Probing SUSY in its most elusive guises

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RPP

LPC, January 24, 2019

based on 1803.03651 [JHEP] + work in progress

with Hsin-Chia Cheng, Chris Verhaaren (UC Davis), Lingfeng Li (HKUST)

Motivation: naturalness

- Supersymmetry or new strong dynamics are most solid approaches to Higgs naturalness problem

- Very different, but share one crucial feature for phenomenology: top loop is cut off by new colored particles, the "top partners"

$$U^c \sim \begin{pmatrix} u^c \\ \tilde{u}^c \end{pmatrix}$$

top squark

SUSY **commutes** with gauge $SU(3)_c$

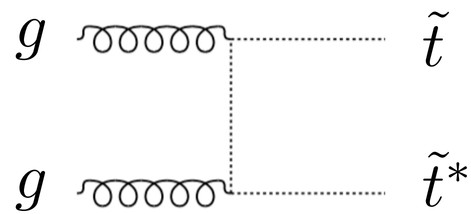
$$\mathcal{L}_{\rm mix} \sim y\, u^c \mathcal{O}_u + \text{h.c.}$$

fermionic operator

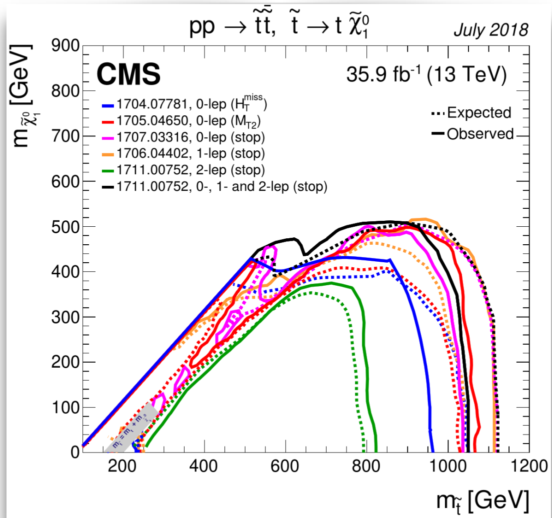
for composite Higgs, partial compositeness forces the strong sector to have color symmetry

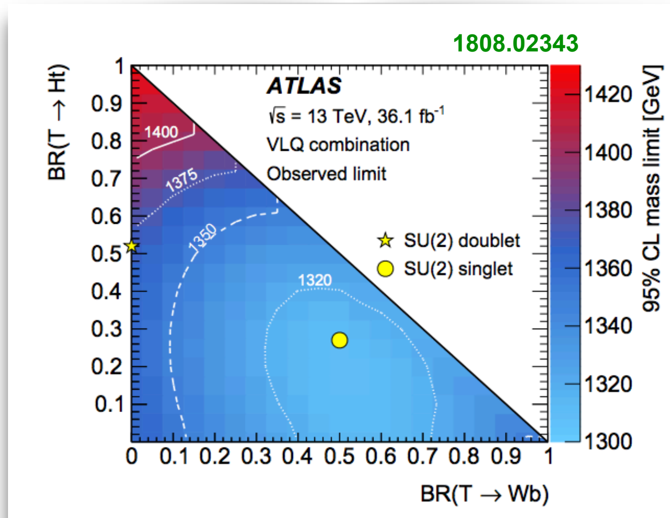
Motivation: naturalness

- But so far, no signs of colored top partners at the **LHC**



scalars





fermions

- Makes following question very relevant:

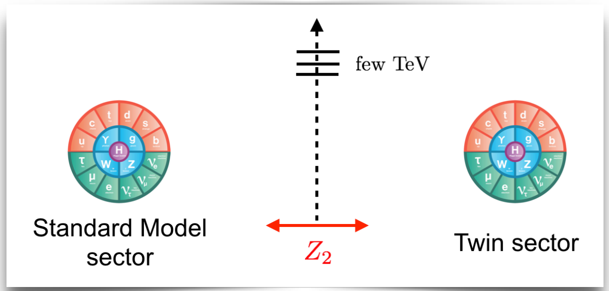
What if the top partners do not have color charge?

Neutral Naturalness

- Symmetry-based solutions to little hierarchy problem with **color-neutral top partners**
- Stabilize weak scale up to $\Lambda \sim 5\text{-}10\ \mathrm{TeV}$. Above: SUSY/compositeness/…

Chacko, Goh, Harnik 2005

- Proof of principle was **Twin Higgs** framework



Top partners are **SM-singlet fermions**

Hidden sector phenomenology is model-dependent (*another talk…*)
But, we have robust indirect probe:

Higgs is pseudo-Goldstone with decay constant f

$$\frac{hZZ}{(hZZ)_{\rm SM}} = \cos\frac{v_A}{f} \simeq 1 - \frac{v^2}{2f^2}$$

Supersymmetric Neutral Naturalness?

- If top partner is color-singlet, SUSY can only be **accidental,** realized at the level of spectrum

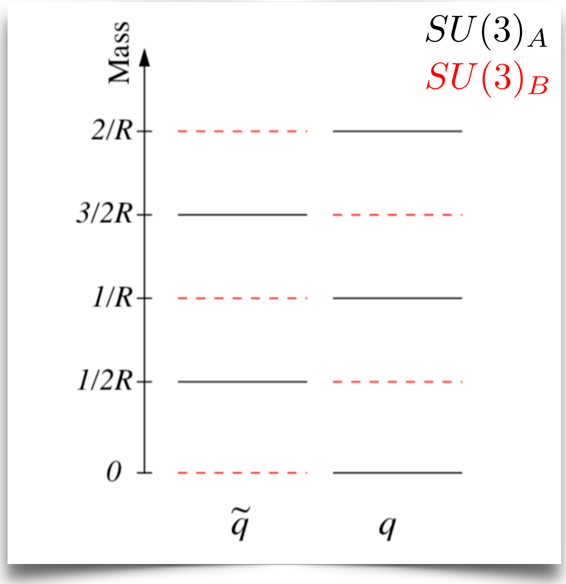
- **Folded SUSY:** orbifold extra dimension with Scherk-Schwarz SUSY breaking

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

$$Z_2$$

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

Burdman, Chacko, Goh, Harnik 2006



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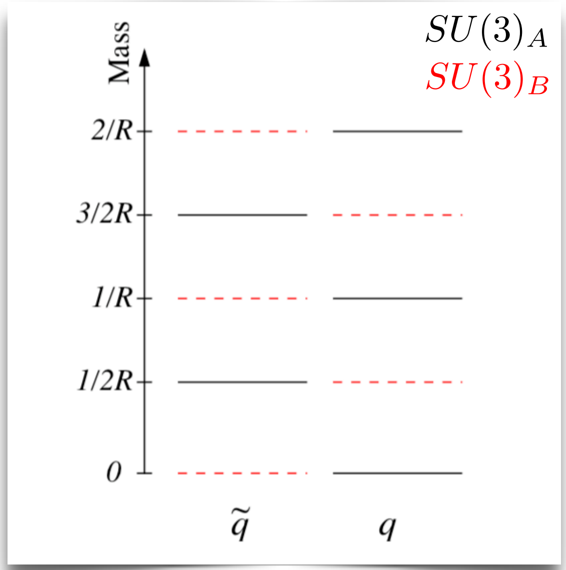

- In this talk: **accidental SUSY from the bottom-up**

  New set of exotic signatures at colliders

- In SUSY, Higgs coupling modifications are less robust

Cheng, Li, Salvioni, Verhaaren 1803.03651

A Tripled Top model

Cheng, Li, Salvioni, Verhaaren 1803.03651

- 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

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

$$Z_3 \qquad\qquad\qquad\qquad Z_2$$

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

raise SM-colored stops

lower *SU*(2)-singlet hidden stops

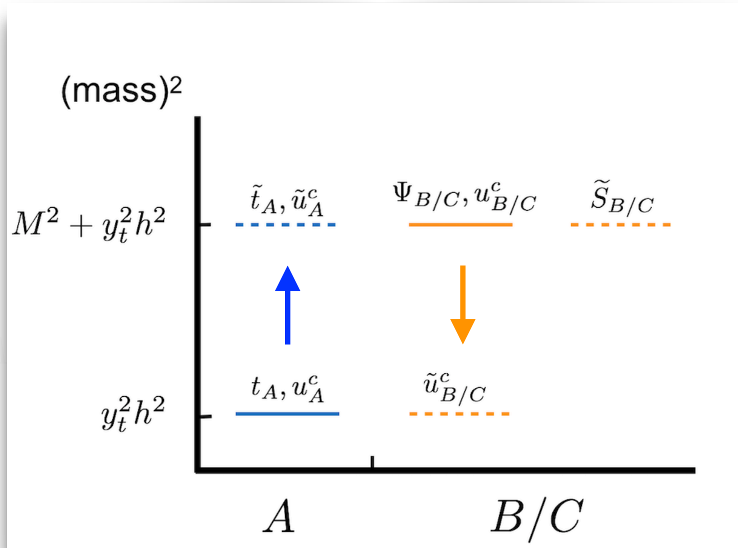
A Tripled Top model

Cheng, Li, Salvioni, Verhaaren 1803.03651

accidental SUSY

for

$\tilde{m} \to M$



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Z_3 $\quad$ Z_2

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A Tripled Top model

- Departures from accidental SUSY limit: $\Delta \equiv \sqrt{M^2 - \widetilde{m}^2} \neq 0$

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

Both OK as long as $\Delta, \omega \ll \mathrm{TeV}$, 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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$$\delta m_H^2 \approx -\frac{N_c y_t^2}{8\pi^2}\,\omega^2 \ln \frac{M^2}{\omega^2}$$

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

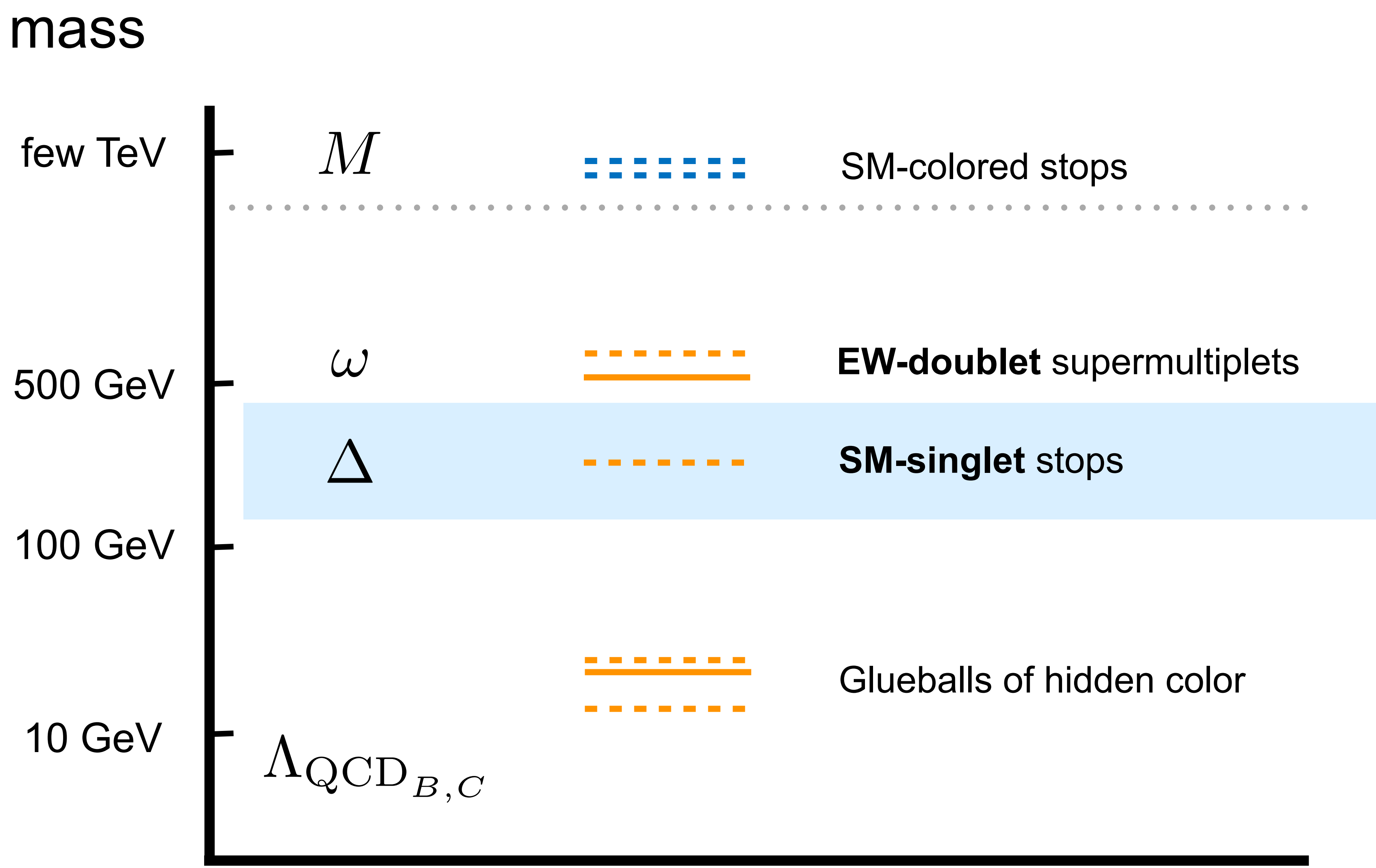
$$W = y_t\,(Q_A H u_A^c + Q_B H u_B^c + Q_C H u_C^c)$$

We can choose $Q_{B,C}, \sim \mathbf{2}_{-1/2}$ $\quad u_{B,C}^c \sim \mathbf{1}_0$

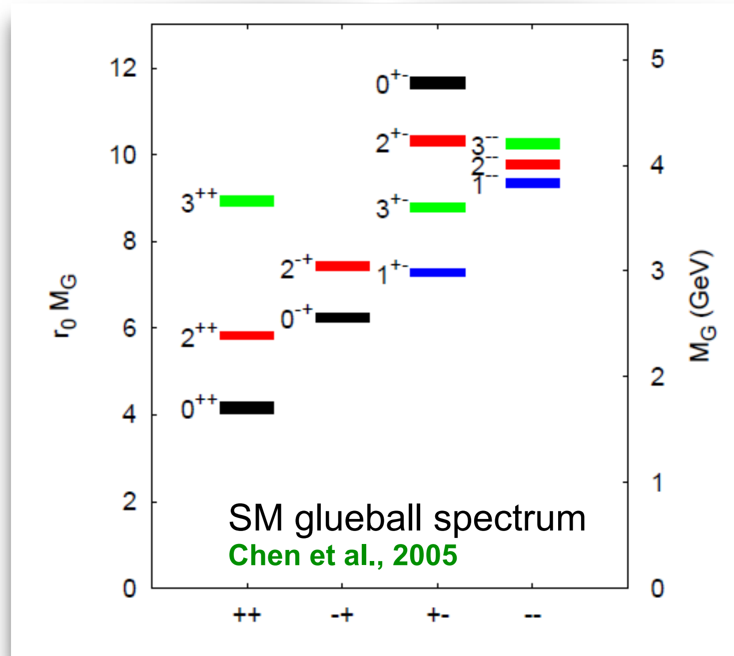
SM-singlet scalar top partners

same result, very different model:
Cohen, Craig, Giudice, McCullough 2018

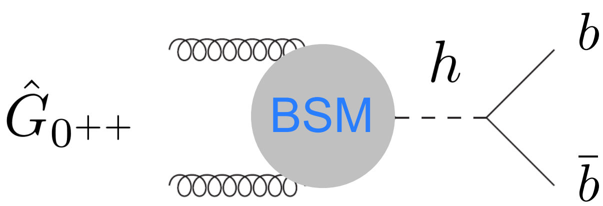
BSM spectrum



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



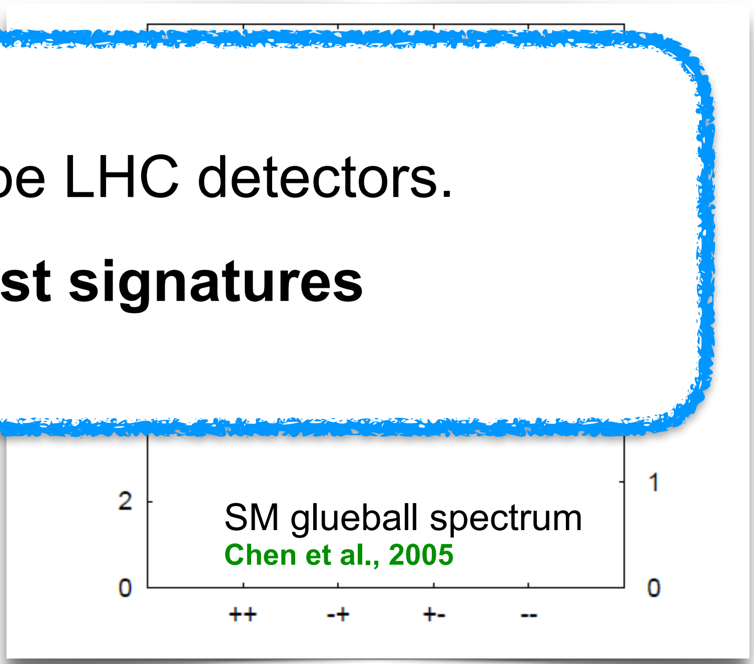
$$c\tau_{0++} \sim 1.2\,\mathrm{m}\left(\frac{5\ \mathrm{GeV}}{\Lambda_{\mathrm{QCD}_{B,C}}}\right)^7\left(\frac{\omega}{500\ \mathrm{GeV}}\right)^4\left(\frac{\Delta}{300\ \mathrm{GeV}}\right)^4\left(\frac{100\ \mathrm{GeV}}{\delta m}\right)^4$$

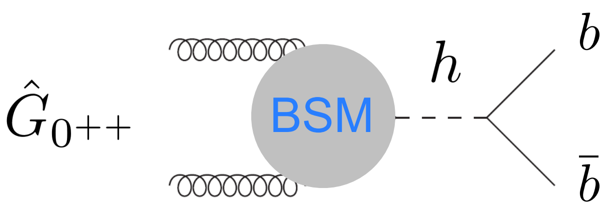
- Lifetime is much **longer** than e.g. in Folded SUSY (~ mm)
- **Large uncertainty** because depends on subleading soft masses

Hidden sector confinement

Assume hidden glueballs escape LHC detectors.

Look for other, more robust signatures





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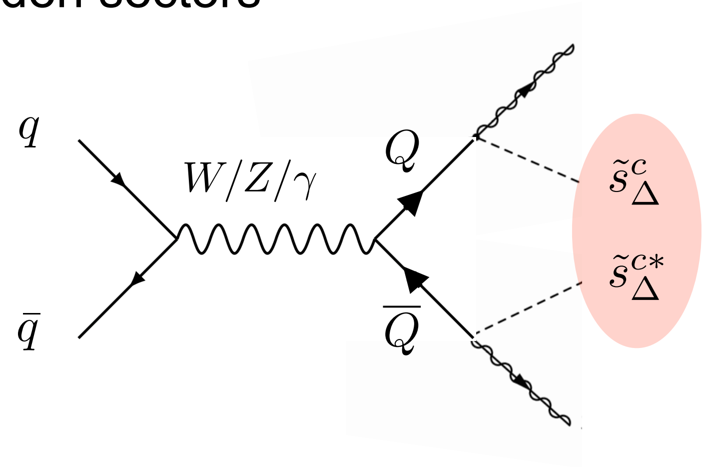
Light singlet scalars

- The **singlet scalars** are lightest matter in hidden sectors
- Dominant production from EW-doublets, decay down to light scalar $\tilde{s}^c_\Delta$



typical LHC event results **in formation of "squirky" pair**

De-excitation mechanism?

Kang, Luty 2008

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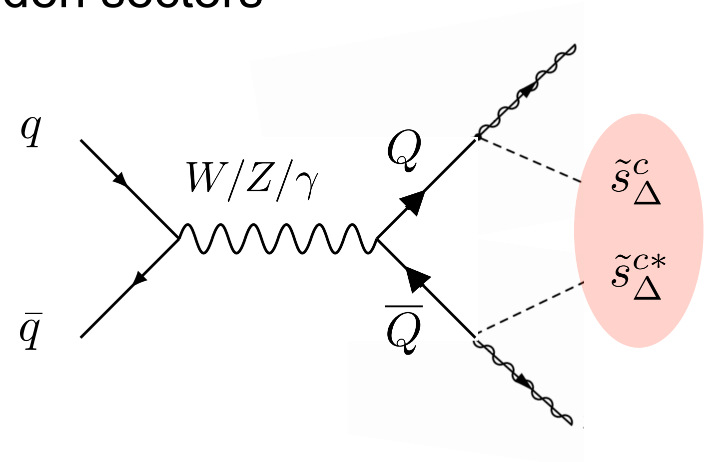

typical LHC event results **in formation of “squirky” pair**

De-excitation mechanism?

Glueball radiation is prompt, but does not complete de-excitation down to ground state

Residual kinetic energy

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

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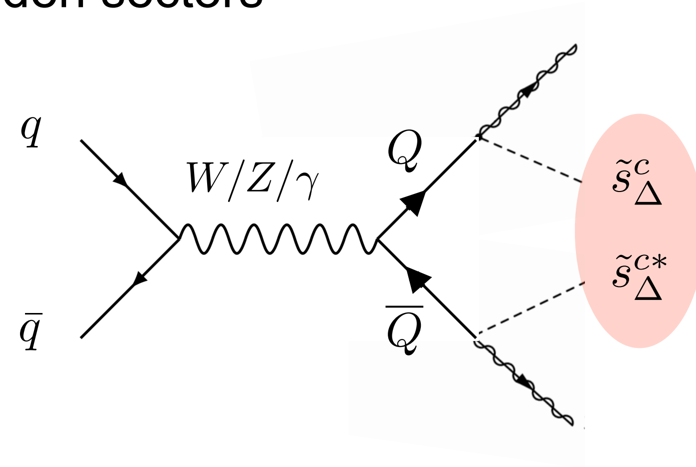

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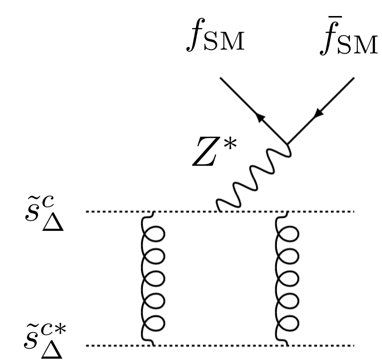


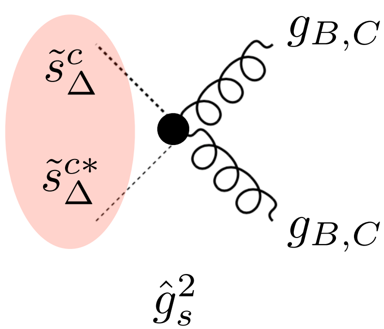
The Higgs VEV gives **small mass mixing** of singlet and doublet scalars, $\tilde{s}^c_\Delta$ inherits **coupling to Z**

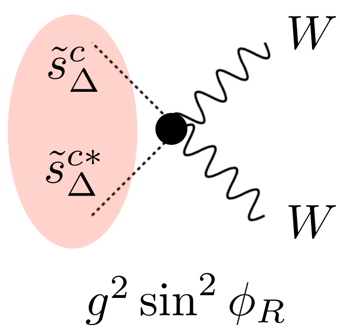
$$t^Z_{\text{de-excite}} \sim \frac{32}{27\pi^4}\frac{\cos^4\theta_w}{\alpha_W^2 \sin^4\phi_R N_f}\frac{m_Z^4 m_{\tilde{s}^c_\Delta}^4 m_0^3}{\sigma^6} \sim 4\cdot 10^{-13}\,\mathrm{s}\left(\frac{5\,\mathrm{GeV}}{\Lambda_{\mathrm{QCD}_{B,C}}}\right)^9\left(\frac{m_{\tilde{s}^c_\Delta}}{300\,\mathrm{GeV}}\right)^4$$

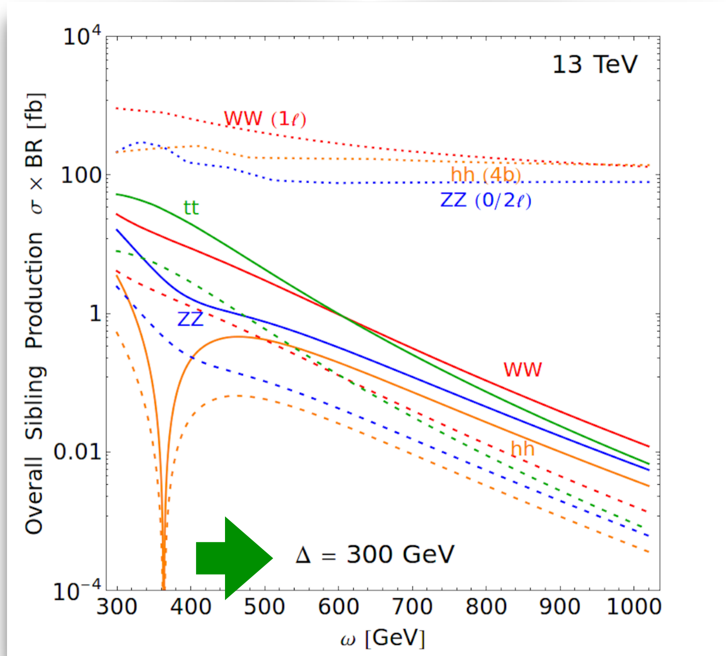
~ 0.1 mm, still prompt

Light singlet scalars

- Lowest-lying bound state has $J^{PC} = 0^{++}$
- Annihilates dominantly to invisible glueballs, **BR(SM) ~ % level**







➡ Resonant signals well below current sensitivity

➡ **Very light singlets are allowed**

- Extra particles from cascade decays may give further constraints

Cheng, Li, Salvioni, Verhaaren, in progress

Light hidden mesons

Cheng, Li, Salvioni, Verhaaren, in progress

- **Switch everywhere**

weak doublets ⟷ singlets

➡ Higgs potential is **unaffected**

- Top partners are now EW-doublet scalars, Drell-Yan + resonant signals

- ω is SM-singlet SUSY mass, technically natural to have $\omega \ll \Lambda_{\mathrm{QCD}_{B,C}}$

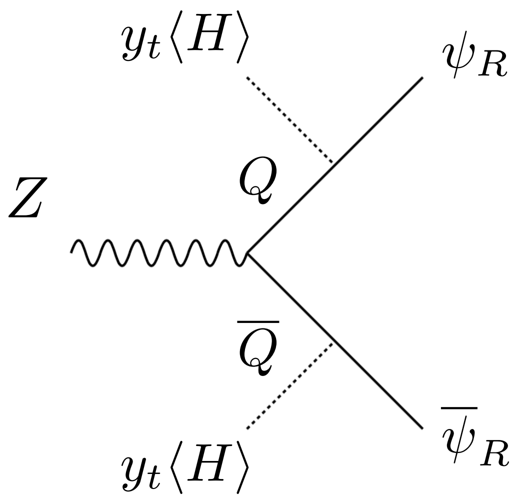
- Lightest hidden hadrons are not glueballs, but $(\overline{\psi}\psi)$ **mesons**

	$\hat{\eta}$	$\hat{\Upsilon}$	$\hat{\chi}$
$J^{PC} =$	0^{-+}	1^{--}	0^{++}

(1-flavor QCD)

Z portal to hidden sector

- Top Yukawa mixes doublets and singlets when Higgs gets VEV



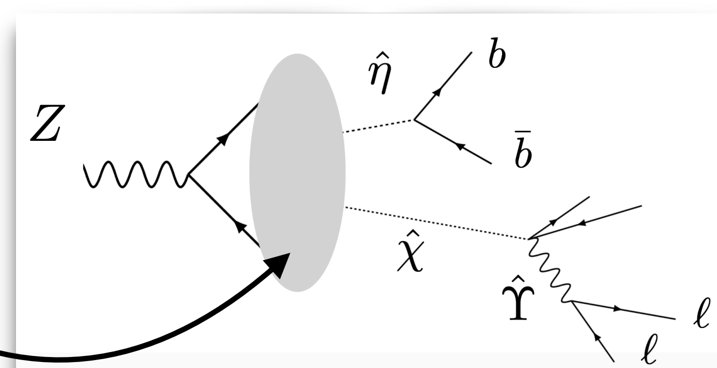
$$\sim g_Z \frac{m_t^2}{M^2} \quad \Rightarrow \quad \mathrm{BR}(Z \to \overline{\psi}_B \psi_B) \sim 10^{-5} \left(\frac{2\ \mathrm{TeV}}{M}\right)^4$$

- For meson masses $\gtrsim 20\ \mathrm{GeV}$, **decays are prompt**

  Most promising signature at LHC:

Cheng, Li, Salvioni, Verhaaren, in progress

EFT $\quad Z_\mu(\hat{\eta}\,\partial_\mu\hat{\chi} - \partial_\mu\hat{\eta}\,\hat{\chi})$

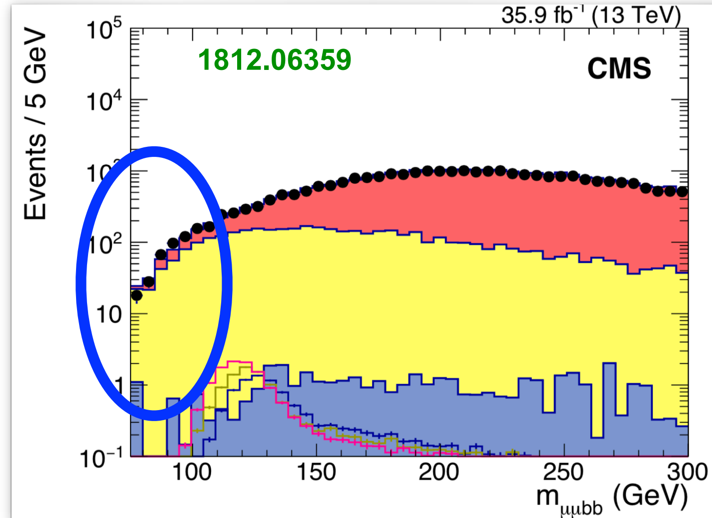


Z portal to hidden sector

- Recent CMS search for $h \to a\, a \to b\bar{b}\,\mu\mu$ has some sensitivity

Compute (suppressed) signal efficiency,

find $N_S \approx 16\left(\frac{2\ \mathrm{TeV}}{M}\right)^4$ signal events



$\{M_\eta, M_\Upsilon, M_\chi\} = \{24, 25, 30\}\ \mathrm{GeV}$

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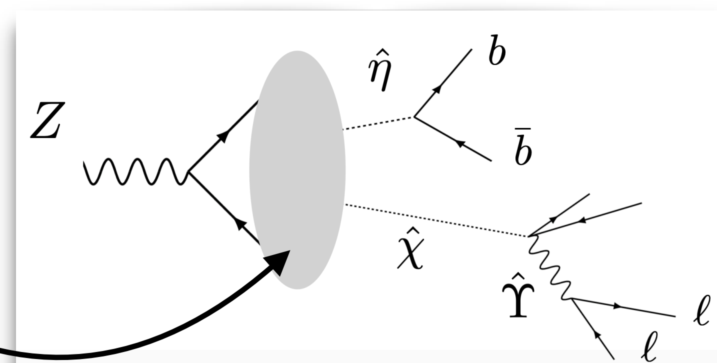

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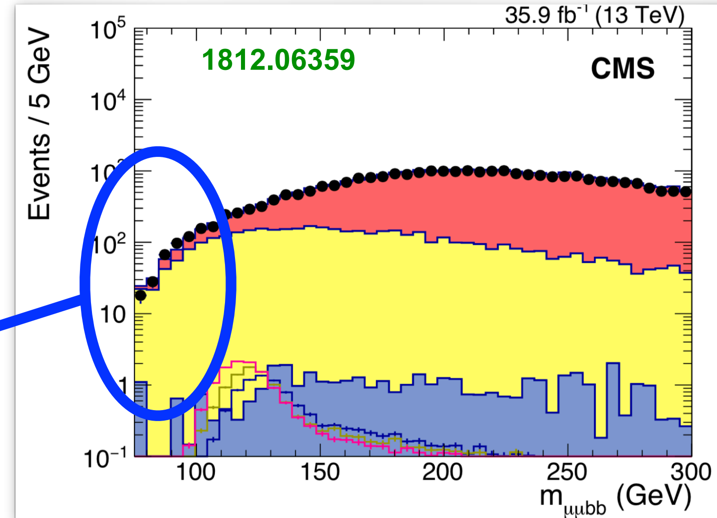

$$M \gtrsim 1.9\ \text{TeV}$$

preliminary

$\{M_\eta, M_\Upsilon, M_\chi\} = \{24, 25, 30\}$ GeV

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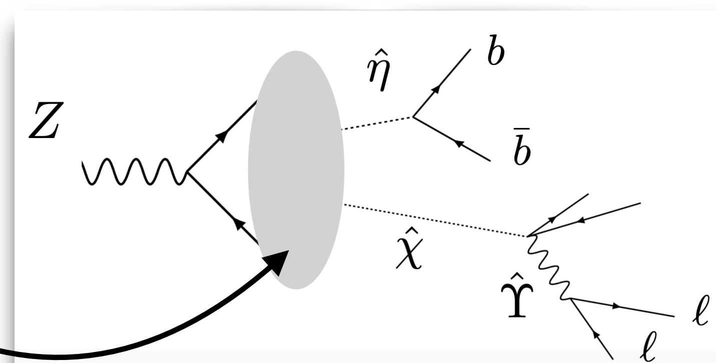

Summary

- Connection between naturalness and LHC coverage is so crucial, it **must** be analyzed in all possible guises

- **Neutral naturalness** theories challenge standard assumption that top partners interact via QCD

- "Tripled Top" is new framework, based on **accidental SUSY**

- In one limit, top partners are *singlet scalars*

  — arguably, the most elusive kind

- In other limit, hidden sector accessible via *rare Z decays*

  At LHC, challenge to keep cuts as soft as possible

  Reach at future *Z* factories? *In progress…*

Backup

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”

$$\widetilde{m} \sim M$$

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?

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

1. First guess: *D*-term of 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 spoil the Z_3

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

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

The soft masses

Cheng, Li, Salvioni, Verhaaren, 1803.03651

$$SU(2) \qquad F = 3$$

$$\begin{array}{cc} & \begin{array}{ccc} \widetilde{m}_P^2 & \widetilde{m}_P^2 & \widetilde{m}_P^2 \end{array} \\ \begin{array}{c} \widetilde{m}_{\overline{P}_2}^2 \\ \widetilde{m}_{\overline{P}_2}^2 \\ \widetilde{m}_{\overline{P}_1}^2 \end{array} & \left(\begin{array}{ccc} & & \\ & Q_A & \\ \hline & & \end{array} \right) \end{array} \qquad \begin{array}{cc} & \begin{array}{ccc} \widetilde{m}_P^2 & \widetilde{m}_P^2 & \widetilde{m}_P^2 \end{array} \\ \begin{array}{c} \widetilde{m}_{\overline{P}_2}^2 \\ \widetilde{m}_{\overline{P}_2}^2 \\ \widetilde{m}_{\overline{P}_1}^2 \end{array} & \left(\begin{array}{ccc} & u_A^c & \\ \hline & & \\ & & \end{array} \right) \end{array} \qquad \begin{array}{cc} & \begin{array}{ccc} \widetilde{m}_P^2 & \widetilde{m}_P^2 & \widetilde{m}_P^2 \end{array} \\ \begin{array}{c} \widetilde{m}_{\overline{P}_1}^2 \\ \widetilde{m}_{\overline{P}_1}^2 \\ \widetilde{m}_{\overline{P}_2}^2 \end{array} & \left(\begin{array}{ccc} & u_{B,C}^c & \\ \hline & & \\ & & \end{array} \right) \end{array}$$

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

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

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

$$(b = 3N - F)$$

- Z_3 - symmetric Yukawas

$$W \ni \frac{g_t}{\Lambda_{\mathrm{UV}}^2} P \overline{P} P \overline{P} H \quad \longrightarrow \quad y_t \sim g_t \frac{\Lambda_G^2}{\Lambda_{\mathrm{UV}}^2}$$

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 $\quad Z \to Z\chi\chi^\dagger, \quad P \to P/\chi, \quad S(\mu_{\rm UV}) \to S(\mu_{\rm UV}) + \frac{T}{4\pi^2}\ln\chi$

  Z is promoted to background vector superfield

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

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

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

$$K \supset c_{M_{ij}}\frac{M_{ij}^\dagger Z_i Z_{\bar j} M_{ij}}{I} + \cdots$$

$$\underset{\mu_{\rm IR}\to 0}{m^2_{M_{ij}}} = -\left[\ln\frac{Z_i Z_{\bar j}}{I}\right]_{\theta^2\bar\theta^2} = -[\ln Z_i]_{\theta^2\bar\theta^2} - [\ln Z_{\bar j}]_{\theta^2\bar\theta^2} + [\ln I]_{\theta^2\bar\theta^2}$$

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

Higgs quartic and *T* parameter

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

contribution of unmixed MSSM stops with mass ω

$(\Delta \ll \omega)$

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…

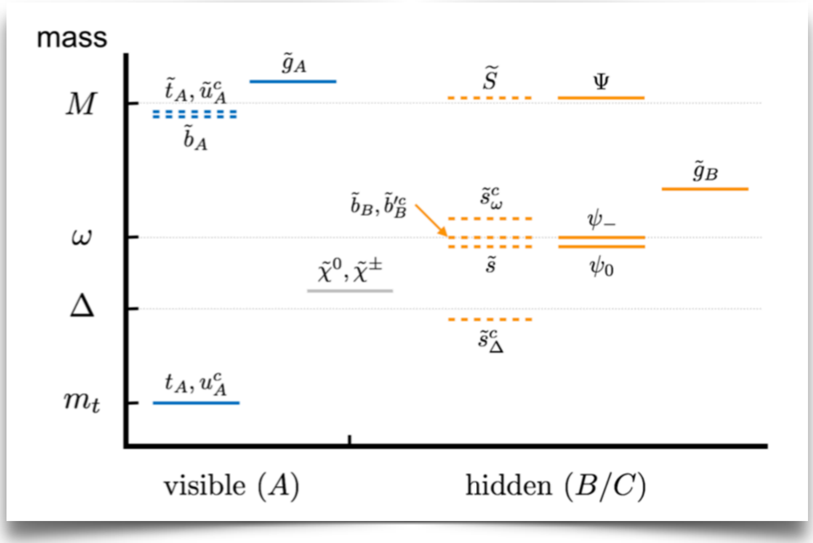
- *T* parameter: leading contribution comes from light scalars,

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

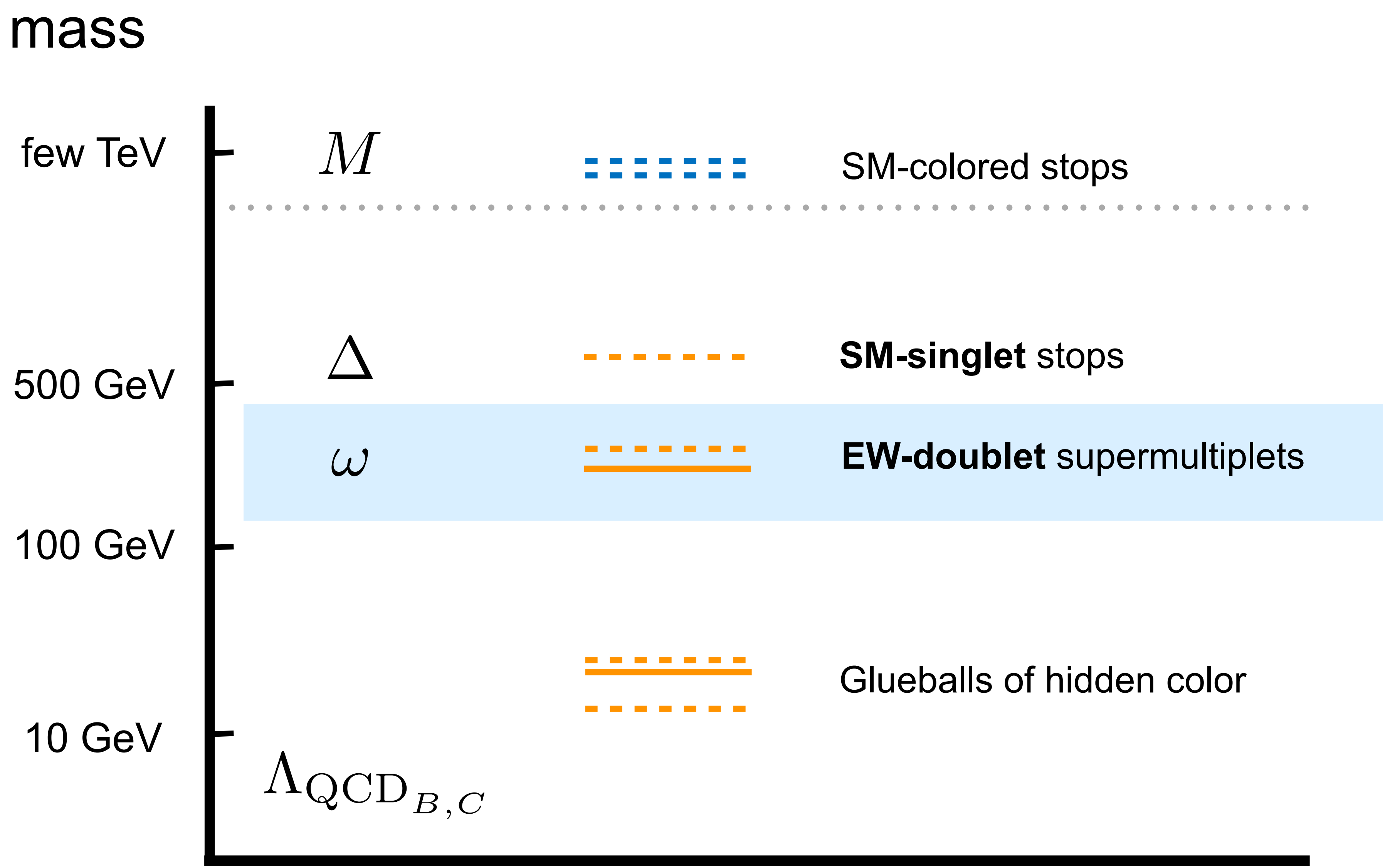
$$\omega = 500\ \mathrm{GeV}, \quad \Delta = 300\ \mathrm{GeV}$$

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

under control



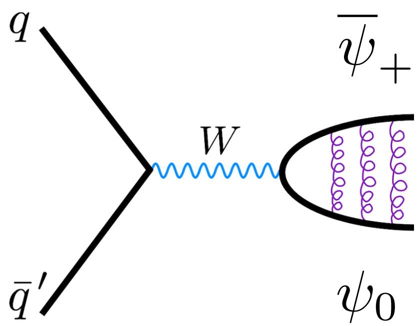
Spectrum of BSM states: $\Delta > \omega$



$\Delta > \omega$: quirk phenomenology

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

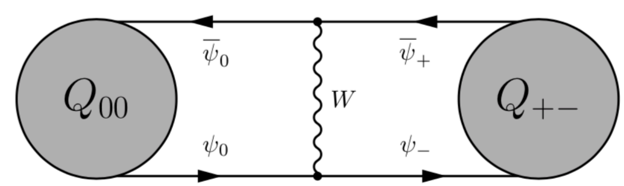
$$Q_{B,C} \sim \mathbf{2}_{-1/2} \sim \begin{pmatrix} \psi_0 \\ \psi_- \end{pmatrix}$$



"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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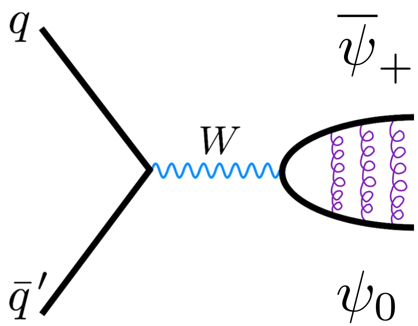
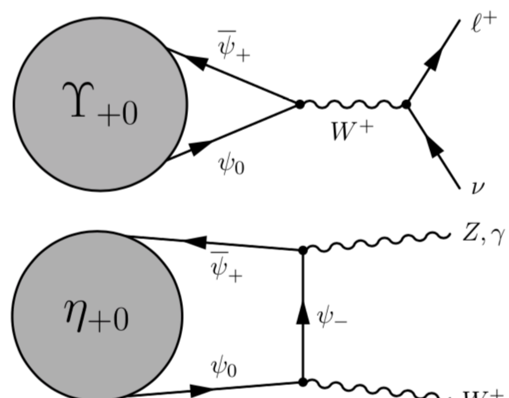


"quirky" bound state

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

annihilation of $n = 1$ states



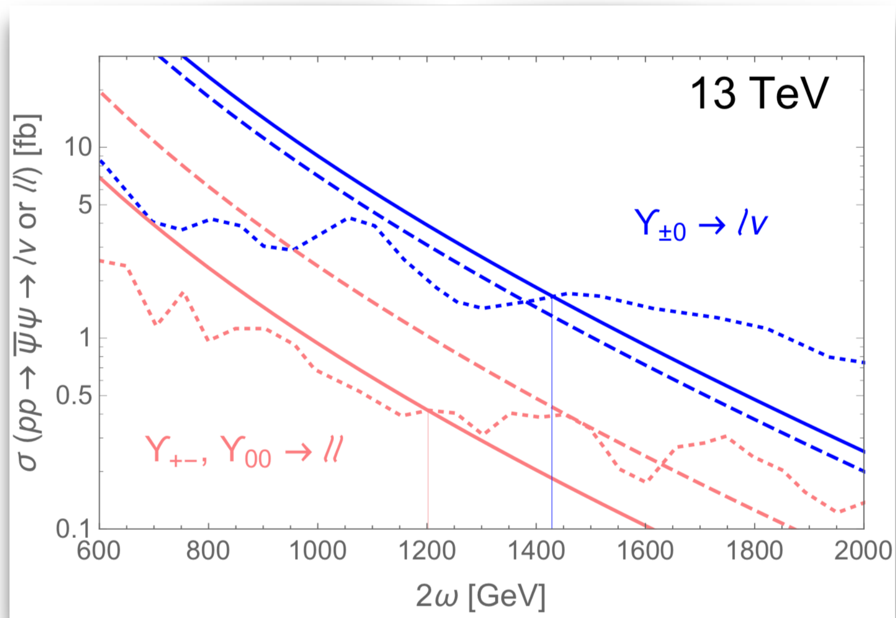
resonant signals

$\Delta > \omega$: quirk phenomenology

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

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

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

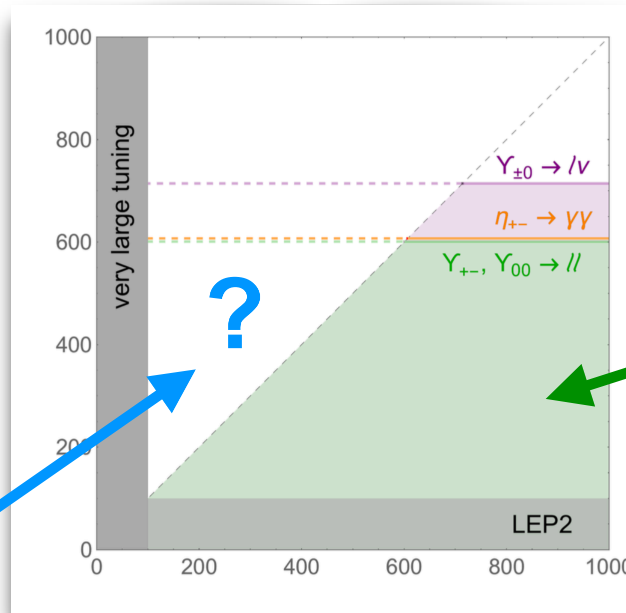


- Neutral channels give $\omega \gtrsim 600 \text{ GeV}$ from $\eta_{+-} \to \gamma\gamma$, $\Upsilon_{+-,00} \to \ell\ell$

Tripled Top parameter space

ω [GeV]

(EW-charged supermultiplets)



Drell-Yan
+
quirk
resonant signals

cascade decays to light singlets

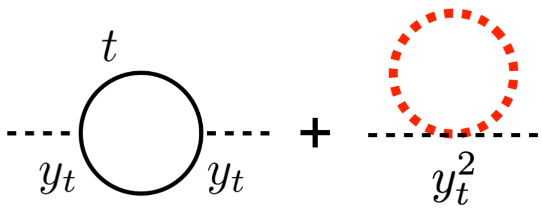
Δ [GeV]

(singlet scalar top partners)

Cheng, Li, Salvioni, Verhaaren 2018

More neutral naturalness

- The **top partner zoo**



	scalar	*fermion*
QCD	SUSY	Composite Higgs
EW	Folded SUSY	Quirky Little Higgs
singlet	?	Twin Higgs

$$\mathcal{L}_{\text{SUSY}} \sim y_t q H u^c + y_t^2 |\tilde{q} H|^2 + y_t^2 |\tilde{u}^c|^2 |H|^2$$

Can give stops hidden color, but they still **carry SM electroweak charges**

More neutral naturalness

- The **top partner zoo**

	scalar	*fermion*
QCD	SUSY	Composite Higgs
EW	Folded SUSY	Quirky Little Higgs
singlet	?	Twin Higgs

$$\mathcal{L}_{\mathrm{SUSY}} \sim y_t q H u^c + y_t^2 |\tilde{q} H|^2 + y_t^2 |\tilde{u}^c|^2 |H|^2$$

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

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,

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

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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

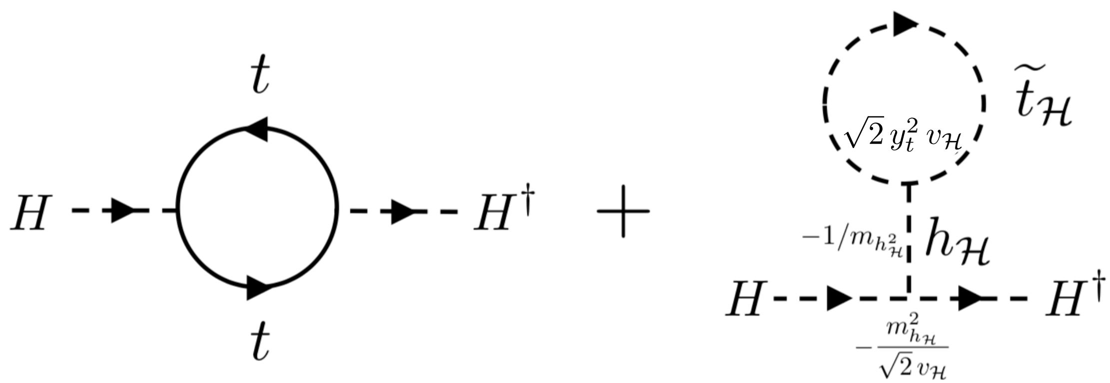
$$\delta V \sim \frac{N_c y_t^2}{16\pi^2} \Lambda^2 \left(|H_{\mathcal{H}}|^2 - |H|^2\right)$$

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,
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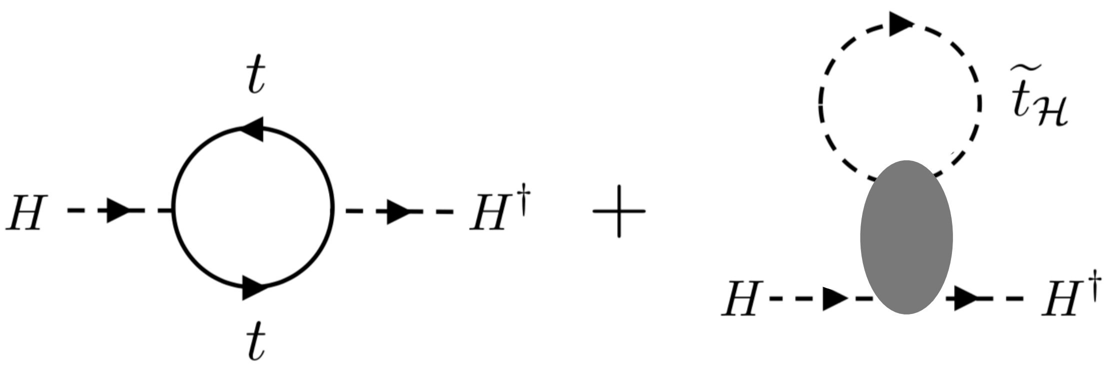
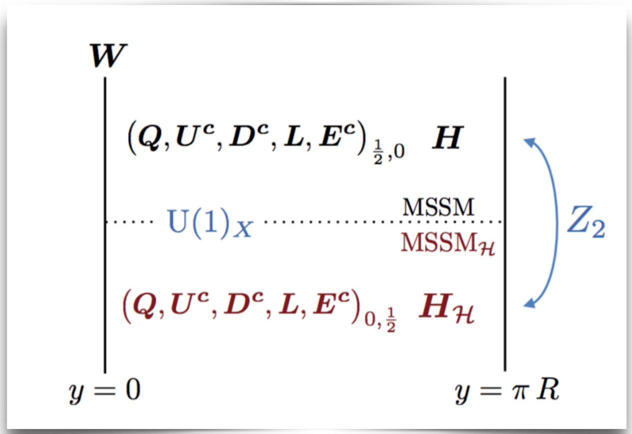


Integrate out heavy radial mode

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

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

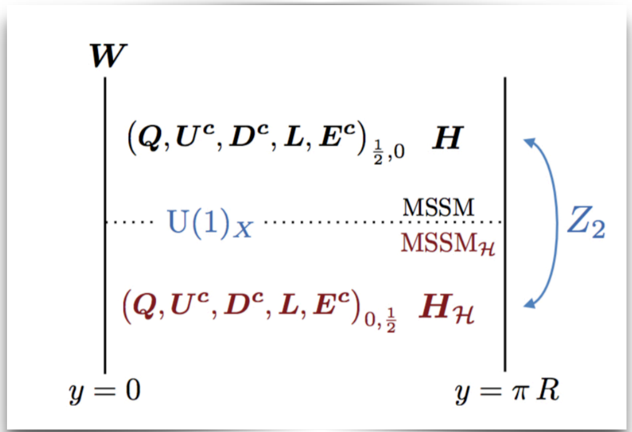
A 5D SUSY completion



$$\Lambda \sim 1/R$$

- $U(1)_X$ 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



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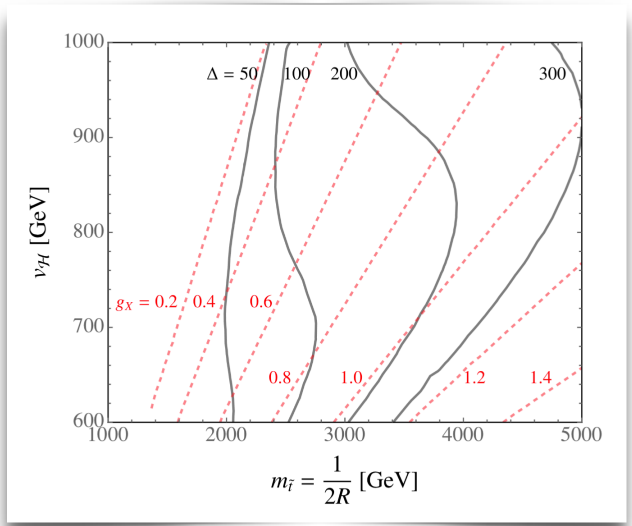
- $U(1)_X$ D-term potential $\quad V_X = \frac{g_X^2}{2}\xi(|H_{\mathcal{H}}|^2 - |H|^2 - f_X^2)^2$

- 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**

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

+ non-universal correction for the top

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

- Higgs decays to hyperbolic glue,

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

Spontaneous breaking of hidden color?

Cohen, Craig, Giudice, McCullough 2018

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

  - 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**

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

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

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

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