

NEUTRAL NATURALNESS

OR: YES-GO THEOREMS FOR NATURALNESS

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*BASED PRIMARILY ON WORKS IN PROGRESS
WITH SIMON KNAPEN & PIETRO LONGHI; ANDREY
KATZ, MATT STRASSLER, & RAMAN SUNDRUM*

FERMILAB: NATURE GUIDING THEORY 2014

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- SYMMETRY SOLUTIONS GIVE TOP PARTNERS, **NO SIGNS SO FAR @ LHC**.

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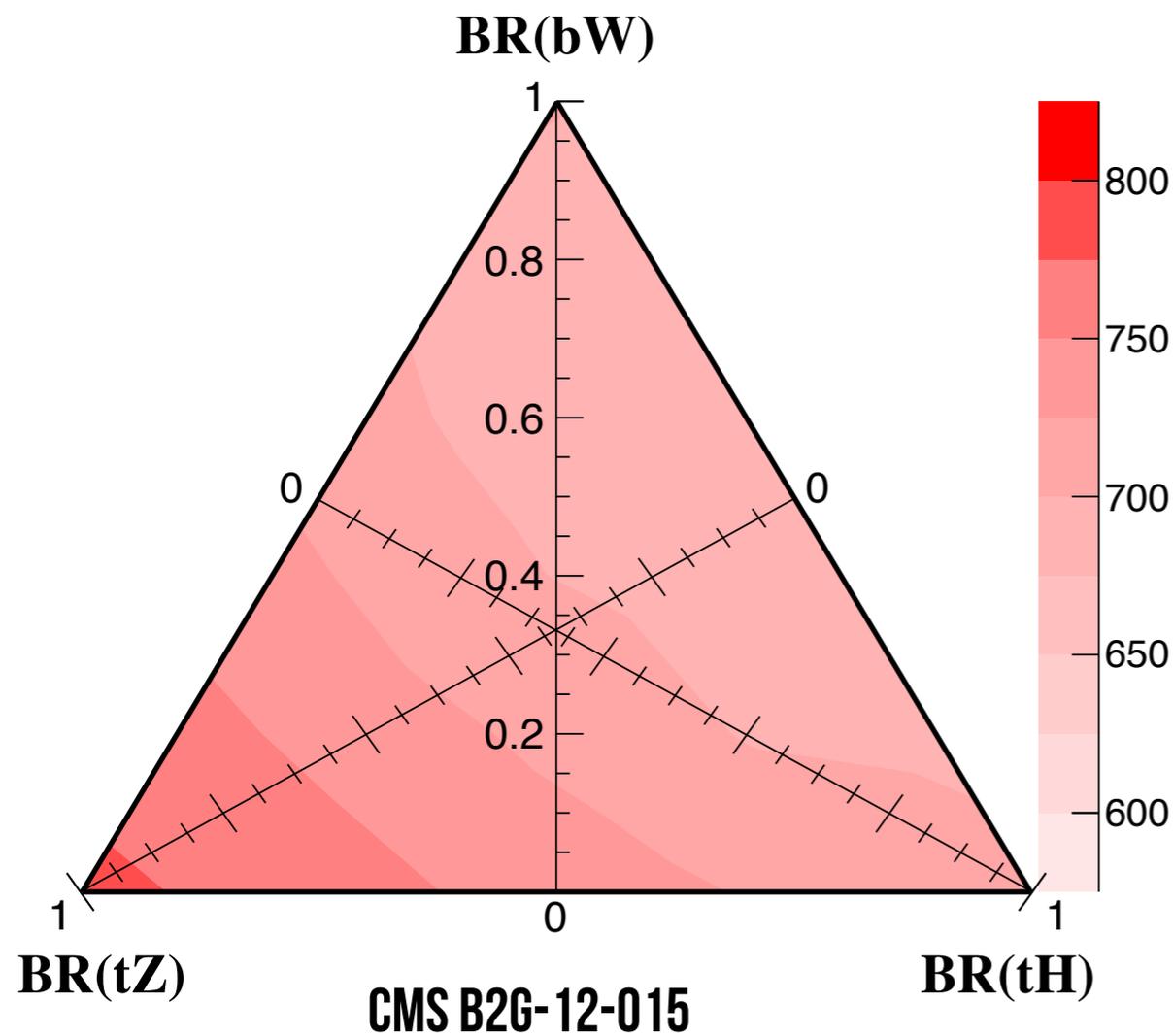
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- SUSY: SCALAR TOP PARTNERS. GLOBAL SYMMETRY: FERMIONS.
- DECAY MODES VARY BUT GUARANTEED LARGE QCD CROSS SECTION.

MISSING TOP PARTNER PROBLEM

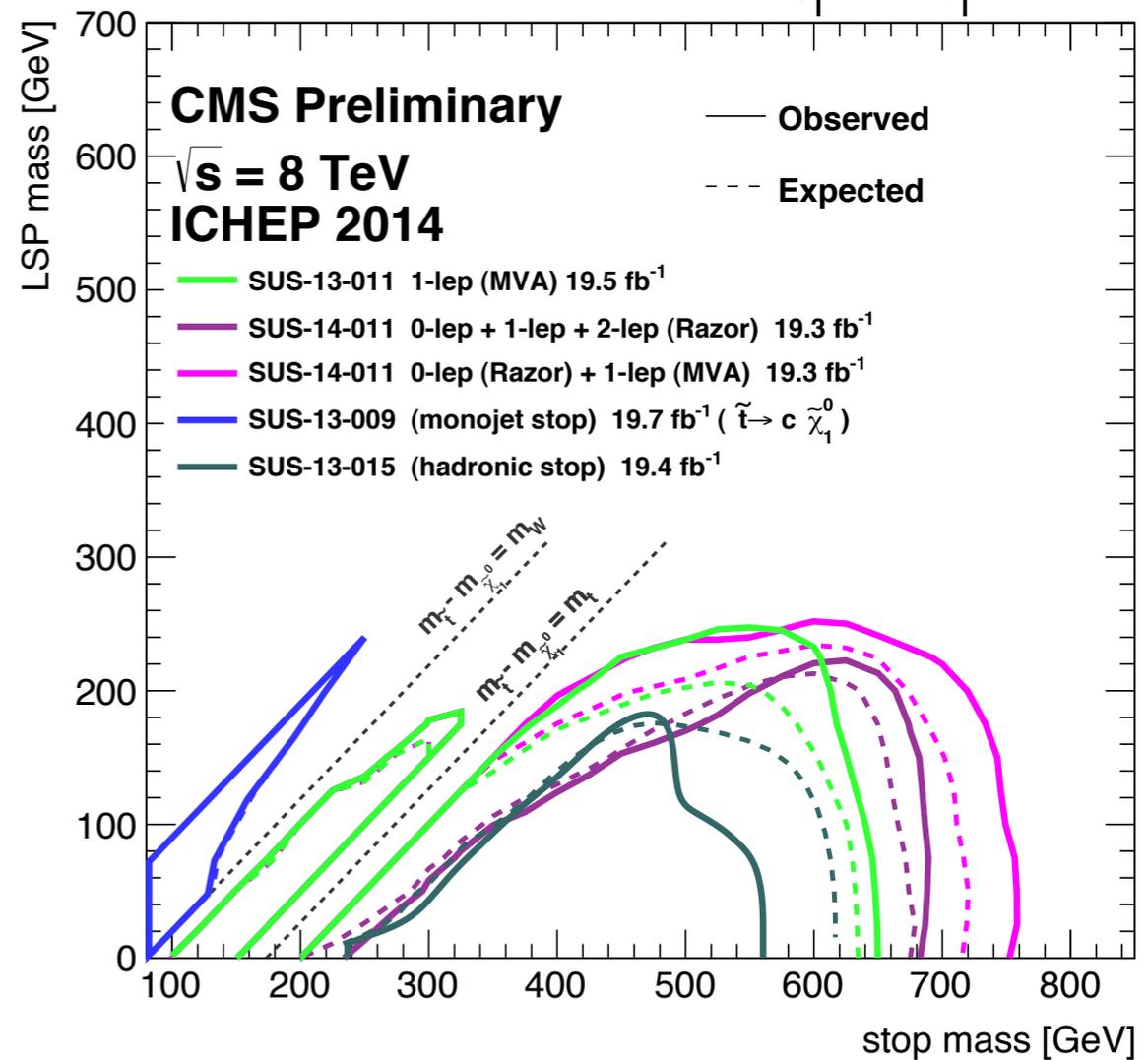
GLOBAL SYMMETRY

CMS preliminary $\sqrt{s} = 8 \text{ TeV}$ 19.6 fb^{-1}

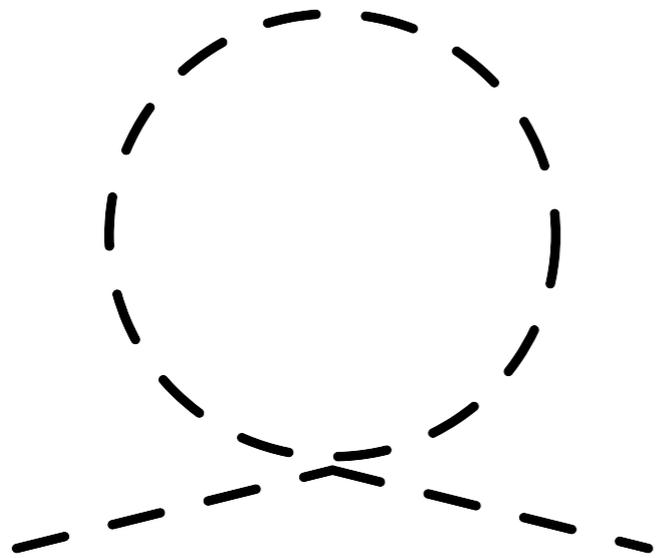


SUPERSYMMETRY

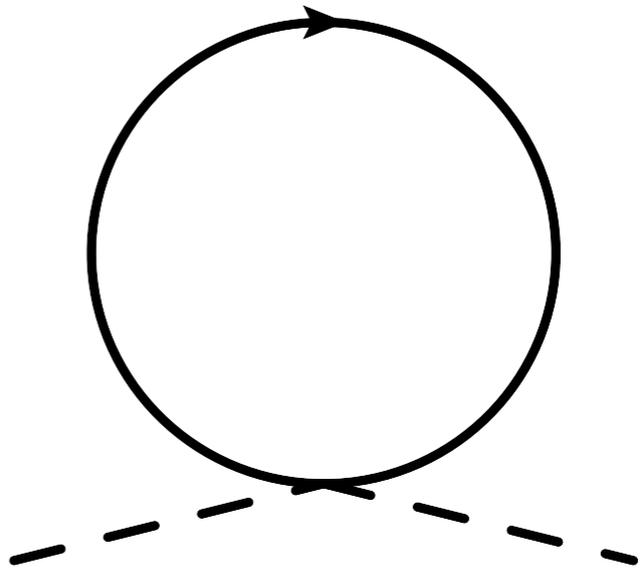
$\tilde{t}\text{-}\tilde{t}$ production, $\tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0$



NATURALNESS?



$$\delta m_H^2 = -\frac{3}{8\pi^2} \lambda_t^2 \tilde{m}_t^2 \log(\Lambda^2 / \tilde{m}_t^2)$$



$$\delta m_H^2 = -\frac{3}{8\pi^2} \lambda_t^2 m_T^2 \log(\Lambda^2 / m_T^2)$$

Irreducible tuning: ~5%. Complete model: $\approx 0.1-1\%$

SO WE'RE GROWING NERVOUS
ABOUT NATURALNESS.

BUT: HAVE WE
WRITTEN DOWN
ALL NATURAL
THEORIES?

MAYBE NATURE IS JUST GUIDING
THEORY AWAY FROM OUR
FAVORITE LAMP-POSTS.



"I'M SEARCHING FOR SUSY"

WHAT ABOUT...

THE TWIN HIGGS

[Z. CHACKO, H.-S.
GOH, R. HARNIK '05]



electroweak constraints are satisfied by construction. These models demonstrate that, contrary to the conventional wisdom, stabilizing the weak scale does not require new light particles charged under the Standard Model gauge groups.

SYMMETRY IS $SM_A \times SM_B \times Z_2$

**SEE RONI'S TALK FROM THURSDAY*

THE TWIN HIGGS

CONSIDER A SCALAR H TRANSFORMING AS A FUNDAMENTAL UNDER A GLOBAL $SU(4)$:

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

POTENTIAL LEADS TO SPONTANEOUS SYMMETRY BREAKING,

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

$$SU(4) \rightarrow SU(3)$$

YIELDS SEVEN GOLDSTONE BOSONS.

UV: $\lambda \gg 1$ NLSM; $\lambda \lesssim 1$ LSM

THE TWIN HIGGS

NOW GAUGE $SU(2)_A \times SU(2)_B \subset SU(4)$, w/ $H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$

US

TWINS

Then 6 goldstones are eaten, leaving one behind.

EXPLICITLY BREAKS THE $SU(4)$; EXPECT RADIATIVE CORRECTIONS.

$$V(H) \supset \frac{9}{64\pi^2} (g_A^2 \Lambda^2 |H_A|^2 + g_B^2 \Lambda^2 |H_B|^2)$$

BUT THESE BECOME $SU(4)$ SYMMETRIC IF $G_A = G_B$ FROM A Z_2

Quadratic potential has accidental $SU(4)$ symmetry.

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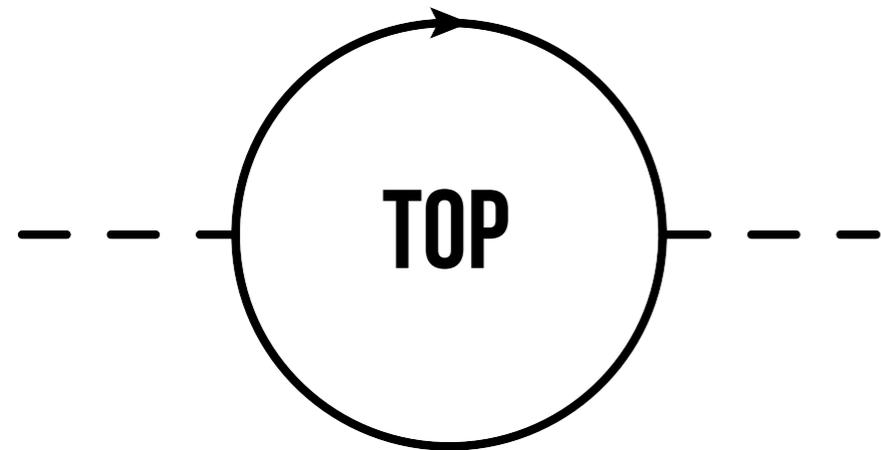
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TWIN HIGGS SLOGAN

“HIGGS IS PSEUDO-GOLDSTONE OF
THE ACCIDENTAL GLOBAL
SYMMETRY OF QUADRATIC ACTION
OBEYING DISCRETE SYMMETRY”*

*PLUS SYMMETRIC QUARTIC.

THE TWIN TOP

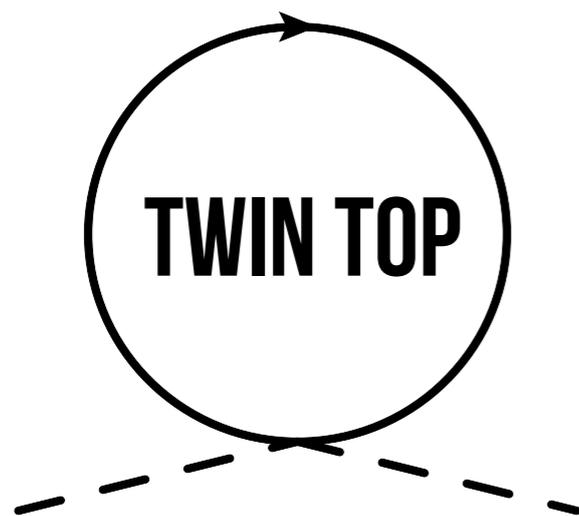


THE TOP PARTNER ACTS AS EXPECTED FROM GLOBAL SYMMETRY PROTECTION, BUT NOT CHARGED UNDER QCD.

$$\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$$

$$\downarrow$$
$$h + \dots$$

$$\downarrow$$
$$f - \frac{h^2}{2f} + \dots$$



NO DIRECT LIMIT ON TOP PARTNER.

WHAT TO MAKE OF THIS?

EVADES "TOP PARTNER THEOREM",
HINTS AT NEW NATURAL THEORIES, BUT...

- DEMANDING EXACT Z_2 MEANS **TWIN LIGHT GENERATIONS**; USELESS FOR NATURALNESS BUT TROUBLE FOR COSMOLOGY (N_{EFF}).
- SYMMETRY STRUCTURE SLIGHTLY AWKWARD; REALLY ASKING FOR Z_2 PLUS APPROXIMATE $SU(4)$ OF HIGGS POTENTIAL??

BIGGER QUESTION: JUST A SPECIAL CASE, OR EXAMPLE OF DEEPER/GENERAL STRUCTURE?

[KACHRU & SILVERSTEIN '98; BERSHADSKY & JOHANSEN '98, SCHMALTZ '99]

ORBIFOLD FIELD THEORY

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- E.G. **PARENT** $SU(2N)$, DISCRETE Z_2 , **DAUGHTER** $SU(N) \times SU(N) \times S_2$, MATTER TRANSFORMING ONLY IN IRREPS OF THE **DAUGHTER**.

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- IF THE **PARENT** SYMMETRY PROTECTS THE HIGGS, OFTEN THE **DAUGHTER** DOES AS WELL, BUT WITHOUT THE FULL REPRESENTATIONS REQUIRED BY THE **PARENT**.

SOUND FAMILIAR?

TWIN HIGGS IS AN ORBIFOLD

PARENT: $SU(6) \times SU(4) / Z_2$

VARIOUS $U(1)$ CHOICES: $U(2)/Z_2$, $U(1)^2/Z_2$, $U(1)$, $SU(5)$, ETC.

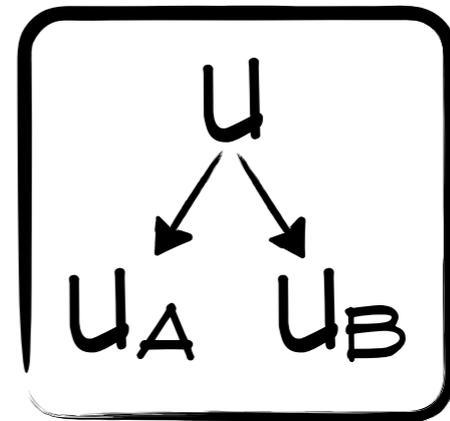
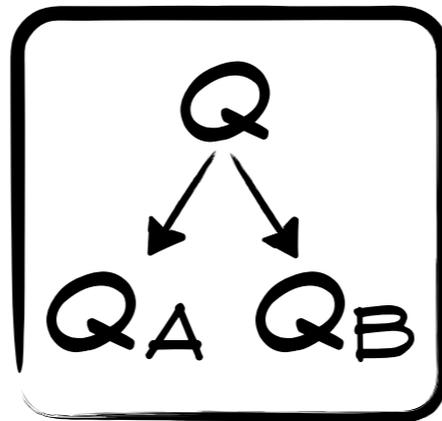
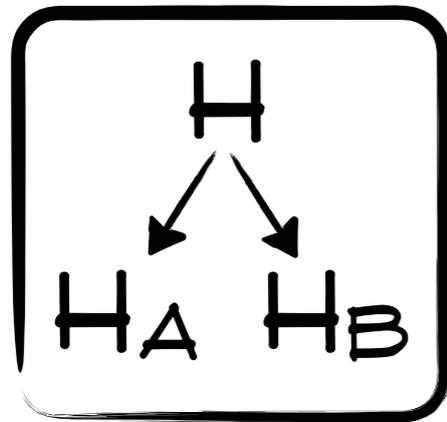
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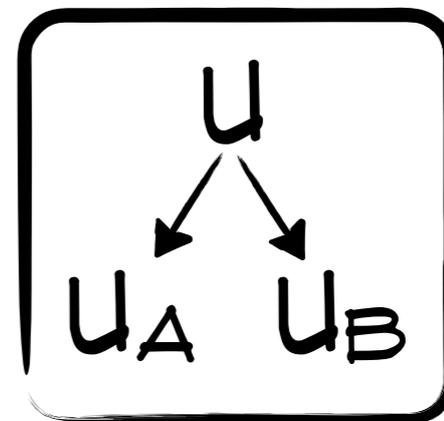
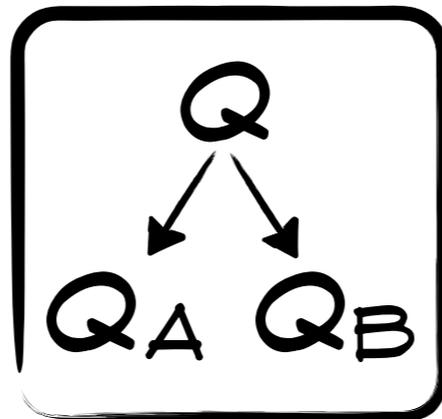
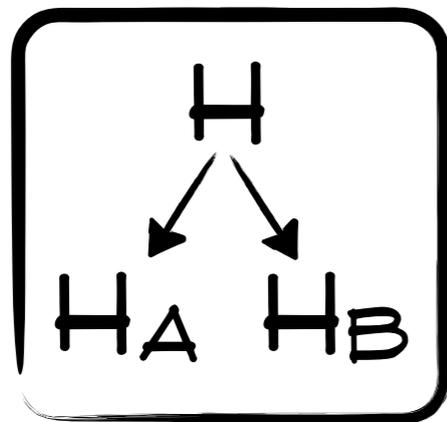


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$$HQU \begin{cases} \rightarrow H_A Q_A U_A \\ \rightarrow H_B Q_B U_B \end{cases}$$

$$|H|^4 \rightarrow (|H_A|^2 + |H_B|^2)^2$$

GIVES YOU ALL THE COUPLINGS REQUIRED BY TWIN HIGGS.

UV COMPLETIONS

WE KNOW HOW TO THINK OF ORBIFOLDS
GEOMETRICALLY...

$SU(6) \times SU(4)$

$[SU(3) \times SU(2)]^2$



$H, Q_3, U_3 (D_3?)$

$Q_{1,2}, U_{1,2}, D_{1,2} (D_3?)$

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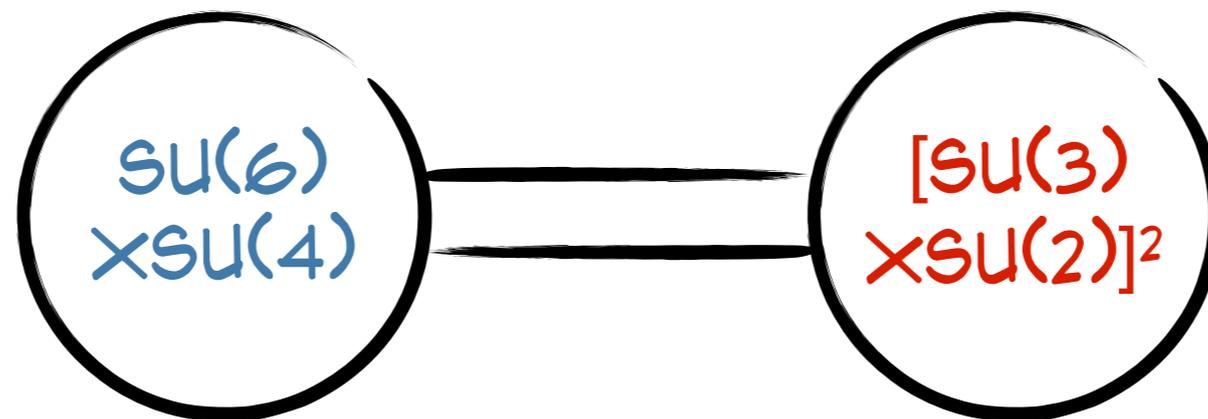
$$[SU(3) \times SU(2)]^2$$



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...OR BY DECONSTRUCTING THE GEOMETRY:



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NEW PHENOMENOLOGY

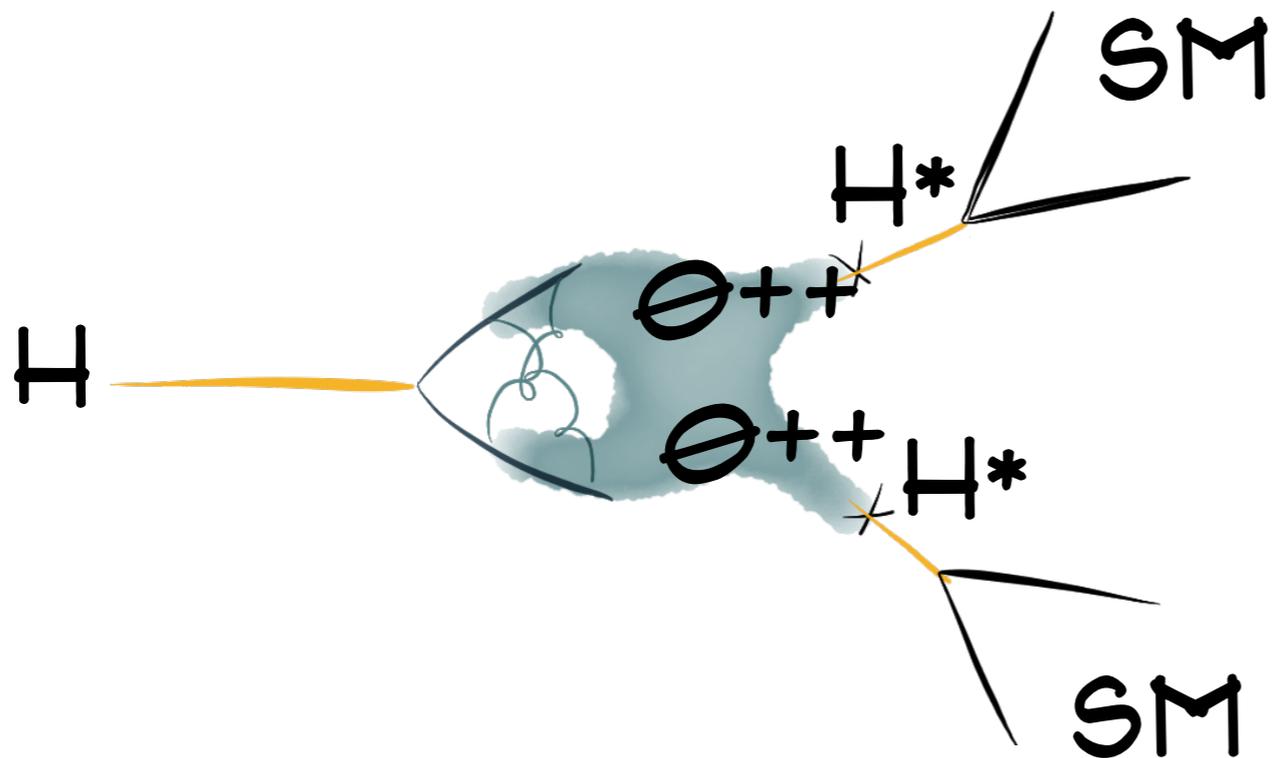
*ELIMINATING LIGHT TWIN FERMIONS IN THE
ORBIFOLD POINTS TO NEW SIGNS OF NATURALNESS*

IF NO LIGHT TWIN FERMIONS, GLUEBALLS OF TWIN
QCD AT BOTTOM OF TWIN SPECTRUM. \emptyset^{++}
DECAYS VIA HIGGS: HIDDEN VALLEY SIGNATURE.

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AT LHC, ENTER TWIN SECTOR VIA TWIN BOTTOM PAIRS ANNIHILATING INTO TWIN GLUEBALLS, OR VIA TWIN GLUE COUPLING.

INTRIGUING LIFETIME:

$$c\tau \approx 18 \text{ m} \times \left(\frac{10 \text{ GeV}}{m_0} \right)^7 \left(\frac{f}{500 \text{ GeV}} \right)^4$$

THE GENERALIZATION

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- RECIPE SEEMS TO BE $SU(3) \times SU(2) / \Gamma$. WE EXPECT FROM THE ORBIFOLD CORRESPONDENCE THAT **ALL SUCH THEORIES GIVE ORBIFOLD HIGGS MODELS.**

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- THE OBVIOUS ABELIAN GENERALIZATION: $\Gamma = Z_N$ INSTEAD OF Z_2 . STRAIGHTFORWARD BUT BORING; N -HIGGS.
- SO WHAT ABOUT NON-ABELIAN DISCRETE SYMMETRIES? E.G. $S_N, A_N, \text{ETC.}$ **EXPECT SOMETHING QUALITATIVELY NEW.**

THE S_3 HIGGS

PARENT: $SU(18) \times SU(12) / S_3$

DAUGHTER: $[SU(3) \times SU(2)]^2 \times [SU(6) \times SU(4)]$

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$$L = HQU$$

	SU(2)	SU(2)	SU(4)
H_A	\square		
H_B		\square	
H_C			\square
H_D			\square

	SU(3)	SU(3)	SU(6)
U_A	$\bar{\square}$		
U_B		$\bar{\square}$	
U_C			$\bar{\square}$
U_D			$\bar{\square}$

	3x2	3x2	6x4
Q_A	$\square \bar{\square}$		
Q_B		$\square \bar{\square}$	
Q_C			$\square \bar{\square}$

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$$L = HQU$$

	SU(2)	SU(2)	SU(4)
H_A	\square		
H_B		\square	
H_C			\square
H_D			\square

	SU(3)	SU(3)	SU(6)
U_A	$\bar{\square}$		
U_B		$\bar{\square}$	
U_C			$\bar{\square}$
U_D			$\bar{\square}$

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"HIGGS IS PSEUDO-GOLDSTONE OF THE ORBIFOLDED
 $SU(12)$ SYMMETRY"

HOW TO NORMALIZE YOUR ORBIFOLD HIGGS

NOT AT ALL OBVIOUS THAT RADIATIVE
CORRECTIONS PRESERVE THE $SU(12)$! BUT
ORBIFOLD CORRESPONDENCE DEMANDS IT...

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GIVEN PARENT COUPLINGS g, Y, λ ,

FIELD THEORY ORBIFOLD + CANONICAL
NORMALIZATION OF DAUGHTER STATES \rightarrow
 d_α DAUGHTER SECTOR INHERITS COUPLINGS

$$g \rightarrow \frac{g}{\sqrt{d_\alpha}} \quad Y \rightarrow \frac{Y}{\sqrt{d_\alpha}} \quad \lambda \rightarrow \lambda$$

QUADRATIC SENSITIVITY

CW POTENTIAL FOR SCALAR TRANSFORMING AS A FUNDAMENTAL UNDER $SU(2_{d_\alpha})$ WITH APPROPRIATE YUKAWA:

$$\delta m_{H_\alpha}^2 = \frac{\Lambda^2}{16\pi^2} \left[-6d_\alpha y_\alpha^2 + 3 \left(d_\alpha - \frac{1}{4d_\alpha} \right) g_\alpha^2 + \dots \right]$$

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$$\rightarrow \frac{\Lambda^2}{16\pi^2} \left[-6Y^2 + 3 \left(1 - \frac{1}{4d_\alpha^2} \right) g^2 + \dots \right]$$

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$$\rightarrow \frac{\Lambda^2}{16\pi^2} \left[-6Y^2 + 3 \left(1 - \frac{1}{4d_\alpha^2} \right) g^2 + \dots \right]$$

TOTAL ONE-LOOP CW POTENTIAL FOR S_3 HIGGS SCALARS:

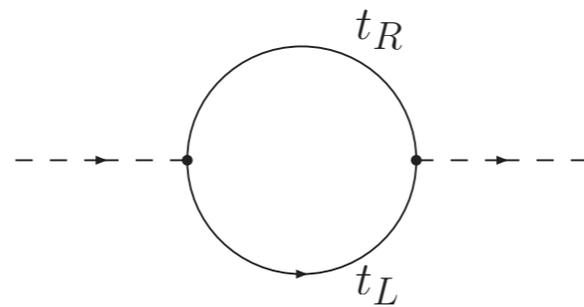
$$\propto \frac{\Lambda^2}{16\pi^2} \left[-6Y^2 + 3g^2 + \dots \right] (|H_A|^2 + |H_B|^2 + |H_C|^2 + |H_D|^2)$$

SU(12) INVARIANT ↗

$$\sim 1/N \text{ ORBIFOLD CORRECTIONS } \rightarrow -\frac{3\Lambda^2}{256\pi^2} g^2 (|H_C|^2 + |H_D|^2)$$

THE 3' IS NOT EVEN A SIMPLE 3!
 TOP PARTNERS ARE LINEAR
 COMBINATION OF FERMIONS
 CHARGED UNDER HIDDEN COLOR
 GROUPS OF DIFFERENT SIZE.

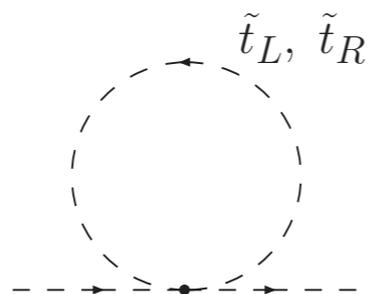
Just a Factor of 3



Standard Model

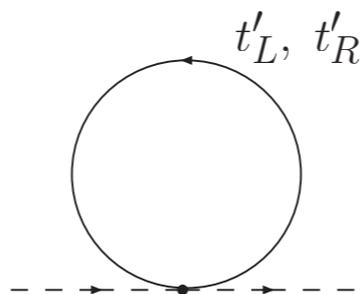
color factor:

$$\times 3$$



Supersymmetry

or



Little Higgs

~~$$\times 3$$~~

3'
 symmetry does not
 commute with color

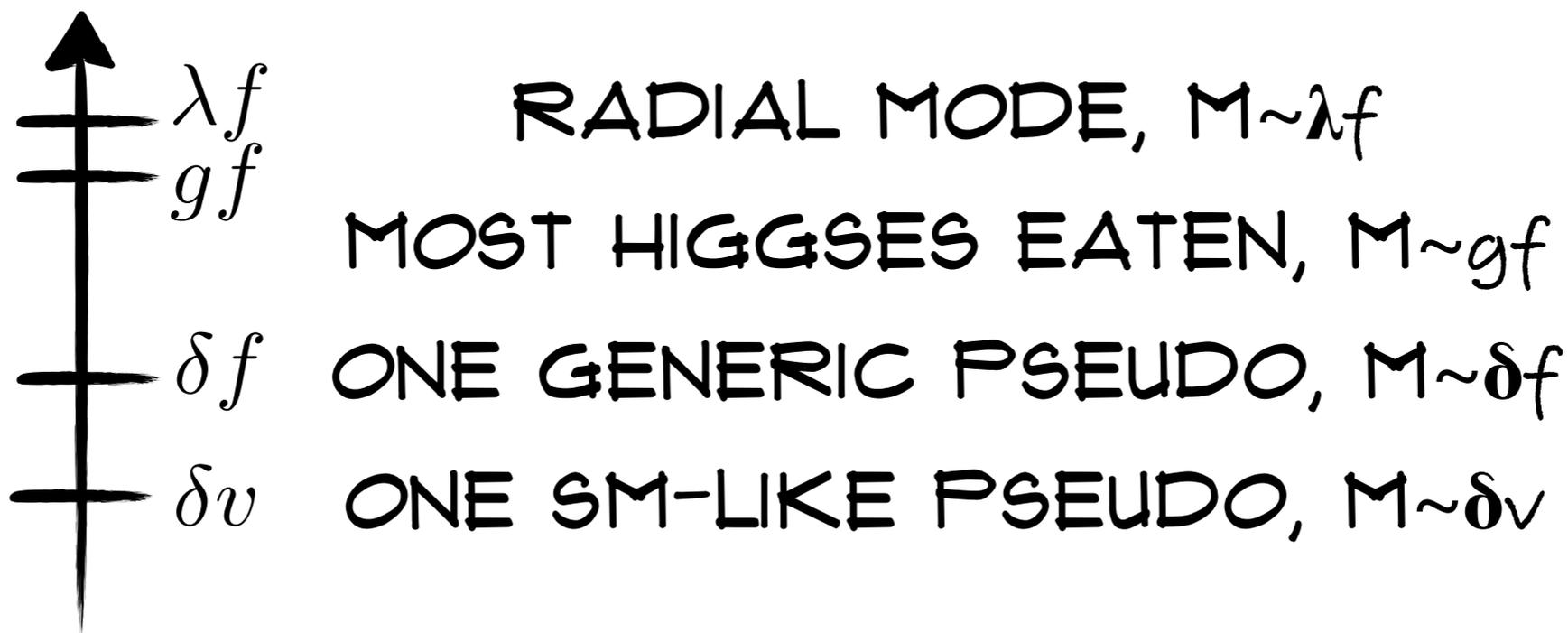
QUALITATIVE PHENOMENOLOGY

$SU(12) \rightarrow SU(11)$: 23 (PSEUDO)GOLDSTONES.
3+3+15=21 EATEN, 2 PSEUDOS REMAIN

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IN TYPICAL VACUUM $v \sim f$ & PSEUDOS ONLY PARTIALLY
ALIGNED W/SM VEV. AS IN TWIN HIGGS, NEED TO TILT
POTENTIAL TO GET $v \ll f$ & ONE SM-LIKE PSEUDO.



THE A_4 HIGGS

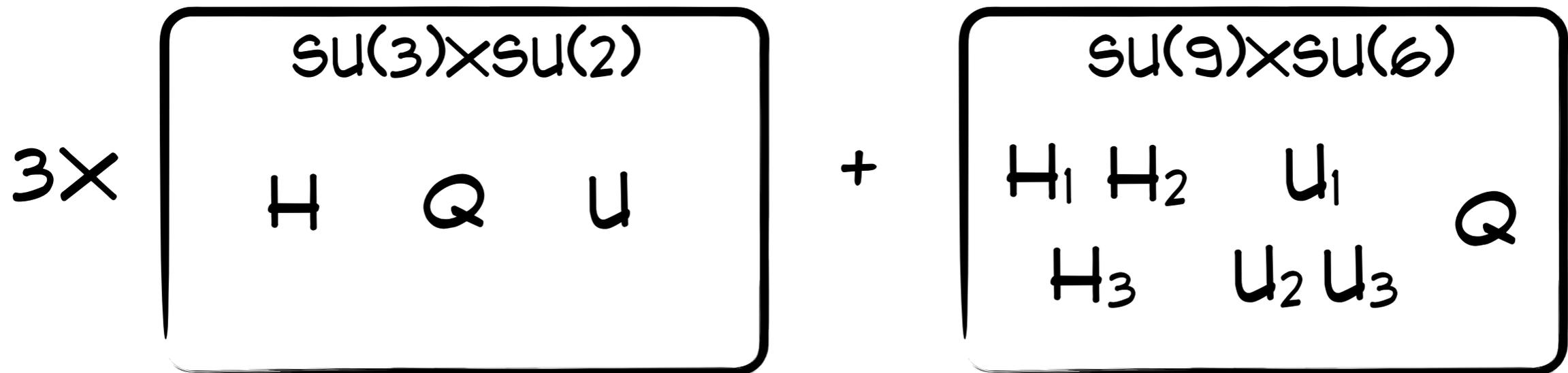
PARENT: $SU(36) \times SU(24) / A_4$

DAUGHTER: $[SU(3) \times SU(2)]^3 \times [SU(9) \times SU(6)]$

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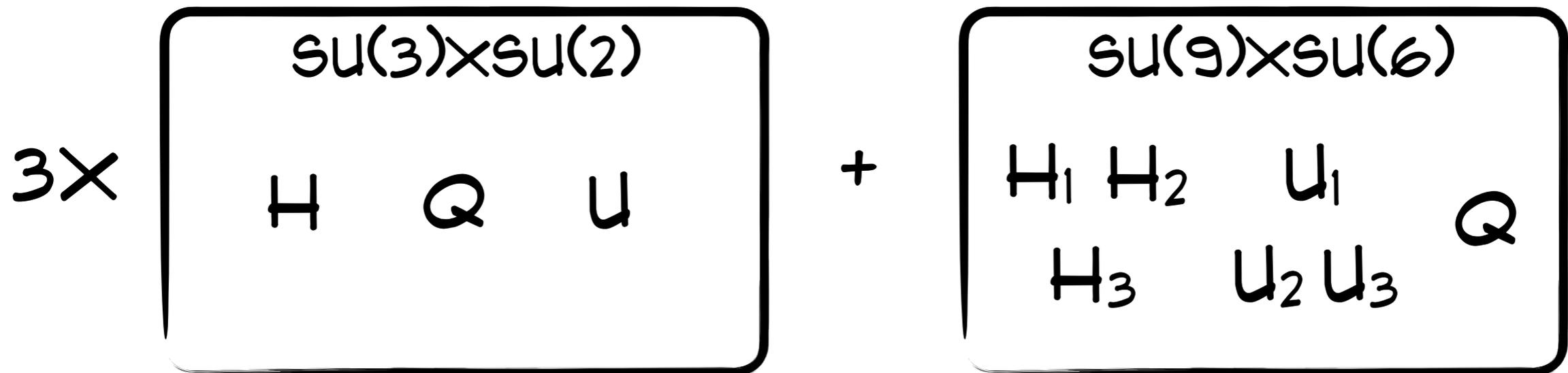
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$SU(24) \rightarrow SU(23)$: 41 (PSEUDO)GOLDSTONES.
 $3+3+3+35=44$ EATEN, 3 PSEUDOS REMAIN

"HIGGS IS PSEUDO-GOLDSTONE OF THE ORBIFOLDED
 $SU(24)$ SYMMETRY"

REALISTIC MODELS

I'VE JUST SKETCHED TOY MODELS FOCUSING ON THE HIGGS POTENTIAL; REALISTIC MODELS...

- NEED TO MAKE CHOICES FOR B_R ; PART OF PARENT SYMMETRY (2HDM) OR NOT (DEFECT).
- NEED TO MAKE CHOICES FOR $U(1)$; MANY OPTIONS.
- NEED TO MAKE CHOICES FOR 1ST/2ND GENERATIONS; SIMPLEST CHOICE IS @ DEFECT.
- NEED TO DEAL WITH ANOMALIES OF PARENT AND DAUGHTER SYMMETRIES.

THESE CAN ALL BE ACCOMPLISHED BY LOOKING TOWARDS UV COMPLETION.

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- THERE ARE ***MANY MORE THEORIES OF THIS TYPE***, WITH HIDDEN SECTORS NOT SIMPLY RELATED TO THE STANDARD MODEL!

THE BIG PICTURE

- INTENSE DEBATE ABOUT NATURALNESS POST-HIGGS, MANY CONCLUSIONS BEING DRAWN.
- BUT WE'RE FAR FROM WRITING DOWN ALL NATURAL THEORIES USING SYMMETRIES.
- WE SHOULD TRY REDUCTIONS OF ALL SYMMETRY SOLUTIONS TO THE HIERARCHY PROBLEM.
ORBIFOLDS OF GLOBAL SYMMETRY ONLY ONE AVENUE -- ORBIFOLDS ALSO OF R-SYMMETRY? ORIENTIFOLDS? OTHER STRINGY SINGULARITIES?

IT'S IRRESPONSIBLE TO GIVE UP ON NATURALNESS UNTIL WE'VE EXPLORED ALL NATURAL THEORIES.