Gauge Mediation Signatures w/o SUSY

anomalous extra dimensional symmetries

Jay Hubisz
Syracuse University
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w/ Csaba Csaki, Johannes Heinonen and Yuri Shirman

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LHC^{-1} problem

Go from data space to theory space

smoking guns: MET + jets = SUSY (MSSM)

NO!

UED, little Higgs w/ T-parity

high p_T photons, Z's, possible displaced vertex

A surefire SUSY smoking gun (gauge mediation)

Gauge Mediation

Pheno:

Gravitino mass:

$$m_{3/2} = \frac{F}{k\sqrt{3}M_P} = \frac{1}{k}\left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^2 2.4\ \mathrm{eV}$$

Interactions are due to Goldstino
(eaten by massive gravitino)

$$\mathcal{L} = -\frac{1}{F_0} J^\mu_Q \partial_\mu \tilde{G}$$

$$\mathcal{L} = -\frac{k}{F}\left(\bar{\psi}_L \gamma^\mu \gamma^\nu \partial_\nu \phi - \frac{i}{4\sqrt{2}} \bar{\lambda}^a \gamma^\mu \sigma^{\nu\rho} F^a_{\nu\rho}\right) \partial_\mu \tilde{G} + \mathrm{h.c.}$$

$$\chi^0_1 \to \gamma(Z) + \tilde{G}$$

(Giudice, Rattazzi 1998)

NLSP decays

Decay length in colliders:

$$L = \frac{1}{\kappa_\gamma}\left(\frac{100\ \mathrm{GeV}}{m}\right)^5 \left(\frac{\sqrt{F/k}}{100\ \mathrm{TeV}}\right)^4 \sqrt{\frac{E^2}{m^2} - 1}\ \times 10^{-2}\ \mathrm{cm}$$

m is NLSP mass, F/k is SUSY breaking scale

$$\sqrt{\frac{F}{k}} \sim 10^6\ \mathrm{GeV}$$

prompt, long lived, or displaced vertex

Can we get the same signals from a very different model?

variation on Universal Extra Dimensions or Little Higgs?

UED

- All SM fields propagate in the bulk
  - 5D - flat extra dimension (size L O(1/TeV))
- SM fermions get zero modes through orbifold compactification (boundary cond.)
  - SM zero modes have ++ BC
- KK-parity is imposed (remnant of 5D mom. cons)
  - EWP, Dark matter (Missing ET)

The first “bosonic” SUSY

(Cheng, Matchev, Schmaltz 2002)

KK-parity

- branes break 5D trans. invariance
  - discrete momentum cons. (KK-number)
- Loops further break it to KK-parity
  - reflection about midpoint of extra dim.
- Certain terms forbidden (5D fermion masses)

The Model

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

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

$\times U(1)_{PQ}$

2 Higgs Doublets

H_u, H_d

z=0 z=L

	H_u	H_d	Q	$\bar{u}$	$\bar{d}$	L	$\bar{e}$
Y	$1/2$	$-1/2$	$1/6$	$-2/3$	$1/3$	$-1/2$	1
PQ	1	1	$-1/2$	$-1/2$	$-1/2$	$-1/2$	$-1/2$

← Anomalous →

$\mu H_u^T i\tau_2 H_d$ $\mu H_u^T i\tau_2 H_d$

A broken 5D gauge symmetry

Gauge a U(1) in the bulk of the flat extra dimension

(bulk gauge coupling g_{PQ})

Break it by boundary conditions:

$$B_\mu|_{z=0,L} = 0$$

Symmetry is **global** on boundaries:

$$B_M \to B_M + \partial_M \beta(x,z) \qquad \partial_\mu \beta(x,z)|_{z=0,L} = 0$$

Gauge fixing in the bulk

$$\int dz \frac{-1}{4g_{\rm PQ}^2}\left[B_{\mu\nu}B^{\mu\nu} - 2(\partial_5 B_\mu)^2 - 2(\partial_\mu B_5)^2 + 4(\partial_\mu B^\mu)(\partial_5 B_5)\right]$$

Bulk gauge fixing:

$$\mathcal{L}_{\rm GF} = -\int dz \frac{1}{2}G^2 \equiv \int dz \frac{-1}{2g_{\rm PQ}^2 \xi_B}\left[\partial_\mu B^\mu - \xi_B \partial_5 B_5\right]^2$$

Residual gauge symmetry:

$$\partial_\mu \partial^\mu \beta(x,y) - \xi_B \partial_5^2 \beta(x,y) = 0$$

5D unitary gauge: $\xi_B \longrightarrow \infty$

$$\beta_{\rm res}(x,z) = \beta^+ + \beta^- \left(\frac{2z-L}{2L}\right)$$

A 5D Goldstone Boson

with BC's we chose, a zero mode remains uneaten

under residual gauge transform:

$$\beta_{\rm res}(x,z) = \beta^+ + \beta^- \left(\frac{2z-L}{2L}\right) \qquad B_5 \to B_5 + \frac{\beta^-}{L}$$

massless with shift symmetry = Goldstone

Additional Spontaneous Breaking

U(1) is broken by boundary conditions, and there's also a Higgs field(s) with charge under this gauge group

$$\mathcal{L} = -V_{\rm bound}(H(0)) - V_{\rm bound}(H(L)) + \int dz \frac{-1}{4g_{5D}^2} B_{MN}B^{MN} + \frac{1}{L}|D_M H|^2 - V(H)$$

$$H \sim \frac{v(z)}{\sqrt{2}} e^{i\pi(x,z)/v(z)} \qquad \mathcal{L}_{\rm mix} = -\frac{1}{g_{5D}^2}(\partial_5 B^\mu)(\partial_\mu B_5) + \frac{1}{L} v \partial_\mu \pi B^\mu$$

New Gauge fixing potential

$$\frac{1}{2}G^2 = \frac{-1}{2\xi g_{5D}^2}\left[\partial_\mu B^\mu - \xi\left(\partial_5 B_5 + \frac{g_{5D}^2}{L} v\pi\right)\right]^2$$

Two Zero Modes

KK-parity odd

$$\pi^{(0)\mathrm{odd}} = A'_B \frac{v}{\kappa} \sinh \kappa(z - L/2) \zeta^{\mathrm{odd}}(x)$$

$$B_5^{(0)\mathrm{odd}} = A'_B \cosh \kappa(z - L/2) \zeta^{\mathrm{odd}}(x)$$

KK-parity even

$$B_5^{(0)\mathrm{even}} = B'_B \sinh \kappa(z - L/2) \zeta^{\mathrm{even}}(x)$$

$$\pi^{(0)\mathrm{even}} = -B'_B \frac{v}{\kappa} \cosh \kappa(z - L/2) \zeta^{\mathrm{even}}(x)$$

$$\kappa \equiv g_{5D} v / \sqrt{L}$$

Small kappa:

KK-parity odd

$$B_5^{(0)\mathrm{odd}} \approx \frac{g_{5D}}{\sqrt{L}} \zeta^{\mathrm{odd}}$$

$$\pi^{(0)\mathrm{odd}} \approx \frac{g_{5D}}{\sqrt{L}} v (z - L/2) \zeta^{\mathrm{odd}}$$

KK-parity even

$$B_5^{(0)\mathrm{even}} \approx -\frac{g_{5D}^2 v}{L} (z - L/2) \zeta^{\mathrm{even}}$$

$$\pi^{(0)\mathrm{even}} \approx \zeta^{\mathrm{even}}$$

The 5D Goldstone

Interactions arise from 5D kinetic term

$$\bar{\Psi} i D_M \gamma^M \Psi \supset \bar{\Psi} i \left(\partial_5 - i \frac{g_{5D}}{\sqrt{L}} B_5^{(0)} \right) \gamma^5 \Psi$$

Field redefinition: (Wilson line)

The B_5 couples derivatively:

$$\bar{\Psi} i \partial\!\!\!/ \Psi \to \bar{\Psi}' i \partial\!\!\!/ \Psi' + \int_{z_0}^{z} dz' B_5^{(0)} \partial_\mu \left(\bar{\Psi}' \gamma^\mu \Psi' \right)$$

Anomalies in 4D

Under chiral redefinitions, the Jacobian in the PI measure is generically non-trivial

$$\Psi = e^{-i\frac{\pi}{2v}\gamma^5}\Psi' \qquad \int \mathcal{D}\bar{\Psi}\mathcal{D}\Psi \rightarrow \int \mathcal{D}\bar{\Psi}'\mathcal{D}\Psi' \, [J]$$

$$[J] = \exp\left[\frac{i}{v}\int d^4x\pi(x)\mathcal{A}\right]$$

Where $\mathcal{A}$ is the axial vector current anomaly:

$$\mathcal{A} = \frac{\alpha}{8\pi}\mathcal{F}\cdot\tilde{\mathcal{F}}$$

Anomalies in 5D

5D theory is vectorlike in bulk (no anomalies)

Chiral theory is arranged via orbifold projection

Theory is chiral only on the branes (z=0,L)

Anomalies restricted to the branes

(does not follow profile of zero mode)

(Arkani-Hamed, Cohen, Georgi)

Anomalies in 5D

The Complete Anomaly:

$$\mathcal{A}(x,z) = \frac{1}{2}\left[\delta(z)+\delta(z-L)\right]\sum_f q^f_{\rm PQ}\left(\frac{q^{f2}_{\rm Y}}{16\pi^2}F\cdot\tilde{F} + \frac{{\rm Tr}\ \tau^f_a\tau^f_a}{16\pi^2}W\cdot\tilde{W} + \frac{{\rm Tr}\ t^f_a t^f_a}{16\pi^2}G\cdot\tilde{G}\right)$$
$$\equiv \frac{1}{2}\left[\delta(z)+\delta(z-L)\right]\mathcal{Q}_{\rm PQ}(x,z)$$

Our chiral redefinition was:

$$\Psi = \exp\left[iq\left(\frac{\pi(z_0)}{v(z_0)} + \int_{z_0}^{z} dz' B_5^{(0)}\right)\right]\Psi'$$

PI measure shifts, new terms in eff. Lagrangian are:

$$\mathcal{L}^{\rm eff}_{B_5 AA} = \frac{g'^2_{5D}g^{\rm PQ}_{5D}}{16\pi^2\sqrt{L}}B_5^{(0)}(x)\sum_{m\geq n\geq 0} c_{nm}F^{(n)}\cdot\tilde{F}^{(m)}$$

$$c_{nm} = \begin{cases} 0 & n+m \text{ even} \\ \sum_f q^f_{\rm PQ}q^{f2}_Y & n+m \text{ odd},\ n,m\geq 1 \\ \frac{1}{\sqrt{2}}\sum_f q^f_{\rm PQ}q^{f2}_Y & n+m \text{ odd},\ n\cdot m = 0. \end{cases}$$

Massless modes are bad

pi is a would-be "electroweak axion" if it is very light (exact PQ symmetry)

(Weinberg-Wilczek)

interactions only suppressed by v = 246 GeV

completely ruled out by astro and nuclear physics

also need at least a small mass for B5

Explicit breaking

Symmetry is only global on boundaries

$$V_{\text{bound}} = -\tfrac{\mu}{2}(H^2 + H^{*2}) \ \sim \mu\pi^2|_{0,L}$$

(very similar for 2HDM)

$$V_{\text{eff}} = 2\mu\zeta_+^2 + \frac{1}{2}g_{4D}^2\mu v^2 L^2 \zeta_-^2$$

Scalar "Axino" gets a potentially small mass:

$$m_{\text{light}} = 74\ \text{MeV}\left(\frac{g}{3\cdot 10^{-4}}\right)\left(\frac{\mu}{300^2\ \text{GeV}^2}\right)^{1/2}(L\cdot 1000\ \text{GeV})$$

(has small - negligible - contribution to EWP)

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$\mu H_u^T i\tau_2 H_d$

$\mu H_u^T i\tau_2 H_d$

Spectrum

mass

100's of GeV:

Rest of level 1 KK-modes

Level 1 hypercharge gauge KK-mode

B_5 "axino" ~10 keV to GeV

Collider Pheno

NLSP decays:

partner of hypercharge gauge boson decays through the anomaly

$$A_\mu^{(1)} \to \gamma(Z) + B_5 \qquad\qquad f_{\rm PQ} \equiv \frac{1}{g_{5D}^{\rm PQ}\sqrt{L}}$$

$$\Gamma_{\gamma,Z} \approx \frac{\alpha^2}{192\pi^3 c_w^4 f_{\rm PQ}^2} m^{(1)3} \left(\sum_f q_{\rm PQ}^f q_Y^{f2} \right)^2 (c_w^2, s_w^2).$$

$$\Delta x = \gamma v \tau \approx 46 \text{ cm} \left(\frac{10^3 \text{ GeV}}{m^{(1)}} \right)^3 \left(\frac{f_{\rm PQ}}{10^9 \text{ GeV}} \right)^2 \sqrt{\left(\frac{E}{m^{(1)}} \right)^2 - 1}.$$

Other NLSP's ?

Some rough constraints

- to be safe, want NLSP lifetime < 1s
  - hadronic decays of the Z are dangerous
  - $f_{PQ} < 10^{14}$ GeV
- also want to avoid HDM so m_{B5} > keV ($g>10^{-9}$)
- for ‘interesting’ coll. pheno, f < 10^10 GeV

Dark Matter Pheno

Small gauge coupling:

too much if thermal

reheat (what is thy?)

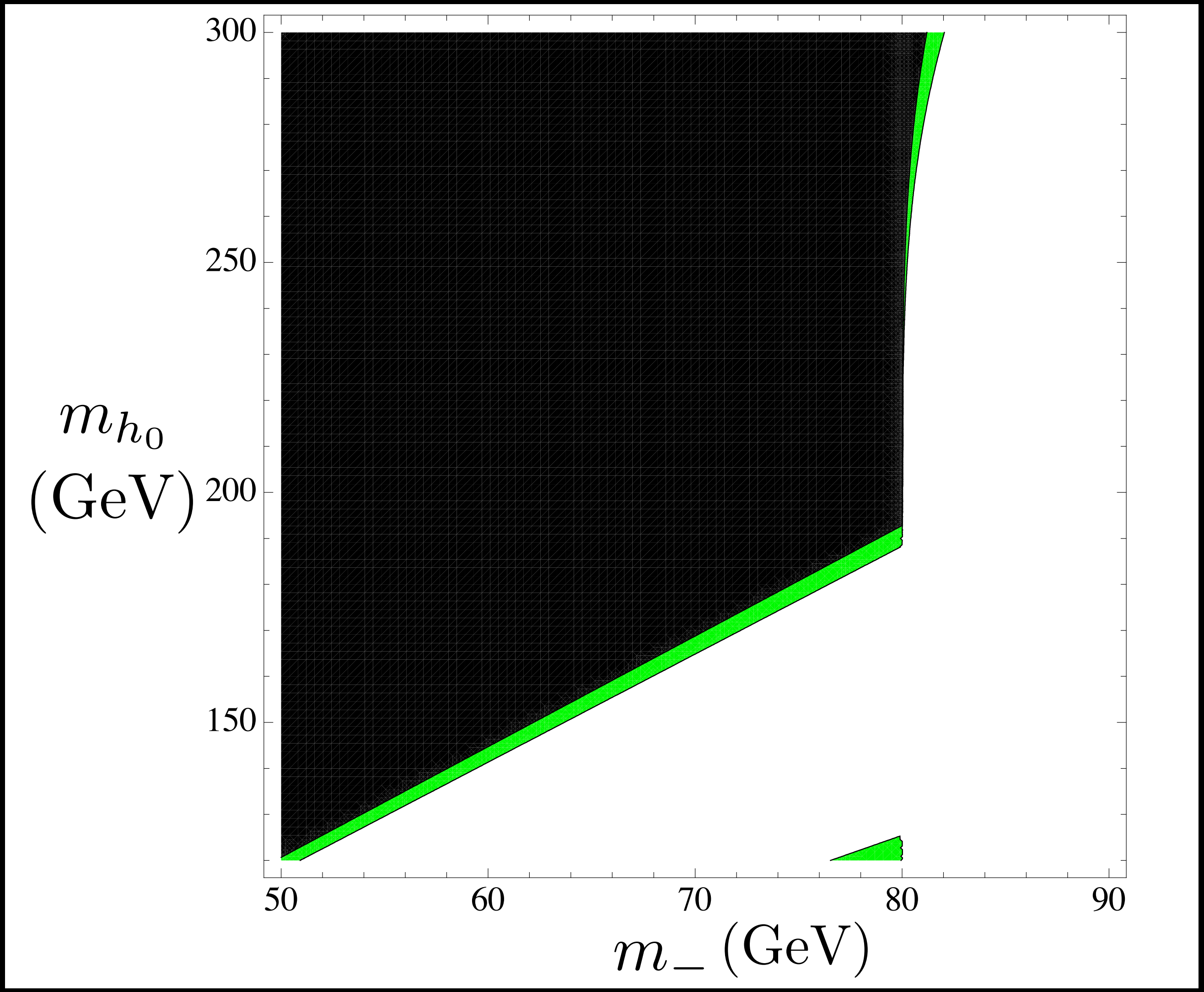
good reason to believe okay
(studies of axino dm)

O(1) gauge coupling (weak scale Goldstone mass)

Standard WIMP analysis:

annihilation through s-channel Higgses

large $\tan\beta$



Future Study

- Can something like this be done in a little Higgs with T-parity (deconstruction)?
  - non-trivial (NN no-go, orbifolds are special)
- Warped space
- collider study of look-alikes
  - model distinction?
- detailed DM study
- Strong CP problem - other related scenarios
- other NLSP's? Heavy charged tracks - late decay

Conclusions

- We found a way to fake signals of GMSB
  - copious Z's and photons (displaced decays)
  - model is a bit of a "straw man" (little Higgs?)
- some cool physics along the way
  - anomalies, spontaneous/explicit symmetry breaking, non-local interactions, 5D goldstones
- new DM candidate in PQ-UED
- Not immediately ruled out - further study