Discovering Neutral Naturalness
(in long-lived particle searches)

LHC Searches for Long-Lived BSM Particles:
Theory Meets Experiment

UMass Amherst
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based on
DC, Verhaaren 1506.06141
Chacko, DC, Verhaaren, 1512.XXXXX
(also DC, Saraswat 1509.04284)
Neutral Naturalness is a class of models where displaced searches are the primary discovery channel.
The Hierarchy Problem
The Hierarchy Problem

... can be solved by top partners
The Hierarchy Problem

… can be solved by top partners

top quark $t$ \quad \text{continuous symmetry} \quad \text{top partner } T

e.g., Supersymmetry, modern composite Higgs models, etc…
The Hierarchy Problem

The symmetry need not commute with SM color!

top quark $t$ \rightarrow \text{top partner } T

Folded SUSY (EW-charged stops), Twin Higgs (SM singlet $T$-partners)

hep-ph/0609152 Burdman, Chacko, Goh, Harnik
hep-ph/0506256 Chacko, Goh, Harnik
Theory Example: Folded SUSY

SS breaking to $N = 1$

$y = 0$

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

SS breaking to $N = 1'$

$y = \pi R$

Boundary conditions break $A \leftrightarrow B$ symmetry and globally break $N=2$ to $N=0$ SUSY.

Normal MSSM EW sector.

$SU(3)$ sectors: only zero modes are $A$-fermions, $B$-sfermions.

‘Accidental supersymmetry’ protects Higgs @ 1-loop with EW charged top partners.
Theory Example: Twin Higgs

$\text{SM}_A \times \text{SM}_B$ (mirror sector) particle content with $Z_2$ symmetry

Higgs sector: $\text{SU}(4)$, broken by Gauge + Yukawa interactions to $\text{SU}(2)_A \times \text{SU}(2)_B \times Z_2$, which generate mass for goldstone boson.

$$\Delta V = \frac{3}{8\pi^2} \Lambda^2 \left( \lambda_A^2 H_A^\dagger H_A + \lambda_B^2 H_B^\dagger H_B \right)$$

$$\lambda_A = \lambda_B \equiv \lambda ; \quad \Delta V = \frac{3\lambda^2}{8\pi^2} \Lambda^2 \left( H_A^\dagger H_A + H_B^\dagger H_B \right) = \frac{3\lambda^2}{8\pi^2} \Lambda^2 H^\dagger H$$

$Z_2$ symmetry of quadratically divergent contributions mimics full $\text{SU}(4)$ symmetry, protects pNGB Higgs mass @ 1-loop.

SM singlet top partners.
Folded SUSY: $\mathbb{Z}_2$ mimics protection of SUSY
at one-loop $O(\Lambda^2)$ level

Twin Higgs: $\mathbb{Z}_2$ mimics protection of SU(4) goldstone
at one-loop $O(\Lambda^2)$ level

Can be generalized to other discrete symmetries.

1411.7393 Craig, Knapen, Longhi
Typical Low-Energy Spectra

FSUSY (EW charged partners)
- SM sector
- mirror sector
- SU(2) x U(1)
- SU(3)\textsubscript{A}
- SU(3)\textsubscript{B}
- sleptons, EWinos, ...
- \(\tilde{t}_B, \tilde{b}_B, \ldots\)
- \(W, Z, h\)
- \(\tau, \mu\) etc
- \(b_A\) etc

\(~ O(1) \text{ TeV} ~

Twin Higgs (SM singlet partners)
- SM sector
- mirror sector
- SU(3)\textsubscript{A} x SU(2)\textsubscript{A} x U(1)\textsubscript{A}
- SU(3)\textsubscript{B} x SU(2)\textsubscript{B} x U(1)\textsubscript{B}
- \(h_B\)
- \(t_B\)
- \(W_B, Z_B\)
- \(b_B\)
- \(\tau_B, \mu_B, \ldots\)
- \(b_A, \tau_A, \text{ etc} \)
Typical Low-Energy Spectra

FSUSY (EW charged partners)
- SM sector
- mirror sector
- SU(2) x U(1)
- SU(3)_A
- SU(3)_B
- sleptons, EWinos,...
- \( \tau, \bar{\tau}, \bar{B}, \ldots \)
- \( t_A, b_A \)
- etc

\( \sim \) O(1) TeV
- Light Higgs talks to both sectors

Twin Higgs (SM singlet partners)
- SM sector
- mirror sector
- SU(3)_A x SU(2)_A x U(1)_A
- SU(3)_B x SU(2)_B x U(1)_B
- W, Z, h
- t_A, \bar{t}_B, \ldots
- b_A, \tau_A, etc
- \( h_A \)
- etc
- \( W_B, Z_B \)
- \( t_B \)
- \( b_B \)
Neutral Naturalness

Why would we think about this?

1. The LHC is *great* at making colored particles, but so far no top partner discovery…

2. Want to examine naturalness as generally as possible: **test the mechanism, not the model!**

Neutral Naturalness generates radically different phenomenology from colored partners!
What are the most important questions right now?
1. What signals of Neutral Naturalness could we probe today?
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2. If the signatures are this malleable... will we be able to probe the *general mechanisms* underlying naturalness *tomorrow*?
1. What signals of Neutral Naturalness could we probe **today**?

2. If the signatures are this malleable… will we be able to probe the mechanisms **tomorrow**

See Naturalness No-Lose Theorem, DC, Saraswat 1509.04284
Probing Naturalness today:

Signatures of Neutral Naturalness at the LHC
In theories of Neutral Naturalness, the partners in the mirror sector are usually charged under a copy of QCD.
Typical Low-Energy Spectra

FSUSY (EW charged partners)

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

SM sector

$SU(3)_B$

mirror sector

sleptons, EWinos, ...

$\tilde{t}_B, \tilde{b}_B, ...$

$\tau, \mu$ etc

$W, Z, h$

$b_A$

e tc

$\sim O(1)$ TeV

mirror QCD

Twin Higgs (SM singlet partners)

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

SM sector

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

mirror sector

$W_B, Z_B$

$\tilde{t}_B$

$b_B$

e tc

$W_A, Z_A$

$b_A, \tau_A, \text{etc}$
Hidden Valley Phenomenology

c.f. Strassler, Zurek ‘06 etc..

Mirror gluons talk to the Higgs via top partner loops!

\[ \mathcal{L}^{(6)} = \frac{\alpha_v y^2}{3\pi M^2} H^\dagger H \, \text{tr} \, F_{\mu\nu} F^{\mu\nu} \]

The mirror sector contains mirror hadrons.

Detailed consequences depend on the mirror spectrum:

- pions?
- quarkonia?
- glueballs?

(just like the top quark connects the Higgs to SM QCD)
Typical Low-Energy Spectra

FSUSY (EW charged partners)
- SM sector
- mirror sector
- SU(2) x U(1)
- SU(3)_A
- sleptons, EWinos, ...
- τ_B, ῦ_B, ...
- LEP limits
- b_A, etc
- glueballs

Twin Higgs (SM singlet partners)
- SM sector
- mirror sector
- SU(3)_A x SU(2)_A x U(1)_A
- SU(3)_B x SU(2)_B x U(1)_B
- W_B, Z_B
- h_B
- t_B
- b_B
- etc

~ O(1) TeV
Typical Low-Energy Spectra

FSUSY (EW charged partners)

- SM sector
- mirror sector
- SU(2) x U(1)
- SU(3)_A
- SU(3)_B
- sleptons, EWinos, ...
- ~ t_B, \tilde{b}_B, ...
- \tau, \mu, etc
- b_A, etc
- LEP limits
- glueballs

~ O(1) TeV

Fraternal Twin Higgs (SM singlet partners)

- SM sector
- mirror sector
- SU(3)_A x SU(2)_A x U(1)_A
- SU(3)_B x SU(2)_B x U(1)_B
- W_B, Z_B
- h_B
- t_B
- \tau_A, h_A
- b_A, \tau_A, etc

Cosmology motivates removing light mirror states, only keep 3rd gen

1501.05310 Craig, Katz, Strassler, Sundrum

Glueballs or bottomonia
Mirror Glueballs
Mirror Glueballs

If the mirror sector has no light matter, the mirror QCD hadrons are glueballs.

Stable glueball states in pure SU(3) gauge theory

“Required” for EW charged top partners.

Possible (motivated by cosmology) for SM singlet top partners.

c.f. Strassler, Zurek ’06 etc..

m_0 \approx 7 \Lambda_{QCD}'}
Glueball-Higgs Coupling

Glueballs mix with the Higgs via top partner loop:
0++ would eventually decay back to SM!

The Higgs could also decay to these glueballs:
sizable exotic Higgs decays with displaced vertices!

(much bigger branching fraction than expectation from mixing due to small wave function overlap between the “big” glueball and the “small” Higgs compared to Higgs coupling to mirror gluons)

Key signature of uncolored naturalness!

1501.05310 Craig, Katz, Strassler, Sundrum
Is this signature realized?

**Mass:** $m_0 \sim 7\Lambda_{QCD} \sim 10 - 60$ GeV from RG arguments, but can move that around in Twin Higgs theories.

⇒ can be produced in exotic Higgs decays!

**Lifetime of $0^{++}$:** $c\tau \sim \mu\text{m - 1km}$ (using lattice results)

⇒ displaced decays at colliders! 

($\text{mostly to } bb, \tau\tau$)

\[ \Gamma(0^{++} \rightarrow \xi\xi) = \left( \frac{1}{12\pi^2} \left[ \frac{y^2}{M^2} \right] \frac{v}{m_h^2 - m_0^2} \right)^2 (4\pi\alpha_s^B F_{0^{++}})^2 \Gamma_{h \rightarrow \xi\xi}^{SM}(m_0^2). \]
How many glueballs from Higgs decays?

Estimate *inclusive* mirror-glue production by rescaling SM $\text{Br}(h \rightarrow gg)$ by top partner loop and mirror $\alpha_S'$ (also from RG arguments).

LHC 14 with 300fb-1 makes $O(10$ million $)$ higgs bosons.

Could probe TeV-scale top partners if exotic Higgs decays conspicuous enough!
How many glueballs from Higgs decays?

Conservatively estimate **exclusive** production of unstable 0++ glueball by parameterizing our ignorance about mirror hadronization:

\[
\text{Br}(h \rightarrow 0^{++}0^{++}) = \text{Br}(h \rightarrow \text{mirror glue}) \cdot \kappa \cdot \sqrt{1 - \frac{4m_0^2}{m_h^2}}
\]

Let \( \kappa \) range from

\(~ 1/12 \text{ (somewhat democratic)} \) to

\(~ 1 \text{ (optimistic)} \).
Displaced Vertices from exotic Higgs decays can be a powerful probe of Neutral Naturalness!

Example of exotic Higgs decays providing sensitive probe of new physics!

Displaced searches probe TeV-scale uncolored top partners!
LHC reach

ATLAS 300fb$^{-1}$

$\sqrt{s} = 14$ TeV, 300fb$^{-1}$

(VBF $h\rightarrow$bb) $\times$ (IT, $r > 4$ cm)

(single lepton) $\times$ (IT, $r > 50$ $\mu$m)

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CMS 20 fb$^{-1}$

Expected 95% CL Exclusion $\sqrt{s} = 13$ TeV, 20 fb$^{-1}$

Csaki, Kuflik, Lombardo, Slone 1508.01522
LHC reach

ATLAS $300 \text{fb}^{-1}$

CMS $20 \text{ fb}^{-1}$

$\sqrt{s} = 14 \text{ TeV}, 300 \text{fb}^{-1}$

$(\text{MS})x(\text{MS or IT})$

$(\text{VBF } h \rightarrow \text{bb}) \times (\text{IT}, r > 4\text{cm})$

$(\text{single lepton}) \times (\text{IT}, r > 50\mu\text{m})$

Expected 95% CL Exclusion $\sqrt{s} = 13 \text{ TeV}, 20 \text{ fb}^{-1}$

Csaki, Kuflik, Lombardo, Slone 1508.01522
LHC reach

ATLAS $300\text{fb}^{-1}$

CMS $20\text{fb}^{-1}$

Expected 95% CL Exclusion $\sqrt{s} = 13\text{ TeV}, 20\text{ fb}^{-1}$

Needs new searches:
- one DV + lepton
- one DV + VBF
- close DV reconstruction

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Csaki, Kuflik, Lombardo, Slone 1508.01522
Mirror Bottomonia

In Fraternal Twin Higgs, Mirror Bottomonia can be at bottom of QCD’ spectrum

- Higgs branching ratio to mirror bottoms is much larger than to mirror glue
- lifetime of bottomonium 0++ state can be much shorter than for glueball
- broadly same phenomenology, same decay modes

Covered by ~ same search strategies!
Top partner direct production
Top partner direct production

T pair production via DY or h* (PERTURBATIVE)

(s)quirkonium de-excitation

emission of soft photons / glueballs

T annihilation to hard mirror gluons (PERTURBATIVE)

Some glueballs will decay visibly in detector: EMERGING JETS*

shower & hadronize into two DARK GLUEBALL JETS

Chacko, DC, Verhaaren, 1512.XXXXX

* see also 1502.05409 Schwaller, Stolarski, Weiler

Work in progress!
Top partner direct production

Great opportunity:
- direct evidence of uncolored top partners.
- might have comparable reach to exotic Higgs decays
- could allow measurement of couplings and masses.
- potentially spectacular signatures: several DVs, or many $bb, \tau\tau$ pairs

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Top partner direct production

T pair production via DY or h* (PERTURBATIVE)

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Work in progress!
Top partner direct production

T pair production via DY or h* (PERTURBATIVE)

(p)quirkonium de-excitation

emission of soft photons / glueballs

T annihilation to hard mirror gluons (PERTURBATIVE)

Some glueballs will decay visibly in detector: EMERGING JETS*

shower & hadronize into two DARK GLUEBALL JETS

perturbative production of TT system: OK

* see also 1502.05409 Schwaller, Stolarski, Weiler

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Top partner direct production

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- T pair production via DY or h* (PERTURBATIVE)
- emission of soft photons / glueballs
- (s)quirkonium de-excitation
- slow Ts
- T annihilation to hard mirror gluons (PERTURBATIVE)
- Some glueballs will decay visibly in detector: EMERGING JETS*
  - shower & hadronize into two DARK GLUEBALL JETS

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* see also 1502.05409 Schwaller, Stolarski, Weiler
Top partner direct production

- T pair production via DY or h⁺ (PERTURBATIVE)
- (s)quirkonium de-excitation
- Emission of soft photons / glueballs
- T annihilation to hard mirror gluons

Some glueballs will decay visibly in detector: EMERGING JETS*

- Shower & hadronize into two DARK GLUEBALL JETS

Annihilation of bound state into mirror glueballs and hidden/SM states: OK (c.f. stoponia etc)

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*see also 1502.05409 Schwaller, Stolarski, Weiler

Work in progress!
Top partner direct production

T pair production via DY or $h^*$ (PERTURBATIVE)

(s)quirkonium de-excitation

hadronization of mirror gluon jets into glueballs: hmmm.....

emission of soft photons / glueballs

T annihilation to hard mirror

Some glueballs will decay visibly in detector: EMERGING JETS*

shower & hadronize into two DARK GLUEBALL JETS

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* see also 1502.05409 Schwaller, Stolarski, Weiler

Work in progress!
Mirror Hadronization

How do these mirror gluon jets evolve?

Can convince yourself behavior is broadly QCD-like ⇒ form jets or mirror glueballs!

How to estimate glueball multiplicity?

How to estimate fraction of $0^{++}$ (i.e. potentially visible) glueballs?

Could just parameterize our ignorance by varying:

$$N_{\text{avg}} \equiv \langle N_{\text{tot}} \rangle \quad r \equiv \left\langle \frac{N_{0^{++}}}{N_{\text{tot}}} \right\rangle$$

But we know *a little bit* about how jets evolve…
Mirror Hadronization

Evolve dummy fragmentation functions with DGLAP equations!

\[ N_{\text{avg}} \equiv \langle N_{\text{tot}} \rangle \quad r \equiv \left\langle \frac{N_{0^{++}}}{N_{\text{tot}}} \right\rangle \]

Decouples ‘perturbative’ model parameter space \((m_T, m_0, \ldots)\) from non-perturbative 2D-parameterization of ignorance
Full exploration of signal in this factorized (theory) x (hadronization) parameter space is in progress…

But first easy comparison to make:

compare number of mirror glueballs produced in top partner production vs exotic Higgs decays!

\[
R \equiv \frac{\sigma(pp \rightarrow TT) \cdot \text{Br}(TT \rightarrow gBgB) \cdot N_{\text{avg}}(m_T)}{\sigma_{\text{VBF}}(pp \rightarrow hjj) \cdot \epsilon_{\text{VBF}} \cdot \text{Br}(h \rightarrow gBgB)}
\]

\( r \) (fraction of 0^{++})
\~ cancels out

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Compare to Higgs Decays

Folded SUSY

$t_1 = \text{RH stop}$
$t_2 = \text{LH stop}$

# glueballs from stop pair production

$> \#$ glueballs from exotic Higgs decays

Chacko, DC, Verhaaren, 1512.XXXXX
Folded SUSY

\( t_1 = \) RH stop
\( t_2 = \) LH stop

\# glueballs from stop pair production > \# glueballs from exotic Higgs decays

Even with this extremely pessimistic signal yield estimation, top partner direct production can be the discovery channel!

\[
\langle N_0^{\rightarrow} \rangle_{\text{DGLAP}} \sigma_{\text{DY}}(pp \rightarrow \tilde{t}_1 \tilde{t}_1) \times Br(\tilde{t}_1 \tilde{t}_1 \rightarrow g_B g_B) / (\sigma_{\text{VBF}}(pp \rightarrow h) \times Br(h \rightarrow g_B g_B) \times \epsilon_{\text{VBF}}) \theta_t = \pi/2
\]

Blue Shading \( m_{\tilde{b}_1} \leq m_{\tilde{t}_1} \), \( m_0 = 30 \)
Probing Naturalness today:
Experimental
Upshot
Experimental Upshot

Expand DV searches to include final states with just ONE displaced vertex

Trigger/suppress background by requiring lepton or VBF jets

Expand sensitivity to shorter lifetimes using tracker reconstruction. $O(0.1 \text{ mm})$?
Experimental Upshot

signal toy model:
$H \rightarrow XX \rightarrow (bb's \ and \ \tau\tau's)$

<table>
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<th>$m_X$ (GeV)</th>
<th>$c\tau_X (m)$</th>
<th>$10^{-5}$</th>
<th>$10^{-1}$</th>
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<td>55</td>
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Cover these benchmark points and your searches will be sensitive to DV’s from Neutral Naturalness at the LHC

HXSWG report preview. PRELIMINARY!
Experimental Upshot

Simple Neutral Naturalness is the Show-Pony model for presenting results

at each point in this \((m_0, m_T)\) plane, glueball lifetime is determined

hidden hadronization uncertainty: don’t know this quantity, but should be few \(\times 0.1\)

\[
\kappa^\text{ex}(m_0, m_T) \equiv \frac{\sigma_h \times \text{Br}(h \to XX)}{\sigma_{\text{SM}} \times \text{Br}(h \to \text{hidden glue})}
\]

Show \(\kappa\) exclusions in \((m_0, m_T)\) space to assess improvement of searches and get rough idea of model exclusion

HXSWG report preview. PRELIMINARY!
Summary

Displaced signatures are a great LHC opportunity, and a “smoking gun” for most theories with EW top partners (e.g. FSUSY) and some singlet top partners (Fraternal Twin Higgs).

DV’s can be produced in exotic Higgs decays or direct production of hidden sector states (top partners). LHC has TeV-scale reach for uncolored top partners if searches are slightly generalized!

Many signatures still unexplored, e.g. Flavor, Indirect DM Detection…. Keep in mind: quasi-stable light hidden states are well motivated but not Guaranteed in all theories of Neutral Naturalness.

But we’ll still find these theories @ lepton collider/100TeV!

DC, Saraswat 1509.04284

Thank you!
Backup Slides
Probing Naturalness exhaustively:
A No-Lose Theorem for Generalized Top Partners.
Top Partners with SM Charge

Start with TeV-scale top partners that carry SM charge.

If QCD: produce plenty, discover at LHC or 100 TeV.

If partners carry any EW charge, regardless of decay mode etc, will be detectable up to ~ 2+ TeV @ 100 TeV due to RG effects in DY spectrum measurements!

Alves, Galloway, Rudermann, Walsh 1410.6810

TeV-scale SM-charged partners ARE DISCOVERABLE regardless of model details!
Neutral Top Partners

We really only have one class of models for neutral top partners: **Twin Higgs**, which predicts Higgs coupling deviations \( \sim \) tuning at lepton colliders.

Is this general? Would like to understand signatures of neutral top partners **model-independently**!

**Bottom-Up EFT/Simplified Model Approach**

DC, Saraswat 1509.04284
Two distinct low-energy EFTs

Scalar Partners

(Vector partners “same” as scalars)

Fermion Partners

Two distinct low-energy EFTs
Two distinct low-energy EFTs

Scalar Partners
(Vector partners “same” as scalars)

Fermion Partners

Only impose one condition on EFT: cancellation of quadratic divergence from top loop

\[ H \rightarrow t \]
Two distinct low-energy EFTs

Scalar Partners

(Vector partners “same” as scalars)

Relevant terms in the HEFT expansion:

\[ \mathcal{L}_\phi \supset -\sum_i \phi_i^2 \left( \frac{1}{2} \mu^2 \phi_i + \frac{1}{2} \lambda_i |H|^2 \right) \]

Condition to cancel one-loop quadratic divergence from top quark:

\[ \lambda_\phi = \frac{12}{N_f} |y_t|^2 \]

Fermion Partners

Relevant terms in the HEFT expansion:

\[ \mathcal{L}_T \supset \sum_i T_i^c i \bar{T}_i \left( M_{T_i} - \frac{|H|^2}{2M'_i} \right) \]

\[ \frac{M_T}{M'} = \frac{3}{N_f} y_t^2 \]
Two distinct low-energy EFTs

Scalar Partners

(Vector partners "same" as scalars)

\[ \mathcal{L}_\phi \supset -\sum_i \phi_i^2 \left( \frac{1}{2} \mu_{\phi_i}^2 + \frac{1}{2} \lambda_i |H|^2 \right) \]

Fermion Partners

Relevant terms in the HEFT expansion:

\[ \mathcal{L}_T \supset \sum_i T_i \tilde{T}_i \left( M_{T_i} - \frac{|H|^2}{2M'_i} \right) \]

Condition to cancel one-loop quadratic divergence from top quark:

\[ \lambda_\phi = \frac{12}{N_t} |y_t|^2 \]

Non-renormalizable term limits what we can compute.

Need partial UV completion for fermion partners!
Four possible Neutral Top Partner structures

Scalar Partners

Fermion Partners

For fermion partners, have to distinguish how HHTT operator is generated.

Strong Coupling

Scalar Mediator

Fermion Mediator
Four possible Neutral Top Partner structures

Scalar Partners

Fermion Partners

For fermion partners, have to distinguish how HHTT operator is generated.

Strong Coupling

Strong Coupling

Scalar Mediator

Twin Higgs
with composite/holographic UV completion

Twin Higgs
with perturbative UV completion

Fermion Mediator

?
Four possible Neutral Top Partner structures

Scalar Partners

Fermion Partners

For fermion partners, have to distinguish how HHTT operator is generated.

Strong Coupling

Scalar Mediator

Fermion Mediator

? Twin Higgs with composite/holographic UV completion

? Twin Higgs with perturbative UV completion

Much more general than Twin Higgs!
Four possible Neutral Top Partner structures

For fermion partners, have to distinguish how HHTT operator is generated.

Irreducible low-E signatures:
- Zh cross section (lepton collider)
- electroweak precision observables (lepton)
- higgs cubic coupling (100 TeV)
- top partner direct production (100 TeV)
For fermion partners, have to distinguish how HHTT operator is generated.

Irreducible low-E signatures:
- Zh cross section (lepton collider)
- electroweak precision observables (lepton)
- higgs cubic coupling (100 TeV)
- top partner direct production (100 TeV)

Irreducible tunings \( \{\Delta_i\} \) of loop vs tree suffered by scenario \( \Rightarrow \Delta_{\text{tot}} = f(\Delta_i) \)

These will relate to UV completion scale \( \Lambda_{\text{UV}} \).

Existing UV completions & symmetry arguments suggest SM-charged BSM states at this scale \( \Rightarrow \text{Assume} \) production at 100 TeV collider!
Strategy

For each scenario:

- probe with low-E experimental probes
- probe with direct production @ 100 TeV

Find the LEAST TUNED the theory can be while escaping experimental detection:

$$\Delta_{\text{tot}}^\text{min} = \text{Max } f(\Delta_i)$$

This will allow us to determine how natural an “undiscoverable” theory could be...
Preview of Results

\[ \Lambda_{\text{UV}}^{\text{reach}} = 10 \text{ TeV} \quad 20 \text{ TeV} \]

\[ \Delta: \quad \tilde{\Delta}: \]

- **Scalar Partners**

- Fermion Partners
  - Non-Perturbative Completion, General Fermion Mediator
  - Minimal Fermion Mediator
Preview of Results

For each top partner structure...
For each top partner structure...

.. we find the “tuning price” you have to pay to avoid any signatures @ 100 TeV or lepton colliders...
For each top partner structure...

.. we find the “tuning price” you have to pay to avoid any signatures @ 100 TeV or lepton colliders...

... as a function of the number of top partner dof...
Preview of Results

For each top partner structure...

... as a function of the number of top partner dof...

.. we find the “tuning price” you have to pay to avoid any signatures @ 100 TeV or lepton colliders...
For each top partner structure...

.. we find the “tuning price” you have to pay to avoid any signatures @ 100 TeV or lepton colliders...

... as a function of the number of top partners...

Very conservative: only top loop etc. Existing theories need UV completion at ~5 TeV

Even so…

→ need many partners to avoid discovery AND tuning!
How do we get there?
Neutral Naturalness Scenarios

Scalar Partners

Fermion Partners (strong coupling)

Fermion Partners (scalar mediator)

Fermion Partners (fermion mediator)

Trickiest/most interesting case to analyze in complete generality...
Fermion Partner - Scalar Mediator

This is the most complicated and important case.

Contains Twin Higgs & Orbifold generalizations, but is much more general.

Integrate out mediator(s) to match to natural IR theory:

\[
\mathcal{L}_T \supset \sum_i T_i \bar{T}_i \left( M_{T_i} - \frac{|H|^2}{2M'_i} \right)
\]

naturalness matching condition

\[
N_s \frac{\mu_{HHS} y_{STT}}{m_s^2} = \frac{1}{2M'} = \frac{3}{2N_f} \frac{y_t^2}{M_T}
\]
The Scalar Mediator

Before we can proceed, we have to know:

How heavy is the scalar mediator?

**Naive expectation:** new scalars can’t be light, otherwise we have another hierarchy problem!  
⇒ $m_S$ should be significantly above weak scale!

**Naive counterargument:** we know of many ways to solve the hierarchy problem! Dress up mediator sector with partners etc...  

Nope!
The Scalar Mediator

Sacrificial Scalar Mechanism

Consequences:
1. Mass of scalar is tied to UV completion scale!
2. $m_S \gg m_h$ makes it easy to compute experimental signals.
Higgs Mixing

Take one scalar mediator $S$

$$(\text{generalizes simply})$$
Higgs Mixing

Take one scalar mediator $S$

(generalizes simply)

In the $m_S \gg m_h$ limit, mixing angle is simple:

$$s_\theta \approx -\frac{\mu_{HHS}}{m_S^2} \nu$$
Computing Observables

Take one scalar mediator $S$

In the $m_S \gg m_h$ limit, mixing angle is simple:

$$s_\theta \approx -\frac{\mu_{HHS}}{m_S^2} \nu$$

Naturalness condition:

$$\frac{\mu_{HHS} y_{SST}}{m_S^2} = \frac{3}{2N_f} \frac{y_t^2}{M_T}$$

Mediator mass drops out! Only depends on $(M_T, y_{SST})$
Higgs Mixing in \((m_T, y_{STT})\) Plane

Lepton colliders have great sensitivity in much of parameter space.
Twin Higgs models are subspaces (lines) in this more general parameter space.
Higgs Mixing in \((m_T, y_{STT})\) Plane

Lepton colliders have great sensitivity in much of parameter space.

Twin Higgs models are subspaces (lines) in this more general parameter space.

But what if \(y_{STT}\) is large??
Recall our main strategy:

- Probe with low-E experimental probes at 10 TeV or 20 TeV.
- Experimentally inaccessible parameter space: $P$.
- Probe with direct production @ 100 TeV.

Low-energy parameters of the scenario.
Recall our main strategy:

We’ve determined the reach of low-energy observables (higgs mixing).
Recall our main strategy:

Now we exploit the 100 TeV collider’s ability to probe the UV scale.
Recall our main strategy:

Assuming 10 or 20 TeV can be probed, what unavoidable tuning are we stuck with?

- probe with low-E experimental probes
- probe with direct production @ 100 TeV

low-energy parameters of the scenario

$\Lambda_{UV}$

10 TeV or 20 TeV

$\mathbf{m}_{\text{partner, } X, Y, \ldots}$

experimentally inaccessible parameter space: $P$
Tunings (1)

$\Delta_h(S) = \log$ tuning of $m_h$ from mediator loops.

(have to differentiate case where Higgs = PNGB from case without such symmetries....)

Gets worse with large $m_S$!

$\Delta_{S(T)}$ = tuning from quadratic sensitivity of $m_S$ to $T$ loops
(required by Sacrificial Scalar Mechanism!)

Gets better with large $m_S$!

$\Rightarrow \quad \Delta_{H,S} = \max_{m_S} f(\Delta_h(S), \Delta_{S(T)})$

Can find conservative tuning estimate by maximizing over (unknown) mediator mass!
Tunings (I)

\( \Delta_{h(S)} = \) log tuning of \( m_h \) from mediator loops.

\( \Delta_{S(T)} = \) tuning from quadratic sensitivity of \( m_S \) to \( T \) loops (required by Sacrificial Scalar Mechanism!)

\( \Rightarrow \quad \Delta_{H,S} = \max_{m_S} f(\Delta_{h(S)}, \Delta_{S(T)}) \)

Gets worse with large \( m_S \)!

Gets better with large \( m_S \)!

Since we marginalize over \( m_S \), \( \Delta_{H,S} \) is uniquely defined in the \((m_T, y_{STT})\) plane as the tuning from the mediator sector.
Tuning from Mediator in \((m_T, y_{STT})\) Plane

For \(\Lambda_{UV} \geq 20\) TeV (undetectable by 100 TeV), high \(y_{STT}\) is badly tuned!
For $\Lambda_{UV} \equiv 20$ TeV (*undetectable by 100 TeV*), top partners heavier than $\sim 500$ GeV give log-tuning to Higgs mass worse than 10%
Log tuning from $t$ vs $T$ in $(m_T, y_{STT})$ Plane

For $\Lambda_{UV} \geq 20$ TeV (undetectable by 100 TeV), top partners heavier than $\sim 500$ GeV give log-tuning to Higgs mass worse than 10%
Log tuning from t vs T in \((m_T, y_{STT})\) Plane

For $\Lambda_{UV} \geq 20$ TeV (undetectable by 100 TeV), top partners heavier than $\sim 500$ GeV give log-tuning to Higgs mass worse than 10%

No untuned parameter space left for $N_f \times N_S \sim O(\text{SM})$!
A natural theory needs to have VERY MANY fermion partners/scalar mediators to possibly escape detection.
Need both colliders for full coverage!

Large hidden sector coupling:
Higgs mixing is tiny, but need low $\Lambda_{UV}$.  

No guaranteed signal at lepton collider, but slam dunk at 100 TeV!

Small hidden sector coupling:
theory can be healthy even for very large $\Lambda_{UV}$, but Higgs mixing is large.

No guaranteed 100 TeV signals, but slam dunk at lepton colliders!
Need both colliders for full coverage!

Large hidden sector coupling: Higgs mixing is tiny, but need low $\Lambda_{\text{UV}}$.

No guaranteed signal at lepton collider, but slam dunk at 100 TeV!

Small hidden sector coupling: theory can be healthy even for very large $\Lambda_{\text{UV}}$, but Higgs mixing is large.

No guaranteed 100 TeV signals, but slam dunk at lepton colliders!

Model building question: how to realize these non-Twin-Higgs possibilities?
... go through corresponding derivations for the other scenarios, with similar conclusions....
What’s the upshot?
1. Great discovery potential TODAY

Long-lived hidden sector states (mirror glueballs, quarkonia) generate spectacular displaced signals that allow the LHC to probe TeV uncolored top partners

2. Implications for LHC searches

Displaced Vertex searches with just one DV + VBF or lepton are required. Also, need sub-mm decay length reconstruction.

HXSWG yellow report (soon!)
3. **No-Lose Theorem:**

Any theory of $\sim 10\%$ naturalness with $O(SM)$ top partners will be discovered at a planned lepton collider and/or 100 TeV.

→ Model-independent (bottom-up) and very conservative (only top loop etc)

How to avoid this theorem?

Could have top partner swarms, or neutral top partners without SM charges in UV completion.

There might also be weird non-perturbative or stringy constructions that don’t need top partners?
4. Implications for future colliders

Both lepton collider and 100 TeV have to work in tandem for full coverage of general naturalness.

Without lepton collider:

- could miss theory with large-ish Higgs mixing but small hidden sector couplings → very high UV completion scale out of 100 TeV collider reach

Without 100 TeV:

- several scenarios give small IR signatures, need to probe UV
5. For full coverage, need to probe UV completion!

Central assumption of SM-charged BSM states at $\Lambda_{UV}$ allows us to make these very powerful conclusions.

This seems very reasonable, and is certainly the case in all currently proposed UV completions.

Can we formally prove this always has to be the case, or construct counter-examples?
Summary

1. Discovery potential TODAY
   Neutral naturalness motivates spectacular displaced signatures that give the LHC TeV-reach for uncolored top partners.

2. Implications for LHC searches
   Need searches with just one DV + lepton or VBF, and sub-mm decay-length reconstruction for full coverage.

3. No-Lose Theorem
   Any theory of ~10% naturalness with O(SM) top partners will be discovered at a planned lepton collider and/or 100 TeV.

4. Implications for future colliders
   Both lepton collider and 100 TeV have to work in tandem for full coverage of general naturalness.

5. Probing UV completion is vital!
   Can we formally prove that full that SM-charged BSM states appear at $\Lambda_{UV}$ in full symmetry-based theories?

Thank you!
Backup Slides (2)
Neutral Naturalness Scenarios

Scalar Partners

Fermion Partners (strong coupling)

Fermion Partners (scalar mediator)

Fermion Partners (fermion mediator)
Scalar Partner

Low-energy probes only have reach of few 100 GeV

Two tunings in theory:

\[ \Delta_{h}(\phi) = \log \text{tuning from incomplete t-\phi cancellation} \]

\[ \Delta_{\phi}(h) \] from quadratically divergent mass contribution due to higgs loops

For given \( \Delta_{\text{tot}} \), find largest allowed \( \Lambda_{\text{UV}} \):

![Diagram showing scalar partners and their parameters](image_url)
A natural theory needs to have VERY MANY scalar partners to possibly escape detection.
Fermion Partner - Strong Coupling

Log tuning of higgs mass:
for $\Lambda_{\text{UV}} < 10 - 20$ TeV,
$m_T \lesssim 500$ GeV
OR
tuning worse than 10%.

Unitarity constraints place strict upper bound on $\Lambda_{\text{UV}}$ where new physics must get resolved.
A natural theory needs to have VERY MANY fermion partners to possibly escape detection.
Neutral Naturalness Scenarios

Scalar Partners

Fermion Partners (strong coupling)

Fermion Partners (scalar mediator)

Fermion Partners (fermion mediator)
Violation of custodial symmetry $\rightarrow$ large $T$ parameter deviations!

Again, Higgs log tuning prefers top partners $<$ 500 GeV
A natural theory needs to have VERY MANY fermion partners to possibly escape detection.