University of Maryland
Hidden Naturalness Workshop

Neutral Naturalness

28 April 2016

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Go back in time to 2005…

Original motivation for Twin Higgs was the "LEP paradox":

SM as an EFT suffers Hierarchy Problem → New weak scale physics

Generic strongly coupled physics with light scalar → Electroweak Precision Observables

No deviations at LEP → weak-scale physics must be perturbative

Top partners!

Supersymmetry

"modern composite Higgs"
(Little Higgs, RS, ..)

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Neutral Naturalness
(Twin Higgs, Folded SUSY, …)

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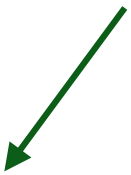

Qualitatively new theories with uncolored top partners

Top partners!

Supersymmetry

"modern composite Higgs"
(Little Higgs, RS, ..)

Neutral Naturalness
(Twin Higgs, Folded SUSY, …)

Qualitatively new theories with uncolored top partners

***NEW**: avoids LHC constraints from colored top partner searches*

Generalize our notion of naturalness

Neutral Naturalness Model Space

	scalar	*fermion*
QCD	SUSY	Composite Higgs/ RS
EW	folded SUSY	Quirky Little Higgs
singlet	?	Twin Higgs

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The Twin Higgs

Duplicate SM gauge groups and all (or part of) the matter:

SM_A x SM_B with Z_2 symmetry
relating the two sectors

$SU(2)_A$ x $SU(2)_B$ x Z_2 scalar sector has approximate SU(4) symmetry at one-loop quadratic level:

$$\Delta V = \frac{3}{8\pi^2}\Lambda^2\left(\lambda_A^2|H_A|^2 + \lambda_B|H_B|^2\right) \xrightarrow[\mathbb{Z}_2]{\lambda_A = \lambda_B = \lambda} \Delta V = \frac{3}{8\pi^2}\Lambda^2\lambda^2|H_{SU(4)}|^2$$

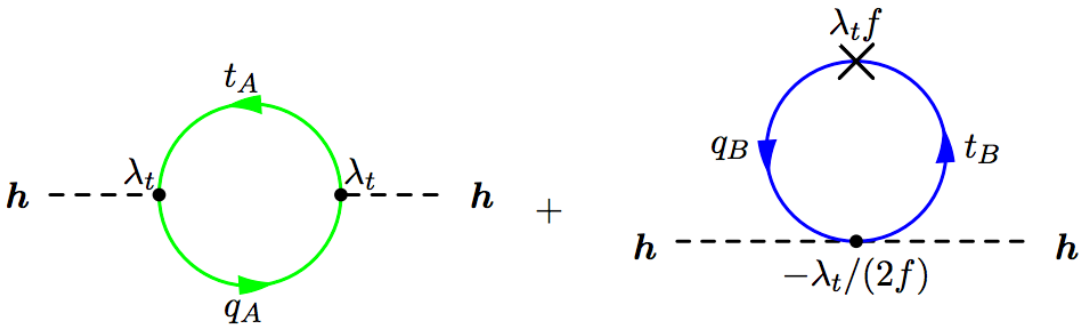
Light Higgs is pNGB of this *approximate* SU(4) breaking

The Twin Higgs

In low-energy EFT, the SM-singlet mirror tops cancel the top quark divergence

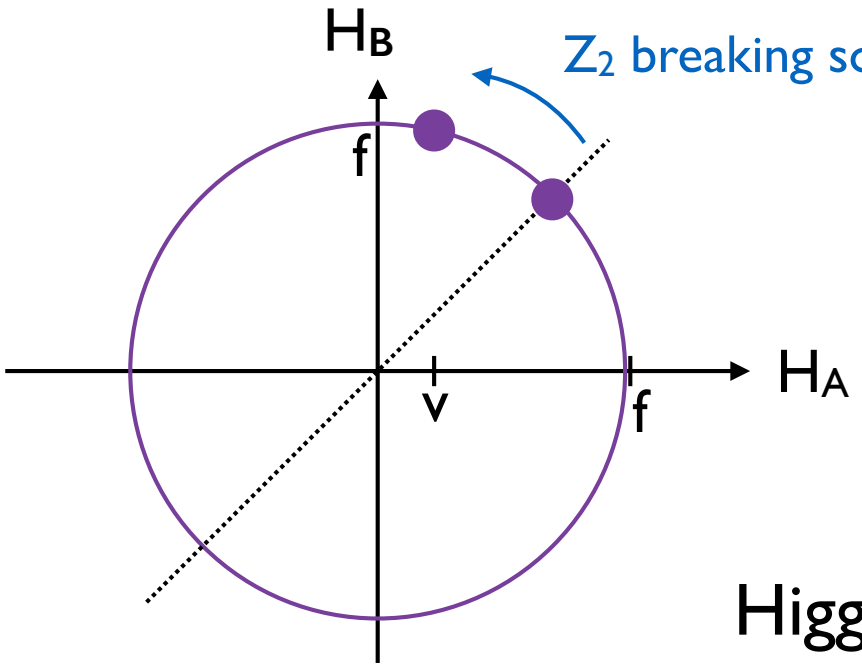
$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \qquad H_A \approx h \qquad H_B = \begin{pmatrix} 0 \\ f^2 - \frac{h^2}{2f} \end{pmatrix}$$

$$\lambda_A H_A q_A t_A + \lambda_B H_B q_B t_B \longrightarrow i\lambda_t \boldsymbol{h} q_A t_A + \lambda_t \left(f - \frac{1}{2f} \boldsymbol{h}^\dagger \boldsymbol{h} \right) q_B t_B$$



The Twin Higgs

Making the pNGB h live mostly in the A-sector requires soft Z_2 breaking and tuning in the model.



Z_2 breaking soft mass vs Z_2 preserving Higgs mass

Higgs mixing angle ~ tuning ~ $\frac{v^2}{f^2}$

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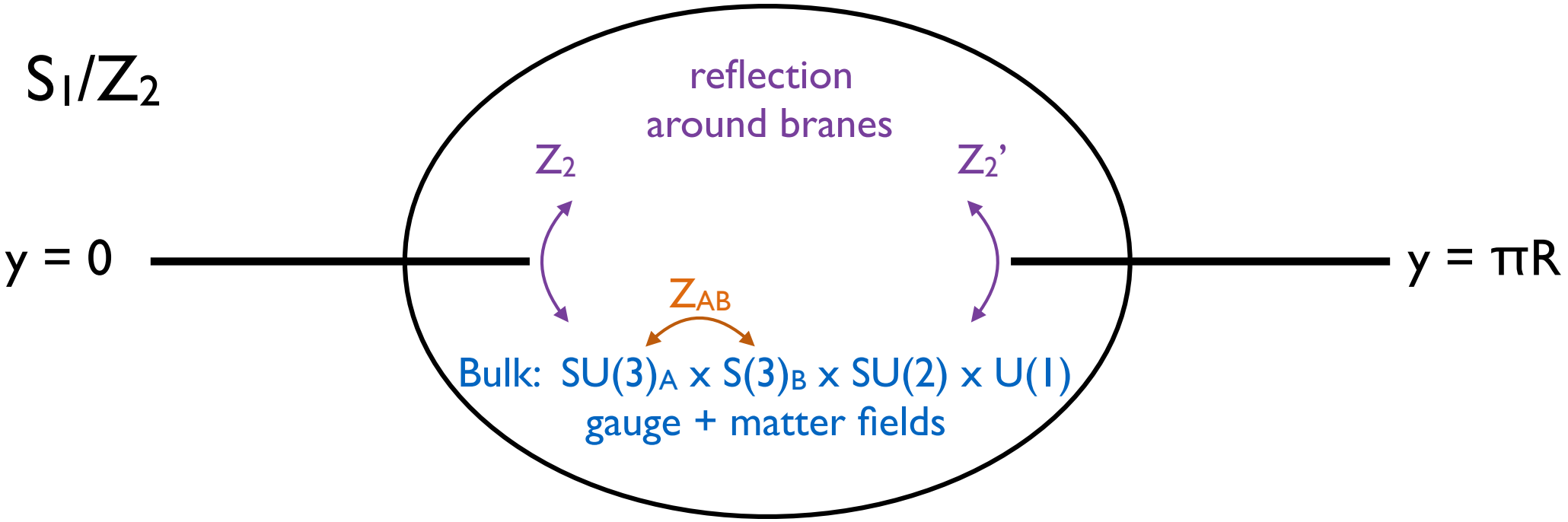
Folded SUSY

Flat 5D minimal SUSY ↔ N=2 4D SUSY



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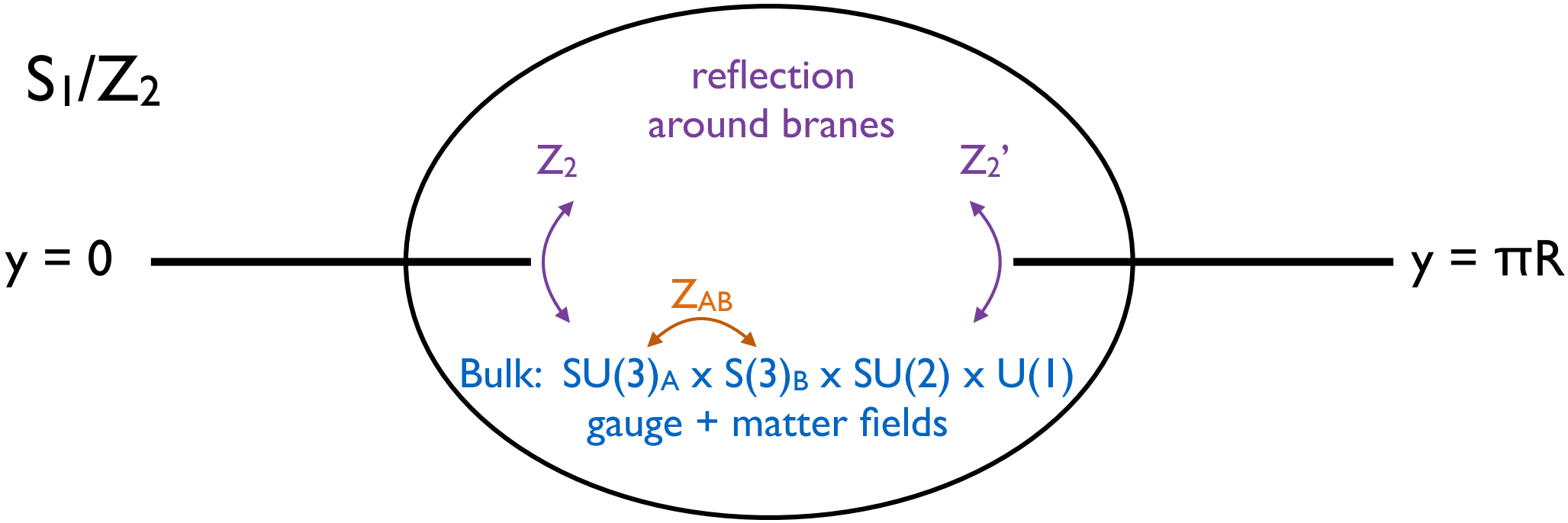


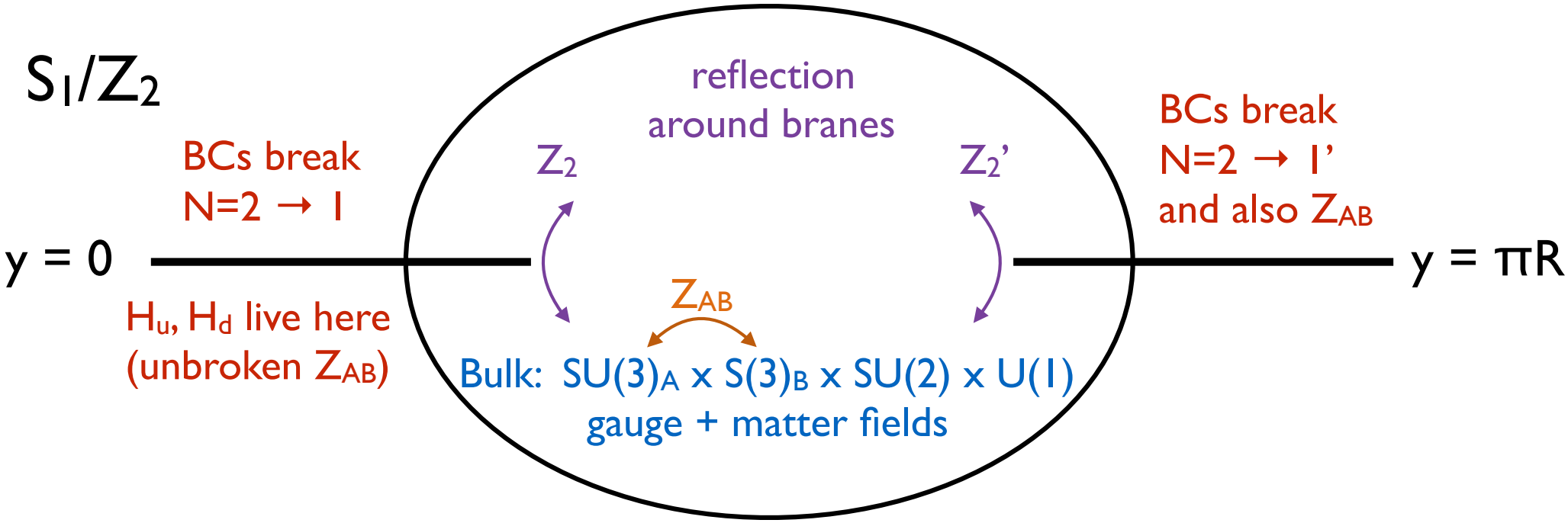
Orbifolding: boundary conditions of matter fields determine reflection properties under Z_2, Z_2', hence **which fields have zero modes.**

Z_2 preserves N=1 SUSY

Z_2' preserves **different** N=1' SUSY **and** breaks Z_{AB}

Folded SUSY

Flat 5D minimal SUSY ↔ N=2 4D SUSY



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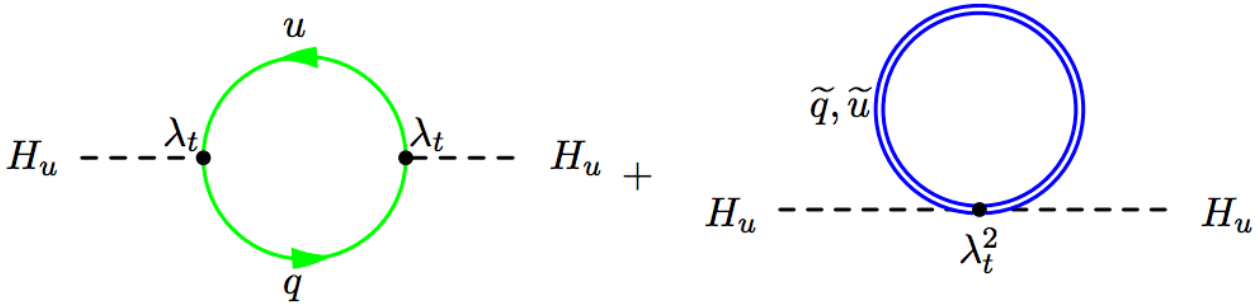
Folded SUSY

4D N=2 4D SUSY broken to N = 0

zero modes:	fermions A	fermions B	gauginos
(i.e ~ MSSM-like soft masses)	sfermions A	sfermions B	Higgs, Higgsinos (on brane)

Z_{AB} respected by Higgs couplings

"accidental SUSY" in low-energy theory protects Higgs mass:



uncolored EW stops cancel SM top loop

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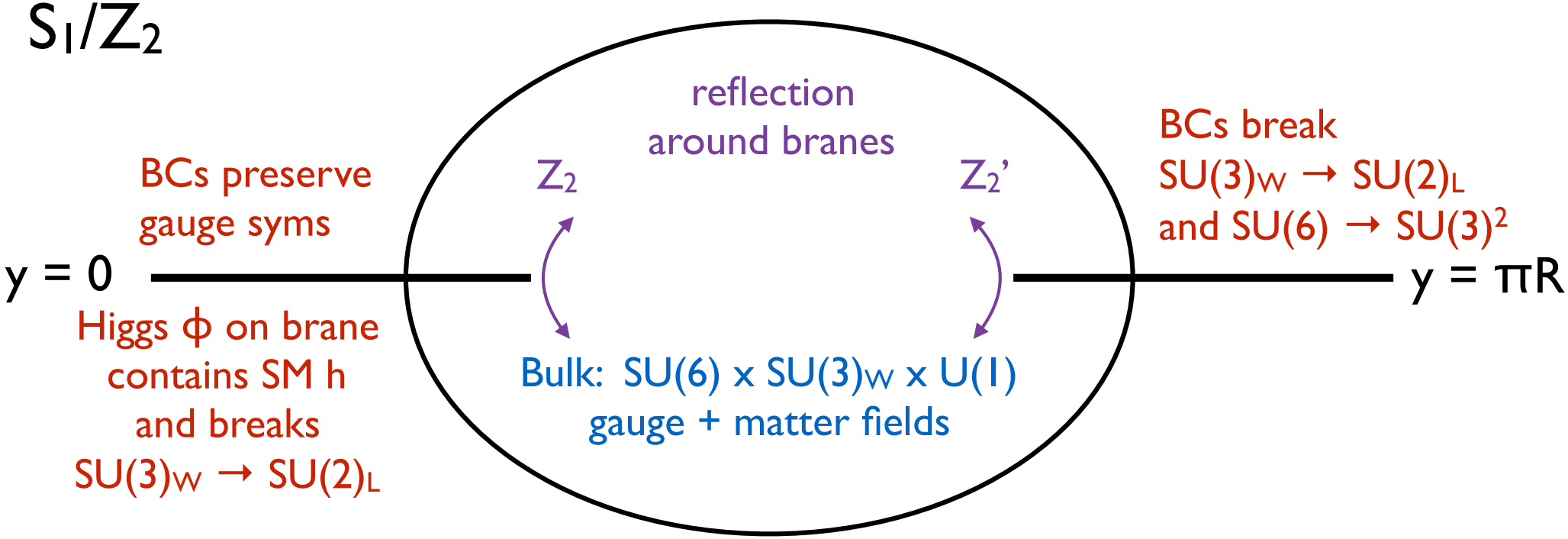
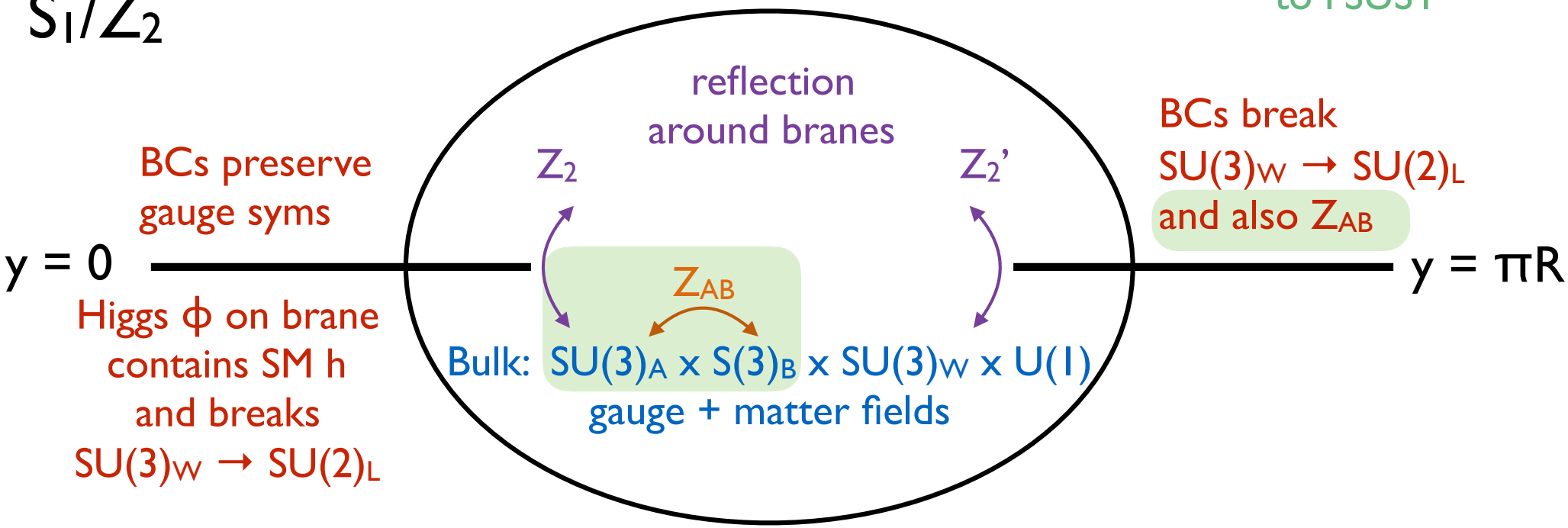
Quirky Little Higgs



Quirky Little Higgs

.. in analogy to FSUSY



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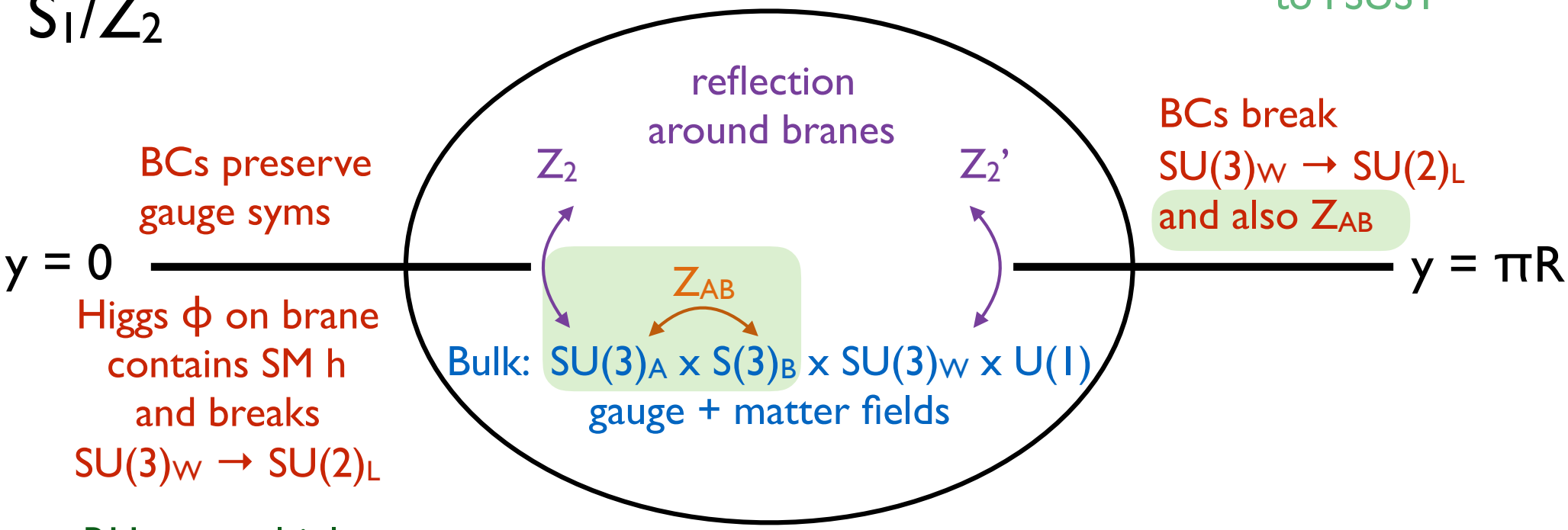


RH top multiplet on brane

LH top multiplet in bulk

$$Q_{t_R}^{(6,1)} = (t_R, T_R)$$

$$Q_{t_L}^{(6,3)} = (Q_{t_L}, Q_{T_L}) = \begin{pmatrix} t_L & T_L \\ b_L & B_L \\ \chi & X \end{pmatrix} \downarrow SU(3)_W$$

$$\mathcal{L} \supset \delta(y)\, y_t \phi\, Q_{t_R} Q_{t_L}$$

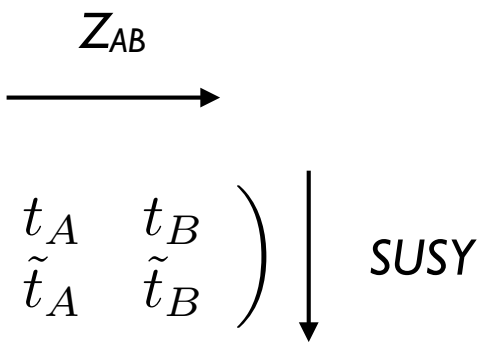
T_R and X pair up via Higgs vev to become **uncolored EW top partner**

FSUSY vs QLH

In FSUSY, N=2 SUSY ensures equality of Yukawa couplings, broken down to Z_2 in low-energy theory.

In Quirky Little Higgs, SUSY is replaced by SU(3)w

cartoon:



$$Q_{t_L}^{(6,3)} = (Q_{t_L}, Q_{T_L}) = \begin{pmatrix} t_L & T_L \\ b_L & B_L \\ \chi & X \end{pmatrix}$$ SU(3)w

EW vs Singlet top partners

Twin Higgs has fermionic SM singlet top partners.
Works because Higgs is pNGB, lives in both sectors.

FSUSY cannot be trivially 'folded again' to get rid of
EW charge of stops, would get e.g. light colored sbottoms.

SM singlet scalar top partners need
something more complicated….

Remarks

Discrete Symmetry

In NN, discrete symmetry gives 'low-energy pNGB/SUSY' limit which protects Higgs mass.

(Can generalize from Z_2 to other discrete groups.)

Craig, Knapen, Longhi '14

This fails at 2-loop, so only solved **Little Hierarchy Problem.**

Generically need UV completion at 5-10 TeV

~ dozen examples in literature

Discrete Symmetry

SM QCD is duplicated in the mirror sector, giving rise to **mirror QCD force.**

Naturalness motivation for Hidden Valleys!
→ hidden hadron production and decay through higgs portal
→ **displaced decays @ LHC!**

note: for EW top partners this is 'guaranteed' by LEP bounds
for singlet top partners this is possible e.g. Fraternal Twin Higgs

Craig, Katz, Strassler, Sundrum '15, Curtin, Verhaaren '15, Csaki, Kuflik, Lombardo, Slone '15, Cheng, Jung, Salvioni, Tsai '15, …..

Can get rid of mirror QCD at cost of lowering scale of UV completion to ~ 2 TeV → different LHC signatures.

Poland, Thaler '08

Experimental Consequences Today

Most well-studied phenomenon: **Displaced Vertices**

.. from the hidden valley

.. from e.g. slepton decay in FSUSY

Burdman, D'Agnolo '15

In pNGB Higgs (TH, QLH) models there are mixing effects which lead to **Higgs coupling deviations.**

… gives lepton colliders ~ 2 TeV reach for top partner masses

Experimental Consequences Today

Cosmology?

Mirror sector has lots of new states.

→ DM candidates, both WIMP and ADM

→ BBN is sensitive to light dof

Garcia Garcia, Lasenby, March-Russell '15, Craig, Katz '15, Farina '15

Baryogenesis?

To what extent are these consequences generic?

Experimental Consequences Today

Flavor?

Composite UV completions have flavor signals

Csaki, Geller, Telem, Weiler '15

Flavor structure in mirror sector often has to be different from SM due to cosmology etc…

→ model-independent flavor signals?

Experimental Consequences Today

750 GeV?

~ 300 papers

→ by now we have some idea of what physical processes can give high-mass diphotons

Of course, more possibilities remain…

This signal doesn't "jump out" at you within Neutral Naturalness… (Who ordered that?)

But could it occur within the Neutral Naturalness Framework?

Naturalness motivation is orthogonal to diphoton mystery!

UV Completion

How "likely" do these models seem?

Is there a beautiful theory hiding somewhere?

Is this worse than tuned SUSY?

UV Completion

What is the structure of the UV completion?

Existing proposals have common features that are what you'd expect from the "full symmetry" becoming apparent in the UV.
(The next layer of the onion..)

e.g. new states with SM charges

Is it possible to UV complete without new SM-charged states?
Seems difficult, since at least new EW states are required to fit Higgs into a multiplet of some enlarged symmetry.

UV Completion

Probing UV theory at 100 TeV collider!

Generically expect new direct production signals.

Can we ask model-independently whether a natural theory can hide from experimental searches?

Curtin, Saraswat '15

Major motivation for building this new machine!

Perspective

Naturalness influences all aspects of theory!

Consider MSSM	Neutral Naturalness
DM candidate	
EWBG possible	features versions of all of these!
naively dead at LEP or Tevatron, but we'll keep playing	Lots of theory and pheno left to understand
flavor signals are model-dependent	

Perspective

"Hidden Naturalness" is
both an experimental and a
theory statement.

If not Neutral Naturalness,
then maybe something even stranger?