The Vector-like Twin Higgs

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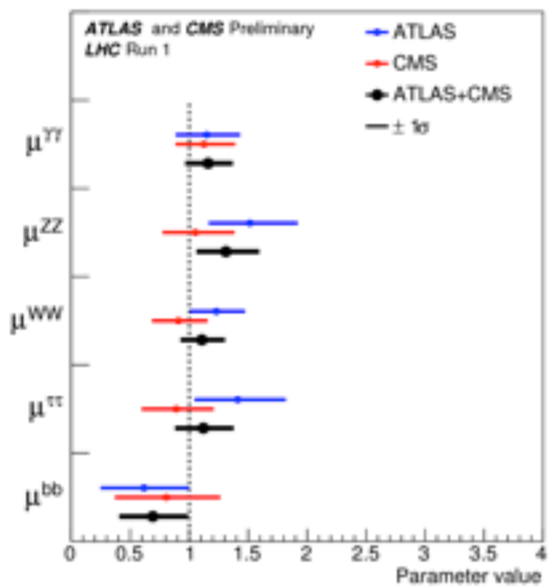
UC Berkeley & LBL

Hidden Naturalness Workshop
@ UMD 28-30 April 2016

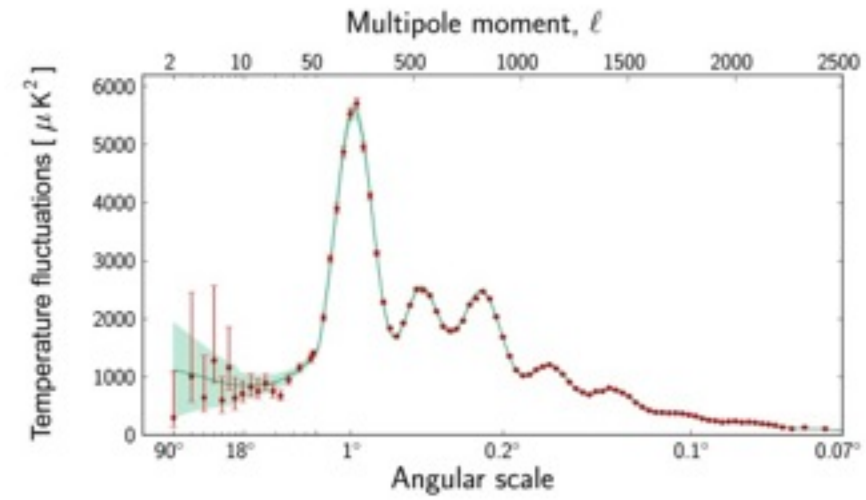
N. Craig, SK, P. Longhi, M. Strassler: 1601.07181

How is the Z_2 broken?

Precision Higgs physics



Precision Cosmology



soft | hard | very hard | violent

Relevant $\not{Z}_2$ operator
Spontaneous breaking

talk by T. Gregoire

Marginal or irrelevant $\not{Z}_2$ operator

Break the spectrum

Break the couplings and the spectrum

$\not{Z}_2$ informs UV completions and phenomenology

Hard $\not{Z}_2$

Z_2 should emerge as accidental symmetry near $\Lambda \sim 5$ TeV

hard → very hard → violent

hard

Marginal or irrelevant $\not{Z}_2$ operator

- quartic: $\delta V = \delta \left|h\right|^4 + \delta' \left|h'\right|^4$
- lower/lepton yukawa's
- …

very hard

Break the spectrum

- Fraternal Twin Higgs
  N. Craig, A. Katz, M. Strassler, R. Sundrum: 1501.05310
- Twin tops as sterile neutrino's
  B. Batell, M. McCullough: 1504.04016
- Vector-like Twin Higgs
- …

violent

Break the couplings and the spectrum

- Non-abelian orbifolds
  N. Craig, SK, P. Longhi 1411.7393, 1410.6808
- No-loose theorem
  D. Curtin, P. Saraswat: 1509.04284
- …

Hidden valley phenomenology

LHC

talks by H. Chen
C. Csaki

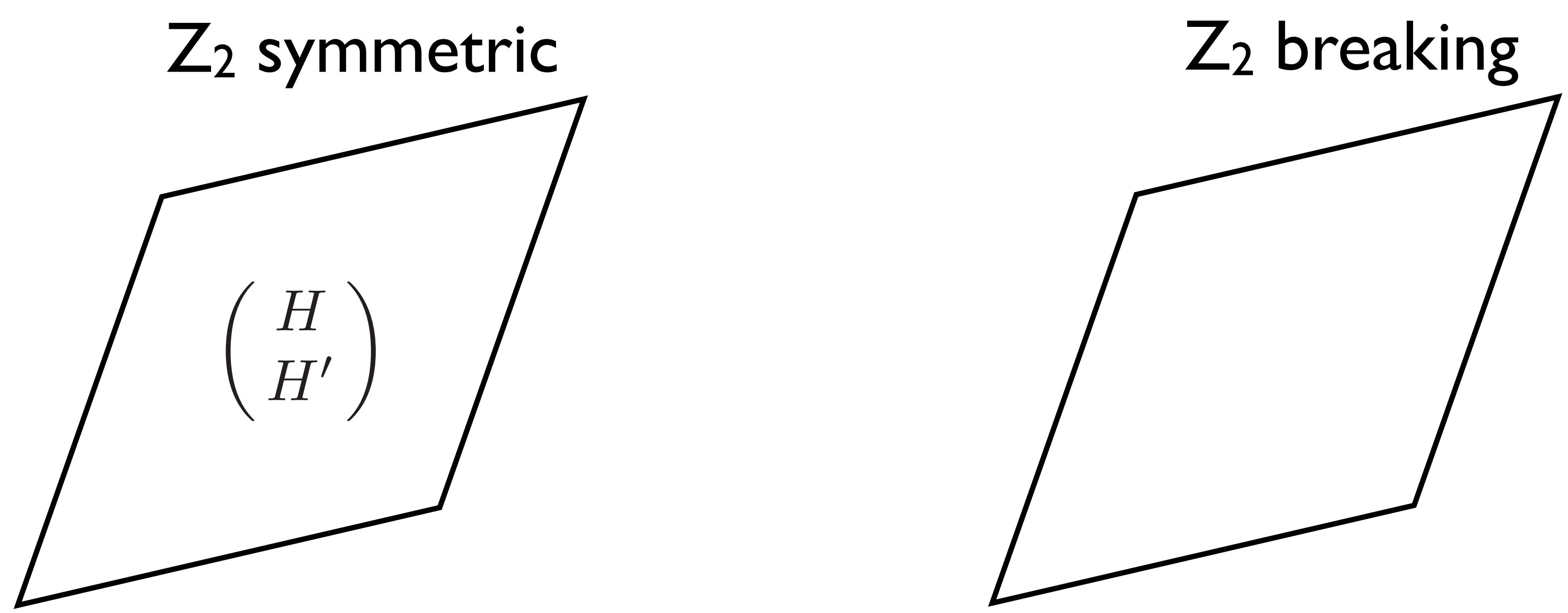
Cosmology / astrophysics

talks by Y. Tsai
M. Farina

Emergent Z_2 symmetry

Sequester the Higgs sector from all sources of explicit Z_2 breaking

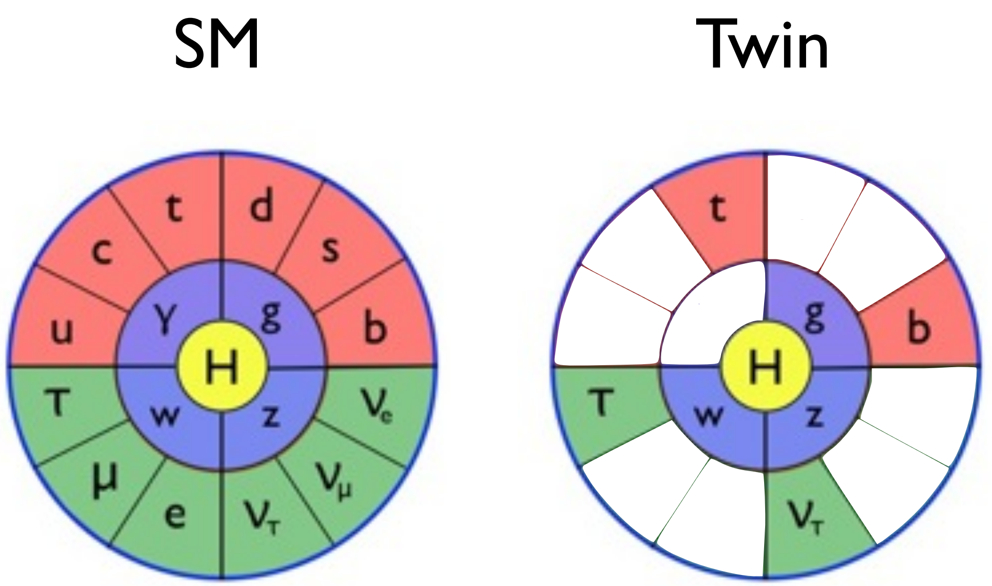
Cartoon:



- Extra dimensions (think folded susy) — talk by D. Pinner
- Strong/holographic models — talk by O. Telem
- Deconstruction — this talk

The Fraternal Twin

Naturalness only requires:
- Twin Higgs
- Twin top
- Twin SU(2) x SU(3)



⟶ Add in full twin third generation to cancel gauge anomalies

"Minimal" matter content, analogous to "Natural SUSY" framework for the MSSM

Interesting collider signatures + better cosmology

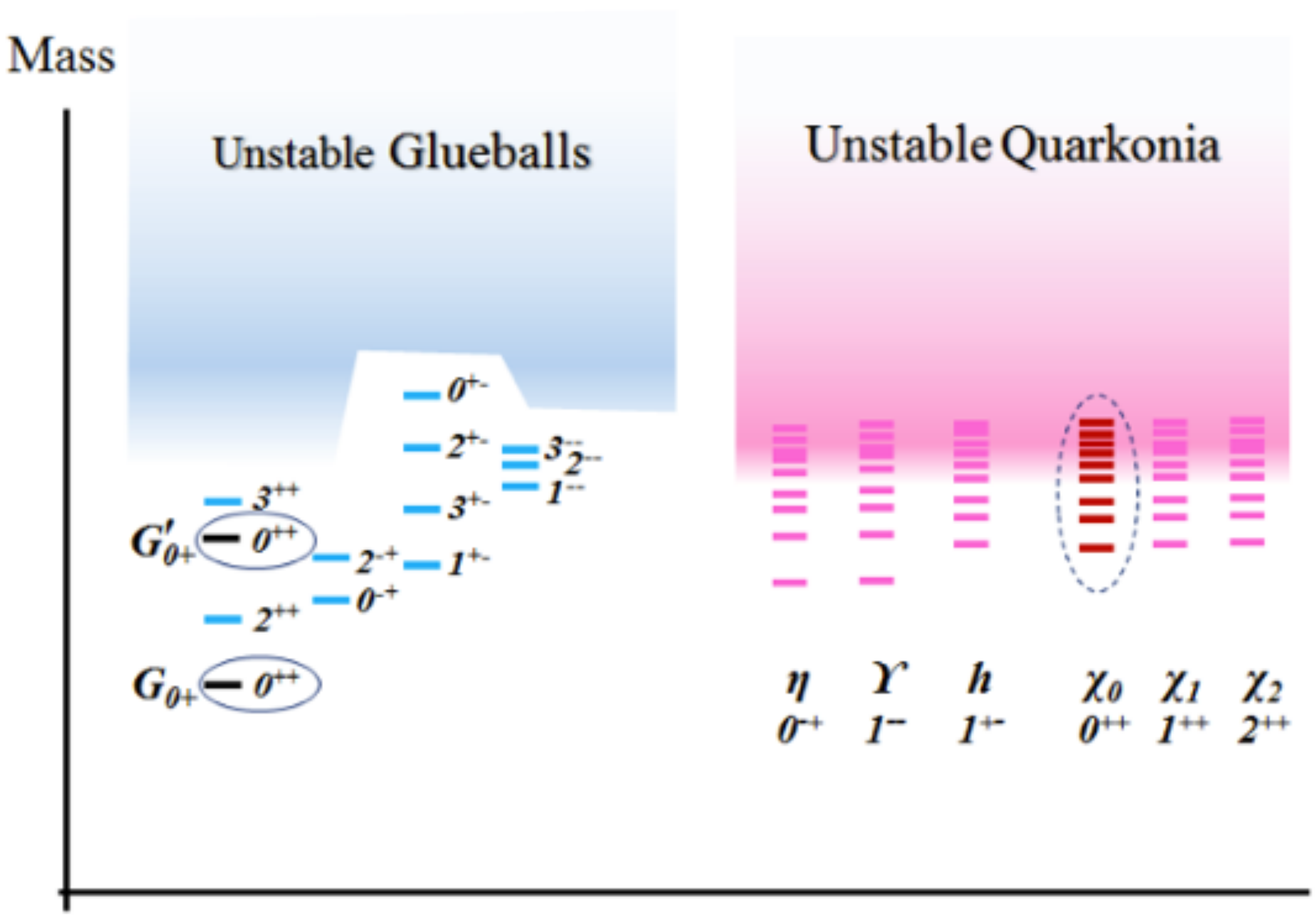
Accuracy needed:

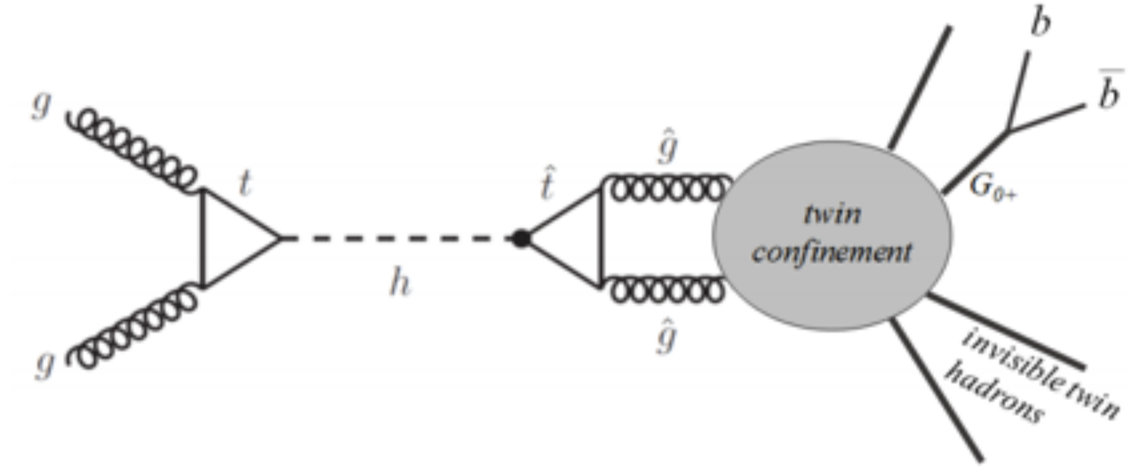
$$y_t = y_t' \quad \text{at} \quad 1\% \text{ level}$$
$$g_2 = g_2' \quad \text{at} \quad 10\% \text{ level} \qquad \text{at} \qquad \Lambda \sim 5 \text{ TeV}$$
$$g_3 = g_3' \quad \text{at} \quad 15\% \text{ level}$$

N. Craig, A. Katz, M. Strassler, R. Sundrum: 1501.05310

Fraternal Phenomenology

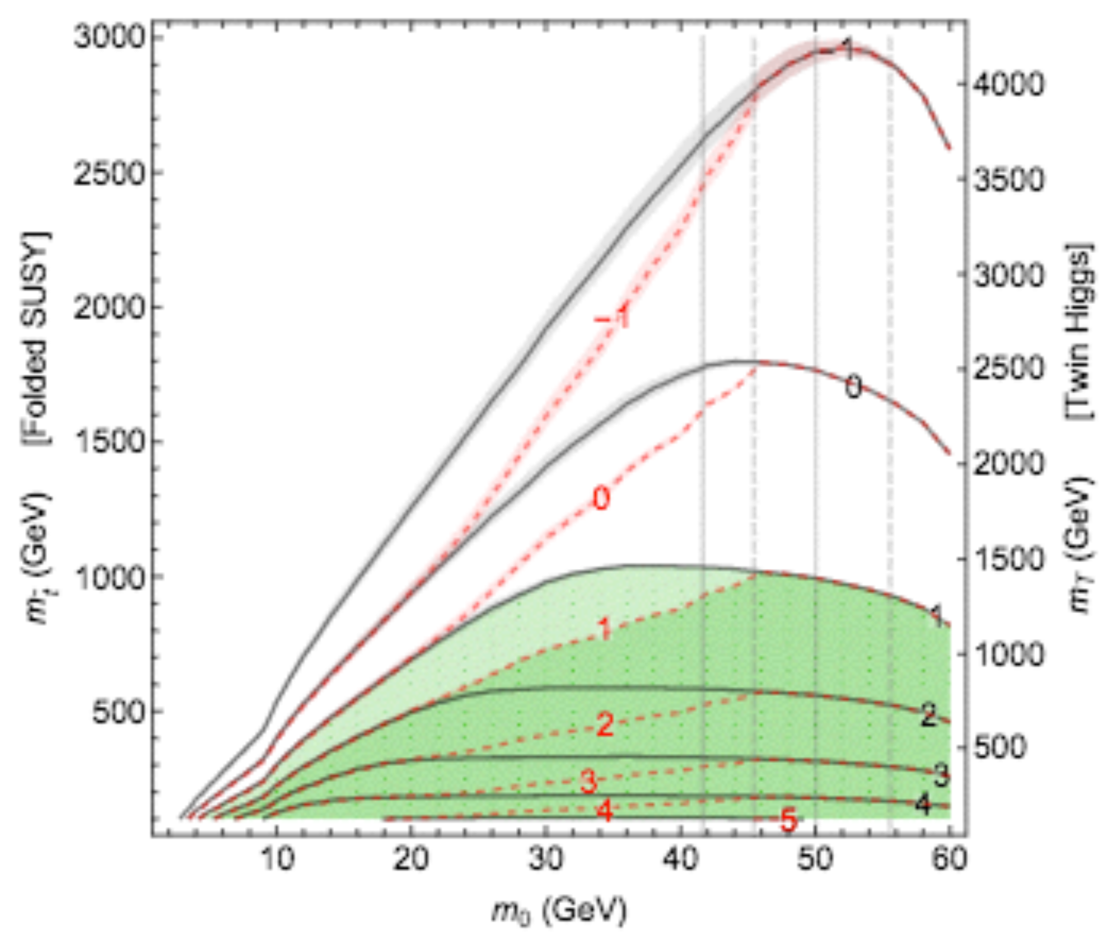
Twin Hadrons





$\sqrt{s} = 8$ TeV

$\mathcal{L} = 20$ fb^{-1}



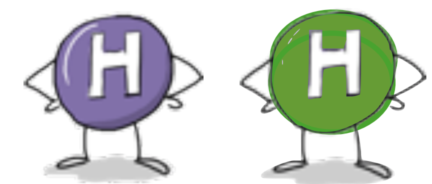
Number of events in tracker

1501.05310: N. Craig, A. Katz, M. Strassler, R. Sundrum

1506.06141: D. Curtin, C. Verhaaren

The vector-like twin

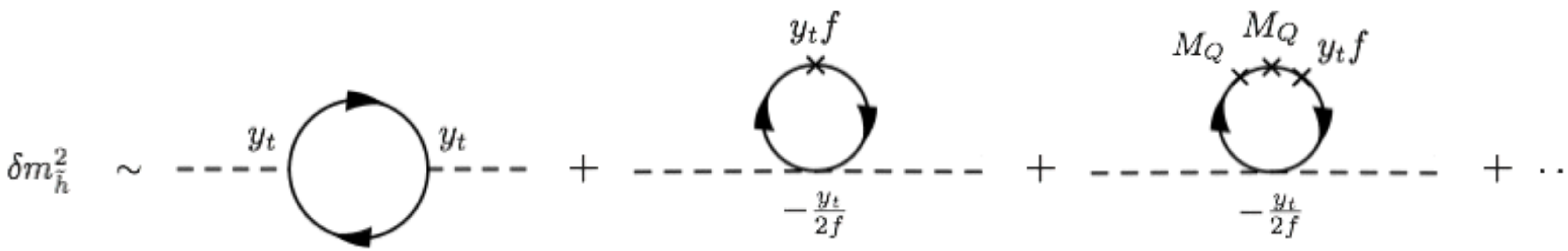
$$\mathcal{L} \supset \underbrace{y_t H q u \quad + \quad y_t H' q' u'}_{\text{Twin Higgs...}} \quad + \quad \underbrace{{\color{red} M_Q q' \bar{q}' \quad + \quad M_U u' \bar{u}'}}_{\text{... but with vector-like Twin fermions}}$$



Twin Higgs… … but with vector-like Twin fermions

No Twin Leptons are needed to cancel Twin gauge anomalies

Vector-like nature of twin quarks is effectively a soft breaking:



these cancel

$$\sim \frac{y_t^2}{16\pi^2} M_Q^2 \log\left[\frac{M_Q^2}{\Lambda^2}\right]$$

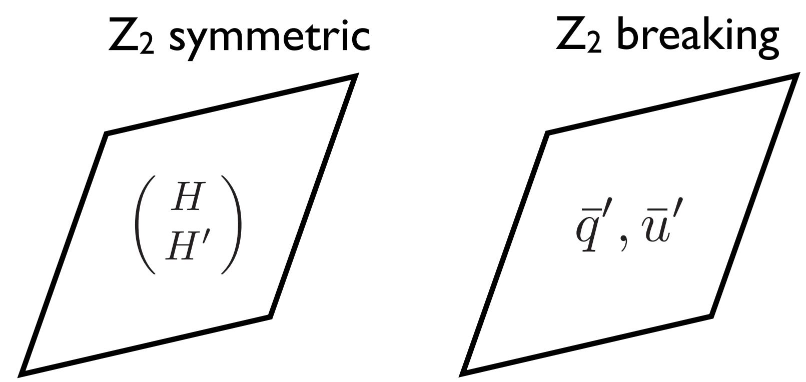
(provided that $M_Q, M_U \lesssim 500$ GeV)

Dangerous operators

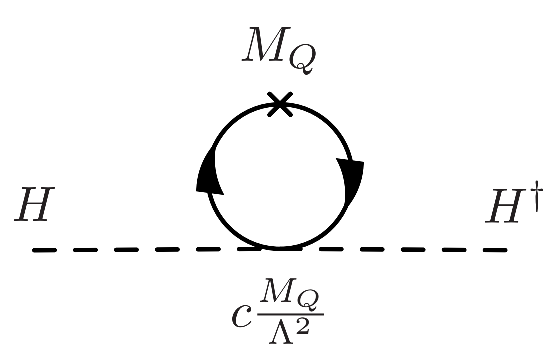
$\tilde{y}_t H'^\dagger \bar{q}' \bar{u}'$

Forbid this one by:

- Holomorphy (SUSY)
- Softly broken PQ-symmetry
- Suppress it $\tilde{y}_t < 0.1$



$c\dfrac{M_Q}{\Lambda^2} H H^\dagger q' \bar{q}'$



$\longrightarrow$ $\delta m_h^2 \sim \dfrac{c}{16\pi^2} M_Q^2$

- Weak coupling: $c \sim 1$ or $c \ll 1$
- Strong coupling: $c \gg 1$

A minimal model

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

$$-\mathcal{L} \supset y_t\, H\, q\, u + y_t\, H'\, q'\, u' + M_Q\, q'\, \bar{q}' + M_U\, u'\, \bar{u}'$$

$$\langle H \rangle = \frac{v}{\sqrt{2}} \qquad \langle H' \rangle = \frac{f}{\sqrt{2}}$$

One generation, two twin tops
No twin D quarks and no twin leptons
No twin hypercharge

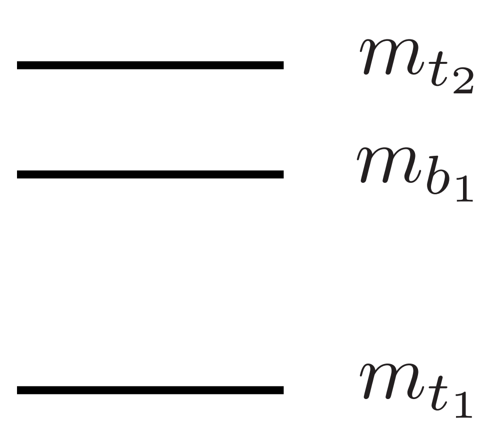
(analogous to fraternal twin)

Two twin tops & one twin bottom

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

$$m_{b_1}^2 \approx M_Q^2$$

$$m_{t_1}^2 \approx 2 \frac{M_Q^2 M_U^2}{y_t^2 f^2}$$



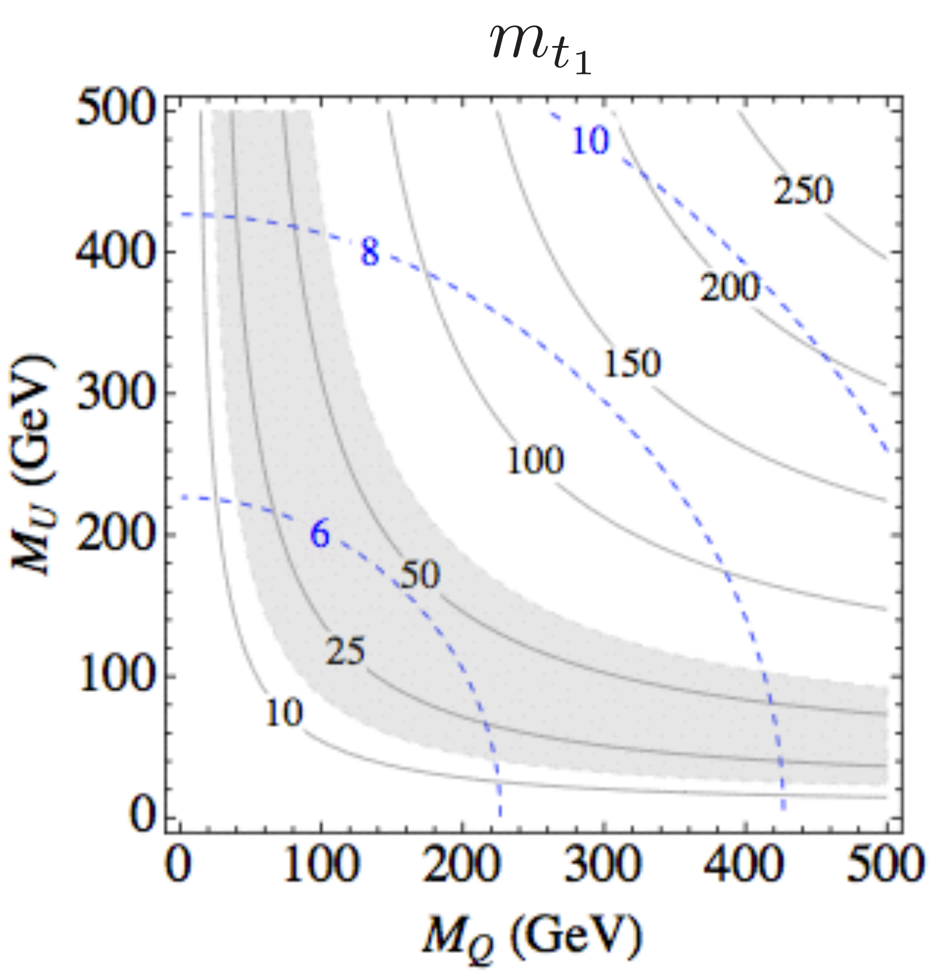
Mini-Seesaw

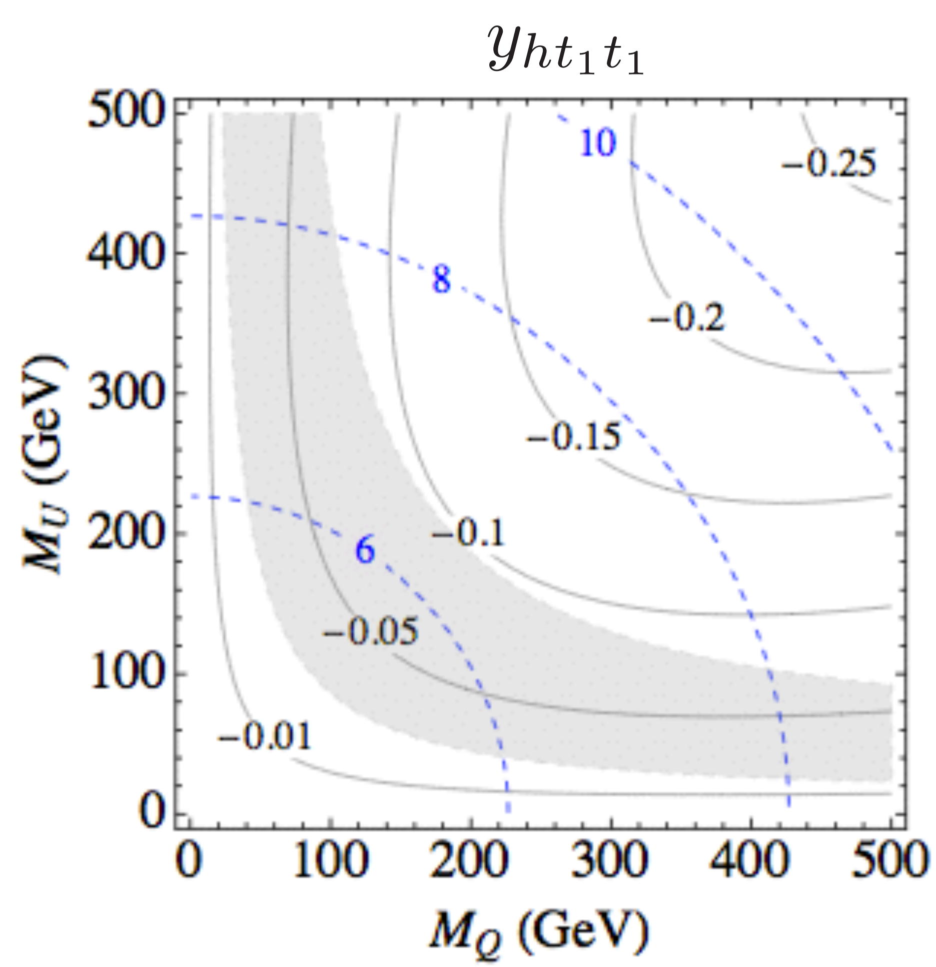
$$M_Q, M_U \ll \frac{y_t}{\sqrt{2}} f$$

The lightest twin top

Vector-like twin: $$-\frac{v}{f}\frac{m_{t_1}}{f} h t'_1 \bar{t}'_1 \left[1 - 2\frac{M_Q^2 + M_U^2}{y_t^2 f^2} + \mathcal{O}\left(\frac{M_Q^4}{y_t^4 f^4}\right)\right]$$

Fraternal twin: $$\frac{v}{f}\frac{m_{b'}}{f} h b' \bar{b}'$$

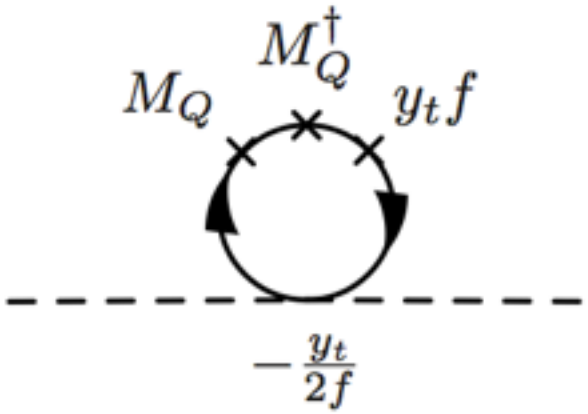




t₁ plays the role of the twin bottom in the fraternal twin Higgs

Fine tuning

$$\delta m_h^2 = -\frac{3}{4\pi^2} y_t^2 m_t^2 \log\left[\frac{m_t^2}{\Lambda^2}\right] + \frac{3}{4\pi^2} y_t^2 \left(m_{t_2}^2 + m_{t_1}^2\right) \log\left[\frac{m_{t_2}^2}{\Lambda^2}\right] + \mathcal{O}\left(\frac{m_{t_1}^4}{m_{t_2}^2}\right)$$



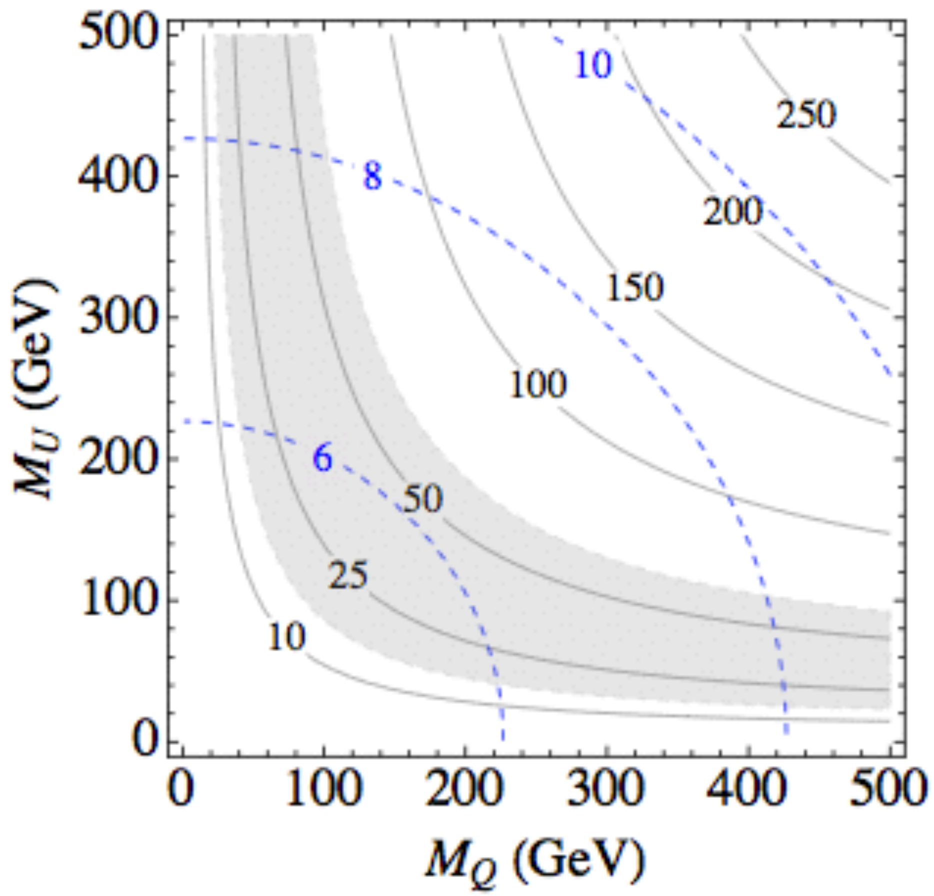
Reduces back to conventional twin Higgs:

$$M_Q, M_U \to 0 \longrightarrow \begin{aligned} m_{t_1} &= 0 \\ m_{t_2} &= \frac{1}{\sqrt{2}} y_t f \end{aligned}$$

$$\Delta \approx \frac{\delta m_h^2}{m_h^2}$$

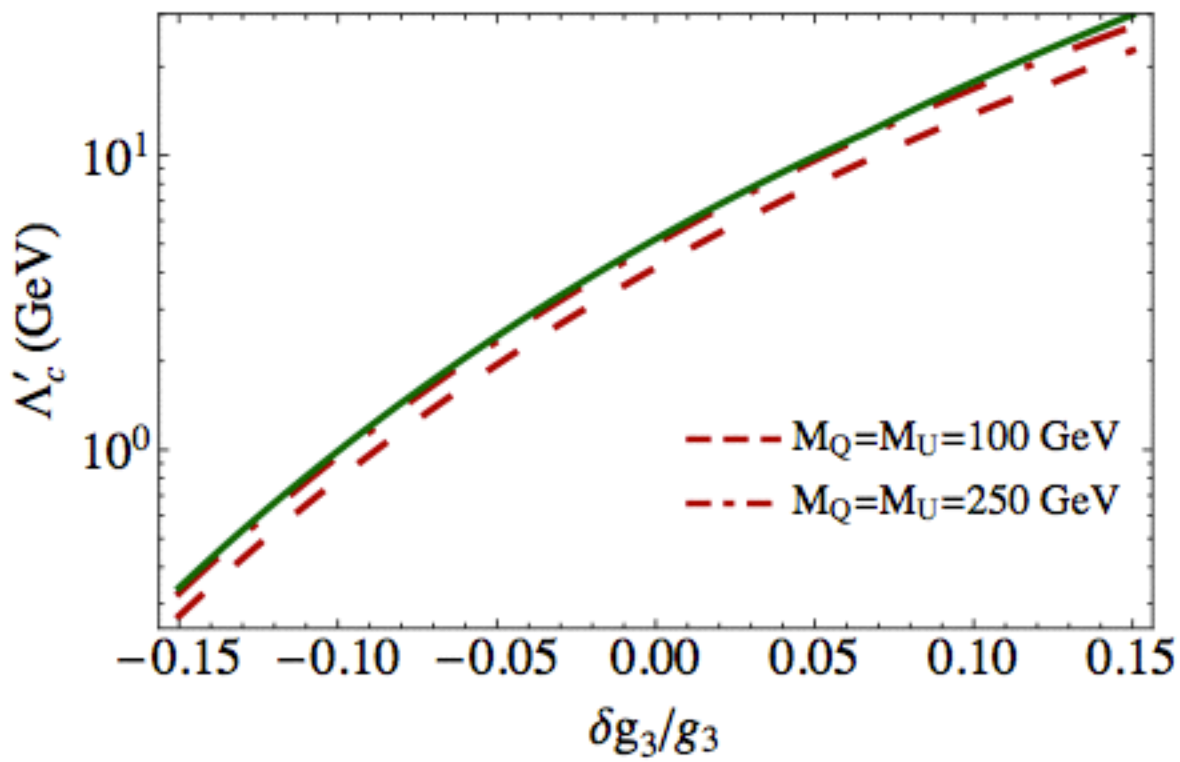
Tuning never worse than ~10%

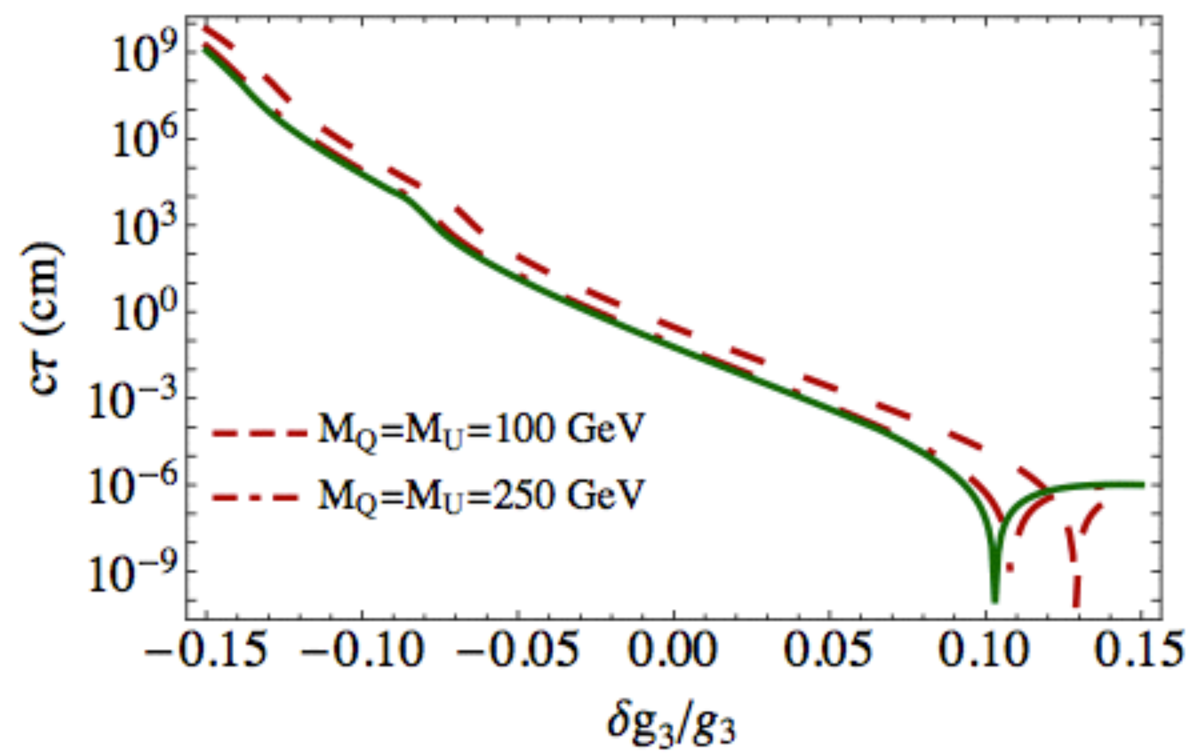
m_{t_1}



Phenomenology

Glueball lifetime:





Other differences:

- No twin leptons, so W' may be stable if $W' \to b'_1 t'_1$ is closed (DM candidate)
- No twin leptons, so toponium bound states more likely to decay visibly
- If $t'_2 \to W' b'_1$ is closed, $t'_2 \to h\, t'_1$ is possible (but production rate probably small)

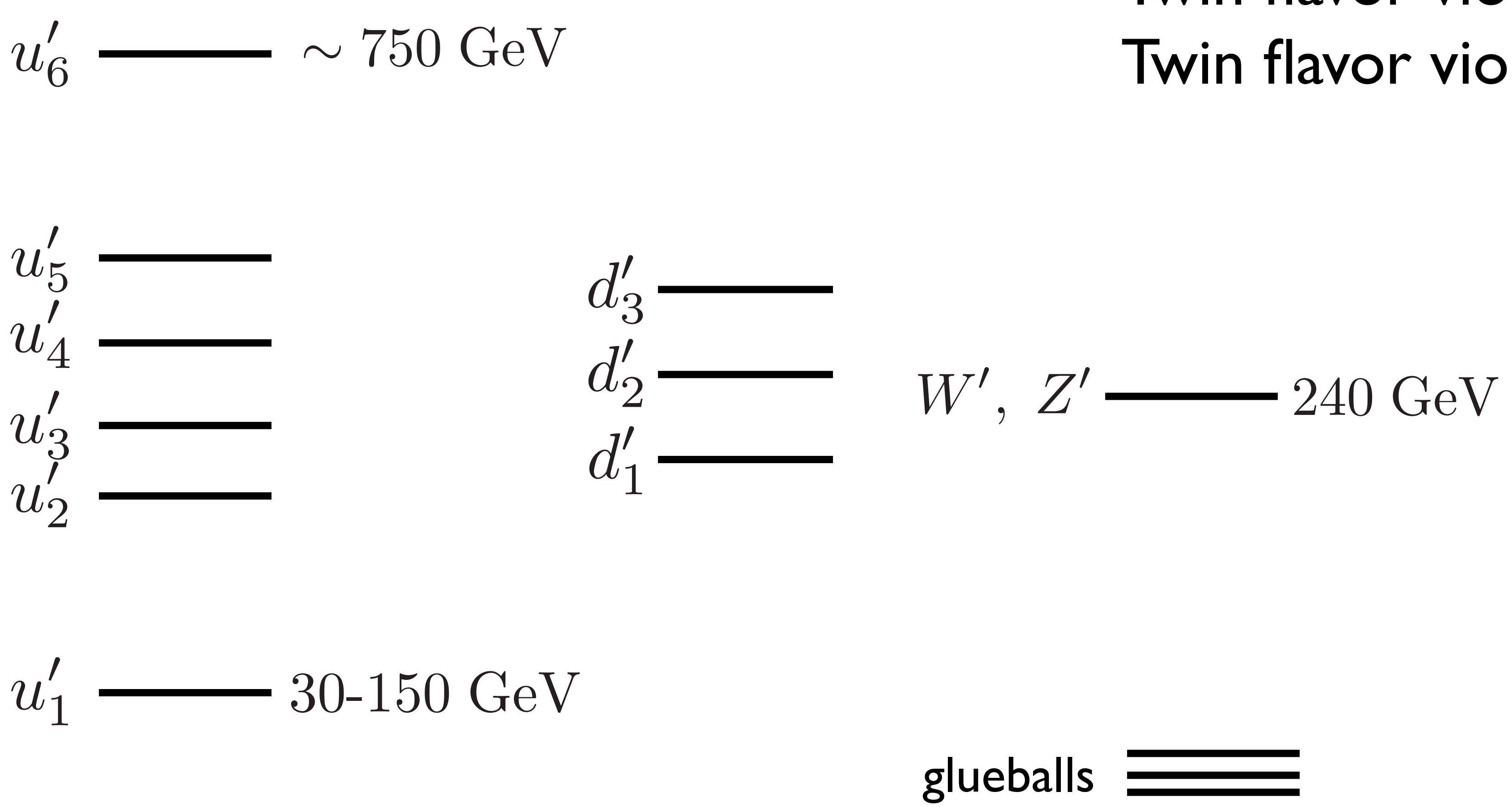
A three generation model

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

$$\mathcal{L} \supset Y_U H' q' u' + M_Q q' \bar{q}' + M_U u' \bar{u}'$$

Fully break flavor symmetries

Twin sector spectrum



Twin flavor violation with W′

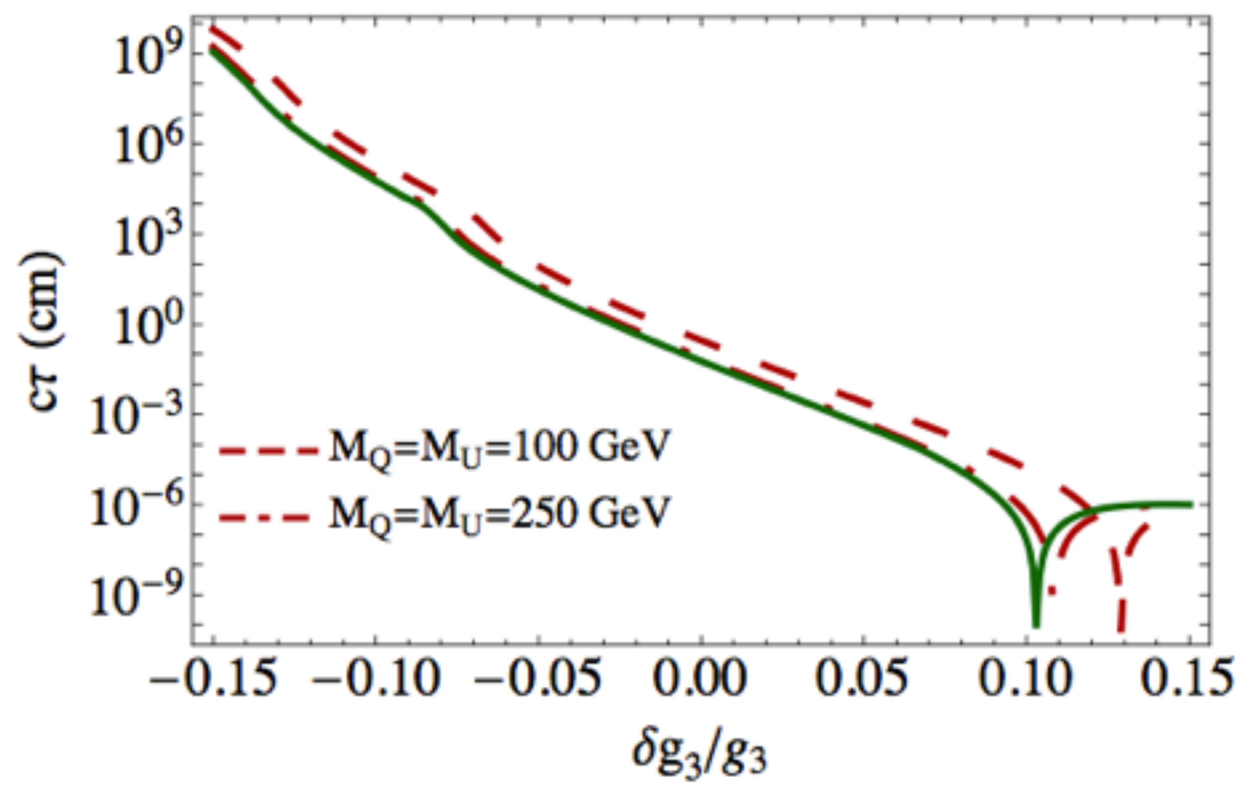
Twin flavor violation with Z′ and h in up-sector

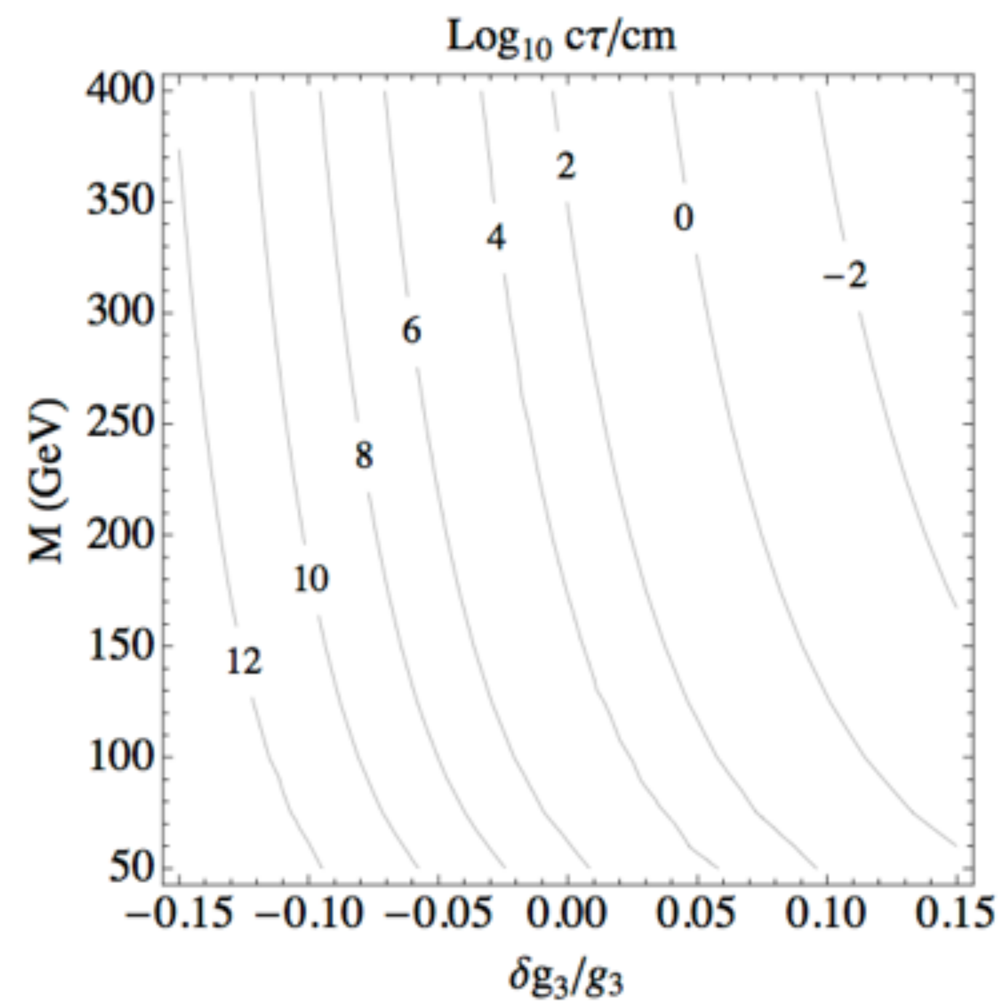
Very complicated hidden sector phenomenology

Glueball lifetime

Due to the large amount of flavors, the confinement scale is usually lower

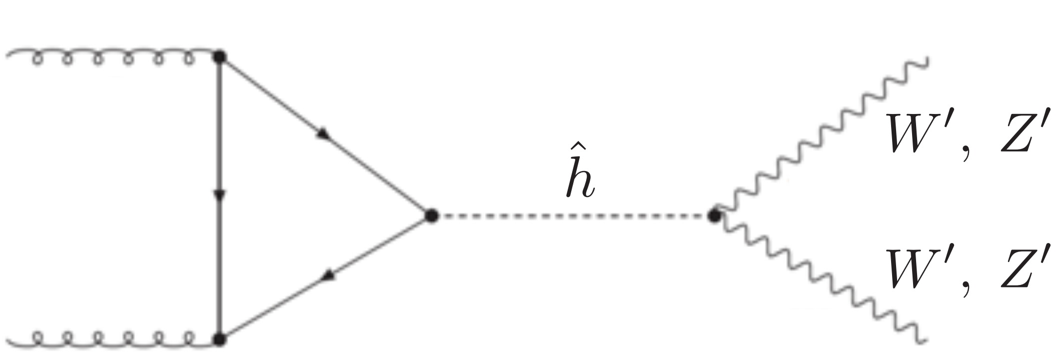
→ glueballs decay more often outside the detector

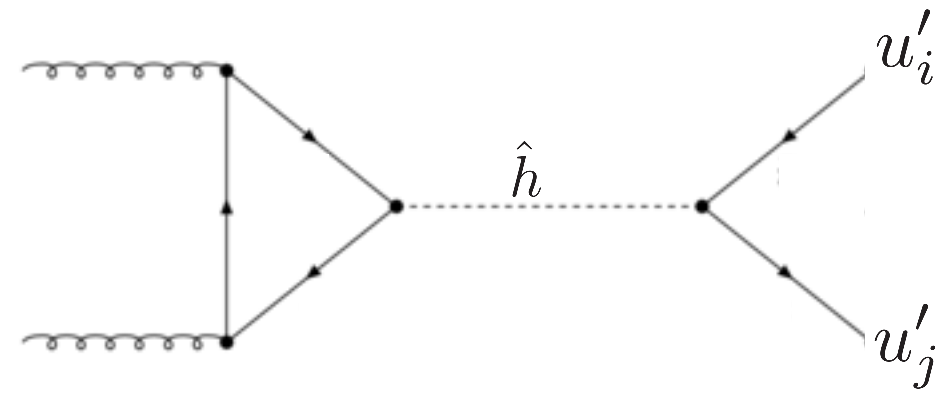




Cascade decays increase glueball multiplicity

Radial mode





Cascade decays:

$W' \to u'_i d'_j$

$Z' \to u'_i u'_j$

$Z' \to d'_i d'_j$

$u'_2 \to W^* d'_1 \to u'_1 d'_1 d'_1$ etc

$u'_2 \to Z^* u'_1 \to u'_1 u'_1 u'_1$ etc   if $m_{u_2} - m_{u_1} > m_h$

$u'_2 \to h u'_1$ Visible

$u'_1 u'_1$, $d'_1 d'_1$ | to glueballs

$u'_1 d'_1$ stable

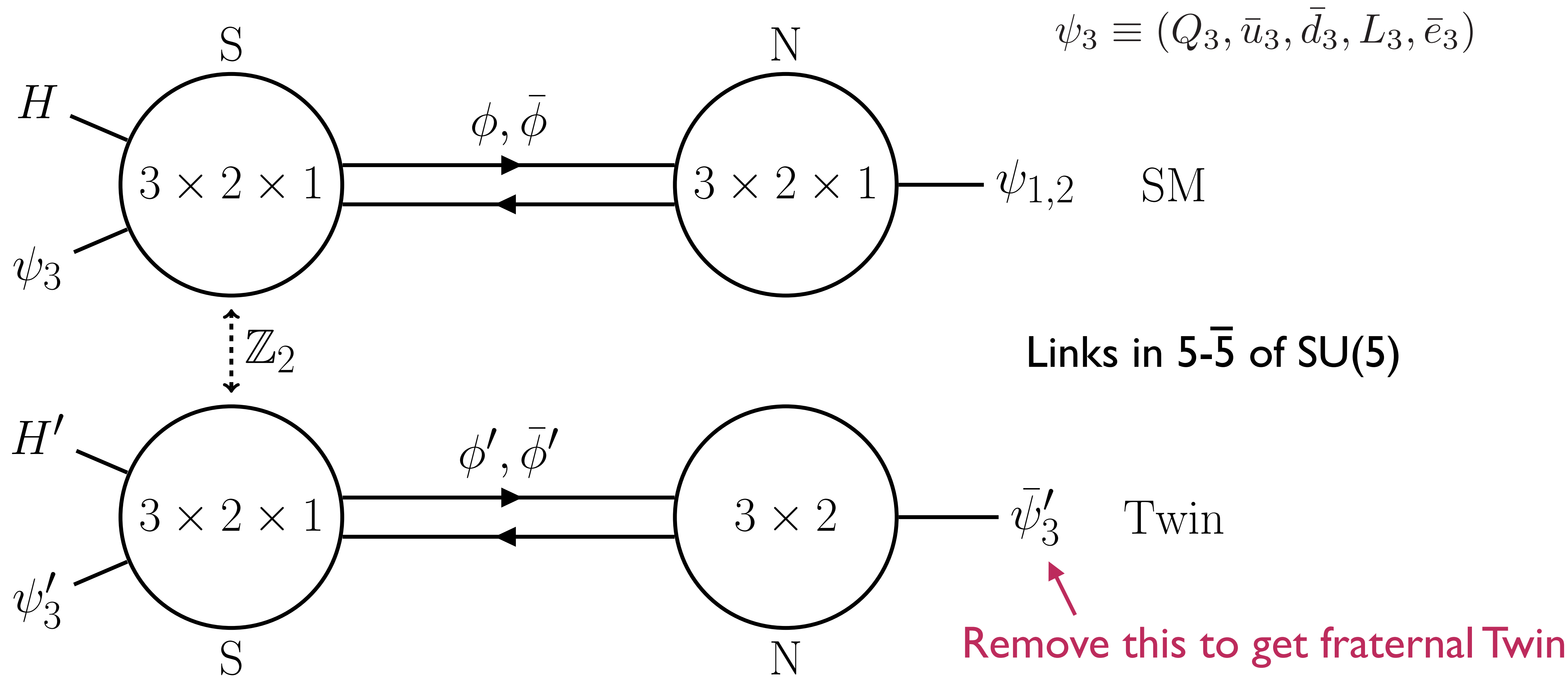
$u'_2 \to W^* d'_1 \to u'_1 d'_1 d'_1$ etc

$u'_2 \to Z^* u'_1 \to u'_1 u'_1 u'_1$ etc   if $m_{u_2} - m_{u_1} < m_h$

$u'_2 \to h^* u'_1$ Visible   if $m_{u_2} < 3 m_{u_1}$

UV completion

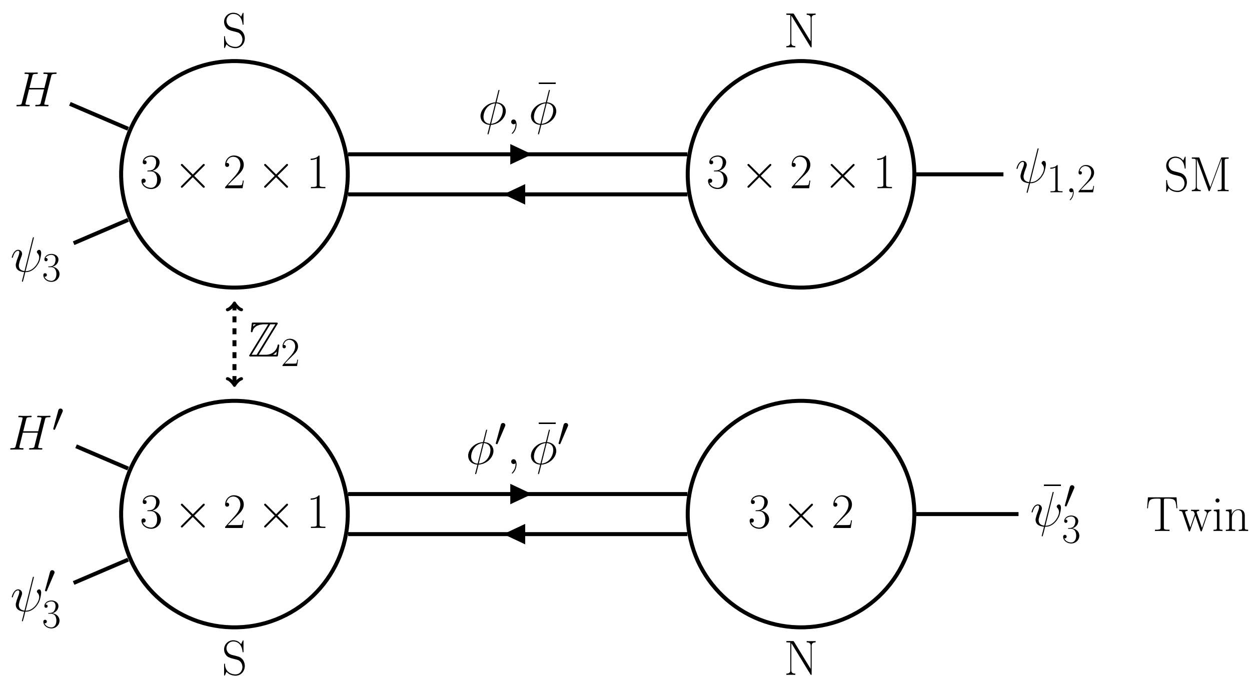
Use deconstruction to get an approximate Z_2 symmetry



Higgsing the links leads to the vector-like twin Higgs: $\langle \phi \rangle \sim \langle \phi' \rangle \sim 5\text{TeV}$

Stabilize this new scale with supersymmetry

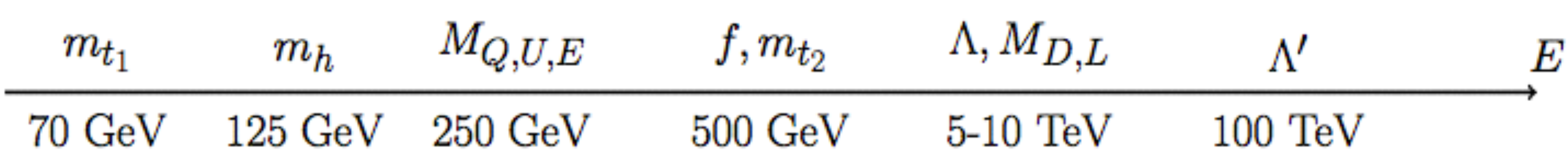
Twin Mass terms



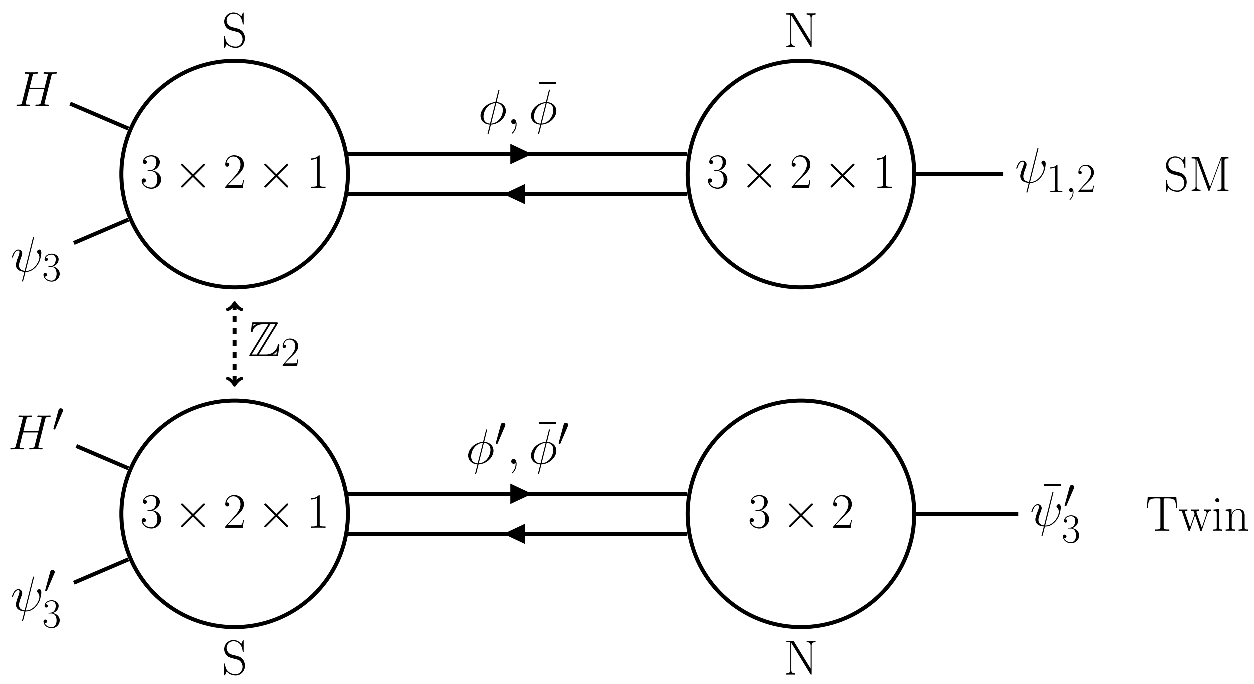
Fields in 5 of SU(5) are lifted, fields in the 10 can remain light

$$\underbrace{d'\bar{\phi}'_T\bar{d}' + \ell'\bar{\phi}'_D\bar{\ell}'}_{5} + \underbrace{\frac{1}{\Lambda'}q'\phi'_T\phi'_D\bar{q}' + \frac{1}{\Lambda'}u'\phi'_T\phi'_T\bar{u}' + \frac{1}{\Lambda'}e'\phi'_D\phi'_D\bar{e}'}_{10}$$

example: $M_{D,L} \sim \Lambda \sim 5\ \mathrm{TeV}$ $\quad M_{Q,U,E} \sim \Lambda^2/\Lambda' \sim 250\ \mathrm{GeV}$



Landau poles



$$\frac{1}{\alpha_{IR}} = \frac{1}{\alpha_S} + \frac{1}{\alpha_N} \quad \text{at} \quad \Lambda \sim 5 \text{ TeV}$$

Naturalness: $\alpha_{2,N} \gtrsim 0.16$, $\alpha_{3,N} \gtrsim 0.38$ if $\alpha_{2,N} = 2\alpha'_{2,N}$, $\alpha_{3,N} = 2\alpha'_{3,N}$

$\alpha_{2,N}$ landau pole around 10^6 TeV

Conclusions

- A vector-like twin sector is effectively a soft Z_2 breaking on the level of the Higgs potential

- (Collider) phenomenology is similar but not identical to fraternal twin Higgs

- Attempt at UV completion through deconstruction

Outlook

- Dark Matter phenomenology: Twin WIMP, asymmetric, SIMP,…
- Add hypercharge to twin quarks?
- Different (better?) UV completions? (Composite models?)

soft | hard | very hard | violent

Relevant $\not{Z}_2$ operator
Spontaneous breaking

talk by T. Gregoire

Marginal or irrelevant $\not{Z}_2$ operator

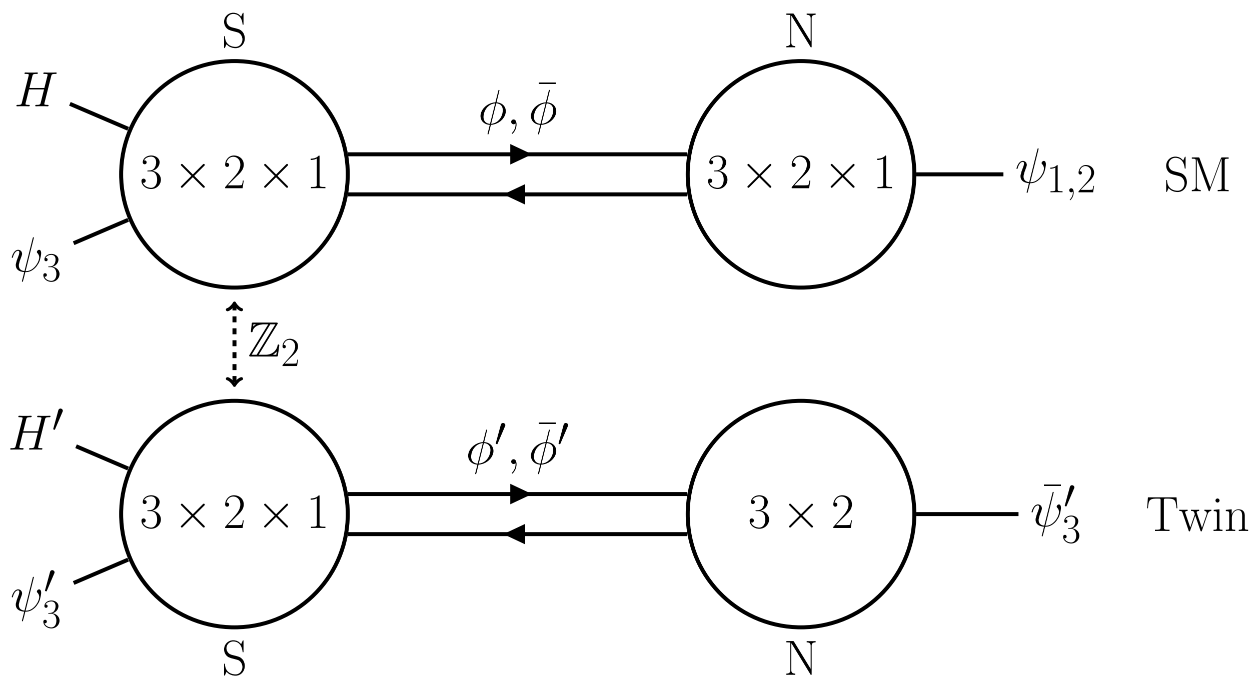
Break the spectrum

Break the couplings and the spectrum

What are the realistic UV completions of hard Z_2 breaking?

Back-up slides

SM Yukawa's



$$\frac{1}{\Lambda'} H_u \phi_D q_f u_g + \frac{1}{\Lambda'^2} H_u \bar{\phi}_T \bar{\phi}_D q_f u_3 \ + \ \text{etc}$$

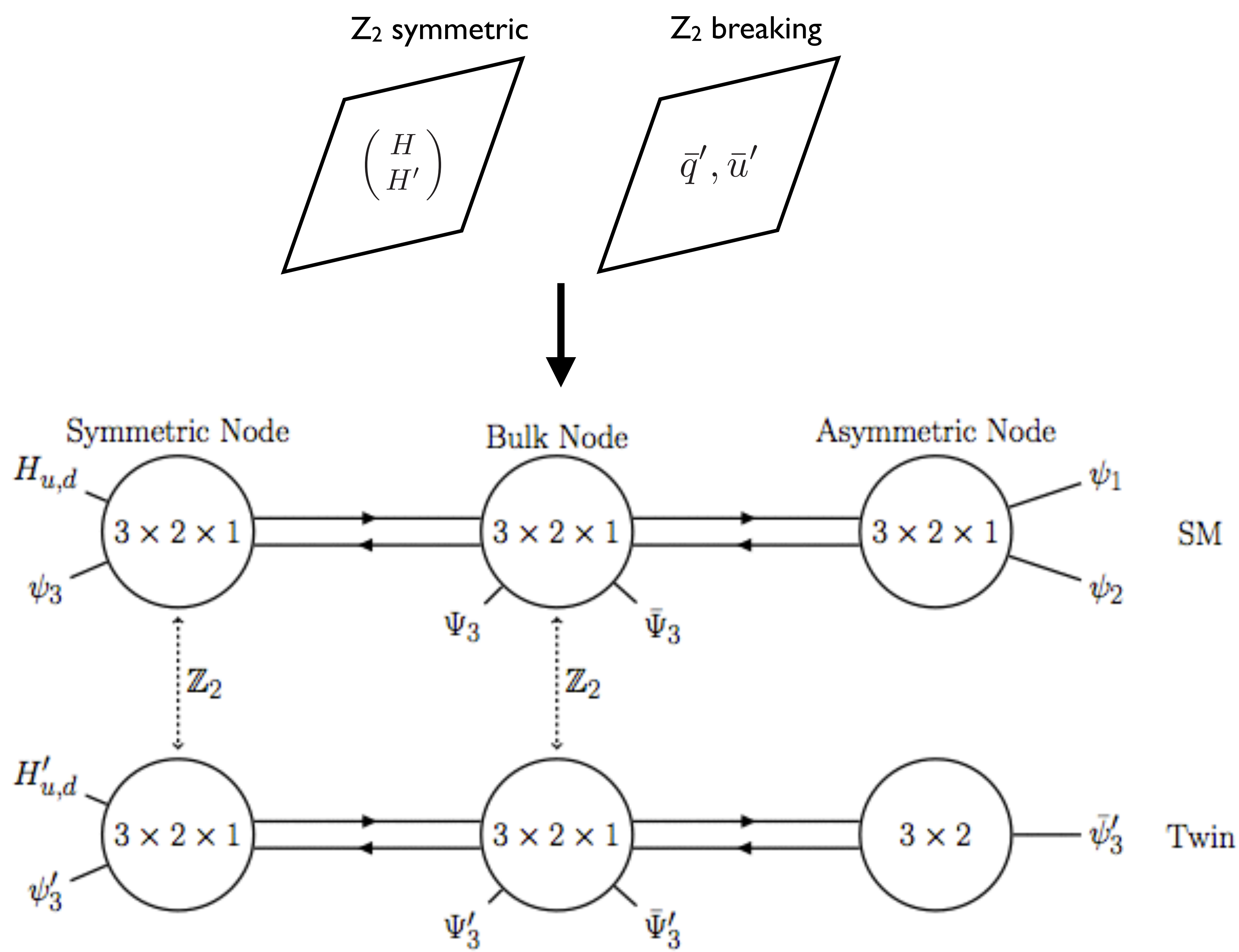
Yukawa texture

$$Y_U \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & \epsilon^2 \\ \epsilon^2 & \epsilon^2 & 1 \end{pmatrix} \qquad Y_D \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & \epsilon^2 \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

Additional suppression needed

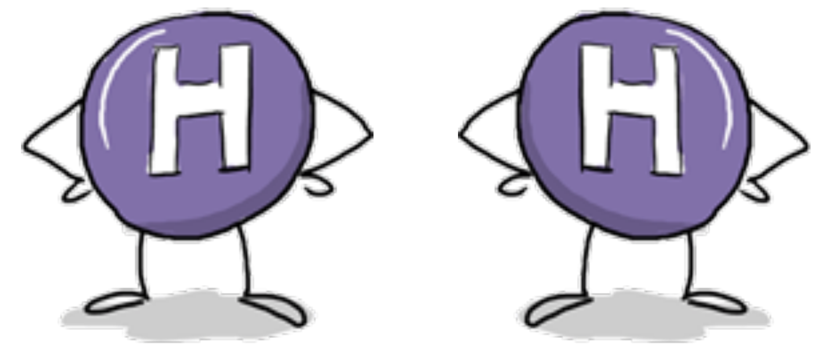
see also: N. Craig, S. Dimopoulos, T. Gherghetta: 1203.0572

Connection with Orbifolds

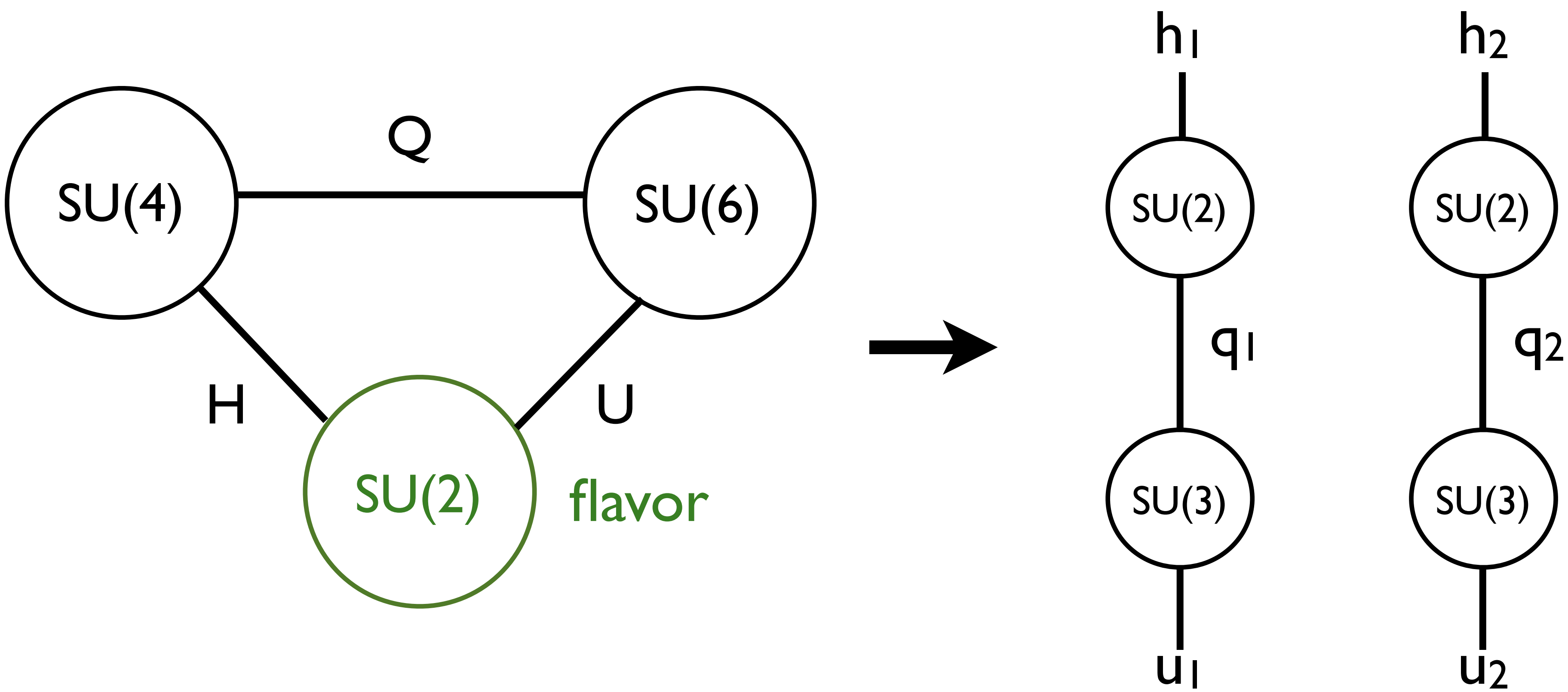


Possible alternative: SU(4) x SU(6) x U(1) x U(1) / Z_2 x Z_3 orbifold

Twin Higgs as an orbifold



$$V(H) = -m^2 \text{Tr } H^\dagger H + \lambda \left[\text{Tr } H^\dagger H \right]^2$$



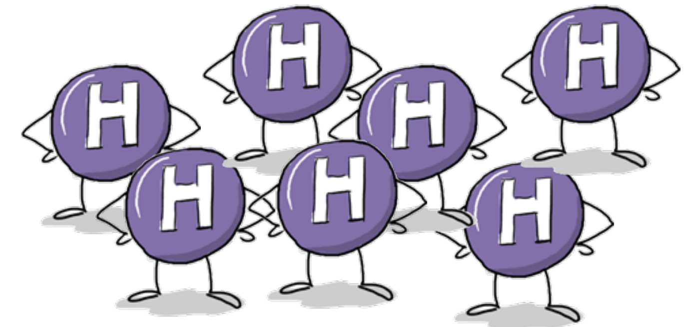
$$SU(6) \times SU(4) \times SU(2)/\mathbb{Z}_2 \quad \longrightarrow \quad [SU(3) \times SU(2)]^2 \times U(1) \times U(1) \times \mathbb{Z}_2$$

Completely analogous to orbifold GUT's: $SU(5)/\mathbb{Z}_2 \to SU(3) \times SU(2) \times U(1)$

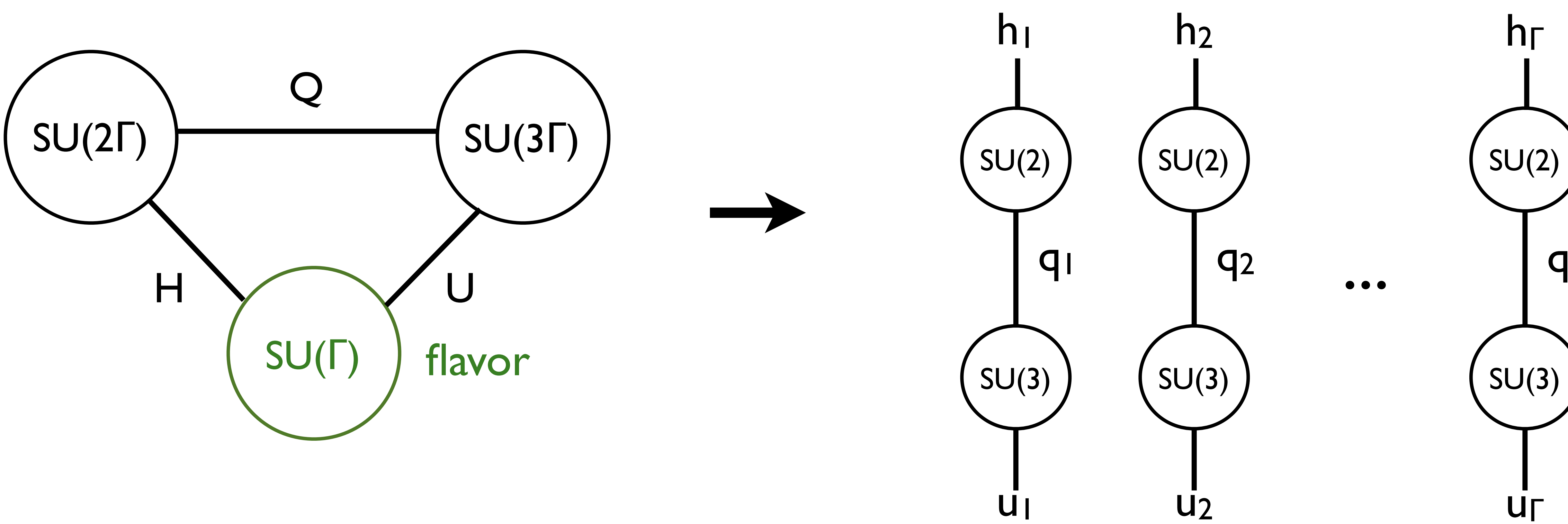
1411.7393: N. Craig, SK, P. Longhi
1410.6808: N. Craig, SK, P. Longhi

Example 1: Z_Γ orbifold

$$SU(2\Gamma)/\mathbb{Z}_\Gamma \quad \to \quad SU(2)^\Gamma \times U(1)^{\Gamma-1}$$
$$SU(3\Gamma)/\mathbb{Z}_\Gamma \quad \to \quad SU(3)^\Gamma \times U(1)^{\Gamma-1}$$

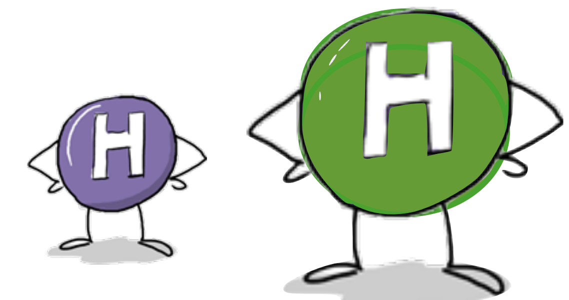


'Twin' Higgs mechanism goes through as before

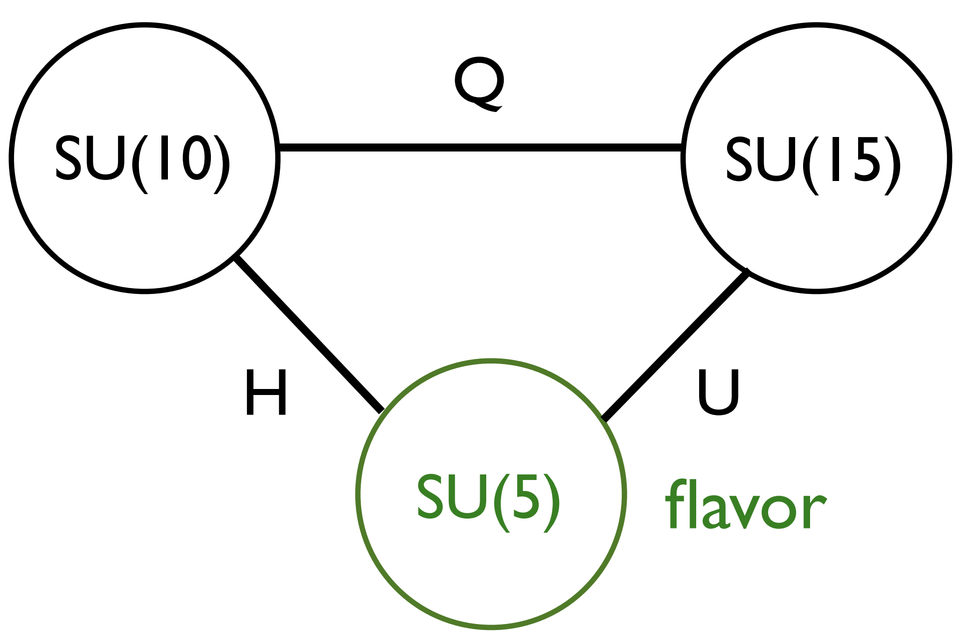


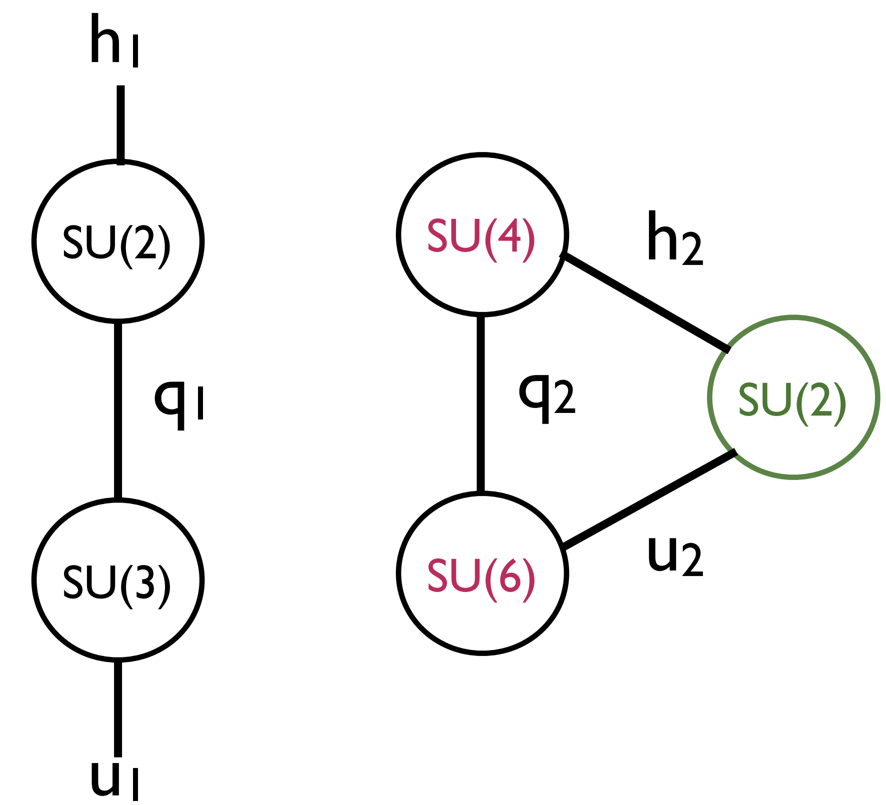
Example 2: S_3 orbifold

$$SU(10)/S_3 \quad \to SU(2)\times SU(4)\times U(1)$$
$$SU(15)/S_3 \quad \to SU(3)\times SU(6)\times U(1)$$



'Twin' Higgs mechanism goes through as before, but non-trivially



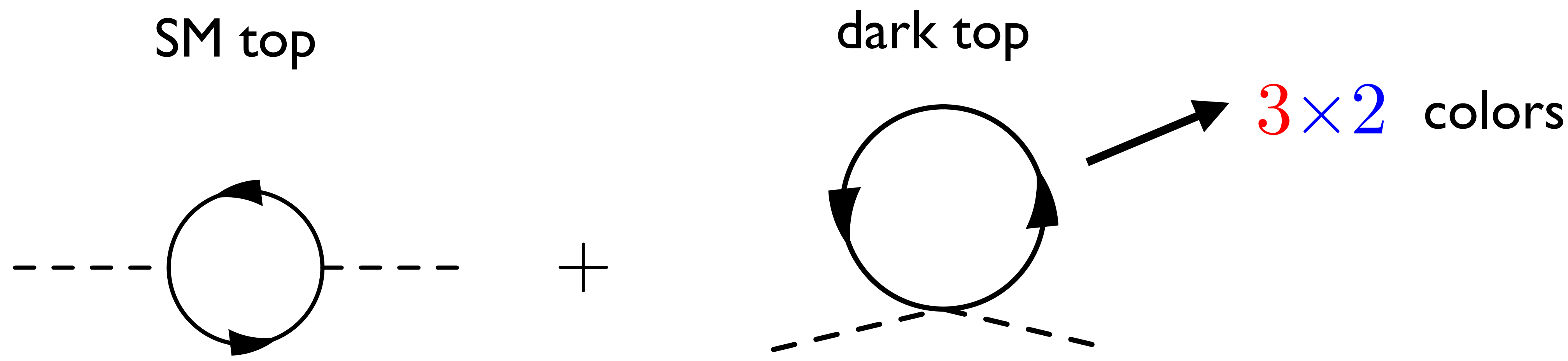


1411.7393: N. Craig, SK, P. Longhi
1410.6808: N. Craig, SK, P. Longhi

with $g^{(1)} = g^{(2)}/\sqrt{2}$

Canceling the divergence

Yukawa and gauge couplings get rescaled



$$\delta m_h^2 = -y_t^2 \frac{3}{8\pi^2}\Lambda^2 + \left(\frac{y_t}{\sqrt{2}}\right)^2 \frac{3\times 2}{8\pi^2}\Lambda^2$$
$$= 0$$

The cancellation goes through, even if the number of dark colors > 3 !

(one can classify all the options, but that's another talk…)

Vector-like twin pheno (one generation)

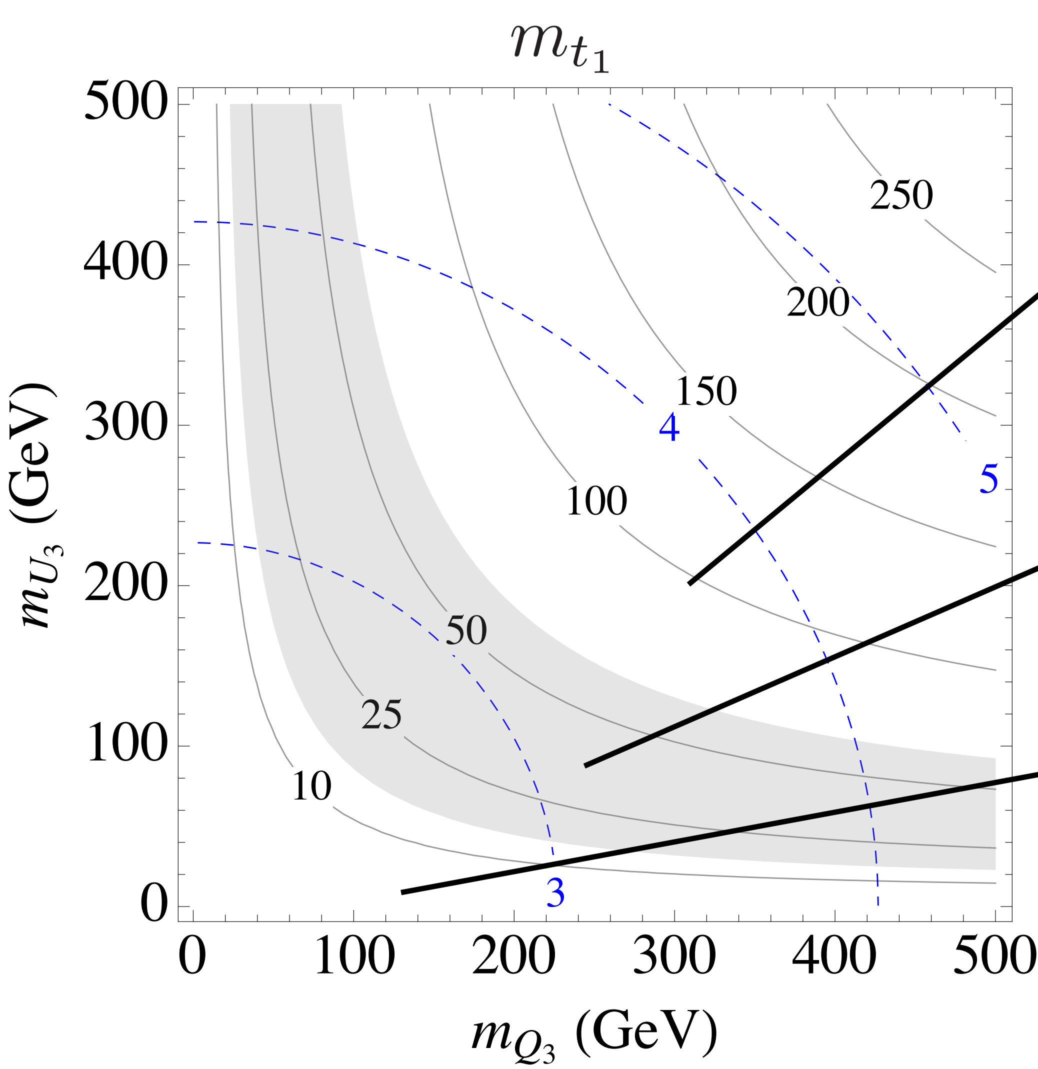
	$SU(3)$	$SU(2)$
q'	$\square$	$\overline{\square}$
$\bar{q}'$	$\overline{\square}$	$\square$
u'	$\overline{\square}$	1
$\bar{u}'$	$\square$	1

(no L′, d′ and e′)

$$\mathcal{L} \supset \begin{pmatrix} \bar{q}'_u \\ u' \end{pmatrix}^T \begin{pmatrix} M_{Q_3} & 0 \\ \frac{y_t f}{\sqrt{2}} & M_{U_3} \end{pmatrix} \begin{pmatrix} q'_u \\ \bar{u}' \end{pmatrix}$$

Mini-Seesaw

Spectrum: $m_{t_1} < m_{b_1} < m_{t_2}$



h → glueballs with branching ratio ~ 10^{-3}
displaced glueball decays possible

h → t_l t_l: excluded

h → t_l t_l: hadronize in glueballs and/or toponinium
displaced glueball/toponinium decays possible

N. Craig, SK, P. Longhi, M. Strassler: in progress

Vector-like twin pheno (3 generations)

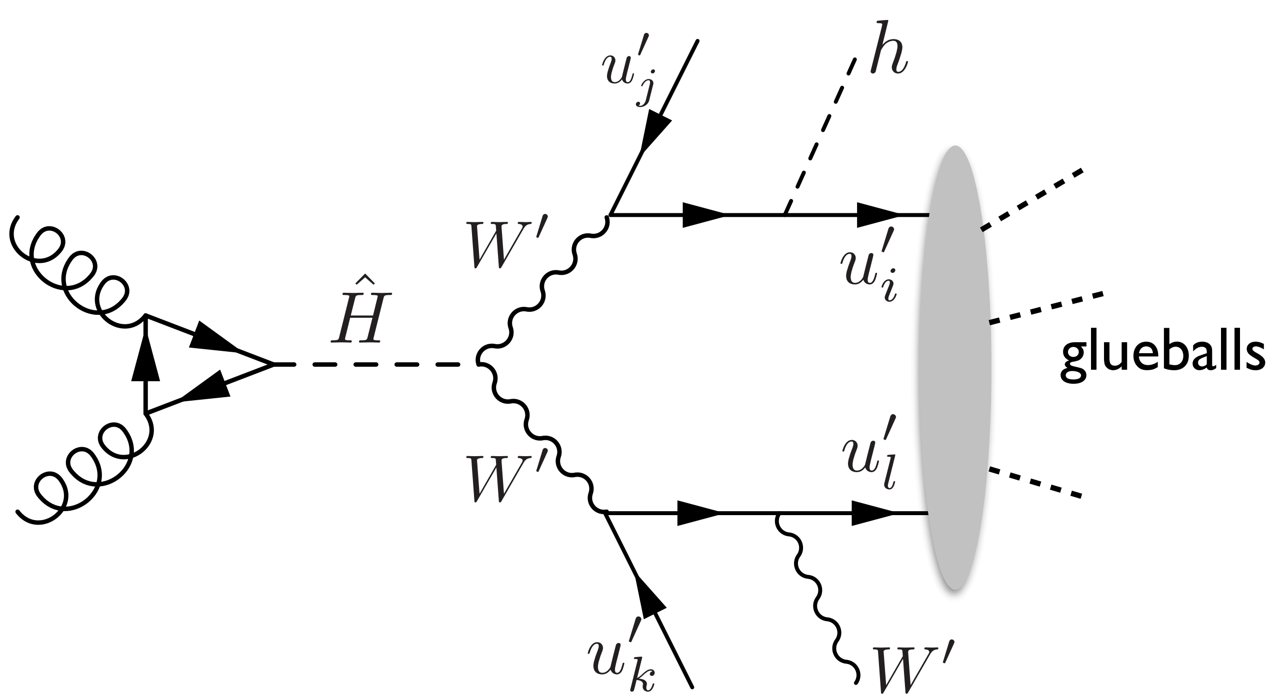
	$SU(3)$	$SU(2)$	$SU(3)_Q$	$\overline{SU(3)_Q}$	$SU(3)_U$	$\overline{SU(3)_U}$
q'	$\square$	$\overline{\square}$	$\square$	1	1	1
$\bar{q}'$	$\overline{\square}$	$\square$	1	$\square$	1	1
u'	$\overline{\square}$	1	1	1	$\square$	1
$\bar{u}'$	$\square$	1	1	1	1	$\square$

$$\mathcal{L} \supset Y_U H' q' u' + M_Q q' \bar{q}' + M_U u' \bar{u}'$$

Fully break flavor symmetries

Due to the large amount of flavors, the confinement scale is usually lower

→ glueballs decay more often outside the detector



… but twin sector generically has large flavor changing currents:

- bb, τ τ pairs + MET
- possibly with displaced vertices

rare, but spectacular cascade decays possible!

N. Craig, SK, P. Longhi, M. Strassler: in progress

Orbifolds

Orbifolds in field theory

Map between two field theories: “Mother” → “Daughter”
(Mother does not necessarily flow to the daughter)

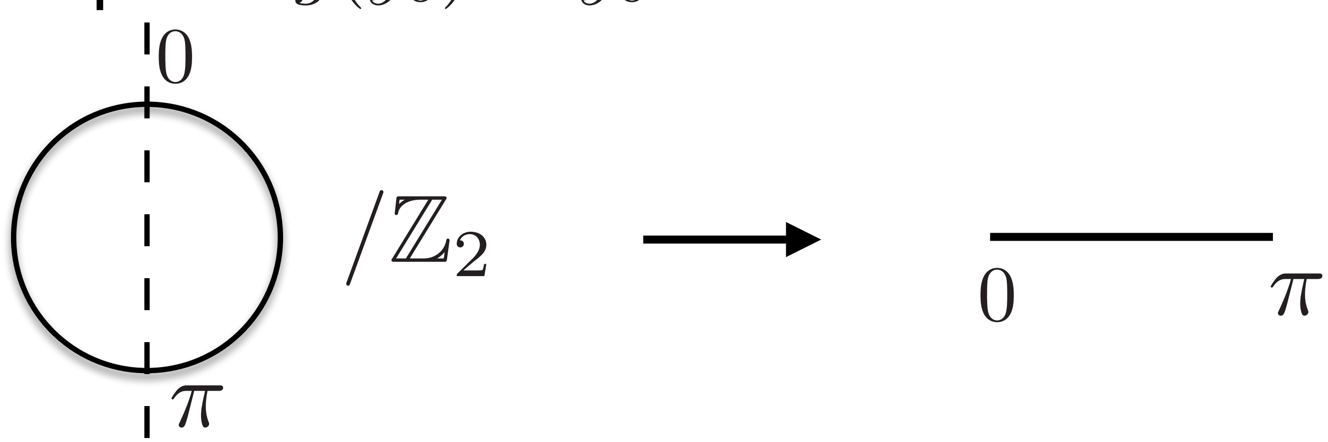
Geometric interpretation

Quotient space of manifold modded out by a discrete group $\mathcal{G}$

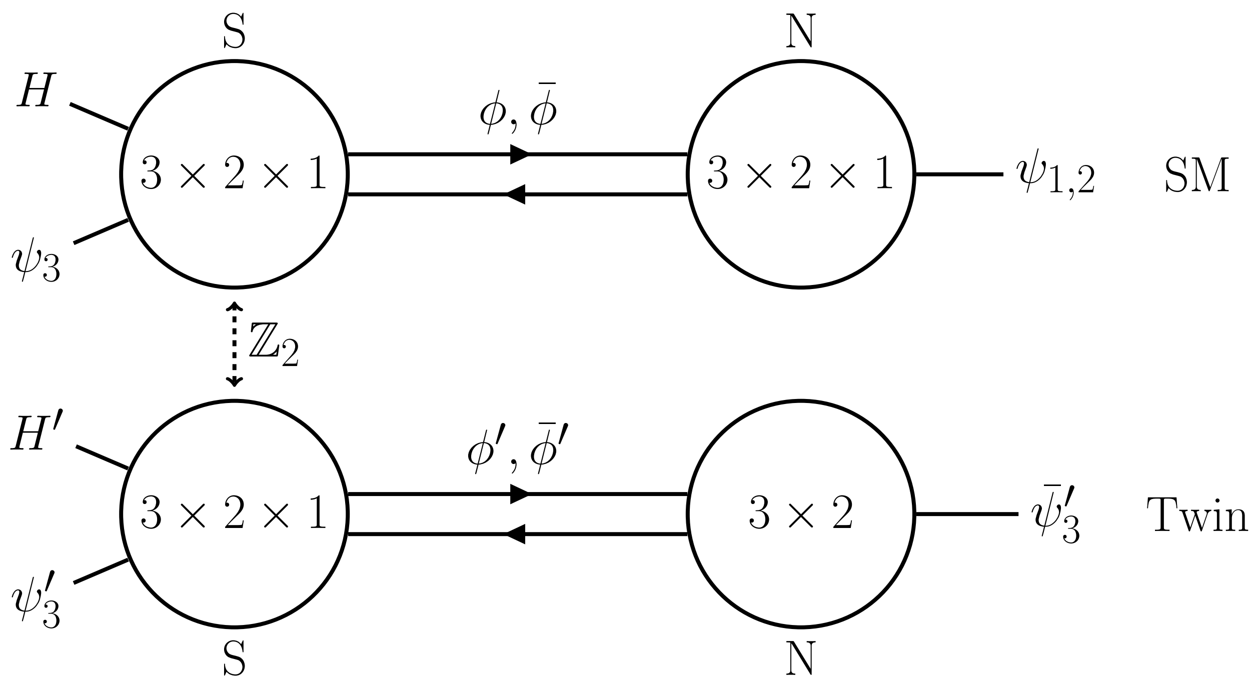
$$\mathcal{G}: \quad \phi^i[y] \quad \rightarrow \quad R(g)_{ij}\, \phi^j[g(y)]$$

Need a space time fixed point: $g(y_0) = y_0$

Example: $S^1/\mathbb{Z}_2$



Landau poles



$$\frac{1}{\alpha_{IR}} = \frac{1}{\alpha_S} + \frac{1}{\alpha_N} \quad \text{at} \quad \Lambda \sim 5 \text{ TeV}$$

$$\frac{\alpha_3 - \alpha'_3}{\bar{\alpha}_3} = \frac{\bar{\alpha}_3}{\bar{\alpha}_{3,N}} \frac{(\alpha'_{3,N} - \alpha_{3,N})}{\bar{\alpha}_{3,N}}$$

$$\bar{\alpha}_3 = \sqrt{\alpha_3 \alpha'_3} \qquad \bar{\alpha}_{3,N} = \sqrt{\alpha_{3,N} \alpha'_{3,N}}$$

Naturalness: $\alpha_{2,N} \gtrsim 0.16$, $\alpha_{3,N} \gtrsim 0.38$ if $\alpha_{2,N} = 2\alpha'_{2,N}$, $\alpha_{3,N} = 2\alpha'_{3,N}$

$\alpha_{2,N}$ landau pole around 10^6 TeV