Folded Supersymmetry

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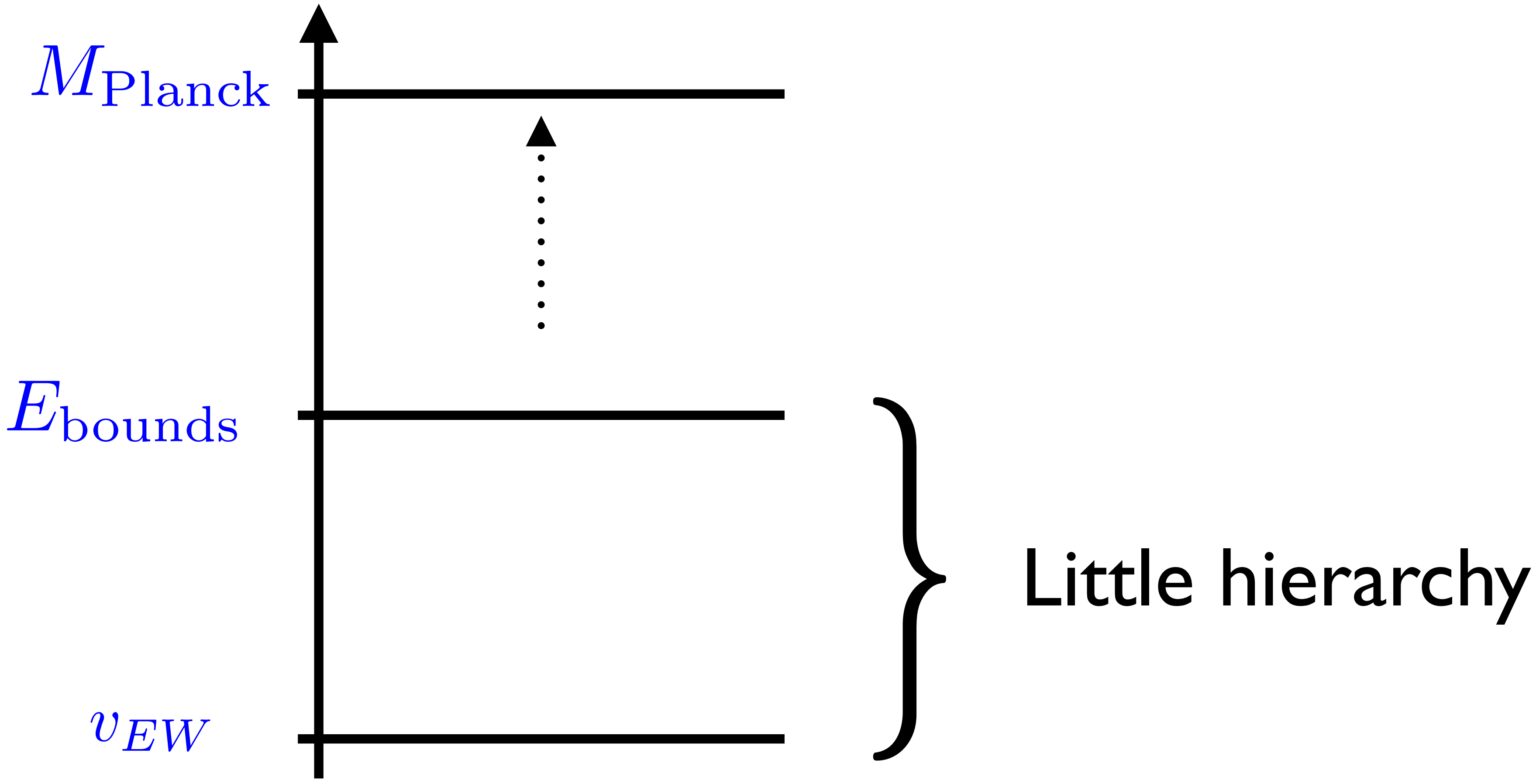
Outline

- Can we save naturalness ?
- Folded Supersymmetry
- Some Phenomenology
- Outlook

Naturalness and the LHC

Is the Electroweak scale natural ?

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



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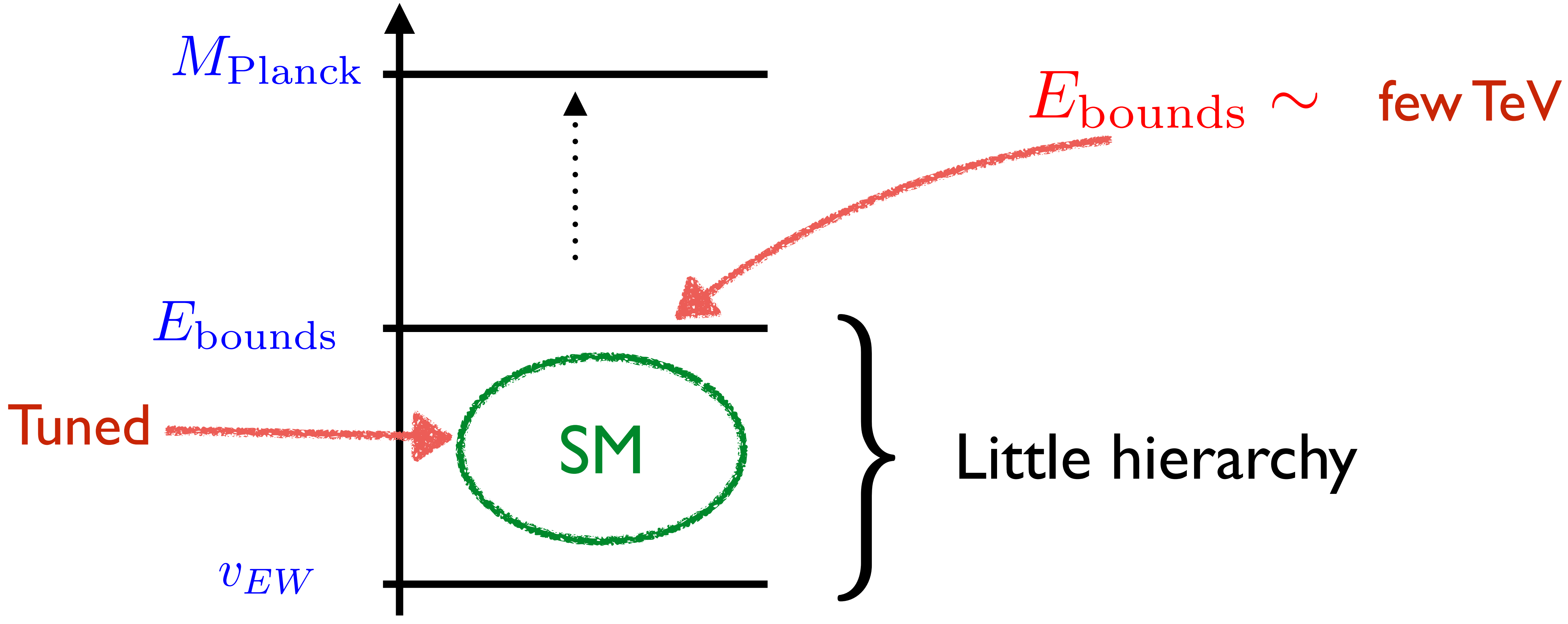
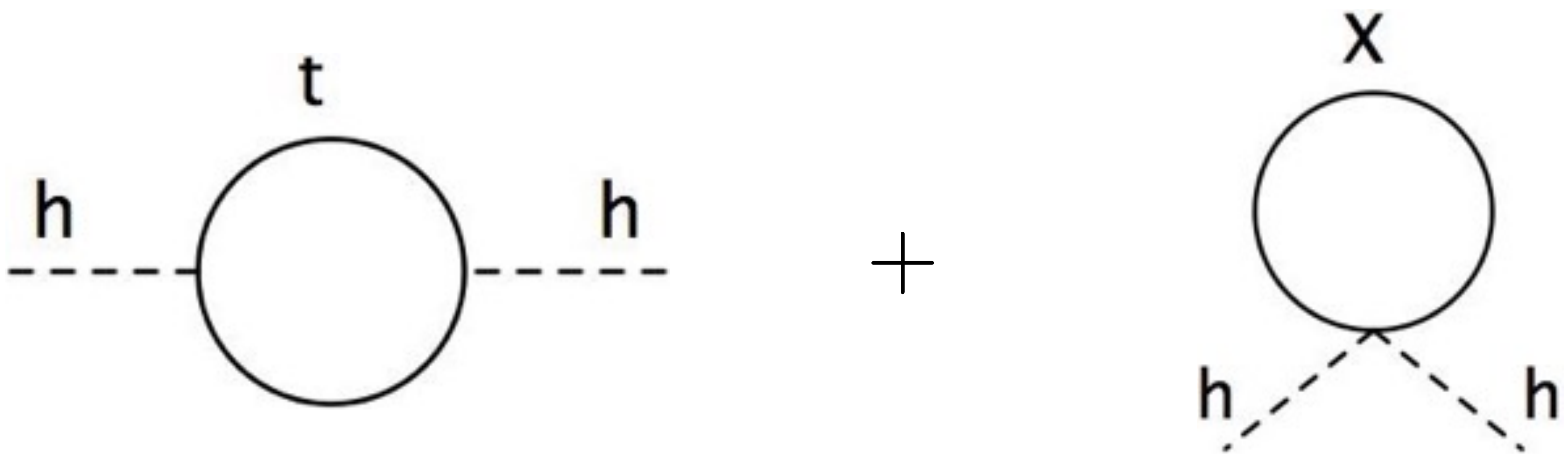


Naturalness and the LHC

UV sensitivity of m_h^2 dominated by top quark



$\Rightarrow$ {
- 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 $SU(3)_c \to SU(3)'$

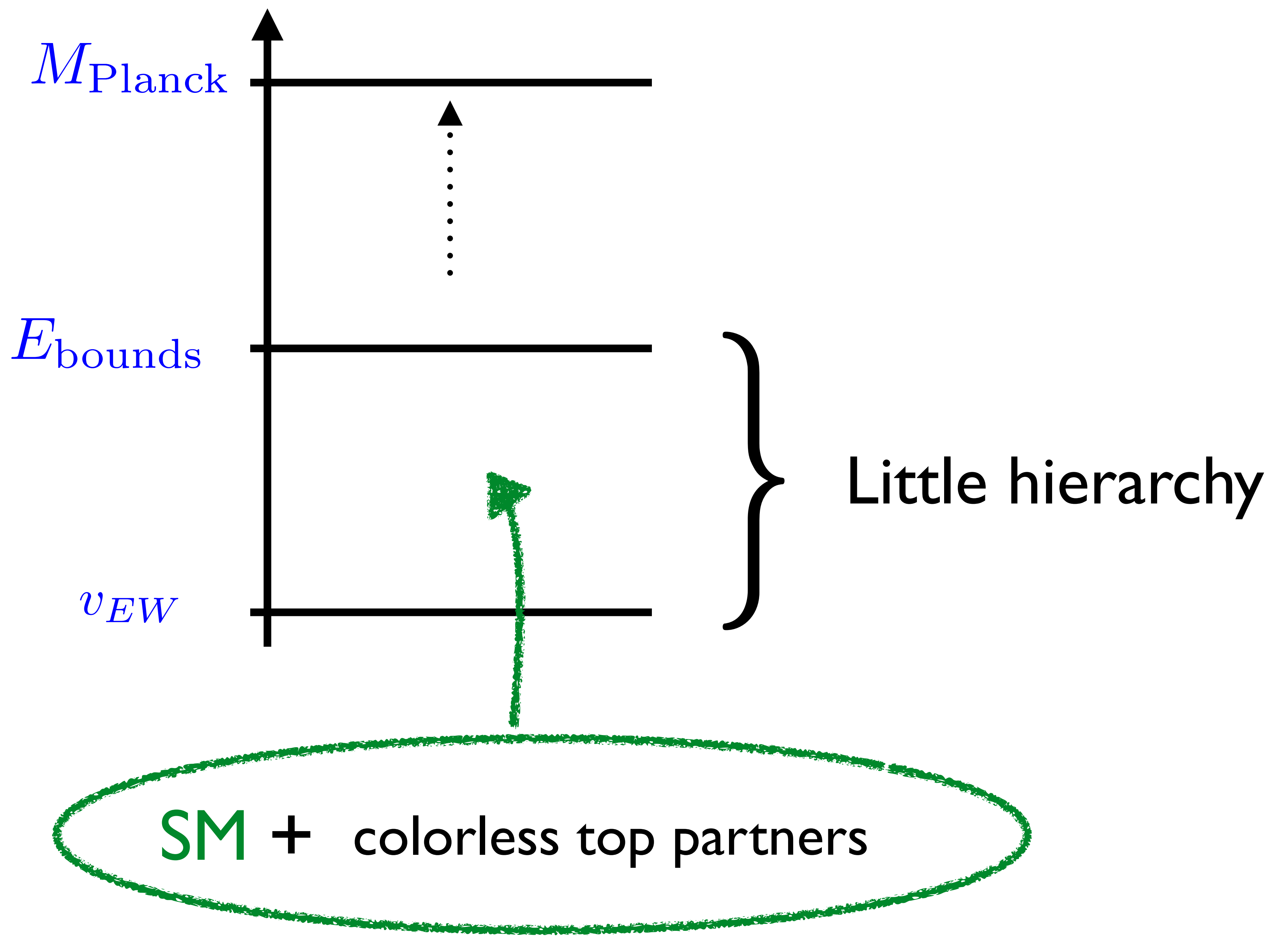
The X's are charged under $SU(3)'$

Bounds on m_X not as stringent

Colorless X models are more natural

Colorless Top Partners

General idea   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

Folded Supersymmetry

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

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

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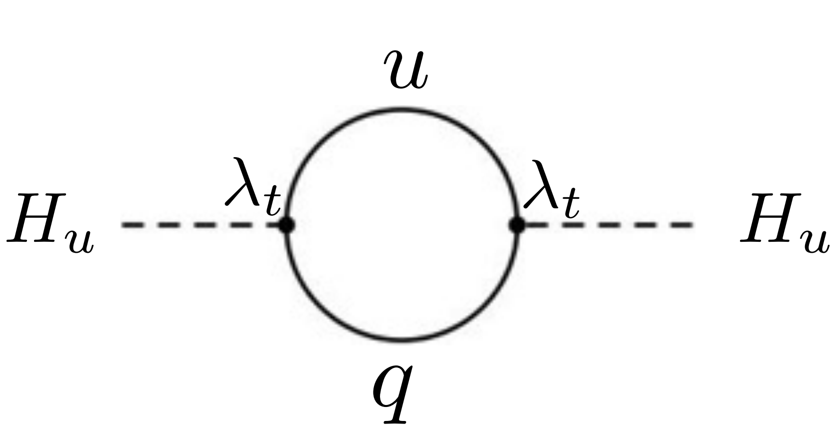
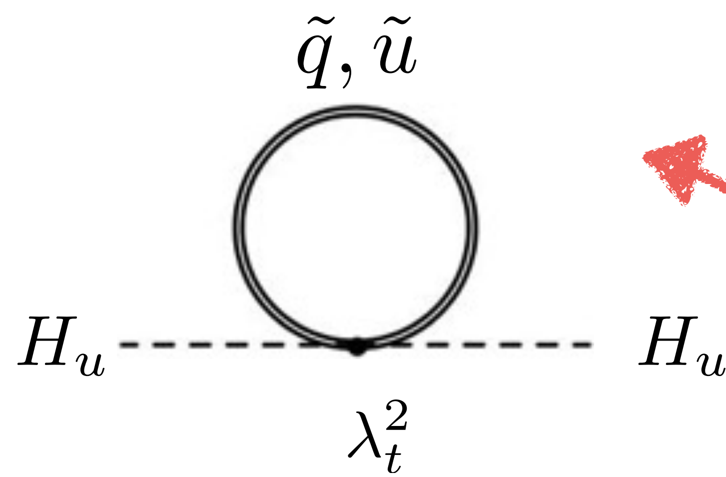




Can we have SUSY with colorless stops ?

Folded Supersymmetry

Ingredients

- Supersymmetry
- Extended gauge symmetry:

$$G \supset SU(3)_A \times SU(3)_B$$

- Break SUSY at a high scale to obtain at low energies

$$q_A \quad , \quad \tilde{q}_B$$

Accidental low energy SUSY cancels quadratic div. at one loop

Large N Orbifold Correspondence

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

$$\text{Parent theory} \xrightarrow{\text{Orbifold}} \text{Daugther theory}$$

$$(\text{C.F.})_{\text{Parent}} = (\text{C.F.})_{\text{Daughter}} + O(\frac{1}{N})$$

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

$$Z_{2\Gamma} \begin{cases} S \rightarrow S \\ Q_i \rightarrow -\Gamma\, Q_i \\ Q_i \rightarrow -\Gamma^*\, \bar{Q}_i \end{cases} \qquad Z_{2R} \begin{cases} \text{fermions odd} \\ \text{bosons} \quad \text{even} \end{cases}$$

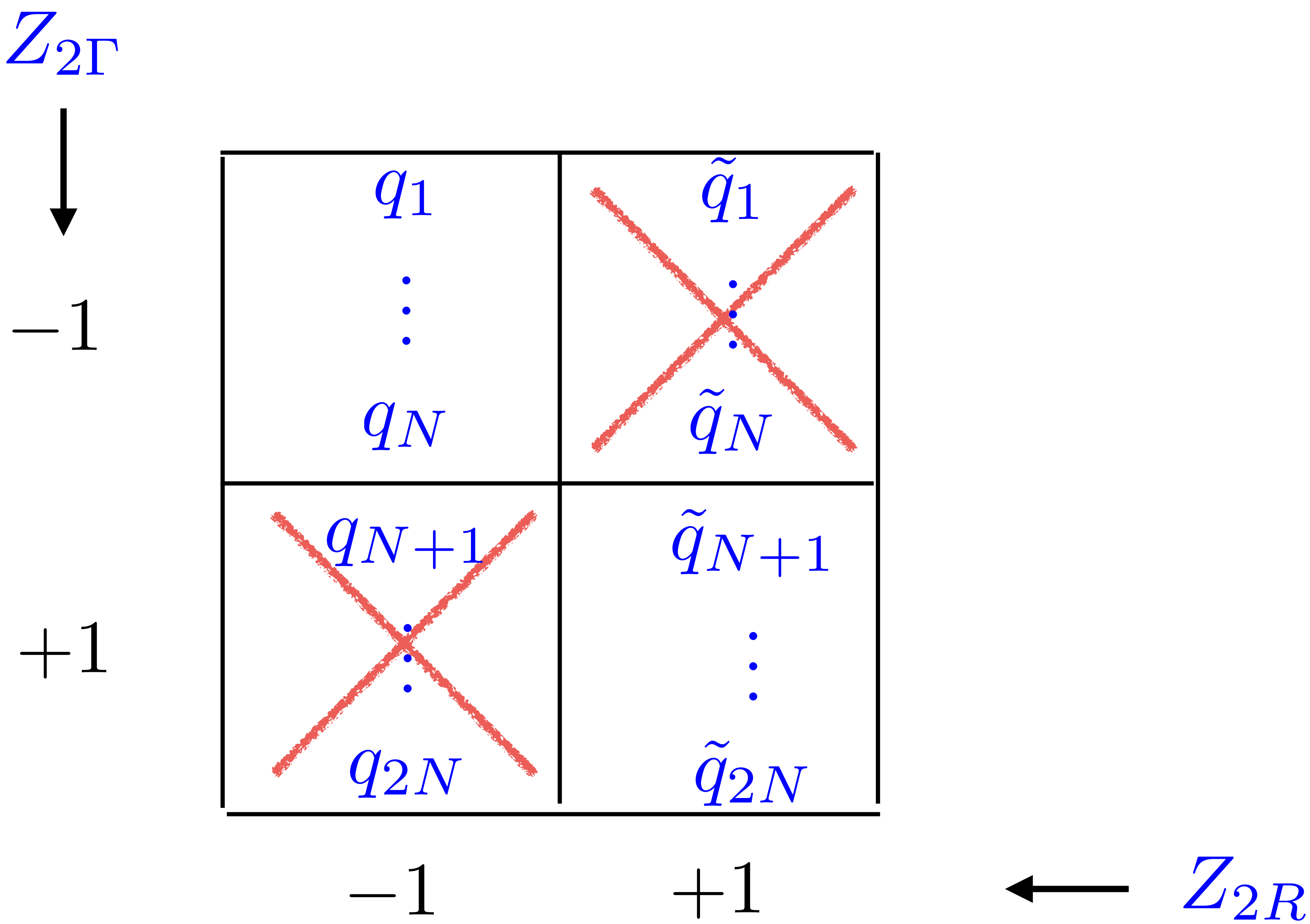
Bifold Protection

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

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

Bifold Protection

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

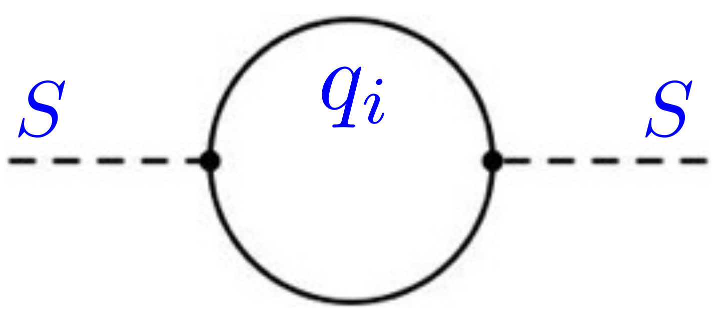


Bifold Protection

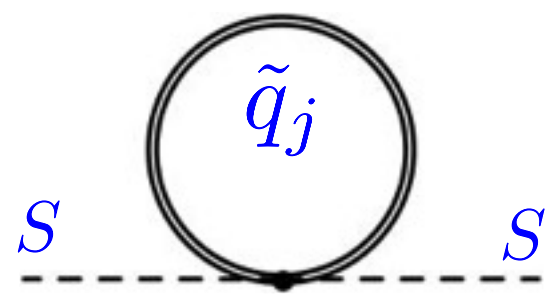
Accidental SUSY: spectrum not supersymmetric

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

But still cancels one-loop quadratic divergence



$i = 1, \ldots, N$



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

Folded SUSY Model

Extend color $SU(3)$ $\longrightarrow$ $SU(3)_A \times SU(3)_B \times Z_2$

Orbifold so that:

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

No gauginos

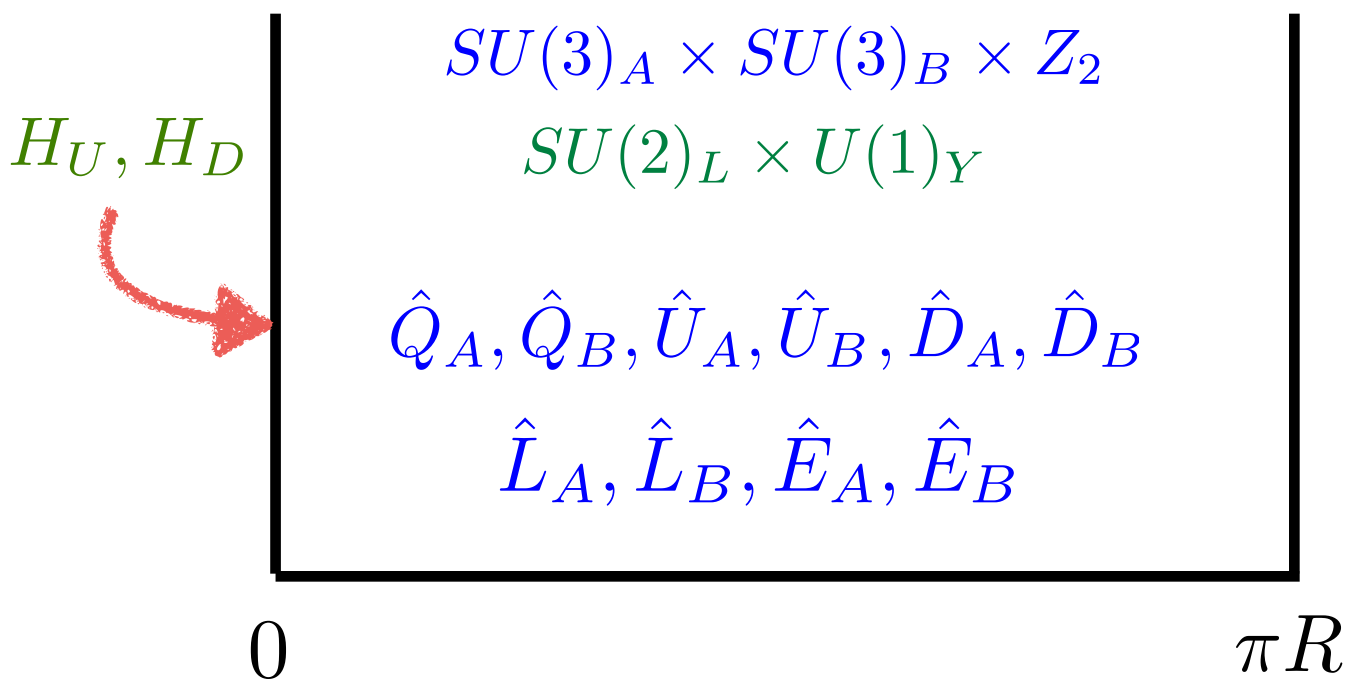
Yukawas obey

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

$\longrightarrow$ 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 UV Completion

- $\mathcal{N} = 1$ in 5D $\longrightarrow$ $\mathcal{N} = 2$ in 4D
- 5D Hypermultiplet $\hat{Q} \sim (Q, Q^c)$ in terms of 4D superfields

$$Q = (\tilde{q}, q) \qquad Q^c = (\tilde{q}^c, q^c)$$

or

$$Q' = (\tilde{q}^{*c}, q) \qquad Q'^{\,c} = (-\tilde{q}^*, q^c)$$

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$$Q = (\tilde{q}, q) \qquad Q^c = (\tilde{q}^c, q^c) \quad \leftarrow \text{at } y = 0$$

or

$$Q' = (\tilde{q}^{*c}, q) \qquad Q'^c = (-\tilde{q}^*, q^c) \quad \leftarrow \text{at } y = \pi R$$

$\Big\}\ \mathcal{N}=1$

related by $SU(2)_R$ rotation parametrized by α

in this example $\alpha = \frac{1}{2}$

(more in David Pinner's talk)

Folded SUSY Spectrum

$$\hat{Q}_A \sim \begin{cases} (Q_A, Q_A^c) & \text{+,- at} \quad y = 0 \\ (Q'_A, Q'^c_A) & \text{+,- at} \quad y = \pi R \end{cases}$$

fermion zero mode

$$\hat{Q}_B \sim \begin{cases} (Q_B, Q_B^c) & \text{+,- at} \quad y = 0 \\ (Q'_B, Q'^c_B) & \text{-,+ at} \quad y = \pi R \end{cases}$$

scalar zero mode

BCs break Z_2 (A ⟷ B) at $y = \pi R$

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

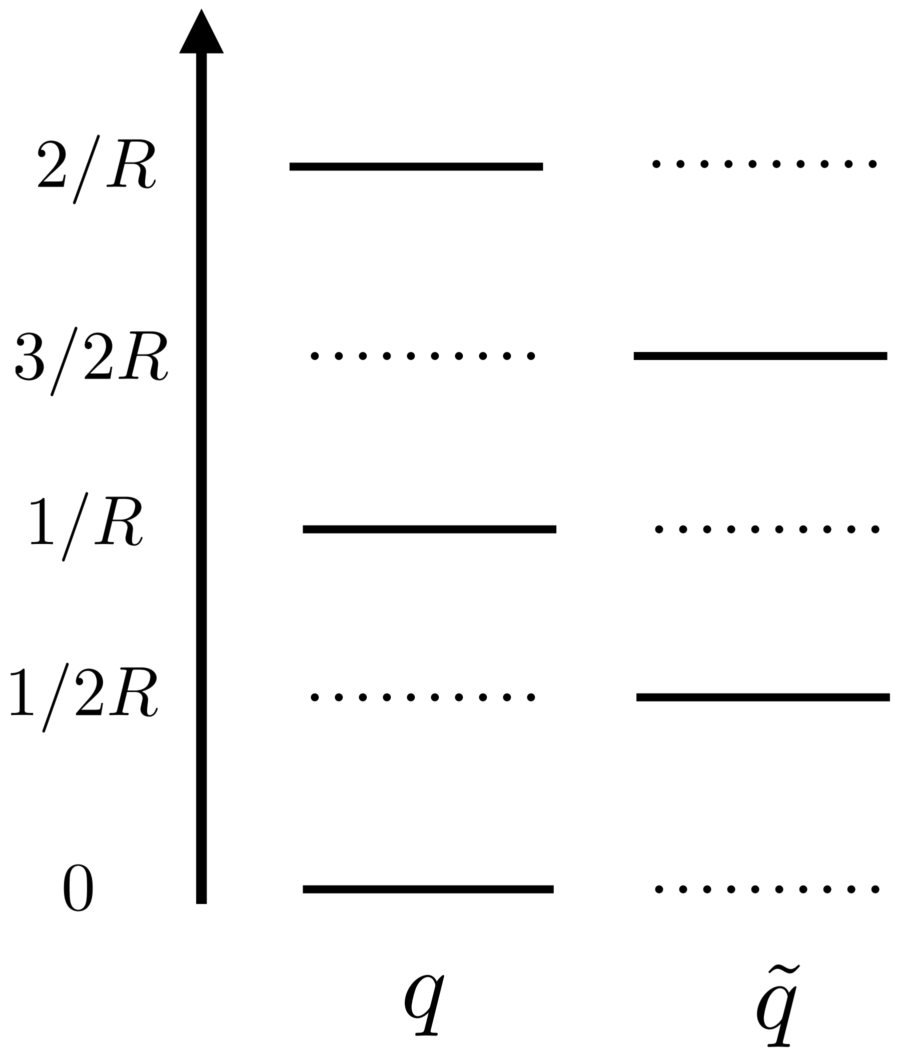
$$\hat{Q}_B, \hat{U}_B, \hat{D}_B, \hat{L}_B, \hat{E}_B$$

- 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



Top contributions cancel in all KK levels at one loop

But weak gauge boson loops give (finite) contributions

Folded SUSY Spectrum

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

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

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

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

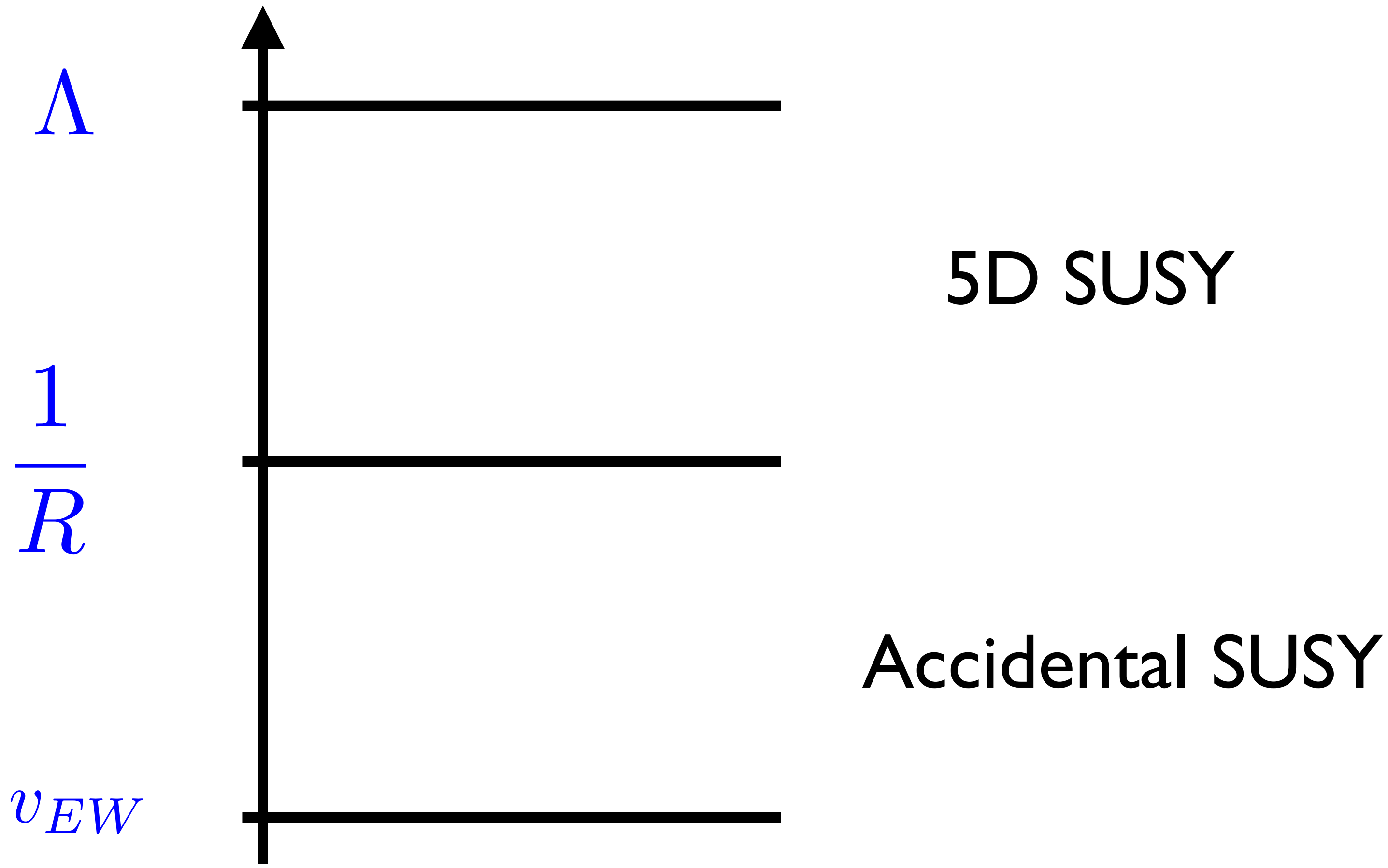
$$m_L^2 = K\frac{1}{4\pi^4}\left(\frac{3}{4}g_2^2 + \frac{1}{4}g_1^2\right)\frac{1}{R^2}$$

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

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



$$\Lambda R \lesssim 4$$

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

Folded SUSY Model Building

Many important issues:

- Smallish ΛR forced by top Yukawa volume suppression

→ Potentially dangerous brane kinetic terms at $y = \pi R$

Requires additional discrete symmetry at $y = \pi R$

- Electroweak symmetry breaking ?

$$(\delta m_H^2)_{\text{gauge}} \simeq \frac{K}{16\pi^4}(3g_2^2 + g_1^2)\frac{1}{R^2}$$ from gauge loops

$$(\delta m_H^2)_{\text{top}} \simeq -\frac{\lambda_t^2}{4\pi^2} M_{\tilde{t}}^2 \log\left(\frac{1}{RM_{\tilde{t}}}\right)$$ from top sector 2 loops

Does this work ? Probably not. See David Pinner's talk.

Folded SUSY Model Building

- Just as the MSSM, Folded MSSM needs help for $m_h = 125 \text{ GeV}$

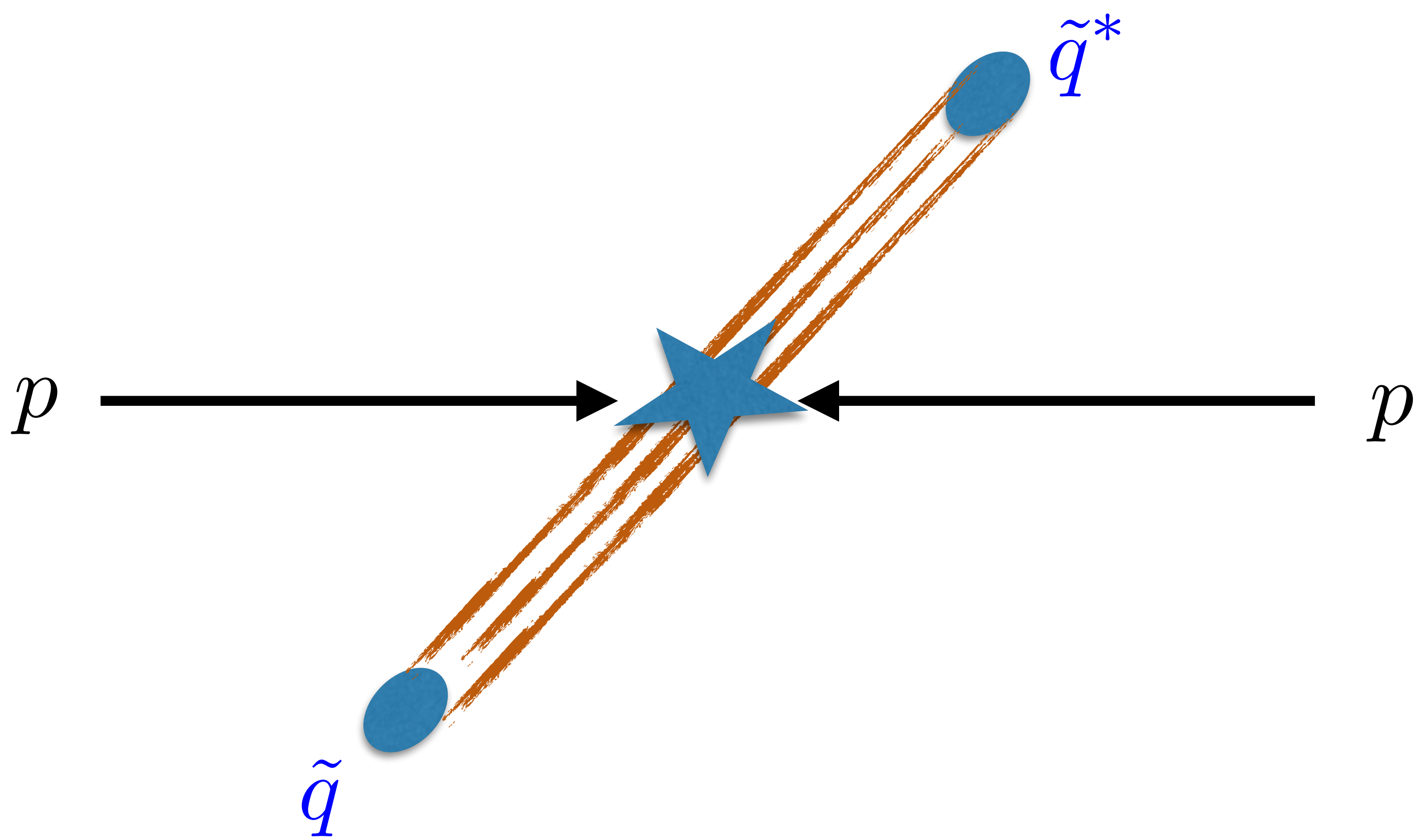
  E.g.: non-decoupling D terms from a $U(1)_X$

Folded SUSY Signals

Folded SUSY Signals at the LHC

Electroweak pair production of F-squarks

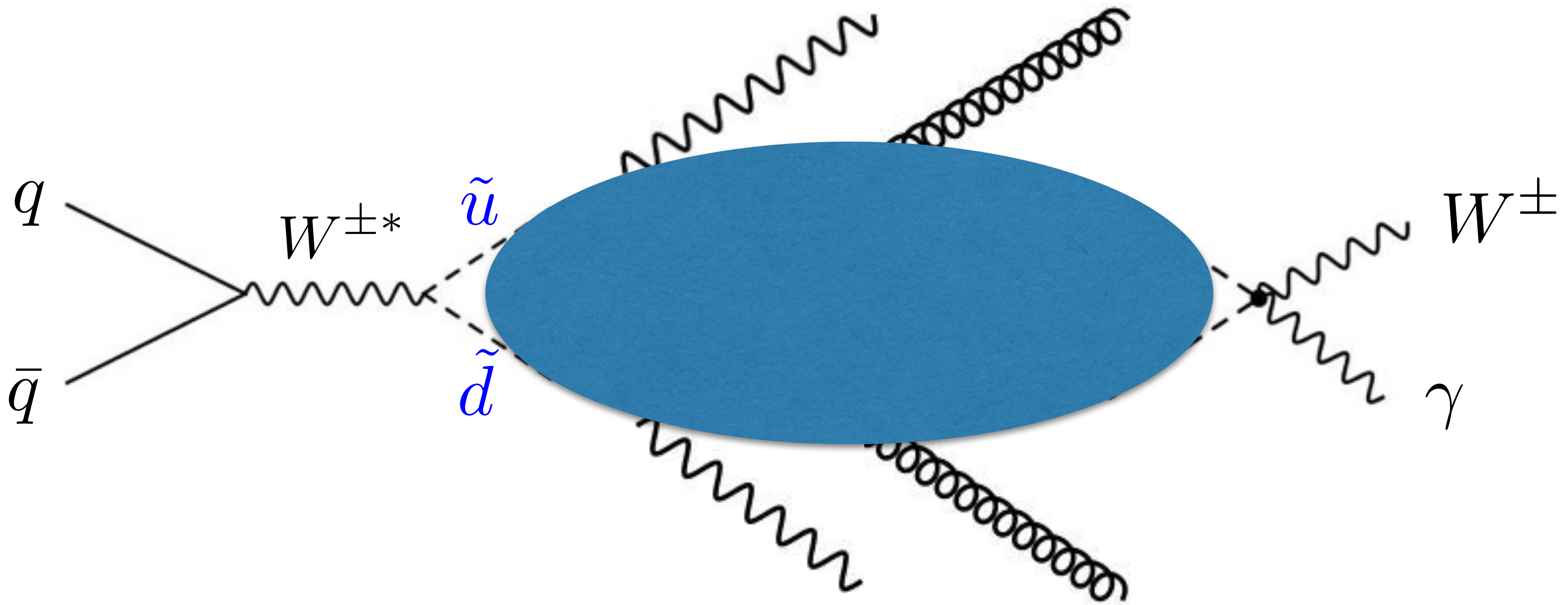
But $m_T \gg \Lambda'_{QCD} \simeq \text{few GeV}$ $\longrightarrow$ they do not hadronize



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

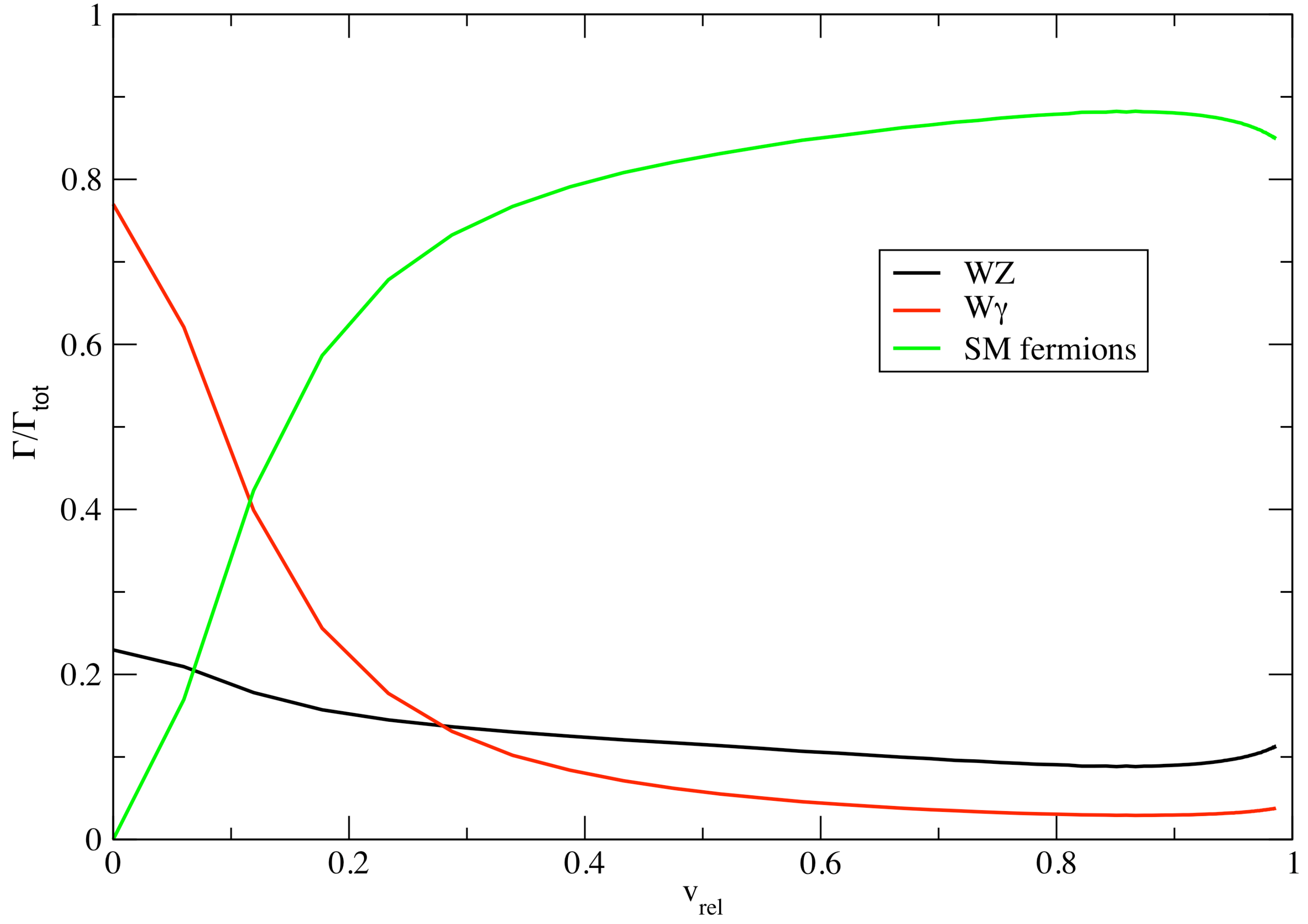
Squirk Annihilation

w/Z.Chacko, H.Goh, R. Harnik, C. Krenke, 0805.4667



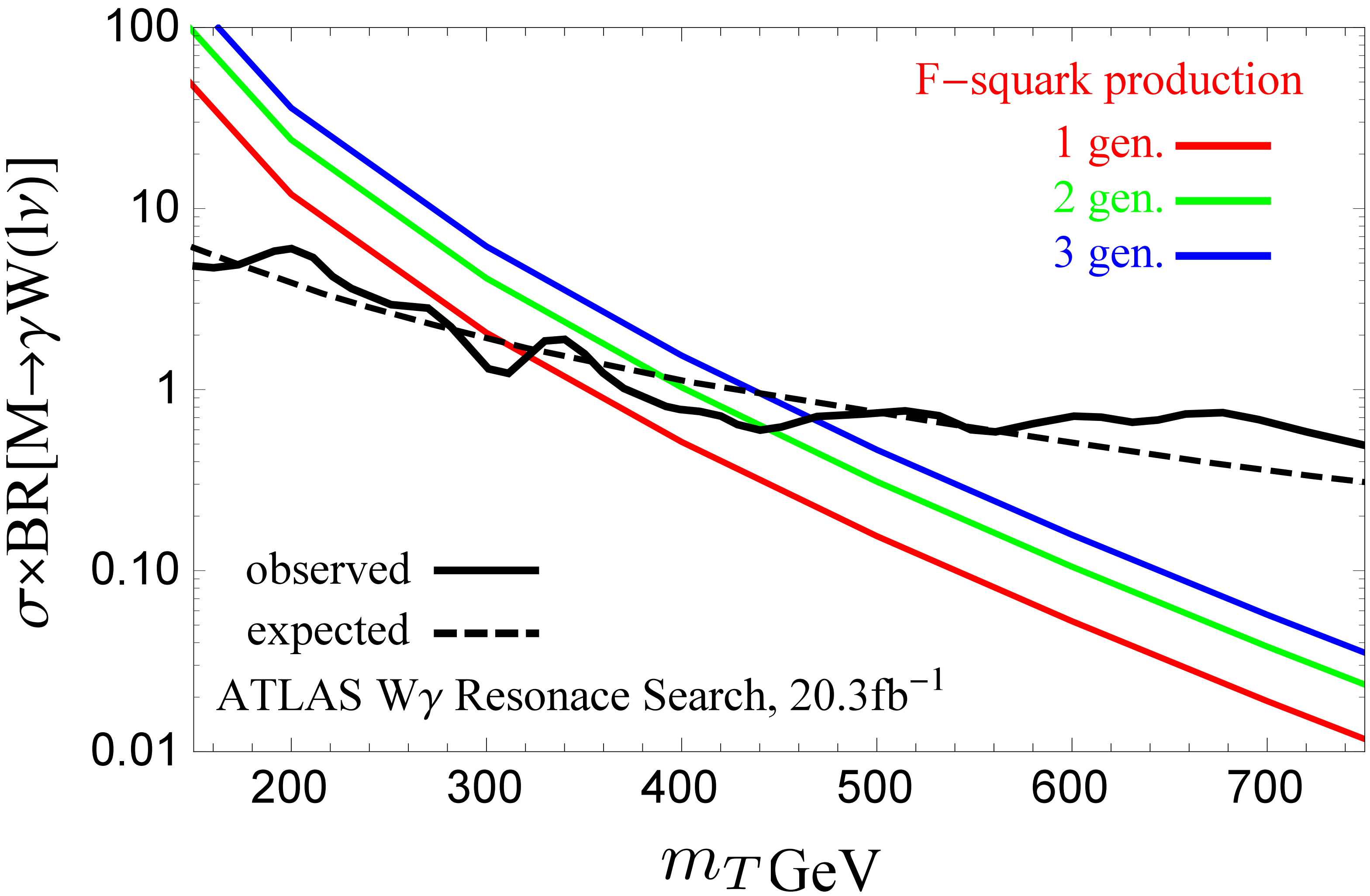
- Annihilation is prompt
- Onium is in s-wave before annihilation

Squirk Annihilation



Bounds from the LHC

w/ Z.Chacko et al., 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 *(in progress)*

In the minimal model, lepton hypermultiplets

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

Zero modes: Leptons F-sleptons

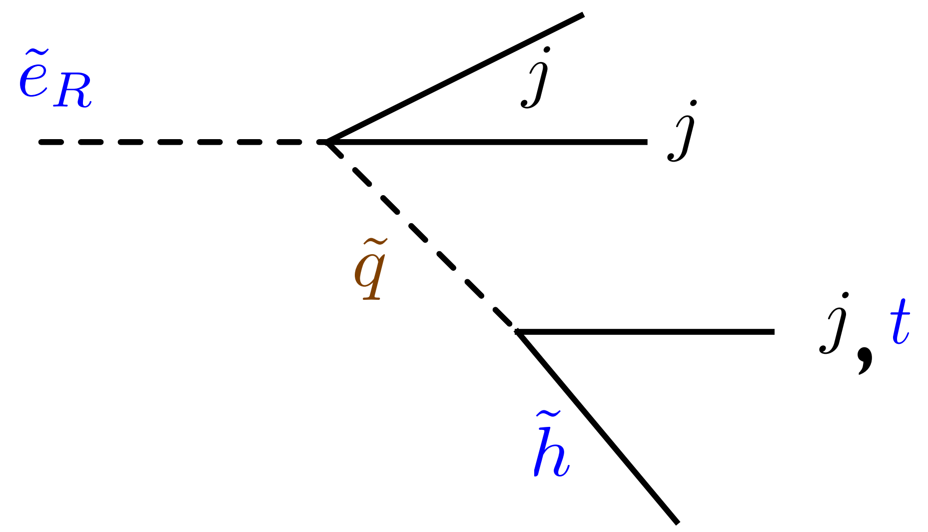
Lightest F-slepton is stable !

Need to add Z_2 preserving HDOs

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

Folded Sleptons Decays

Leading to, e.g.:



- Long lifetime

  goes through detector below or close to top threshold

- Bounds from CMS (*1305.0491*):

$$M_{\tilde{e}_R} > 340\ \mathrm{GeV}$$

Folded Sleptons Decays

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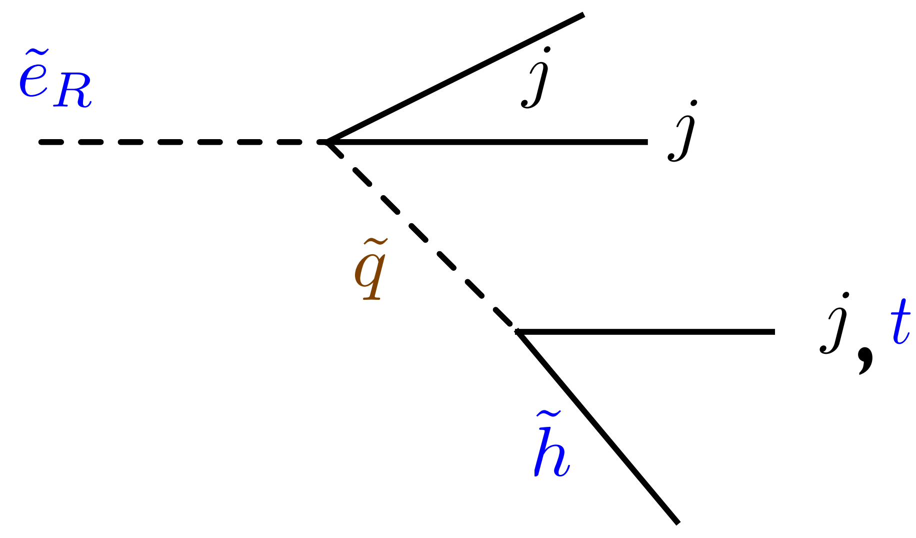

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- Could be an important bound on the naturalness of the model

Folded SUSY Prospects

- LHC searches for $W\,\gamma$

- Model the associated radiation ($\gamma' s$ and glueball)

- Possible signals for glueball decay to SM fermions with displaced vertices *(see David Curtain's talk)*

- Folded sleptons

Conclusions/Outlook

- Folded SUSY: colorless stops

- Experimental signals:
  - ⋆Quirky dynamics: details of highly excited states
  - ⋆ Glueball decay
  - ⋆Folded sleptons

- Model building issues: UV completions, dark matter, …

- For the future (100 TeV): explore the physics of the cut-off.