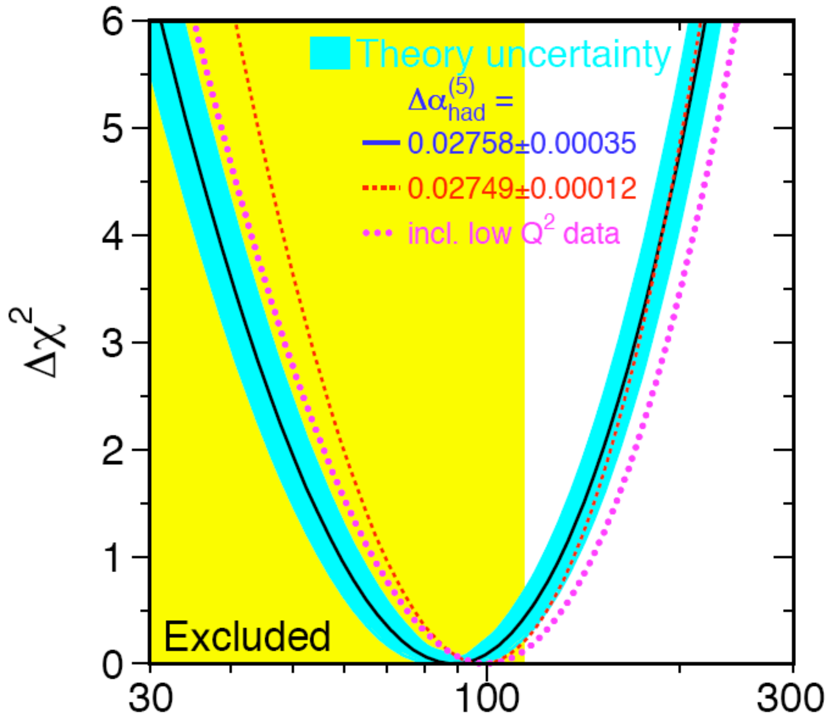
Folded Supersymmetry

Roni Harnik, SLAC/Stanford

with
G. Burdman, Z. Chacko, H.S. Goh - coming soon.

LEP Paradox

Barbieri, Strumia



Dimensions six operators			$m_h = 115$ GeV $c_i = -1$	$m_h = 115$ GeV $c_i = +1$
$\mathcal{O}_{WB}$	$=$	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.7	10
$\mathcal{O}_{H}$	$=$	$\lvert H^\dagger D_\mu H \rvert^2$	4.6	5.6
$\mathcal{O}_{LL}$	$=$	$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	7.9	6.1
$\mathcal{O}'_{HL}$	$=$	$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	8.4	8.8
$\mathcal{O}'_{HQ}$	$=$	$i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma_\mu \tau^a Q)$	6.6	6.8
$\mathcal{O}_{HL}$	$=$	$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	7.3	9.2
$\mathcal{O}_{HQ}$	$=$	$i(H^\dagger D_\mu H)(\bar{Q}\gamma_\mu Q)$	5.8	3.4
$\mathcal{O}_{HE}$	$=$	$i(H^\dagger D_\mu H)(\bar{E}\gamma_\mu E)$	8.2	7.7
$\mathcal{O}_{HU}$	$=$	$i(H^\dagger D_\mu H)(\bar{U}\gamma_\mu U)$	2.4	3.3
$\mathcal{O}_{HD}$	$=$	$i(H^\dagger D_\mu H)(\bar{D}\gamma_\mu D)$	2.1	2.5

SM Higgs seems to be light.

No new physics up to $\Lambda \sim 5 - 10\,\text{TeV}$

Paradox!?

Do We Care?

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There are new light states below Λ

but

They do not contribute to precision EW.

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They do not contribute to precision EW.

New light states just beyond EW scale:
Directly determines NP at LHC.

New Symmetry

* Popular mechanisms:
  - SUSY (with R-parity)
  - Little Higgs (with T-parity)
* In both cases:

new continuous symmetry
guarantees cancelations:

Symmetry	SUSY	Little Higgs
Generator $\equiv G$	Q^α	T^a

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* Particle content of new physics:

$$\delta(\text{top}) = G(\text{top})$$

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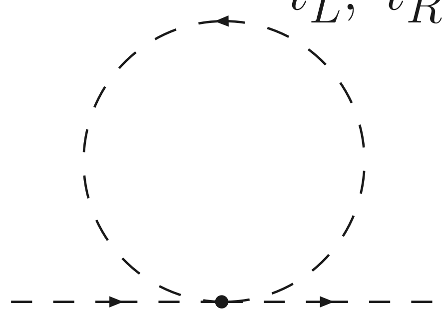
$\tilde{t}_L,\ \tilde{t}_R$



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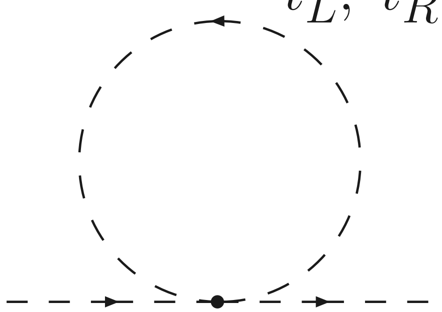

$$\delta(\text{top})_i = (\text{top}')_i$$

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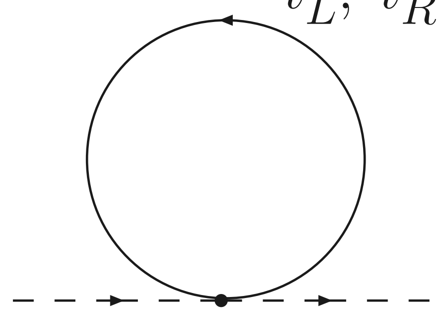

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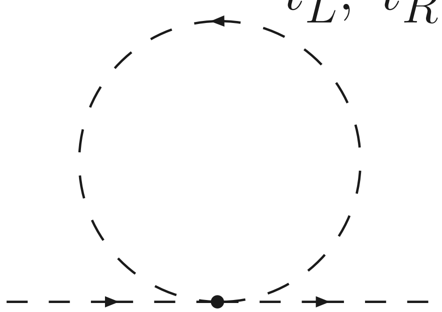

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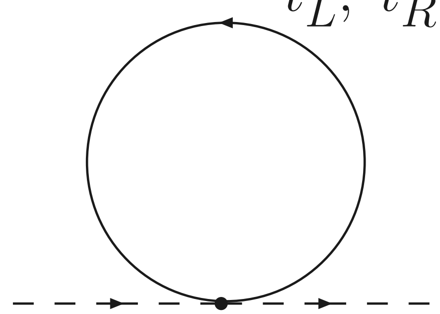

In both cases: **Top partner carries color**

LHC! :-)

Questions

* Colored top-partners have a huge impact on LHC performance.
* Can top partners be uncolored?
  - Fermions? (yes- twin Higgs)
  - Saclars? (yes! folded supersymmetry)
  - Other non-conventional cancelations? (yep...)

Higgs may be protected by a **discrete** symmetry

$$(\mathrm{top})_i \longrightarrow (\mathrm{top}')_{i'}$$

Outline

* Twin Higgs.
* Folded SUSY:
  - Large N orbifold correspondence.
  - Toy Examples.
  - A Model.
  - A UV Completion - 5D orbifold.

Twin Mechanism

Protecting the Higgs with a discrete symmetry

Chacko, Goh, RH

A Toy Example

* A global SU(4) symmetry w/ one fundamental

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

$$\Downarrow$$

$$\langle |H|^2 \rangle = \frac{M^2}{2\lambda} \equiv f^2$$

$$\Downarrow$$

$$SU(4) \longrightarrow SU(3)$$

7 Goldstones

SU(2)$_A$×SU(2)$_B$

- Gauge a subgroup

$$SU(2)_A \times SU(2)_B$$

$SU(2)_A$ → our SM $SU(2)_B$ → twin SM

- In some basis, H transforms as

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

6 eaten.
1 Goldstone left.

- $SU(2)_A \times SU(2)_B$ breaks global $SU(4)$.

The Mechanism

- Impose a Z_2: $A \longleftrightarrow B$

  The only gauge$\times Z_2$ quadratic operator is

$$H_A^\dagger H_A + H_B^\dagger H_B$$

SU(4) invariant!

- If Z_2 is preserved at low energies, radiative corrections will only generate this operator.

No mass for the Goldstone.

Mirror Model

- The whole SM has a mirror copy.

$$\mathcal{L} \supset y_t \underbrace{H_A}_{\displaystyle\downarrow \atop \displaystyle h + \ldots} \bar{t}_A t_A + y_t \underbrace{H_B}_{\displaystyle\downarrow \atop \displaystyle f - \frac{h^2}{2f} + \ldots} \bar{t}_B t_B$$

Mirror Model

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$$\mathcal{L} \supset y_t \underbrace{H_A}\bar{t}_A t_A + y_t \underbrace{H_B}\bar{t}_B t_B$$

$$\downarrow \qquad\qquad \downarrow$$

$$h + \ldots \qquad\qquad f - \frac{h^2}{2f} + \ldots$$

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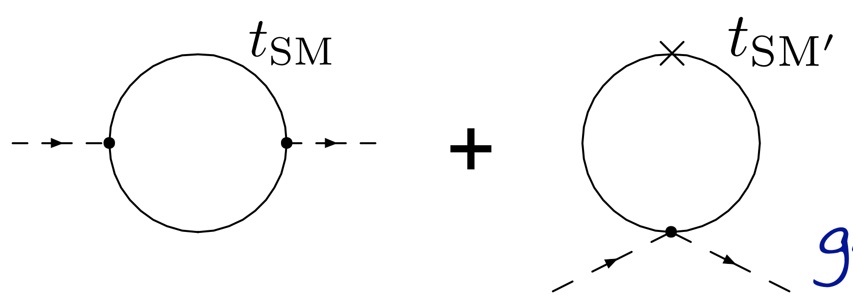

Cancelation guaranteed by Z_2

All new physics is SM singlet

LHC Signals

* A standard model higgs.

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  - Higgs decay to invisibles, $\mathrm{BR} \sim O(v^2/f^2)$.
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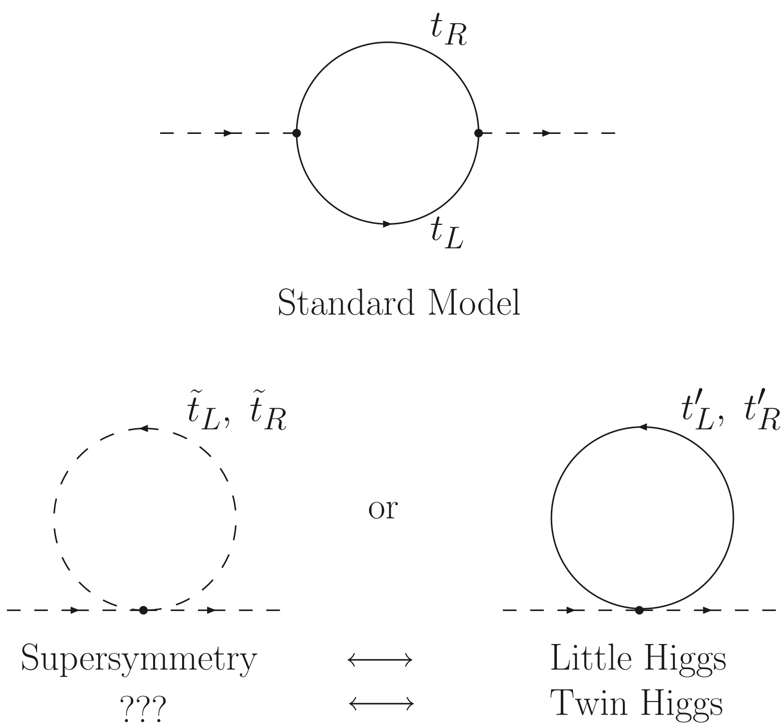
  - Modification of $ZZh, WWh, tth, h^3, \ldots$ also of $O(v/f)$. (correlations).
- If we are *really* lucky (work in progress):

  Twin hadrons decay back to SM with displaced vertices. A "Hidden Valley" signal (Strassler and Zurek).

Left-Right Model

* Goh's talk on Saturday.
* Top partners are colored.
* Exciting LHC signals.

How about SUSY?



Supersymmetry charges don’t act in gauge space.

Superpartners always have the same quantum numbers.

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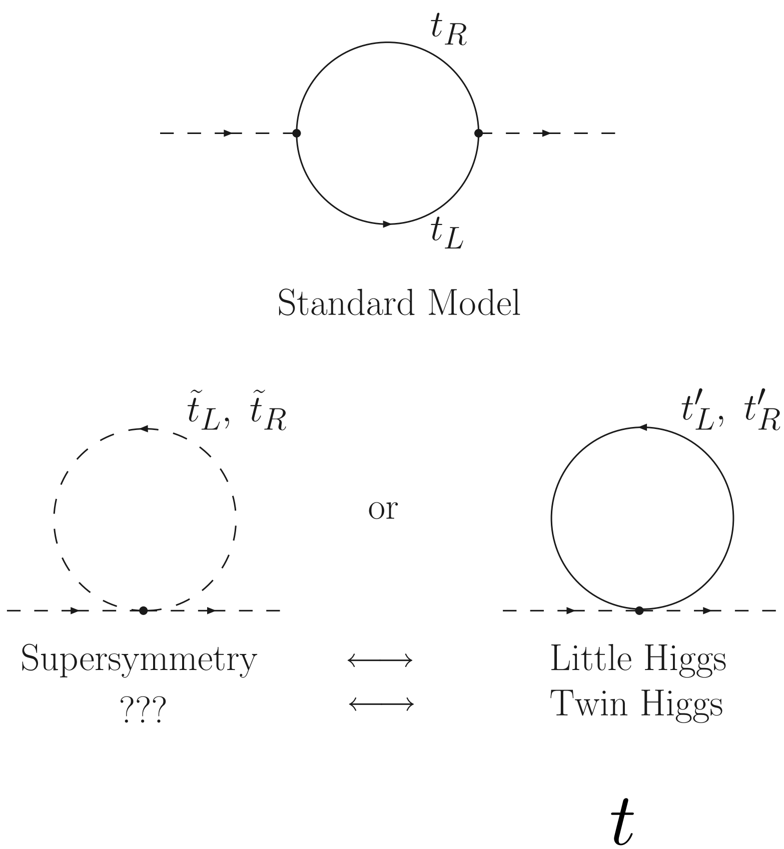

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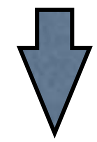

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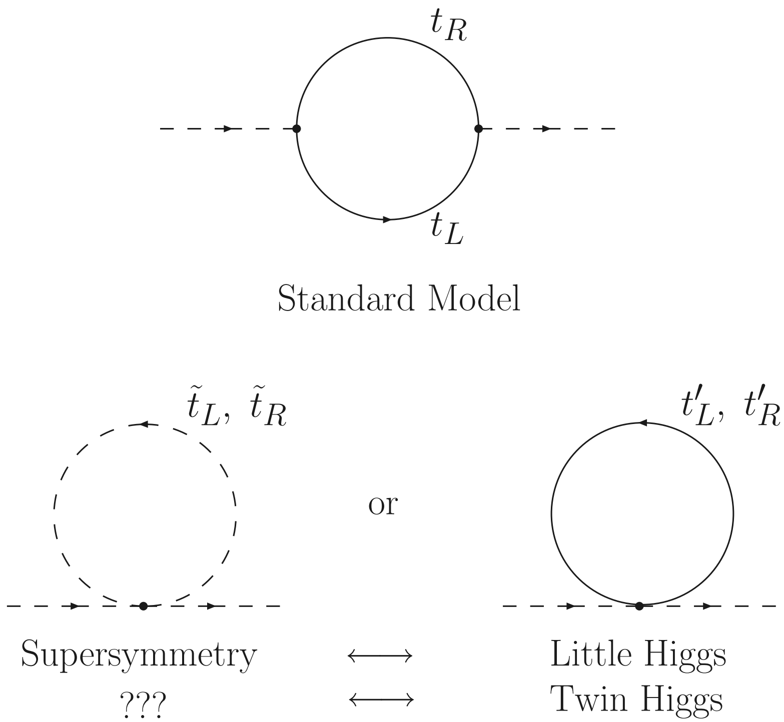

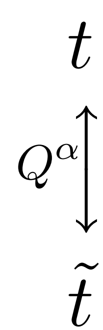

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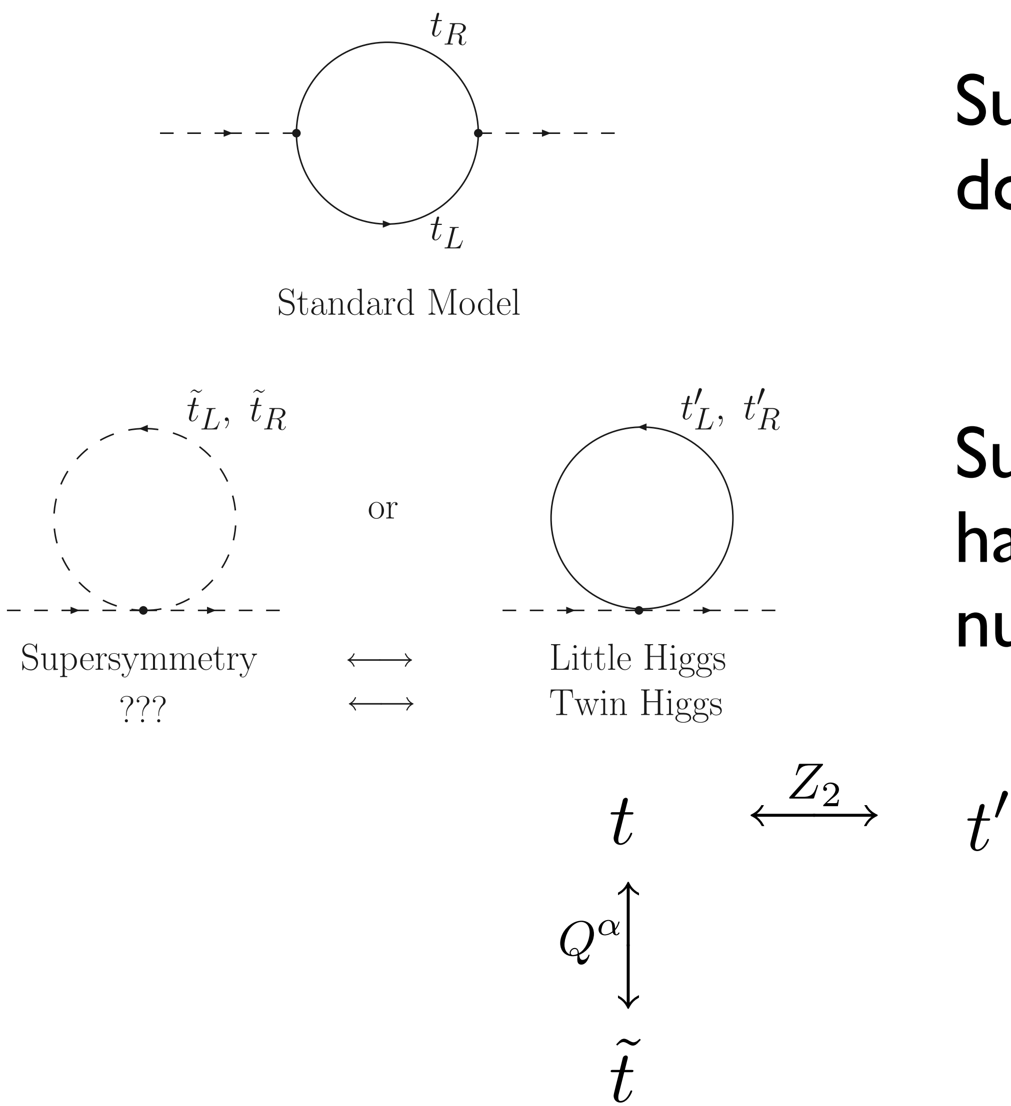

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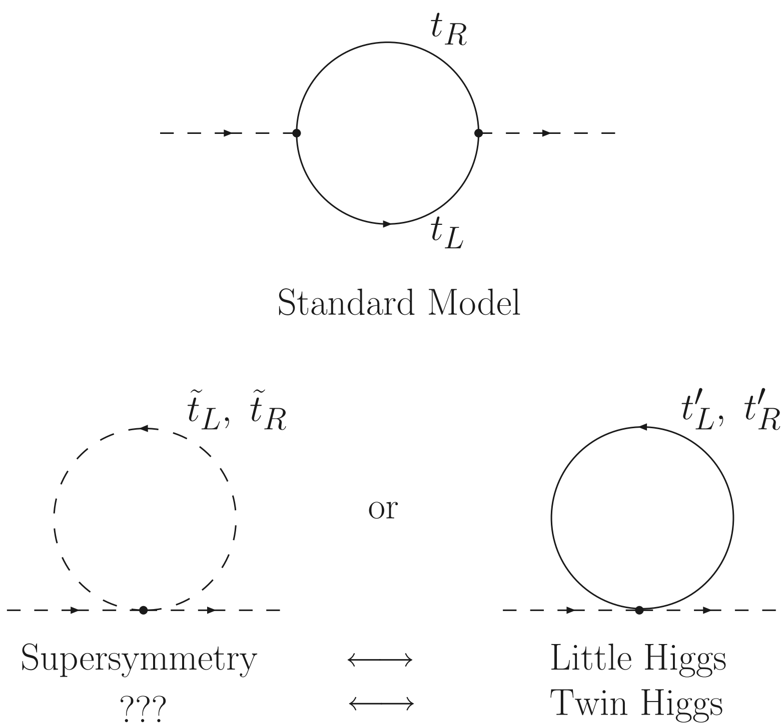

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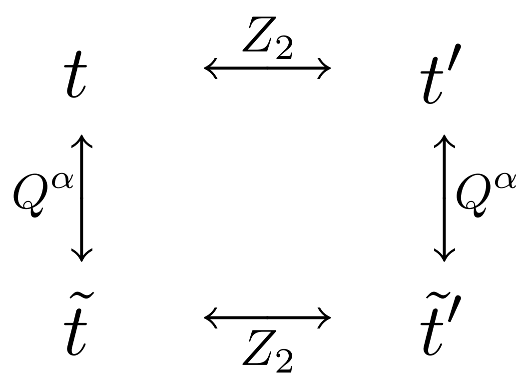

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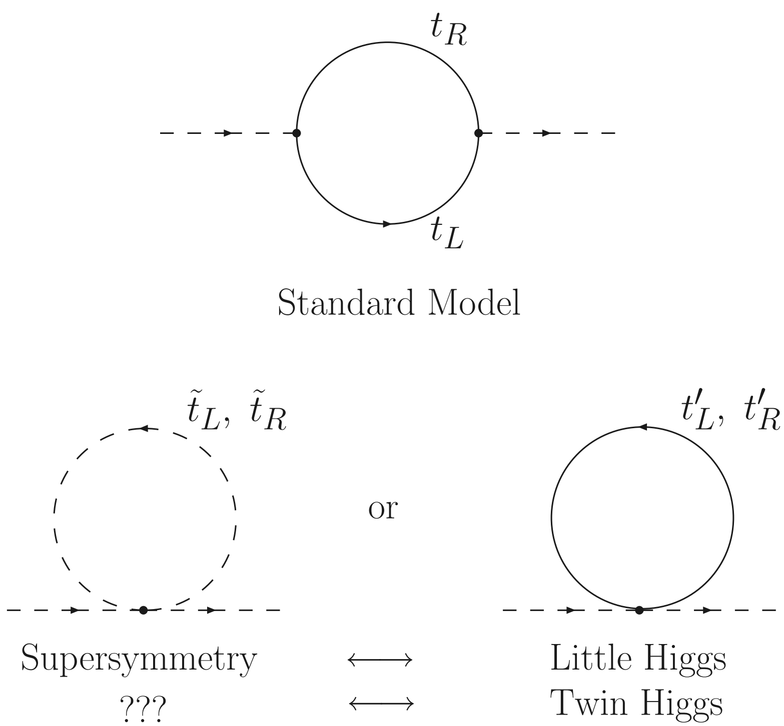

Supersymmetry charges don't act in gauge space.

↓

Superpartners always have the same quantum numbers.

$t \longleftrightarrow \tilde{t}'$

The Large-N Orbifold Correspondence

Kachru and Silverstein (98)
...
Bershadsky and Johansen (98)
...
Schmaltz (99)

Inheritance

Supersymmetric "mother" theory

↓ *orbifolding*

less supersymmetric "daghter"

The daughter theory inherits the correlation functions of its mother in the large N limit (up to a rescaling).

Orbifolding-

1. Identify a discrete symmetry, Γ, of the mother (perhaps an R-symmetry).
2. Eliminate all fields that are not invariant under Γ.

Example I

- A $U(2N)$ SUSY gauge theory with $2N$ flavors.
- A discrete symmetries

$$Z_{2\Gamma}: \quad Q \to \Gamma Q \qquad \bar{Q} \to \Gamma^* \bar{Q} \qquad V \to \Gamma V \Gamma^\dagger$$

$$Z_{2R}: \quad \text{boson} \to \text{boson} \qquad \text{fermion} \to -\text{fermion}$$

$$Z_{2F}: \quad Q \to Q\Gamma_F^\dagger \qquad \bar{Q} \to \bar{Q}\Gamma_F^T$$

$$\Gamma = \Gamma_F = \begin{pmatrix} +1 & & & & & \\ & \ddots & & & & \\ & & +1 & & & \\ & & & -1 & & \\ & & & & \ddots & \\ & & & & & -1 \end{pmatrix}$$

Example I

* The vector superfields transform as

$$A_\mu = \begin{pmatrix} A_{\mu,AA}(+) & A_{\mu,AB}(-) \\ A_{\mu,BA}(-) & A_{\mu,BB}(+) \end{pmatrix}$$

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squarks and quarks w/ different quantum numbers!

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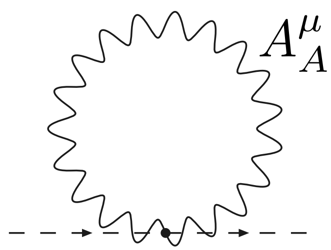
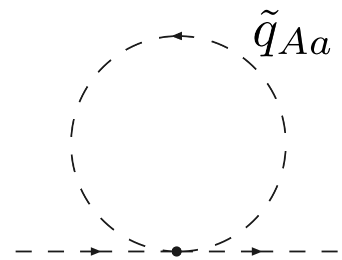
* Calculate radiative corrections to $\tilde{q}_{Aa}$ squark mass



$$\frac{3g^2N}{32\pi^2}\Lambda^2$$



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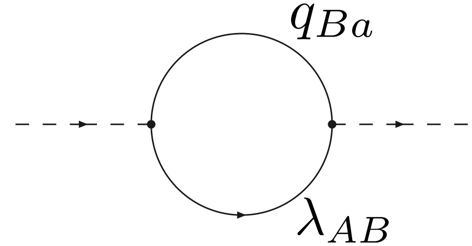

$$-\frac{g^2N}{8\pi^2}\Lambda^2$$

They cancel!

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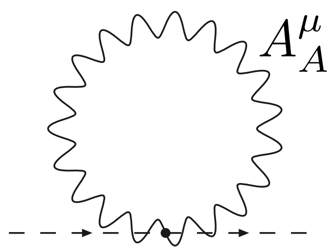

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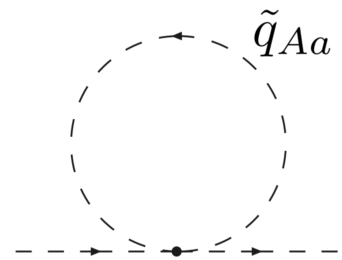

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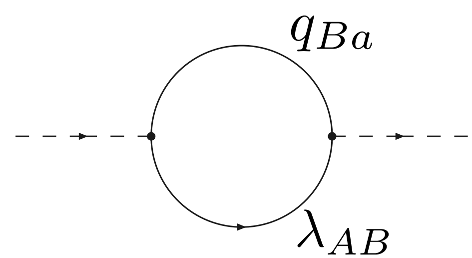

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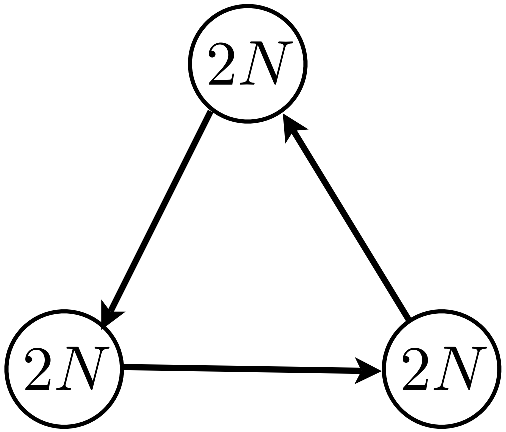
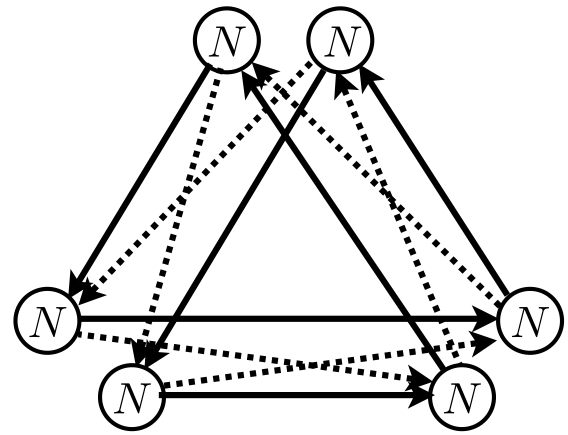
---

* For $SU(2N) \to SU(N) \times SU(N)$:

Cancelation is incomplete: $$-\frac{g^2}{16\pi^2}\frac{1}{N}\Lambda^2$$

Example II - Yukawas

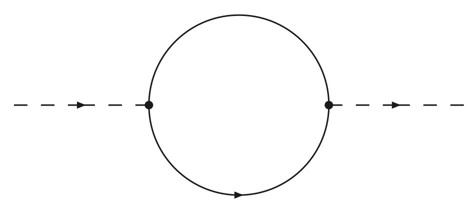


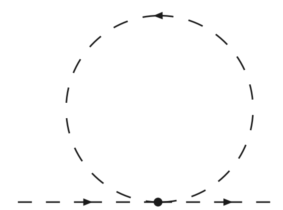


$$\lambda \; Q_{12} \; Q_{23} \; Q_{31}$$

$$\left[\sqrt{2}\lambda \; \tilde{q}_{1A,2A} \; q_{2A,3B} \; q_{3B,1A} \; + \; \text{h.c.} \right] \; + \; 2\;\lambda^2 \; |\tilde{q}_{1A,2A}|^2 \; |\tilde{q}_{3A,1A}|^2 + 2\;\lambda^2 \; |\tilde{q}_{1A,2A}|^2 \; |\tilde{q}_{2A,3A}|^2$$

radiative corrections to all masses are canceled by exotics.





But...

- Pervious example has bi-fundamentals.

  SM does not. :-(
- SM is not quite at large N.
- Recall-
  We are aiming at solving the Little hierarchy problem.
  - Only one loop.
  - Only the Higgs needs protection.
  - Problem is numerically little.

Example III

- Global $U(2N)$.

  A fundamental, anti fundamental and singlet.

$$\lambda \, S \, Q \, \overline{Q}$$

- Orbifold by $Z_{2\Gamma} \times Z_{2R}$

  $Z_{2\Gamma}$: $\quad Q \to \Gamma Q \qquad \bar{Q} \to \Gamma^* \bar{Q}$

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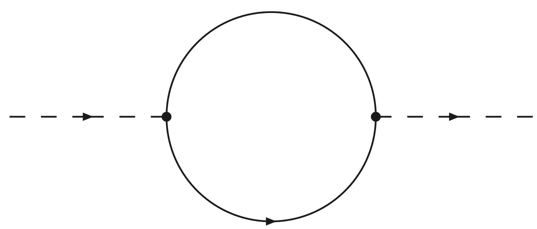

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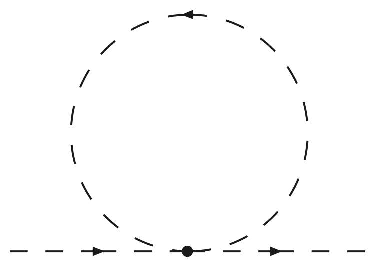

Example III

* The interactions of the daughter,

$$\mathcal{L} = \lambda \tilde{s} q_B \bar{q}_B + \lambda^2 |\tilde{s}|^2 (|\tilde{\bar{q}}_A|^2 + |\tilde{q}_A|^2)$$

look awfully supersymmetric...

* Only $\tilde{s}$ is protected.
* Protection only at one loop.

Smells ripe for the little hierarchy...

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- Daughter theory does not have a symmetry.

UV completion is crutial!

A Model
(with a UV Completion)

SU(3)^2

* Enlarge top sector to $SU(6)$

$$\lambda_t \, (3,2)_{Q_3} \, (1,2)_{H_U} \, (\overline{3},1)_{U_3} \quad \longrightarrow \quad \lambda_t \, (6,2)_{Q_{3T}} \, (1,2)_{H_U} \, (\overline{6},1)_{U_{3T}}$$

* Note:

only *global* $SU(6)$ is needed to ensure cancelation.

It is sufficient to gauge

$SU(3)_A \times SU(3)_B \times Z_2$

(a simpler and more minimal model)

The IR Model

* Below ~10 TeV we have the daughter of

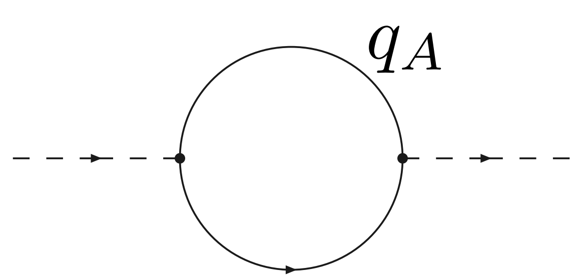
$$(SU(3)_A \times SU(3)_B \times Z_{AB}) \times SU(2)_L \times U(1)_Y$$

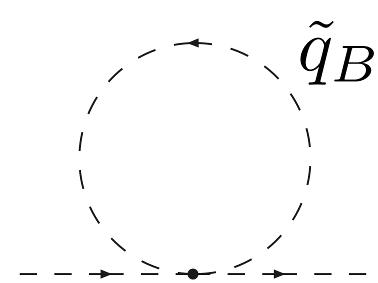
as orbifolded by $Z_{2\Gamma} \times Z_{2R}$:

quarks

$$\tilde{q} = \begin{pmatrix} \tilde{q}_A(-) \\ \tilde{q}_B(+) \end{pmatrix} \qquad q = \begin{pmatrix} q_A(+) \\ q_B(-) \end{pmatrix}$$

F-squarks

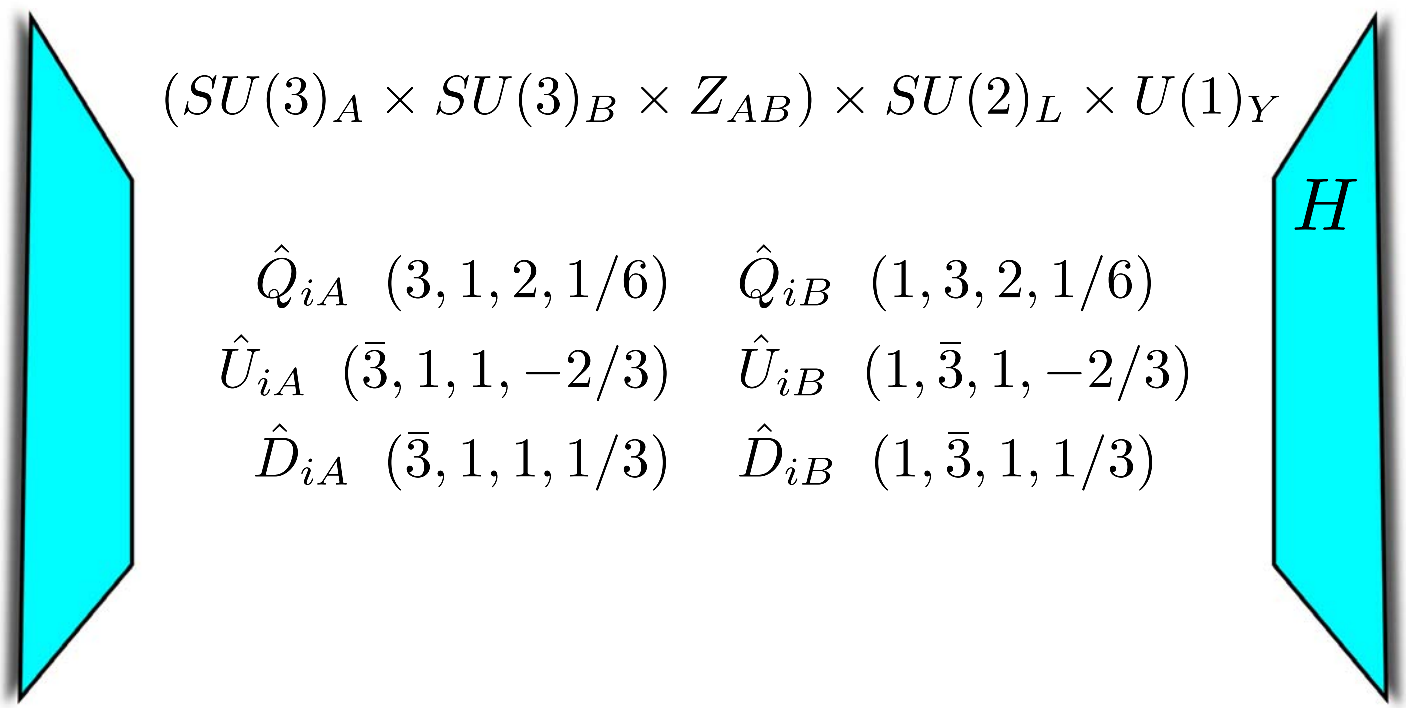




A Full Model

- A supersymmetric theory.

  SUSY is broken at 10 TeV by B.C.'s on 5D orbifold.



$$(SU(3)_A \times SU(3)_B \times Z_{AB}) \times SU(2)_L \times U(1)_Y$$

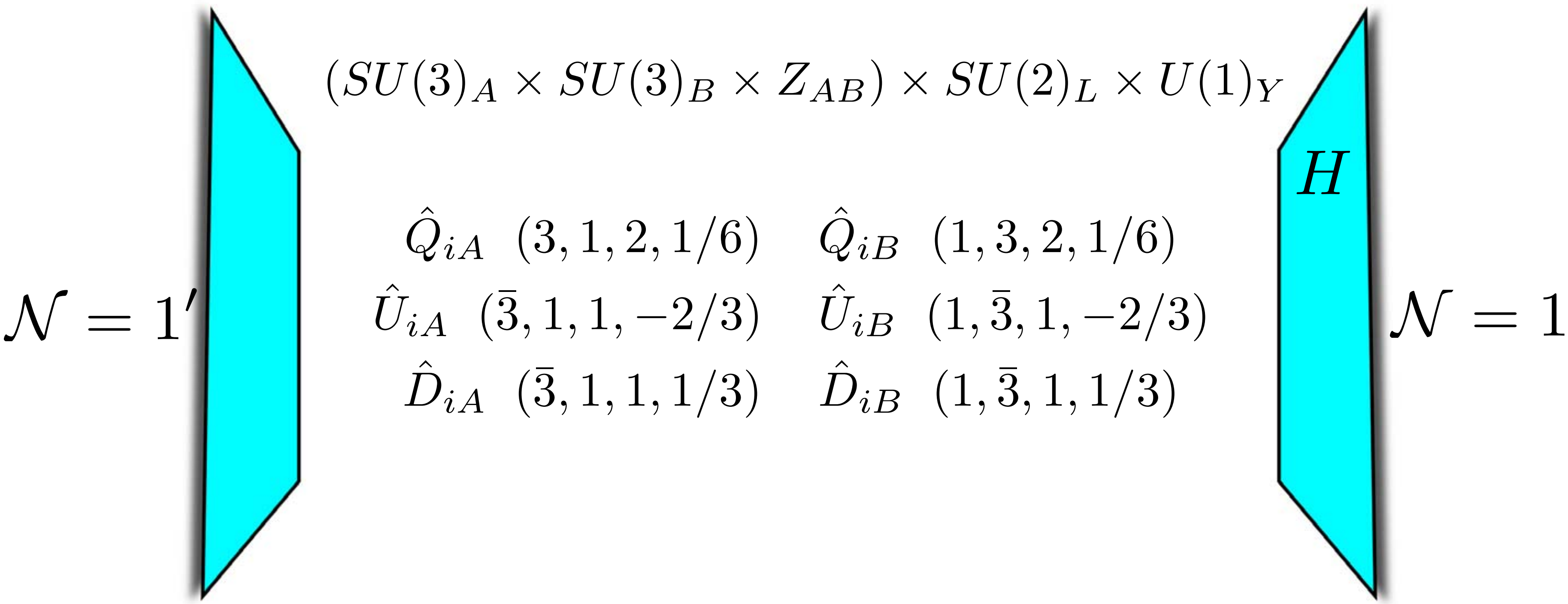
$$\begin{array}{llll} \hat{Q}_{iA} & (3,1,2,1/6) & \hat{Q}_{iB} & (1,3,2,1/6) \\ \hat{U}_{iA} & (\bar{3},1,1,-2/3) & \hat{U}_{iB} & (1,\bar{3},1,-2/3) \\ \hat{D}_{iA} & (\bar{3},1,1,1/3) & \hat{D}_{iB} & (1,\bar{3},1,1/3) \end{array}$$

Technology by Quiros et al and Barbieri, Hall, Nomura et al.

A Full Model

- A supersymmetric theory.

  SUSY is broken at 10 TeV by B.C.'s on 5D orbifold.



Technology by Quiros et al and Barbieri, Hall, Nomura et al.

A Full Model

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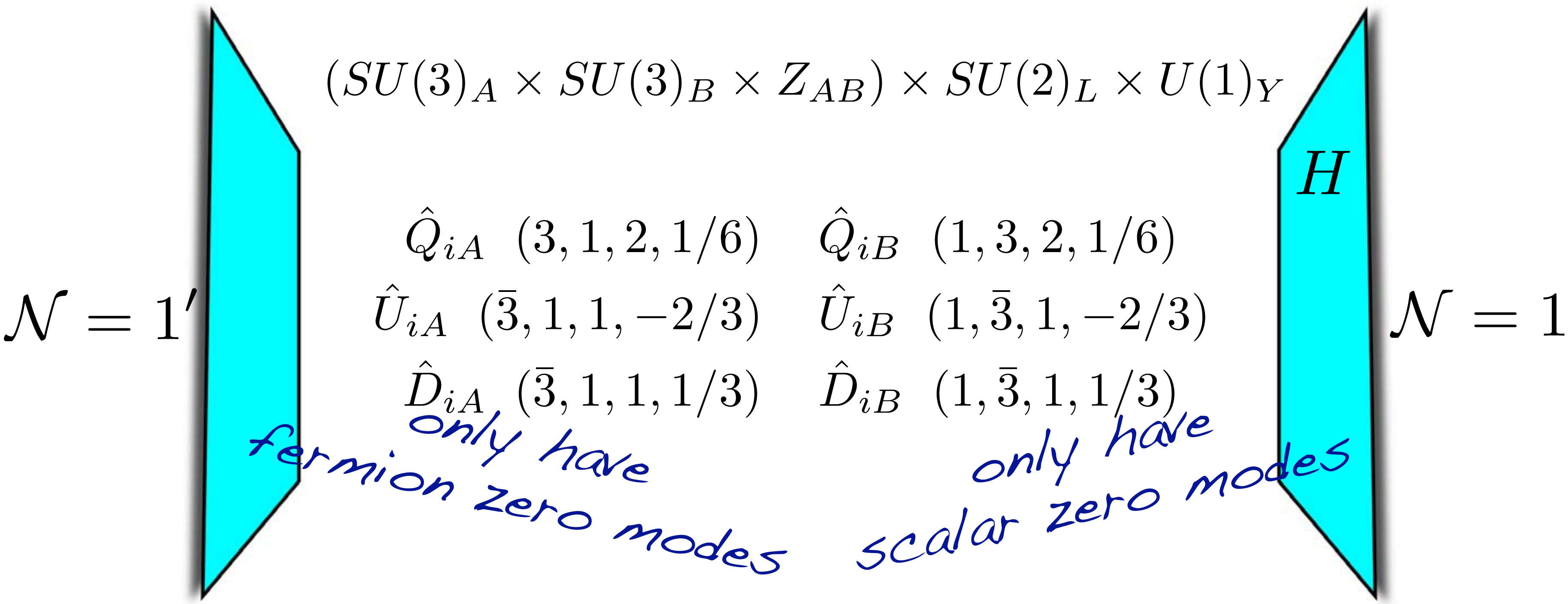


Technology by Quiros et al and Barbieri, Hall, Nomura et al.

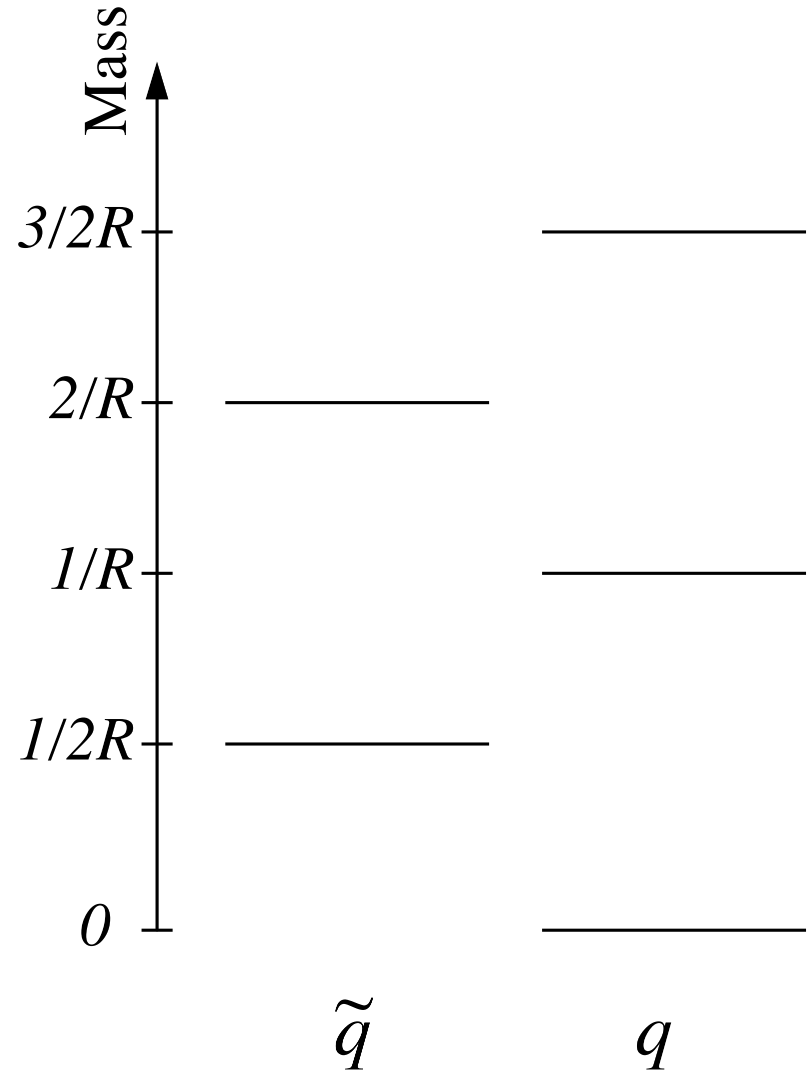
Assignments

$$\hat{Q}_A = (Q_A, Q_A^c) \qquad \hat{Q}_B = (Q_B, Q_B^c)$$

Z_2'	Z_2
$+:\ Q_A' = \begin{pmatrix} \tilde{q}_A^{c*} \\ q_A \end{pmatrix}$ $-:\ Q_A^{c\prime} = \begin{pmatrix} \tilde{q}_A^{*} \\ q_A^c \end{pmatrix}$	$+:\ Q_A = \begin{pmatrix} \tilde{q}_A \\ q_A \end{pmatrix}$ $-:\ Q_A^c = \begin{pmatrix} \tilde{q}_A^c \\ q_A^c \end{pmatrix}$
$+:\ Q_B' = \begin{pmatrix} \tilde{q}_B \\ \bar{q}_B^c \end{pmatrix}$ $-:\ Q_B^{c\prime} = \begin{pmatrix} \tilde{q}_B^c \\ \bar{q}_B \end{pmatrix}$	$+:\ Q_B = \begin{pmatrix} \tilde{q}_B \\ q_B \end{pmatrix}$ $-:\ Q_B^c = \begin{pmatrix} \tilde{q}_B^c \\ q_B^c \end{pmatrix}$

Sherk-Schwartz +

SS SUSY breaking produces a scatagered KK tower.



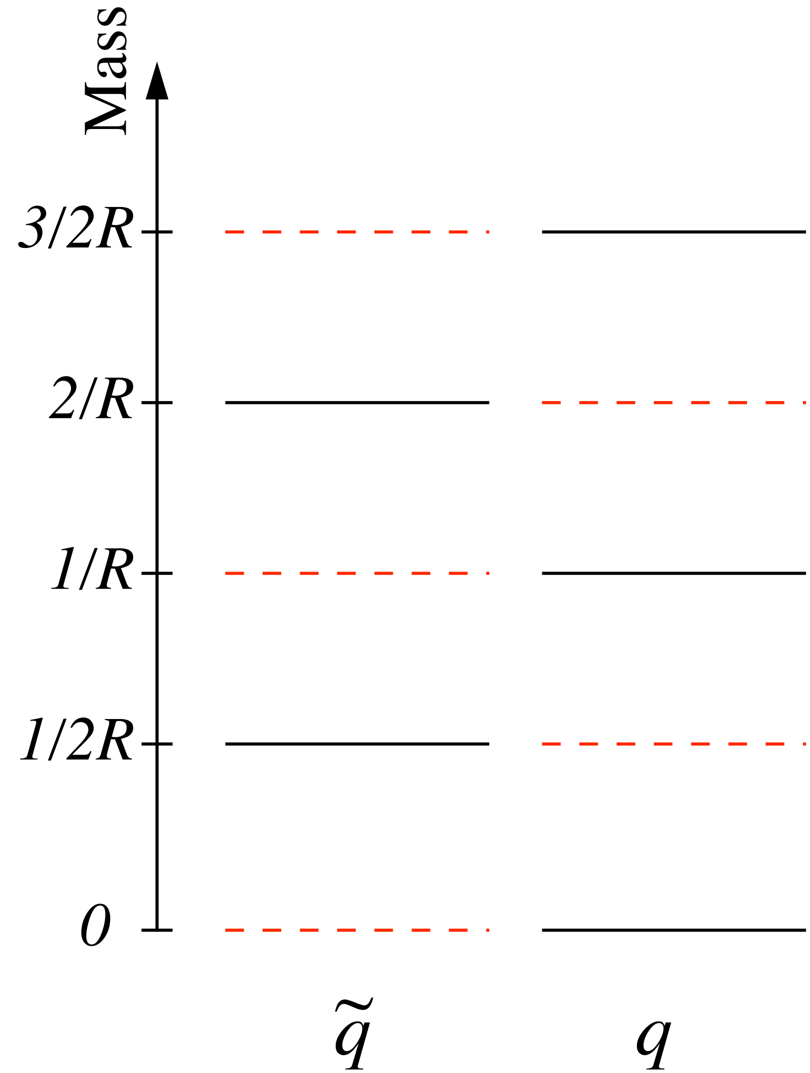
Sherk-Schwartz +

SS SUSY breaking produces a scatagered KK tower.

In our model the tower is supplemented to give the Higgs a “supersymmetric feeling”.

At tree level $m_H^2 = 0$.

Cancelation occurs one KK level at a time.



Finite ~~SUSY~~

* one loop squarks, sleptons get finite soft masses

$$m_Q^2 = \mathrm{K}\,\frac{1}{4\pi^4}\left(\frac{4}{3}g_3^2+\frac{3}{4}g_2^2+\frac{1}{36}g_1^2\right)\frac{1}{R^2}$$
$$m_U^2 = \mathrm{K}\,\frac{1}{4\pi^4}\left(\frac{4}{3}g_3^2+\frac{4}{9}g_1^2\right)\frac{1}{R^2}$$
$$m_D^2 = \mathrm{K}\,\frac{1}{4\pi^4}\left(\frac{4}{3}g_3^2+\frac{1}{9}g_1^2\right)\frac{1}{R^2}$$
$$\cdots$$

* Higgs mass parameter generated at two-loops from top and at one-loop from gauge.

$$\delta m_H^2|_{\mathrm{top}} \approx -\frac{3\lambda_t^2}{4\pi^2}\tilde{m}_t^2\log\left(\frac{1}{R\,\tilde{m}_t}\right)$$

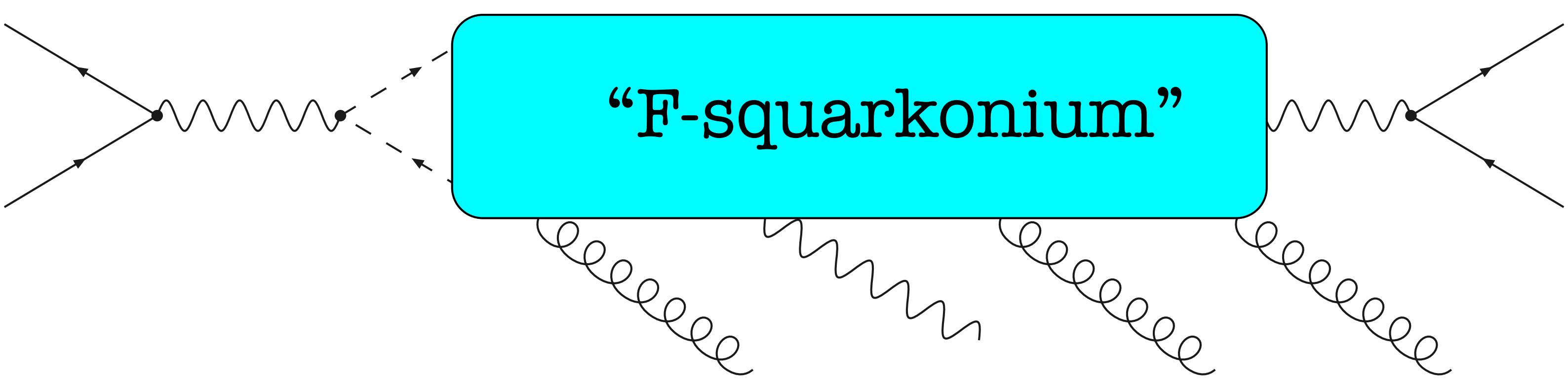
$$\delta m_H^2|_{\mathrm{gauge}} = \mathrm{K}\,\frac{3g_2^2+g_1^2}{16\pi^4}\,\frac{1}{R^2}$$

LHC Phenomenology

LHC

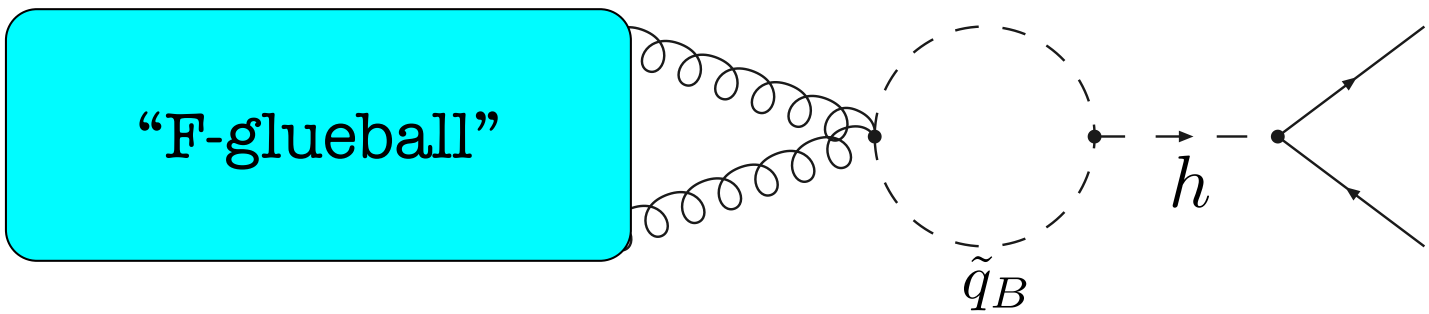
- F-squarks are produced via Drell-Yan.
- But then what?
  - All F-QCD matter is at ~500-700 GeV.
  - Λ_{QCD_B} is at ~ 10 GeV.
- F-squarks are produces and remain bound!

quirks (or squirks, rather) - upcoming by Luty et al



LHC

* F-squarkonium decays promptly to leptons, W's, Z's, photons or jets.
* F-gluballs live for a long time.....

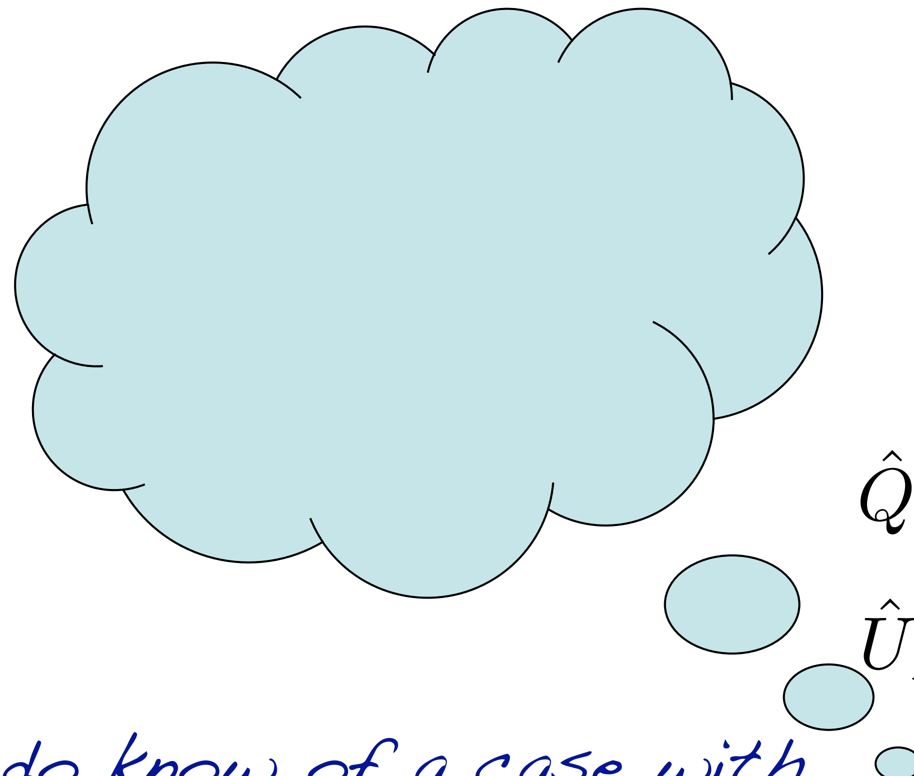


* Likely signal is leptons plus missing E_T.

Conclusion

- Top partners, be they scalars or fermions, need not be colored.
- Uncolored partners lead to new sectors and new LHC signals (or lack thereof).
- Large-N orbifolding provides inspiration for models in which quadratic divergences are canceled by exotics.

EXTRA SLIDES

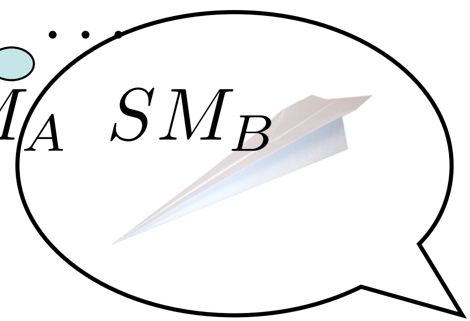


$\hat{Q}_A \quad \hat{Q}_B$

$\hat{U}_A \quad \hat{U}_B$

$\cdots$

$SM_A \quad SM_B$



But we do know of a case with opposite spin cancelation without identical quantum numbers!

Radiative Corrections

* At 1-loop:

$$\Delta V =$$

---

* Impose a Z_2 "twin" symmetry: $A \longleftrightarrow B$

$\Longrightarrow \quad g_A = g_B$

$$\Delta V = \frac{9 g^2 \Lambda^2}{64\pi^2}\left(H_A^\dagger H_A + H_B^\dagger H_B\right)$$

SU(4) invariant!

Does not give a Goldstone mass.

Radiative Corrections

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Radiative Corrections

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$$\Delta V = \frac{9g_A^2\Lambda^2}{64\pi^2}H_A^\dagger H_A + \frac{9g_B^2\Lambda^2}{64\pi^2}H_B^\dagger H_B$$

---

* Impose a Z_2 "twin" symmetry: $A \longleftrightarrow B$

$\Longrightarrow$ $g_A = g_B$

$$\Delta V = \frac{9g^2\Lambda^2}{64\pi^2}\left(H_A^\dagger H_A + H_B^\dagger H_B\right)$$

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