Neutral Naturalness

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Beyond Standard Model:

where do we go from here?

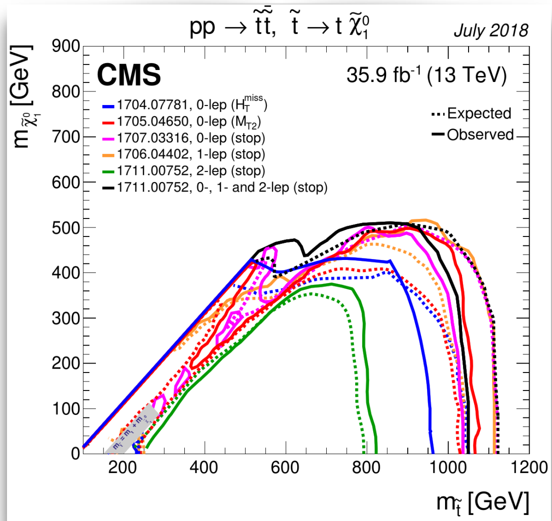
GGI, Arcetri

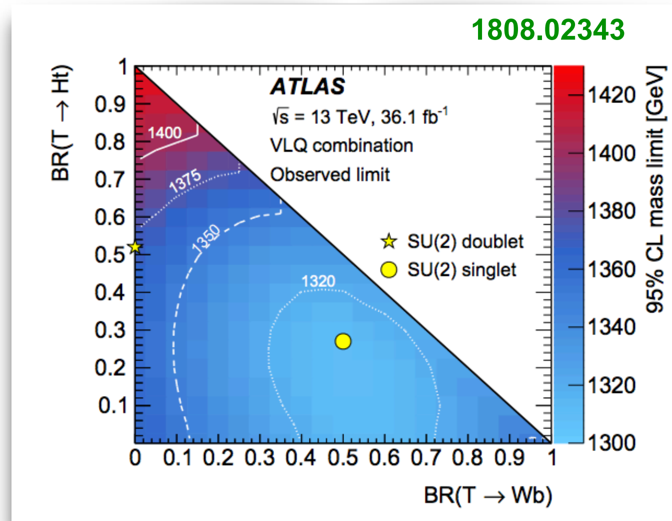
September 18, 2018

Motivation

- So far, no signs of **colored top partners** at LHC

scalars





fermions

see Friday's discussion

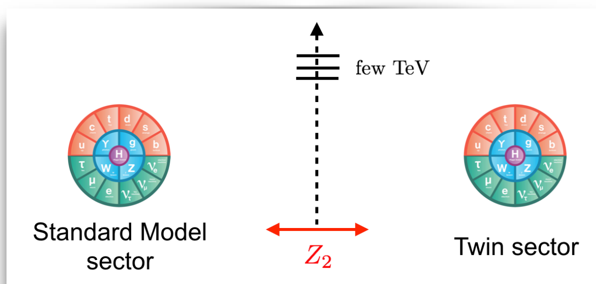
- These bounds have caveats…
- … but they make the following question worth taking seriously:

What if the top partners do not have color charge?

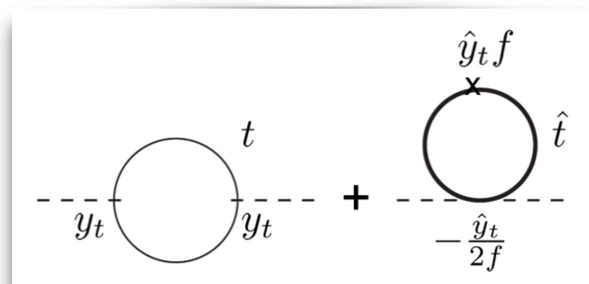
Neutral Naturalness

- Symmetry-based solutions to the little hierarchy problem with **color-less top partners**
- Stabilize weak scale up to $\Lambda \sim 5\text{-}10\ \mathrm{TeV}$, large hierarchy cured by SUSY / compositeness / clockwork / …
- First and best-known example is the **Twin Higgs**

$$y_t \overset{Z_2}{\longleftrightarrow} \hat{y}_t$$



Chacko, Goh, Harnik 2005



- Phenomenology radically non-standard, challenges for collider experiments
- Important interplay with other areas, especially cosmo

The Twin Higgs

- Symmetry breaking pattern

Chacko, Goh, Harnik 2005

7 Goldstones

$$SU(4)/SU(3) \qquad H \sim e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix} \begin{array}{l} \left.\begin{matrix} \\ \\ \end{matrix}\right\} H_A \\ \left.\begin{matrix} \\ \\ \end{matrix}\right\} H_B \end{array}$$

- Top Yukawa couplings $\mathcal{L} = y_t Q_A H_A t_A + \hat{y}_t Q_B H_B t_B$

top partners are **full SM singlets**

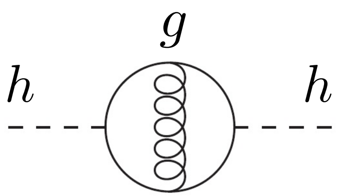
- Quadratic corrections to Higgs potential

$$\delta V = -\frac{N_c}{8\pi^2}\left(y_t^2 \Lambda_A^2 |H_A|^2 + \hat{y}_t^2 \Lambda_B^2 |H_B|^2\right)$$

$A \overset{Z_2}{\longleftrightarrow} B$ ➡ $y_t = \hat{y}_t, \; \Lambda_A = \Lambda_B$ ➡ $\delta V \sim H^\dagger H$ *SU*(4) invariant

Twin Higgs phenomenology

- At one loop, hidden color could be global symmetry. But at two loops



$$\delta m_h^2 \sim \frac{3y_t^2 g_s^2}{4\pi^4}\Lambda^2 \qquad \Delta^{-1} \sim 10\% \text{ for } \Lambda = 5\ \text{TeV}$$

gauge it with $g_s^A \sim g_s^B$, confines at scale $\gtrsim \Lambda_{\mathrm{QCD}}$

Craig, Katz, Strassler, Sundrum 2015

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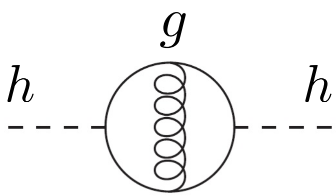

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gauge it with $g_s^A \sim g_s^B$, confines at scale $\gtrsim \Lambda_{\rm QCD}$

Craig, Katz, Strassler, Sundrum 2015

- All new particles are **full SM singlets**

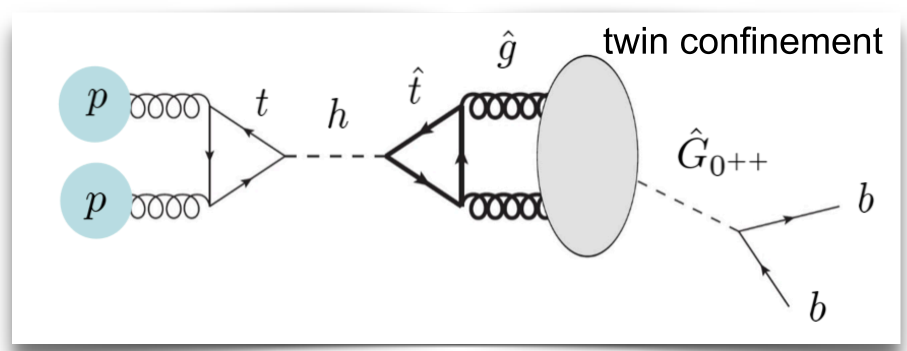
  Only connection between hidden and visible sector is **the Higgs**

- Modifications of couplings to SM $\sim \cos\left(\frac{v_A}{f}\right) \simeq 1 - \frac{v^2}{2f^2}$

- Couplings to light hidden states

$$\sim \sin\left(\frac{v_A}{f}\right) = \frac{v}{f}$$

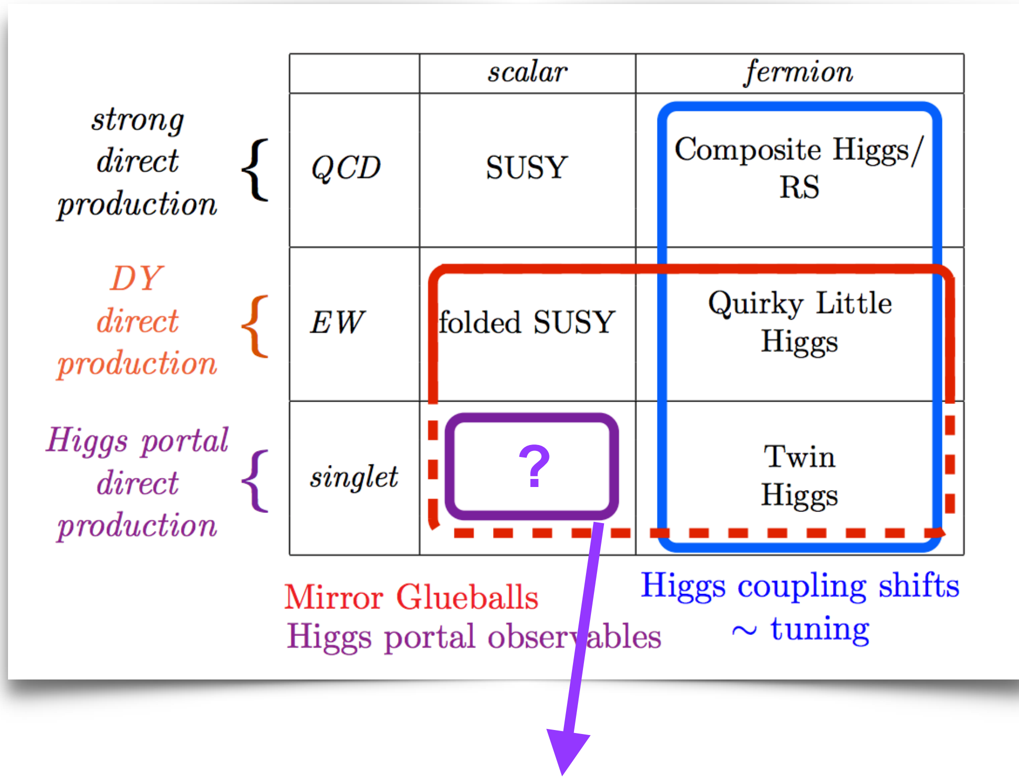
"Higgs decays to hidden valley"



More neutral naturalness

- The **top partner zoo**

Curtin, Verhaaren 2015



Singlet scalar top partners?

More neutral naturalness

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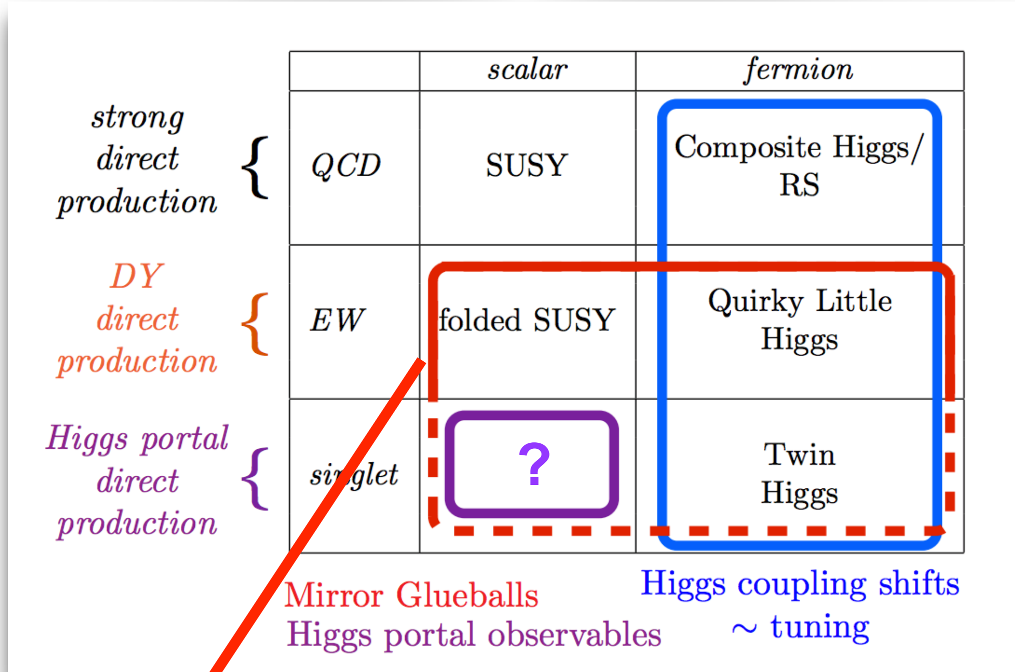

$$\mathcal{L}_{\mathrm{FSUSY}} \sim y_t q_A H u_A^c + y_t^2 \left|\tilde{q}_B H\right|^2 + y_t^2 \left|\tilde{u}_B^c\right|^2 |H|^2$$

The folded stops have hidden color, but need to **carry SM electroweak charges**

More neutral naturalness

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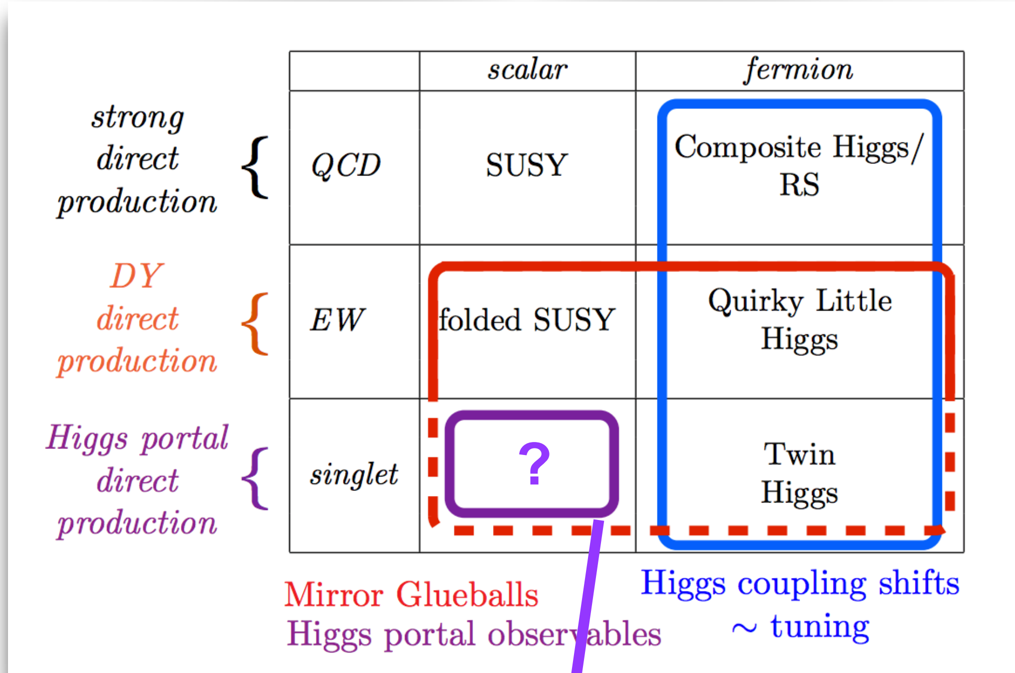

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For fully singlet top partners, need **both** stops coupled in this way

More neutral naturalness

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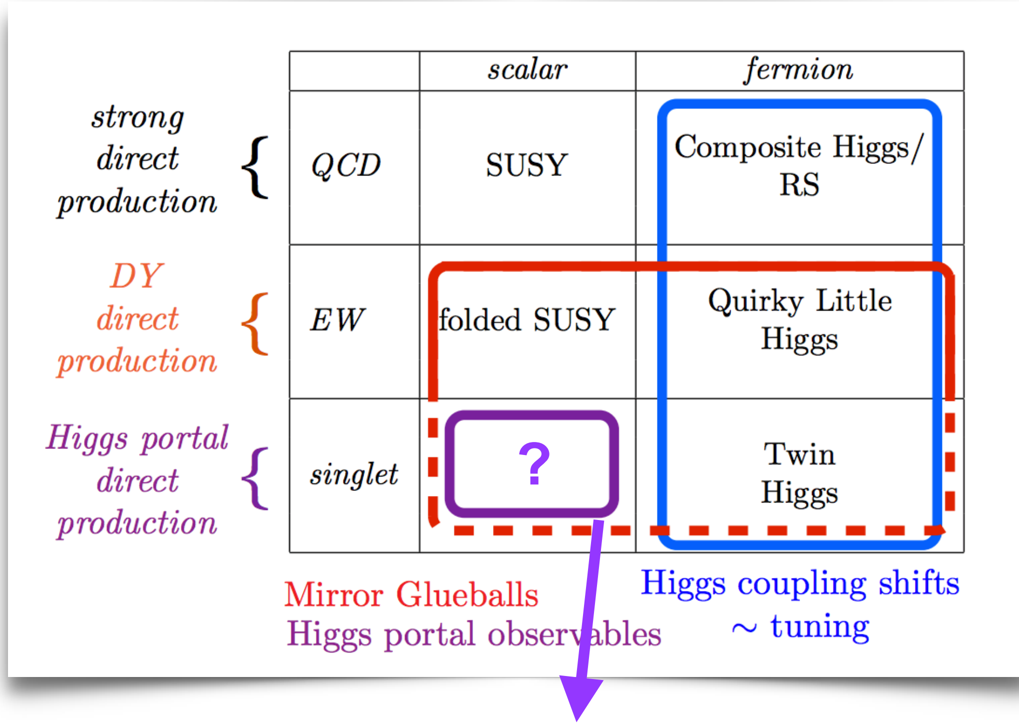


Models with singlet scalar top partners?

From none to two:

- Tripled Top — Cheng, Li, Salvioni, Verhaaren 2018
- Hyperbolic Higgs — Cohen, Craig, Giudice, McCullough 2018

Singlet scalar top partners

- **Tripled Top** — **Cheng, Li, Salvioni, Verhaaren 1803.03651**
- **Hyperbolic Higgs** — **Cohen, Craig, Giudice, McCullough 1803.03647**

- **Very different models:** accidental supersymmetry *vs* accidental $U(2,2)$

  [Twin Higgs: $U(4)$]

- I'll focus mostly on Tripled Top, but also review Hyperbolic Higgs

- Hopefully useful to appreciate (few) similarities and (many) differences

SM-singlet scalar top partners

- Tripled Top
- Hyperbolic Higgs

SM-singlet scalar top partners

- Tripled Top
- Hyperbolic Higgs

Folded Supersymmetry

- **Folded SUSY**

$$SU(3)_A \times {\color{red}SU(3)_B} \times SU(2) \times U(1)$$

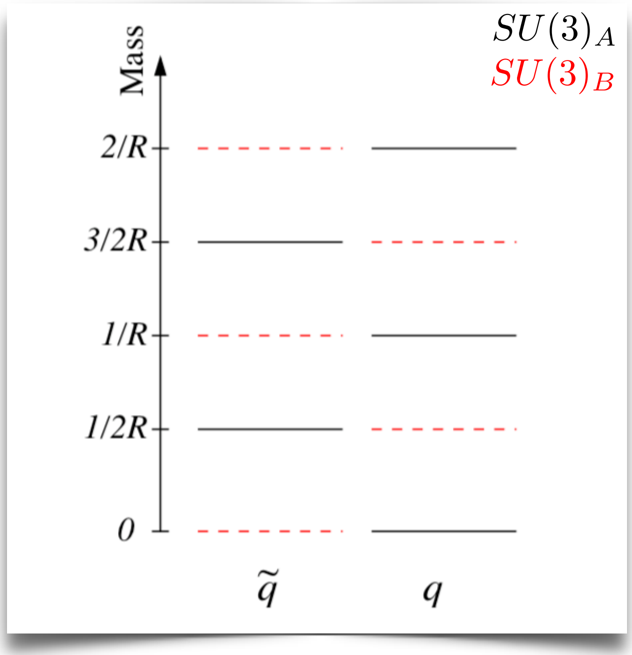
$$Z_2$$

Burdman, Chacko, Goh, Harnik 2006

- Orbifold extra dimension with Scherk-Schwarz SUSY breaking, only SM fermions + folded scalars have **zero modes**

- An **accidental SUSY** is preserved

- Contribution of top sector to Higgs mass vanishes *exactly* at 1-loop



Folded Supersymmetry

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- Contribution of top sector to Higgs mass vanishes *exactly* at 1-loop

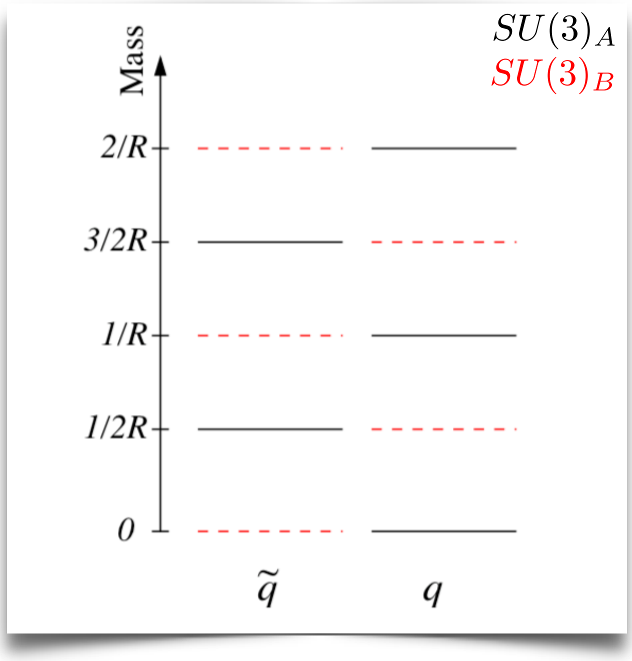
- Protection of Higgs mass is **"too effective:"**

  Gauge/gaugino 1-loop term dominates,

  vacuum preserves EW symmetry

Cohen, Craig, Lou, Pinner 2015

$$\delta m_H^2 \approx +\frac{21\zeta(3)g^2}{64\pi^4 R^2}$$



Folded Supersymmetry

Can we build a model with accidental SUSY in pure 4D?

Z_2

Burdman, Chacko, Goh, Harnik 2006

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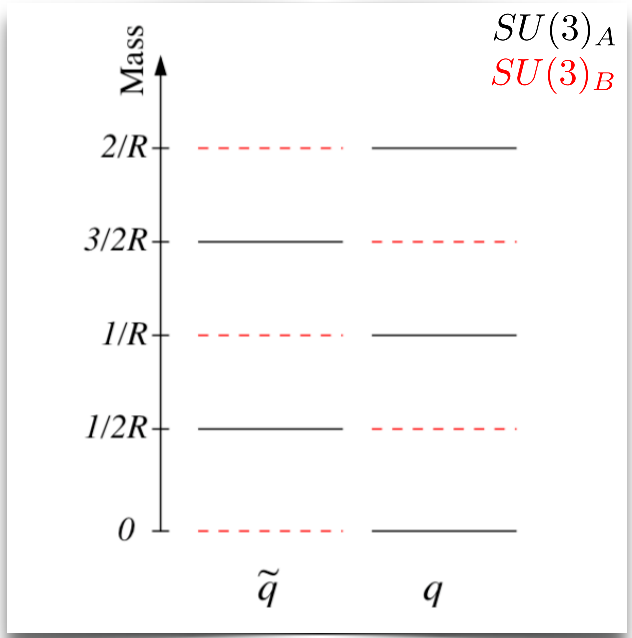

A Tripled Top model

Cheng, Li, Salvioni, Verhaaren 2018

- Add **two** copies of the MSSM top sector,

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

- Superpotential

few TeV

$$W = y_t \left(Q_A H u_A^c + Q_B H u_B^c + Q_C H u_C^c \right) + M (u'_B u_B^c + u'_C u_C^c)$$

$$Z_3 \qquad\qquad Z_2$$

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$$Z_3 \qquad\qquad Z_2$$

- Leading soft masses $V_\mathrm{s} = +\widetilde{m}^2 \left(|\widetilde{Q}_A|^2 + |\tilde{u}_A^c|^2 \right) - \widetilde{m}^2 \left(|\tilde{u}_B^c|^2 + |\tilde{u}_C^c|^2 \right)$

raise SM-colored stops

lower *SU*(2)-singlet hidden stops

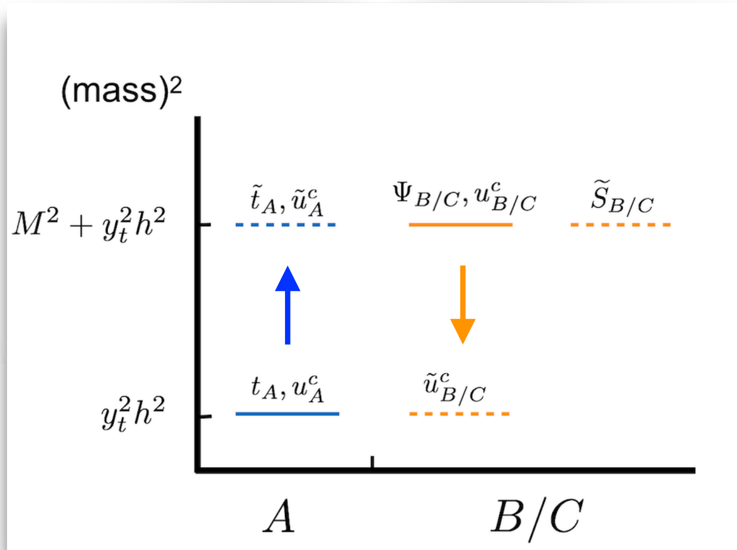
A Tripled Top model

Cheng, Li, Salvioni, Verhaaren 2018

accidental SUSY

for

$\tilde{m} \to M$



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$$W = y_t \left(Q_A H u^c_A + Q_B H u^c_B + Q_C H u^c_C\right) + M\left(u'_B u^c_B + u'_C u^c_C\right)$$

Z_3 $\qquad$ Z_2

- Leading soft masses

$$V_s = +\widetilde{m}^2 \left(|\widetilde{Q}_A|^2 + |\tilde{u}^c_A|^2\right) - \widetilde{m}^2 \left(|\tilde{u}^c_B|^2 + |\tilde{u}^c_C|^2\right)$$

raise SM-colored stops

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A Tripled Top model

- Departures from accidental SUSY limit: $\widetilde{m} \neq M$

  + SUSY mass for doublets, $\omega(Q_B Q_B'^c + Q_C Q_C'^c) \in W$

Both OK as long as $\sqrt{M^2 - \widetilde{m}^2},\ \omega \ll \mathrm{TeV}$, for example

$$\delta m_H^2 \approx -\frac{N_c y_t^2}{8\pi^2}\,\omega^2 \ln \frac{M^2}{\omega^2}$$

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also: **Kats, McCullough, Perez, Soreq, Thaler 2017**

- Hypercharge assignments for hidden fields are **free**, only requirement is invariance of Yukawas

$$W = y_t\,(Q_A H u_A^c + Q_B H u_B^c + Q_C H u_C^c)$$

➡ We can choose $Q_{B,C}, \sim \mathbf{2}_{-1/2}$ $u^c_{B,C} \sim \mathbf{1}_0$ **SM-singlet scalar top partners**

Necessary ingredients

- A particular structure for the soft masses

$$V_{\rm s} = +\widetilde{m}^2\left(|\widetilde{Q}_A|^2 + |\tilde{u}^c_A|^2\right) - \widetilde{m}^2\left(|\tilde{u}^c_B|^2 + |\tilde{u}^c_C|^2\right)$$

Possible origins in next slide

- A “coincidence” $\quad \widetilde{m} \sim M$

soft SUSY-breaking **SUSY**

If no mechanism can explain it, **tuning** $\sim \dfrac{\Delta^2}{M^2} \sim$ few %

$M \sim$ few TeV

$(\Delta = \sqrt{M^2 - \widetilde{m}^2})$

$\Delta \sim$ few $\times$ (100 GeV)

The soft masses?

- Soft masses of equal size and opposite sign?

$$V_{\mathrm{s}} = +\,\widetilde{m}^2\left(|\widetilde{Q}_A|^2 + |\tilde{u}^c_A|^2\right) - \widetilde{m}^2\left(|\tilde{u}^c_B|^2 + |\tilde{u}^c_C|^2\right)$$

1. First guess: *D*-term of an extra *U*(1), charges +1 and -1

But then, Yukawas are not invariant $W \ni y_t\,(Q_A H u^c_A + Q_B H u^c_B + Q_C H u^c_C)$

Insertions of *U*(1)-breaking field will spoil the Z_3

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2. Working model: exploit properties of strongly coupled SUSY gauge theories

Top fields are **composite mesons** $P_i \overline{P}_j$ of s-confining SQCD

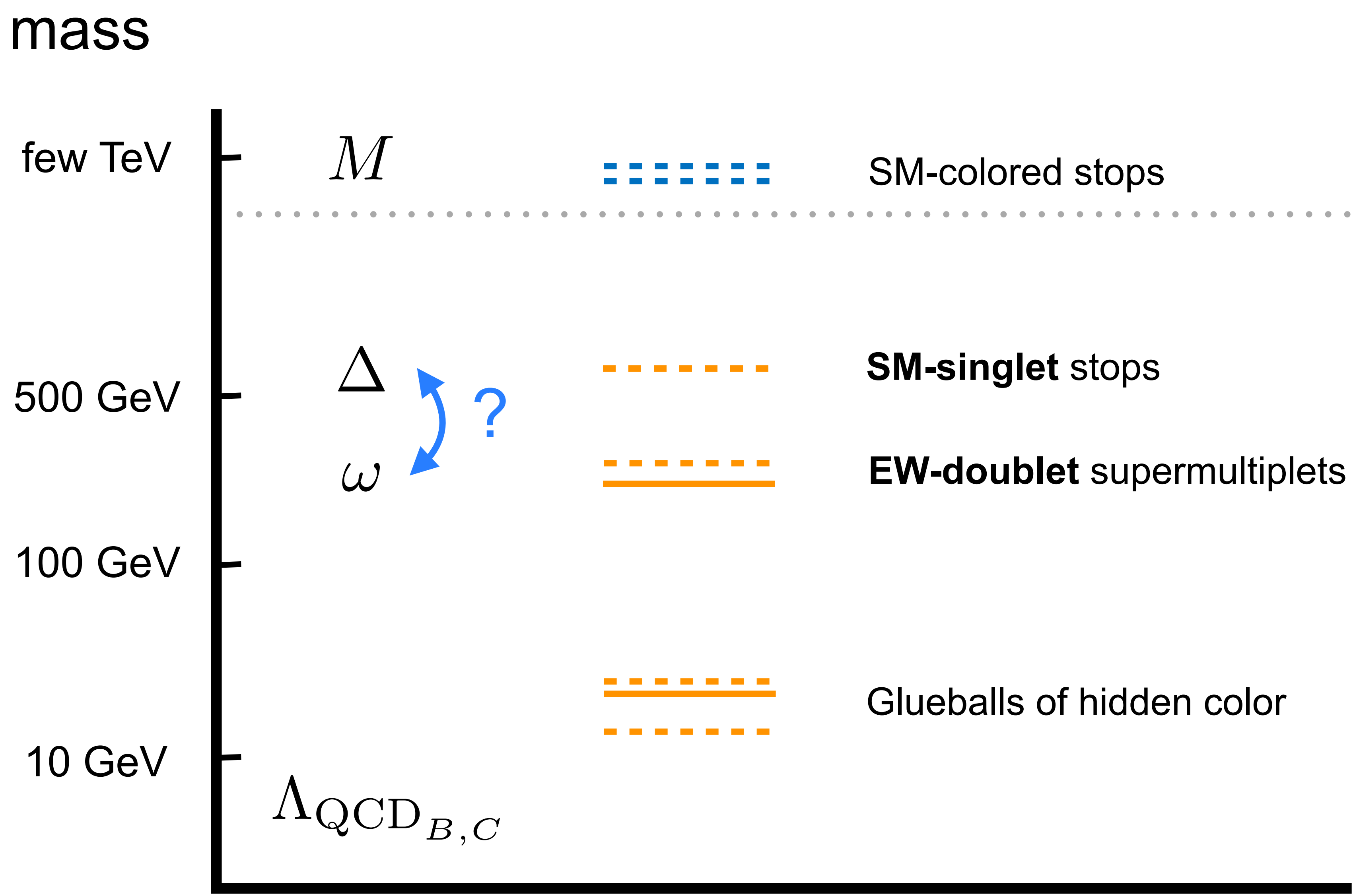
$SU(N), \quad F = N+1$ **Arkani-Hamed, Rattazzi 1998**

$$m^2_{ij} = m^2_{P_i} + m^2_{\overline{P}_j} - \frac{2}{b}\sum_k T_{r_k}(m^2_{P_k} + m^2_{\overline{P}_k})$$

soft masses of IR composites

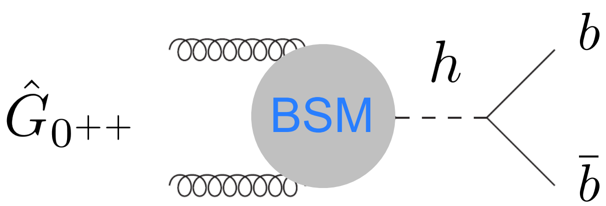
soft masses of UV constituents

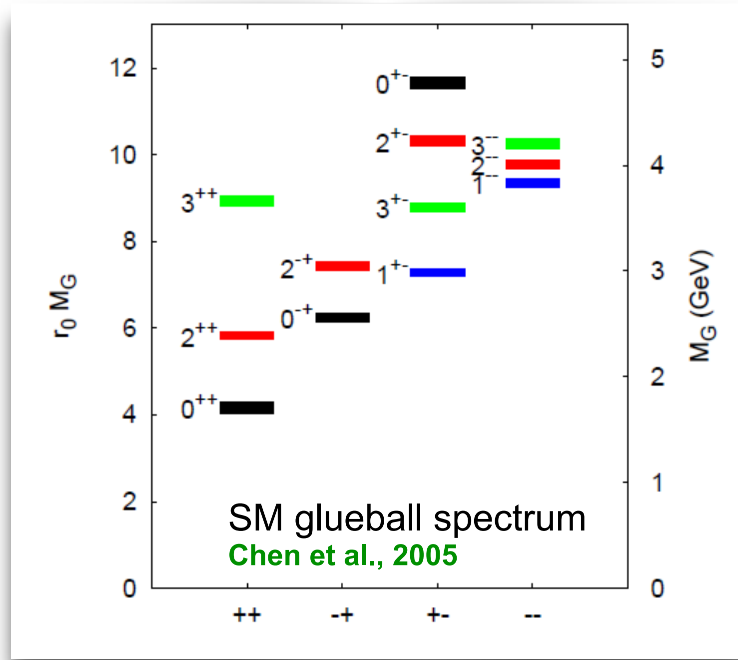
Spectrum of BSM states



Hidden sector confinement

- Hidden QCD confines at few GeV
- No light matter, low-energy spectrum is made of **glueballs**
- Lightest glueball has $J^{PC} = 0^{++}$, decays to SM via mixing with the Higgs





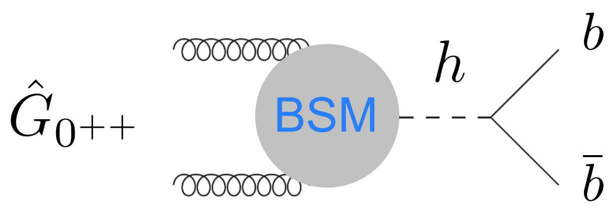
$$c\tau_{0++} \sim 1.2\,\mathrm{m} \left(\frac{5\ \mathrm{GeV}}{\Lambda_{\mathrm{QCD}_{B,C}}}\right)^7 \left(\frac{\omega}{500\ \mathrm{GeV}}\right)^4 \left(\frac{\Delta}{300\ \mathrm{GeV}}\right)^4 \left(\frac{100\ \mathrm{GeV}}{\delta m}\right)^4$$

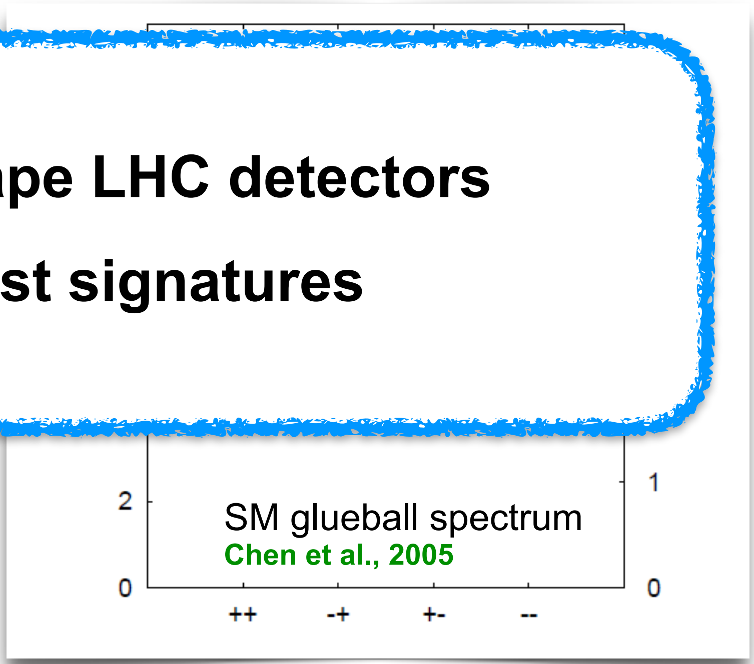
- Lifetime is much **longer** than e.g. in Folded SUSY (~ mm)
- **Large uncertainty** because depends on subleading soft masses

Hidden sector confinement

Assume hidden glueballs escape LHC detectors

Look for other, more robust signatures





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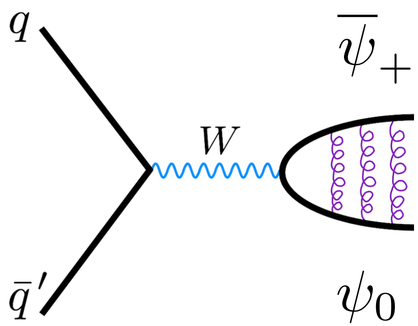
Spectrum of BSM states: $\Delta > \omega$

$\Delta > \omega$: quirk phenomenology

- If $\Delta > \omega$, then target are the EW-doublet supermultiplets with mass $\sim \omega$
- Fermions have larger Drell-Yan production than scalars,

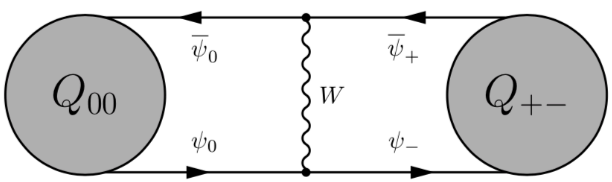
$$Q_{B,C} \sim \mathbf{2}_{-1/2} \sim \begin{pmatrix} \psi_0 \\ \psi_- \end{pmatrix}$$



"quirky" bound state

de-excites down to ground state via emission of **soft photons**

$$\hat{s} > 4m_\psi^2$$



(electrically-neutral pairs too, via mass mixing)

Kang, Luty 0805.4642
Burdman et al. 0805.4667

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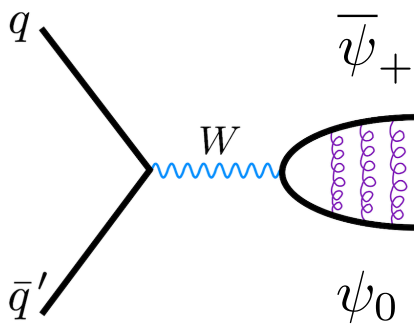

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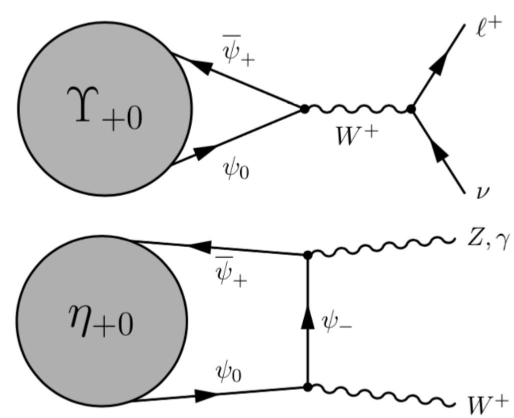
annihilation of $n = 1$ states



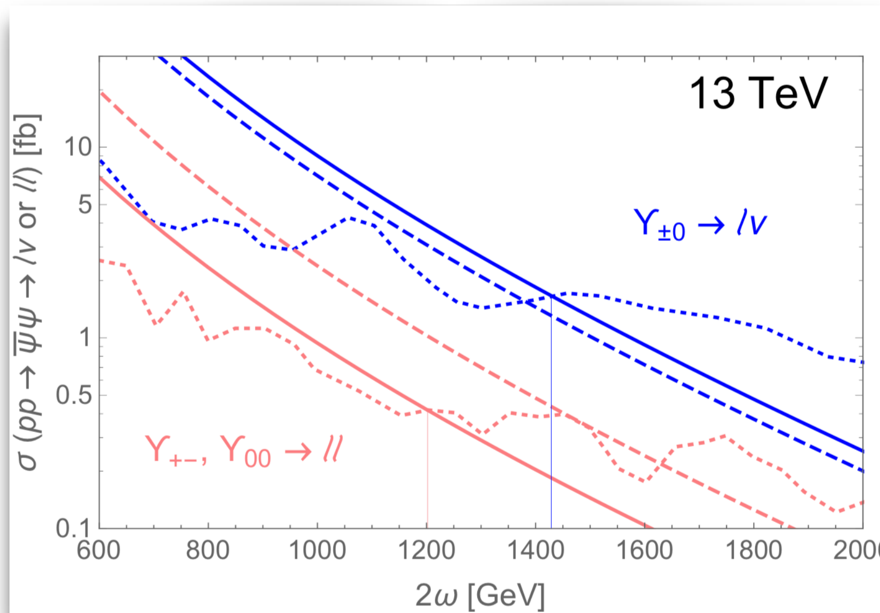
resonant signals

$\Delta > \omega$: quirk phenomenology

- Strongest bounds come from **charged channel** (decays to pure hidden gluons forbidden)

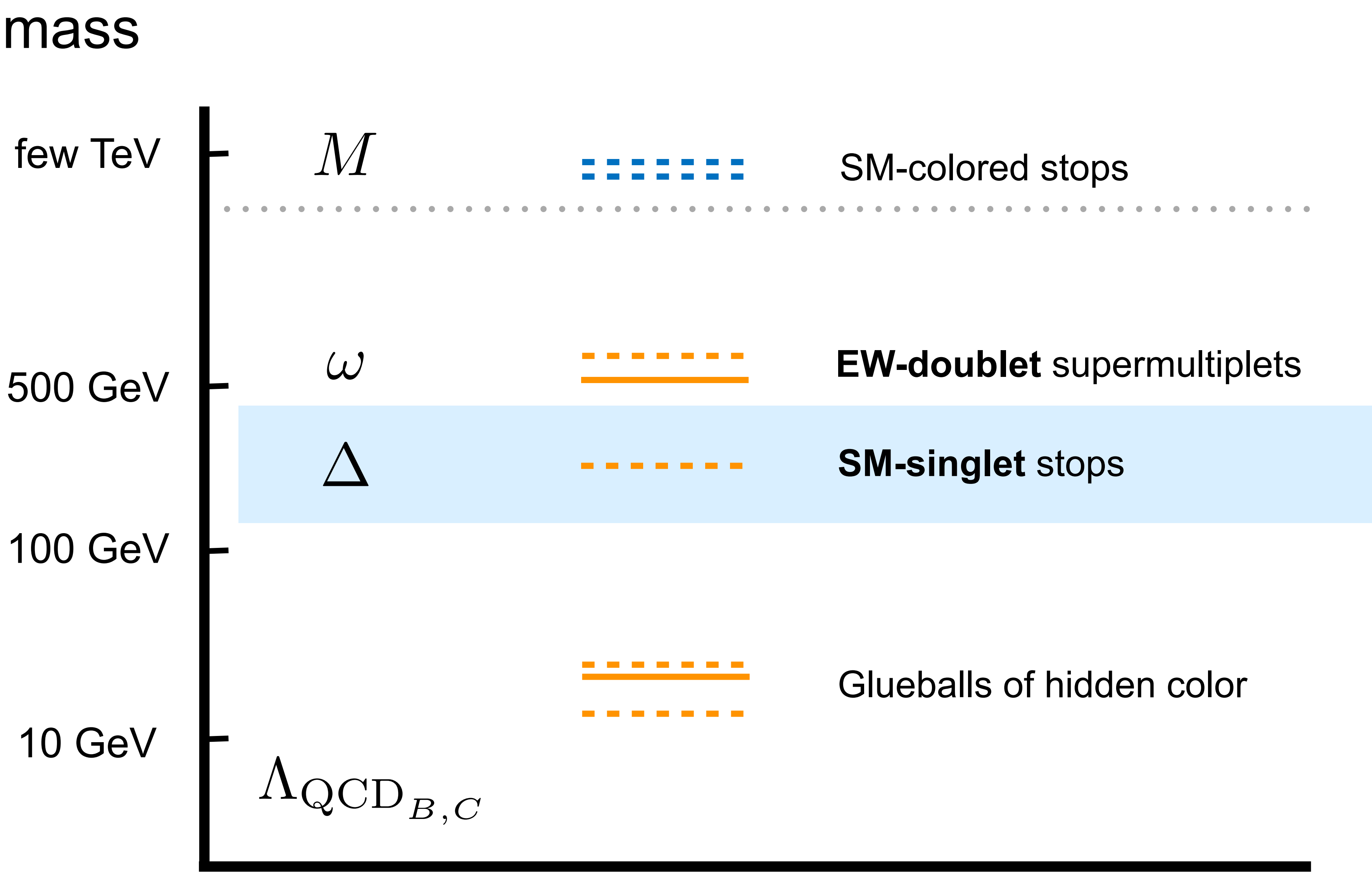
$$\omega \gtrsim 700\ \mathrm{GeV}$$

from $\Upsilon_{+0} \to \ell\nu$



- Neutral channels give $\omega \gtrsim 600\ \mathrm{GeV}$ from $\eta_{+-} \to \gamma\gamma$, $\Upsilon_{+-,00} \to \ell\ell$

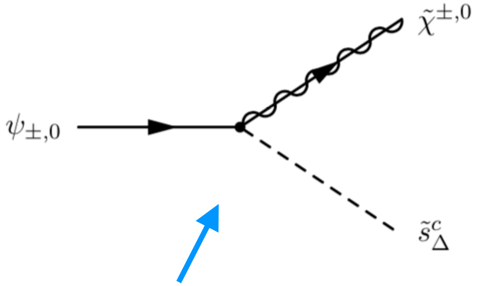
Spectrum of BSM states: $\Delta < \omega$



$\Delta < \omega$: light singlet scalars

- If $\Delta < \omega$, the **singlet scalars** are at the bottom of matter spectrum in hidden sectors
- Dominant production of heavier EW-doublet states, they decay down to light scalar $\tilde{s}^c_\Delta$

typical LHC event results **in formation of $\tilde{s}^c_\Delta \tilde{s}^{c*}_\Delta$ "squirky" pair**



decay of fermions requires light neutralino

How does the $\tilde{s}^c_\Delta \tilde{s}^{c*}_\Delta$ system de-excite?

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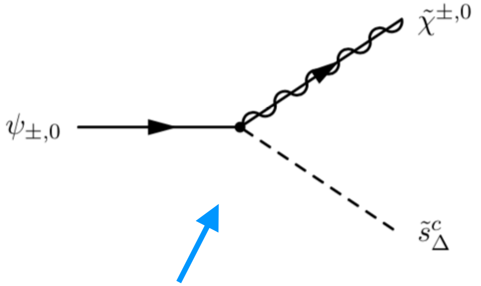

decay of fermions requires light neutralino

How does the $\tilde{s}^c_\Delta \tilde{s}^{c*}_\Delta$ system de-excite?

Glueball radiation is prompt, but does not complete de-excitation

Residual kinetic energy

$$K \lesssim m_0 \simeq 7\Lambda_{\mathrm{QCD}_{B,C}} \quad \longleftrightarrow \quad n \sim 10$$

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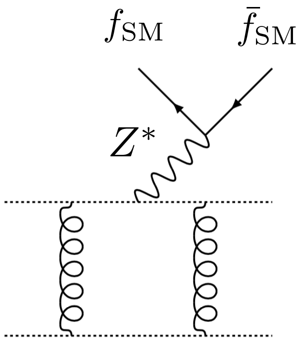


The Higgs VEV gives a **small mass mixing** of singlet and doublet scalars, $\tilde{s}^{c}_{\Delta}$ inherits **coupling to the Z**

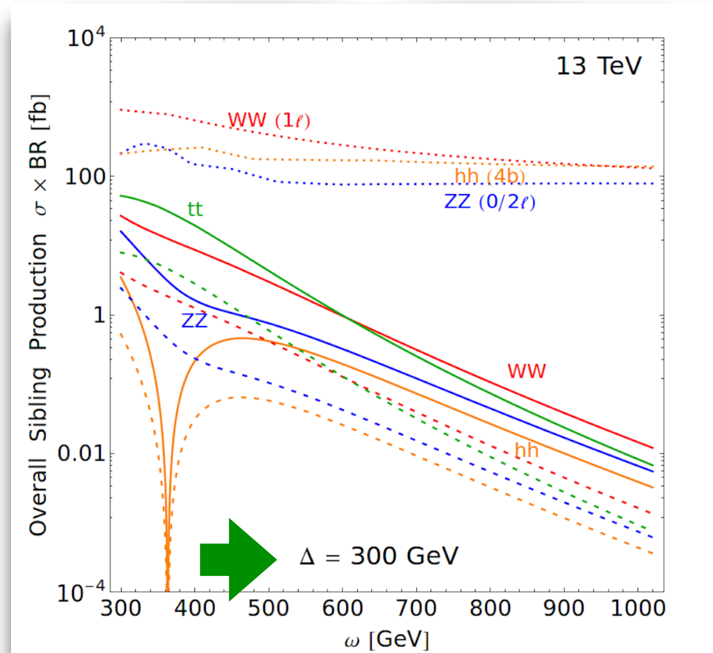
$$t^{Z}_{\text{de-excite}} \sim \frac{32}{27\pi^4}\frac{\cos^4\theta_w}{\alpha_W^2\sin^4\phi_R N_f}\frac{m_Z^4 m_{\tilde{s}^c_\Delta}^4 m_0^3}{\sigma^6} \sim 4\cdot 10^{-13}\,\mathrm{s}\left(\frac{5\,\mathrm{GeV}}{\Lambda_{\mathrm{QCD}_{B,C}}}\right)^9\left(\frac{m_{\tilde{s}^c_\Delta}}{300\,\mathrm{GeV}}\right)^4$$

~ 0.1 mm, still prompt

$\Delta < \omega$: light singlet scalars

- Lowest-lying bound state is 0^{++}
- Annihilates dominantly to hidden glueballs, BR(SM) ~ % level

see also: **Burdman, Lichtenstein 2018**



➡ Resonant signals well below current sensitivity

➡ **Very light singlets are allowed**

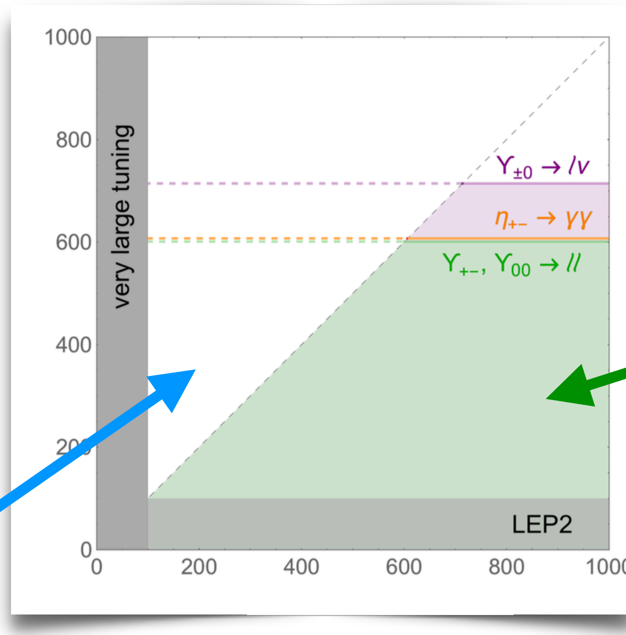
- Extra particles from cascade decays may give further constraints

Cheng, Li, Salvioni, Verhaaren, work in progress

Tripled Top parameter space

ω [GeV]

(EW-charged supermultiplets)



Drell-Yan
+
quirk
resonant signals

cascade decays
to light singlets

Δ [GeV]

(singlet scalar top partners)

Cheng, Li, Salvioni, Verhaaren 2018

Higgs quartic and *T* parameter

- Higgs quartic: for example $\lambda \simeq \frac{N_c y_t^4}{16\pi^2}\left(\frac{3}{2} + \log\frac{\omega^2}{m_t^2}\right) + \frac{m_Z^2}{2v^2}\cos^2(2\beta)$

$(\Delta \ll \omega)$

Numerically,

$$M = 2\ \mathrm{TeV}, \quad \Delta = 300\ \mathrm{GeV}, \quad \omega = 500\ \mathrm{GeV} \quad \rightarrow \quad \lambda \lesssim 0.14$$

but, 2-loop corrections important…

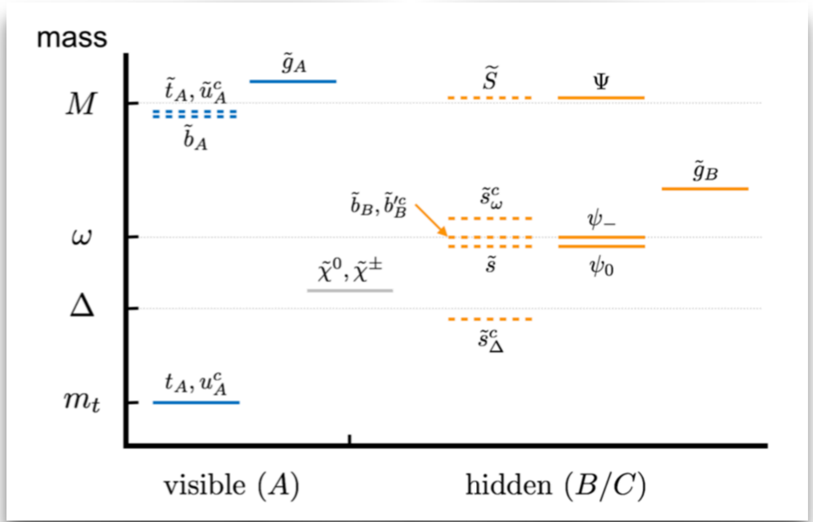
- *T* parameter: leading contribution comes from light scalars,

$$\widehat{T}_{s^c,B+C} \approx + \frac{N_c y_t^2}{48\pi^2}\frac{m_t^2}{\omega^2}$$

$$\omega = 500\ \mathrm{GeV}, \quad \Delta = 300\ \mathrm{GeV}$$

$$\rightarrow \quad \widehat{T}_{s^c,B+C} \approx +4 \times 10^{-4}$$

under control



SM-singlet scalar top partners

- Tripled Top
- **Hyperbolic Higgs**

The Hyperbolic Higgs

Cohen, Craig, Giudice, McCullough 2018

- Tree-level potential with flat direction

$$V = \lambda \left(|H_{\mathcal{H}}|^2 - |H|^2 - f^2\right)^2$$

Accidentally *U*(2,2) symmetric [not a symmetry of full theory]

- Each Higgs charged under its own $SU(2) \times U(1)$

One massless mode,

$$h_{\rm SM} = \cos\theta \, h + \sin\theta \, h_{\mathcal{H}} \qquad\qquad \tan\theta = \frac{v}{v_{\mathcal{H}}}$$

The Hyperbolic Higgs

Cohen, Craig, Giudice, McCullough 2018

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$$V = \lambda \left(|H_{\mathcal{H}}|^2 - |H|^2 - f^2 \right)^2$$

Accidentally *U*(2,2) symmetric [not a symmetry of full theory]

- Couplings to matter

Z_2 symmetry

$$\mathcal{L} = (y_t H \psi_Q \psi_{U^c} + \text{h.c.}) + y_t^2 \left(|H_{\mathcal{H}} \cdot \widetilde{Q}_{\mathcal{H}}|^2 + |H_{\mathcal{H}}|^2 |\widetilde{U}^c_{\mathcal{H}}|^2 \right)$$

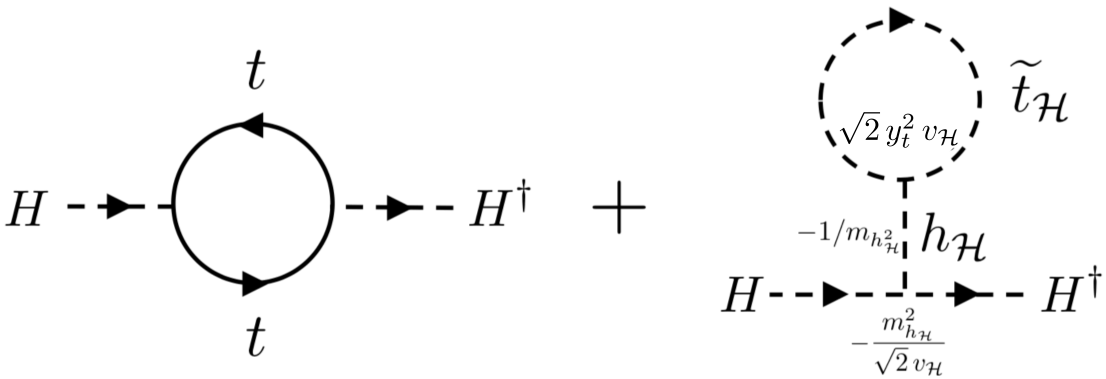
quadratic 1-loop correction $\Rightarrow$ $\delta V \sim \frac{N_c y_t^2}{16\pi^2} \Lambda^2 \left(|H_{\mathcal{H}}|^2 - |H|^2 \right)$

respects *U*(2,2)

The Hyperbolic Higgs

Cohen, Craig, Giudice, McCullough 2018

- Diagrammatic cancellation

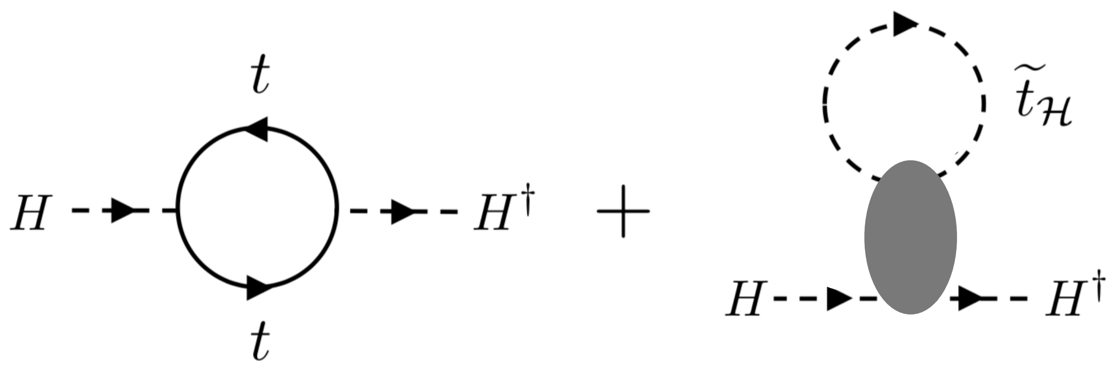


$$\mathcal{L} = (y_t H \psi_Q \psi_{U^c} + \text{h.c.}) + y_t^2 \left(|H_{\mathcal{H}} \cdot \widetilde{Q}_{\mathcal{H}}|^2 + |H_{\mathcal{H}}|^2 |\widetilde{U}^c_{\mathcal{H}}|^2 \right)$$

The Hyperbolic Higgs

Cohen, Craig, Giudice,
McCullough 2018

- Diagrammatic cancellation

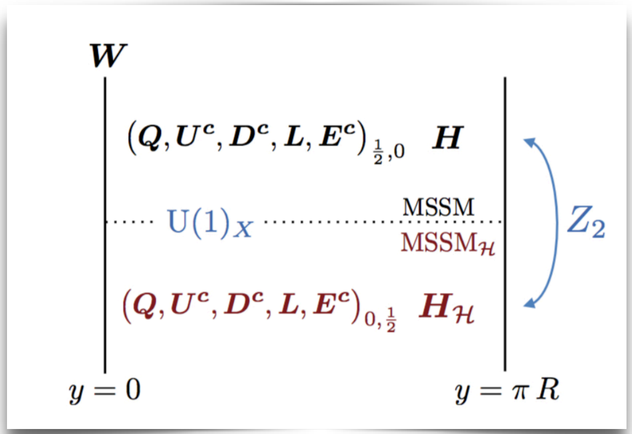


Integrate out heavy radial mode

$$\mathcal{L}_{\text{eff}} = (y_t H \psi_Q \psi_{U^c} + \text{h.c.}) + y_t^2 \, |H|^2 \left(|\widetilde{t}^L_{\mathcal{H}}|^2 + |\widetilde{t}^R_{\mathcal{H}}|^2 \right)$$

$SU(2)_{\mathcal{H}}$ broken below $v_{\mathcal{H}}$

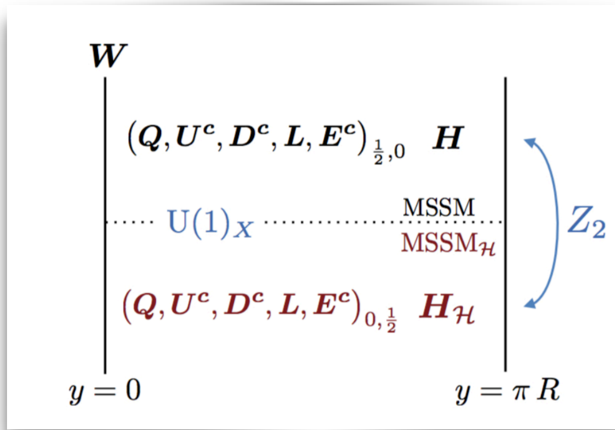
A 5D SUSY completion



$$\Lambda \sim 1/R$$

- *U*(1)$_X$ *D*-term potential $\quad V_X = \frac{g_X^2}{2}\,\xi(|H_{\mathcal{H}}|^2 - |H|^2 - f_X^2)^2$

A 5D SUSY completion



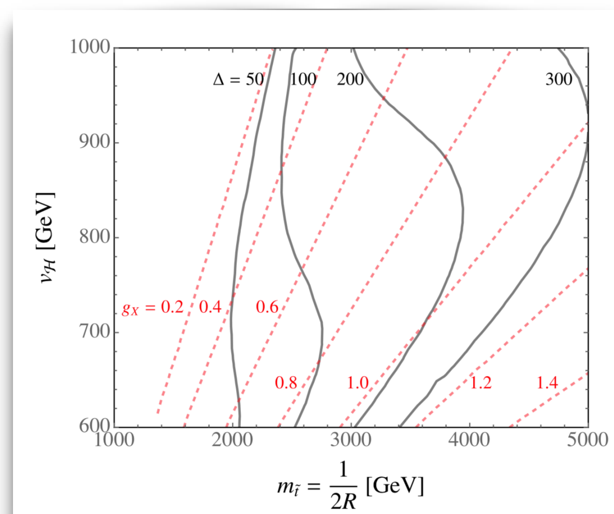
$$\Lambda \sim 1/R$$

- *U*(1)$_X$ *D*-term potential $$V_X = \frac{g_X^2}{2}\,\xi(|H_{\mathcal{H}}|^2 - |H|^2 - f_X^2)^2$$

- SUSY breaking gives at 1-loop

$$V_{U(\cancel{2},2)} \sim \frac{g_X^2 M_X^2}{16\pi^2}\left(|H|^2 + |H_{\mathcal{H}}|^2\right)$$

T parameter ➡ $$\frac{M_X}{g_X} \gtrsim 8.6\ \mathrm{TeV}$$



Phenomenology

- SM and hyperbolic Higgses mix, **universal coupling modification**

$$\frac{y_{hPP}}{y_{hPP}^{\rm SM}} = \cos\theta \simeq 1 - 1.5\%\,\rho^2 \left(\frac{\rm TeV}{v_{\mathcal{H}}}\right)^2$$

+ non-universal correction for the top

$$m_t(H) = \frac{1}{\pi R}\arctan(\pi R\, y_t |H|) \quad \Rightarrow \quad -\pi^2 R^2 y_t^2 v^2 \simeq -1.2\% \left(\frac{5\ \rm TeV}{1/R}\right)^2$$

- Higgs decays to hyperbolic glue,

$$\mathrm{BR}(h_{\rm SM} \to g_{\mathcal{H}} g_{\mathcal{H}}) \sim 2 \times 10^{-5} \rho^2 \left(\frac{\rm TeV}{v_{\mathcal{H}}}\right)^4$$

Summary

- **Singlet scalar top partners** are “most elusive” incarnation of naturalness
- First models written down just this year

- **Tripled Top:** accidental SUSY à la Folded SUSY, Z_3 symmetry

  No Higgs couplings modifications,

  but supermultiplets with EW charge provide portal to hidden sectors

  Roles of EW doublets and singlets can be switched, new pheno (ongoing)

Cheng, Li, Salvioni, Verhaaren 2018 + in progress

- **Hyperbolic Higgs:** flat direction with accidental $U(2,2)$, with Z_2

  Higgs couplings modifications, pheno mostly unexplored

Cohen, Craig, Giudice, McCullough 2018

- Both models have residual tuning of few % (for very different reasons)

Backup

Spontaneous breaking of hidden color?

Cohen, Craig, Giudice, McCullough 2018

- What if the hyperbolic stops get VEVs? $\langle \tilde{t}_{\mathcal{H}}^{L,R} \rangle \neq 0$

  - 8 dofs eaten by massive $SU(3)_{\mathcal{H}}$ gluons
  - radial modes mix with the Higgs

  $\rightarrow$ *Higgs is partly its own top partner*

- No hidden confinement, **collider pheno strongly altered**

Spontaneous breaking of hidden color?

Cohen, Craig, Giudice, McCullough 2018

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    $\rightarrow$ *Higgs is partly its own top partner*

- No hidden confinement, **collider pheno strongly altered**

- For Tripled Top: only **one** light singlet stop in each sector, expect

$$SU(3)_B \xrightarrow{\langle \tilde{u}^c_B \rangle} SU(2)_B$$

depending on VEV size, *SU*(2) glueballs may still be at bottom of the spectrum

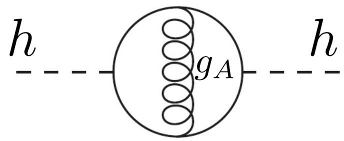
SU(N) glueballs: **Teper hep-th/9812187**

Spontaneous breaking of hidden color?

Craig, Katz, Strassler, Sundrum 2015

- **Broader question:**

Gauged and unbroken hidden $SU(3)$ motivated by 2-loop naturalness,



$$\delta m_h^2 \sim \frac{3 y_t^2 g_s^2}{4\pi^4}\Lambda^2$$

$$\Delta^{-1} \sim 10\% \text{ for } \Lambda = 5 \text{ TeV}$$

(numerically, ~ weak gauge)

Yields **very rich phenomenology**, hidden hadron signatures

- Does relaxing this (motivated) assumption lead to *different* signatures, as opposed to just *subtracting* some?

If so, may be worthwhile to pursue…

Batell, McCullough 2015

The soft masses

Cheng, Li, Salvioni, Verhaaren, 1803.03651

$SU(2) \qquad F = 3$

$$
\begin{array}{c|c}
 & \widetilde{m}^2_P \quad \widetilde{m}^2_P \quad \widetilde{m}^2_P \\
\begin{array}{c} \widetilde{m}^2_{\overline{P}_2} \\ \widetilde{m}^2_{\overline{P}_2} \\ \widetilde{m}^2_{\overline{P}_1} \end{array} & \left(\begin{array}{ccc} & Q_A & \\ & & \\ \hline & & \end{array} \right)
\end{array}
\qquad
\begin{array}{c|c}
 & \widetilde{m}^2_P \quad \widetilde{m}^2_P \quad \widetilde{m}^2_P \\
\begin{array}{c} \widetilde{m}^2_{\overline{P}_2} \\ \widetilde{m}^2_{\overline{P}_2} \\ \widetilde{m}^2_{\overline{P}_1} \end{array} & \left(\begin{array}{ccc} & u^c_A & \\ \hline & & \\ & & \end{array} \right)
\end{array}
\qquad
\begin{array}{c|c}
 & \widetilde{m}^2_P \quad \widetilde{m}^2_P \quad \widetilde{m}^2_P \\
\begin{array}{c} \widetilde{m}^2_{\overline{P}_1} \\ \widetilde{m}^2_{\overline{P}_1} \\ \widetilde{m}^2_{\overline{P}_2} \end{array} & \left(\begin{array}{ccc} & u^c_{B,C} & \\ \hline & & \\ & & \end{array} \right)
\end{array}
$$

$$m^2_{ij} = m^2_{P_i} + m^2_{\overline{P}_j} - \frac{2}{b} \sum_k T_{r_k} (m^2_{P_k} + m^2_{\overline{P}_k})$$

$(\text{e.g.:} \;\; m^2_{\overline{P}_2} > 0 \, , \quad m^2_{\overline{P}_1} = 0)$

$$V_{\rm s} = + \widetilde{m}^2 \left(|\widetilde{Q}_A|^2 + |\widetilde{u}^c_A|^2 \right) - \widetilde{m}^2 \left(|\widetilde{u}^c_B|^2 + |\widetilde{u}^c_C|^2 \right)$$

- Z_3 - symmetric Yukawas

$$W \ni \frac{g_t}{\Lambda^2_{\rm UV}} P \overline{P} P \overline{P} H \quad \longrightarrow \quad y_t \sim g_t \frac{\Lambda^2_G}{\Lambda^2_{\rm UV}}$$

Soft masses of composite mesons

- s-confinement = smooth confinement without chiral symmetry breaking and with non-vanishing confining superpotential

Arkani-Hamed, Rattazzi
hep-th/9804068

- In the UV, from $P \to \sqrt{Z}\, P$

$$\frac{1}{4}\int d^2\theta\, S(\mu_{\rm UV}) W^2 + {\rm h.c.} + \int d^4\theta Z\, F\left(S(\mu_{\rm UV}) + S^\dagger(\mu_{\rm UV}) - \frac{T}{4\pi^2}\ln Z \right) P^\dagger e^V P$$

- Anomalous *U*(1) symmetry $Z \to Z\chi\chi^\dagger, \quad P \to P/\chi, \quad S(\mu_{\rm UV}) \to S(\mu_{\rm UV}) + \dfrac{T}{4\pi^2}\ln\chi$

  Z is promoted to background vector superfield

- Only invariant object is $I = \Lambda_h^\dagger Z^{2T/b}\Lambda_h \qquad (\Lambda_h = \mu_{\rm UV} e^{-8\pi^2 S/b})$

  and $m_P^2(\mu_{\rm UV}) = -[\ln Z]_{\theta^2\bar\theta^2} - [\ln F(\mu_{\rm UV})]_{\theta^2\bar\theta^2} \xrightarrow{\mu_{\rm UV}\to\infty} -[\ln Z]_{\theta^2\bar\theta^2}$

- In the IR, effective Kähler potential for mesons starts with

$$K \supset c_{M_{ij}} \frac{M_{ij}^\dagger Z_i Z_{\bar j} M_{ij}}{I} + \cdots \quad \Rightarrow \quad m^2_{M_{ij}}\Big|_{\mu_{\rm IR}\to 0} = -\left[\ln\frac{Z_i Z_{\bar j}}{I}\right]_{\theta^2\bar\theta^2} = -[\ln Z_i]_{\theta^2\bar\theta^2} - [\ln Z_{\bar j}]_{\theta^2\bar\theta^2} + [\ln I]_{\theta^2\bar\theta^2}$$

$$= m^2_{P_i} + m^2_{\bar P_j} - \frac{2}{b}\sum_k T_{r_k}\left(m^2_{P_k} + m^2_{\bar P_k}\right)$$