SUSY Neutral Naturalness: the Tripled Top

Ennio Salvioni

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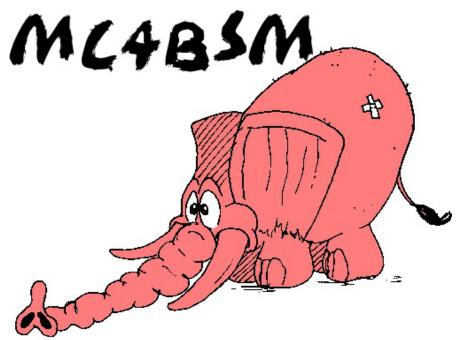


12th MC4BSM

IPPP Durham

April 21, 2018

based on **arXiv:1803.03651 [hep-ph]**

with **H.C.Cheng, L.Li, C.Verhaaren (UC Davis)**

Motivation/1

see Chris' talk

- **Neutral naturalness:** theories with color-less top partners

- Scalar top partners $\longleftrightarrow$ supersymmetry: **Folded SUSY**

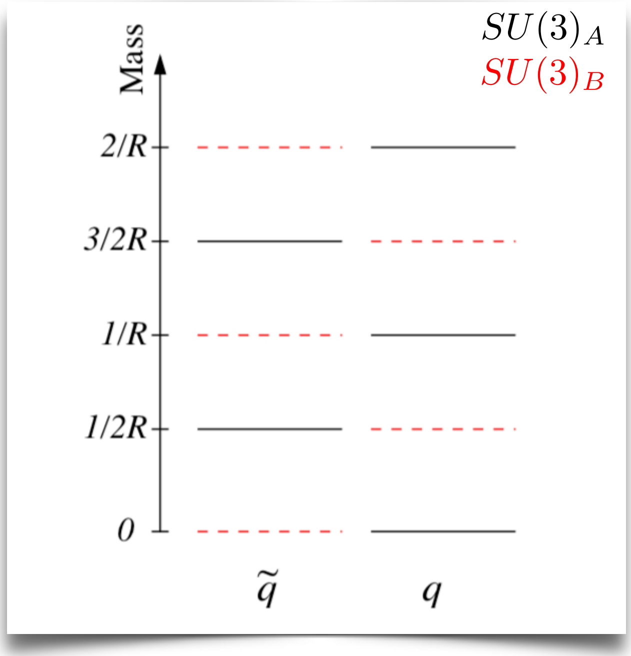
$$SU(3)_A \times SU(3)_B \times SU(2) \times U(1)$$

$$Z_2$$

Burdman, Chacko, Goh, Harnik hep-ph/0609152

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

- Theory is manifestly non-SUSY, but **accidental SUSY is preserved**



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

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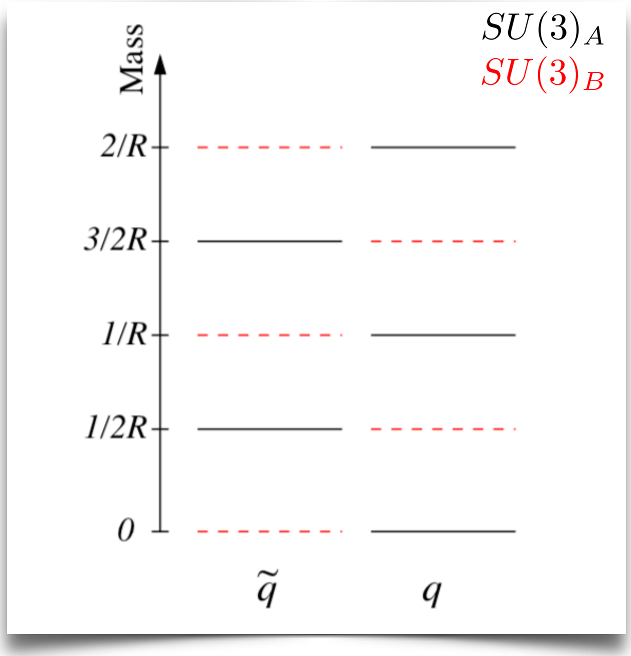
- Protection of Higgs mass is **"too effective:"**

  Gauge/gaugino 1-loop term dominates,

  vacuum preserves EW symmetry

Cohen, Craig, Lou, Pinner 1508.05396

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



Motivation/1

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

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

Z_2

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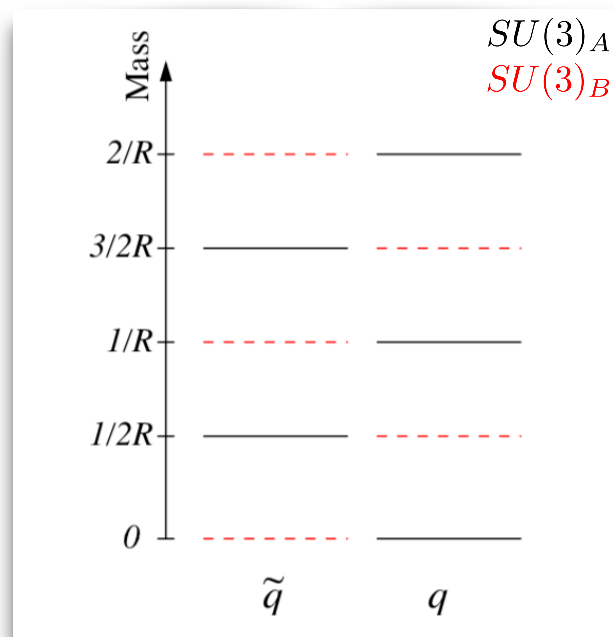

Motivation/2

- **Neutral naturalness:** theories with color-less top partners

Curtin, Verhaaren
1506.06141

- Can the top partners be
  scalars and **complete SM singlets?**

	scalar	*fermion*
QCD	SUSY	Composite Higgs/ RS
EW	folded SUSY	Quirky Little Higgs
singlet	?	Twin Higgs

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

In Folded SUSY, folded stops **carry SM electroweak charges**

Motivation/2

- **Neutral naturalness:** theories with color-less top partners

Curtin, Verhaaren
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Can we provide the first example?

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

$$W = y_t \left(Q_A H u_A^c + Q_B H u_B^c + Q_C H u_C^c \right) \qquad Z_3$$

$$+ M (u'_B u_B^c + u'_C u_C^c) + \omega (Q_B Q'^c_B + Q_C Q'^c_C) \qquad Z_2$$

~ few TeV

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Cheng, Li, Salvioni, Verhaaren 1803.03651

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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

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Cheng, Li, Salvioni, Verhaaren 1803.03651

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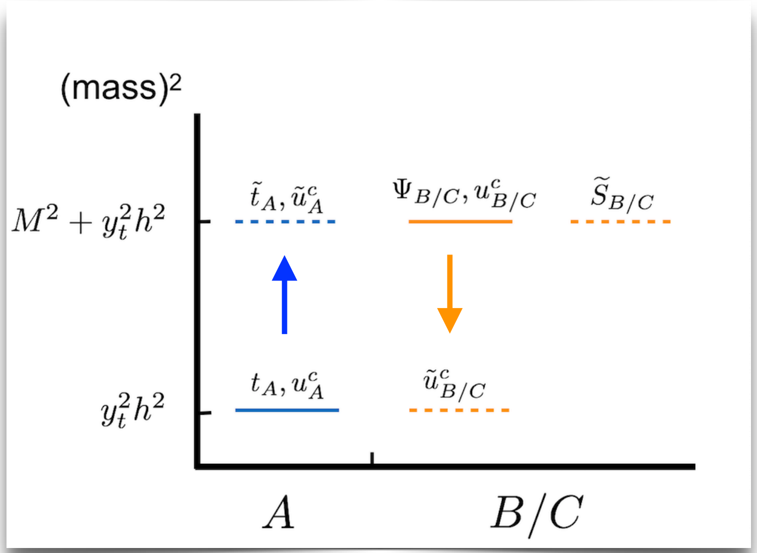


- Leading soft masses

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

raise SM-colored stops

lower *SU*(2)-singlet hidden stops

accidental SUSY

for

$$\tilde{m} \to M$$

$$\omega \to 0$$

A Tripled Top model

- Moderate departures from accidental SUSY limit $\tilde{m} = M, \quad \omega = 0$
  do not spoil naturalness: for example

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

  Not worrisome as long as $\omega \ll \mathrm{TeV}$

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

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

➡ We can choose

$$Q_{B,C}, \sim \mathbf{2}_{-1/2} \qquad u_{B,C}^c \sim \mathbf{1}_0$$

SM-singlet scalar top partners

see also:
Cohen, Craig, Giudice, McCullough 1803.03647

Necessary ingredients

- A particular structure for the soft masses

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

I will discuss possible origins in next slide

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

soft SUSY-breaking mass $\quad$ **SUSY mass**

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

$M \sim \text{few TeV}$

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

$\Delta \sim \text{few} \times (100 \text{ GeV})$

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 a 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

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

Top fields are **composite mesons** $P_i\overline{P}_j$ of SUSY QCD

$$SU(N), \quad F = N+1$$

Arkani-Hamed, Rattazzi
hep-th/9804068

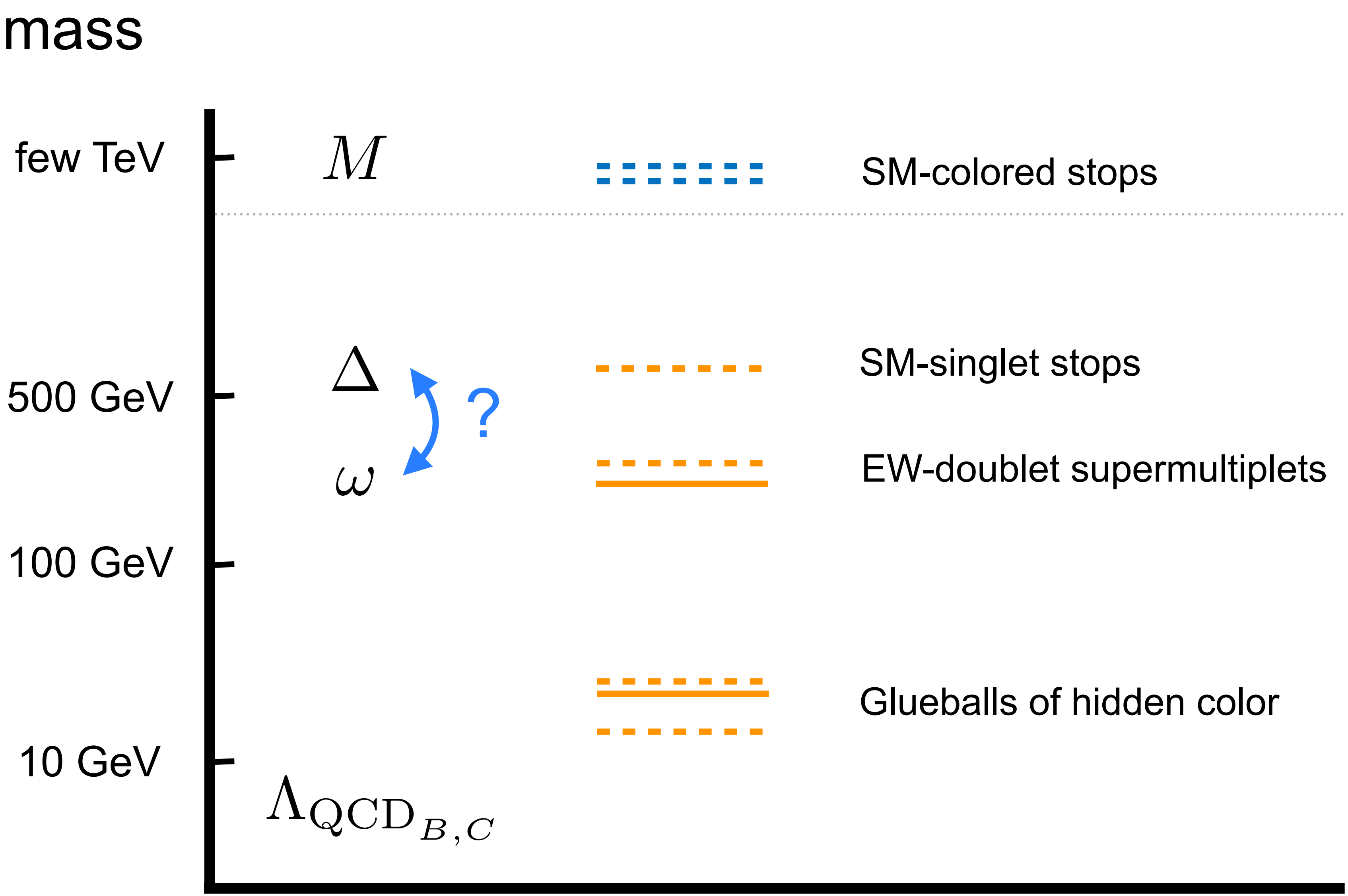
$$m^2_{ij} = m^2_{P_i} + m^2_{\overline{P}_j} - \frac{2}{b}\sum_k T_{r_k}(m^2_{P_k} + m^2_{\overline{P}_k})$$

soft masses of IR composites

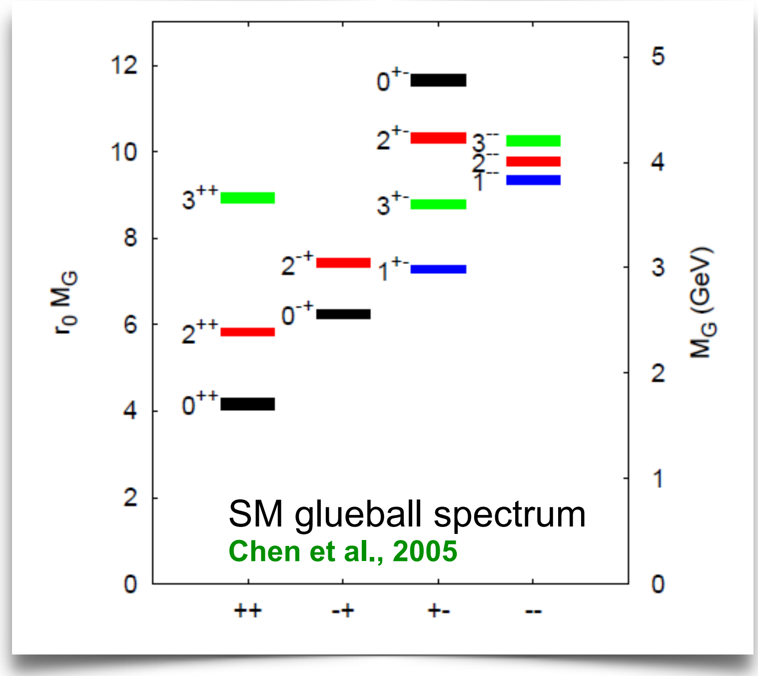
soft masses of UV constituents

Phenomenology

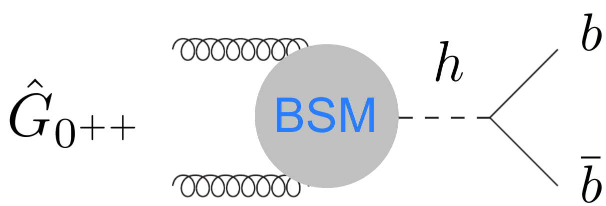
Spectrum of BSM states



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



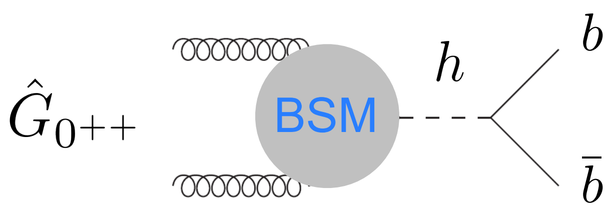
$$c\tau_{0++} \sim 1.2\,\mathrm{m}\left(\frac{5\ \mathrm{GeV}}{\Lambda_{\mathrm{QCD}_{B,C}}}\right)^7 \left(\frac{\omega}{500\ \mathrm{GeV}}\right)^4 \left(\frac{\Delta}{300\ \mathrm{GeV}}\right)^4 \left(\frac{100\ \mathrm{GeV}}{\delta m}\right)^4$$

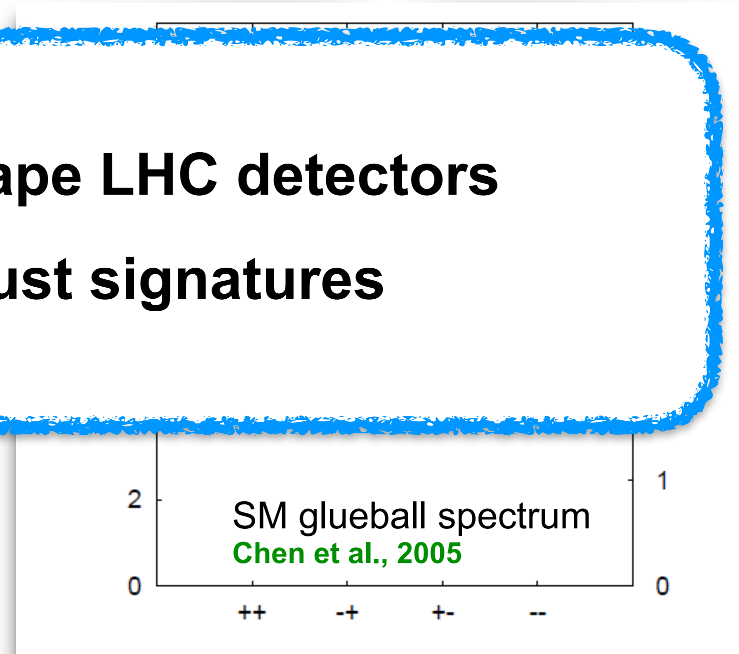
- Lifetime is much **longer** than e.g. in Folded SUSY (~ mm)
- **Large uncertainty** due to dependence on subleading soft masses

Hidden sector confinement

Assume hidden glueballs escape LHC detectors

Focus on other, more robust signatures





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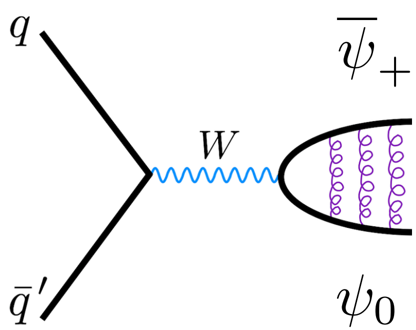
$\Delta > \omega$: quirk phenomenology

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

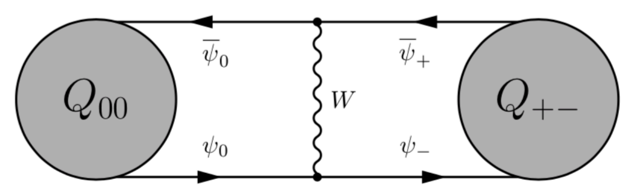
$$Q_{B,C} \sim \mathbf{2}_{-1/2} \sim \begin{pmatrix} \psi_0 \\ \psi_- \end{pmatrix}$$



"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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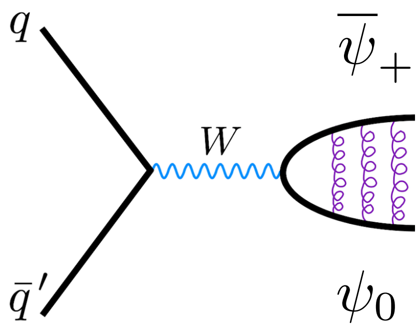

"quirky" bound state

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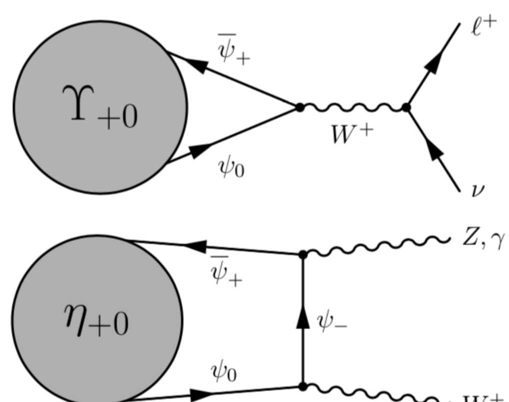
annihilation of $n = 1$ states



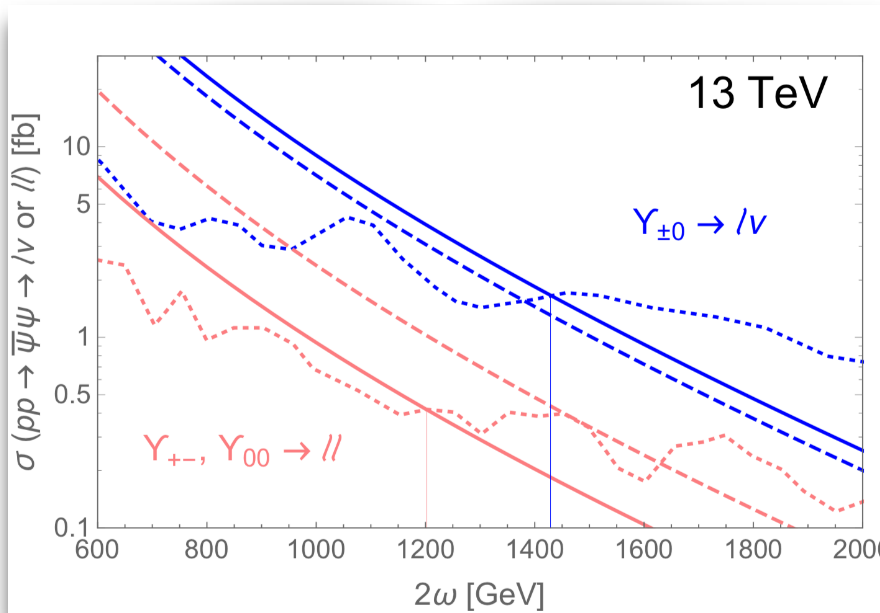
resonant signals

$\Delta > \omega$: quirk phenomenology

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

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

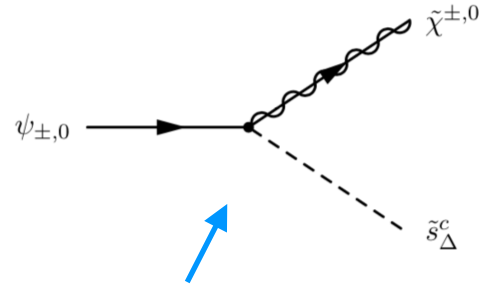
from $\Upsilon_{+0} \to \ell\nu$



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

Δ < ω : light singlet scalars

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



decay of fermions requires light neutralino

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

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

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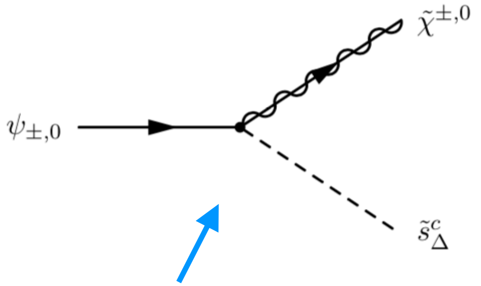

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➡ typical LHC event results

in formation of $\tilde{s}^{C}_{\Delta}\tilde{s}^{C*}_{\Delta}$ "squirky" pair

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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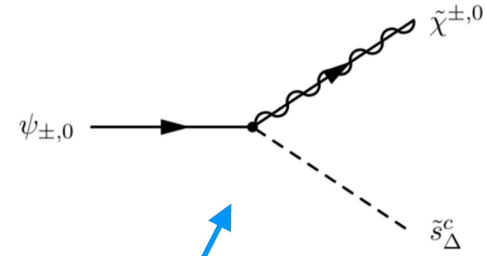

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How does the $\tilde{s}^C_\Delta \tilde{s}^{C*}_\Delta$ system de-excite?

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

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

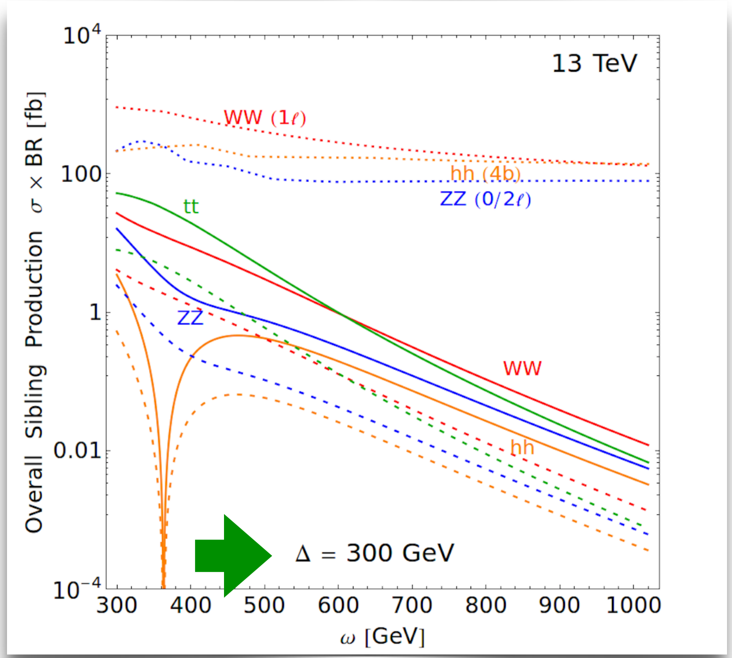
~ 0.1 mm, still prompt

$\Delta < \omega$: light singlet scalars

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

➡ Resonant signals well below current sensitivity

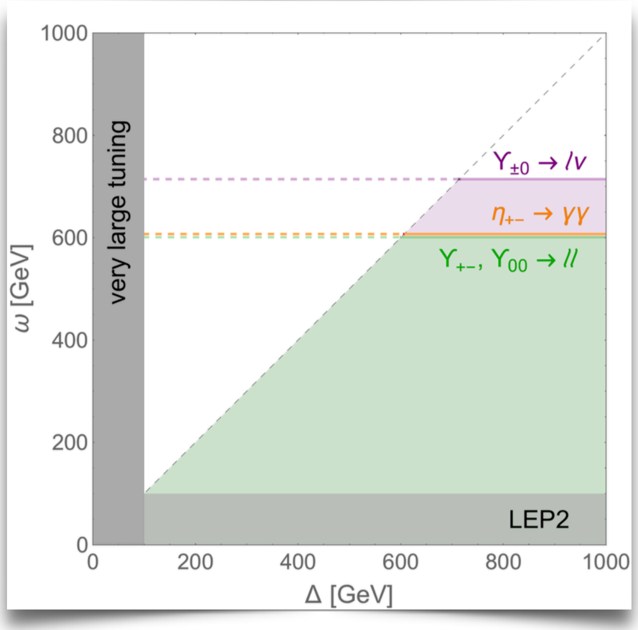
➡ **Very light singlets are allowed**



- Extra particles from cascade decays may give further constraints

Cheng, Li, Salvioni, Verhaaren, work in progress

Summary



- Tripled Top is **new guise of neutral naturalness**
- Accidental supersymmetry realized in 4 dimensions, thanks to Z_3 symmetry
- Top partners can be **complete SM singlets**, very elusive at LHC
  May be as light as few 100's of GeV
- Some EW-charged particles also present, they determine phenomenology
  Many possibilities, study is ongoing

Backup

The soft masses

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

$SU(2)$

$F = 3$

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

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

$$\begin{array}{c|ccc} & \widetilde{m}^2_P & \widetilde{m}^2_P & \widetilde{m}^2_P \\ \hline \widetilde{m}^2_{\bar{P}_1} & & & \\ \widetilde{m}^2_{\bar{P}_1} & & u^c_{B,C} & \\ \widetilde{m}^2_{\bar{P}_2} & & & \end{array},$$

$$\begin{array}{c|ccc} & \widetilde{m}^2_P & \widetilde{m}^2_P & \widetilde{m}^2_P \\ \hline \widetilde{m}^2_{\bar{P}} & & & \\ \widetilde{m}^2_{\bar{P}} & & Q_{B,C} & \\ \widetilde{m}^2_{\bar{P}} & & & \end{array}$$

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$$\widetilde{m}^2_{Q_{B,C}} = \widetilde{m}^2_P + \widetilde{m}^2_{\bar{P}} - \widetilde{m}^2_P - \widetilde{m}^2_{\bar{P}} = 0,$$

$$\widetilde{m}^2_{u^c_{B,C}} = \widetilde{m}^2_P + \widetilde{m}^2_{\bar{P}_1} - \widetilde{m}^2_P - \frac{2}{3}\widetilde{m}^2_{\bar{P}_1} - \frac{1}{3}\widetilde{m}^2_{\bar{P}_2} = \frac{\widetilde{m}^2_{\bar{P}_1} - \widetilde{m}^2_{\bar{P}_2}}{3},$$

$$\widetilde{m}^2_{Q_A,u^c_A} = \widetilde{m}^2_P + \widetilde{m}^2_{\bar{P}_2} - \widetilde{m}^2_P - \frac{2}{3}\widetilde{m}^2_{\bar{P}_2} - \frac{1}{3}\widetilde{m}^2_{\bar{P}_1} = \frac{\widetilde{m}^2_{\bar{P}_2} - \widetilde{m}^2_{\bar{P}_1}}{3} = -\widetilde{m}^2_{u^c_{B,C}}$$

Cheng, Li, Salvioni, Verhaaren, 1803.03651