Dark Gauge-Mediated SUSY Breaking

with a Massless Dark Photon

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Based on [arXiv:2412.XXXXX]

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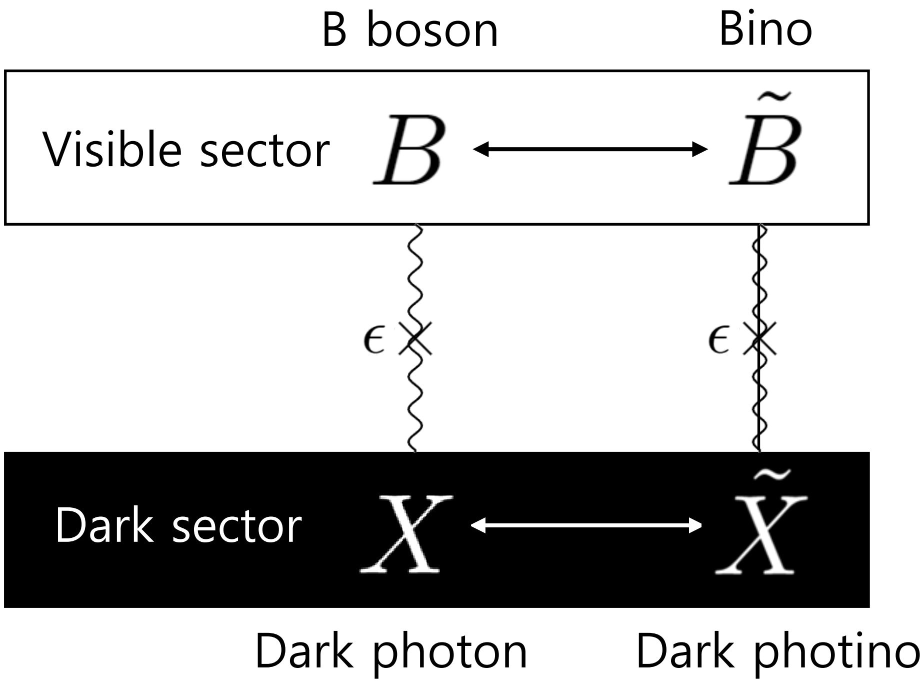
Kinetic mixing & SUSY



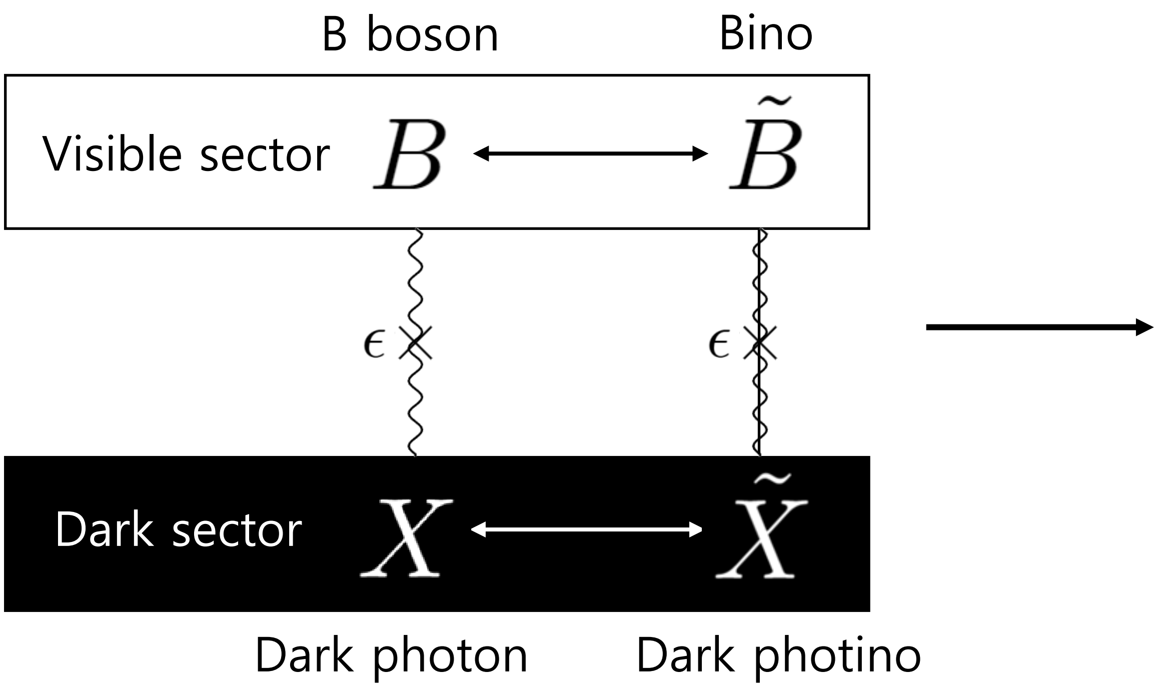
$$\mathcal{L} \supset \int d^2\theta \left(\frac{1}{4}\hat{\mathcal{W}}_B \hat{\mathcal{W}}_B + \frac{1}{4}\hat{\mathcal{W}}_X \hat{\mathcal{W}}_X + \frac{\epsilon}{2}\hat{\mathcal{W}}_B \hat{\mathcal{W}}_X \right)$$

$$= -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}X^{\mu\nu}$$

$$+ i\tilde{B}^\dagger \sigma^\mu \partial_\mu \tilde{B} + i\tilde{X}^\dagger \sigma^\mu \partial_\mu \tilde{X} + i\epsilon \tilde{B}^\dagger \sigma^\mu \partial_\mu \tilde{X}$$

SUSY Kinetic mixing

Kinetic mixing & SUSY



Kinetic mixing
for **SUSY breaking**
transfer

+

GMSB
(**G**auge-**M**ediated
SUSY **B**reaking)

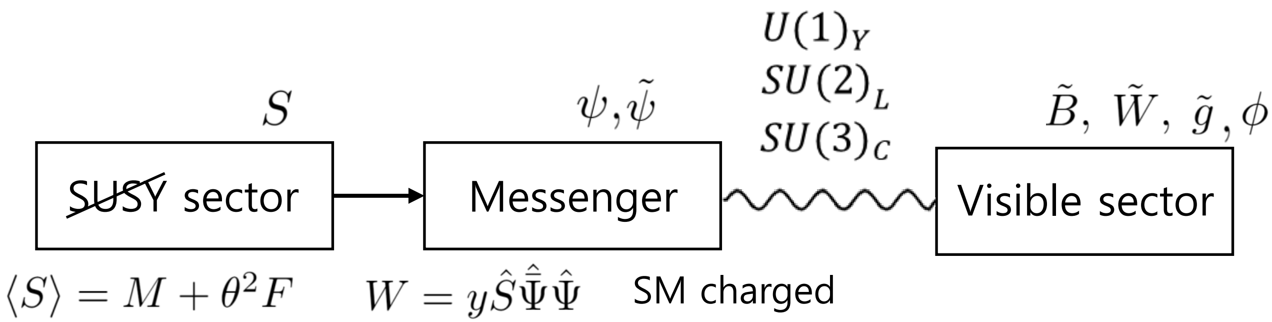
=

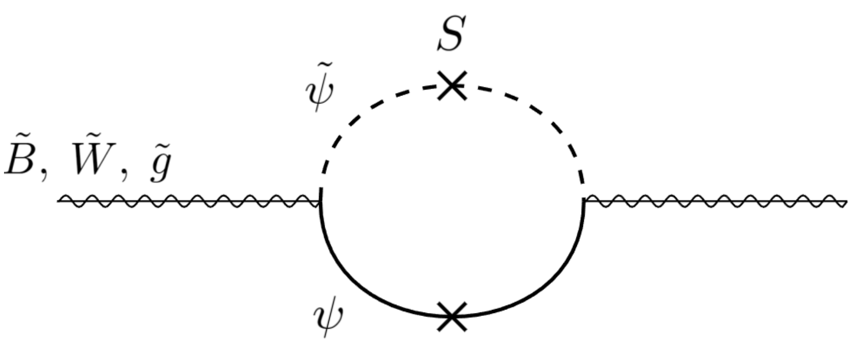
"Dark GMSB"

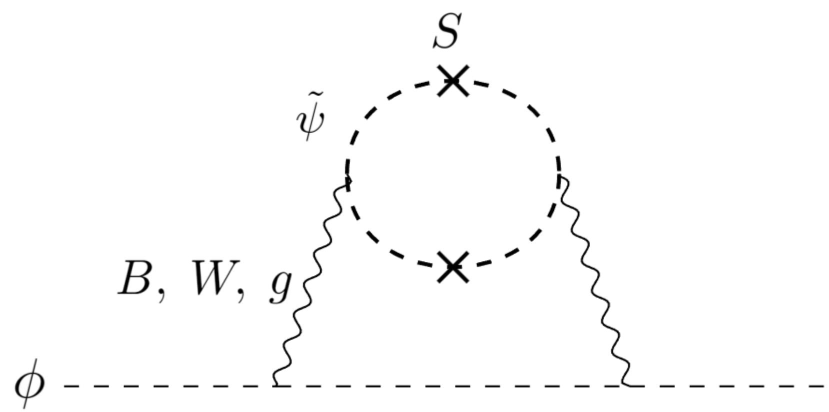
Contents

- Kinetic mixing & SUSY
- GMSB vs Dark GMSB
- Soft mass in Dark GMSB
- Mass spectrum
- Phenomenology
- Summary

GMSB vs Dark GMSB







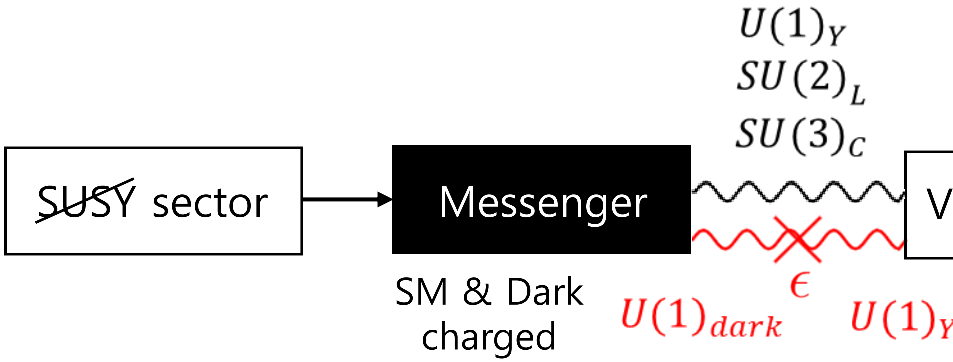
$$M_a \simeq \frac{g_a^2}{16\pi^2}\frac{F}{M}$$

Gaugino soft mass

$$m_\phi^2 \simeq \sum_a \left(\frac{g_a^2}{16\pi^2}\right)^2 \left(\frac{F}{M}\right)^2$$

Scalar soft mass

GMSB vs Dark GMSB



Ex) $\hat{\Psi}_1 : (\mathbf{3}, 1, -1/3, D_\Psi)$

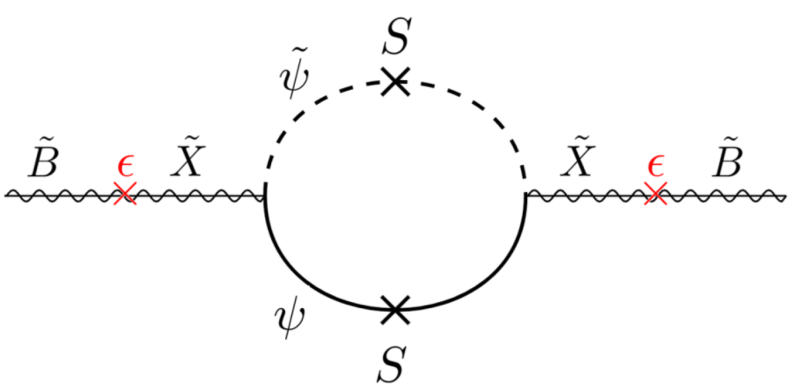
$\hat{\Psi}_2 : (1, \mathbf{2}, 1/2, D_\Psi)$

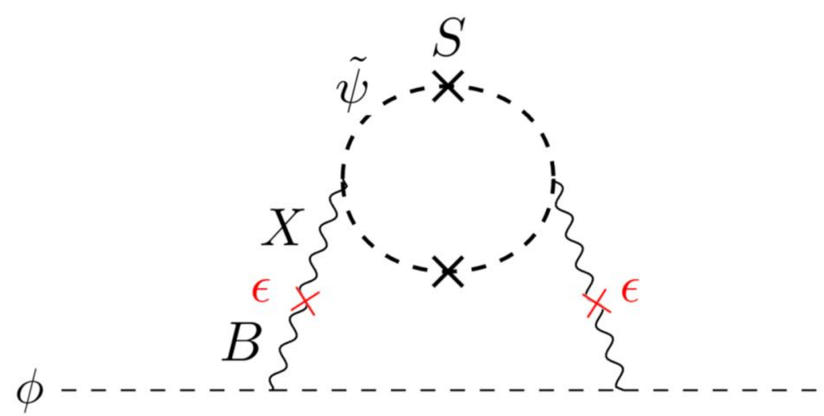
or

$\hat{\Psi} : (\mathbf{3}, \mathbf{2}, 1/6, D_\Psi)$

$$m_{\rm soft}(\epsilon) \simeq \frac{g_{\rm eff}^2(\epsilon)}{16\pi^2}\frac{F}{M}$$

ϵ-dependent soft mass



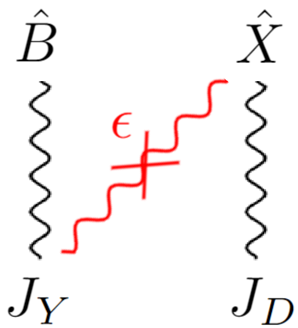


Soft mass in Dark GMSB

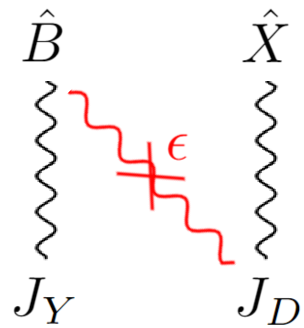
$$\mathcal{L}_{\text{kin}} \supset \int d^2\theta \left(\frac{1}{4}\hat{\mathcal{W}}_B \hat{\mathcal{W}}_B + \frac{1}{4}\hat{\mathcal{W}}_X \hat{\mathcal{W}}_X + \frac{\epsilon}{2}\hat{\mathcal{W}}_B \hat{\mathcal{W}}_X \right)$$
$$\rightarrow \int d^2\theta \left(\frac{1}{4}\hat{\mathcal{W}}_B \hat{\mathcal{W}}_B + \frac{1}{4}\hat{\mathcal{W}}_X \hat{\mathcal{W}}_X \right)$$

Kinetic term diagonalization
by GL(2) transformation

$$\begin{pmatrix} \hat{X} \\ \hat{B} \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\epsilon^2}} & 0 \\ -\frac{\epsilon}{\sqrt{1-\epsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} \cos\omega & -\sin\omega \\ \sin\omega & \cos\omega \end{pmatrix} \begin{pmatrix} \hat{X}' \\ \hat{B}' \end{pmatrix}$$



Massive dark photon



Massless dark photon
(for large kinetic mixing)

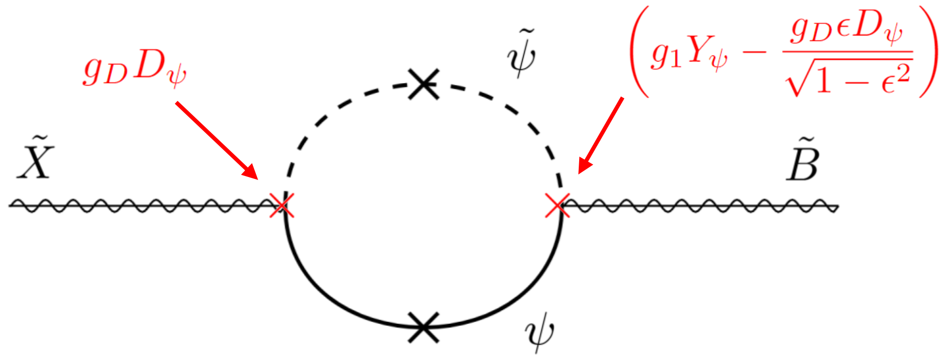
$$\sin\omega = \epsilon, \quad \cos\omega = \sqrt{1-\epsilon^2}.$$

$$\mathcal{L}_{\text{int}} \supset g_Y Y J_Y B + g_D D J_D X$$
$$\rightarrow \left[g_1 Y J_Y - \frac{g_D \epsilon}{\sqrt{1-\epsilon^2}} D J_D \right] B + g_D D J_D X$$

where $g_1 = g_Y / \sqrt{1-\epsilon^2}$

Soft mass in Dark GMSB - (1) Gaugino mass

$$\mathcal{L}_{\text{int}} \supset \left[g_1 Y J_Y - \frac{g_D \epsilon}{\sqrt{1-\epsilon^2}} D J_D \right] B + g_D D J_D X$$



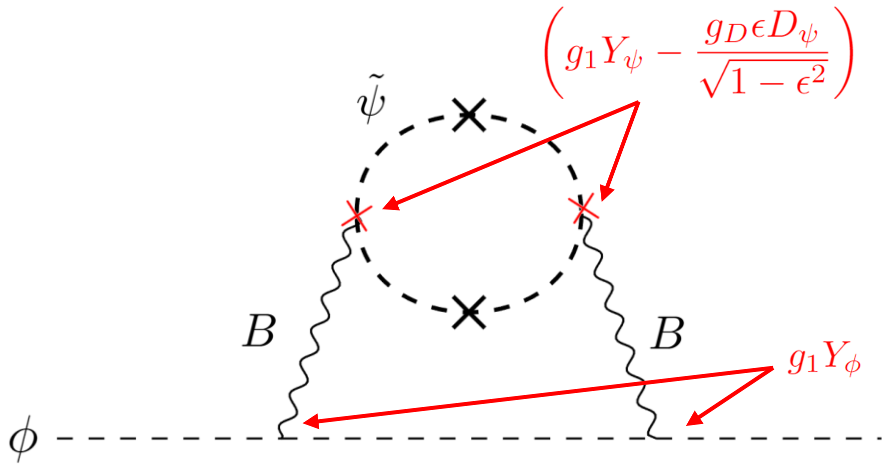
$$\mathcal{L} \supset M_D \tilde{X}\tilde{X} + 2 M_K \tilde{X}\tilde{B} + M_1 \tilde{B}\tilde{B}$$

$$M_D \simeq \frac{1}{16\pi^2} \frac{F}{M} g_D^2 D_\Psi^2$$

$$M_K \simeq \frac{1}{16\pi^2} \frac{F}{M} g_D D_\Psi \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)$$

$$M_1 \simeq \frac{1}{16\pi^2} \frac{F}{M} \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2$$

Soft mass in Dark GMSB - (2) Scalar soft mass



$$m_{\tilde{q}_L}^2 \simeq \left(\frac{1}{16\pi^2}\frac{F}{M}\right)^2 \left[\frac{2g_3^4}{3} + \frac{3g_2^4}{8} + g_1^2 Y_{\tilde{q}_L}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2\right]$$

$$m_{\tilde{u}_R}^2 \simeq \left(\frac{1}{16\pi^2}\frac{F}{M}\right)^2 \left[\frac{2g_3^4}{3} + g_1^2 Y_{\tilde{u}_R}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2\right]$$

$$m_{\tilde{d}_R}^2 \simeq \left(\frac{1}{16\pi^2}\frac{F}{M}\right)^2 \left[\frac{2g_3^4}{3} + g_1^2 Y_{\tilde{d}_R}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2\right]$$

$$m_{H_i}^2 = m_{\tilde{\ell}_L}^2 \simeq \left(\frac{1}{16\pi^2}\frac{F}{M}\right)^2 \left[\frac{3g_2^4}{8} + g_1^2 Y_{\tilde{\ell}_L}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2\right]$$

$$m_{\tilde{e}_R}^2 \simeq \left(\frac{1}{16\pi^2}\frac{F}{M}\right)^2 \left[g_1^2 Y_{\tilde{e}_R}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2\right]$$

Soft mass in Dark GMSB - (3) Tachyonic sfermion for some ϵ

$$m^2_{\tilde{e}_R} \simeq \left(\frac{1}{16\pi^2}\frac{F}{M}\right)^2 \left[g_1^2 Y^2_{\tilde{e}_R}\left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2\right]$$

Effective coupling

Scenario I - GUT complete representation

$\hat{\Psi}_1 : (\mathbf{3}, 1, -1/3, D_\Psi)$

$\hat{\Psi}_2 : (1, \mathbf{2}, 1/2, D_\Psi)$

Linear term of ϵ is canceled out

→ **Symmetric under $\epsilon \to -\epsilon$**

Scenario II - GUT incomplete representation

$\hat{\Psi} : (\mathbf{3}, \mathbf{2}, 1/6, D_\Psi)$

Linear term of ϵ is remained

→ **Effective coupling vanishes at specific ϵ**

$$\frac{d}{dQ}X = \frac{1}{16\pi^2}\beta_X^{(1)} + \frac{1}{(16\pi^2)^2}\beta_X^{(2)}$$

$$\beta^{(1)}_{m_e^2} = (4m^2_{H_d} + 2\mathbf{m}_e^2)\mathbf{Y}_e\mathbf{Y}_e^\dagger + 4\mathbf{Y}_e\mathbf{m}_L^2\mathbf{Y}_e^\dagger + 2\mathbf{Y}_e\mathbf{Y}_e^\dagger\mathbf{m}_e^2 + 4\mathbf{h}_e\mathbf{h}_e^\dagger + \frac{6g_1^2\mathcal{S}}{5} - \frac{24g_1^2}{5}(|M_1|^2 + |M_K|^2)$$

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

RG running

RH slepton (like stau) can be tachyon around specific value of ϵ

Soft mass in Dark GMSB - (4) No EWSB for large ϵ

$$m_{H_i}^2 \simeq \left(\frac{1}{16\pi^2}\frac{F}{M}\right)^2 \left[\frac{3g_2^4}{8} + g_1^2 Y_{\tilde{\ell}_L}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2\right]$$

$M_1(\epsilon), M_K(\epsilon)$ effect in RG beta function

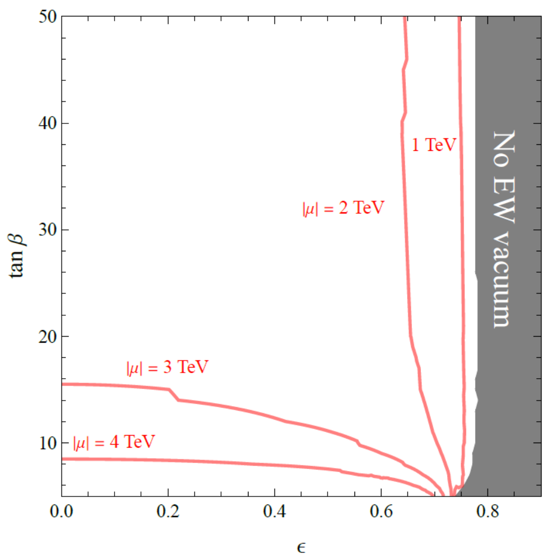
$$\beta_{m_{H_u}^2}^{(1)} = 6\mathrm{Tr}[(m_{H_u}^2 + \mathbf{m}_Q^2)\mathbf{Y}_u^\dagger \mathbf{Y}_u + \mathbf{Y}_u^\dagger \mathbf{m}_u^2 \mathbf{Y}_u + \mathbf{h}_u^\dagger \mathbf{h}_u] - 6g_2^2|M_2|^2 + \frac{3g_1^2 \mathcal{S}}{5} - \frac{6g_1^2}{5}(|M_1|^2 + |M_K|^2)$$

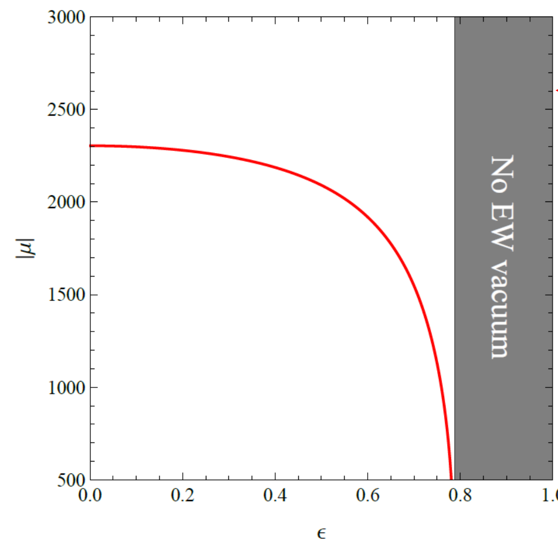
$$\mathcal{S} \equiv m_{H_u}^2 - m_{H_d}^2 + \mathrm{Tr}[\mathbf{m}_Q^2 - 2\mathbf{m}_u^2 + \mathbf{m}_d^2 - \mathbf{m}_L^2 + \mathbf{m}_e^2]$$

RG running

$$|\mu(\epsilon)|^2 = -\frac{m_Z^2}{2} - \frac{m_{H_u}^2(\epsilon) + m_{H_d}^2(\epsilon)}{2} + \frac{m_{H_u}^2(\epsilon) - m_{H_d}^2(\epsilon)}{2\cos(2\beta)}$$

μ-term has ϵ-dependence to satisfy EWSB condition.





For large ϵ, EWSB condition cannot be satisfied

$F/M_{\rm mess}$	$M_{\rm mess}$	g_D	$\tan\beta$	$F/M_{\rm mess}^2$
800 TeV	1200 TeV	0.4	15	2/3

Soft mass in Dark GMSB

$$m^2_{\tilde{\ell}_L} \simeq \left(\frac{1}{16\pi^2}\frac{F}{M}\right)^2 \left[\frac{3g_2^4}{8} + g_1^2 Y^2_{\tilde{\ell}_L}\left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2\right]$$

$$m^2_{\tilde{e}_R} \simeq \left(\frac{1}{16\pi^2}\frac{F}{M}\right)^2 \left[g_1^2 Y^2_{\tilde{e}_R}\left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2\right]$$

Effective coupling

More sensitive to ϵ for large hypercharge → RH/LH sfermion mass hierarchy can be swapped

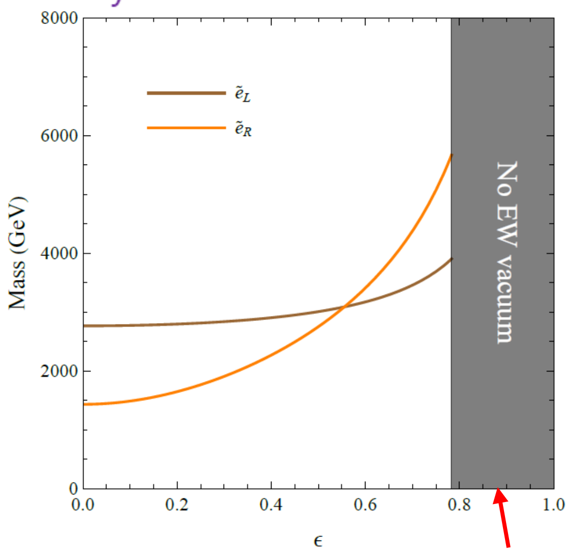
$$Y_{\tilde{\ell}_L} < Y_{\tilde{e}_R}$$

Scenario I - GUT complete representation

$\hat{\Psi}_1 : (\mathbf{3}, 1, -1/3, D_\Psi)$

$\hat{\Psi}_2 : (1, \mathbf{2}, 1/2, D_\Psi)$

Symmetric under $\epsilon \to -\epsilon$

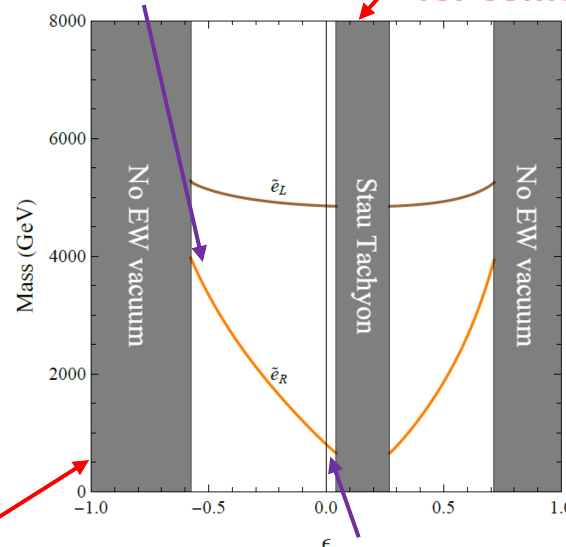


Scenario II - GUT complete representation

$\hat{\Psi} : (\mathbf{3}, \mathbf{2}, 1/6, D_\Psi)$

Maximum at $\epsilon = -0.576$

Stau tachyon for some ϵ

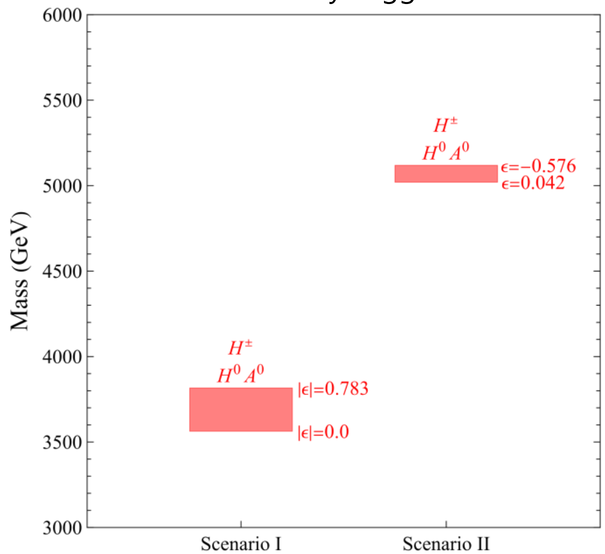


No EWSB vacuum in large $|\epsilon|$

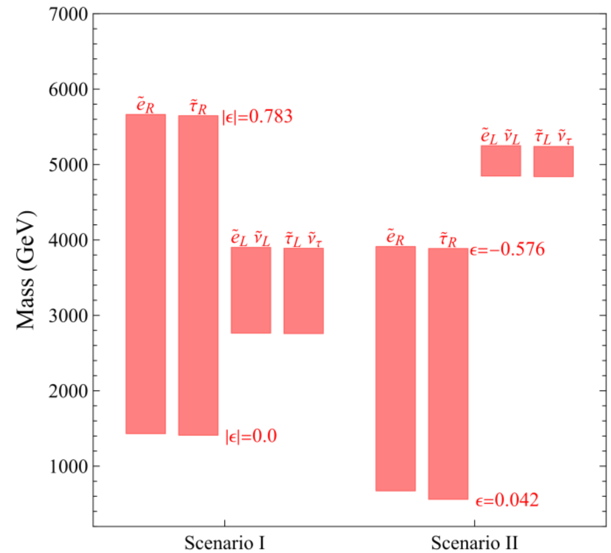
Minimum at $\epsilon = 0.042$

Mass spectrum - (1) Higgs & Sfermion sectors

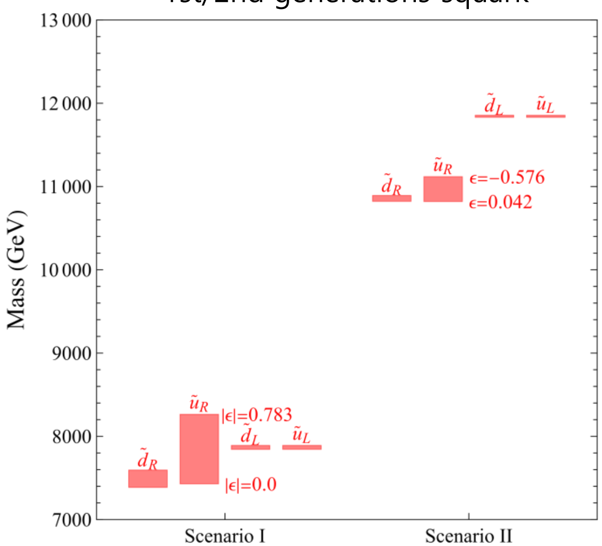
Heavy Higgs



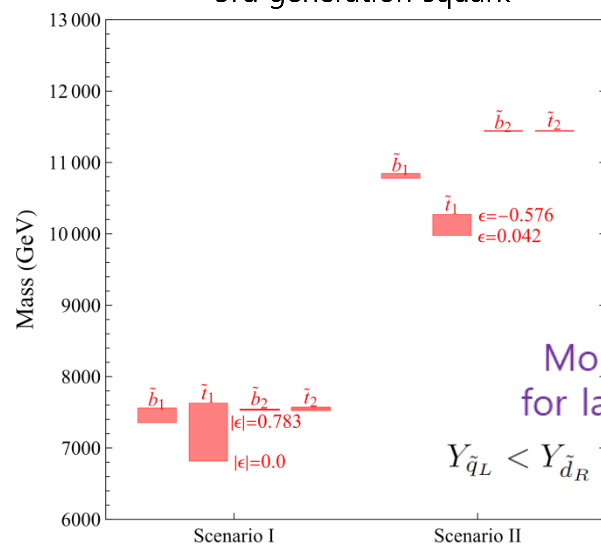
Slepton



1st/2nd generations squark



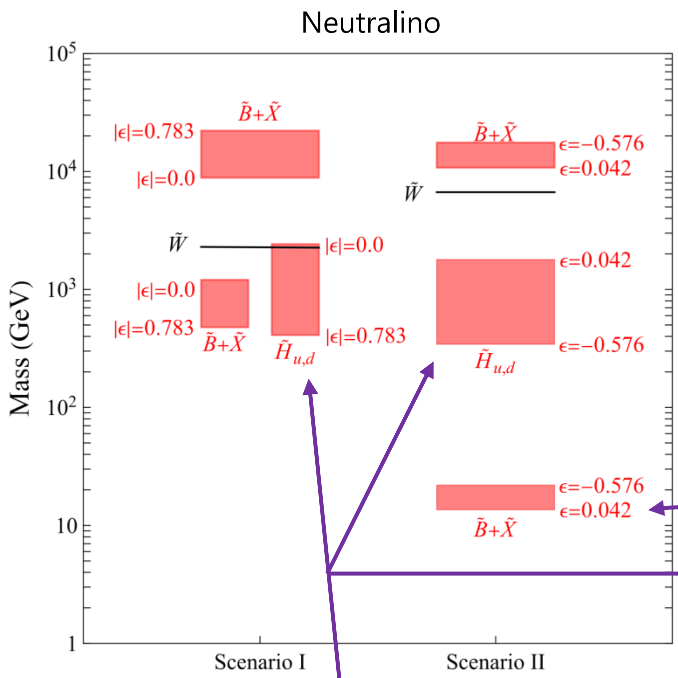
3rd generation squark

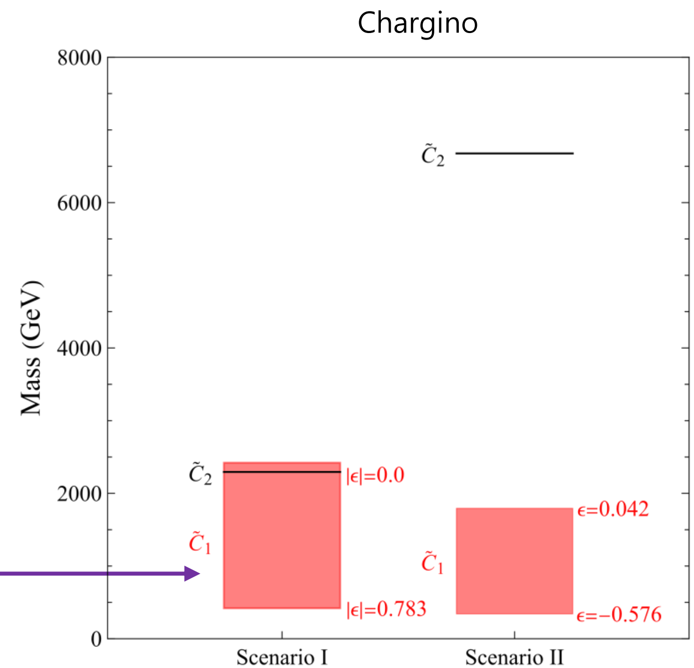


More sensitive to ϵ
for large hypercharge

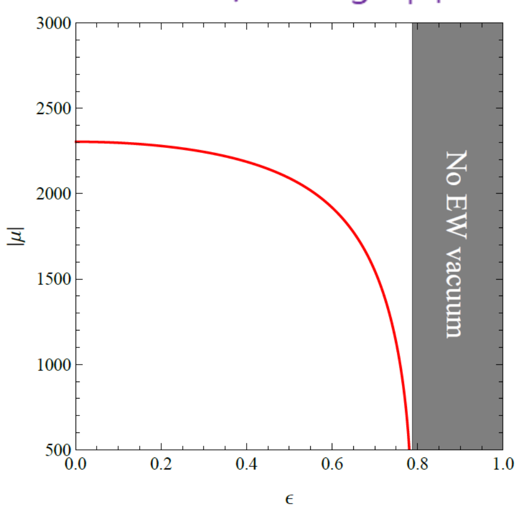
$$Y_{\tilde q_L} < Y_{\tilde d_R} < Y_{\tilde \ell_L} = Y_H < Y_{\tilde u_R} < Y_{\tilde e_R}$$

Mass spectrum - (2) Neutralino & Chargino sectors





Small μ in large |ϵ|



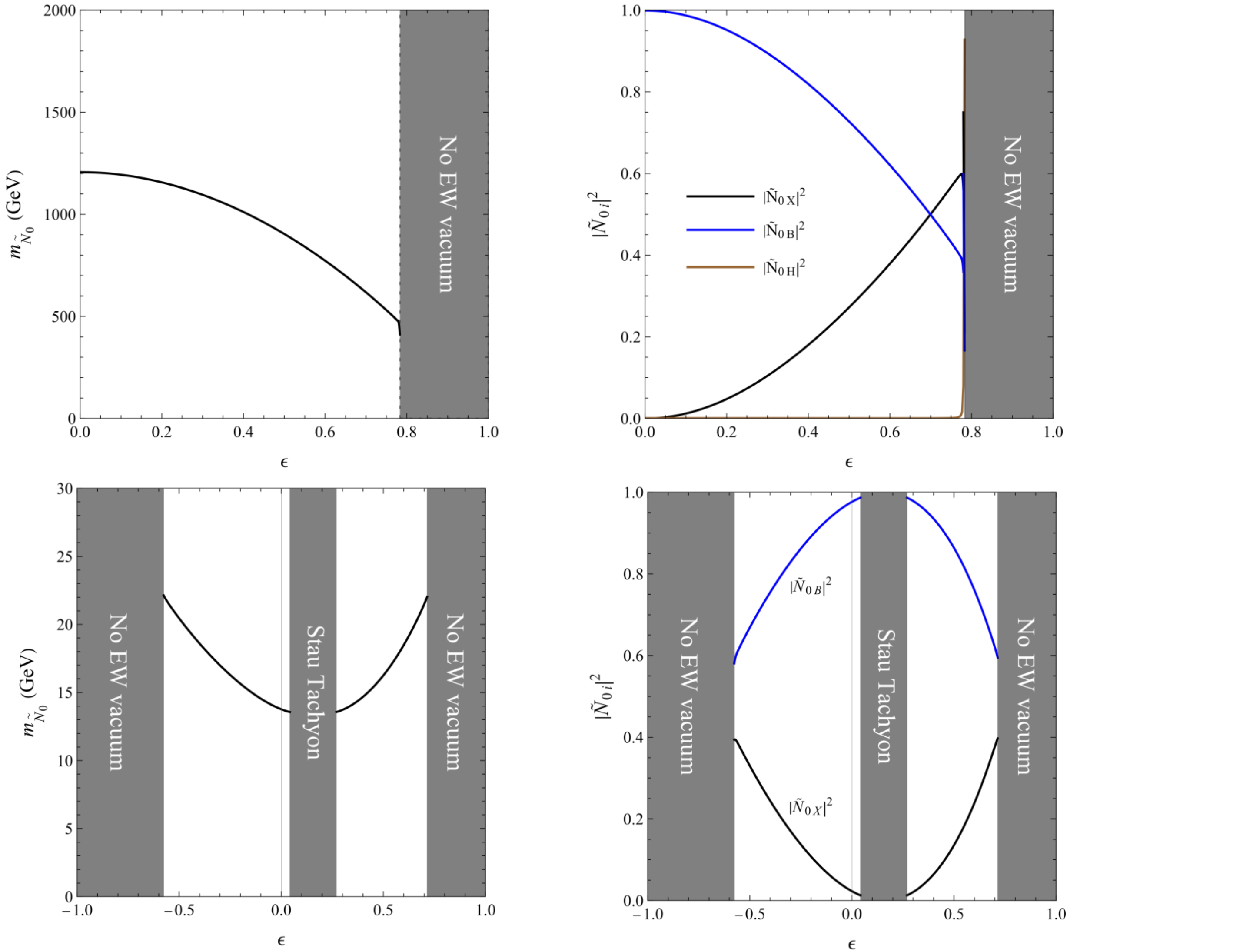
Dark photino-Bino submatrix
has zero determinant in Scenario II

$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_D & M_K(\epsilon) & 0 & 0 & 0 \\ M_K(\epsilon) & M_1(\epsilon) & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ 0 & -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ 0 & s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}$$

Mass spectrum - The lightest neutralino mass & composition

Scenario I

Scenario II

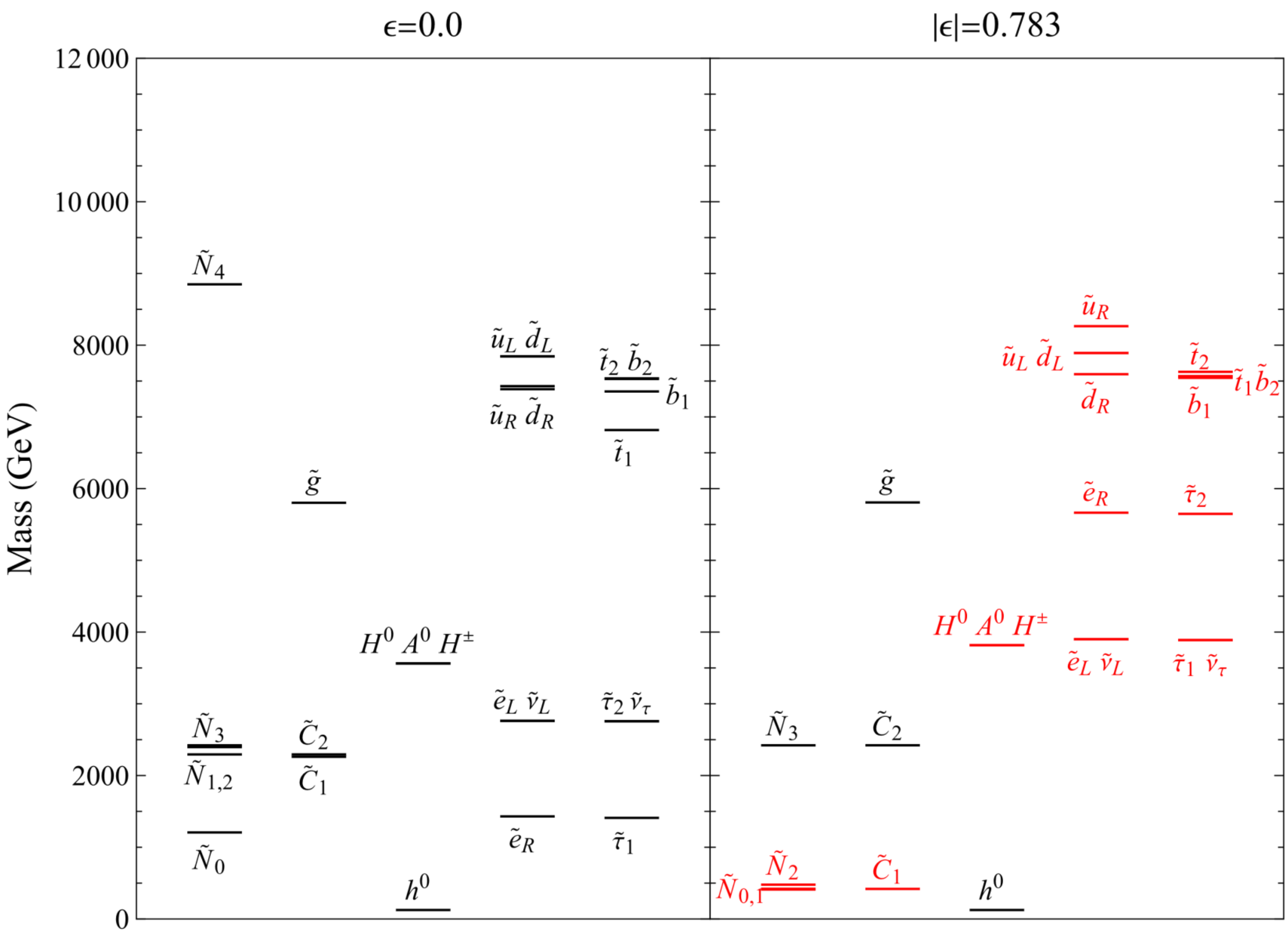


$$|\tilde{N}_{0X}| : |\tilde{N}_{0B}| \simeq |M_K(\epsilon)| : |M_D| = \left| g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right| : |g_D D_\Psi|$$

Neutralino composition depends on ϵ

Mass spectrum (Complete representation)

$F/M_{\rm mess}$	$M_{\rm mess}$	g_D	$\tan\beta$	$F/M^2_{\rm mess}$
800 TeV	1200 TeV	0.4	15	2/3

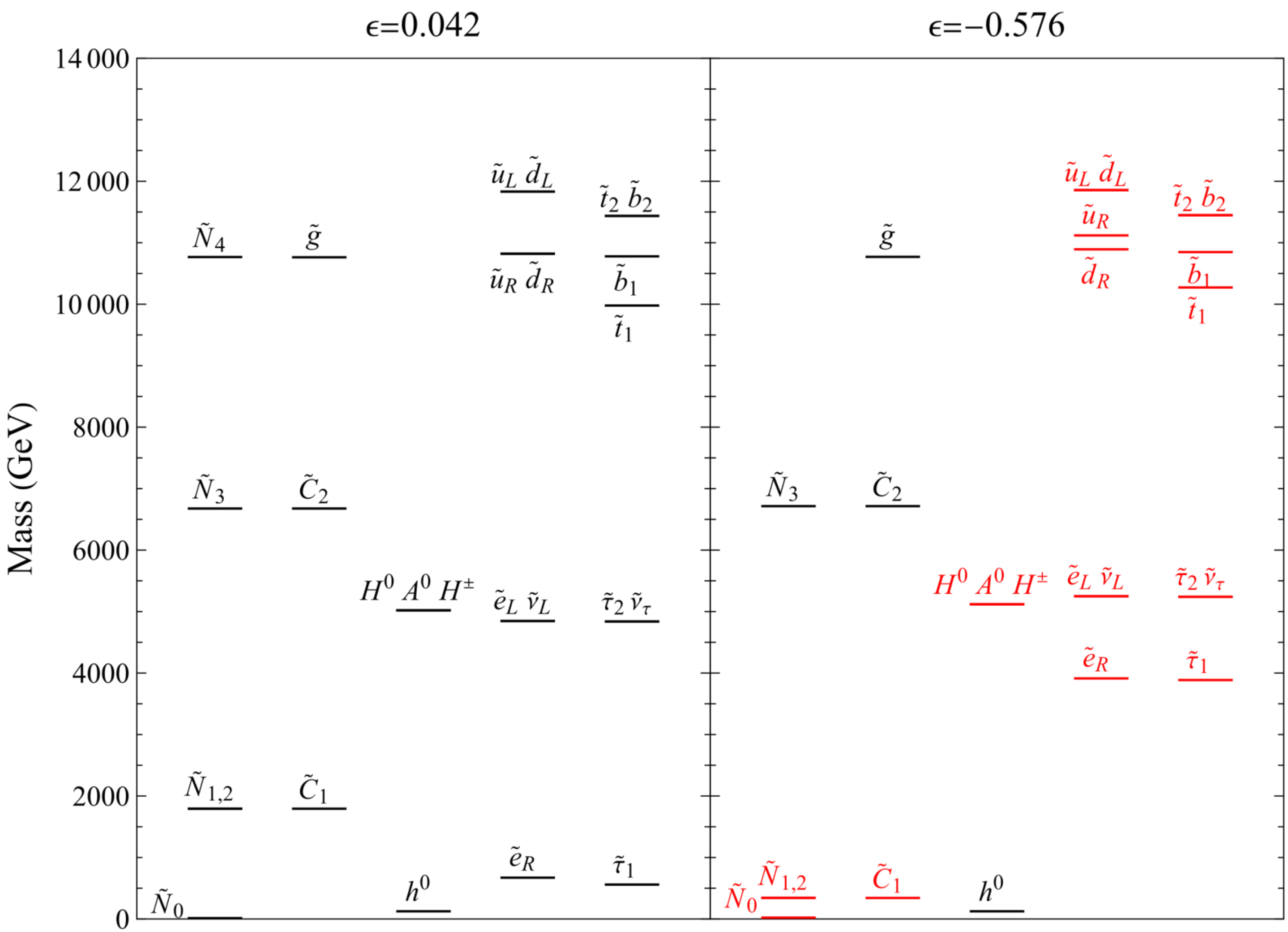


LH/RH slepton hieararchy swapped

Small μ in large $|\epsilon|$

Mass spectrum (Incomplete representation)

F/M_{mess}	M_{mess}	g_D	$\tan\beta$	F/M^2_{mess}
800 TeV	1200 TeV	0.4	15	2/3

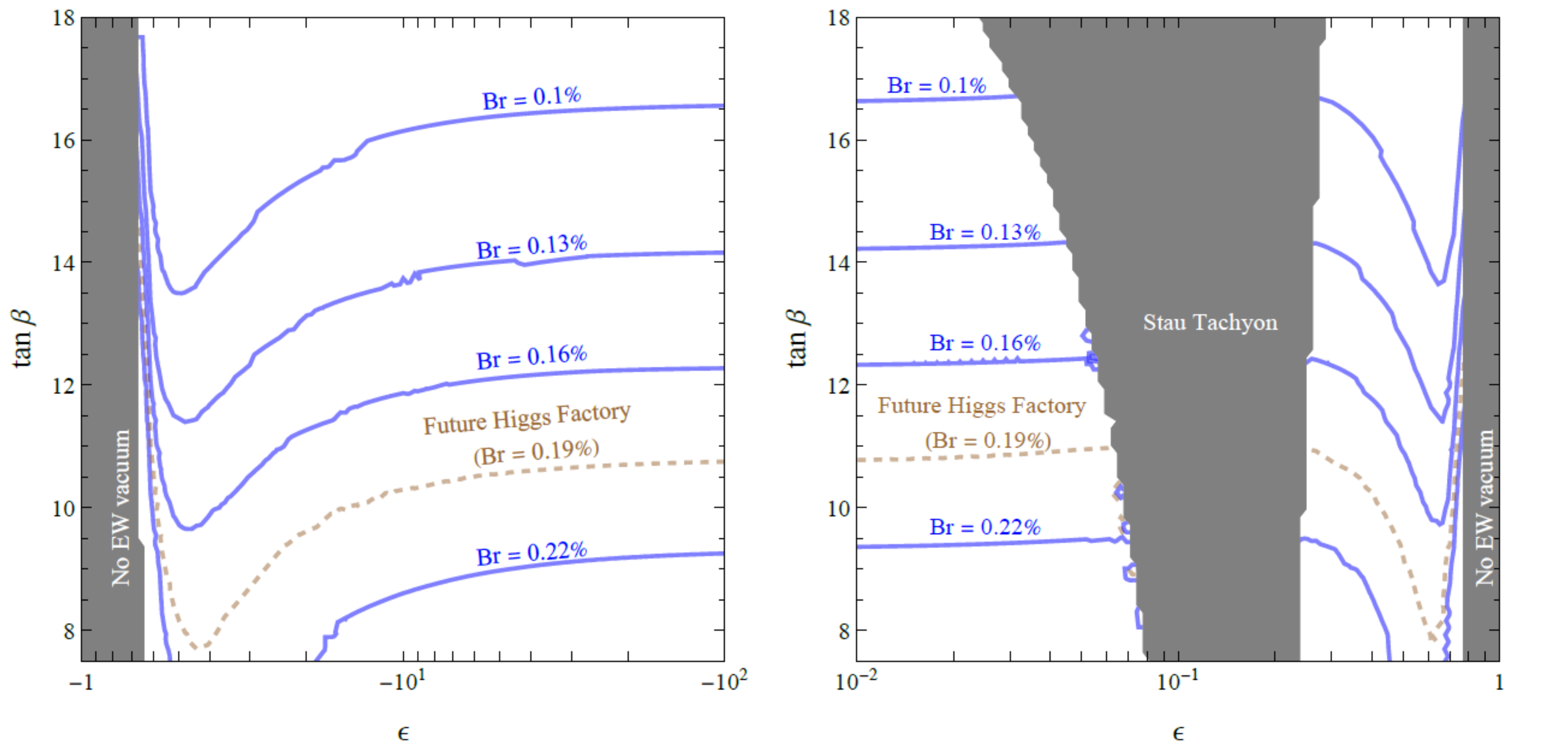


The lightest neutralino
(bino-dark photino mixture)
w/ Suppressed mass

Phenomenology

Higgs decay $h^0 \to \tilde{N}_0\tilde{N}_0$ in Scenario II with suppressed mass of the lightest neutralino

$$\Gamma(h^0 \to \tilde{N}_0\tilde{N}_0) = \frac{g_2^2 m_{h^0}}{16\pi}\left(1 - \frac{4m_{\tilde{N}_0}^2}{m_{h_0}^2}\right)^{3/2} \left|(\tilde{N}_{0W} - \tilde{N}_{0B}\tan\theta_W)(\tilde{N}_{0H_u}\cos\alpha + \tilde{N}_{0H_d}\sin\alpha)\right|^2$$



Phenomenology

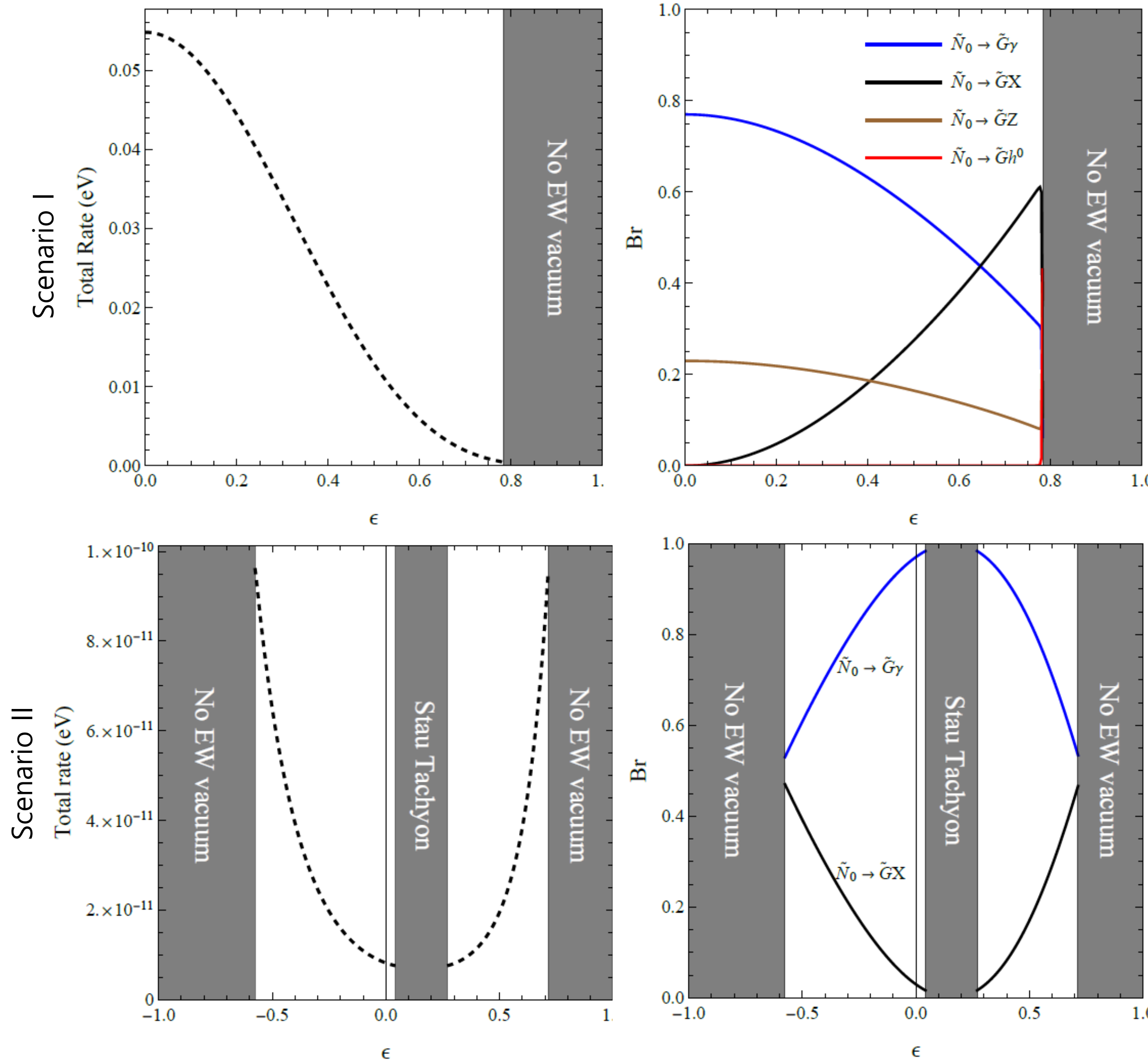
NLSP decay to Gravitino $m_{3/2} \simeq \frac{F}{\sqrt{3}M_{\rm Pl}}$ ~ few eV

$$\Gamma(\tilde{N}_0 \to \tilde{G}\gamma) = \frac{m_{\tilde{N}_0}^5}{16\pi F^2}|N_{0\tilde{B}}\cos\theta_W + N_{0\tilde{W}}\sin\theta_W|^2$$

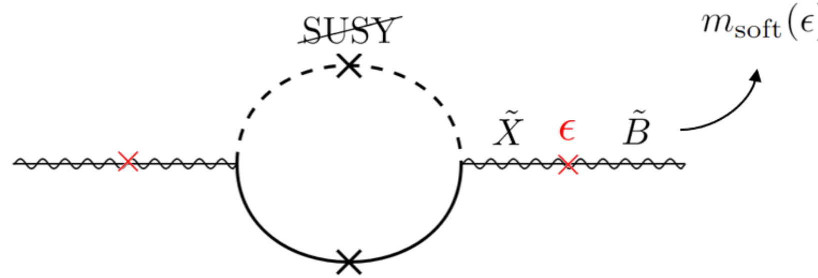
$$\Gamma(\tilde{N}_0 \to \tilde{G}X) = \frac{m_{\tilde{N}_0}^5}{16\pi F^2}|N_{0\tilde{X}}|^2,$$

$$\Gamma(\tilde{N}_0 \to \tilde{G}Z) = \frac{m_{\tilde{N}_0}^5}{16\pi F^2}\left(1 - \frac{m_Z^2}{m_{\tilde{N}_0}^2}\right)^4 \times \left(|N_{0\tilde{B}}\sin\theta_W - N_{0\tilde{W}}\cos\theta_W|^2 + \frac{1}{2}|N_{0\tilde{H}_d}\cos\beta - N_{0\tilde{H}_u}\sin\beta|^2\right)$$

$$\Gamma(\tilde{N}_0 \to \tilde{G}h^0) = \frac{m_{\tilde{N}_0}^5}{32\pi F^2}\left(1 - \frac{m_{h^0}^2}{m_{\tilde{N}_0}^2}\right)^4 \times |N_{0\tilde{H}_d}\sin\alpha - N_{0\tilde{H}_u}\cos\alpha|^2.$$



Summary



“Dark GMSB”

- Supersymmetric kinetic mixing can be a new method of SUSY breaking transfer. As a result, the mass spectrum get the dependence on the new variables (g_D and ϵ) of dark sector. We call this **“Dark GMSB”**.
- EWSB condition cannot be satisfied in large ϵ due to the modified RG beta function. Besides, stau can become tachyonic if the effective coupling vanishes around specific value of ϵ.
- Scalar particle mass is more sensitive to ϵ if it has large hypercharge, so the mass hierarchy between LH/RH sfermion can be swapped.
- Dominant composition of dark photino-bino mixture neutralino state is swapped at the critical value of ϵ.
- The Higgs can decay to the lightest neutralino with suppressed mass, and this can be tested by the future Higgs factory.