Neutral Naturalness

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Neutral Naturalness

- Practical definition: symmetry-based solutions to the little hierarchy problem with **color-less top partners**

- Stabilize weak scale up to $\Lambda \sim 5$ - $10\ \mathrm{TeV}$, large hierarchy cured by SUSY / compositeness / clockwork /…

- Phenomenology radically non-standard, poses challenges to collider-based experiments

- Important interplay with other areas, especially cosmo

About this discussion

- I will cover a few selected aspects of Neutral Naturalness,
  focusing mostly on very recent work

- Not a comprehensive review.
  I expect **you** will contribute more topics to the discussion

- No relaxion & related theories, although they may broadly fit in NN
  See dedicated sessions later in this workshop

Plan

(1) SM-singlet scalar top partners

- Tripled Top
- Hyperbolic Higgs

(2) Z_N models

(3) Probing UV completions at colliders

(4) Signatures in cosmology

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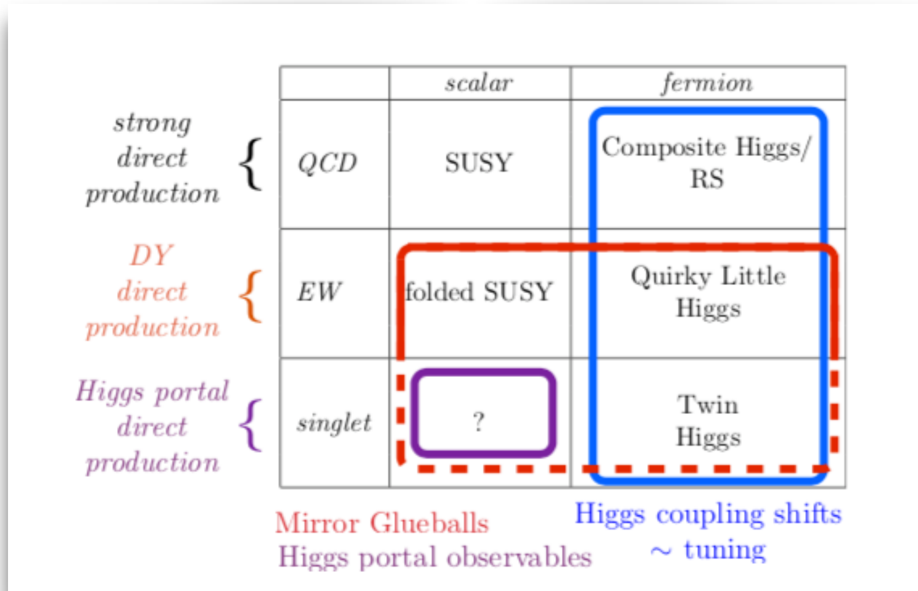
Singlet scalar top partners

- The **top partner zoo**

Curtin, Verhaaren 2015



		scalar	*fermion*
strong direct production	*QCD*	SUSY	Composite Higgs/ RS
DY direct production	*EW*	folded SUSY	Quirky Little Higgs
Higgs portal direct production	*singlet*	?	Twin Higgs

Singlet scalar top partners

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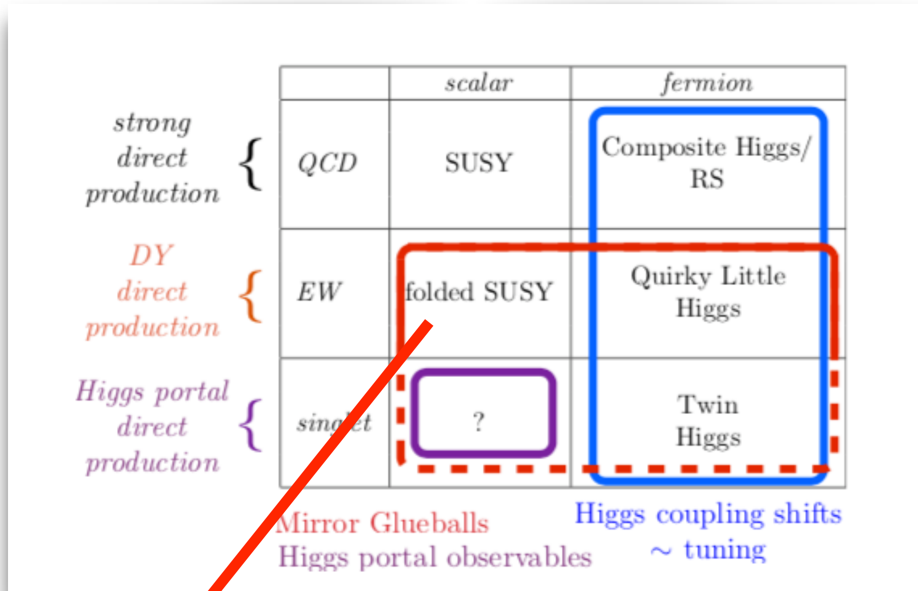
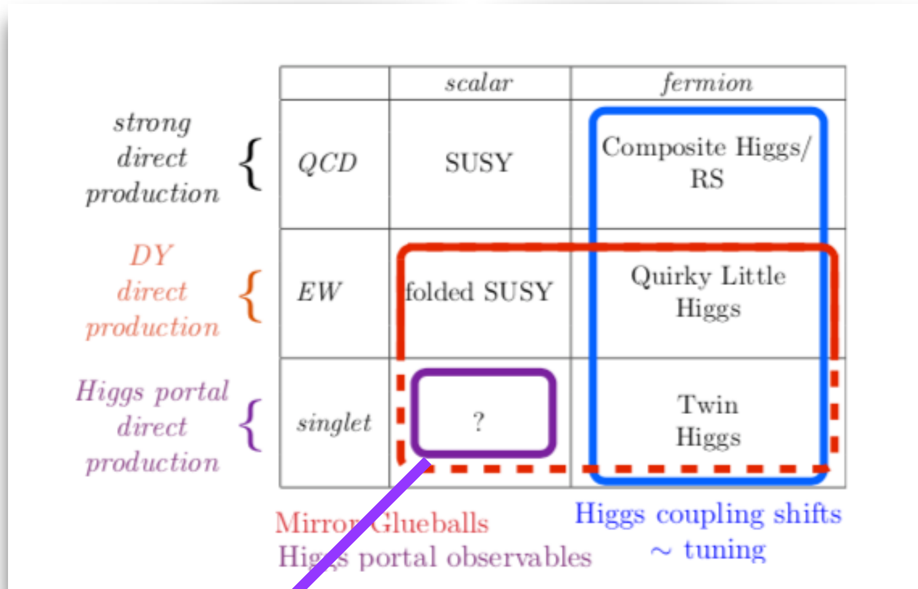


$$\mathcal{L}_{\rm FSUSY} \sim y_t q_A H u_A^c + y_t^2 \left|\tilde{q}_B H\right|^2 + y_t^2 \left|\tilde{u}_B^c\right|^2 |H|^2$$

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

Singlet scalar top partners

- The **top partner zoo**



Models with singlet scalar top partners?

From zero to two:

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

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Folded Supersymmetry

- **Folded SUSY**

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

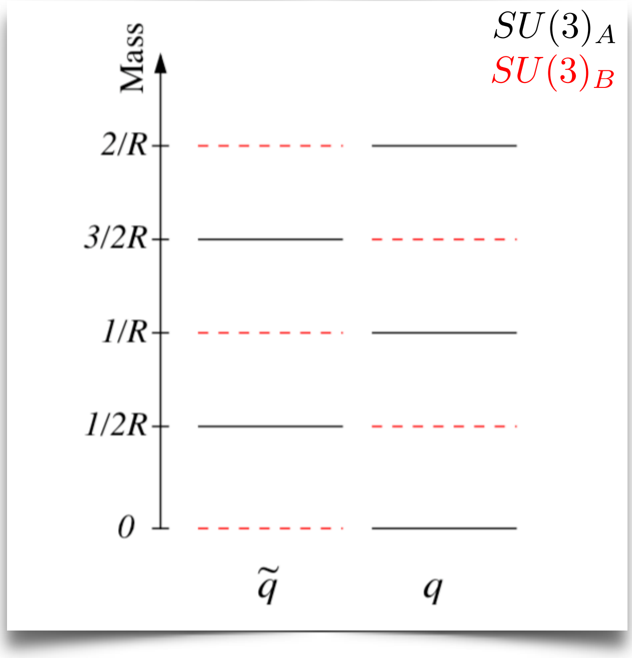
$$Z_2$$

Burdman, Chacko, Goh, Harnik 2016

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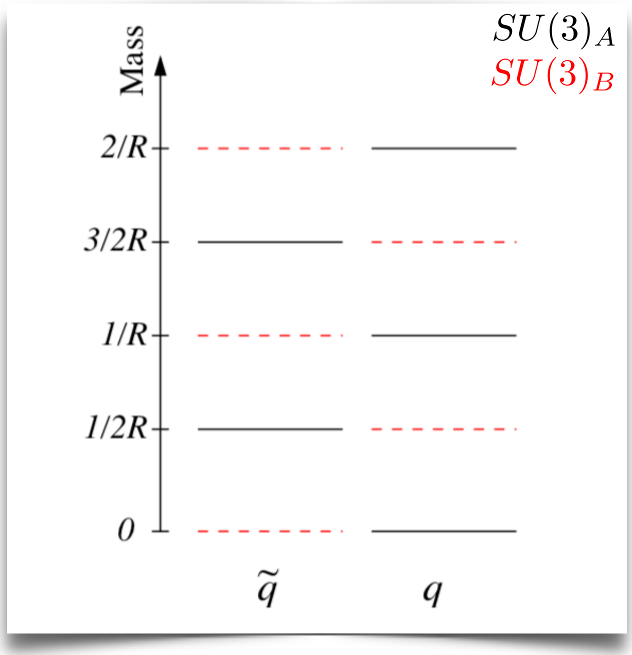
- Protection of Higgs mass is **"too effective:"**

  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 2016

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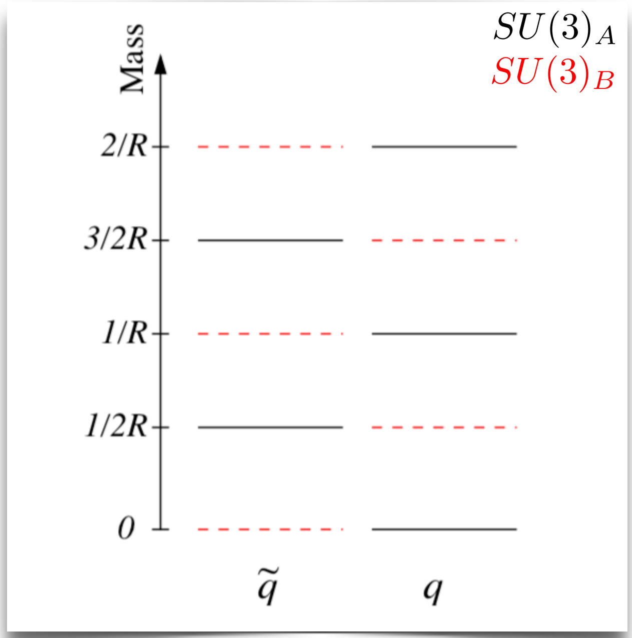

A Tripled Top model

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

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

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

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$$Z_3 \qquad\qquad Z_2$$

- Leading soft masses

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

raise SM-colored stops

lower *SU*(2)-singlet hidden stops

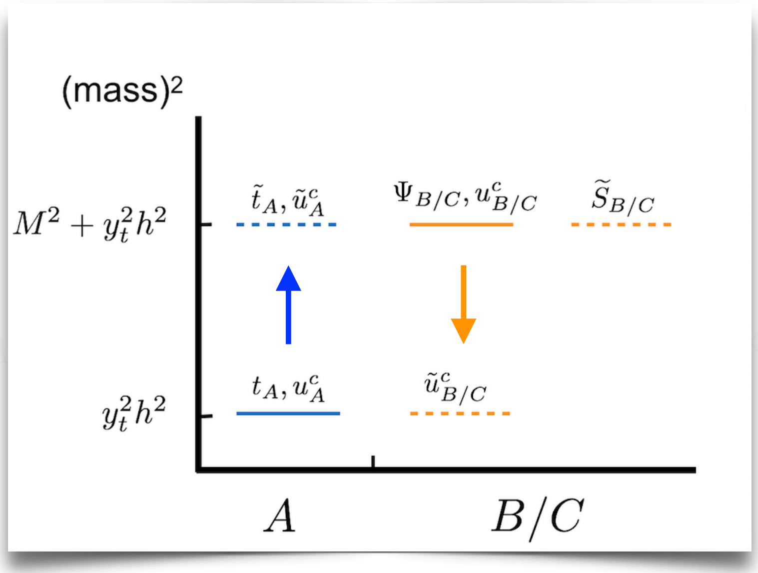
A Tripled Top model

Cheng, Li, Salvioni, Verhaaren 2018

accidental SUSY

for

$\tilde{m} \to M$



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Z_3 $\quad$ Z_2

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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

$$W = y_t\,(Q_A H u^c_A + Q_B H u^c_B + Q_C H u^c_C)$$

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

SM-singlet scalar top partners

Necessary ingredients

- A particular structure for the soft masses

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

Possible origins in next slide

- A "coincidence"

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

soft SUSY-breaking **SUSY**

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

$M \sim \text{few TeV}$

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

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

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 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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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

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

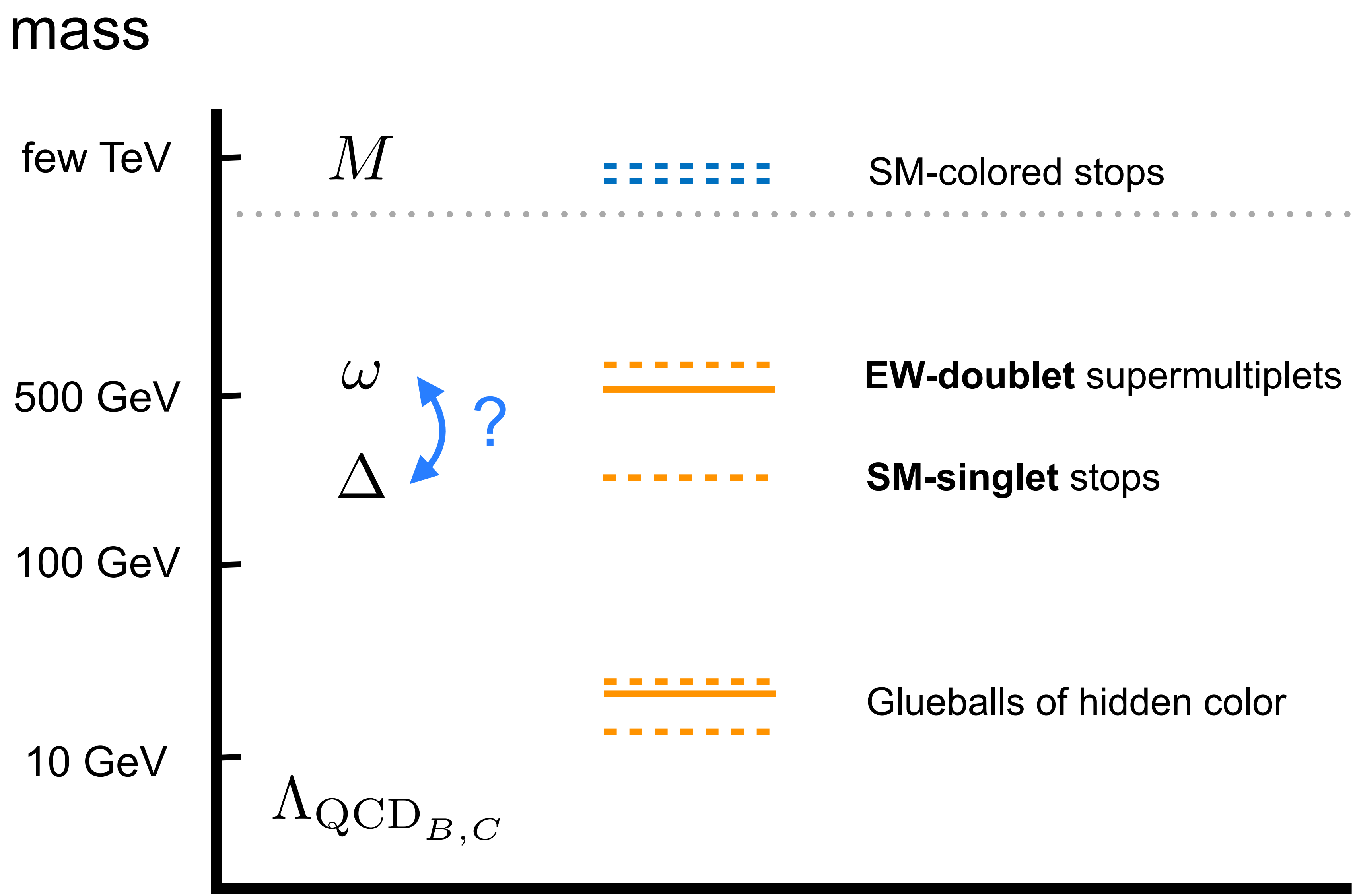
Arkani-Hamed, Rattazzi 1998

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

soft masses of IR composites

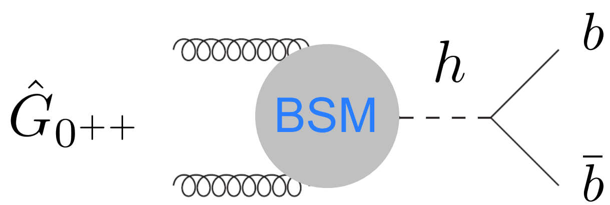
soft masses of UV constituents

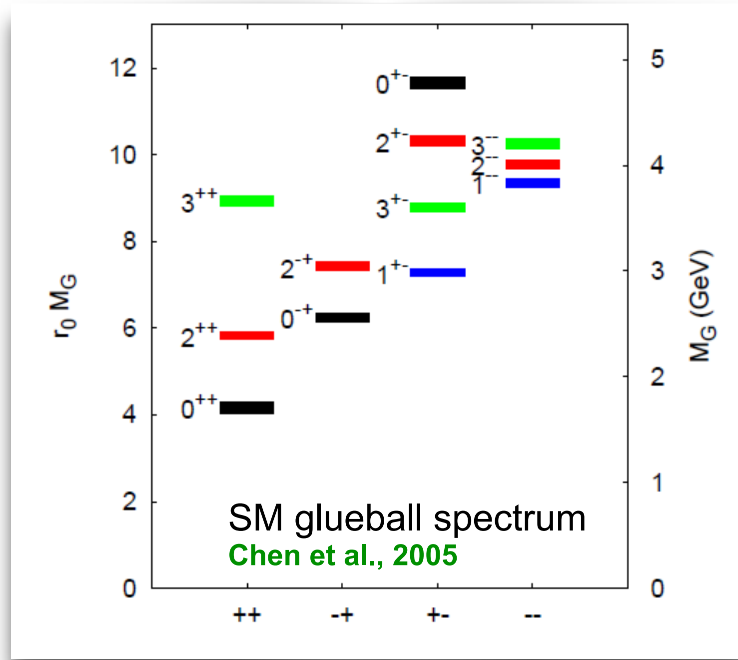
Spectrum of BSM states



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





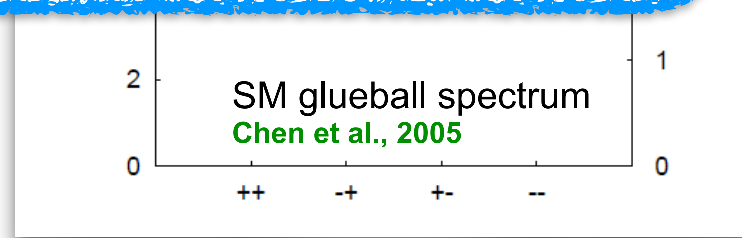
$$c\tau_{0++} \sim 1.2\,\mathrm{m}\left(\frac{5\ \mathrm{GeV}}{\Lambda_{\mathrm{QCD}_{B,C}}}\right)^7 \left(\frac{\omega}{500\ \mathrm{GeV}}\right)^4 \left(\frac{\Delta}{300\ \mathrm{GeV}}\right)^4 \left(\frac{100\ \mathrm{GeV}}{\delta m}\right)^4$$

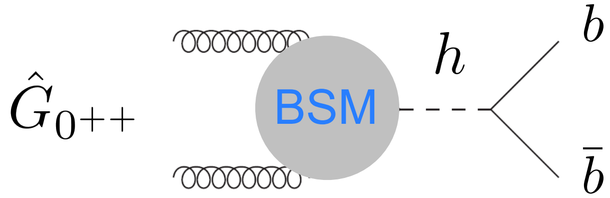
- Lifetime is much **longer** than e.g. in Folded SUSY (~ mm)
- **Large uncertainty** because depends on subleading soft masses

Hidden sector confinement

Assume hidden glueballs escape LHC detectors

Look for other, more robust signatures





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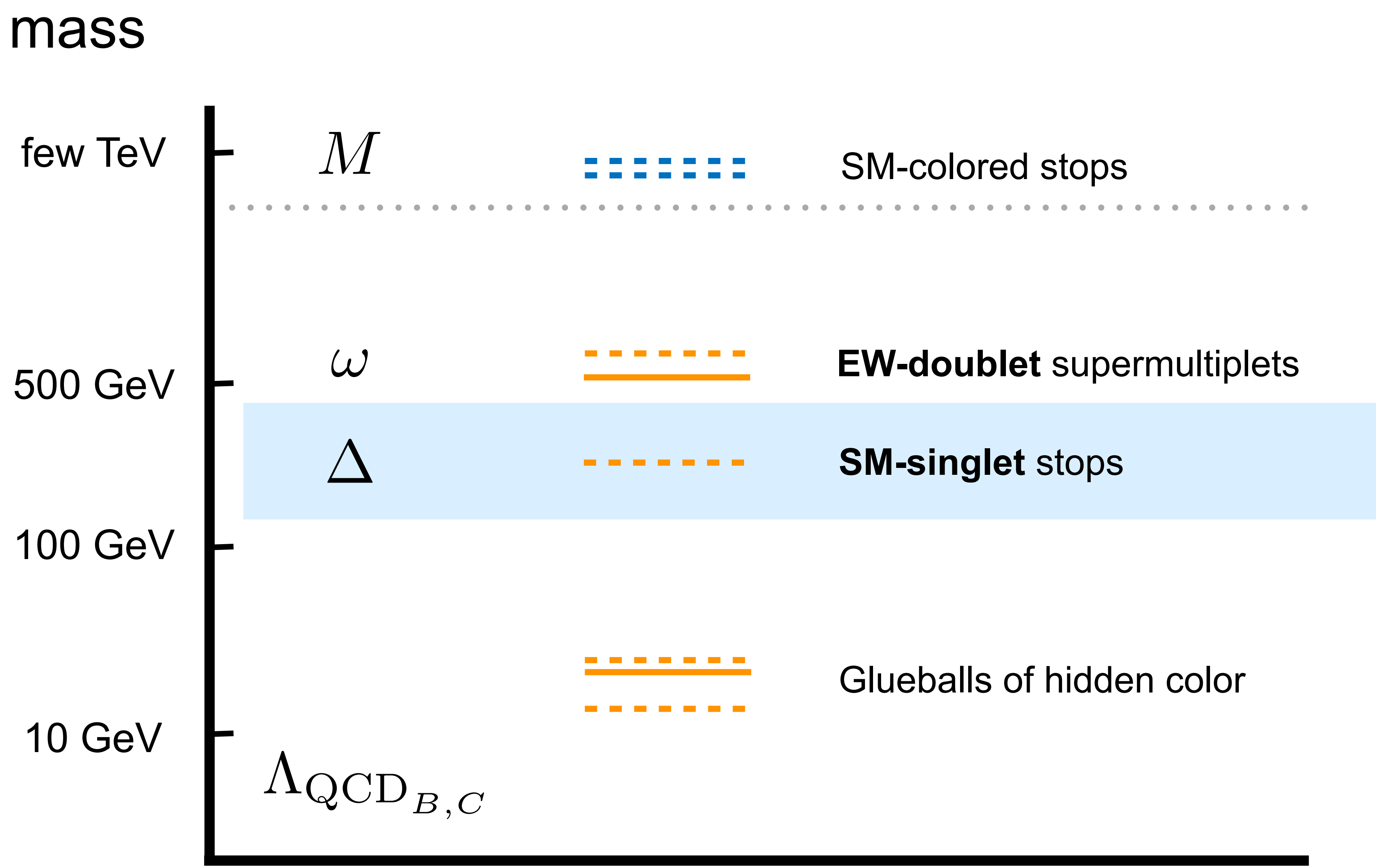
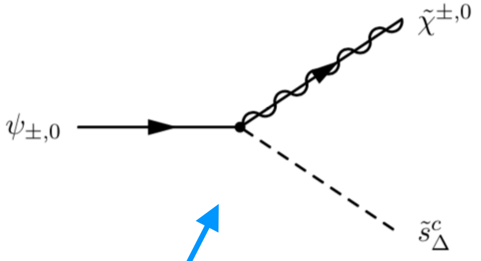
Spectrum of BSM states: $\Delta < \omega$



$\Delta < \omega$: 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 $\tilde{s}^c_\Delta$



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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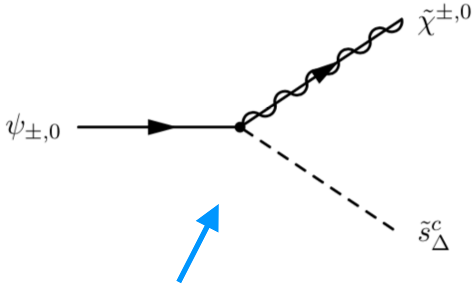

decay of fermions requires light neutralino

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

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

$\Delta < \omega$: light singlet scalars

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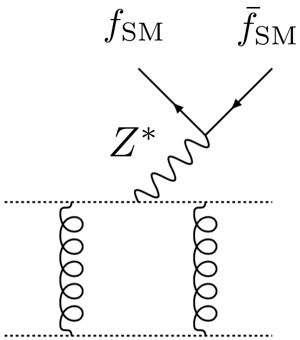


The Higgs VEV gives a **small mass mixing** of singlet and doublet scalars, $\tilde{s}^{c}_{\Delta}$ inherits **coupling to the Z**

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

~ 0.1 mm, still prompt

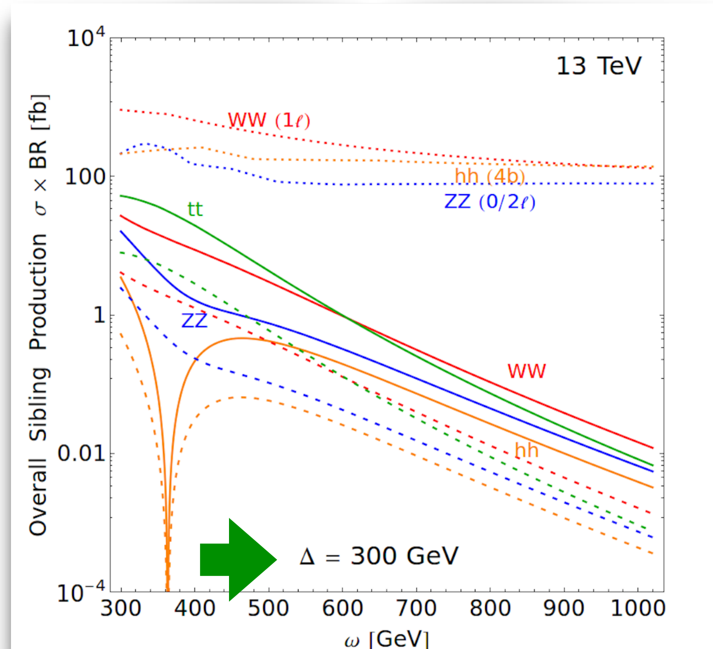
$\Delta < \omega$: light singlet scalars

- 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**

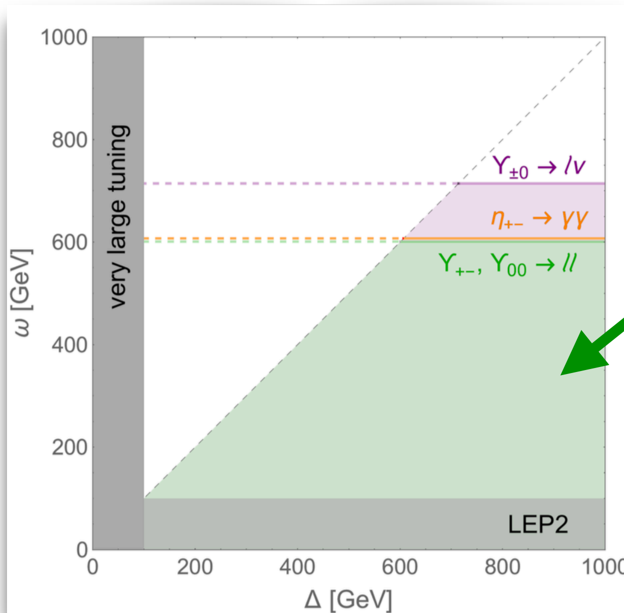


- Extra particles from cascade decays may give further constraints

Cheng, Li, Salvioni, Verhaaren, in progress

Tripled Top parameter space

EW-charged supermultiplets



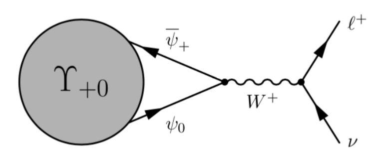
singlet scalar top partners

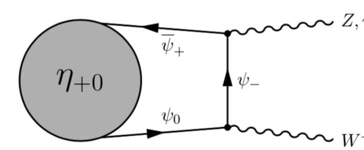
$$\Delta > \omega$$

Drell-Yan

+

resonant signals





Cheng, Li, Salvioni, Verhaaren 2018

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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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Cohen, Craig, Giudice, McCullough 2018

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

- Couplings to matter

Z_2 symmetry

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

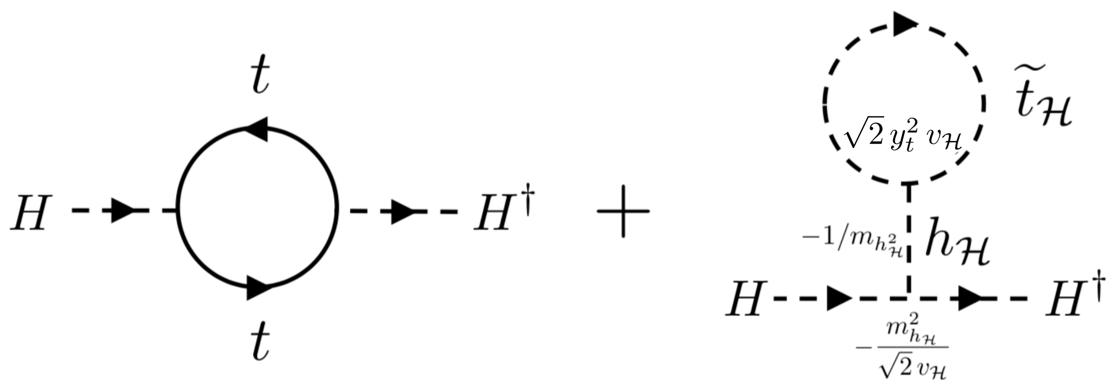
quadratic 1-loop correction $\Rightarrow$ $\delta V \sim \frac{N_c y_t^2}{16\pi^2}\Lambda^2\left(|H_{\mathcal{H}}|^2 - |H|^2\right)$

respects *U*(2,2)

The Hyperbolic Higgs

Cohen, Craig, Giudice, McCullough 2018

- Diagrammatic cancellation



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The Hyperbolic Higgs

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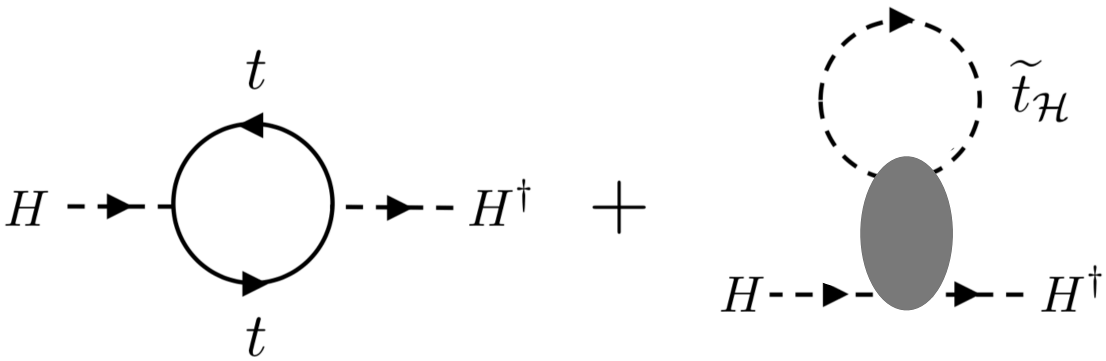
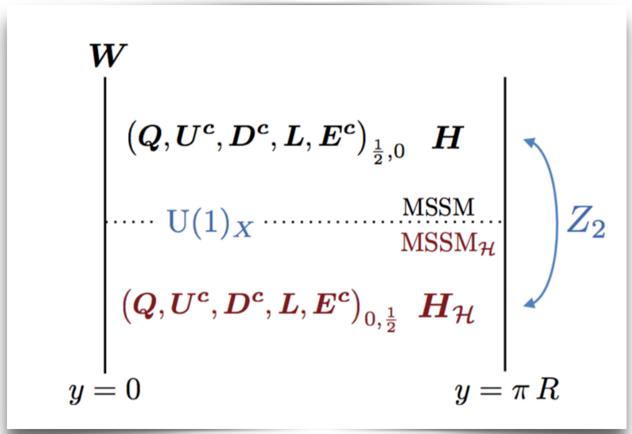


Integrate out heavy radial mode

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

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

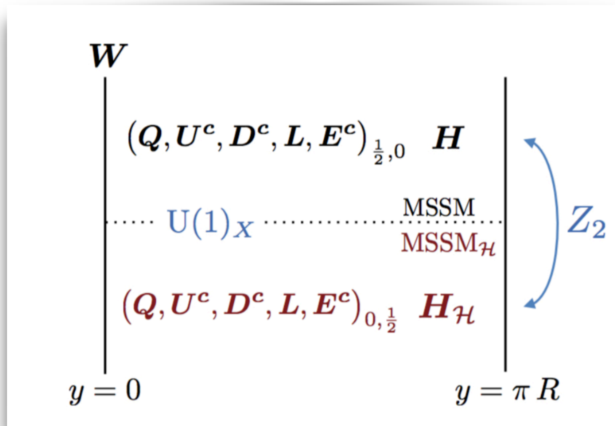
A 5D SUSY completion



$$\Lambda \sim 1/R$$

- $U(1)_X$ *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



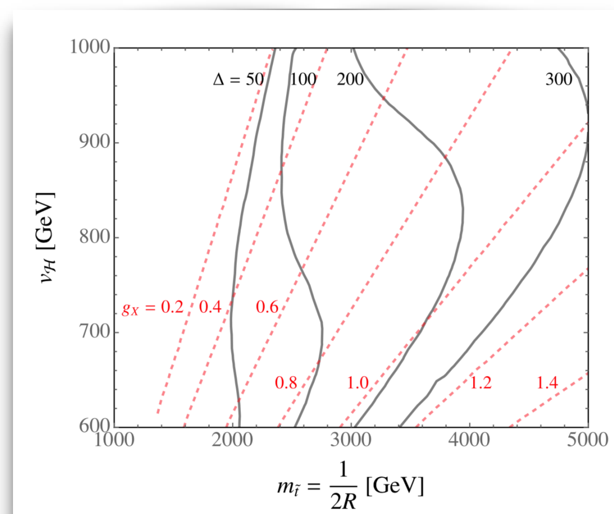
$$\Lambda \sim 1/R$$

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

- 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**

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

+ 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,

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

Spontaneous breaking of hidden color?

Cohen, Craig, Giudice, McCullough 2018

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

Spontaneous breaking of hidden color?

Cohen, Craig, Giudice, McCullough 2018

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

Source: 45worlds.com

  - 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

- 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*

Source: 45worlds.com

- 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

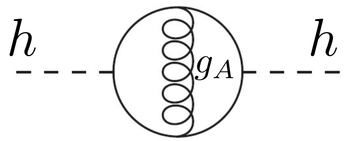
SU(N) glueballs: **Teper hep-th/9812187**

Spontaneous breaking of hidden color?

Craig, Katz, Strassler, Sundrum 2015

- **Broader question:**

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



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

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

(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…

A Twin Higgs example

Batell, McCullough 2015

- Top partners = right-handed neutrinos N

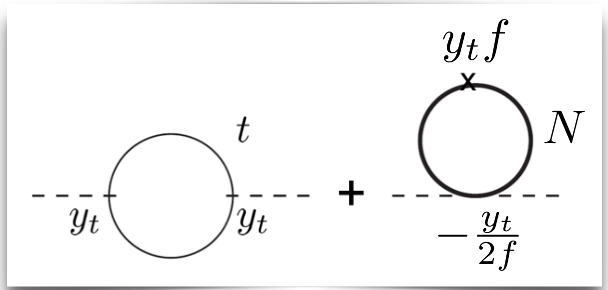
  $SU(3)_N$ cannot be exact, broken by Yukawas $\sim y_\nu \ell H N$

- Take e.g. $SU(6)\times SU(4)$ invariant theory, $SU(4) \xrightarrow{\langle\Sigma\rangle} SU(3)$

$$Q = \begin{pmatrix} q_A & \\ & \begin{pmatrix} N_i \\ E_i \end{pmatrix} \end{pmatrix} \sim (\mathbf{6},\mathbf{4})$$

$$Q^c = \begin{pmatrix} t_A^c & N_i^c \end{pmatrix} \sim (\bar{\mathbf{6}},\mathbf{1})$$

$$\mathcal{L}_t = y_t \Sigma Q Q^c \quad \Rightarrow \quad y_t q_A H t_A^c + y_t f\left(1 - \frac{H^\dagger H}{2f^2}\right) N_i N_i^c + \dots$$



Chacko, Goh, Harnik 2005

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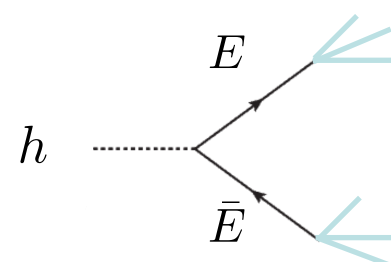
- The "twin bottom" E has mass $\sim y_E f \cos(h/f) E E^c$

  and can mix with the SM neutrinos,

  example $\sim \frac{\phi}{M} E^c (H_A \cdot \ell)$



"sterile neutrino," decays to 3 SM fermions

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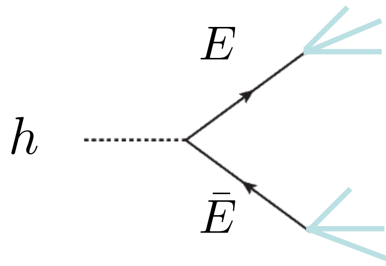

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- If $SU(3)_N$ spontaneously broken at $\sim f$, can we access massive gluons at (future) colliders?

- Recent work with "minimal ingredients:" $SO(6)/SO(5)$ Twin Higgs

Serra, Torre 2017
Csáki, Ma, Shu 2017

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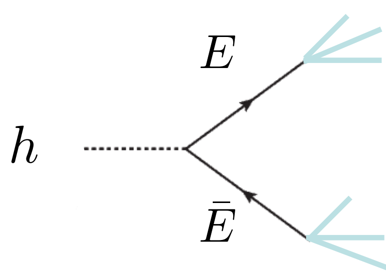


Plan

(1) SM-singlet scalar top partners

- Tripled Top
- Hyperbolic Higgs

(2) Z_N models

(3) Probing UV completions at colliders

(4) Signatures in cosmology

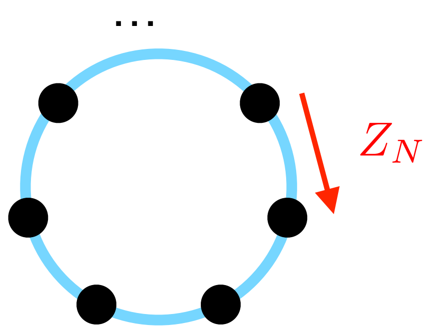
Z_N - symmetric quantum corrections

Hook 2018

- A scalar coupled in Z_N - invariant way can have its scalar potential **exponentially suppressed** in N
- Concretely: ϕ periodic, shift symmetry broken to $\phi \to \phi + 2\pi f$ by $\epsilon \sin\left(\frac{\phi}{f} + \theta\right)$

  Z_N acts as $\phi \to \phi + \frac{2\pi f}{N}$

$$\mathcal{L} = \sum_{k=1}^{N} \left[m_\psi + \epsilon \sin\left(\frac{\phi}{f} + \frac{2\pi k}{N}\right)\right] \psi_k \psi_k^c$$



- A Z_N - invariant potential for ϕ requires at least N insertions, since for $m < N$

$$\sum_{k=1}^{N} \sin^m\left(\frac{\phi}{f} + \frac{2\pi k}{N}\right) = \text{constant}$$

Z_N - symmetric quantum corrections

Hook 2018

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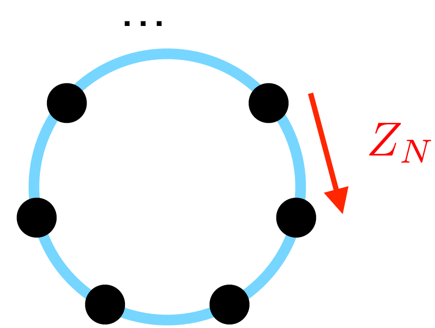

- A Z_N - invariant potential for ϕ requires at least N insertions, so

$$V \sim \frac{\epsilon^N}{\Lambda^{N-4}} \sum_{k=1}^{N} \sin^N\left(\frac{\phi}{f} + \frac{2\pi k}{N}\right) \sim \frac{N\epsilon^N}{\Lambda^{N-4}} \cos\left(\frac{N\phi}{f}\right) \Rightarrow m_\phi^2 \sim \frac{N^3 \epsilon^N}{\Lambda^{N-4} f^2}$$

[frequencies must match, $e^{iN\phi/f} = (e^{i\phi/f})^N$]

Z_N - symmetric quantum corrections

Hook 2018

- TH cancellation is a version of $N = 4$, but **2** copies are enough (gauge invariance forbids odd powers of h)

$$\sum_{k=0}^{N-1} \sin^2\left(\frac{h}{f} + \frac{2\pi k}{N}\right) = \sin^2\left(\frac{h}{f}\right) + \sin^2\left(\frac{h}{f} + \frac{\pi}{2}\right) + \cancel{\sin^2\left(\frac{h}{f} + \pi\right)} + \cancel{\sin^2\left(\frac{h}{f} + \frac{3\pi}{2}\right)}$$

- First non-vanishing term is familiar quartic, $\sim \sin^4\left(\frac{h}{f}\right) + \cos^4\left(\frac{h}{f}\right)$

- A Z_N - invariant potential for ϕ requires at least N insertions, so

$$V \sim \frac{\epsilon^N}{\Lambda^{N-4}} \sum_{k=1}^{N} \sin^N\left(\frac{\phi}{f} + \frac{2\pi k}{N}\right) \sim \frac{N\epsilon^N}{\Lambda^{N-4}} \cos\left(\frac{N\phi}{f}\right) \quad \Rightarrow \quad m_\phi^2 \sim \frac{N^3\epsilon^N}{\Lambda^{N-4} f^2}$$

[frequencies must match, $e^{iN\phi/f} = (e^{i\phi/f})^N$]

Solving the hierarchy problem discretely

Hook 2018

- Exponential suppression holds as long as ϕ does not hit a phase transition
- V can be unsuppressed on other side of transition

➡ **exploit this to address little hierarchy problem**

Solving the hierarchy problem discretely

Hook 2018

- ϕ as modulus of the Higgs mass. Take *N* copies of the SM, for example *N* = 3

$$V = \sum_k m^2_{H,k}(\phi)\,|H_k|^2 + \lambda|H_k|^4, \qquad m^2_{H,k}(\phi) = -m_H^2 + \epsilon^2 \cos\left(\frac{\phi}{f} + \frac{2\pi k}{N}\right)$$

where $m_H^2 = \frac{N_c y_t^2}{8\pi^2}\Lambda^2$ and $m_H^2 \lesssim \epsilon^2 \lesssim 2m_H^2$

across ϕ field space, **one** of the masses flips sign

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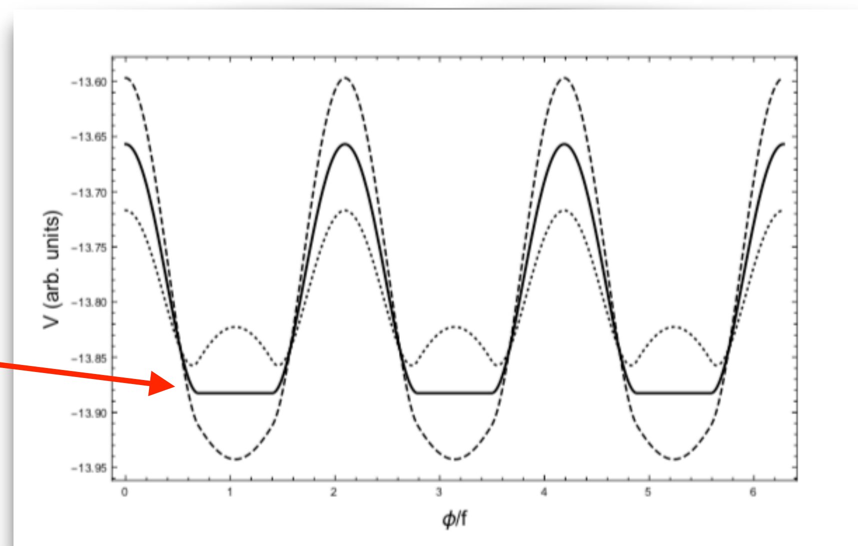
across ϕ field space, **one** of the masses flips sign

- Integrate Higgses out classically

$$V_H = -\sum_k \frac{m_{H,k}^4(\phi)}{4\lambda}\,\Theta\left[-m_{H,k}^2(\phi)\right]$$

ϕ - independent if **all masses negative**

(would need at least N insertions)



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$$V_{\rm UV} \sim \frac{\epsilon^{2N}}{\Lambda^{2N-4}} \cos\left(\frac{N\phi}{f} + \theta\right) \qquad \theta = 0$$

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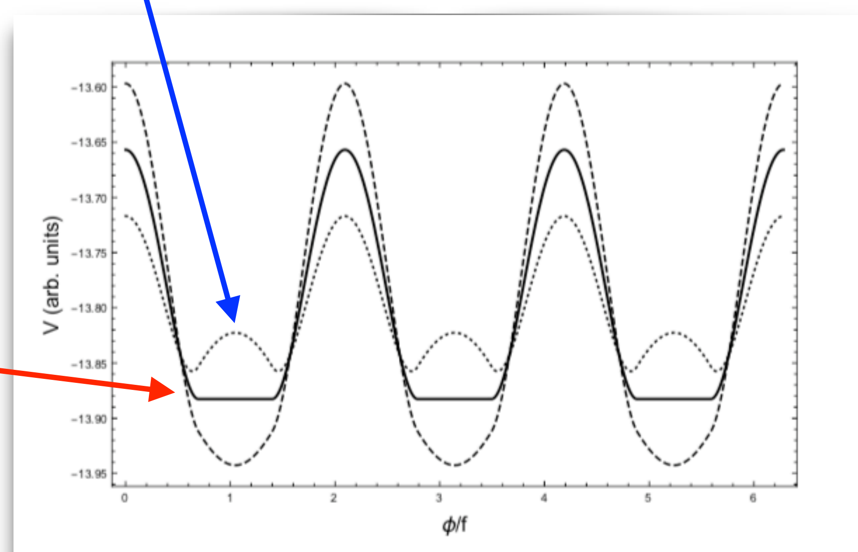

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$$V_{\rm UV} \sim \frac{\epsilon^{2N}}{\Lambda^{2N-4}} \cos\left(\frac{N\phi}{f} + \theta\right) \qquad \theta = 0$$

at minimum, one of the masses is small (and positive)

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$$V_H = -\sum_k \frac{m^4_{H,k}(\phi)}{4\lambda}\,\Theta\left[-m^2_{H,k}(\phi)\right]$$

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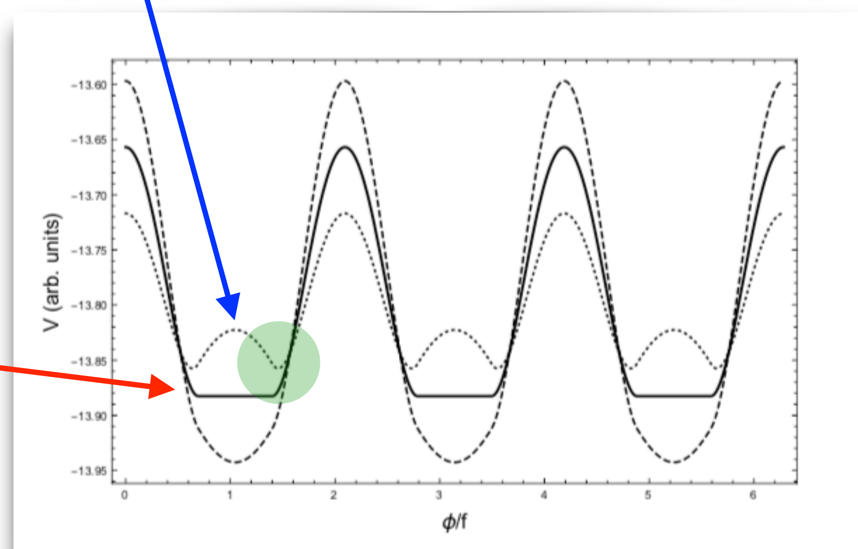

Questions/comments

- Wrong sign of SM Higgs mass can be fixed, e.g. by adding $\delta V \sim \cos\left(\frac{M\phi}{f}\right), \quad M \gg N$
- Larger *N* faces two issues:

$$m_H^2 \lesssim \epsilon^2 \lesssim \frac{m_H^2}{\cos(\pi/N)}$$

tuning ~ 1/*N*^2

$$V_{\rm CW} \sim \frac{\beta}{16\pi^2} \sum_k |H_k|^4 \log \frac{|H_k|^2}{\Lambda^2}$$

dominates over UV potential,
too large for light Higgs

- Our sector is reheated preferentially, à la Nnaturalness

Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner 2016

- Cross-quartics lead to Higgs mixing, decays to hidden sectors
- Constraints on ϕ need to be worked out
- A model where the other masses are large and *positive,* so only the Higgs is copied *N* times?

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Probing UV completions

- In neutral naturalness, low-energy theory is elusive by construction

  Furthermore, signatures (e.g. coupling modifications) are not unique to NN

- UV completion at multi-TeV can be key to characterisation, even **discovery**

  Assess reach of **future colliders**

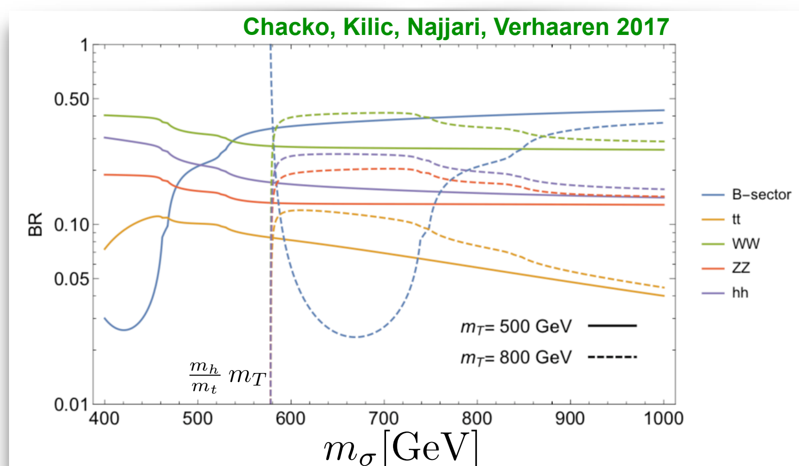
- Example: **Twin Higgs**

  In weakly coupled completions, **scalar radial mode** is robust feature

$$SO(8) \xrightarrow{f} SO(7)$$

$$V \ni \lambda |H|^4 \;\to\; \lambda f \sigma \left(\textstyle\sum_i \pi_i^2\right)$$

$$\mathrm{BR}(\sigma \to WW) \simeq 2\,\mathrm{BR}(\sigma \to hh) \simeq \tfrac{2}{7}$$

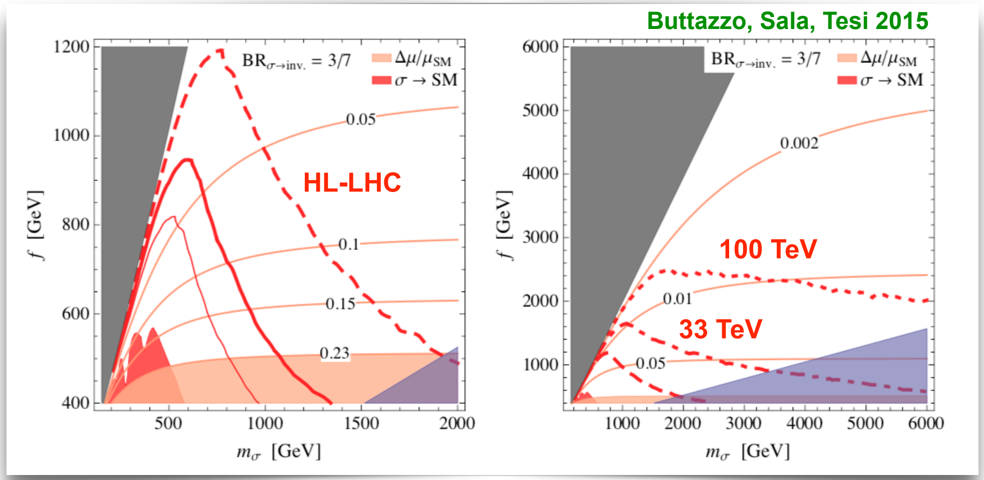


Radial mode at colliders

- At hadron colliders σ produced in gluon fusion

  Best reach in $\sigma \to VV$

Buttazzo, Sala, Tesi 2015

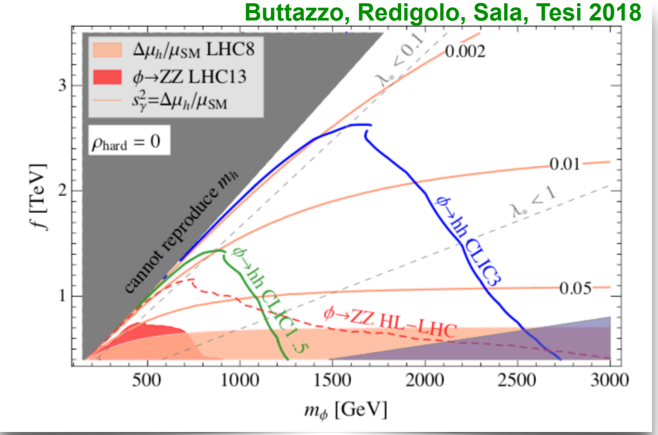


also: **Katz, Mariotti, Pokorski, Redigolo, Ziegler 2016**

- At high-energy lepton colliders dominant production in *WW* fusion

  Best reach in $\sigma \to hh \to 4b$

Buttazzo, Redigolo, Sala, Tesi 2018



- If Z_2 is broken **only softly**, $\{G_F, m_h, g_{hVV}/g_{hVV}^{\rm SM}, m_\sigma\}$ completely fix potential

  ➡ $\sigma \to \rm SM\ SM$ is genuine **test** of TH mechanism

Chacko, Kilic, Najjari, Verhaaren 2017

Strongly coupled UV completions

- Radial mode may be too broad to observe
- Expect new **vector-like fermions** charged under **both SM and Twin**
- Simplest way to introduce them: $SU(6) \times SU(4)$ invariant top Yukawa

$$Q^c = \begin{pmatrix} t_A^c & t_B^c \end{pmatrix} \sim (\bar{\mathbf{6}}, \mathbf{1})$$

$$Q = \begin{pmatrix} q_A & \widetilde{q}_B \\ \widetilde{q}_A & q_B \end{pmatrix} \sim (\mathbf{6}, \mathbf{4})$$

$$\mathcal{L}_t = y_t \Sigma Q Q^c + \widetilde{M}(\,\bar{\widetilde{q}}_A \widetilde{q}_A + \bar{\widetilde{q}}_B \widetilde{q}_B)$$

Chacko, Goh, Harnik 2005

- Their mass $\widetilde{M}$ cuts off logarithmic divergences in Higgs potential

- More in general, they appear as composite resonances / KK modes

Geller, Telem 2014
Barbieri, Greco, Rattazzi, Wulzer 2015
Low, Tesi, Wang 2015

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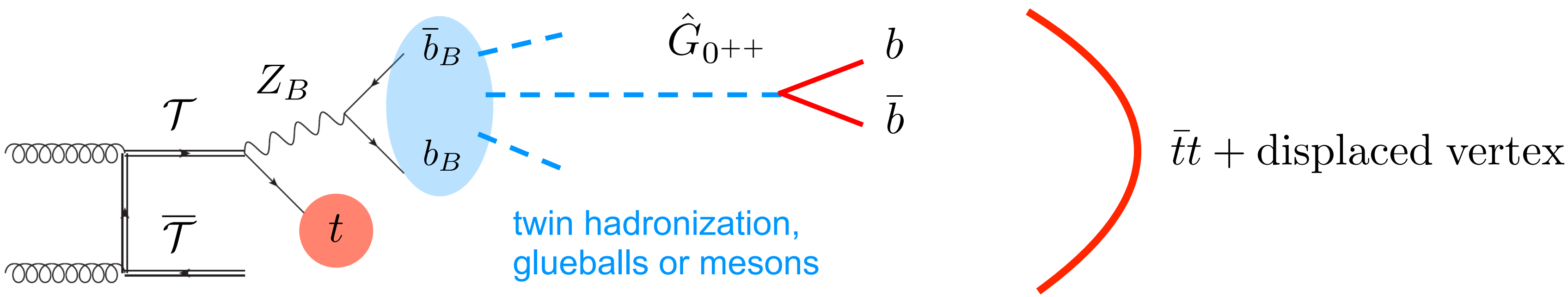
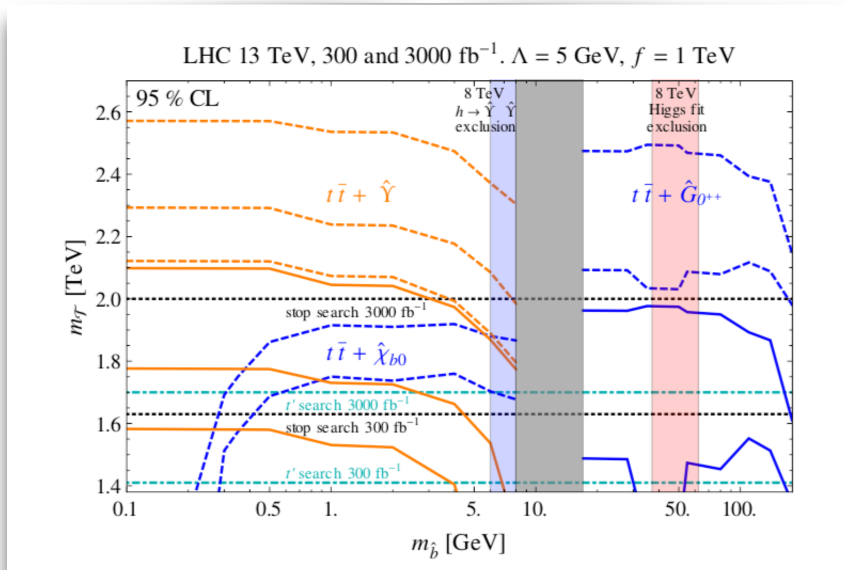
$$Q = \begin{pmatrix} q_A & \tilde{q}_B \\ \tilde{q}_A & q_B \end{pmatrix} \sim (\mathbf{6}, \mathbf{4})$$

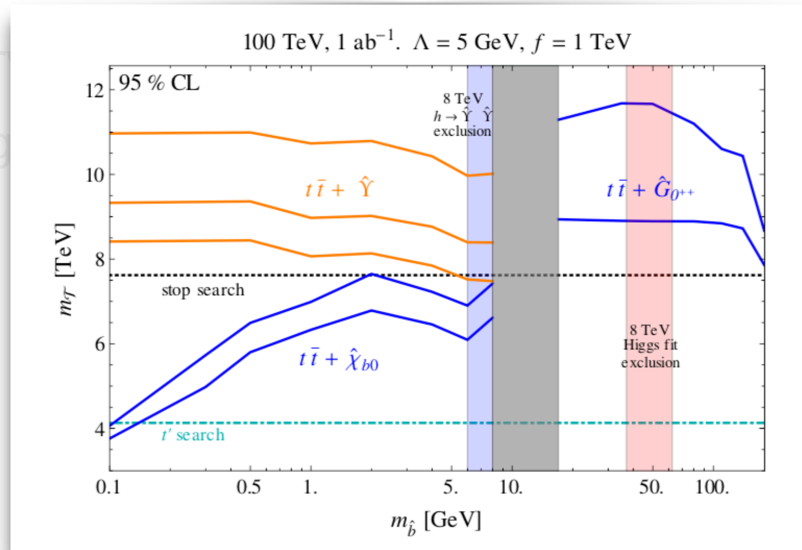
SM color *and* twin weak $\rightarrow$ high-energy portal at hadron colliders

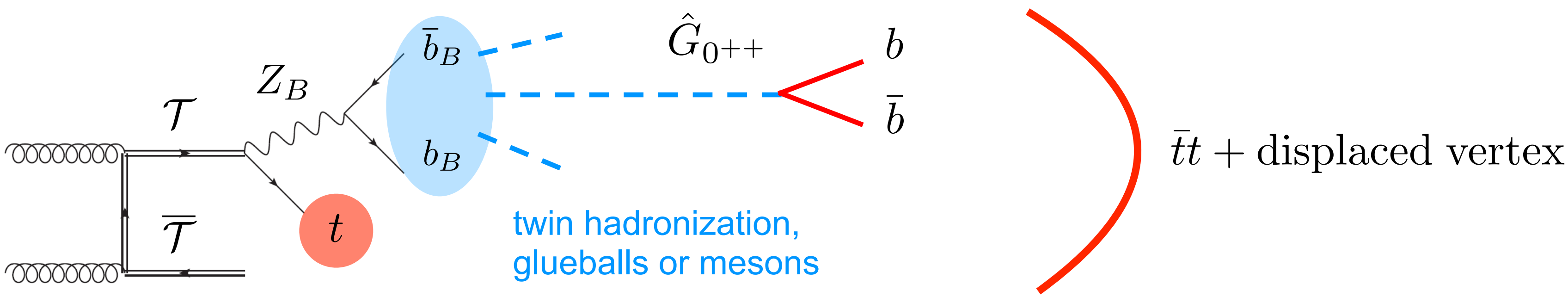


Cheng, Jung, Salvioni, Tsai 2015 [assume Fraternal TH setup]

Strongly coupled UV completions







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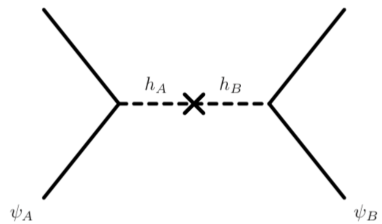
Cosmology of Mirror Twin Higgs

- The Mirror TH (= Z_2 broken only softly) has well-known conflict with cosmology: too much dark radiation in the form of twin photon and neutrinos

$$\Delta N_{\rm eff} \approx 5.6 \qquad (\Delta N_{\rm eff} \lesssim 0.6 \text{ at } 95\% \text{ CL})$$



$$T_{\rm dec} \sim 3 \text{ GeV}$$

- **Several solutions proposed in last ~ 2 years**

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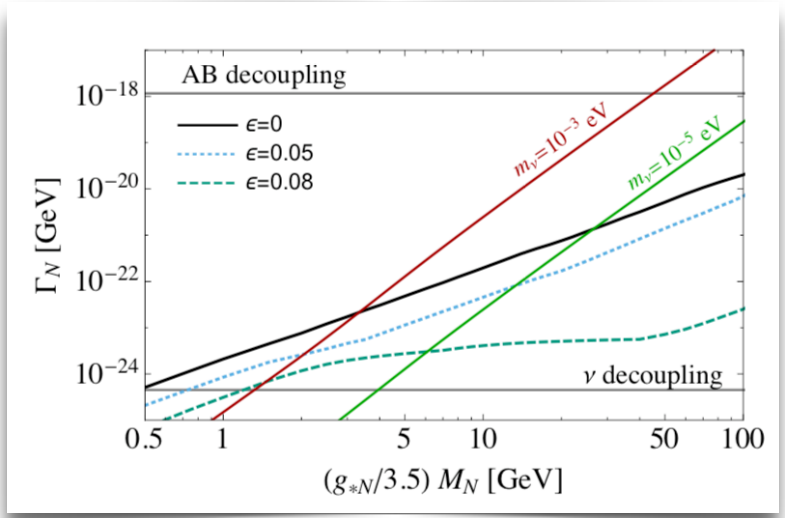
$$\Delta N_{\text{eff}} \approx 5.6 \qquad (\Delta N_{\text{eff}} \lesssim 0.6 \text{ at } 95\% \text{ CL})$$

- **Asymmetric reheating** of the two sectors after decoupling, for example by decays of right-handed neutrinos

$$\Delta N_{\text{eff}} \approx 7.4 \, \frac{v^2}{f^2}$$

Chacko, Craig, Fox, Harnik 2016



- Does not require hard Z_2 breaking

also: **Craig, Koren, Trott 2016**

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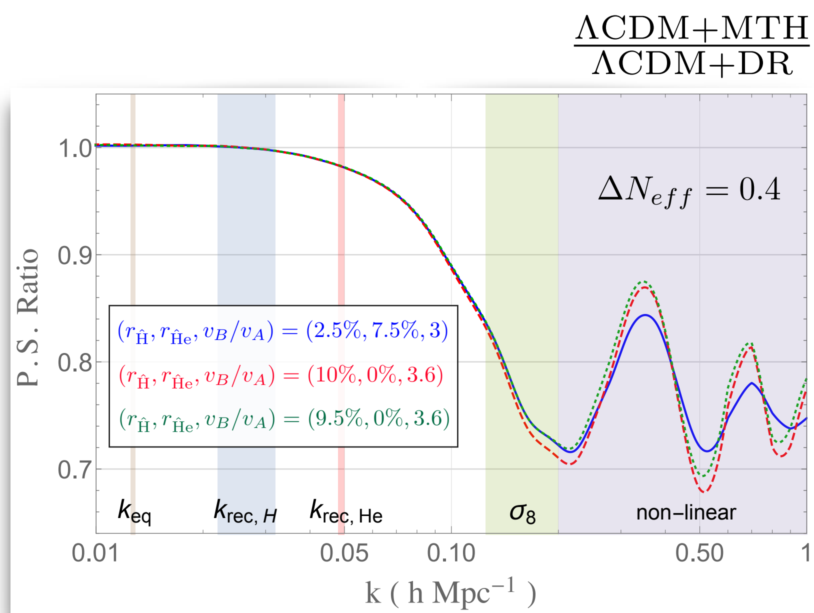
- Cosmological signatures predicted both in large scale structure (twin BAO)



Chacko, Curtin, Geller, Tsai 2018

and in CMB: different effects from twin photon / neutrinos (scattering *vs* free stream), testable prediction

$$\frac{\Delta N_{\rm eff}^{\nu B}}{\Delta N_{\rm eff}^{\gamma B}} = \frac{3}{\frac{8}{7}\left(\frac{11}{4}\right)^4} \approx 0.68$$

Cosmology of Mirror Twin Higgs

- "Minimal Mirror TH", **hard *Z*$_2$ breaking from Yukawas**

➡ raise temperature of twin QCD phase transition to $T^B_{\rm QCD} > T_{\rm dec} > T^A_{\rm QCD}$

Barbieri, Hall, Harigaya 2016

- **Neutrino portal** can also help, delaying decoupling to < 1 GeV

Csáki, Kuflik, Lombardo 2017

- *Z*$_2$ - breaking mass in Higgs potential can be generated radiatively

- In all cases, the extra radiation should be detectable in future CMB experiments: at Stage-IV

$$\Delta N_{\rm eff} \lesssim 0.04 \ (95\% \ {\rm CL})$$

(Snowmass, 1309.5383)

More…

- Fine tuning analyses — Katz, Mariotti, Pokorski, Redigolo, Ziegler 2016; Contino, Greco, Mahbubani, Rattazzi, Torre 2017
- Electroweak precision — Contino, Greco, Mahbubani, Rattazzi, Torre 2017
- Tadpole-induced EWSB — Harnik, Howe, Kearney 2016
- Twin SIMPs — Hochberg, Kuflik, Murayama 2018

Thanks!

Backup

The soft masses

Cheng, Li, Salvioni, Verhaaren, 1803.03651

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

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

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

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

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

- Z_3 - symmetric Yukawas

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

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

  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

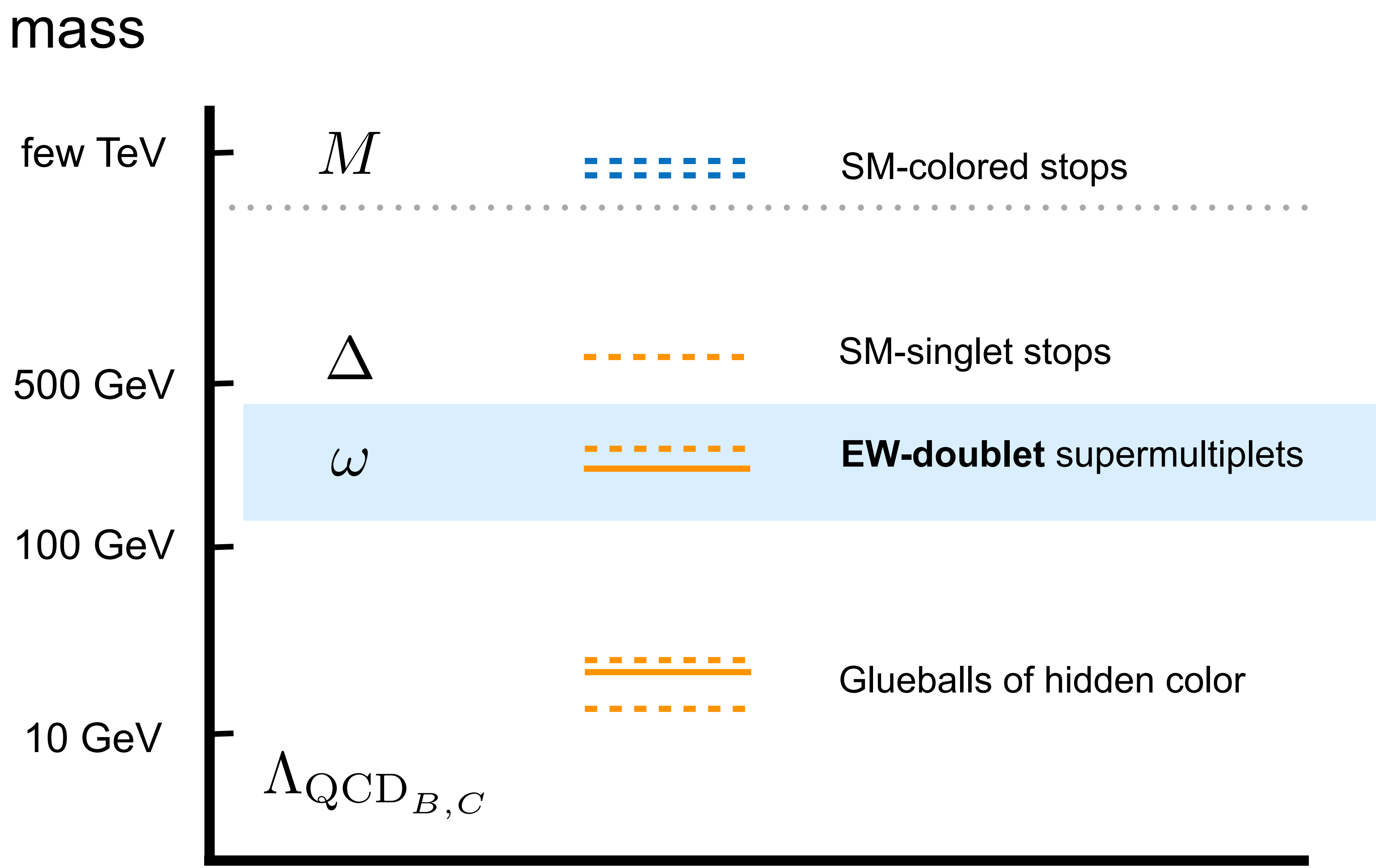
$$K \supset c_{M_{ij}} \frac{M_{ij}^\dagger Z_i Z_{\bar j} M_{ij}}{I} + \cdots$$

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

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

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

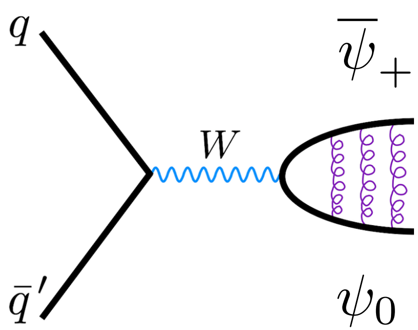
Spectrum of BSM states: Δ > ω



$\Delta > \omega$: quirk phenomenology

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

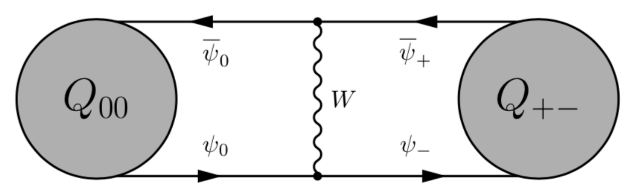
$$Q_{B,C} \sim \mathbf{2}_{-1/2} \sim \begin{pmatrix} \psi_0 \\ \psi_- \end{pmatrix}$$



"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

$\Delta > \omega$: quirk phenomenology

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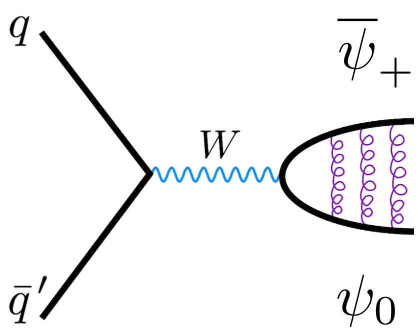
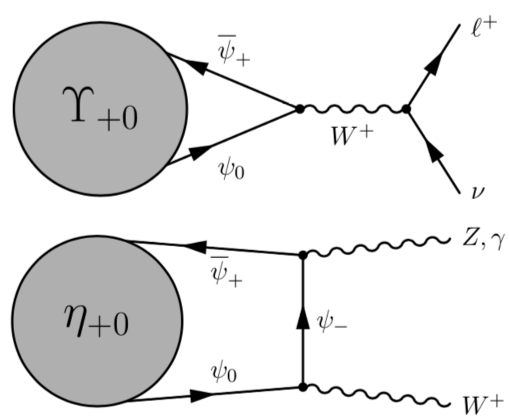


"quirky" bound state → de-excites down to ground state via emission of **soft photons**

→ annihilation of $n = 1$ states



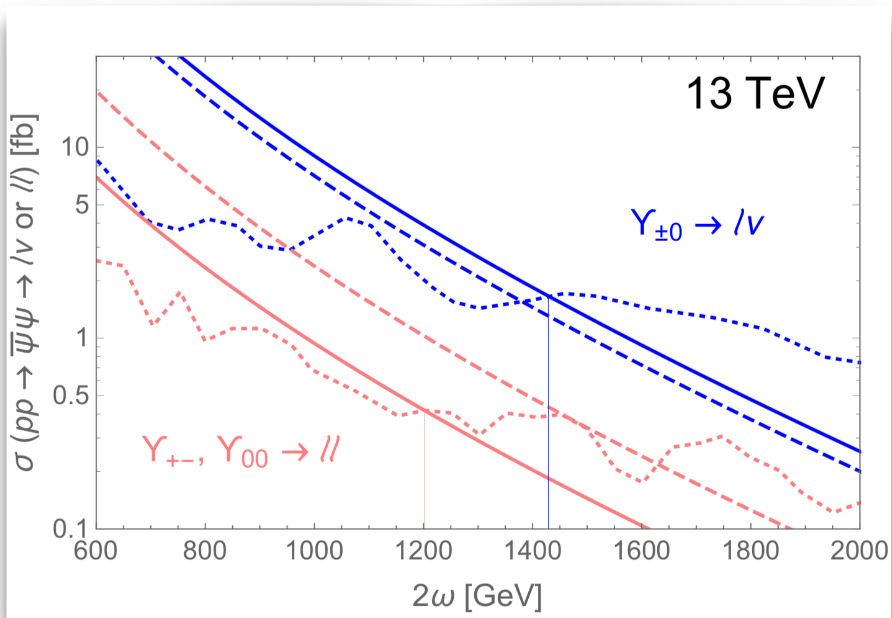
resonant signals

$\Delta > \omega$: 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 $\eta_{+-} \to \gamma\gamma$, $\Upsilon_{+-,00} \to \ell\ell$

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,

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

but, 2-loop corrections important…

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

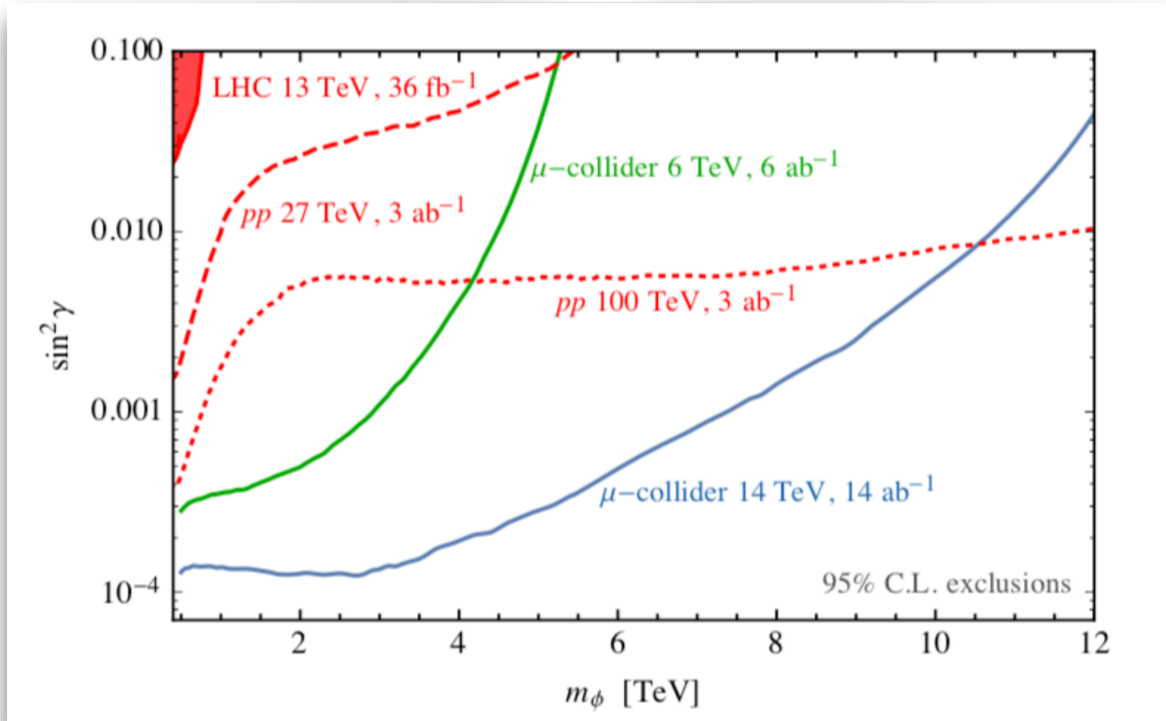
$$\widehat{T}_{s^c,B+C} \approx \frac{1}{3}\frac{N_c y_t^2}{16\pi^2} m_t^2 \omega^2 \left[\frac{\omega^6 + 9\,\omega^4\Delta^2 - 9\,\omega^2\Delta^4 - 6\,\omega^2\Delta^2(\omega^2+\Delta^2)\log\frac{\omega^2}{\Delta^2} - \Delta^6}{(\omega^2-\Delta^2)^5}\right]$$

Numerical example:

under control (even welcome)

$$\Delta = 300\ \mathrm{GeV}, \quad \omega = 500\ \mathrm{GeV} \quad \to \quad \widehat{T}_{s^c,B+C} \approx 4\times 10^{-4}$$

Reach on scalar singlets at future colliders



hadron: $\phi \to ZZ$, lepton: $\phi \to hh \to 4b$

$\mathrm{BR}(\phi \to ZZ, hh) = 1/4$

Buttazzo, Redigolo, Sala, Tesi 2018