Gauge mediation signatures without SUSY

How to fake GMSB with a UED model

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Outline

- Motivation: Fake GMSB
- How to build the fake model: step by step
  - Basic UED setup with $U(1)_{PQ}$
  - Anomalies in 5D
- Phenomenology (and Dark Matter)
- Summary
Motivation

SUSY with **Gauge mediated SUSY breaking**

- Can solve hierarchy problem without messing up flavor.
- Breaking scale can be quite low.
  → Gravitino is LSP. Neutralinos decay

\[ \chi_1^0 \rightarrow \gamma + \tilde{G} \]

- All decays end up with photons & missing energy.
- If **SUSY** scale low enough:
  delayed/non-pointing photons = signature of GMSB?
Ingredients

What do we need to fake this signal with a non/SUSY model?

- A flat extra dimension (UED)  [Appelquist, Cheng, Dobrescu ’00]
  → UED can fake SUSY-spectra.  [Cheng, Matchev, Schmaltz ’02]
- Impose KK-parity  
  → KK-parity protects EWPO at tree level  [Servant, Tait ’02; Cheng, Feng, Matchev ’02]
- Want to get the decay

\[ \gamma^{(1)} \rightarrow \gamma + \text{MET} \]

- How do we decay the 1\textsuperscript{st} KK-modes?
  → Anomalous global symmetry that gives this decay vertex.
  ⇒ Need two Higgs doublets $H_u$ and $H_d$.  

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Basic Setup

**UED**
- All SM fields in the bulk.
- KK-parity.
- $U(1)_{PQ}$ gauged:
  - $Q_{PQ} = +1$ (higgses)
  - $Q_{PQ} = -\frac{1}{2}$ (fermions)
  - → broken by BC.

$\Rightarrow$ Anomalous $U(1)_{PQ,\text{global}}$

- Scalar $B_5$ zero mode
  - (MET)

$SU(3)_c \times SU(2)_L \times U(1)_Y$

- $U(1)_{PQ}$

- $Q, \bar{u}, \bar{d}, L, \bar{e}$
- $H_u, H_d$

$KK - parity$

$y = 0 \quad \Rightarrow \quad y = L$
The $B_5$ zero mode - I

KK - parity of $B_5$

- BC: $\partial_5 B_5 = 0 \Rightarrow B_5$ zero mode has a flat wave function.
- But always appears in the combination $D_5 = \partial_5 + ig_{PQ}B_5$

$\Rightarrow B_5$ is internally KK - odd!

e.g. couplings to fermions, $f_{PQ} = 1/g_{PQ}\sqrt{L}$,

$$
\mathcal{L}_{\text{eff}} = -\frac{1}{f_{PQ}L} q \sum_{m,n} c_{nm} B_5(x) \left[ \psi_n \chi_m - \bar{\chi}_m \bar{\psi}_n \right]
$$

$$
c_{nm} = \begin{cases} 
\frac{4}{\pi} \frac{n}{m^2 - n^2} & m + n \text{ odd, } m \neq 0 \\
\frac{2\sqrt{2}}{\pi n} & m + n \text{ odd, } m = 0 \\
0 & m + n \text{ even}
\end{cases}
$$
The $B_5$ zero mode - II

- Boundary conditions:
  \[ B_\mu = 0 \quad \text{and} \quad \partial_5 B_5 = 0 \]
  
  → Allow for residual gauge transformation

\[ B_M \rightarrow B_M + \partial_M \beta_{\text{res}} \quad \text{and} \quad \psi \rightarrow e^{i \beta_{\text{res}} \psi} \]

with \[ \beta_{\text{res}} = \beta^+ + \beta^- \frac{2y-L}{2L} \] (unitary gauge)

- Under this residual symmetry: \[ B_5 \rightarrow B_5 + \beta^- / L \]
  \[ B_5 \] has a shift symmetry \[ \cong B_5 \] is a Goldstone.
Spontaneous $U(1)_{\text{PQ}}$ breaking

EWSB

- $U(1)_{\text{PQ,global}}$ broken spontaneously by Higgs VEVs.
  \[ \Rightarrow 2^{\text{nd}} \text{ Goldstone, living in the Higgses.} \]
- Mixes with the $B_5$:

\[
\mathcal{L}_{\text{mix}} = -f_{\text{PQ}}^2 \mathcal{L}(\partial_5 B^\mu)(\partial_\mu B_5) - \frac{1}{L} v B^\mu \partial_\mu \pi
\]

$SU(3)_c \times SU(2)_L \times U(1)_Y$

$U(1)_{\text{PQ,global}}$

$Q, \bar{u}, \bar{d}, L, \bar{e}$

$H_u, H_d$

$\langle H_u \rangle, \langle H_d \rangle$

$KK - \text{parity}$

$y = 0$ \quad $y = L$
Mixing of Goldstones

- For simplicity assume only one Higgs: $H = \frac{v}{\sqrt{2}} e^{i\pi/v}$.
- Residual gauge transformation ($\kappa = v/f_{\text{PQ}}L$)

$$
\beta_{\text{res}} = \beta^+ \cosh(\kappa(y - L/2)) + \beta^- \sinh(\kappa(y - L/2))
$$

**KK-odd mode:** $\zeta_-(x)$
- $B_{5}^{(0)\text{odd}} \sim \cosh \kappa (y - L/2) \zeta_-(x)$
- $\pi^{(0)\text{odd}} \sim \frac{v}{\kappa} \sinh \kappa (y - L/2) \zeta_-(x)$

**KK-even mode:** $\zeta_+(x)$
- $B_{5}^{(0)\text{even}} \sim \sinh \kappa (y - L/2) \zeta_+(x)$
- $\pi^{(0)\text{even}} \sim \frac{v}{\kappa} \cosh \kappa (y - L/2) \zeta_+(x)$

$\Rightarrow B_{5}$ has “wrong” wavefunctions, but couplings are ok.
Explicit $U(1)_{PQ}$ breaking

- We have two massless Goldstones $\zeta_-$ and $\zeta_+$.

Explicit breaking on the boundaries

$$V_{\text{bound}} = -\frac{\mu}{2} \left( H^2 + H^*2 \right) |_{y=0,L}$$

$$= \frac{1}{2} 2\mu \zeta_+^2 + \frac{1}{2} \frac{\mu v^2}{f_{PQ}^2} \zeta_-^2 + \ldots$$

$\Rightarrow$ Goldstones get massive.

**KK-even: heavy**

$$m_+ = 2\sqrt{\mu}$$

**KK-odd: light**

$$m_- = \sqrt{\mu} \frac{v}{f_{PQ}}$$
Two doublet model

- Now generalize to two Higgs doublets
  \[ H_u = \frac{v_u}{\sqrt{2}} e^{i\pi/V} , \quad H_d = \frac{v_d}{\sqrt{2}} e^{i\pi/V} \quad \text{with} \quad V \equiv \sqrt{v_u^2 + v_d^2} \]

- Explicit breaking through \( \mu \)-term

\[ \mathcal{L}_{\text{mix}} = \left. \frac{\mu}{2} H_u^T (i \tau_2) H_d \right|_{y=0,L} \]

- All previous calculations apply with:
  \[ v \to V = \sqrt{v_u^2 + v_d^2} \quad \text{and} \quad \mu \to \frac{\mu}{2} \sin 2\beta \]

**KK-even: heavy**

\[ m_+^2 = 2\mu \sin 2\beta \]

**KK-odd: light**

\[ m_-^2 = \frac{\mu V^2}{2f^2_{\text{PQ}}} \sin 2\beta \]
Recap: The model

Setup

- **UED with global $U(1)_{PQ}$**
  - $Q_{PQ} = +1$ (higgses)
  - $Q_{PQ} = -\frac{1}{2}$ (fermions)
- $U(1)_{PQ}$ explicitly broken.

- **KK-even:** $\zeta_+ \sim \text{few 100 GeV}$
- **KK-odd:**
  - $\zeta_- \sim \left(\frac{\sqrt{\mu_{\text{eff}}}}{300 \text{ GeV}}\right) \left(\frac{10^9 \text{ GeV}}{f_{PQ}}\right)$ 74 keV

- Anomaly $\Rightarrow$ couplings

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$U(1)_{PQ}$

$U(1)_{PQ,\text{global}}$

$\zeta_-, \zeta_+$

$Q, \bar{u}, \bar{d}, L, \bar{e}$

$H_u, H_d$

$\langle H_u \rangle, \langle H_d \rangle$

$\leftrightarrow \text{KK – parity}$

$y = 0$

$y = L$
**U(1)\textsubscript{PQ} anomalies**

- **Anomalous U(1)\textsubscript{PQ}**
  
<table>
<thead>
<tr>
<th></th>
<th>$H_\text{u}$</th>
<th>$H_\text{d}$</th>
<th>$Q$</th>
<th>$\bar{u}$</th>
<th>$\bar{d}$</th>
<th>$L$</th>
<th>$\bar{e}$</th>
</tr>
</thead>
</table>
  $Y$ | $1/2$ | $-1/2$ | $1/6$ | $-2/3$ | $1/3$ | $-1/2$ | $1$ |
  PQ | $1$ | $1$ | $-1/2$ | $-1/2$ | $-1/2$ | $-1/2$ | $-1/2$ |

⇒ non-vanishing anomalies:
$SU(3)_c^2 U(1)_{PQ}$, $SU(2)_L^2 U(1)_{PQ}$, $U(1)_Y U(1)_{PQ}^2$ and $U(1)_{\bar{Y}}^2 U(1)_{PQ}$

- But 5D bulk is non-chiral
  
  ⇒ Anomalies are located on the boundaries

[Arkani-Hamed, Cohen, Georgi '01]

$$\mathcal{A}(x, y) \equiv \frac{1}{2} \left[ \delta(y) + \delta(y - L) \right] Q_{PQ}(x, y)$$

with $Q_{PQ} = \sum_f q_{PQ}^f \frac{q_{f2}^Y}{16\pi^2} F(x, y) \cdot \tilde{F}(x, y)$
Anomaly coupling:
Recall: 4D pion anomaly for $\pi^0 \rightarrow \gamma\gamma$

Anomalous global symmetry

$$
\begin{pmatrix}
  u \\
  d
\end{pmatrix}
\rightarrow
\begin{pmatrix}
  u \\
  d
\end{pmatrix} + i\alpha\gamma^5
\begin{pmatrix}
  1 & 0 \\
  0 & -1
\end{pmatrix}
\begin{pmatrix}
  u \\
  d
\end{pmatrix}
$$

- under this symmetry:

$$
\mathcal{D}\psi\mathcal{D}\bar{\psi} \rightarrow \mathcal{D}\psi\mathcal{D}\bar{\psi} e^{-i\int d^4x\alpha Q(x)}
$$

$$
\mathcal{L} \rightarrow \mathcal{L} - \alpha Q(x)
$$

$$
\pi(x) \rightarrow \pi(x) + \alpha f_\pi \quad \text{(shift symmetry!)}
$$

- Integrate out the fermions $\Rightarrow$ effective Lagrangian

$$
\mathcal{L}_{\text{eff}} \sim -\frac{1}{f_\pi} \pi(x)Q(x)
$$
Anomalous global $U(1)_{PQ}$ symmetry

$$\beta_{\text{res}} = \beta^+ \cosh(\kappa(y - L/2)) + \beta^- \sinh(\kappa(y - L/2))$$

under this symmetry:

$$\mathcal{D}\psi \mathcal{D}\bar{\psi} \rightarrow \mathcal{D}\psi \mathcal{D}\bar{\psi} \ e^{-i \int d^5x \beta_{\text{res}} A(x,y)}$$

$$\mathcal{L} \rightarrow \mathcal{L} - \int d^5x \ \beta_{\text{res}} \ A(x, y)$$

$$\zeta_\pm \rightarrow \zeta_\pm + v \sqrt{\frac{\sinh \kappa L}{\kappa L}} \beta_\pm$$

⇒ To lowest order in $f_{PQ}$ described by

$$\mathcal{L}_{\text{eff \ anomaly}}^{\text{anomaly}} = \frac{1}{4f_{PQ}} \zeta_- [\mathcal{Q}_{PQ}(x, L) - \mathcal{Q}_{PQ}(x, 0)] + \frac{1}{2v} \zeta_+ [\mathcal{Q}_{PQ}(x, L) + \mathcal{Q}_{PQ}(x, 0)]$$
Anomaly coupling

\[ \mathcal{L}_{\text{anomaly}}^{\text{eff}} = \frac{1}{4f_{\text{PQ}}} \zeta_- [Q_{\text{PQ}}(x, L) - Q_{\text{PQ}}(x, 0)] \]

\[ = \frac{\alpha_1}{4\pi} \frac{1}{f_{\text{PQ}}} \zeta_-(x) \sum_{m \geq n \geq 0} c_{nm} F^{(n)} \cdot \tilde{F}^{(m)} \]

with

\[ c_{nm} = \begin{cases} 
0 & n + m \text{ even} \\
2 \sum_f q_{\text{PQ}}^f q_Y^{f2} & n + m \text{ odd, } n, m \geq 1 \\
\sqrt{2} \sum_f q_{\text{PQ}}^f q_Y^{f2} & n + m \text{ odd, } n \cdot m = 0.
\end{cases} \]

- coupling to \( F^{(0)} \tilde{F}^{(1)} \Rightarrow \text{decay of NLKP.} \)
- no coupling to \( F^{(0)} \tilde{F}^{(0)} \Rightarrow \text{no solution to strong CP problem.} \)
Decay of 1st KK-modes

\[
\frac{\alpha_1}{4\pi} \frac{\sqrt{2}}{f_{PQ}} \left( \sum_f q_{PQ}^f q_Y^f \right) \zeta^- F^{(0)} \cdot \tilde{F}^{(1)}
\]

\[
\Gamma_{\text{tot}} \approx \frac{\alpha^2}{192\pi^3 c_w^4} \frac{m^{(1)}^3}{f_{PQ}^2} \left( \sum_f q_{PQ}^f q_Y^f \right)^2
\]

⇒ Decay length can be macroscopic

\[
\tau = 1.5 \cdot 10^{-9} \text{ s} \left( \frac{10^3 \text{ GeV}}{m^{(1)}} \right)^3 \left( \frac{f_{PQ}}{10^9 \text{ GeV}} \right)^2
\]

\[
\Delta x \approx 46 \text{ cm} \left( \frac{10^3 \text{ GeV}}{m^{(1)}} \right)^3 \left( \frac{f_{PQ}}{10^9 \text{ GeV}} \right)^2 \sqrt{\left( \frac{E}{m^{(1)}} \right)^2 - 1}
\]
For $m^{(1)} \sim 1$ TeV and $f_{PQ} \sim 10^9$ GeV:

$$\tau \sim 10^{-9} \text{ s} \quad \text{or} \quad \Delta x \sim 10 \text{ cm}$$

⇒ Signal like in GMSB scenario:
Many events with (non-pointing) photons and MET.
Dark Matter: Only if $f_{\text{PQ}}$ is low

\[
\langle \sigma v \rangle \sim \frac{2m_\rho^6}{\pi v_\text{eff}^4} \frac{1}{(4m_\rho^2 - m_h^2)^2 + m_h^2 \Gamma_h^2} \sqrt{1 - \frac{m^2}{m_\rho^2} \left( 1 - \frac{m^2}{m_\rho^2} + \ldots \right)}
\]

\begin{align*}
\zeta \zeta &\rightarrow h_0 \rightarrow \text{SM SM} \\
\tau, b &\rightarrow \text{SM SM} \\
W, Z &\rightarrow \text{SM SM}
\end{align*}

- usual WIMP dark matter, BUT only prompt decays.
Summary

**UED with KK-parity**
- Global, anomalous $U(1)_{\text{PQ}}$.
- Explicitly broken:
  - KK-even: $\zeta^+ \sim \text{few 100 GeV}$
  - KK-odd: $\zeta^- \sim \sqrt{\frac{\mu_{\text{eff}}}{300 \text{ GeV}}} \left( \frac{10^9 \text{ GeV}}{f_{\text{PQ}}} \right) 74 \text{ keV}$
- Anomaly $\sim \zeta_{\pm} F \cdot \tilde{F}$

- NLSP decay: $\gamma^{(1)} \rightarrow \gamma + \zeta^-$
- Fake GMSB signal: Many events with non-pointing photons and MET.

**SU(3)_c \times SU(2)_L \times U(1)_Y**

- $U(1)_{\text{PQ}}$ broken
- $U(1)_{\text{PQ,global}}$
- $\zeta^-, \zeta^+$
- $Q, \bar{u}, \bar{d}, L, \bar{e}$
- $H_u, H_d$
- $\langle H_u \rangle, \langle H_d \rangle$

- **KK – parity**
- $y = 0$
- $y = L$
Outlook

- More intensive pheno study
  - How to distinguish from GMSB at the LHC?
  - Decays of $\zeta_+$?
  - Serious DM study?
  - ...

- Use similar model to solve strong CP problem?
  - KK-odd $\zeta_-$ has no $g\tilde{g}$ coupling, while KK-even $\zeta_+$ is too heavy.

- Warped space version?
  - (J. Hubisz, D. Bunk, to appear soon)

- Deconstructed or Little Higgs version?

Lot’s of things to do!
Deconstructed picture

- \( N \) gauged and 2 global \( U(1) \)s \( \rightarrow U(1)_{\text{diag}} \)

\[ \Rightarrow N + 1 \text{ Goldstones} = N \text{ Goldstones} + 1 \text{ Goldstone} \]

- Can be seen in the residual gauge transformation:

\[ \beta_{\text{res}} = \beta^+ \text{ unbroken } U(1) + \beta^- \text{ shift in } B_5 \cdot \frac{2y-L}{2L} \]