THE HIGGS MASS, TOP PARTNERS, AND COLLIDERS: WHAT WE LOSE BY LETTING GO

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HIGGSDEPENDENCE DAY!

Most important lessons:
- Higgs boson exists!
- Weakly coupled!!
Most important lessons:

- Higgs boson exists!
- Weakly coupled!!

**Electroweak physics is calculable!**
Set the low energy Higgs mass and forget it.

Make predictions.

No conflict with experiment (so far).
BRIEF SIDEBAR
DIMENSIONFUL SCALES

**Relativity:**

Space $\equiv$ Time

Convert meters to seconds with speed of light: $c$.

Mass $\equiv$ Energy

Convert mass to energy with speed of light: $c$. 
DIMENSIONFUL SCALES

Relativity:
Space ≡ Time
Convert meters to seconds with speed of light: \( c \).
Mass ≡ Energy
Convert mass to energy with speed of light: \( c \).

Quantum Mechanics:
Energy ≡ 1/Time
Convert energy to time with Planck’s constant: \( \hbar \).
DIMENSIONFUL SCALES

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Quantum Mechanics:
Energy ≡ 1/Time
Convert energy to time with Planck’s constant: \( \hbar \).

Large mass scales are like short distance scales.
The LHC is a giant microscope!
END SIDEBAR
REDUCTIONISM

What does it mean to have a theory for the Higgs mass?

Higgs mass is a function of well defined (finite) inputs. The Standard Model encompassed by larger framework.

*Naively: Higgs mass quadratically sensitive to new mass scales.*

Historical precedent for reductionism:

Underlies progress in fundamental physics. New frameworks encompass the old, giving “reasons”.
What does it mean to have a theory for the Higgs mass?

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NEW SCALES?

Evidence for physics beyond the Standard Model:

- dark matter
- matter/anti-matter asymmetry
- neutrino masses
- gravity

Very likely new dimensionful scale exists.

Want to protect the Higgs from physics at high energy scales.
ELECTRON SELF-ENERGY
ELECTRON SELF-ENERGY

\[ \Delta m_e \sim \frac{e^2}{r_e} \]

\[ \frac{\Delta m_e}{m_e} \sim 10^9 \left( \frac{r_{\text{Planck}}}{r_e} \right) \]

"electron radius"
ELECTRON SELF-ENERGY

\[ \Delta m_e \sim \frac{e^2}{r_e} \]

\[ \frac{\Delta m_e}{m_e} \sim 10^9 \left( \frac{r_{\text{Planck}}}{r_e} \right) \]
ELECTRON SELF-ENERGY

CLASSICAL

$$\Delta m_e \sim \frac{e^2}{r_e}$$

$$\frac{\Delta m_e}{m_e} \sim 10^9 \left( \frac{1}{r_e} \right)$$

QUANTUM

$$\Delta m_e \sim m_e \frac{e^2}{16\pi^2} \log \left( m_e r_e \right)$$

$$\frac{\Delta m_e}{m_e} \sim 10^{-2}$$
ELECTRON SELF-ENERGY

\[ \Delta \mathcal{H} \sim \frac{e^2}{r_e} \]

\[ \frac{\Delta m_e}{m_e} \sim 10^9 \left( \frac{m_e}{r_e} \right)^{\frac{1}{3}} \]

\[ \Delta m_e \sim m_e \frac{e^2}{16\pi^2} \log \left( \frac{m_e r_e}{\hbar^2} \right) \]

\[ \frac{\Delta m_e}{m_e} \sim 10^{-2} \]

“electron radius”

Requires new particle!

(virtual) electron/positron pair
I. The Higgs and its Potential
II. Supersymmetry: An Example Theory
III. SUSY Naturalness Confronts Experiment
IV. Alternative Theories
V. Summary
I. THE HIGGS AND ITS POTENTIAL
Introduce a charged scalar state: $\phi$.

“$\phi$ carries a charge”

is equivalent to

$$\phi \rightarrow \phi' = e^{i q \phi} \xi \phi$$

under a symmetry (gauge) transformation.

“Charge is conserved”

is equivalent to

Lagrangian $\mathcal{L}$ invariant under transformation.

$\phi$ and $\phi^*$ have opposite charge.
SCALAR MASS

Scalar mass always phase rotation invariant:

$$\mathcal{L} \supset m^2 |\phi|^2$$

No phase rotation can forbid mass.

Anything can happen in quantum mechanics!

Implication:
If $\phi$ interacts, quantum corrections can generate a mass.

$$\sim \frac{\text{coupling}^2}{16\pi^2} \Lambda^2$$
SCALAR MASS
Scalar mass always phase rotation invariant:
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Implication:
If \( \phi \) interacts, quantum corrections can generate a mass.

Problem for Higgs boson!

The cutoff: \( \Lambda \to \infty \)
Add quartic for scalar (phase rotation invariant):

$$\mathcal{L} \ni m^2|\phi|^2 + \frac{\lambda}{4}|\phi|^4$$

The “potential” $V(\phi)$. 

For $m^2 > 0$:

$$\langle \phi \rangle = 0$$

For $m^2 < 0$:

$$\langle \phi \rangle \neq 0$$
VACUUM EXPECTATION VALUE

\[ \langle \phi \rangle : \text{vacuum expectation value (vev).} \]

Vacuum “sees” the phase.

The vev spontaneously breaks the symmetry.

This is how the Higgs vev breaks electroweak symmetry.
THE HIGGS BOSON

\[ \phi \rightarrow H \]
HIGGS POTENTIAL

\[ V(v, H) = -\frac{\mu^2}{2} |v + H|^2 + \frac{\lambda_H}{16} |v + H|^4 \]

Solving \( \frac{\partial V(v, 0)}{\partial v} = 0 \) \( \Rightarrow \)
\[ v^2 = \frac{2 \mu^2}{\lambda_H} \]

Solving \( \frac{\partial^2 V(v, 0)}{\partial v^2} = m_H^2 \)
\( \Rightarrow \)
\[ m_H^2 = 2 \mu^2 \]

\[ \langle H \rangle \equiv v \]

\( W^\pm \) mass \( \Rightarrow \)
\[ v \approx 246 \text{ GeV} \]

Higgs mass \( \Rightarrow \)
\[ m_H \approx 125 \text{ GeV} \]

Yields \( \lambda_H \approx 0.26 \)
\[ \mu \approx 88 \text{ GeV} \]

Value for all SM parameters known!
HIGGS MASS CORRECTIONS

\[ \mathcal{L} \supset y_t H \bar{t} t \]

\[ m_t = \frac{y_t}{\sqrt{2}} \langle H \rangle \]

Top quark is heaviest particle; has strongest coupling to Higgs.

\[ \sim \frac{y_t^2}{16 \pi^2} \Lambda^2 |H|^2 \]
**Higgs Mass Corrections**

\[ \mathcal{L} \supset y_t H \bar{t} t \quad \Rightarrow \quad m_t = \frac{y_t}{\sqrt{2}} \langle H \rangle \]

Top quark is heaviest particle; has strongest coupling to Higgs.

**Incalculable Higgs mass...**

The cutoff: \( \Lambda \to \infty \)
To make sense of the model, “renormalize.”

\[ m^2_{\text{finite}} = m^2_{\text{bare}} + m^2_{\text{loop}} \]

\[ \mu^2 = \left( \frac{y_t}{16\pi^2} \Lambda^2 + \mu^2 \right) - \left( \frac{y_t}{16\pi^2} \Lambda^2 \right) \]

Recall: \( \mu^2 = (88 \text{ GeV})^2 \) extracted from experiment.
IS THERE A PHYSICAL INTERPRETATION OF THE CUTOFF?!!?
WILL SEE THAT THIS REQUIRES A THEORY OF THE HIGGS MASS.
II. SUPERSYMMETRY: AN EXAMPLE THEORY
FERMION MASS

Fermions have spin 1/2. Is my fermion left or right handed?
Fermions have spin 1/2. Is my fermion left or right handed?

Take an electron spinning “up”.

$e^-$
FERMION MASS

Fermions have spin 1/2. Is my fermion left or right handed?

Move into its rest frame.
FERMION MASS

Fermions have spin 1/2.
Is my fermion left or right handed?

Stand on your head.

$e^-$
FERMION MASS

Fermions have spin 1/2.
Is my fermion left or right handed?

From your point of view, chirality is flipped.
FERMION MASS

Fermions have spin 1/2. Is my fermion left or right handed?

From your point of view, chirality is flipped.

Going to rest frame is crucial step: flipping chirality requires mass.

\[ \mathcal{L} \supset m \psi_L \psi_R \]

Fermion mass mixes left and right chiralities.
FERMION MASS
Recall, scalar mass always symmetric under phase rotation.

\[ \mathcal{L} \supset m_\phi |\phi|^2 \]

What about fermion mass?

\[ \mathcal{L} \supset m_\psi \psi_L \psi_R \]
FERMION MASS
Recall, scalar mass always symmetric under phase rotation.

$$\mathcal{L} \supset m_\phi |\phi|^2$$

What about fermion mass?

$$\mathcal{L} \supset m_\psi \psi_L \psi_R$$

“Chiral” rotation:

$$\psi_R \rightarrow \psi'_R = e^{i\zeta} \psi_R$$

$$\psi_L \rightarrow \psi'_L = e^{i\zeta} \psi_L$$

$$\mathcal{L} \rightarrow \mathcal{L}' \subset e^{2i\zeta} m_\psi \psi_L \psi_R$$
FERMION MASS

Recall, scalar mass always symmetric under phase rotation.

\[ \mathcal{L} \supset m_\phi |\phi|^2 \]

What about fermion mass?

\[ \mathcal{L} \supset m_\psi \psi_L \psi_R \]

"Chiral" rotation:

\[ \psi_R \to \psi'_R = e^{i\xi} \psi_R \]

\[ \psi_L \to \psi'_L = e^{i\xi} \psi_L \]

\[ \mathcal{L} \to \mathcal{L}' \subset e^{2i\xi} m_\psi \psi_L \psi_R \]

Chiral symmetry can forbid fermion mass.

Fermion mass correction proportional to \( m_\psi \).

**Cutoff does not infect fermion masses!**
“CHIRALITY” FOR SCALARS

Scalars inherit chirality of partner fermions.

Calculability of fermion masses inherited by scalars.
A NEW KIND OF SYMMETRY

**Gauge invariance:**
Phase rotation compensated by states of opposite charge:
electron needed positron.

**Supersymmetry:**
“Rotation” compensated by states of different spin
Top is a massive fermion; has $L$ and $R$ chirality. Consistency requires introducing two stops: $\tilde{t}_L$ and $\tilde{t}_R$. Free parameters: two masses and a mixing angle.

Top coupling to the Higgs: $Y_t$.

Strength of top partner coupling to the Higgs set by $Y_t$. 
HIGGS MASS CORRECTIONS

\[ H \quad \sim \quad \frac{y_t^2}{16 \pi^2} \Lambda^2 |H|^2 \]

Incalculable Higgs mass…
HIGGS MASS CORRECTIONS

\[ H \xrightarrow{t} H^\dagger \xrightarrow{\bar{t}} H \]

\[ \sim \frac{y_t^2}{16 \pi^2} \Lambda^2 |H|^2 \]

\[ + \]

\[ H \xrightarrow{\tilde{t}} H^\dagger \xrightarrow{\tilde{t}} H \]

\[ \sim -\frac{y_t^2}{16 \pi^2} \left( \Lambda^2 + cm_{\tilde{t}}^2 \right) |H|^2 \]
Calculable Higgs mass!
**SUSY HIGGS POTENTIAL**

“Naturalness in SUSY”

$$V \simeq \left( m_H^2 - \frac{3}{4\pi^2} y_t^2 m_t^2 \right) |H|^2$$

Calculable Higgs mass.

Stop mass give physical meaning to quadratic divergence.

Heavier stops imply larger cancellation.

**Stop mass below \(\sim 1\) TeV extremely plausible!**

* in a simplified limit
SUSY HIGGS POTENTIAL

\[ V \approx \left( m_H^2 - \frac{3}{4\pi^2} y_t^2 m_t^2 \right) |H|^2 + \left( \frac{g^2 + g'^2}{8} + \frac{3}{8\pi^2} y_t^4 \log \frac{m_{\tilde{t}}}{m_t} \right) |H|^4 \]

Calculable Higgs mass.
Stop mass give physical meaning to quadratic divergence.
Heavier stops imply larger cancellation.

Stop mass below \( \sim 1 \) TeV extremely plausible!

Heavier stops yield larger quartic.

* in a simplified limit
HIGGS MASS IN MSSM

\[ m_h \] vs. stop mixing parameter normalized by the SUSY scale, \( X_t = m_t/M_S \). We have fixed the values \( \tan b = 20 \), \( \mu = 200 \text{ GeV} \), and the (solid black, blue dot-dashed, red dashed) contours correspond to \( M_S = (1, 2, 4) \text{ TeV} \).

For maximal mixing, \( m_h \) greatly constrains the parameter space. The central value favours \( M_S < 2(1) \text{ TeV} \) for \( \tan b > 10 \) for \( \mu = M_S \)(200 GeV). Here, we again see the larger spread in \( M_S \) at low \( \tan b \). As in the case for zero mixing, this allowed range of a few TeV can be mapped to the equivalent shallow slope in Fig. 2.

We can also plot the Higgs mass as a function of the normalized stop mixing parameter \( X_t \), fixing the scale \( M_S \), \( \tan b \), and \( \mu \). This is shown in Fig. 6, where we have chosen \( \tan b = 20 \), \( \mu = 200 \text{ GeV} \), and plotted three curves for \( M_S = 1, 2, 4 \text{ TeV} \). The asymmetry in \( X_t \), which was noted in [18] and [12], is due to the odd powers of \( X_t \) in the \( O(\cosh X_t) \) threshold correction to MSSM (\( M_S \)), Eq. (24). For large \( \tan b \) and \( M_S = 1 \text{ TeV} \), it is possible to obtain \( m_h = 125.6 \text{ GeV} \) with \( X_t > 0 \) and near the maximum value. For \( M_S = 2 \text{ TeV} \), we require \( |X_t| \ll 1 \).5 \text{ TeV}. We note that even for \( M_S = 4 \text{ TeV} \), \( m_h = 125.6 \text{ GeV} \) is not achieved for zero mixing, which was also shown in the top-left plot of Fig. 5.

Lastly, we comment on some comparisons with existing calculations. We have generally presented Higgs masses which are lower than those computed by, e.g. CPSuperH [29], FeynHiggs [30], SoftSUSY [31], SPheno [32], and H3M [21] for \( M_S \ll 1 \text{ TeV} \). There are three differences between the calculations. First, we have used the NNLO value of \( \gamma_t \), which leads to a running top quark mass \( m_t(m_t) \) that is 2 GeV lower than the NLO value. 23

Draper, Lee, Wagner [arXiv:1312.5743]
SUSY PARAMETER SPACE

Highly simplified assumption for inputs (the CMSSM).

Boundaries from requiring Higgs mass and relic density of dark matter.

TC, Wacker [arXiv:1305.2914]
III. SUSY NATURALNESS CONFRONTS EXPERIMENT
Biggest contributions to Higgs mass, ordered by size:

\[ m^2_H = m^2_{\text{Higgsino}} + m^2_{\text{stop}} + m^2_{\text{gluino}} + \ldots \]

- tree-level
- one-loop
- two-loop

Minimal spectrum:

- \( h \rightarrow h \) → 1 TeV
- \( h \rightarrow \tilde{t} \) → 100 GeV

NATURAL THEORIES HAVE OBSERVABLES

Existence of top partners $\Rightarrow$ physical observables!

Loop corrections to Higgs properties.

Direct production in proton collisions.
Modification to Higgs production and decay.

Yields bounds independent of stop decay modes.
Figure 2: Assuming no other contributions to Higgs digluon coupling $r_G$ other than stops', region of natural stop that has been ruled out by Higgs coupling measurements. The three shaded purple regions, from darkest to lightest, are excluded at 3 $\sigma$ (99.73%) level; 2 $\sigma$ (95.45%) level; and 1 $\sigma$ (68.27%) level. The dashed purple line is the boundary of the region excluded at 90% CL. The red solid lines are contours of Higgs mass fine-tuning assuming $\tilde{\mu} = 30$ TeV, $\mu = 200$ GeV and $\tan \beta = 10$. We have evaluated the tuning with $X_t = X_{\min t}$, the smallest mixing allowed by the data at 2 $\sigma$ for a given pair of masses. The blue dashed line is a contour of 10% fine-tuning associated with $r_{\tilde{t} G}$. 

So far the precision level of Higgs coupling measurements is still low, thus the fine-tuning of Higgs couplings is not very large in general. In Fig. 2, we plot the boundary corresponding to 10% fine-tuning in Higgs coupling, which excludes the possibility that even one stop is below about 100 GeV. (This is, essentially, the same observation that was made in the context of electroweak baryogenesis in Refs. [20, 21].) We also considered contributions from light stops to electroweak precision observables, in particular, the $\alpha_s$ parameter, but the constraints there are much weaker compared to those from current Higgs coupling measurements.

From Fig. 2, we see that regions with both stops lighter than about 400 GeV is excluded by the Higgs coupling measurements at 90% C.L. Along the diagonal line where both stops are degenerate in mass, the constraint gets stronger and extends to 450 GeV. In general, although one could construct clever natural models where stops...
SIMPLIFIED MODEL FOR PROTON COLLIDERS

Stop-neutralino

\[ t \quad \tilde{t} \quad \chi \]

Gluino-stop-neutralino

\[ \tilde{g} \quad \bar{t} \quad \tilde{t} \quad t \quad \chi \]

Simplified Model for Proton Colliders

Stop-neutralino

$p p \rightarrow \tilde{t} \tilde{t}^* \rightarrow t \bar{t} \chi \chi$

SEARCH STRATEGY

MAIN REQUIREMENTS

ATLAS [arXiv:1407.0583]; see also CMS [arXiv:1502.00300]
**SEARCH STRATEGY**

**Main Requirements**

- 1 lepton

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SEARCH STRATEGY

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- 1 lepton
- ≥ 4 jets

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SEARCH STRATEGY

Main requirements

- 1 lepton
- $\geq 4$ jets
- $\geq 1$ $b$-jet(s)

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SEARCH STRATEGY

**Main Requirements**

- 1 lepton
- \( \geq 4 \) jets
- \( \geq 1 \) b-jet(s)
- One “hadronic top”

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SEARCH STRATEGY

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- 1 lepton
- $\geq 4$ jets
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- Few hundred GeV missing energy

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- …

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SEARCH STRATEGY

**Main requirements**

- 1 lepton
- $\geq 4$ jets
- $\geq 1$ $b$-jet(s)
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- Few hundred GeV missing energy
- Few hundred GeV transverse mass
- ...

**Dominant backgrounds**

$t\bar{t}$, $W + \text{jets}$, $t\bar{t} + W/Z$, ...

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ATLAS [arXiv:1407.0583]; see also CMS [arXiv:1502.00300]
1-LEPTON RESULTS

**Figure 15.** Expected (black dashed) and observed (red solid) 95% CL excluded region in the plane of $m_{\tilde{\chi}^0_1}$ vs. $m_{\tilde{t}_1}$, assuming $BR(\tilde{t}_1 \rightarrow t \tilde{\chi}^0_1) = 100\%$. In the region $m_{\tilde{t}_1} < m_{\tilde{t}_1} < m_{t} + m_{\tilde{\chi}^0_1}$, the decay of the $\tilde{t}_1$ involves a virtual top quark (three-body decay), while in the region $m_{\tilde{t}_1} < m_{b} + m_{W} + m_{\tilde{\chi}^0_1}$ it involves both a virtual top quark and a virtual $W$ boson (four-body decay).

The $m_{\tilde{t}_1} < 100$ GeV region for the three-body decay mode is excluded by the search described in ref. [38]. Furthermore, the $m_{\tilde{t}_1} < 78$ GeV region in the four-body scenario is excluded by the search in ref. [144].

The results are in agreement with predictions from the Standard Model, and are thus translated into 95% CL upper limits on the stop and $\tilde{\chi}^0_1$ masses in various supersymmetric scenarios. For models where the stop decays exclusively into a top quark and a $\tilde{\chi}^0_1$ (scenario (1) above), stop masses between 210 and 640 GeV are excluded for a massless LSP, and stop masses around 550 GeV are excluded for LSP masses below 230 GeV. Limits are also derived in the three- and four-body scenarios. For scenarios where the stop decays exclusively into a bottom quark and a $\tilde{\chi}^0_1$ (scenario (2) above), the excluded stop and $\tilde{\chi}^0_1$ masses depend strongly on the mass of the $\tilde{\chi}^0_1$. For models where the mass of the $\tilde{\chi}^0_1$ is twice that of the LSP, stop masses up to 500 GeV are excluded for an LSP mass in the range of 100 to 150 GeV. For models in which the $\tilde{\chi}^0_1$ mass is only 20 GeV above the LSP mass, stop masses

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ATLAS [arXiv:1407.0583]; see also CMS [arXiv:1502.00300]
1-LEPTON RESULTS

Figure 15. Expected (black dashed) and observed (red solid) 95% CL excluded region in the plane of \( m_{\tilde{t}_1} \) vs. \( m_{\tilde{t}_1} \), assuming \( \text{BR}(\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0) = 100\% \). In the region \( m_b + m_W + m_{\tilde{\chi}_1^0} \leq m_{\tilde{t}_1} \), the decay of the \( \tilde{t}_1 \) involves a virtual top quark (three-body decay), while in the region \( m_{\tilde{t}_1} \leq m_b + m_W + m_{\tilde{\chi}_1^0} \) it involves both a virtual top quark and a virtual \( W \) boson (four-body decay).

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- For a model motivating compressed region, see TC, Kearney, Luty [arXiv:1501.01962]

ATLAS [arXiv:1407.0583]; see also CMS [arXiv:1502.00300]

~ 670 GeV
FUTURE COLLIDERS

Higgs factory and 100 TeV proton collider?

IHEP in China?

CERN in Europe?

Talk by X. Lou [Aspen Future Colliders Conference, 2015]

Talk by M. Benedikt [Aspen Future Colliders Conference, 2015]

QingHuangDao site investigation

Future Circular Collider Study
Michael Benedikt
Aspen Winter Conference 27 January 2015

Forming an international collaboration to study:

- $p$-$p$-collider ($FCC_{hh}$) – main emphasis, defining infrastructure requirements
- $e^+e^-$ collider ($FCC_{ee}$) – as potential intermediate step
- $p$-$e$ ($FCC_{he}$) option – $\sim 16 T \leq 100 TeV$ $p$-$p$ in 100 km
- $\sim 20 T \leq 100 TeV$ $p$-$p$ in 80 km

Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Higgs factory and 100 TeV proton collider? IHEP in China? CERN in Europe?
MORE HIGGS MEASUREMENTS

Previous indirect probe required top partner be colored and charged.

Completely model independent probe: Modification to $Z^0 - h$ associated production cross section $\delta\sigma_{Zh}$.

Craig, Englert, McCullough [arXiv:1305.5251]
AT A FUTURE LEPTON COLLIDER

For a generic top partner $t'$,
with number of degrees of freedom $n_{t'}$.

Craig, Englert, McCullough [arXiv:1305.5251]
STOP DECAYS AT A 100 TEV COLLIDER

"Top is the new bottom."

Angular distance between top decay products

$t \rightarrow t\tilde{\chi}_1^0, \sqrt{s}=100$ TeV

SUPER BOOSTED TOP TAGGING

 Require isolated lepton.

\[
\begin{align*}
\text{LHC} & \quad \bar{b} \\
& \quad W^+ \\
& \quad \mu^+ \\
\sim t & \quad t \\
& \quad \chi
\end{align*}
\]

Require muon inside a jet.

\[
\begin{align*}
\text{100 TeV collider} & \quad \bar{b} \\
& \quad \mu^+ \\
& \quad \bar{\nu}_\mu \\
\sim t & \quad t \\
& \quad \chi
\end{align*}
\]
SUPER BOOSTED TOP TAGGING

Require muon inside a jet.

Main requirements

- $\geq 2$ jets
- $\geq 1$ muon inside a jet
- 0 isolated leptons
- Few TeV missing energy
- ...

Dominant background

$t\bar{t} + W/Z, \ldots$
SUPER BOOSTED TOP TAGGING

Require muon inside a jet.

100 TeV collider

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- $\geq 2$ jets
- $\geq 1$ muon inside a jet
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- ...

Dominant background

$t\bar{t} + W/Z, \ldots$
PROJECTED LIMITS

$\sqrt{s} = 100$ TeV
$\int L dt = 3000$ fb$^{-1}$
$\varepsilon_{\text{sys,bkg}} = 20\%$
$\varepsilon_{\text{sys,sig}} = 20\%$

$\sim 8$ TeV

ALTERNATIVE THEORIES
COMPOSITE HIGGS

What if the Higgs were **not** an elementary scalar?

Requires new strong dynamics.

New strong dynamics scale

\[ f \]

Electroweak scale

\[ \nu \]

Kaplan, Georgi [1984];
Kaplan, Georgi, Dimopoulos [1984]; …
for a recent review: Bellazzini, Csaki, Serra [arXiv:1401.2457]
COMPOSITE HIGGS

What if the Higgs were not an elementary scalar?
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FERMIONIC TOP PARTNERS

Calculable requires new fermions, $T$. Quadratic divergences canceled by fermionic top partner loops.

Observables

- Search for top partners: $T \rightarrow t + Z^0$, $T \rightarrow t + H$, $T \rightarrow \bar{b} + W^+$, ...
- Modified Higgs properties set by $v/f$. 
Do top partners have to be colored?

**TWO OPTIONS**

- Fermionic neutral top partners: Twin Higgs
- Scalar neutral top patterns: Folded Supersymmetry
  Burdman, Chacko, Goh, Harnik [arXiv:hep-ph/0609152]
SUMMARY
Reductionism: Want “theory” of the Higgs potential.

Loops of top partners render Higgs mass calculable.

**Many Manifestations:**
- Supersymmetry: stops (scalars)
- Composite Higgs: $T$ (fermions)
- SM x SM: neutral scalars or fermions

**Testable Consequences:**
- Direct production at colliders
- Modification of Higgs properties