Recent Progress in Neutral Naturalness

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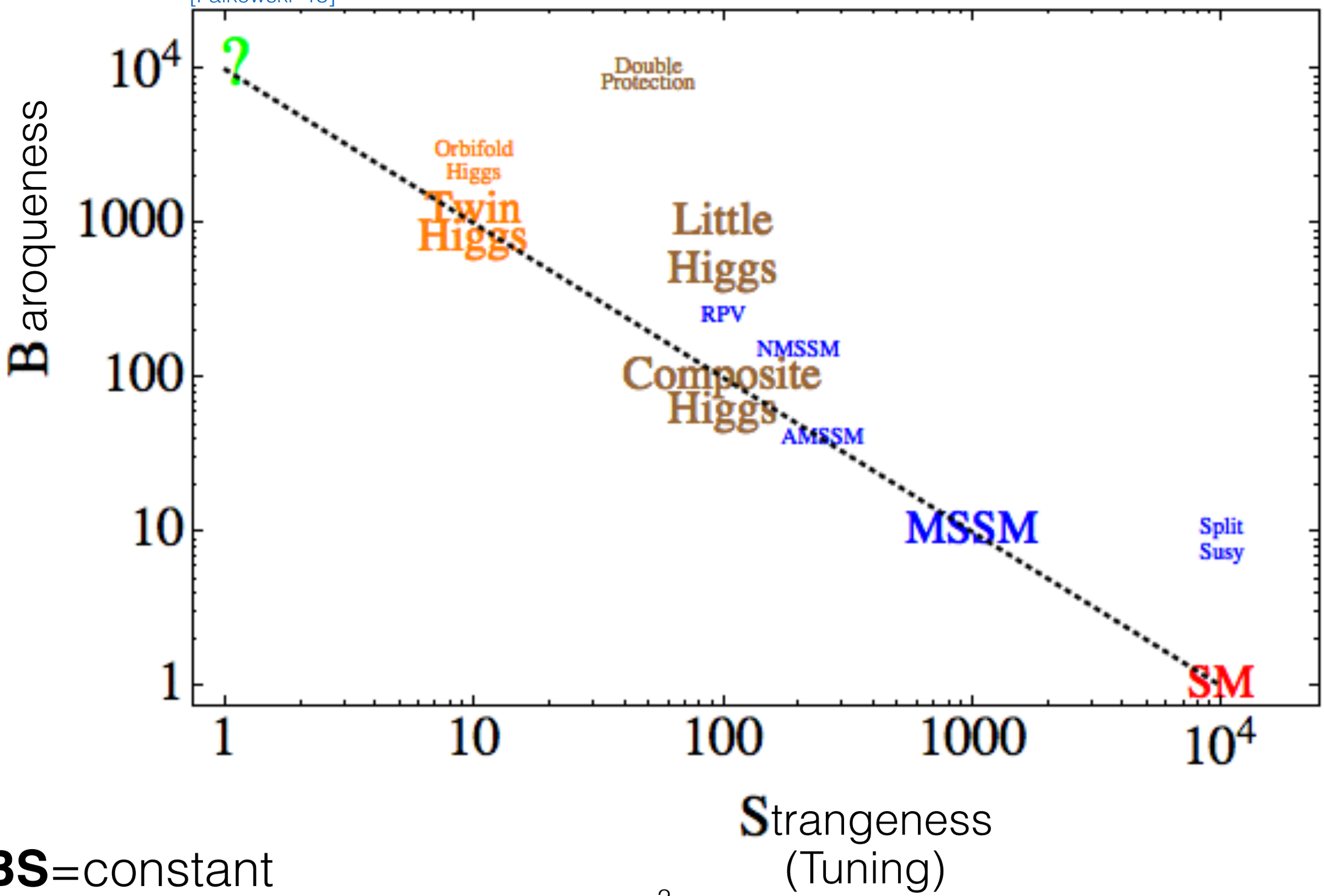
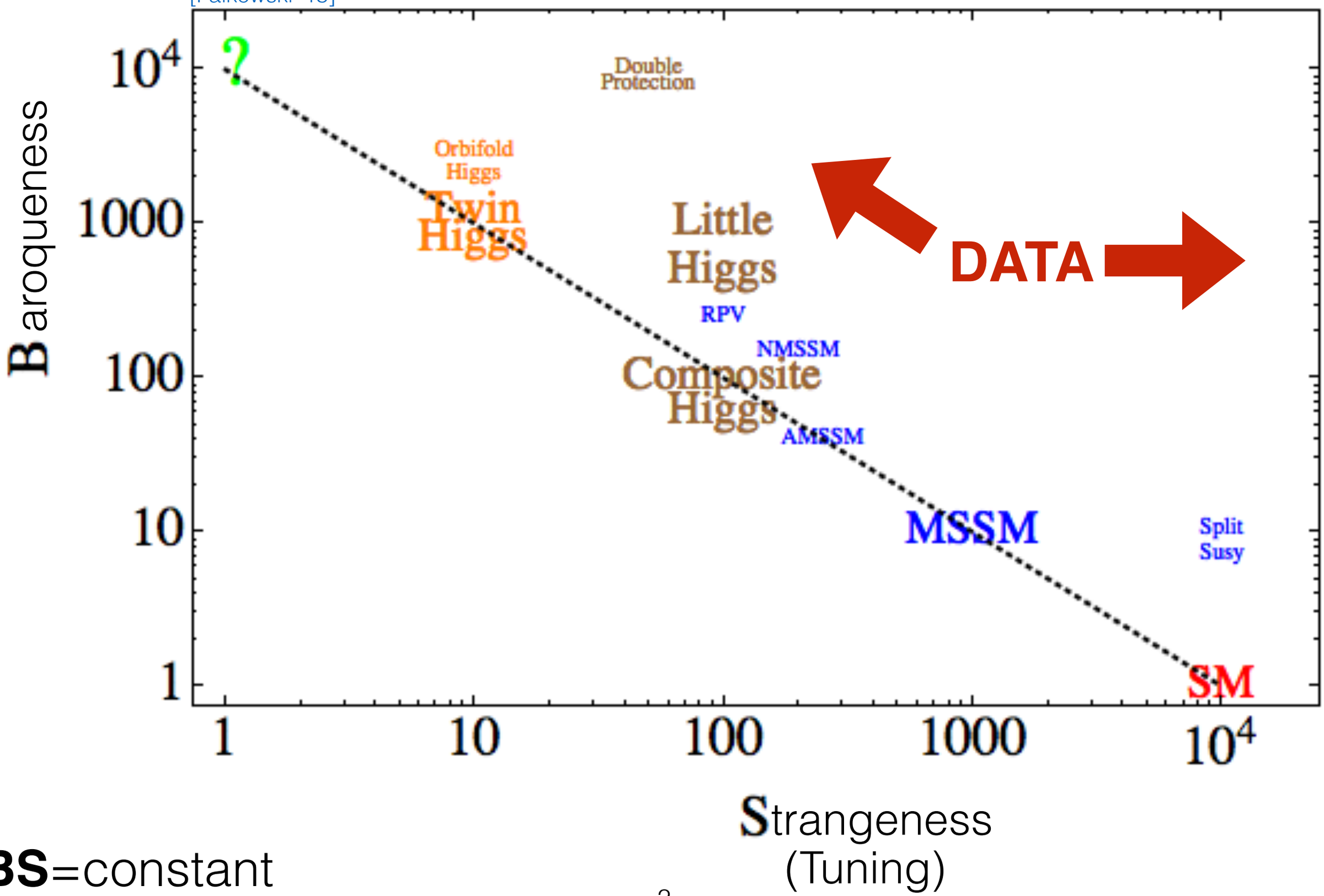
CERN TH Institute: Charting the Unknown

[Falkowski '15]



BS=constant

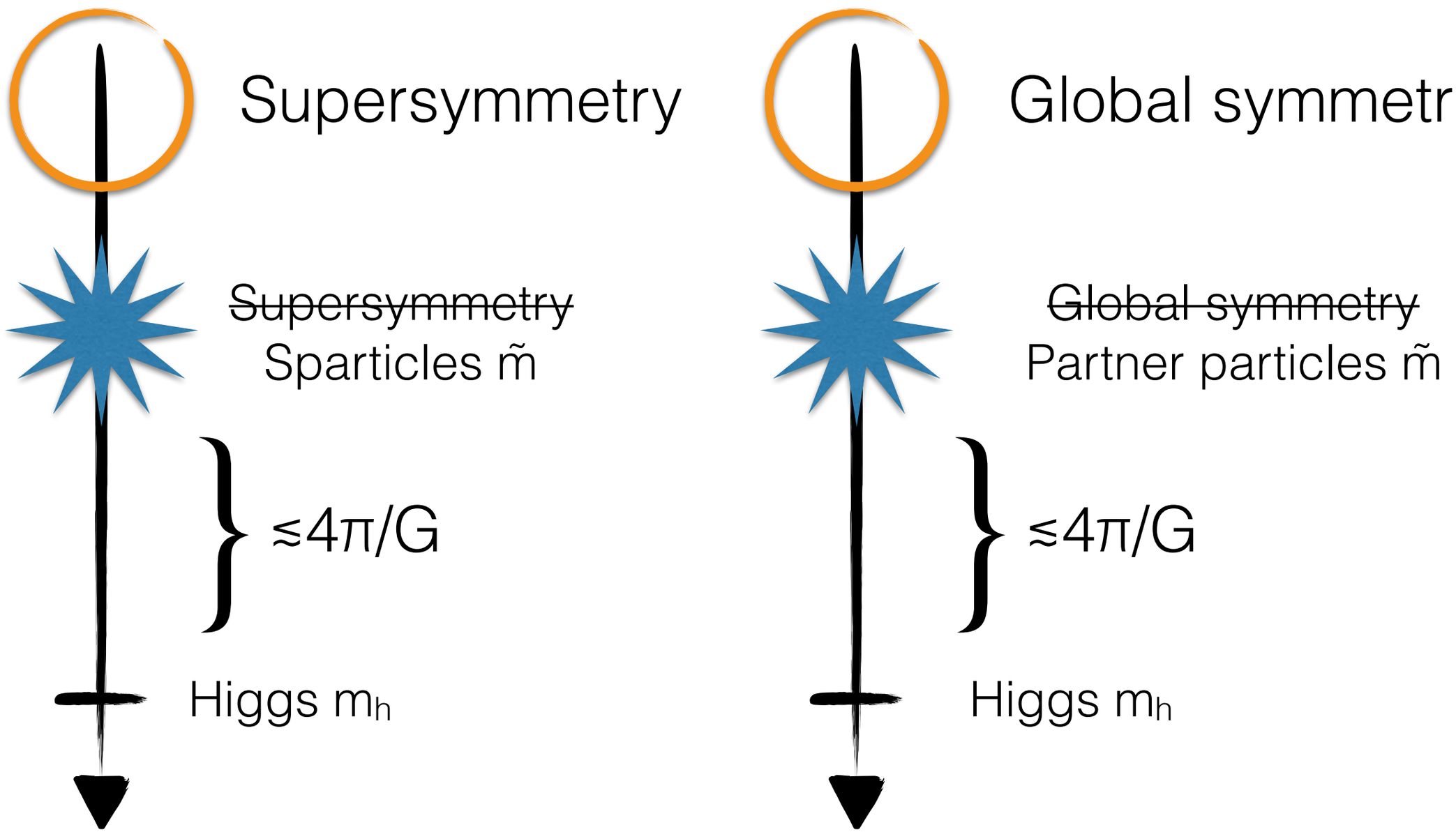
[Falkowski '15]



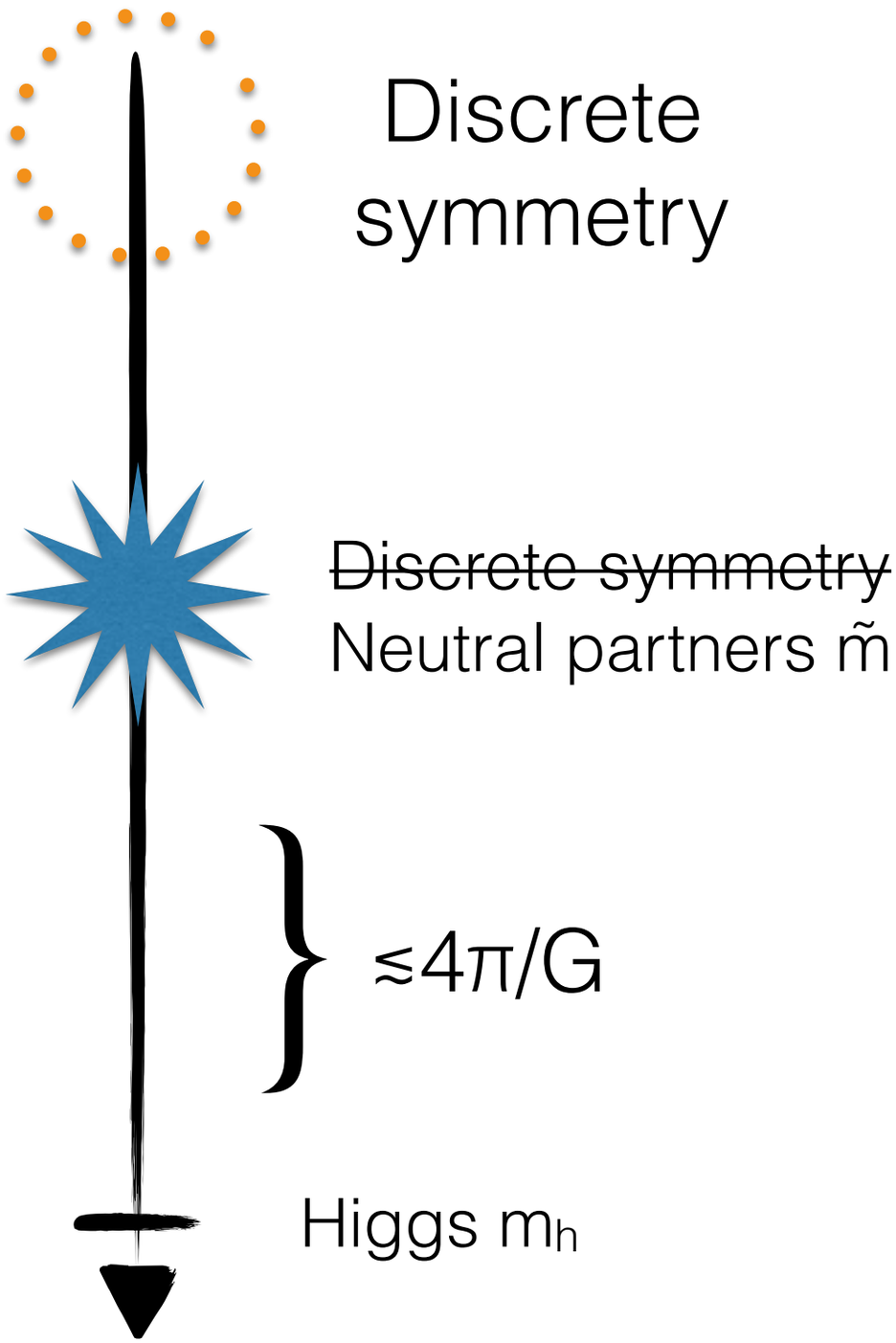
BS=constant

Symmetry Solutions

Extend the SM with a symmetry acting on the Higgs



Discrete symmetries



Symmetry-based approaches to hierarchy problem employ *continuous symmetries.*

Leads to partner states w/ SM quantum numbers.

Discrete symmetries can also serve to protect the Higgs.

Leads to partner states w/ non-SM quantum numbers.

"Neutral naturalness"

“Is neutral naturalness the beautiful reason we haven’t seen anything, or the last desperate hope of theorists?”

–G. Giudice

Progress in NN

[Chacko, Goh, Harnik '05; Barbieri, Gregoire, Hall '05; Chacko, Nomura, Papucci, Perez '05; Falkowski, Pokorski, Schmaltz '06; Chang, Hall, Weiner '06; Burdman, Chacko, Harnik '06; Foot, Volkas '06; Poland, Thaler '08; Harnik, Wizansky '08; Batra, Chacko '08; Cai, Cheng, Terning '08; NC, Englert, McCullough '13; Chacko, Cui, Hong '13; NC, Howe '13; NC, Knapen, Longhi '14; Geller, Telem '14; Burdman, Chacko, Harnik, Lima, Verhaaren '14; NC, Lou, McCullough, Thalapillil '14; NC, Katz, Strassler, Sundrum '15; Batell, McCullough '15; Barbieri, Greco, Rattazzi, Wulzer '15; Low, Tesi, Wang '15; NC, Katz '15; Garcia Garcia, Lasenby, March-Russell '15; Farina '15;

CERN-CKC TH Institute on Neutral Naturalness

23-26 April 2015
CERN
Europe/Zurich timezone

Curtin, Verhaaren '15, Csaki, Kuflik, Lombardo, Slone '15; Kilic, Swaminathan '15; Cohen, NC, Lou, Pinner '15; Curtin, Saraswat '15; Beauchesne, Earl, Gregoire '15; Burdman, D'Agnolo '15; Cheng, Jung, Salvioni, Tsai '15; Csaki, Geller, Telem, Weiler '15; Bai, Lu, Lu, Salvado, Stefanek '15; Chacko, Curtin, Verhaaren '15; NC, Knapen, Longhi, Strassler '16; Freytsis, Knapen, Robinson, Tsai '16; ……..<<750 GeV>>…… Harnik, Howe, Kearney '16; Farina, Monteux, Shin '16; NC, Koren, Trott '16; Chacko, NC, Fox, Harnik '16;…]

A plethora of new naturalness-related signatures to look for @ LHC and beyond

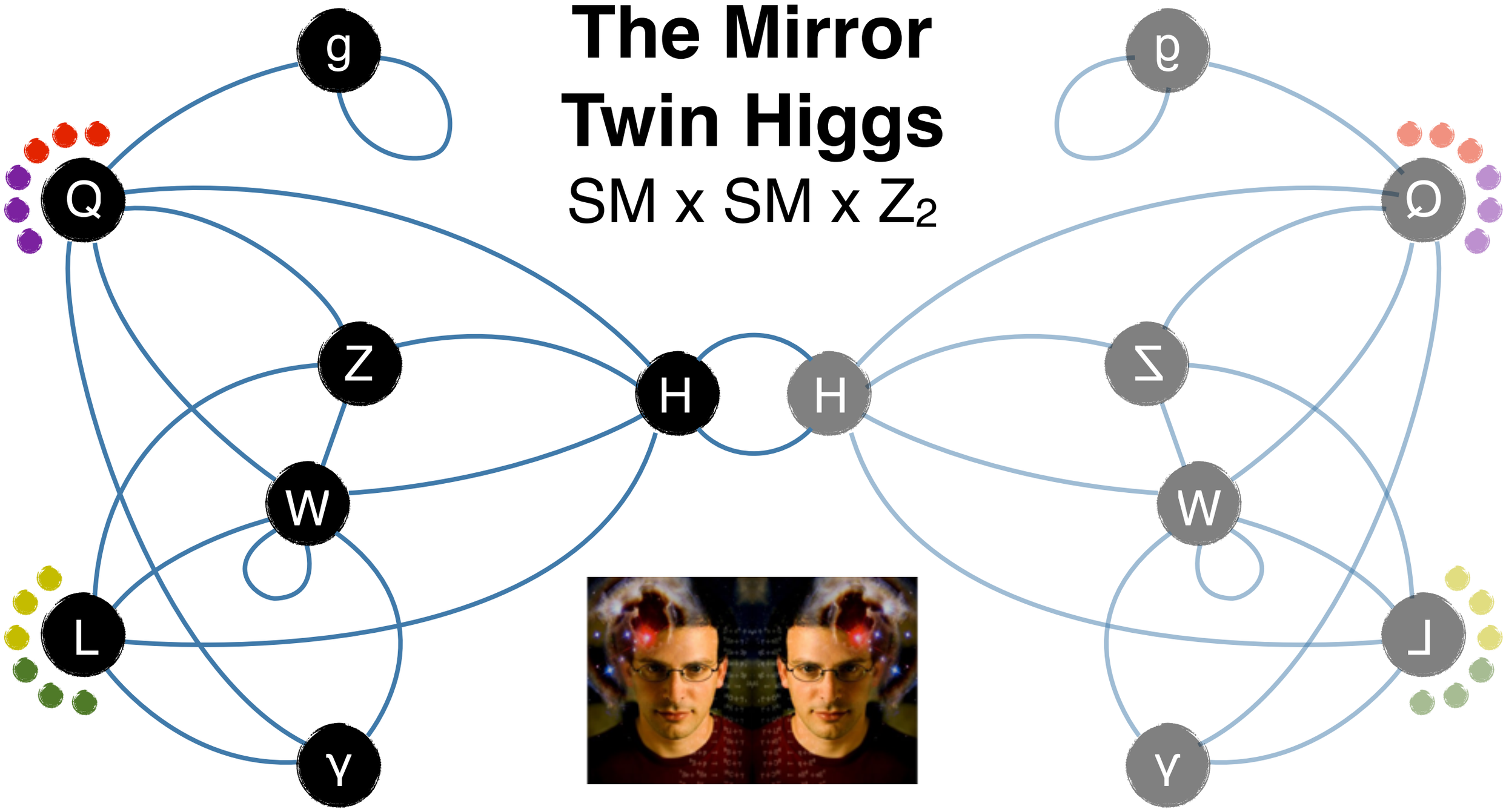
(Wasn't great for 750 GeV)

Much to look forward to throughout the lifetime of the LHC, even after ICHEP.

The Simplest Theory

The Mirror Twin Higgs

SM x SM x Z_2



[Z. Chacko, H.-S. Goh, R. Harnik '05]

Why not?

Higgs portal maintains equilibrium down to T~GeV

$\Delta N_{eff} >> 1$

Options are

Change cosmology

Signals in BBN & CMB

See Roni's talk

Change the spectrum

Copious new physics at ~few TeV
Signals @ LHC

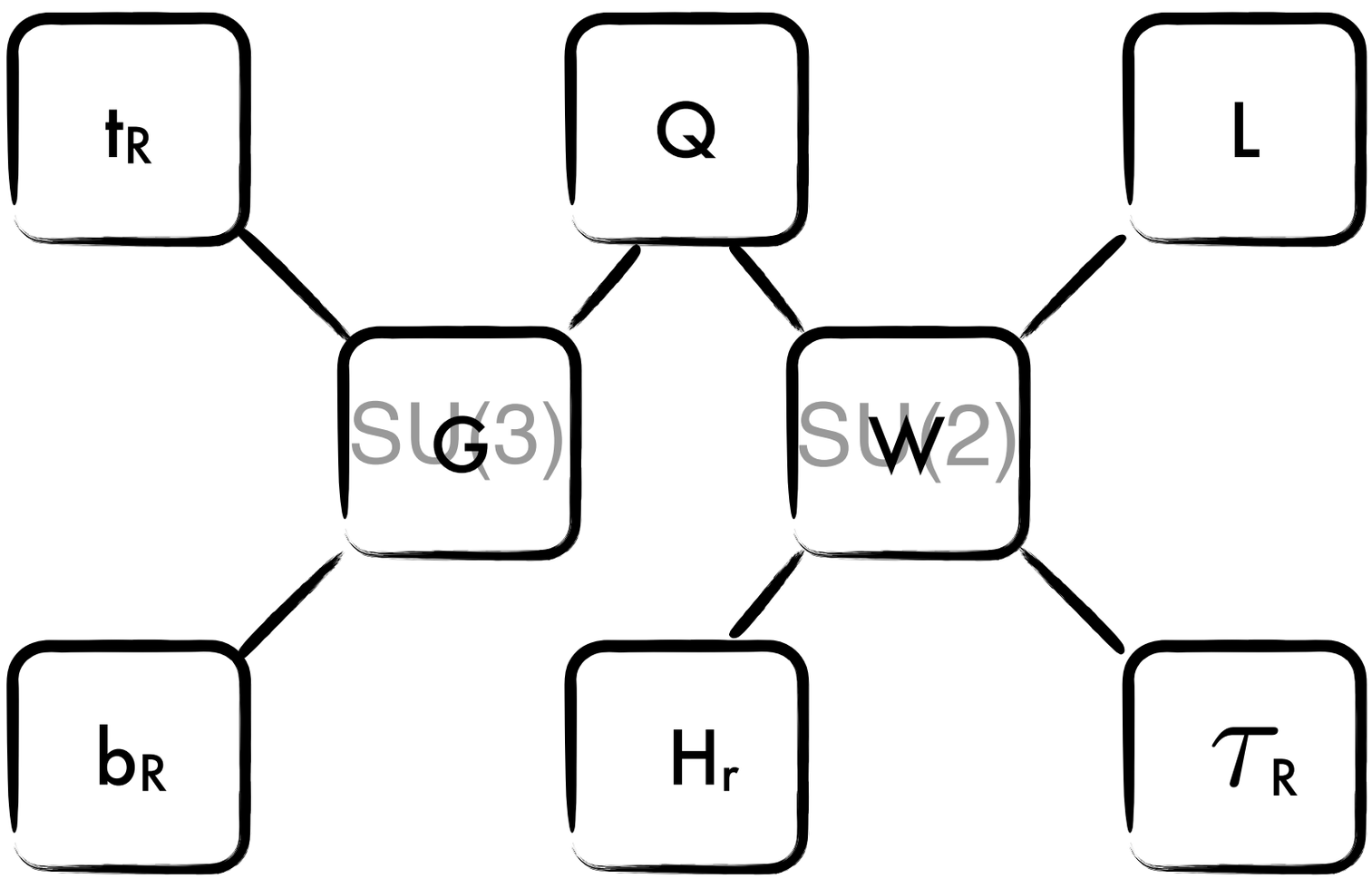
- Fraternal Twin Higgs
- Holographic Twin Higgs
- Composite Twin Higgs
- Orbifold Higgs
- …

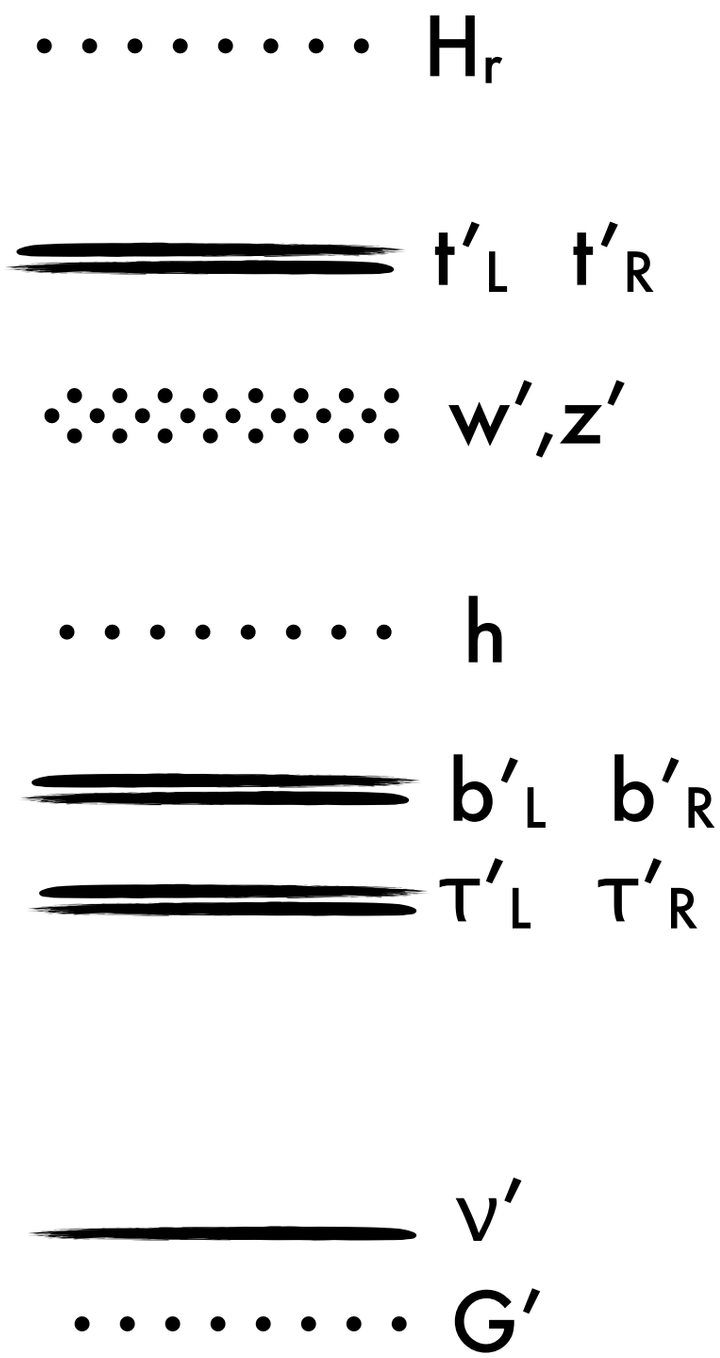
[NC, A. Katz, M. Strassler, & R. Sundrum '15]

See also: [Geller, Telem '14, Barbieri, Greco, Rattazzi, Wulzer '15; Low, Tesi, Wang '15]

The Fraternal Twin

The "natural SUSY" of Twin Higgs





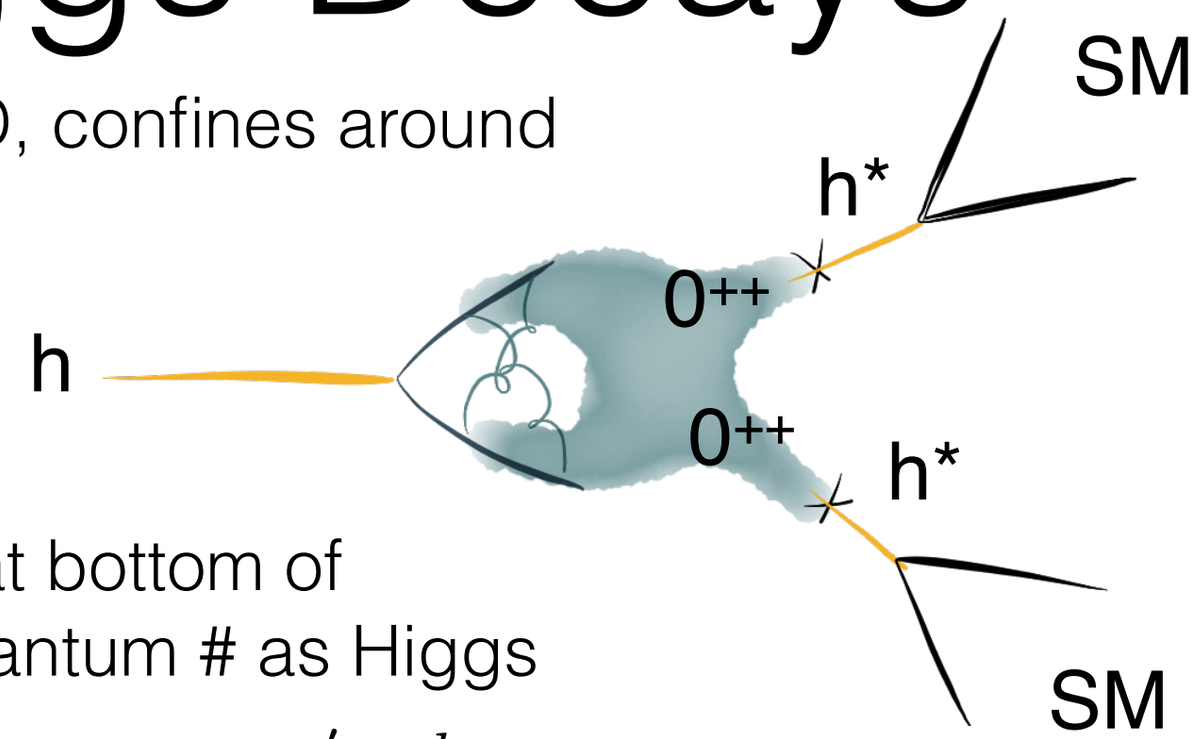
Just Z_2 partner states for the third generation, float couplings not crucial for naturalness

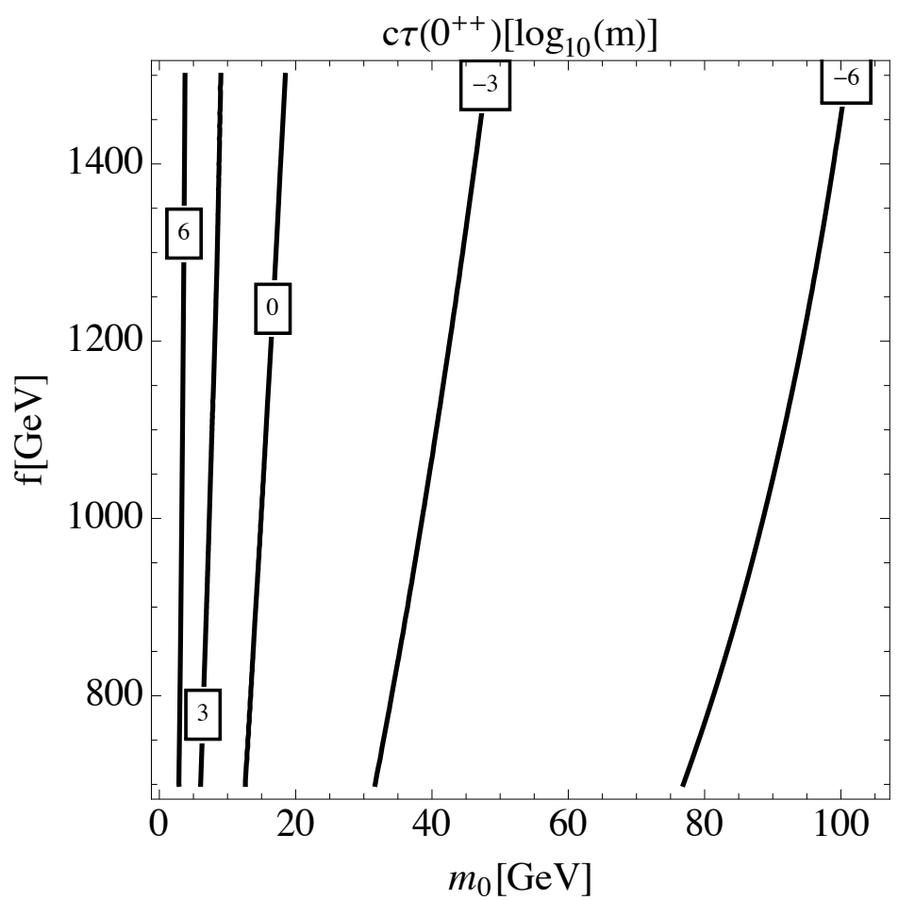
See D. Curtin's talk

[NC, Katz, Strassler, Sundrum '15; Curtin, Verhaaren '15; Chacko, Curtin, Verhaaren '16]

Exotic Higgs Decays

- Twin sector must have twin QCD, confines around QCD scale
- Higgs boson couples to bound states of twin QCD
- Various possibilities. Glueballs at bottom of spectrum, lightest has same quantum # as Higgs





$$\mathcal{L} \supset -\frac{\alpha_3'}{6\pi}\frac{v}{f}\frac{h}{f}G'^{a}_{\mu\nu}G'^{\mu\nu}_{a}$$

Produce in rare Higgs decays (BR~10^{-3}-10^{-4})

$$gg \to h \to 0^{++} + 0^{++} + \ldots$$

Decay back to SM via Higgs

$$0^{++} \to h^* \to f\bar{f}$$

Long-lived, decay length is macroscopic; length scale ~ LHC detectors

Fraternity & its discontents

Fraternal Twin analogy with Natural SUSY is imperfect

- Twin sector also chiral! Symmetry breaking is hard, not soft.
- Limited freedom for twin fermion masses. $\delta m_H^2 \propto (\tilde{y}^2 - y^2)\Lambda^2$
- Need a picture for physics at cutoff.
- Inessential baggage (leptons) from anomaly cancellation.

What if the twin sector were vector-like?

Still need to address physics @ cutoff *but*

- Preserve Z_2 in couplings (modulo running); breaking in spectrum now soft.
- More freedom in fermion masses, anomalies trivial, …

[NC, S. Knapen, P. Longhi, & M. Strassler '16]

The Vector-like Twin

The usual (chiral twin) story:

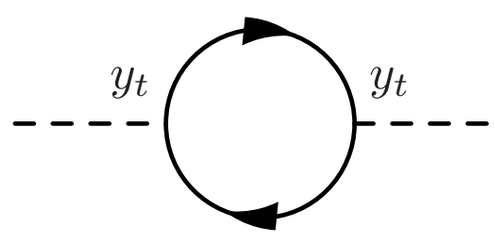
$$-\mathcal{L} \supset -m^2\Big[|H|^2+|H'|^2\Big]+\lambda\Big[|H|^2+|H'|^2\Big]^2+\delta\Big[|H|^4+|H'|^4\Big]$$
$$+\,y_t\,H\,q\,u+y_t\,H'q'u'+\text{h.c.}$$

UV sensitivity at one loop:

$$-\mathcal{L}^{(1)} \supset \frac{\Lambda^2}{16\pi^2}\Big(-6y_t^2+\frac{9}{4}g_2^2+10\lambda+6\delta\Big)\Big(|H|^2+|H'|^2\Big)$$

PNGB Higgs protected

$\delta m_h^2 \sim$



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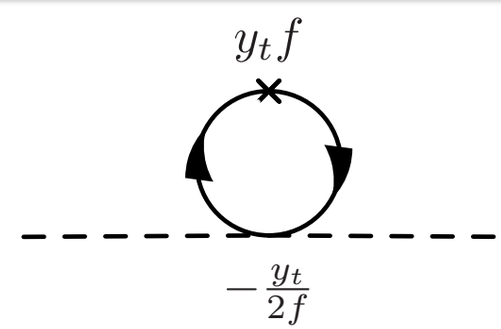


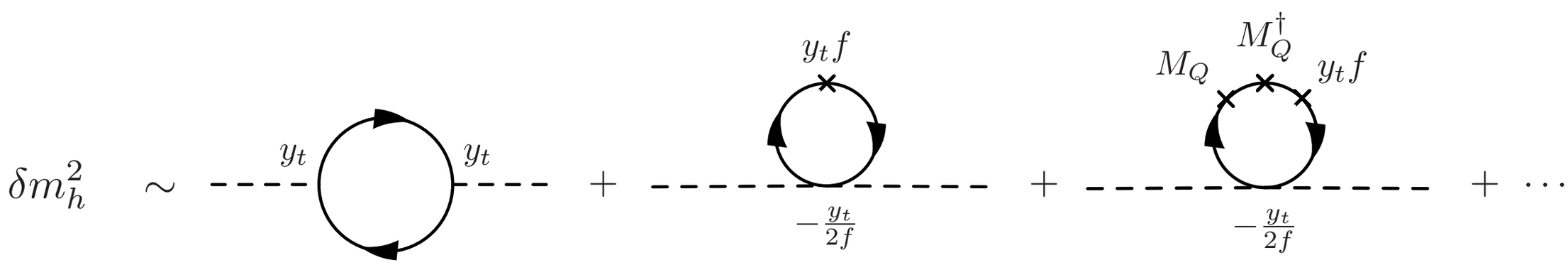
The Vector-like Twin

Now make twin fermions vector-like w/ mass terms:

$$-\delta\mathcal{L} = M_Q\, q'\bar{q}' + M_U\, u'\bar{u}'$$

No change in quadratic UV sensitivity from vector-like masses; only log-divergent correction

$$\delta m_h^2 \sim \frac{3y_t^2}{4\pi^2}\left(M_Q^2 \log\left[\frac{M_Q^2}{\Lambda^2}\right] + M_U^2 \log\left[\frac{M_U^2}{\Lambda^2}\right]\right)$$



The Fine Print

- Need to forbid "wrong" yukawa couplings:

$$\mathcal{L} \supset \tilde{y}_t H'^\dagger \bar{q}' \bar{u}' + \text{h.c.}$$

No biggie: holomorphy, locality, softly broken PQ symmetry,…

- Need to suppress irrelevant operators:

$$\mathcal{L} \supset c\frac{M_Q}{\Lambda^2} H H^\dagger \bar{q}' q' + \text{etc} \Rightarrow \delta m_h^2 \sim \frac{c}{16\pi^2} M_Q^2$$

Perturbative UV completion or locality or just M_Q not too large

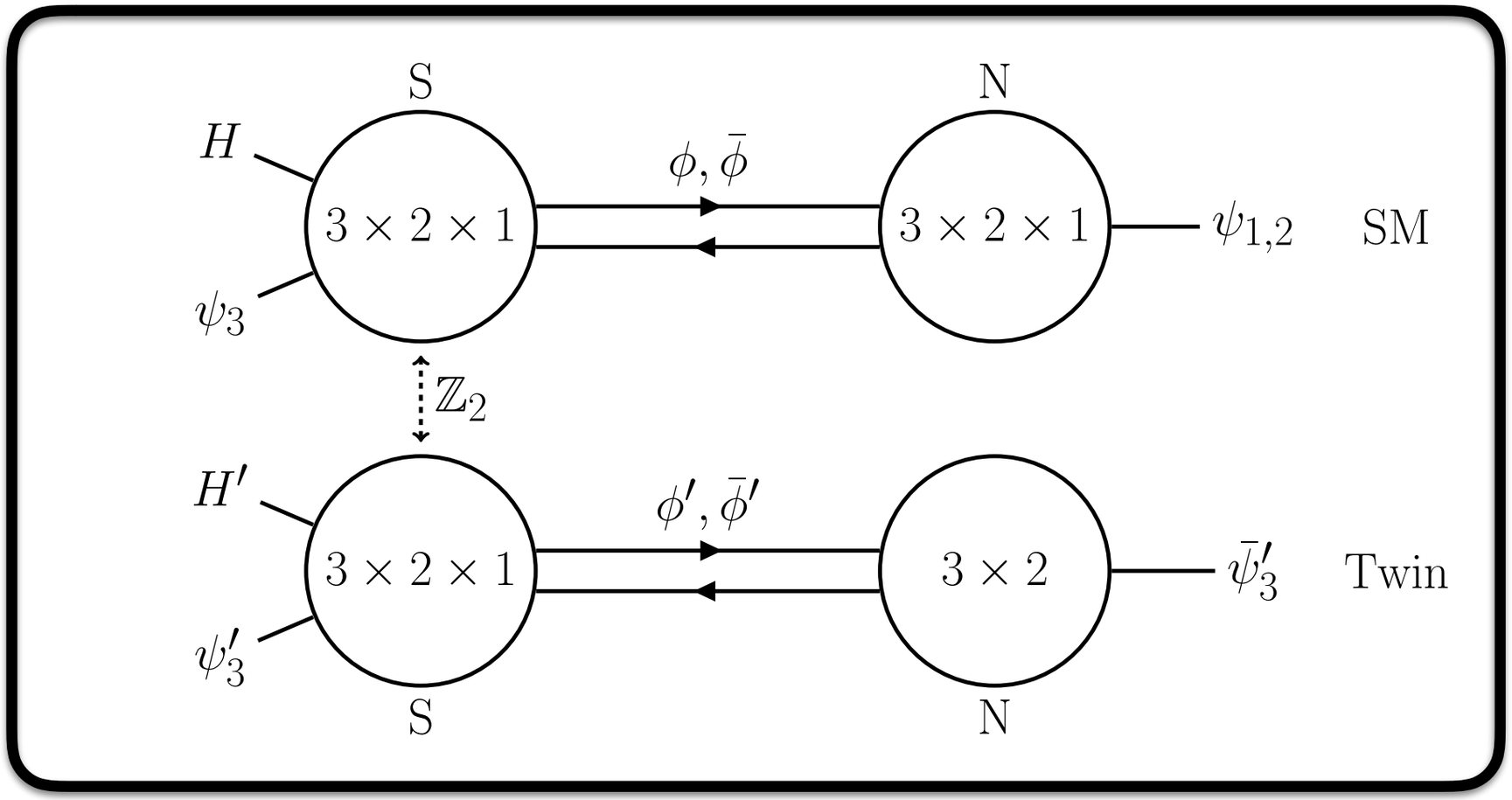
- Couplings run differently below cutoff:

$$\beta_{g_3} = -7\frac{g_3^3}{16\pi^2} \qquad \beta_{g_3'} = -3\frac{g_3'^3}{16\pi^2}$$

Doesn't spoil UV sensitivity, does require Z_2 restored at cutoff

A Simple Completion

Supersymmetrize it, compositize it, put it in an extra dimension…



Higgs quiver to diagonal around ~5-10 TeV

Amusing features: flavor texture, vector-like mass texture

$$c_d\, d' \bar{\phi}'_T \bar{d}' + c_\ell\, \ell' \bar{\phi}'_D \bar{\ell}' + \frac{c_q}{\Lambda'} q' \phi'_T \phi'_D \bar{q}' + \frac{c_u}{\Lambda'} u' \phi'_T \phi'_T \bar{u}' + \frac{c_e}{\Lambda'} e' \phi'_D \phi'_D \bar{e}' \Rightarrow M_{D,L} \sim \Lambda,\ M_{Q,U,E} \sim \Lambda^2/\Lambda'$$

A minimal model

	q'	$\bar{q}'$	u'	$\bar{u}'$
$SU(3)'$	$\square$	$\overline{\square}$	$\overline{\square}$	$\square$
$SU(2)'$	$\overline{\square}$	$\square$	1	1

(look, ma, no leptons!)

Three Dirac mass eigenstates:

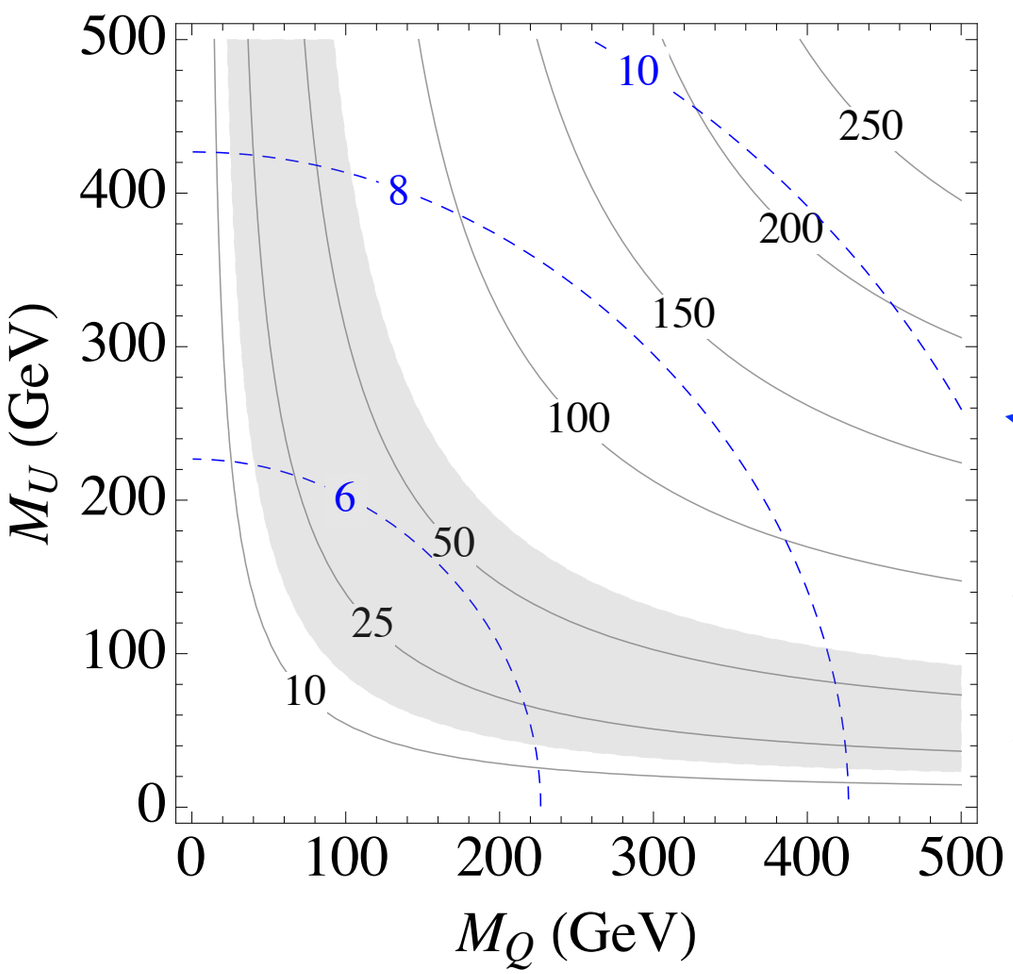
$$b_1', t_1', t_2'$$

$$m_{b_1} = M_Q \qquad \mathcal{M}_{t_1,t_2} = \begin{pmatrix} M_Q & 0 \\ \frac{y_t f}{\sqrt{2}} & M_U \end{pmatrix}$$

Mini see-saw for $y_t f \gtrsim M_Q, M_U$

$$m_{t_1}^2 \approx 2\frac{M_Q^2 M_U^2}{y_t^2 f^2} \qquad m_{t_2}^2 \approx \frac{1}{2} y_t^2 f^2 + M_Q^2 + M_U^2$$

Spectrum still very "fraternal": raise twin b, lower twin t_1



$$\text{Tuning} : \Delta = \frac{f^2}{2v^2} + \text{threshold}$$

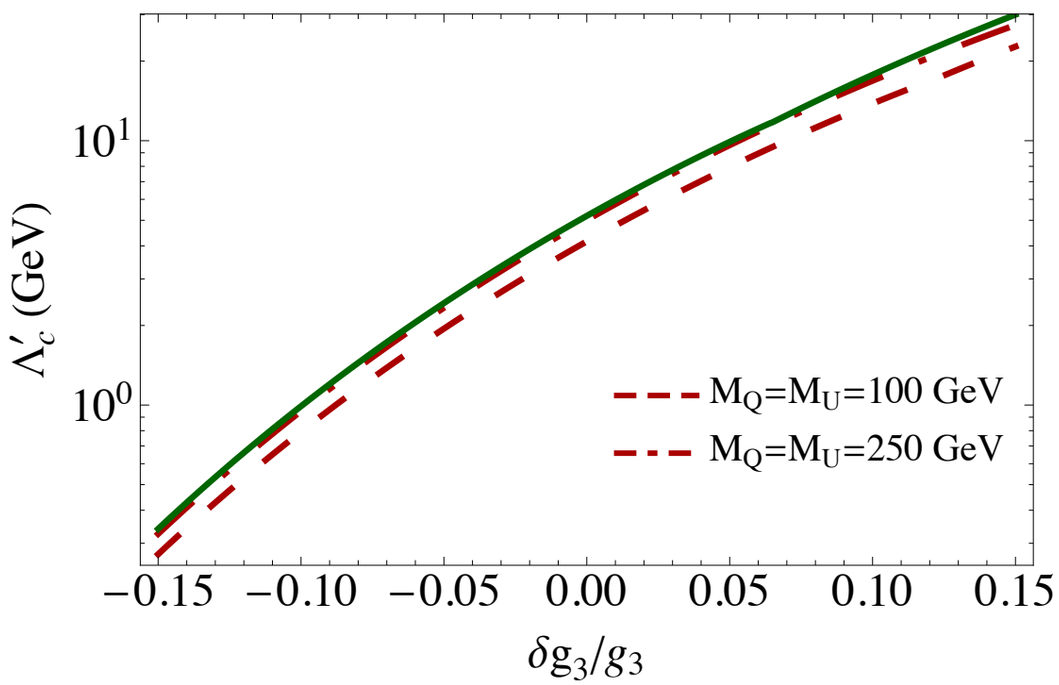
$$m_{t_1} \; (m_{b_1} = M_Q,\, m_{t_2} \sim 500\,\text{GeV})$$

Excluded by $h \to t_1' t_1'$

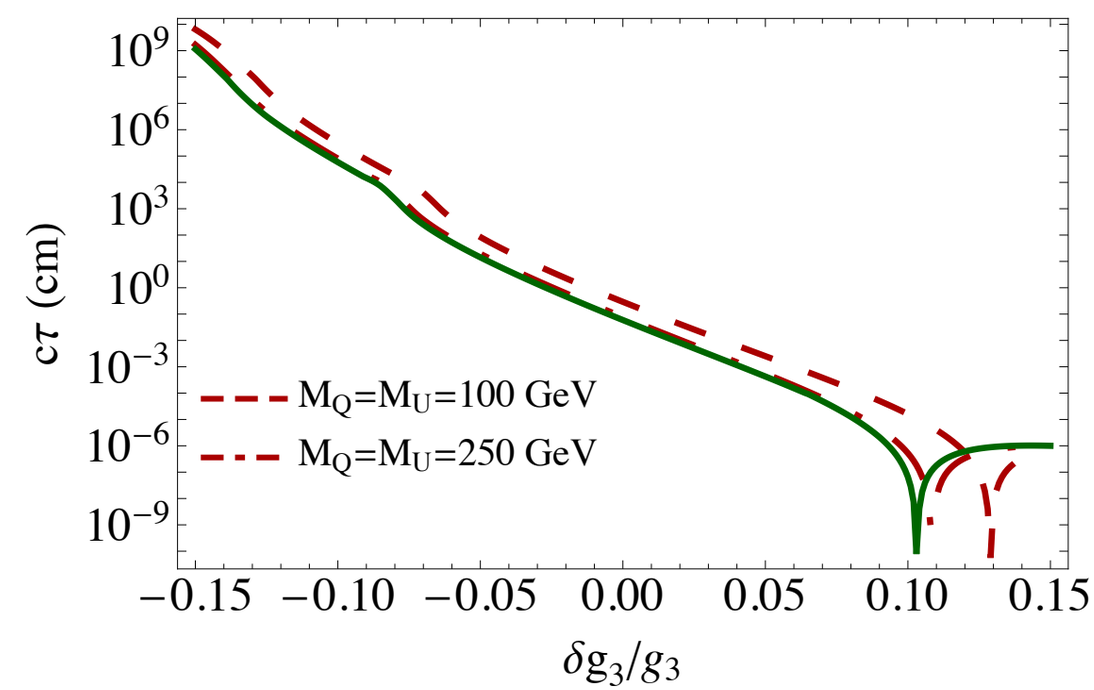
Phenomenology

Spectrum, features much like fraternal twin

Twin QCD Scale



Twin Glueball Lifetime



Rare Higgs decays to glueballs, bottomonia; these undergo displaced decay back to SM, often on LHC length scales

Some novelties:

- No twin leptons, so both glueballs & onia must decay visibly
- W' may be stable (dark matter?) if W'→t_1'b_1' closed
- t2'→t_1'h if twin weak decays t2'→W'b_1' closed

“Is neutral naturalness the beautiful reason we haven’t seen anything, or the last desperate hope of theorists?”

–G. Giudice

Above my pay grade, but at the very least: discrete symmetries have the same parametric freedom as “Natural SUSY” or your other favorite models.

If you do not find it beautiful, I leave you to Roni’s talk.

Looking forward…

"Outmaneuver Rattazzi"

Does *UV-complete* neutral naturalness always give SM-charged states at two loops?

$$m_H^2 \sim \left(\frac{1}{16\pi^2}\right)\frac{3y_t^2}{8\pi^2}m_{\rm color}^2$$

If so, guaranteed collider bound on neutral naturalness

SUSY Twin Tuning "Boost":	$\frac{\lambda_{SM}}{\lambda}$	Composite Twin Tuning "Boost":	$\frac{y_t^2}{g_*^2}$

E.g. in SUSY Twin $\Delta \sim \frac{\tilde{m}^2}{\lambda f^2} \times \frac{f^2}{v^2} = \frac{\tilde{m}^2}{m_H^2}\frac{\lambda_{SM}}{\lambda}$

But: parametrics change if we can eliminate f^2/v^2 tuning

Rattazzi Outmaneuvered?

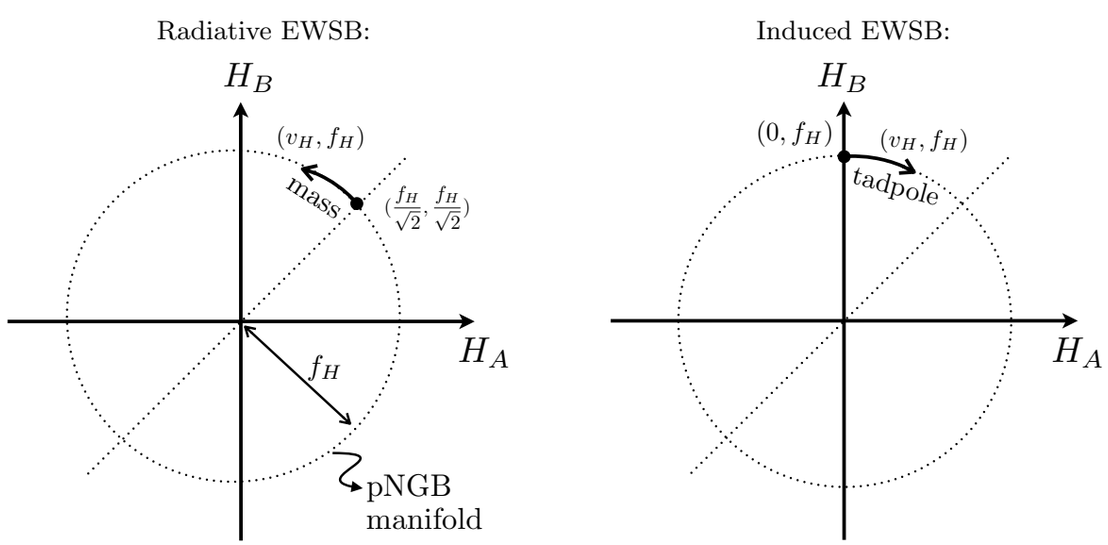
1. v/f tuning due to Z_2 symmetry; fix with hard Z_2-breaking quartic

$$\left(\delta_A |H_A|^4 + \delta_B |H_B|^4\right)$$

Then vev flops into sector w/ smaller quartic:

$$\frac{v_A^2}{v_B^2} \propto \frac{\delta_B}{\delta_A}$$

[Chang, Hall, Weiner '06; Redigolo et al '16]



2. Instead of perturbing symmetric vacuum w/ mass vs. quartic, perturb asymmetric vacuum w/ mass vs. tadpole

[Beauchesne, Earl, Gregoire '15; Harnik, Howe, Kearney '16]

Totally neutral scalars?

In Twin Higgs, always have v^2/f^2 Higgs coupling deviations.
Could avoid this smoking gun w/ scalar top partners.

$SU(6) \times SU(2)_W \times U(1)_Y$

or

$SU(3)_A \times SU(3)_B \times SU(2)_W \times U(1)_Y$

In folded SUSY, common SU(2) factor:

$$\mathcal{L} \supset \lambda_t H_u q_3^A u_3^A + \lambda_t^2 |H_u \cdot \tilde{q}_3^B|^2 + \lambda_t^2 |H_u|^2 |\tilde{u}_3^B|^2$$

so F-stops are electroweak states; bounds from Drell-Yan production.

Is it possible to arrange for completely neutral scalar top partners?

$$\lambda_t H_u q_3^A u_3^A + \lambda_t^2 |H_u|^2 |\tilde{q}_3^B|^2 + \lambda_t^2 |H_u|^2 |\tilde{u}_3^B|^2$$

Need to get the scalar potential without an SU(2) contraction

$$\begin{pmatrix} H_u & \cdot \end{pmatrix} \begin{pmatrix} \cdot & X \\ \cdot & \cdot \end{pmatrix} \begin{pmatrix} \cdot \\ \tilde{q}_3^B \end{pmatrix}$$

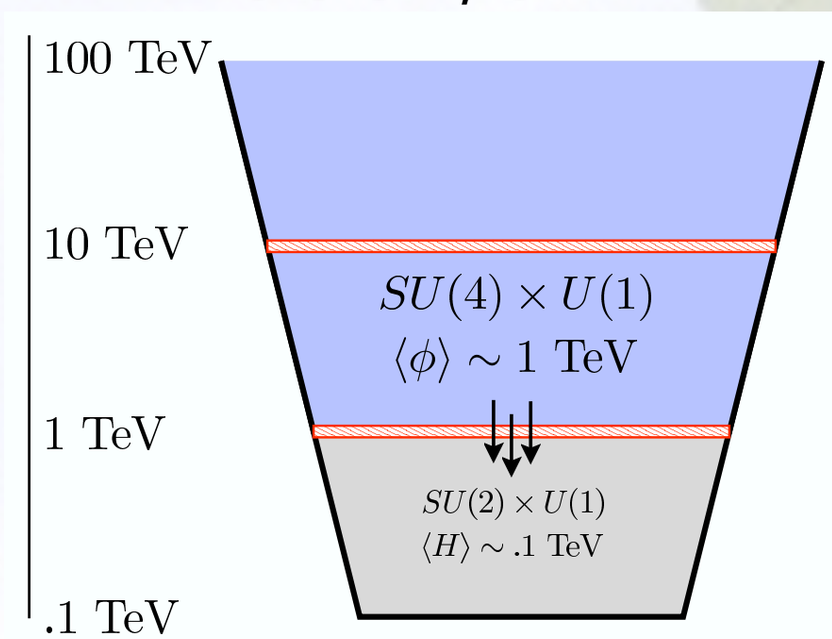
Not impossible; start w/ larger parent symmetry and judicious orbifold projection.

Turtles?

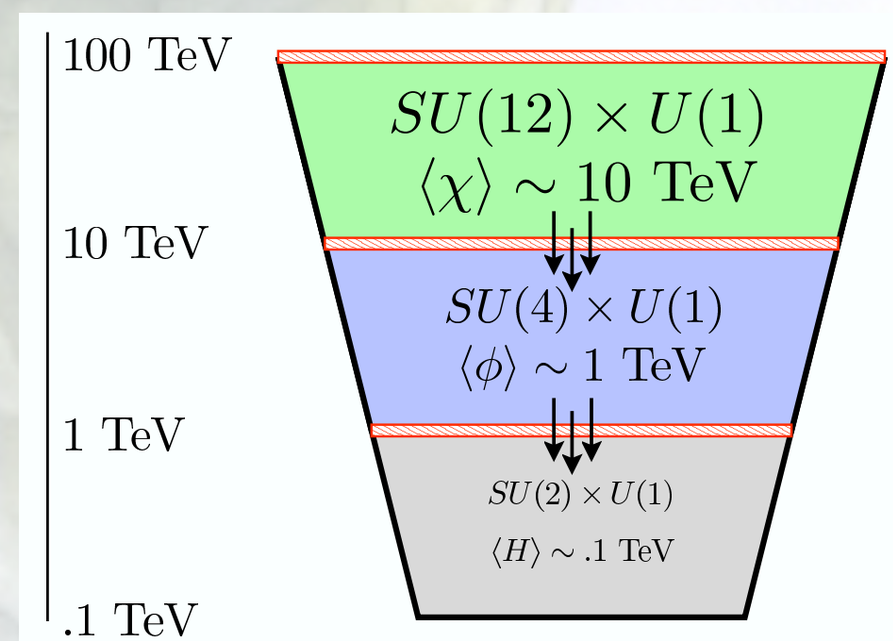
[Batra, Kaplan]

Is there an alternative UV completion to SUSY/compositeness?
Perhaps without colored states at two loops?

SUSY/CHM



Turtles



N grows with each level; couplings rapidly grow strong.

Unless theory has good large-*N* behavior, i.e. 't Hooft couplings Ng^2, Ny^2, $N\lambda^2$ remain under control. Plausible, no examples yet…

Embrace accidents

What if discrete symmetries of neutral naturalness are accidental symmetries of IR fixed point?

E.g. accidental supersymmetry [Sundrum]

IR theory contains SM + scalars

$$\lambda_t H Q_3 \bar{u}_3 \qquad \lambda_\phi |H|^2 |\phi|^2$$

Strong dynamics drives

$$\lambda_\phi \sim \lambda_t^2$$

Neutral naturalness still lacks a "beautiful" theory, perhaps accidental symmetries are the way.

Conclusions

- Neutral naturalness: a response to data that is alive and well in our post-750 GeV world.
- Clearly an excellent signal generator; excellent motivation for new searches at LHC.
- More recently: *discrete symmetries offer the same parametric freedom as natural SUSY.*
- Many opportunities for exploration; likely we'll discover more surprising and delightful ideas.