_{\tilde{g}}^2$$
$$\frac{d}{dt} M_{\tilde{g}} \sim M_{\tilde{g}}$$



$$m_{\tilde{q}}^2(Q) \sim m_{\tilde{q}}^2(M) + a\, m_{\tilde{q}}^2(M) + b\, M_{\tilde{g}}^2(Q)$$

The Forbidden Zone



[1]

[1] Jaeckel, J., Khoze, V. V., Plehn, T., & Richardson, P. (2011). Travels on the squark-gluino mass plane. http://arxiv.org/abs/1109.2072

What is $R-$symmetry?

$$\{Q, Q^\dagger\} = P$$

Invariant under

$$Q \to e^{iR_Q\theta} Q, \quad Q^\dagger \to Q^\dagger e^{-iR_Q\theta}, \quad P \to P$$

Choose $R_Q = -1$

$$[Q, R] = Q \qquad [\theta, R] = -\theta$$

$$[Q^\dagger, R] = -Q^\dagger \qquad [\theta^\dagger, R] = \theta^\dagger$$

R-charge of Gauginos

$$V = V^\dagger \implies R_V = 0$$

$$V \supset \theta^{\dagger 2}\theta\lambda$$

$$R_\theta = -R_{\theta^\dagger} = 1 \implies R_\lambda = 1$$

Majorana Gaugino Masses

$$-\mathcal{L}^{\text{gaugino}}_{\text{Majorana}} \supset M_M(\lambda\lambda + \lambda^\dagger\lambda^\dagger)$$

$$\lambda\lambda \xrightarrow{U(1)_R} e^{2i\theta}\lambda\lambda$$

Majorana gaugino masses violate $U(1)_R$ symmetry

Dirac Gaugino Masses

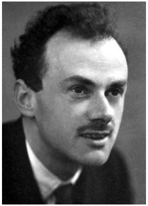
$$-\mathcal{L}_{\text{Dirac}} \supset M_D(\lambda\chi + \lambda^\dagger\chi^\dagger)$$

$$\lambda\chi \xrightarrow{U(1)_R} e^{i(1+R_\chi)\theta}\lambda\chi$$

Dirac gaugino masses can preserve $U(1)_R$ symmetry

The idea

$U(1)_R$	$\longleftrightarrow$	~~$U(1)_R$~~
$M_M \to 0$	$M_M \sim M_D$	$\frac{M_M}{M_D} \gg 1$



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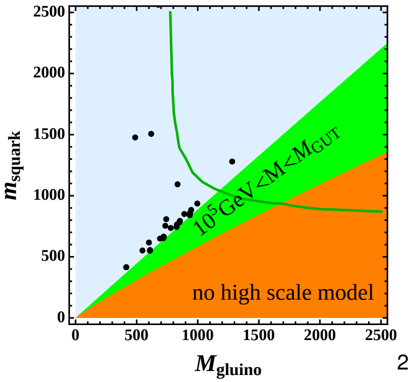


[2]

[2] Jaeckel, J., Khoze, V. V., Plehn, T., & Richardson, P. (2011). Travels on the squark-gluino mass plane. http://arxiv.org/abs/1109.2072

Minimal Dirac Gauginos

$$R_{\chi_g} = -1, \quad \mathbf{O}_g \supset \theta\chi_g, \quad \langle \mathbf{W}'_\alpha \rangle = \theta_\alpha D$$

Names	Superfield	$SU(3)_C$	$U(1)_R$
RHGs	$\mathbf{O}_g$	**Ad**	0
GFs	$\mathbf{W}_{3\alpha}$	**Ad**	1

$$\mathcal{L}^{\text{Dirac}}_{\text{gluino}} = \int d^2\theta \frac{\mathbf{W}'^\alpha}{\Lambda} \text{Tr}\left[\mathbf{W}_{3\alpha}\mathbf{O}_g\right] \supset -m_D\lambda_3\chi_g$$

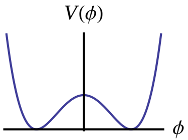
$$m_D = \frac{D}{\Lambda} \tag{1}$$

$\mathcal{N} = 2$ vector multiplet $(\mathbf{O}_g, \mathbf{V}_3)$

MSSM Higgs

$$W_{\text{MSSM}} = y_u \bar{\mathbf{u}}\mathbf{Q}\cdot\mathbf{H}_u + y_d \bar{\mathbf{d}}\mathbf{Q}\cdot\mathbf{H}_d + \mu \mathbf{H}_u\cdot\mathbf{H}_d + \cdots$$

$$\Lambda < \Lambda_{\text{EWSB}}$$



~~GAUGE~~

$$H_u^0 \longrightarrow \nu_u + \cdots$$

$$H_d^0 \longrightarrow \nu_d + \cdots$$

$$\mathcal{L} \supset \int d^2\theta\, W(\Phi_i) \supset -\mu \tilde{\mathbf{H}}_u\cdot\tilde{\mathbf{H}}_d$$

Dirac Higgsinos

Superfield	$SU(2)_L$	$U(1)_Y$	$U(1)_R$
$\mathbf{H}_u$	$\square$	$\frac{1}{2}$	0
$\mathbf{R}_d$	$\square$	$\frac{1}{2}$	2
$\mathbf{H}_d$	$\square$	$-\frac{1}{2}$	0
$\mathbf{R}_u$	$\square$	$-\frac{1}{2}$	2

$$W_{\text{Higgs}} = \left(\mu_u + \lambda_u^S \mathbf{S}\right) \mathbf{H}_u \cdot \mathbf{R}_u + \lambda_u^T \mathbf{H}_u \cdot \mathbf{T} \mathbf{R}_u + (u \leftrightarrow d)$$

$\mathcal{N} = 2$ Hypermultiplet $(\mathbf{H}_u, \mathbf{R}_d)$

Is $R-$symmetry useful?

- Dangerous $\Delta L = \Delta B = 1$ operators forbidden
- Proton decay through $Q_L Q_L Q_L L_L$, $U_R U_R D_R E_R$ forbidden
- Majorana Neutrino mass $H_u H_u L_L L_L$ allowed[3]

[3] Kribs, G., Poppitz, E., & Weiner, N. (2008). Flavor in supersymmetry with an extended R symmetry. Physical Review D, 78(5) 055010

Summary of MRSSM

- All *.inos are Dirac
- Higgs and Gauge sector form $\mathcal{N} = 2$ representations
- Gauginos much heavier than squarks possible

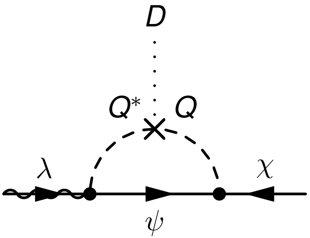
Outlook

- High-scale completion? Gauge mediation?[4]
- Create a consistent effective theory at the high scale
- Identify important phenomenology using simplified models

[4] Benakli, K., & Goodsell, M. D. (2008). Dirac Gauginos in GGM. arXiv:0811.4409

Messenger completion

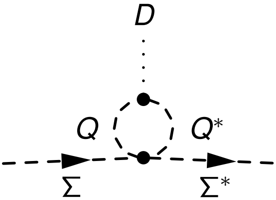
Dirac gaugino D-terms



$$\sim g\lambda QY \frac{1}{16\pi^2}\frac{D}{M_{\text{Mess}}}\left[1+\mathcal{O}\left(\frac{D^2}{M_{\text{Mess}}^4}\right)\right]$$

Messenger completion

Adjoint scalar D-terms



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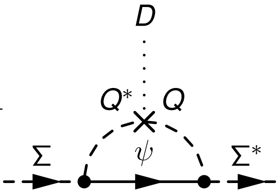
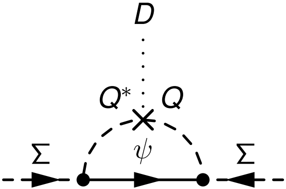


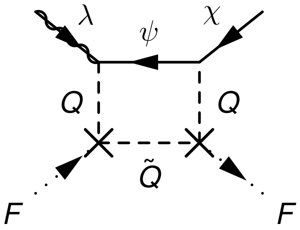
$$\sim \frac{1}{16\pi^2} DQ|\lambda|^2 + \frac{1}{16\pi^2}\frac{D^2}{M_{\mathrm{Mess}}^2} Q^2|\lambda|^2$$



$$\sim -\frac{1}{16\pi^2}\frac{D^2}{M_{\mathrm{Mess}}^2} Q^2|\lambda|^2$$

Messenger completion

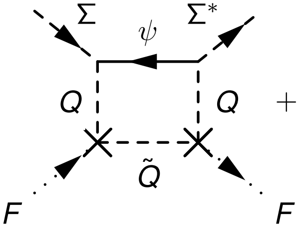
Dirac gaugino F-terms



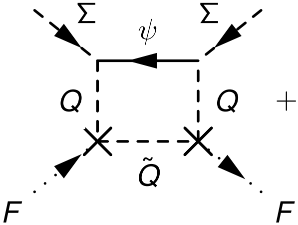
$$\sim \lambda|\kappa|^2 \frac{1}{16\pi^2} \frac{|F|^2}{M^3_{\rm Mess}}$$

Messenger completion

Adjoint scalar F-terms



$$+\,(\text{more diagrams}) \;\sim\; |\lambda|^2|\kappa|^2\frac{1}{16\pi^2}\frac{|F|^2}{M^2_{\text{Mess}}}$$



$$+\,(\text{more diagrams}) \;\sim\; -|\lambda|^2|\kappa|^2\frac{1}{16\pi^2}\frac{|F|^2}{M^2_{\text{Mess}}}$$

Messenger completion

Aim

Identify minimal set of parameters to describe theory at high scale, e.g.

$$m_D(M), m_\Sigma^2(M), m_q^2(M) = f\left(\Lambda_{\langle D\rangle}, \Lambda_{\langle F\rangle}, M\right)$$

Thanks

Thanks for listening!