SUSY Neutral Naturalness: the Tripled Top

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Confronting Naturalness: from LHC to future colliders

DESY, Hamburg

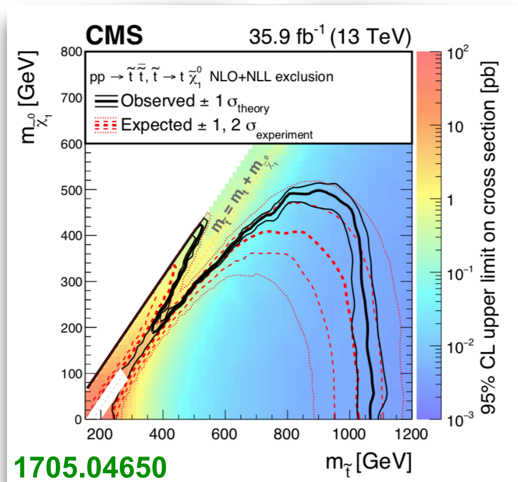
April 26, 2018

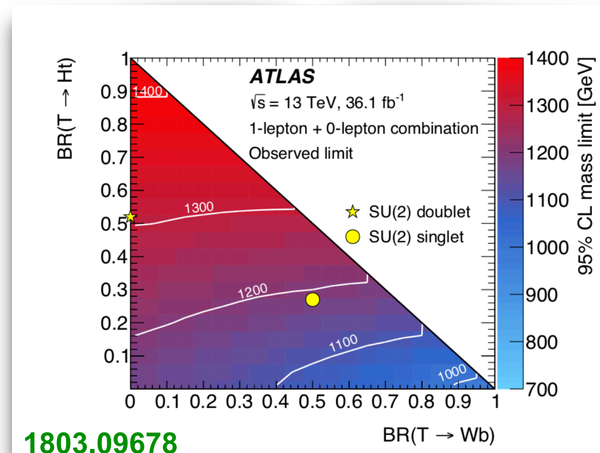
based on arXiv:1803.03651 [hep-ph]

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

Introduction

- So far, the LHC has shown no signs of colored top partners up to ~ 1 TeV





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

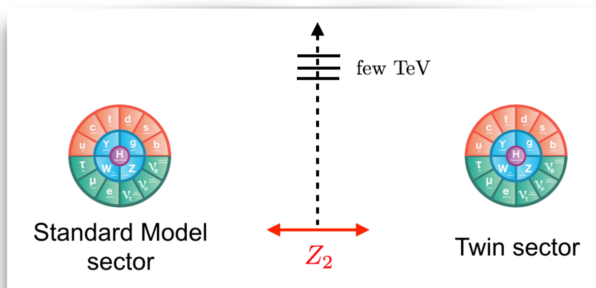
What if the top partners do not have color charges?

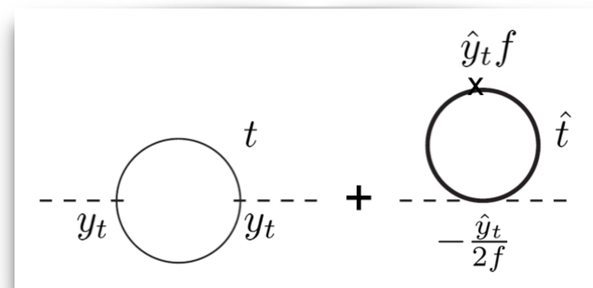
Neutral Naturalness

- Symmetry-based solutions to the hierarchy problem with **color-less top partners**

- First and best-known example is the **Twin Higgs**

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





Chacko, Goh, Harnik 2005

What about SUSY incarnations of neutral naturalness?

Motivation/1

- Neutral naturalness: models with color-less top partners

- **Folded supersymmetry**

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

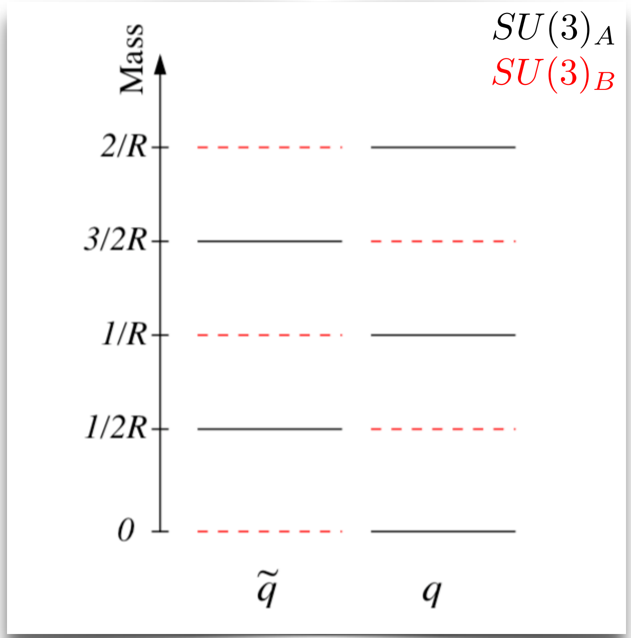
$$Z_2$$

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

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

- An **accidental SUSY is preserved**

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



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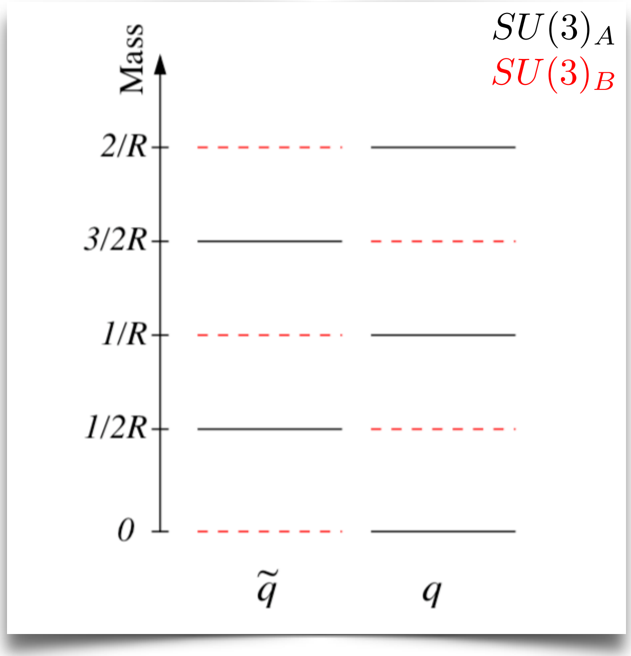

Cohen, Craig, Lou, Pinner 1508.05396

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

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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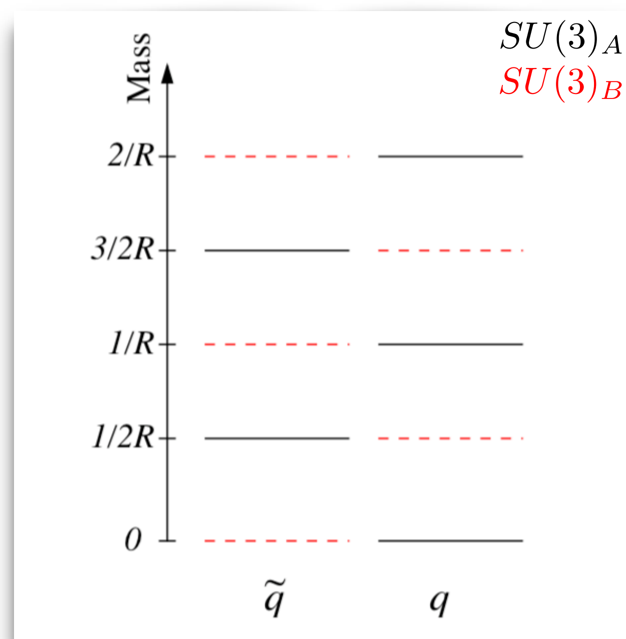

Motivation/2

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

e.g. **Curtin, Verhaaren 1506.06141**

- The **top partner zoo**

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

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

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

Motivation/2

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

- The **top partner zoo**

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

Can we provide the first singlet scalar top partner?

see also: **Cohen, Craig, Giudice, McCullough 1803.03647**

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

$$W = y_t \left(Q_A H u^c_A + Q_B H u^c_B + Q_C H u^c_C\right) \qquad Z_3$$

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

~ few TeV

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~ few TeV

- 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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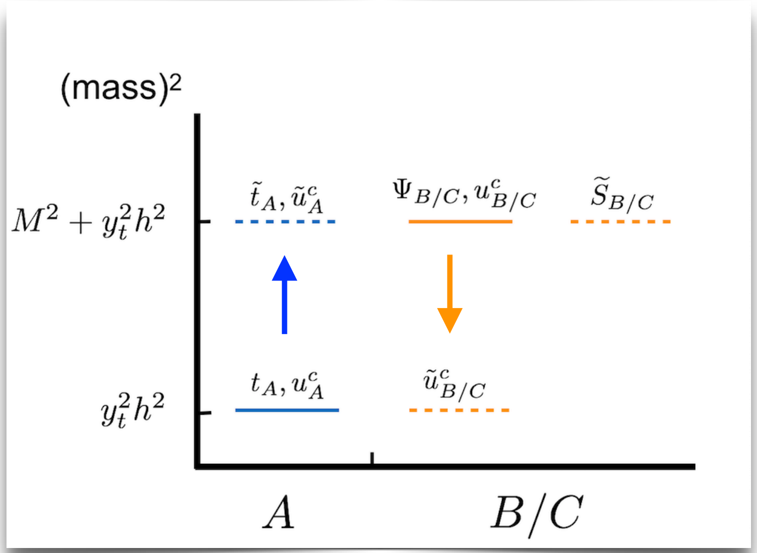

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raise SM-colored stops

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

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

SM-singlet scalar top partners

Necessary ingredients

- A particular structure for the soft masses

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

I will discuss possible origins in next slide

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

soft SUSY-breaking mass → $\widetilde{m}$ $\qquad$ **SUSY mass** → M

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

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

$M \sim \text{few TeV}$

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

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 an extra *U*(1), charges +1 and -1

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

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 s-confining SQCD

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

Arkani-Hamed, Rattazzi
hep-th/9804068

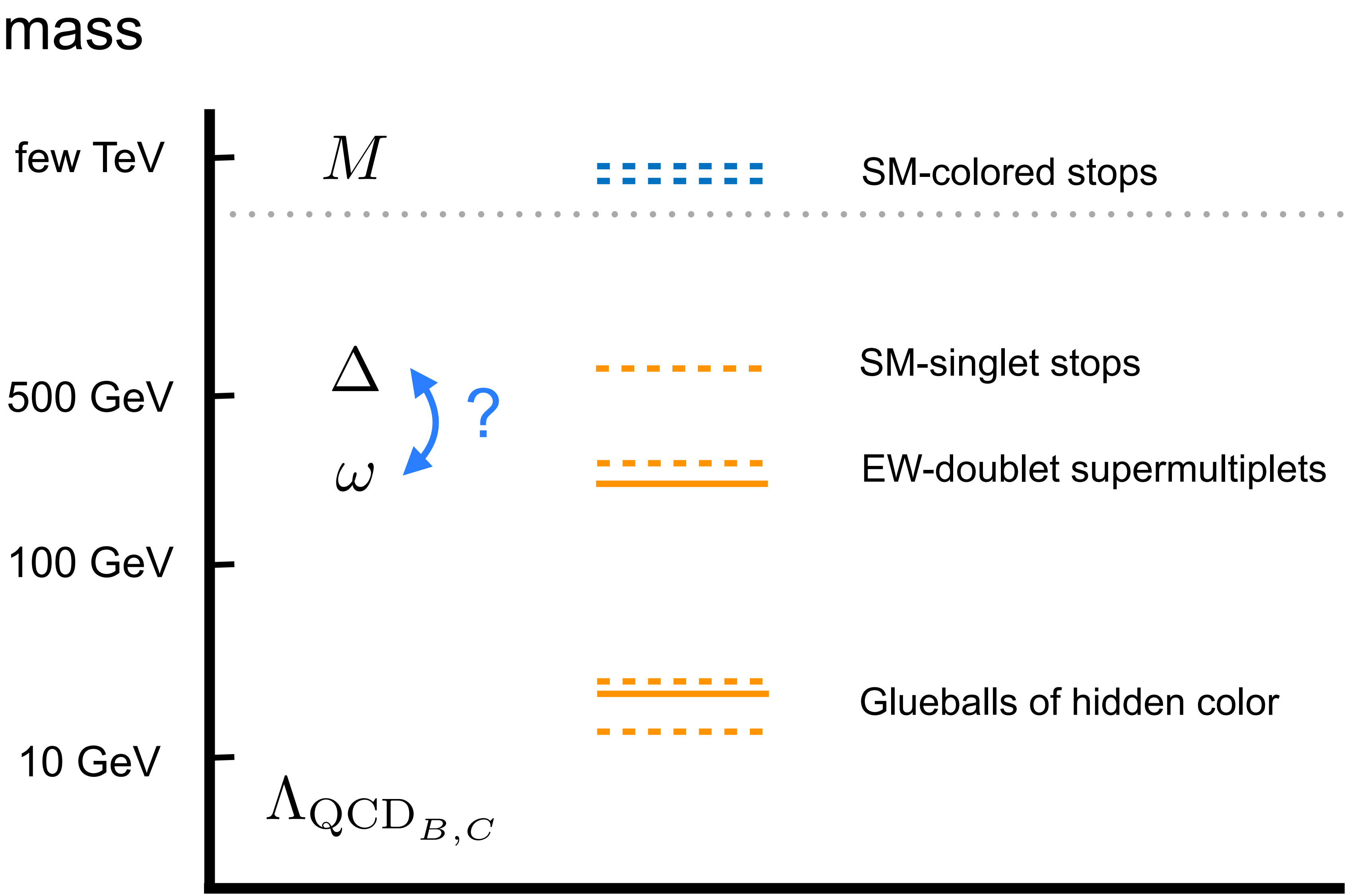
$$m^2_{ij} = m^2_{P_i} + m^2_{\overline{P}_j} - \frac{2}{b} \sum_k T_{r_k} (m^2_{P_k} + m^2_{\overline{P}_k})$$

soft masses of IR composites

soft masses of UV constituents

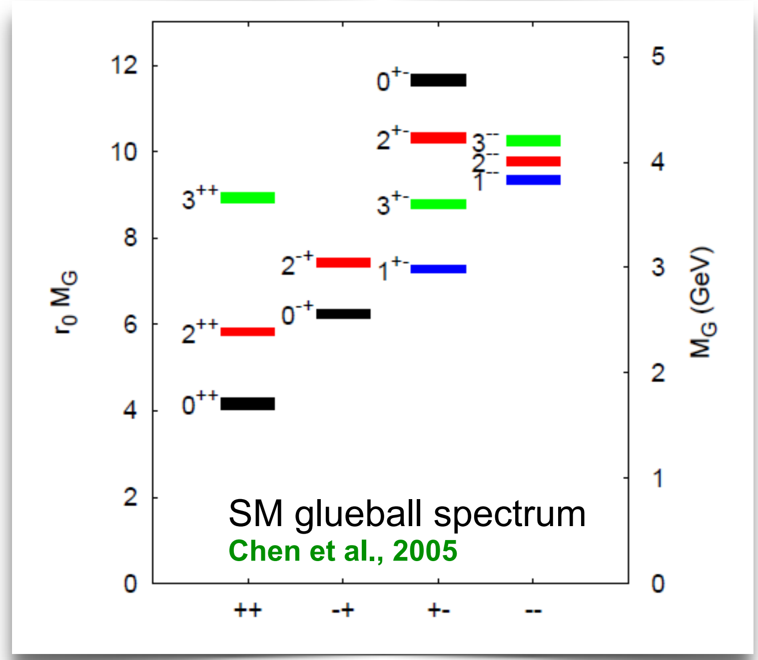
Phenomenology

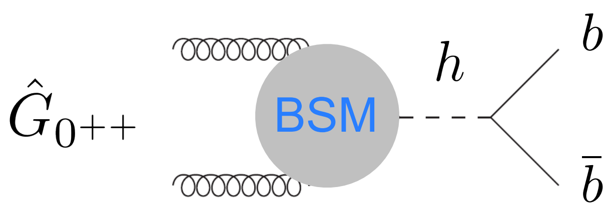
Spectrum of BSM states



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





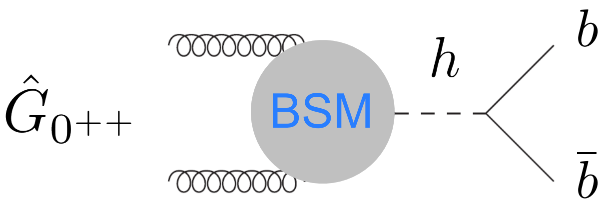
$$c\tau_{0^{++}} \sim 1.2\,\mathrm{m}\left(\frac{5\ \mathrm{GeV}}{\Lambda_{\mathrm{QCD}_{B,C}}}\right)^7 \left(\frac{\omega}{500\ \mathrm{GeV}}\right)^4 \left(\frac{\Delta}{300\ \mathrm{GeV}}\right)^4 \left(\frac{100\ \mathrm{GeV}}{\delta m}\right)^4$$

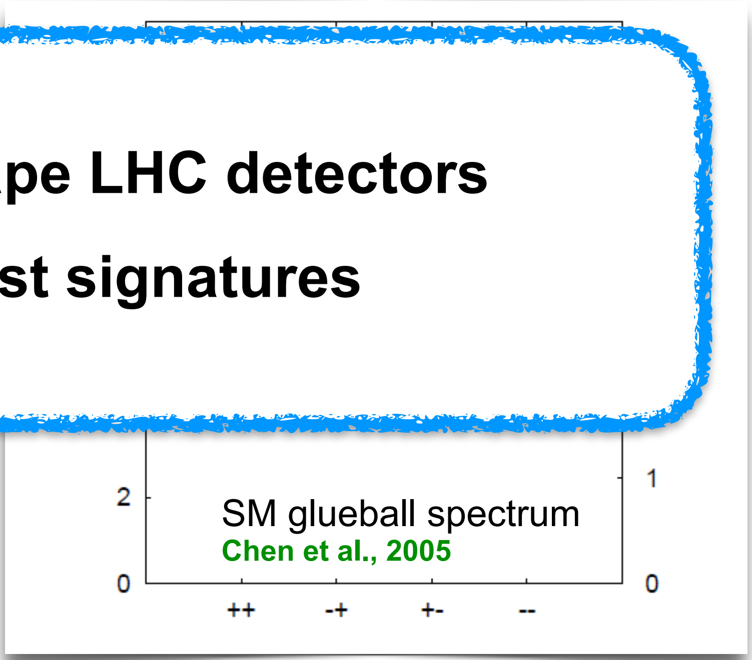
- Lifetime is much **longer** than e.g. in Folded SUSY (~ mm)
- **Large uncertainty** due to dependence on subleading soft masses

Hidden sector confinement

Assume hidden glueballs escape LHC detectors

Look for other, more robust signatures





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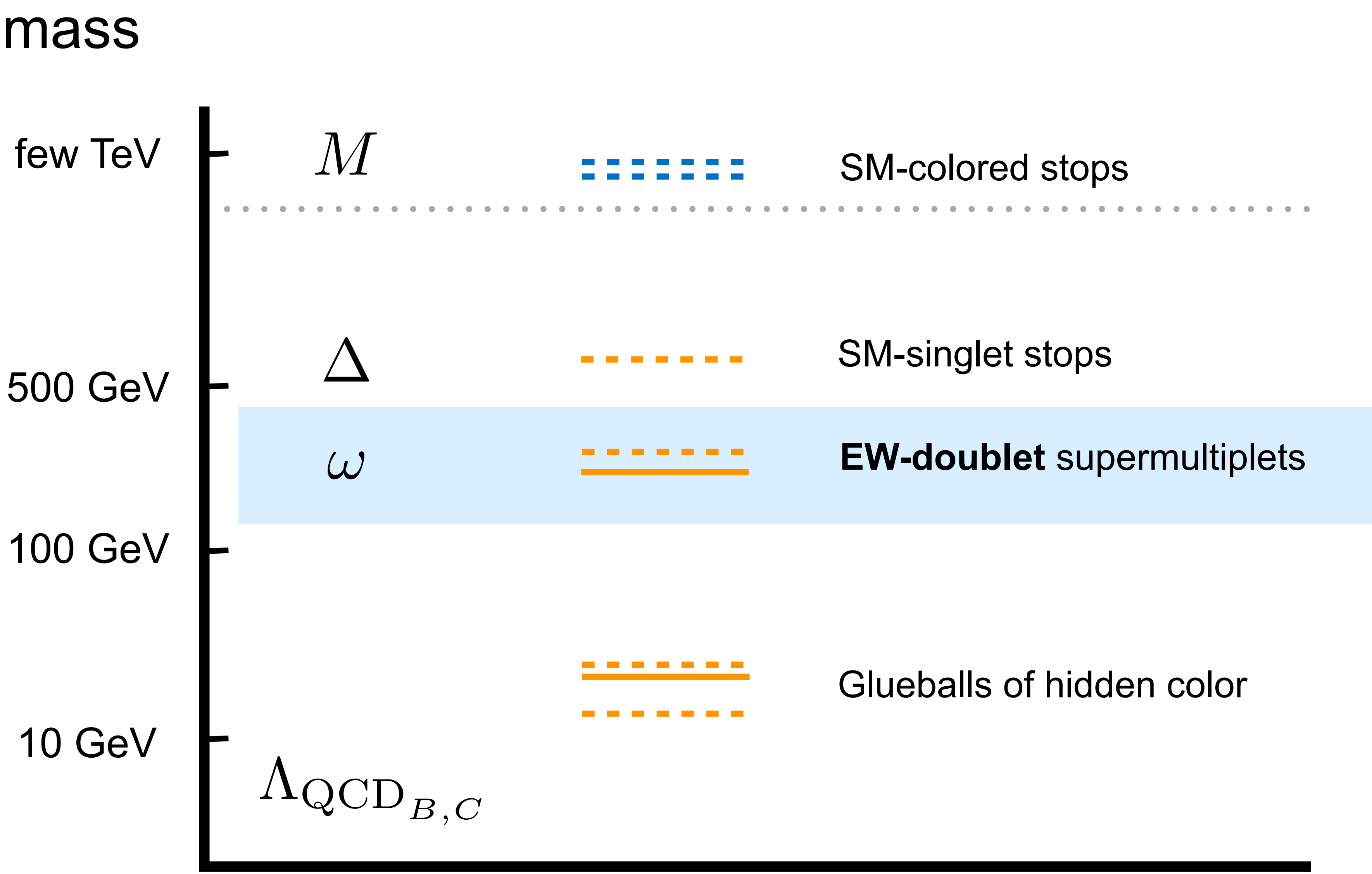
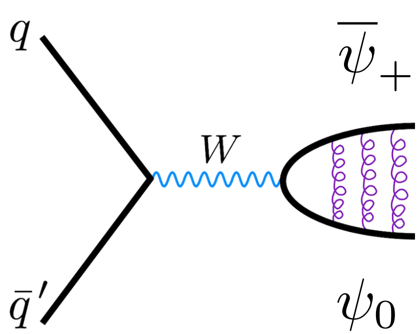
Spectrum of BSM states: $\Delta > \omega$



$\Delta > \omega$: quirk phenomenology

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

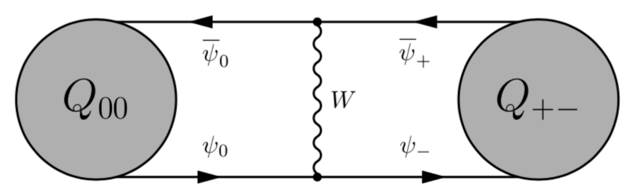
$$Q_{B,C} \sim \mathbf{2}_{-1/2} \sim \begin{pmatrix} \psi_0 \\ \psi_- \end{pmatrix}$$



"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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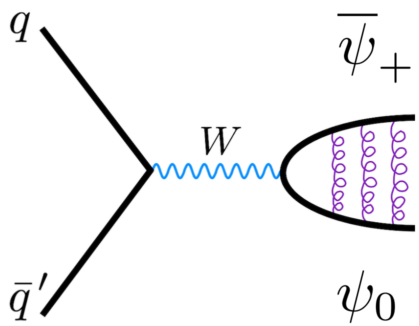

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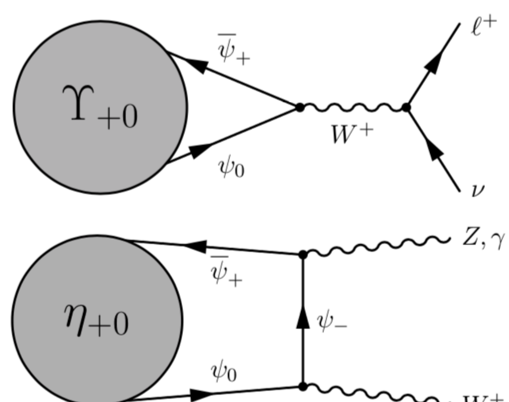
annihilation of $n = 1$ states



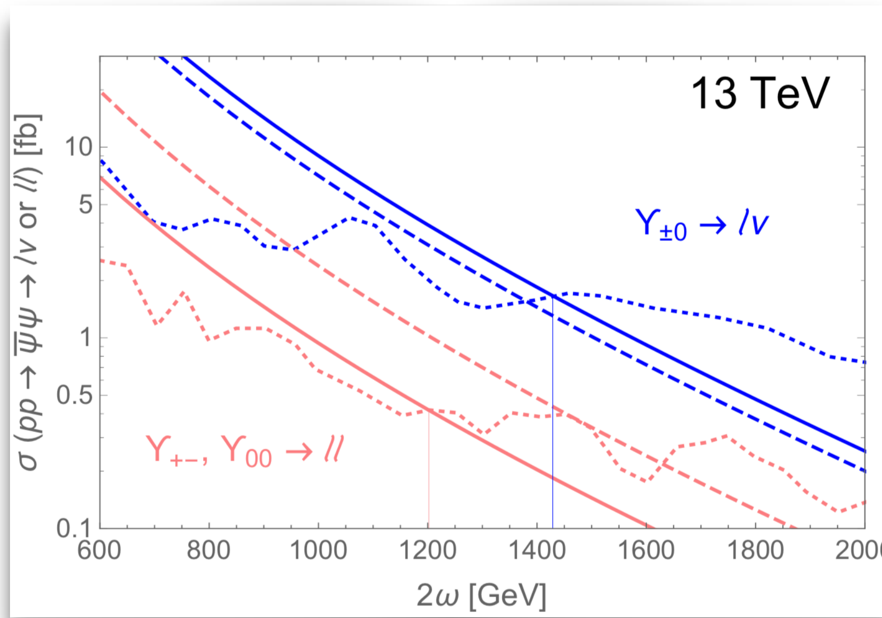
resonant signals

$\Delta > \omega$: quirk phenomenology

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

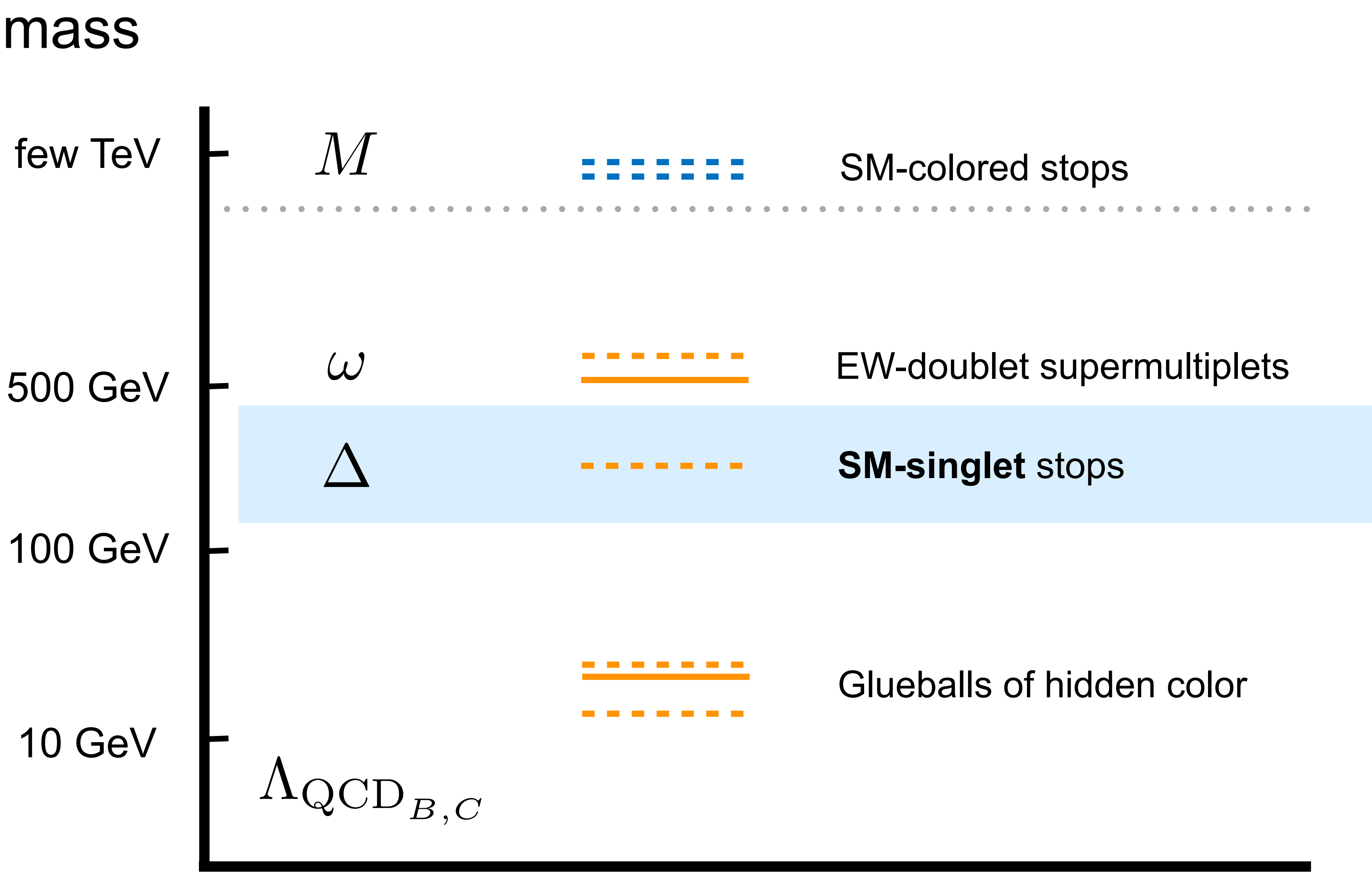
$$\omega \gtrsim 700 \text{ GeV}$$

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



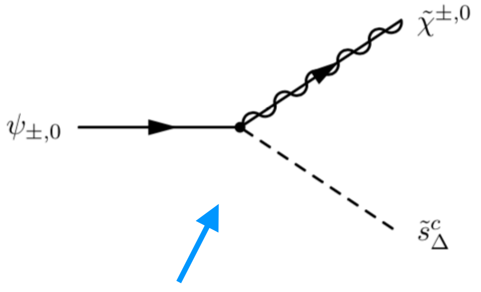
- Neutral channels give $\omega \gtrsim 600 \text{ GeV}$ from $\eta_{+-} \to \gamma\gamma$, $\Upsilon_{+-,00} \to \ell\ell$

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 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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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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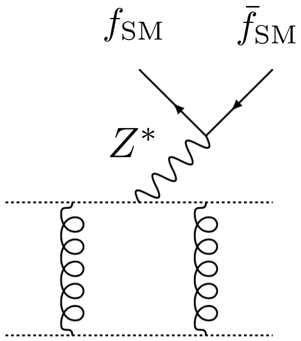


The Higgs VEV gives a **small mass mixing** of singlet and doublet scalars, $\tilde{s}^{c}_{\Delta}$ inherits coupling to the Z

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

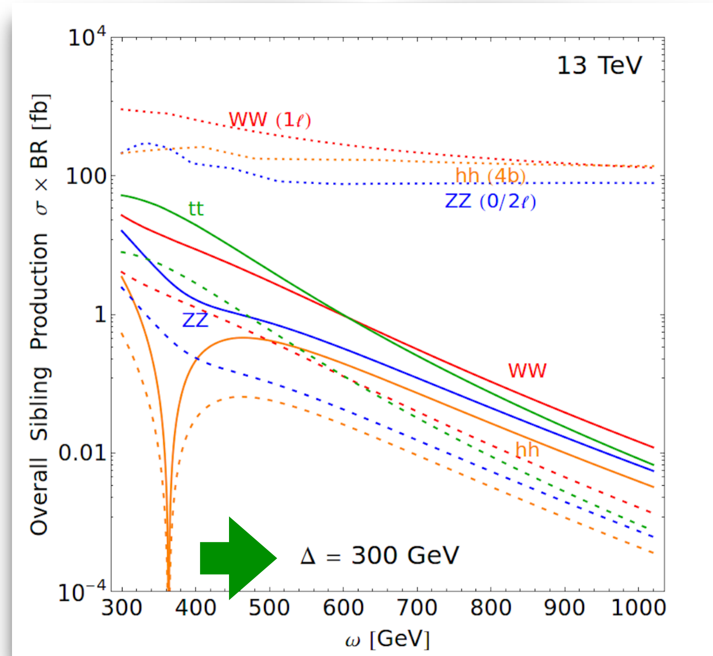
~ 0.1 mm, still prompt

$\Delta < \omega$: light singlet scalars

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

➡ Resonant signals well below current sensitivity

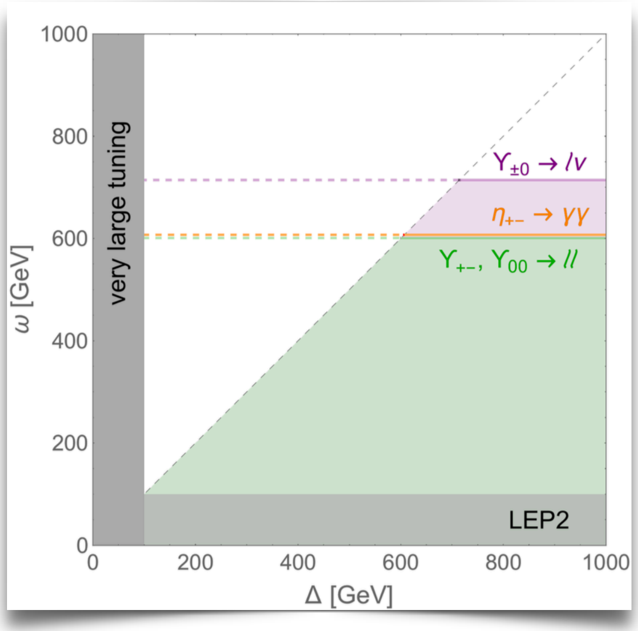
➡ **Very light singlets are allowed**



- Extra particles from cascade decays may give further constraints

Cheng, Li, Salvioni, Verhaaren, work in progress

Summary



- Naturalness can manifest in **unexpected guises**
- Tripled top: accidental SUSY, top partners can be **complete SM singlets**
- May be **as light as few 100's of GeV**
- Full analysis of LHC signatures is ongoing

Backup

The soft masses

Cheng, Li, Salvioni, Verhaaren, 1803.03651

$SU(2) \quad F = 3$

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

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

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

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

- 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 a non-vanishing confining superpotential

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

Arkani-Hamed, Rattazzi
hep-th/9804068

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

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

  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

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

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

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

$\mu_{\rm IR} \to 0$