The Hierarchy Problem on Neutral

Natural Theories with Colorless Top Partners

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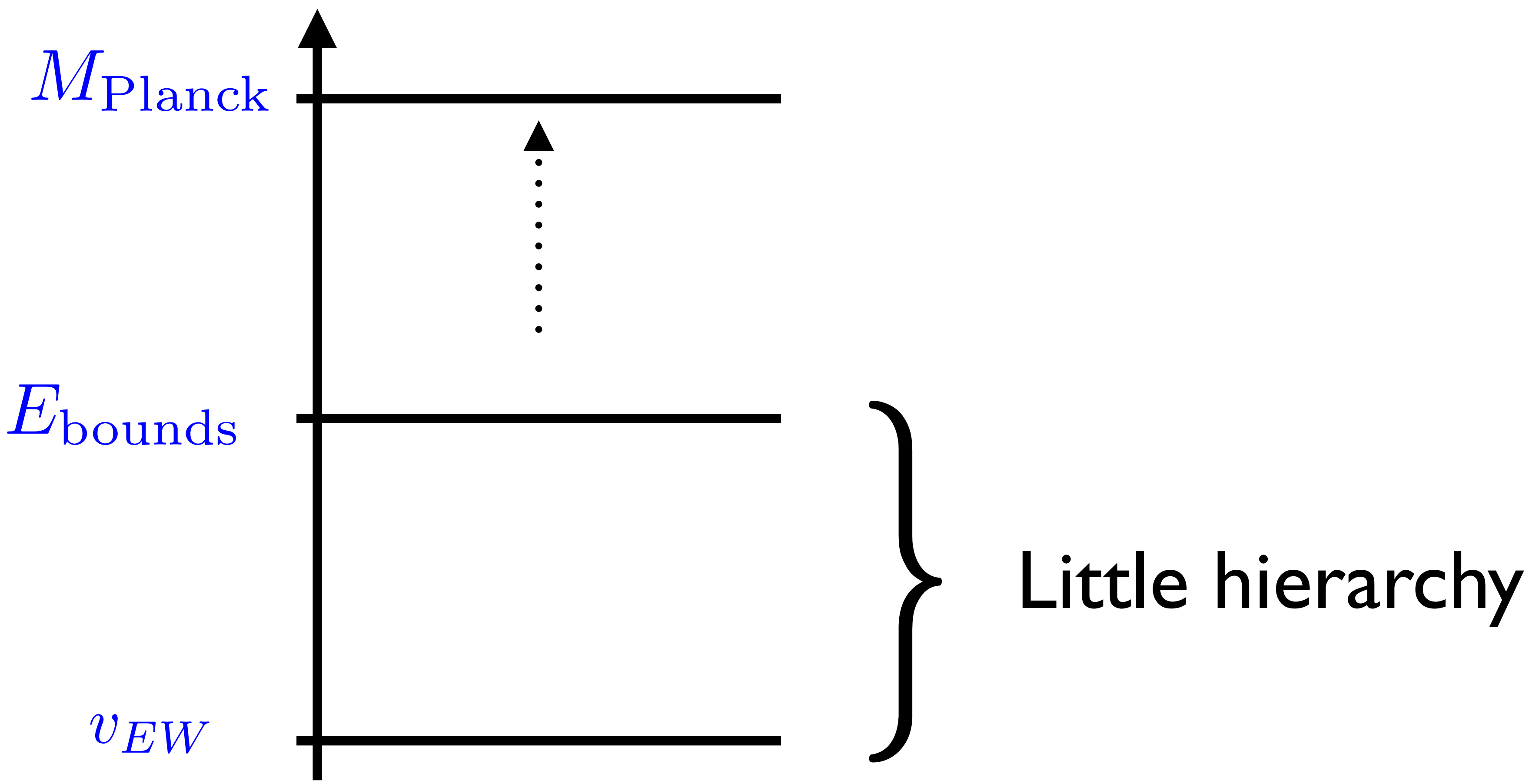
Is the discovery of the Higgs the End of Naturalness ?

Naturalness and the LHC

Is the Electroweak scale natural ?

- The LHC found the Higgs
- Plus … nothing else.



Naturalness and the LHC

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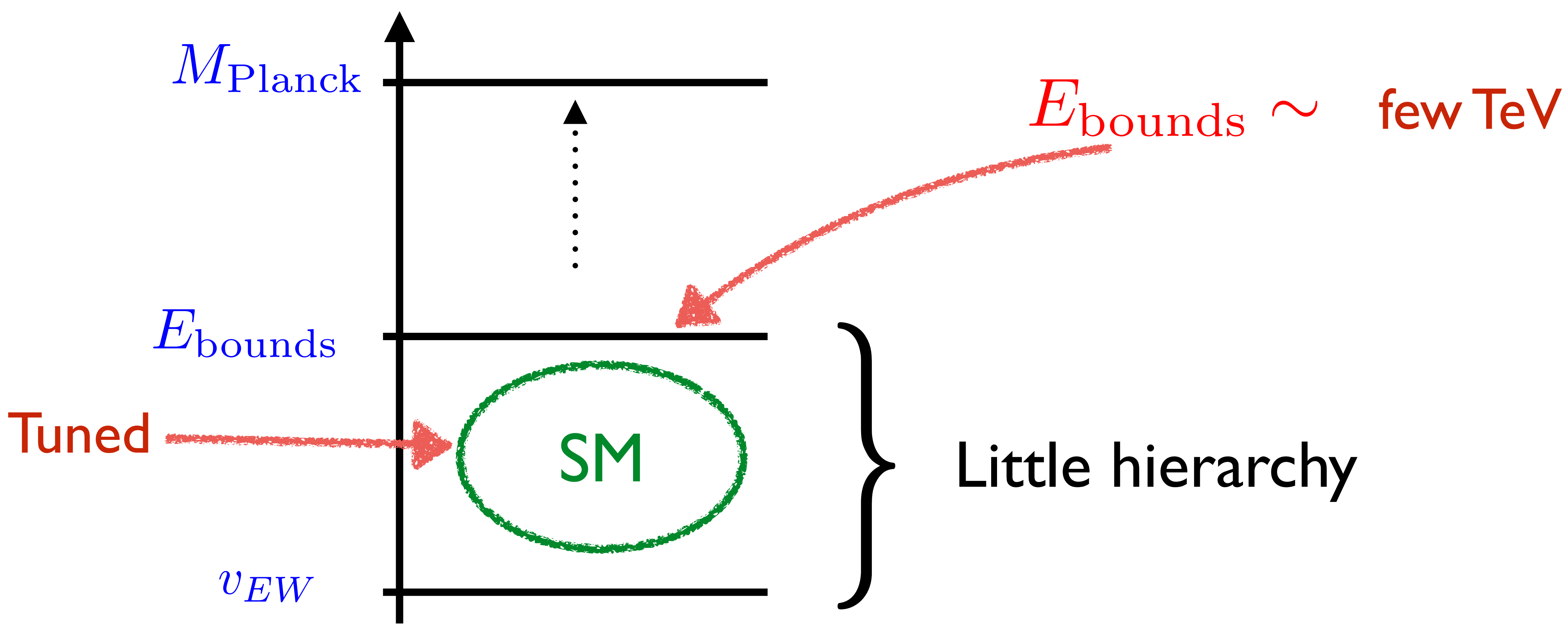
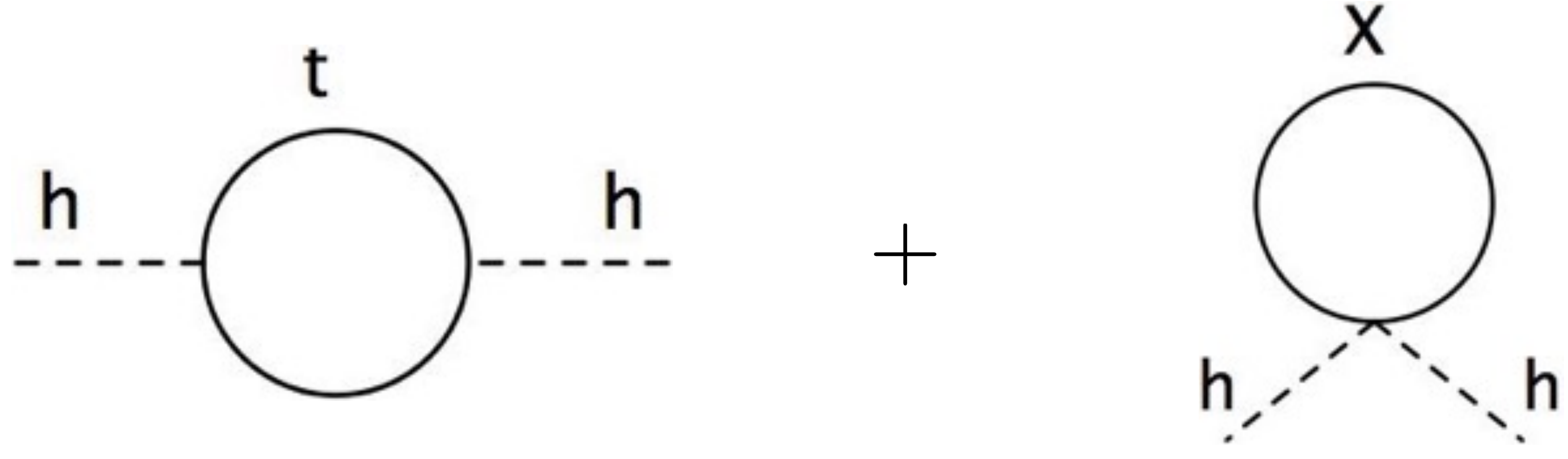


Naturalness and the LHC

UV sensitivity of m_h^2 dominated by top quark



$\Rightarrow \left\{ \right.$
- Top partners X carry color
- Easily produced at the LHC

Colorless Top Partners

Last refuge of naturalness ?

Top partners need not carry color

If symmetry protecting m_h^2 does not commute with $SU(3)_c$

Exchanges $SU(3)_c \to SU(3)'$

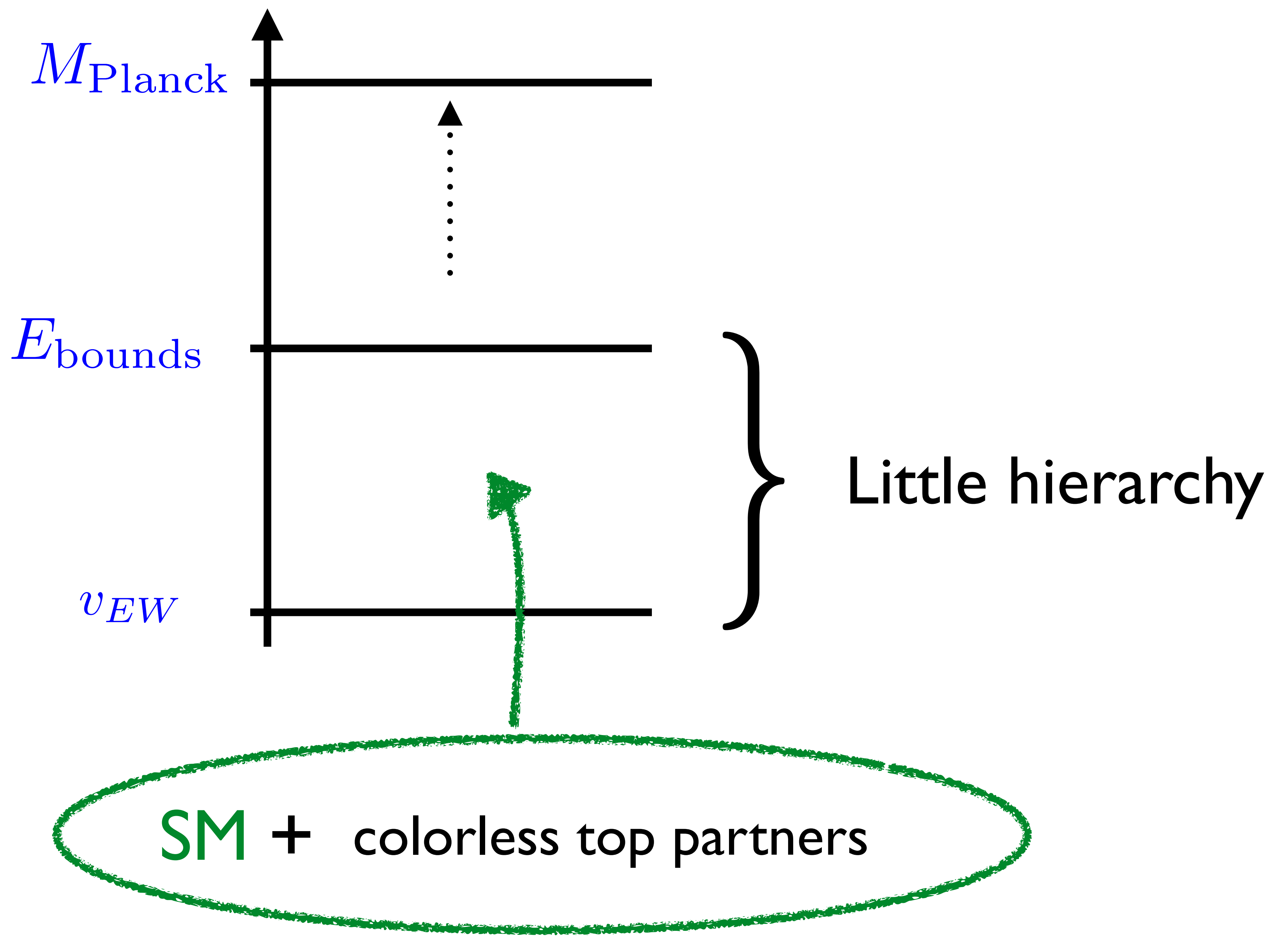
The X's are charged under $SU(3)'$

Bounds on m_X not as stringent

Colorless X models are more natural

Colorless Top Partners

<u>General idea</u>   To solve the Little Hierarchy problem



Colorless Top Partners

Ingredients for neutral naturalness

- Symmetry protecting the Higgs: spontaneously broken global symmetry, SUSY, …
- Extend the color gauge symmetry to have at least $[SU(3)]^2$
- Either impose a discrete symmetry or orbifold

In general, CTP theories can be obtained from orbifolding

N.Craig, S.Knapen, P. Longhi, 1410.6806, 1411.7393

- Models

Twin Higgs *Z. Chacko, H. Goh and R. Harnik, hep-ph/0506256*

Folded SUSY *G.B., Z.Chacko, H. Goh, R. Harnik , hep-ph/0609152*

Quirky Little Higgs *H. Cai, H.-C. Cheng, J. Terning, 0812.0843*

The Twin Higgs

Z. Chacko, H. Goh and R. Harnik, hep-ph/0506256

Higgs is a pNGB of a spontaneously broken global symmetry

Starting with a fundamental with potential

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

$SU(4) \to SU(3)$ ⟶ 7 NGBs

The Twin Higgs

Gauge a subgroup: $SU(2)_A \times SU(2)_B$

$$H = \left(\begin{array}{c} H_A \\ H_B \end{array} \right)$$

Choose $\langle H \rangle$ so that H_A stays massless $\longrightarrow$ SM Higgs doublet

Gauge interactions break global symmetry explicitly

Quadratically divergent contributions to V

The Twin Higgs

Gauge loops lead to

$$\frac{9}{64\pi^2}\left(g_A^2 H_A^\dagger H_A \Lambda_A^2 + g_B^2 H_B^\dagger H_B \Lambda_B^2\right)$$

But imposing a Z_2 symmetry $\longrightarrow$ $g_A = g_B = g$, $\Lambda_A = \Lambda_B$

$$\frac{9}{64\pi^2} g^2 \Lambda^2 H^\dagger H$$ is $SU(4)$ symmetric

The Twin Higgs

Extend to all SM interactions $\longrightarrow$ Mirror SM sector

$$SM_A \times SM_B$$

E.g. Top Yukawas:

$$\lambda_A H_A q_A t_A + \lambda_B H_B q_B t_B$$

generate

$$\frac{3}{8\pi^2} \left(\lambda_A^2 H_A^\dagger H_A \, \Lambda_A^2 + \lambda_B^2 H_B^\dagger H_B \, \Lambda_B^2 \right)$$

$$\xrightarrow{Z_2} \quad \frac{3}{8\pi^2} \, \lambda^2 \, \Lambda^2 \, H^\dagger H$$

Twin Higgs in Non-linear Representation

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = e^{\frac{i}{f}\,\Pi} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

with

$$\Pi = \left(\begin{array}{ccc|c} 0 & 0 & 0 & h_1 \\ 0 & 0 & 0 & h_2 \\ 0 & 0 & 0 & 0 \\ \hline h_1^* & h_2^* & 0 & 0 \end{array}\right)$$

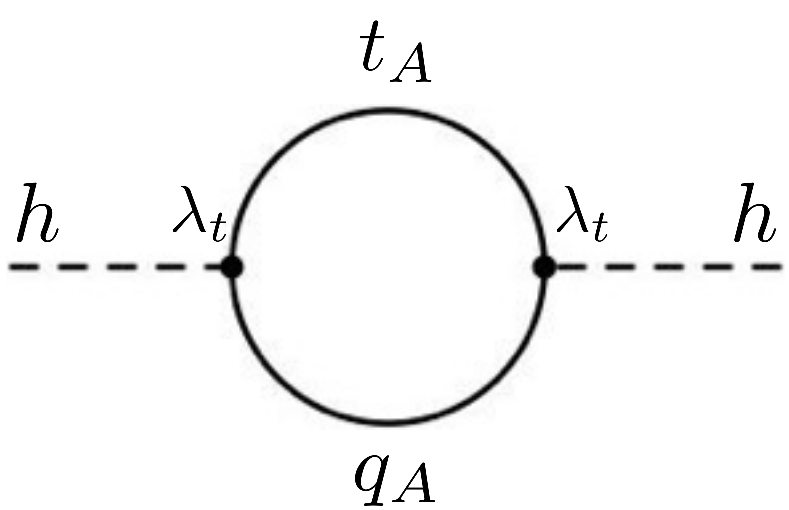
and all the B NGBs were eaten by B gauge bosons

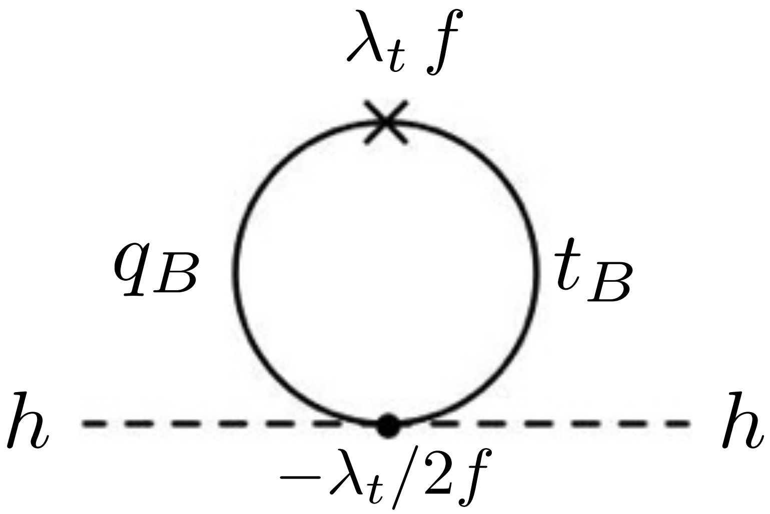
The SM Higgs is

$$h = \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Cancellation

$$\lambda_t\, h\, q_A t_A + \lambda_t \left(f - \frac{1}{2f} h^\dagger h \right) q_B t_B$$





But q_B, t_B have $SU(3)_B$ color

Breaking of Z_2 Symmetry

If Z_2 is exact $\longrightarrow$ $v_{EW} = f$

Adding a soft breaking term $\mu^2|H_A|^2$ allows $v_{EW} < f$

Couplings of the Higgs to SM fields suppressed by

$$\cos\theta = \cos\left(\frac{v}{\sqrt{2}\,f}\right)$$

Twin Higgs Models

<u>Identical Twin:</u> *Chacko, Goh, Harnik*

- Complete copy of the SM
- $\frac{f}{v} \simeq 3 - 10 \Rightarrow \Lambda'_{\mathrm{QCD}} \gtrsim \Lambda_{\mathrm{QCD}}$
- Light quarks and leptons
- $U(1)_B$?

Twin Higgs and Higgs Physics

All Higgs couplings to SM states suppressed by $\cos\theta$

E.g.:

$$\sigma(pp \to \rho) = \cos^2\theta \;\; \sigma_{SM}(pp \to h)$$

$$\Gamma(\rho \to A_i) = \cos^2\theta \;\; \Gamma_{SM}(h \to \mathrm{SM}_i)$$

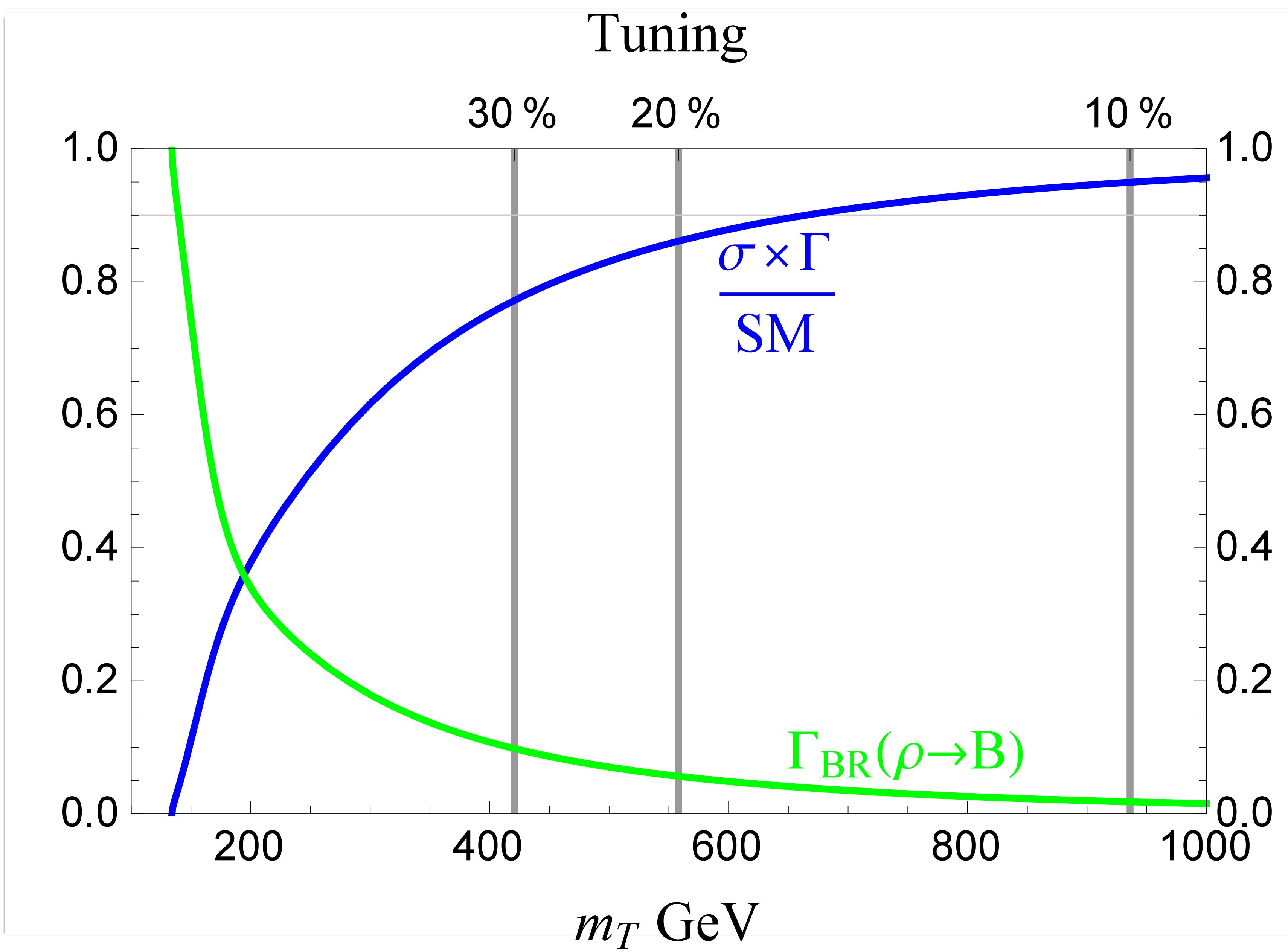
Invisible width

$$\Gamma(\rho \to B) = \Gamma_{SM}(h) \; \sin^2\theta \;\; \delta$$

with $\delta < 1$ for $v_{EW} < f$

Identical Twin

Higgs couplings *G.B., Z.Chacko, R.Harnik, L. Lima, C. Verhaaren, 1411.3310*



Twin Higgs Models

<u>Fraternal Twin</u>: *Craig, Katz, Strassler, Sundrum, 1501.05310*

- Only minimal fermion content to solve hierarchy problem

  $\tilde{Q}^3, \tilde{t}_R, \tilde{b}_R, \tilde{L}^3, \tilde{\tau}_R$ 3rd generation twin fermions

- Higgs $\longrightarrow$ glueballs $\longrightarrow$ SM

$$c\tau_0 \sim 18\text{m} \times \left(\frac{10\ \text{GeV}}{m_0}\right)^7 \times \left(\frac{f}{750\ GeV}\right)^4$$

Twin Higgs Dark Matter

Twin strong sector generates a higher strong scale

$$\Lambda'_{\rm QCD} \gtrsim \Lambda_{\rm QCD} \qquad \Rightarrow \qquad \tilde{m}_n \simeq \text{few } m_n$$

⟶ Possible Asymmetric Dark Matter candidate

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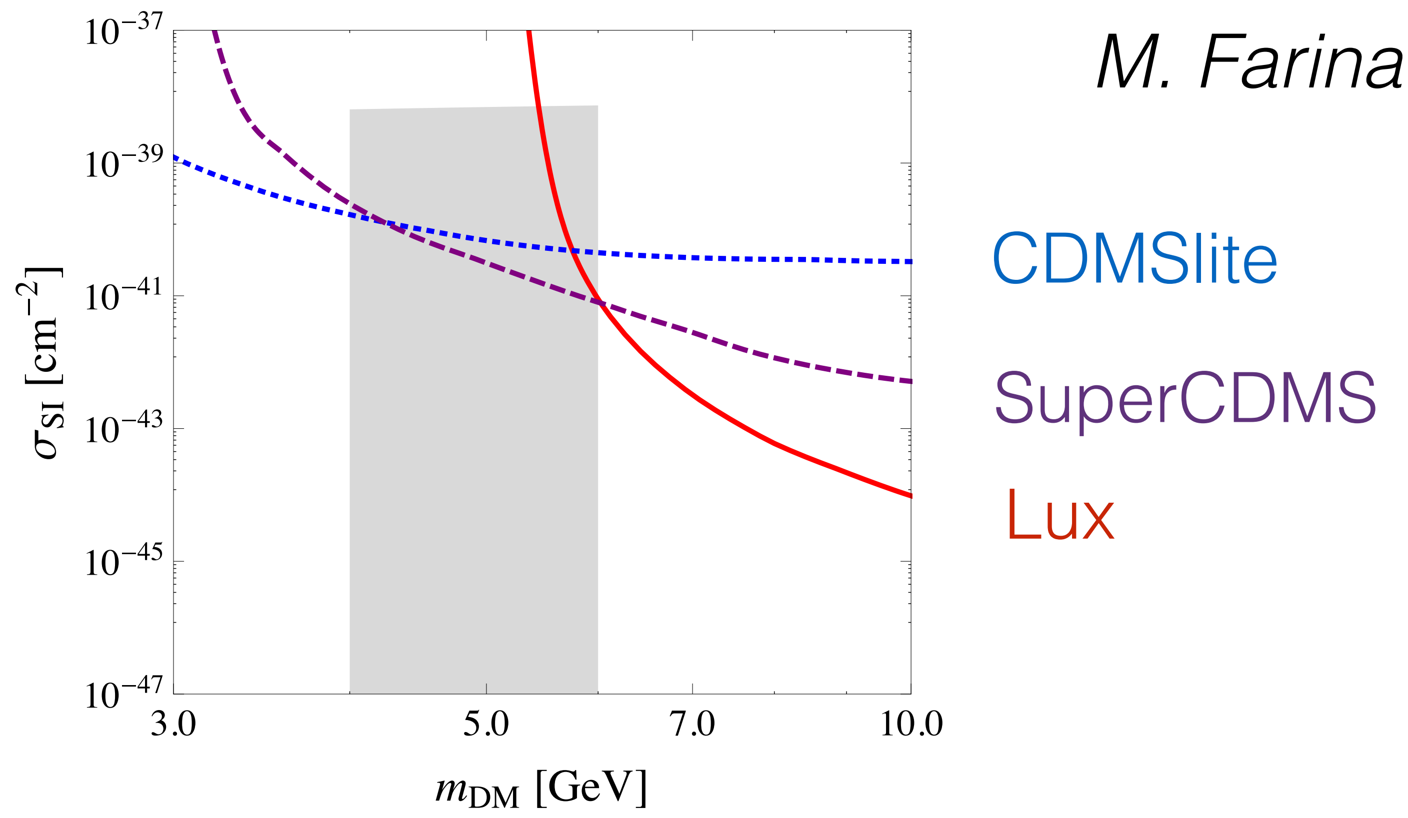
⟶ Possible Asymmetric Dark Matter candidate



M. Farina, 1506.03520

Fraternal Twin Higgs Dark Matter

Asymmetric DM: *I. Garcia, R. Lasemby, J. March-Rusell, 1505.07410*

Twin bottom baryons $\tilde{\Delta}_b$

Thermal Relic (TWIMP ?)

Mostly $\tilde{\tau}$

I. Garcia, R. Lasemby, J. March-Rusell, 1505.07109

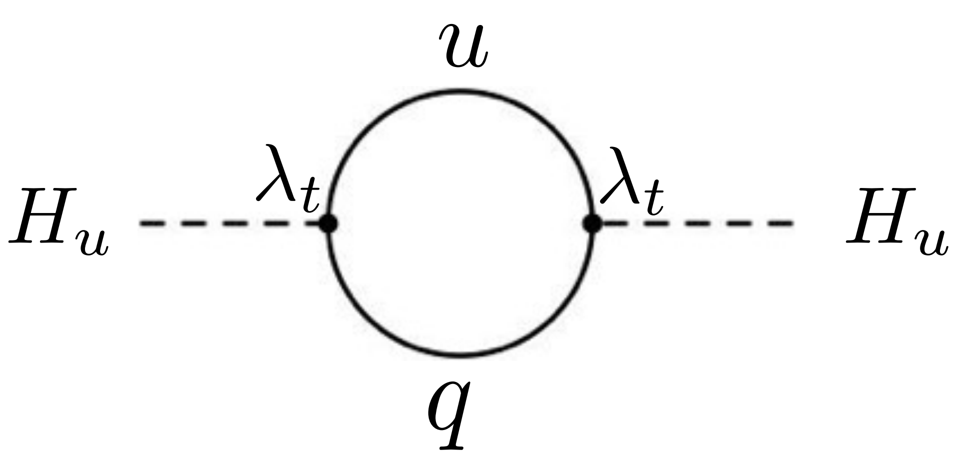
N. Craig, A. Katz, 1505.07113

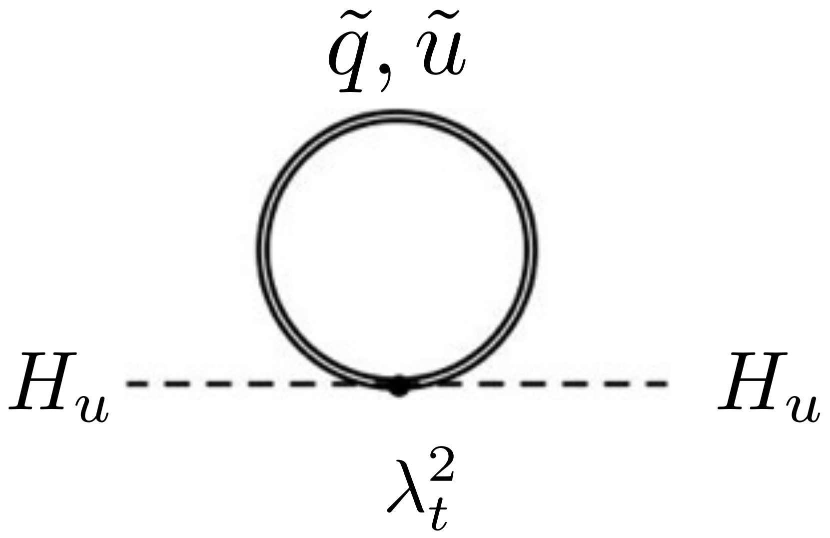
Colorless Top Partners in Supersymmetry

Folded Supersymmetry

G.B., Z.Chacko, H. Goh, R. Harnik , hep-ph/0609152

Cancellation of top divergence





- Squarks need to be charged under $SU(2)_L$
- Need not be charged under $SU(3)_c$

But how ?

Bifold Protection

Global $U(N)$ $\lambda\, S\, Q_i\, \bar{Q}_i$ $i = 1\ldots, N$

M_S^2 is quadratically divergent

- Supersymmetrize

- Duplicate index running in loop: $i = 1, \ldots., 2N$

Bifold Protection

- Define

$$\Gamma = \begin{pmatrix} +1 & & & & & \\ & \ddots & & & & \\ & & +1 & & & \\ & & & -1 & & \\ & & & & \ddots & \\ & & & & & -1 \end{pmatrix} \quad \begin{matrix} 1 \\ \vdots \\ N \\ N+1 \\ \vdots \\ 2N \end{matrix}$$

- Theory is invariant under

$$Z_{2\Gamma} \begin{cases} S \rightarrow S \\ Q_i \rightarrow -\Gamma\, Q_i \\ \bar{Q}_i \rightarrow -\Gamma^*\, \bar{Q}_i \end{cases}$$

Z_{2R} { fermions odd; bosons even

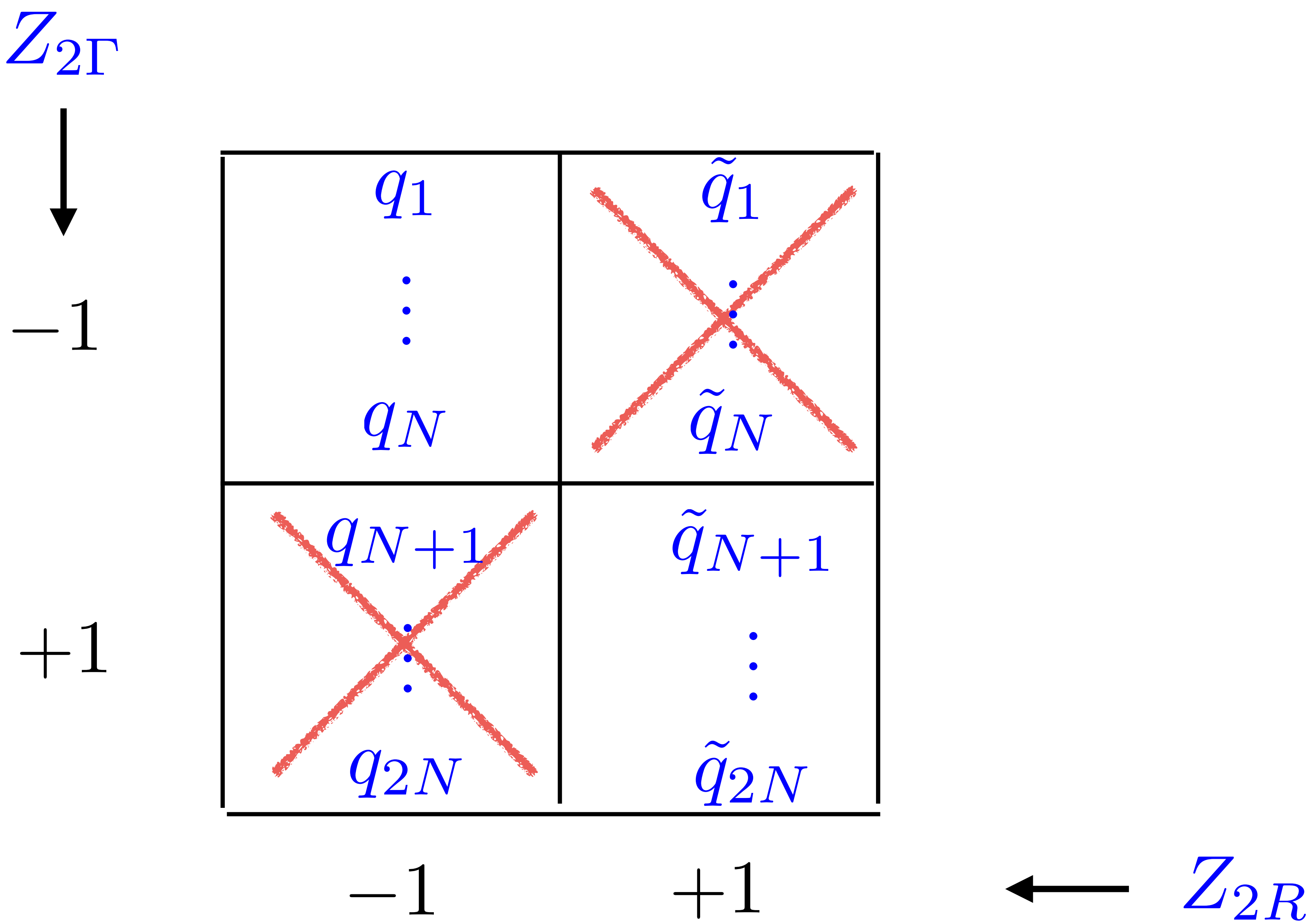
Bifold Protection

Orbifold projection: Project out states odd under $Z_{2\Gamma} \times Z_{2R}$

$Z_{2\Gamma}$ ↓ \ Z_{2R} ←	-1	$+1$
-1	$q_1, \ldots, q_N$	$\tilde{q}_1, \ldots, \tilde{q}_N$
$+1$	$q_{N+1}, \ldots, q_{2N}$	$\tilde{q}_{N+1}, \ldots, \tilde{q}_{2N}$

Bifold Protection

Project out states odd under $Z_{2\Gamma} \times Z_{2R}$

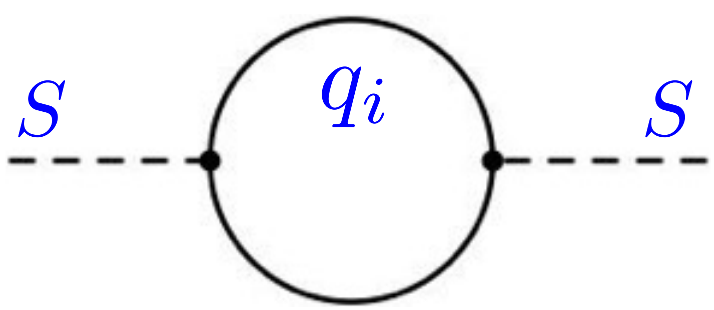


Bifold Protection

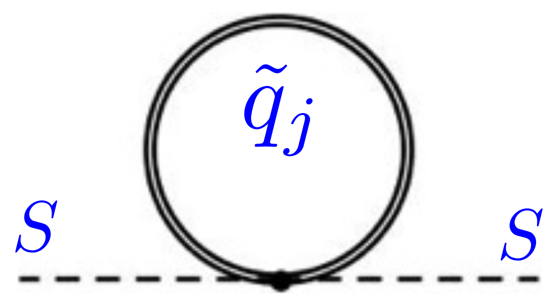
<u>Accidental SUSY</u>: spectrum not supersymmetric

$$\begin{matrix} q_1 \\ \vdots \\ q_N \end{matrix} \quad + \quad \begin{matrix} \tilde{q}_{N+1} \\ \vdots \\ \tilde{q}_{2N} \end{matrix}$$

But still cancels one-loop quadratic divergence



$i = 1, \ldots, N$



$j = N+1, \ldots, 2N$

Large-N orbifold correspondence:

S.Kachru, E. Silverstein, hep-th/9802183; M.Bershadsky, A.Johansen, hep-th/9803248; M.Schmaltz, hep-th/9805218

Realistic Folded SUSY Model

Gauge symmetry: $SU(3)_A \times SU(3)_B \times Z_2 \times SU(2)_L \times U(1)_Y$

Orbifold so that:

q_A, u_A + $\tilde{q}_B, \tilde{u}_B$ remain in the spectrum

No gauginos

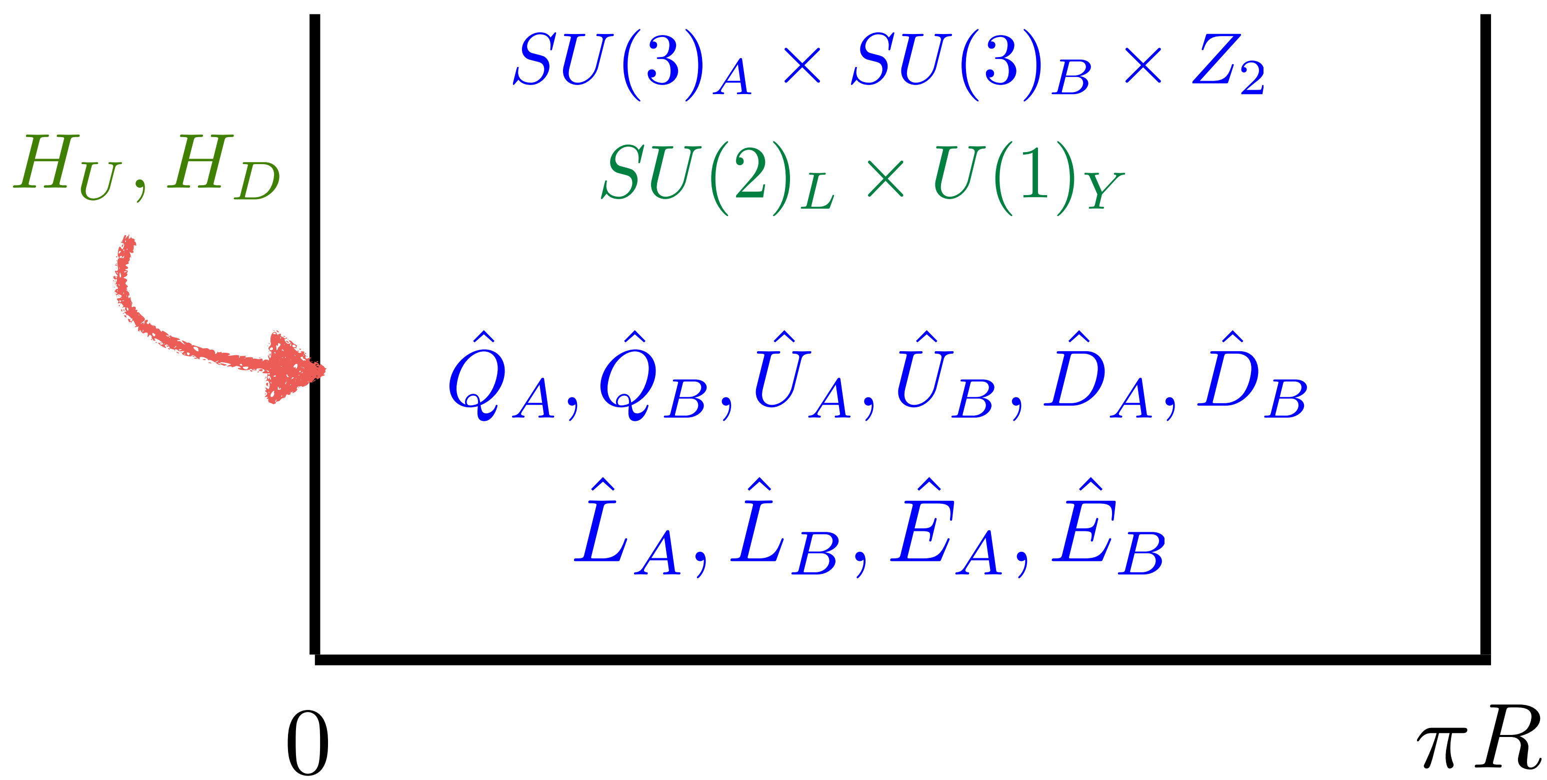
Yukawas obey

$$(\lambda_t\, h_u\, q_A\, u_A + \text{h.c.}) + \lambda_t^2\, |\tilde{q}_B\, h_u|^2 + \lambda_t^2\, |\tilde{u}_B|^2\, |h_u|^2$$

$\longrightarrow$ Accidental SUSY still protects m_h^2

Folded SUSY UV Completion

Can be realized in 5D compactified on S_1/Z_2



SUSY broken by BCs (Scherk-Schwarz)

BCs break Z_2 at πR

Folded SUSY Spectrum

- Fermion zero modes from

$$\hat{Q}_A, \hat{U}_A, \hat{D}_A, \hat{L}_A, \hat{E}_A$$

- Scalar zero modes from

$$\hat{Q}_B, \hat{U}_B, \hat{D}_B, \hat{L}_B, \hat{E}_B$$

- Localize Higgses at $y = 0$

$$\delta(y)\, \lambda_t \, \{Q_{3A} H_U U_{3A} + Q_{3B} H_U U_{3B}\}$$

$\longrightarrow$ generates desired Yukawas at low energies

Folded SUSY Spectrum

Zero-mode Folded sfermions: *A. Delgado, A. Pomarol, M Quiros, hep-ph/9812489*

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

$$m_U^2 = K \frac{1}{4\pi^4} \left(\frac{4}{3} g_3^2 + \frac{4}{9} g_1^2 \right) \frac{1}{R^2}$$

$$m_D^2 = K \frac{1}{4\pi^4} \left(\frac{4}{3} g_3^2 + \frac{1}{9} g_1^2 \right) \frac{1}{R^2}$$

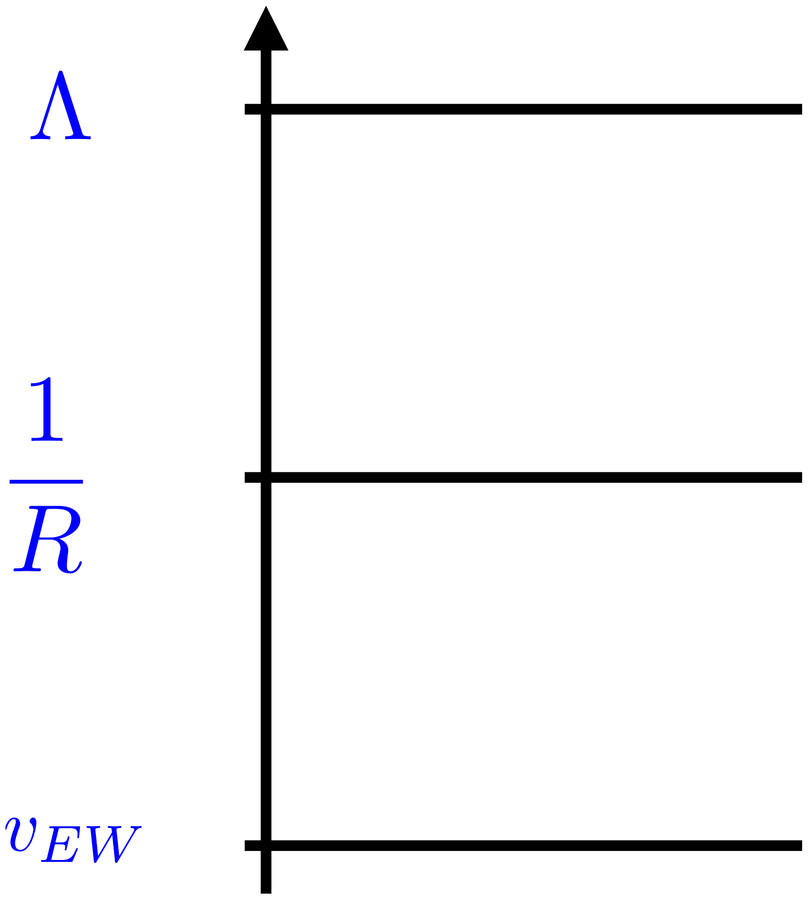
$$m_L^2 = K \frac{1}{4\pi^4} \left(\frac{3}{4} g_2^2 + \frac{1}{4} g_1^2 \right) \frac{1}{R^2}$$

$$m_E^2 = K \frac{1}{4\pi^4} g_1^2 \frac{1}{R^2}$$

plus Yukawa contributions for 3rd generation

$$m_{Q_3}^2 = K \frac{\lambda_t^2}{8\pi^4} \frac{1}{R^2} \qquad m_{U_3}^2 = K \frac{\lambda_t^2}{4\pi^4} \frac{1}{R^2}$$

Folded SUSY



5D SUSY

Accidental SUSY

$$\Lambda R \lesssim 4$$

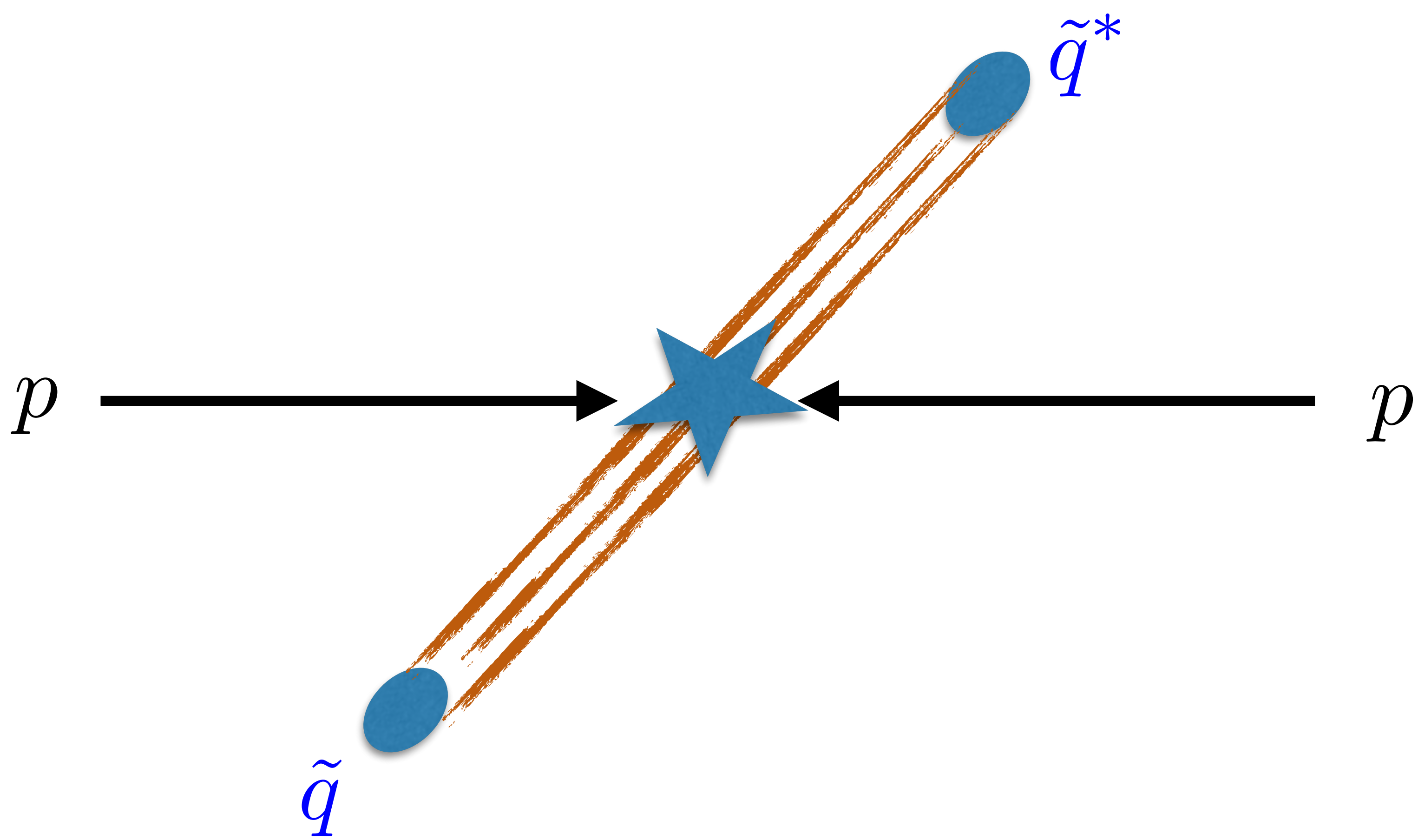
$$\frac{1}{R} \sim (5-7)\ \mathrm{TeV}$$

Folded SUSY Signals

Folded SUSY Signals at the LHC

Electroweak pair production of F-squarks

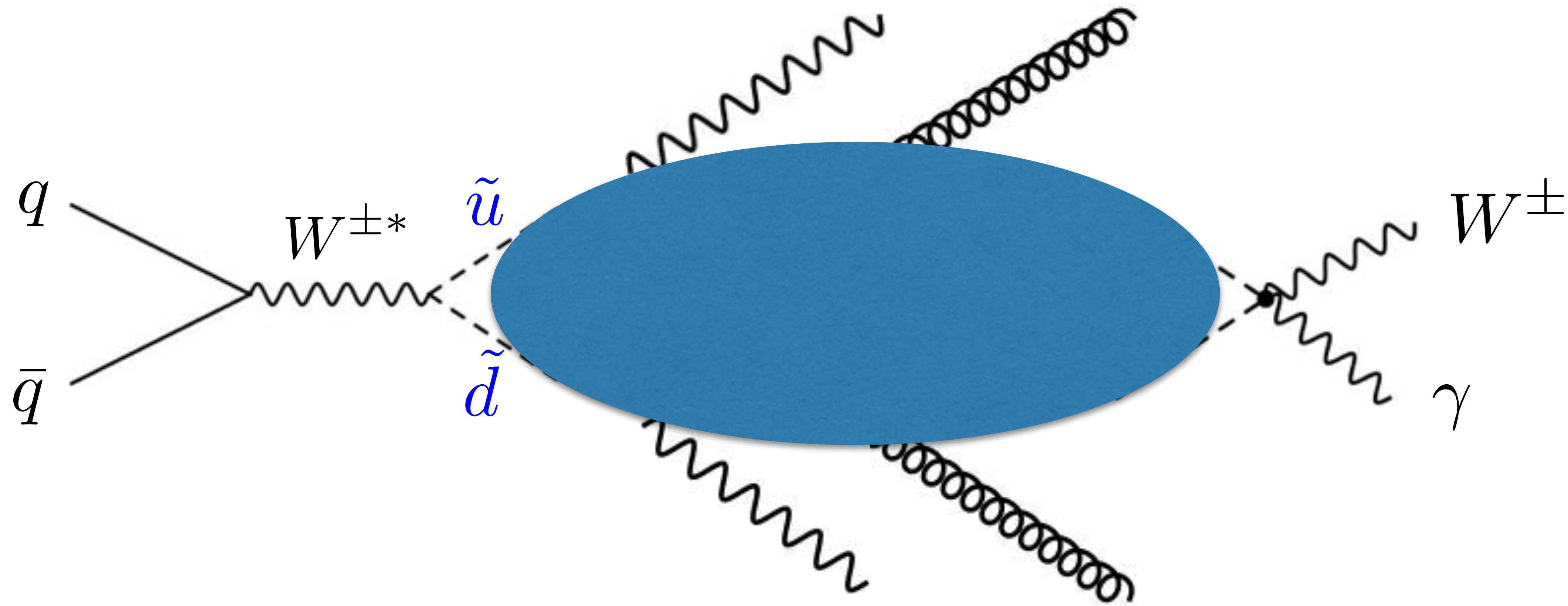
But $m_T \gg \Lambda'_{QCD} \simeq \text{few GeV}$ $\longrightarrow$ they do not hadronize



$\longrightarrow$ "squirks" have to come back for annihilation

Squirk Annihilation

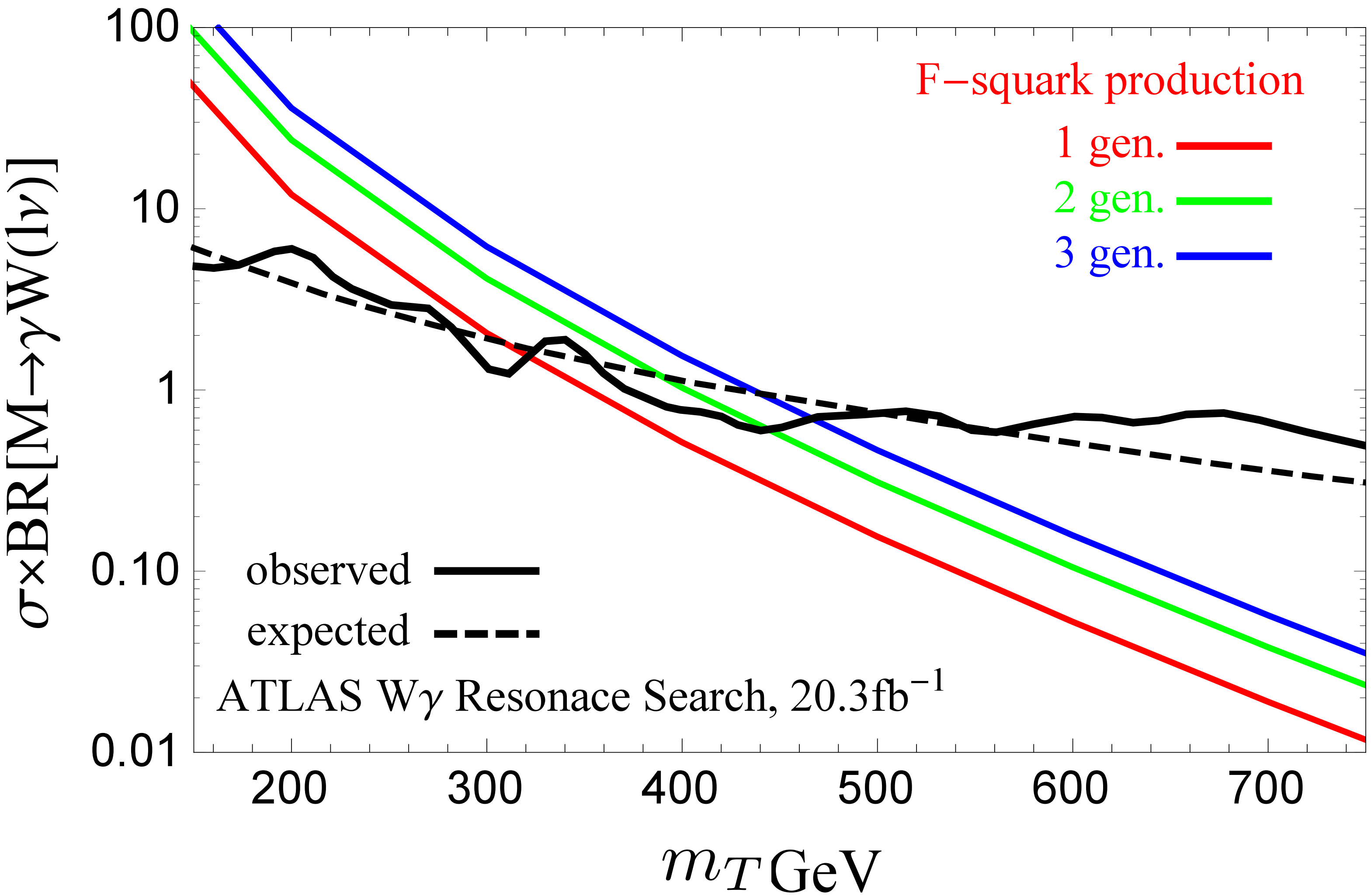
G.B., Z.Chacko, H.Goh, R. Harnik, C. Krenke, 0805.4667



- Annihilation is prompt
- Onium is in s-wave before annihilation

Bounds from the LHC

G.B., Z.Chacko, R.Harnik, L. Lima, C. Verhaaren, 1411.3310



Assumes

- No smearing
- No β decay

$$m_T > \left\{ \begin{array}{c} 320 \\ 445 \\ 465 \end{array} \right\} \text{GeV} \longrightarrow$$

Direct search better than Higgs couplings

Folded Sleptons *(G.B., R. D'Agnolo, 150x.xxxx)*

In the minimal model, lepton hypermultiplets

$$\hat{L}_A(1,1,2,-1/2) \quad \hat{L}_B(1,1,2,-1/2)$$
$$\hat{E}_A(1,1,1,1) \qquad \hat{E}_B(1,1,1,1)$$

Zero modes: Leptons F-sleptons

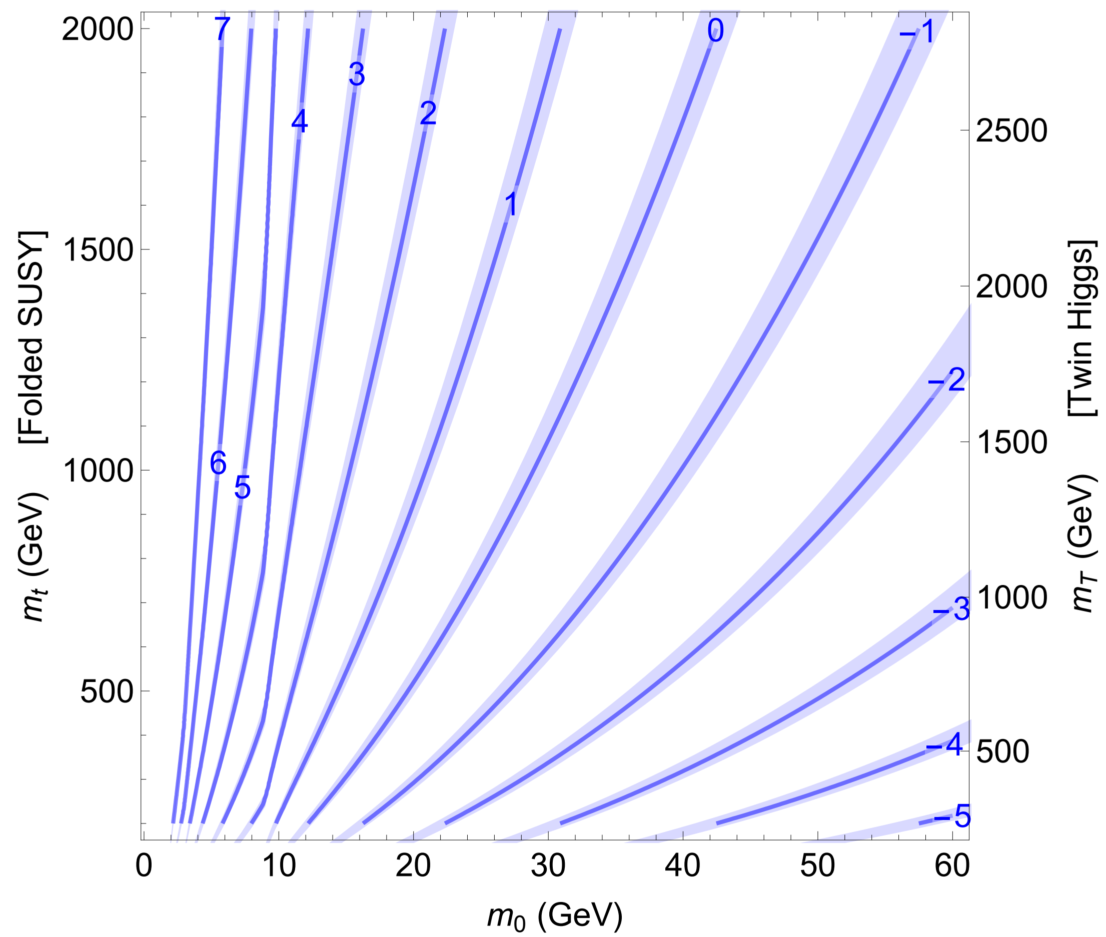
Lightest F-slepton is stable !

Need to add Z_2 preserving HDOs

E.g. $$\delta(y) \int d\theta^2 \left(\frac{U_A U_A D_A E_B}{\Lambda} + \frac{U_B U_B D_B E_A}{\Lambda} \right)$$

Highly displaced vertices

Folded SUSY Glueball Decays



D. Curtin, 1506.06141

Will start being competitive at HL-LHC

Summary

- We still have natural theories of EWSB not ruled out by data
- Signals at colliders are different
- The LHC has sensitivity for a lot of the parameter space
- But not impossible that HL-LHC ends and some "natural" parameter space still there (e.g. Identical Twin Higgs)
- All these theories have low cutoffs (< 20 TeV)

  Experiment: Higher energies

  Theory: UV completions

- Interesting for DM model building (especially ADM)