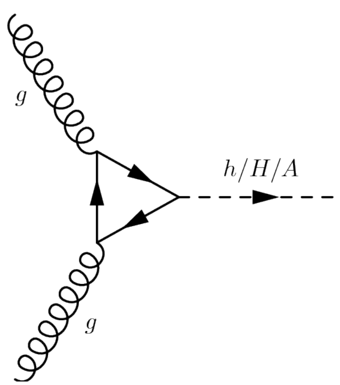
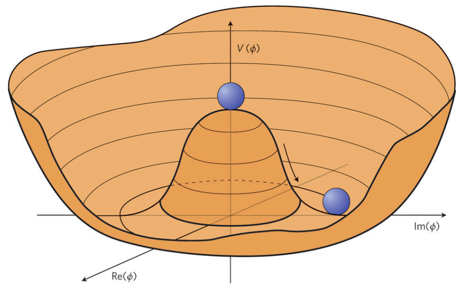
BSM Higgs Sectors

FCC Week 2015
Washington, DC



26 March 2015

David Curtin
University of Maryland



BSM Higgs Sectors

Big Picture Motivations

- Naturalness
  - SUSY
  - pGB
  - uncolored?
- Electroweak Phase Transition
  - Baryogenesis?
- Higgs Portal
  - Dark Matter?
  - *Generic BSM*

IR Models

- SM+S (mixed/unmixed)
- SM+fermions
- 2HDM
- 2HDM+S
- SILH
- ....

UV Completions & Rest of Theory

Observables at Current + Future Colliders

- producing extra higgs states (incl. superpartners)
- Exotic Higgs Decays
- Electroweak Precision Observables
- Higgs coupling measurements
- Higgs portal direct production of new states
- Higgs self coupling measurements
- Zh cross section measurements

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3.

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2.

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1.

UV Completions
&
Rest of Theory

Observables at Current + Future Colliders

Observables at Current + Future Colliders	100 TeV	ILC/TLEP
• producing extra higgs states (incl. superpartners)	✓	
• Exotic Higgs Decays	✓	✓
• Electroweak Precision Observables		✓
• Higgs coupling measurements	✓	✓
• Higgs portal direct production of new states	✓	
• Higgs self coupling measurements	✓	✓
• Zh cross section measurements		✓

Lepton Collider: All about precision.

100 TeV pp: Intensity Frontier experiment for Higgs Sector

Important exception: direct production of heavy higgs siblings, and of course probing the rest of the theory / UV completion!

Production of Heavy States

The Higgs sector could include more scalar states than just the SM higgs. (e.g. $A/h_2/H^{\pm}$ in 2HDMs)

These states are produced via DY or variants of SM Higgs production.

Decay to ff, VV, Vh. Hard decay products and full reconstruction of intermediate state allow for TeV-reach at HL-LHC, and 5-10 TeV reach at 100 TeV collider.

1502.05653 Djouadi, Maiani, Polosa, Quevillon, Riquer

[to appear] Hajer, Li, Liu, Shiu

In SUSY, Higgsinos or EWinos are part of the Higgs sector. Generally similar reach, but invisible particles in decay make compressed spectra very challenging.

1410.6287 Gori, Jung, Wang, Wells

1412.4789 Bramante, Fox, Martin, Ostdiek, Plehn, Schell, Takeuchi

No way around a 100 TeV collider to explore at O(TeV) masses!

Exotic Higgs Decays

.. may give first or only probe of new physics:

Tiny higgs width → light BSM particles can couple very weakly (~0.01) and produce sizable Brs (~ 10%)

Higgs portal: BSM physics wants to couple to the higgs via low-dimensional operators.

$$\Delta\mathcal{L} = \frac{\mu}{\Lambda^2}|H|^2\bar{\psi}\psi \quad \Delta\mathcal{L} = \frac{\zeta}{2}s^2|H|^2$$

Review/Survey: 1312.4992 DC, Essig, Gori, Jaiswal, Katz, T. Liu, Z. Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong

Hadron colliders are HIGGS FACTORIES

HL-LHC makes ~ 10^7 Higgses

100 TeV with 3/ab makes ~10^8 Higgses.

1405.1095 Falkowski, Vega-Morales

1412.0018 DC, Essig, Gori, Shelton

Probe **Br(h→conspicuous)** at the 10^{-8} - 10^{-7} level

Lepton colliders are CLEAN

Probe **Br(h→arbitrarily stealthy)** at the 10^{-3} level

1310.8361 Snowmass Higgs Working Group Report

1312.4974 Peskin

Precision Observables

Higgs couplings to SM particles

1310.8361 Snowmass Higgs Working Group Report
1312.4974 Peskin

HL-LHC will measure at ~5% level
ILC with high lumi can go to ~0.1%, TLEP few x better.

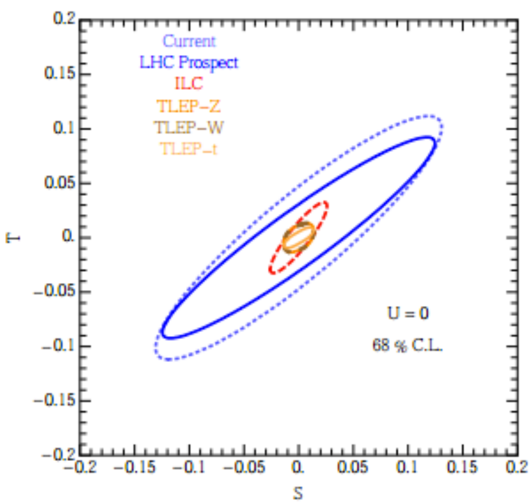
See talks by Tenchini, Klute, Fan

Many BSM theories give O(1-10%) deviations!

Electroweak Precision Observables

1411.1054 Fan, Reece, Wang

m_W, m_t, m_Z uncertainty will be greatly reduced by ILC/TLEP



Experiment	S (68%)	f (GeV)	T (68%)	$m_{\tilde{t}_L}$ (GeV)
ILC	0.012	1.1 TeV	0.015	890 GeV
CEPC (opt.)	0.02	880 GeV	0.016	870 GeV
CEPC (imp.)	0.014	1.0 TeV	0.011	1.1 GeV
TLEP-Z	0.013	1.1 TeV	0.012	1.0 TeV
TLEP-t	0.009	1.3 TeV	0.006	1.5 TeV

Experiment	κ_Z (68%)	f (GeV)	κ_g (68%)	$m_{\tilde{t}_L}$ (GeV)
HL-LHC	3%	1.0 TeV	4%	430 GeV
ILC500	0.3%	3.1 TeV	1.6%	690 GeV
ILC500-up	0.2%	3.9 TeV	0.9%	910 GeV
CEPC	0.2%	3.9 TeV	0.9%	910 GeV
TLEP	0.1%	5.5 TeV	0.6%	1.1 GeV

Lepton collider leads the charge, but 100 TeV (or LHC) has good chance of discovering UV physics responsible for deviations!

Precision Observables

hee coupling: y_e is the smallest coupling in the SM*. Can we probe it?

*Except maybe QCD CP phase

1503.04830 Altmannshofer, Brod, Schmaltz

Dim 6 operators can generate deviations to hee coupling compared to m_e, but $y_e^{BSM} >> y_e^{SM}$ requires tuned cancellation.

Also, Flavor physics consideration in constructing complete model.

Future lepton colliders can probe y_e^{BSM} through higgs production via radiative return: $e^+e^- \rightarrow h\gamma$.

Sensitive to $|y_e^{BSM}/y_e^{SM}| \sim O(10)$

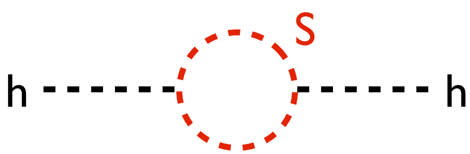
EDM measurements (ACME) constrain CP violation in hee.

Sensitive to $|\textbf{Im}\ y_e^{BSM}/y_e^{SM}| \sim O(10^{-2})$

Important to look for large deviations in y_e^{BSM}/y_e^{SM}, but precision measurements of y_e^{SM} are likely impossible in the near future.

Higgs Portal Observables

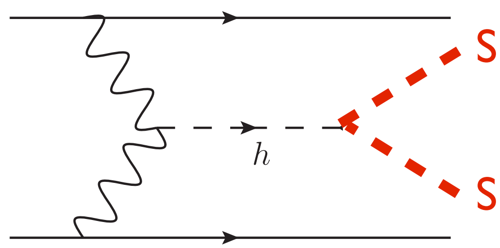
What if TeV-scale new physics ONLY couples to the Higgs?



Craig, Englert, McCullough, 1305.5251

⇛ O(0.5%) σ(Zh) deviations.
TLEP could exclude 0.6%

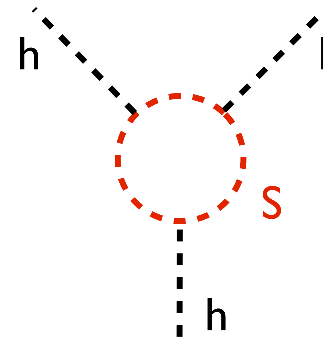
1310.8361 Snowmass Higgs Working Group Report
1312.4974 Peskin



100 TeV with 30/ab collider has mass reach of ~ few 100 GeV via VBF h*→XX production.

1409.0005 DC, Meade, Yu

1412.0258 Craig, Lou, McCullough, Thalapillil



Shift in h^3 coupling.
100 TeV with 30/ab can exclude 10% shift in λ_3.

1412.7154 Barr, Dolan, Englert, de Lima, Spannowsky
[to be released], W. Yao

These *could* be the only signatures. Mass reach of these probes in relevant models is only a few 100 GeV at a 100 TeV collider.

This is sensitivity is enough for very meaningful statements about the electroweak phase transition and naturalness.

IR Models

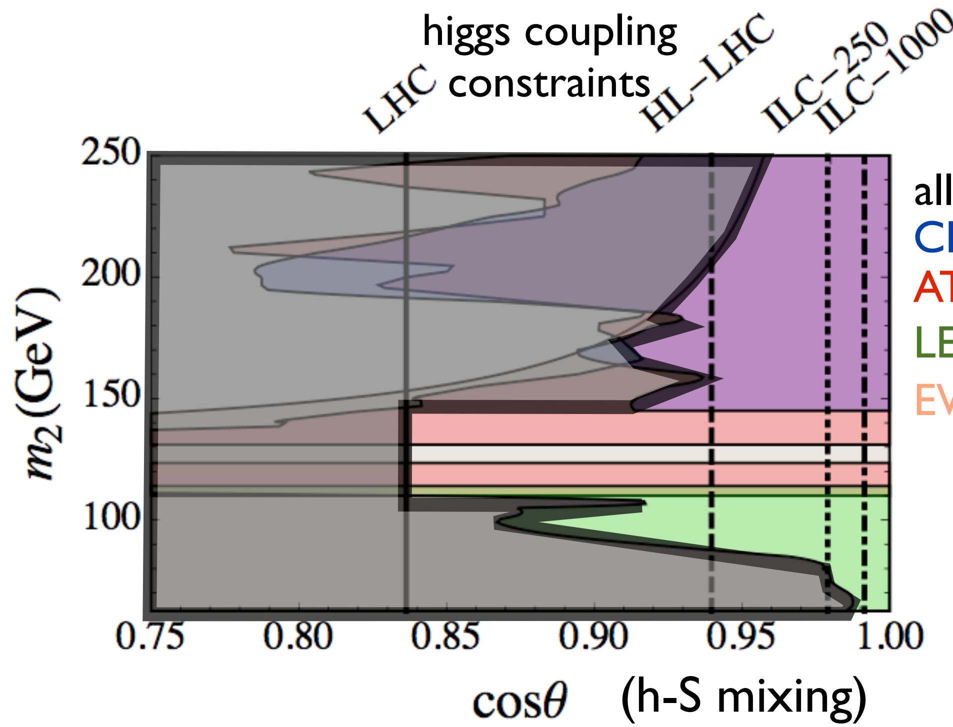
SM + Singlet Scalar

$$V_0^{T=0}(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

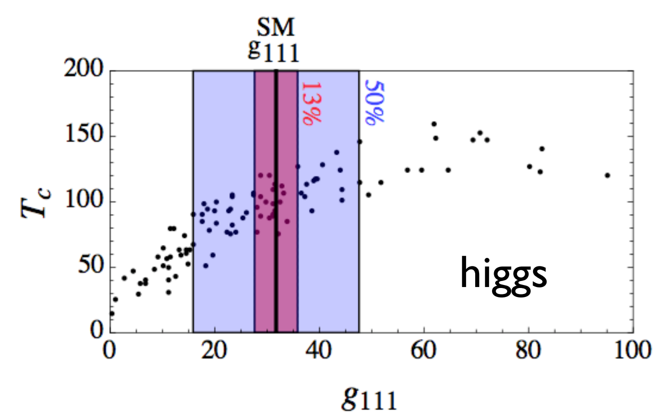
In generality, this scalar mixes with the higgs after EWSB.

heavy Higgs (sibling) production | Exotic Higgs Decays | EWPO | Higgs Couplings

Higgs portal production | h^3 measurement | $\sigma(Zh)$ measurement



allowed by:
CMS heavy higgs search 5+5/fb
ATLAS light higgs search 5+5/fb
LEP
EWPO



Profumo, Ramsey-Musolf, Wainwright, Winslow 1407.5342

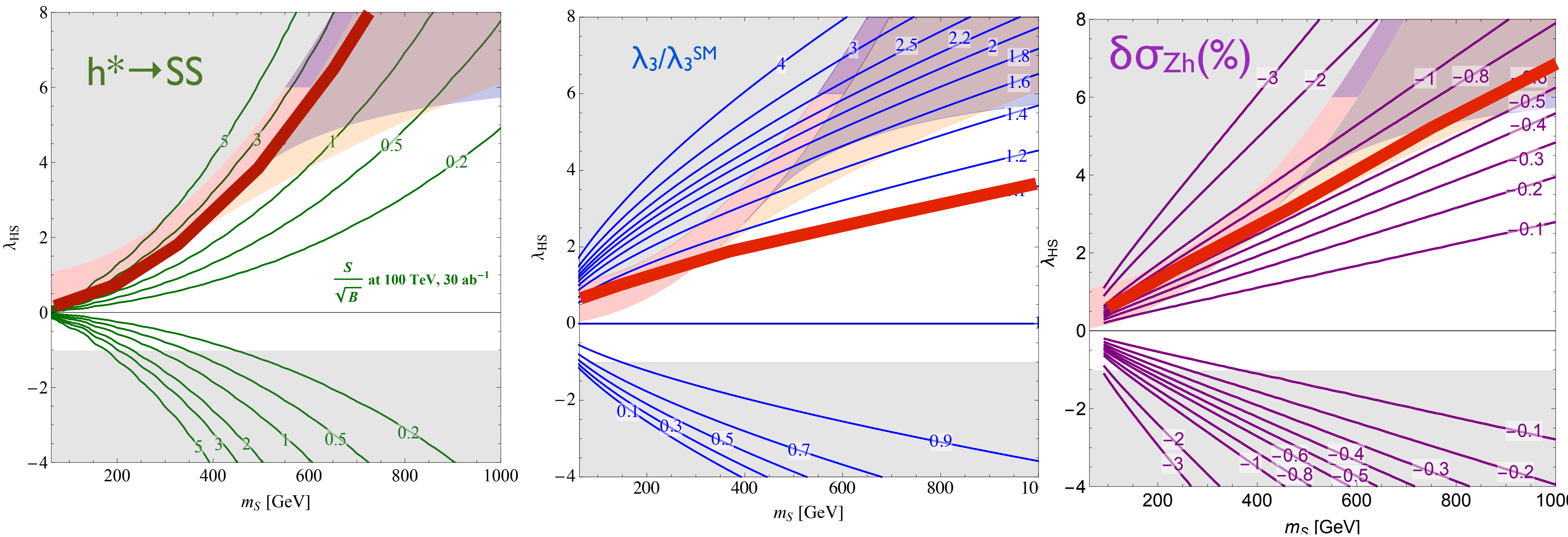
SM + Singlet Scalar

$$V_0^{T=0}(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S + \frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

Difficult case: unbroken Z_2 symmetry S → -S

heavy Higgs (sibling) production | Exotic Higgs Decays | EWPO | Higgs Couplings

Higgs portal production | h^3 measurement | σ(Zh) measurement



Need large higgs portal couplings for $m_S > m_h/2$

1409.0005 DC, Meade, Yu

2HDM (+S)

Most commonly consider four discrete types (Z_2 avoids FCNCs). Type II ⊃ (N)MSSM

Model	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2

Generically, Higgs coupling measurements at ILC/TLEP give mass reach ~ 0.5 - 1 TeV.

$$\kappa_V \sim 1 - 0.5\% \left(\frac{400\text{ GeV}}{M_A}\right)^4 \cot^2\beta$$

$$\kappa_t \sim 1 - \mathcal{O}(10\%) \left(\frac{400\text{ GeV}}{M_A}\right)^2 \cot^2\beta$$

$$\kappa_b = \kappa_\tau \sim 1 + \mathcal{O}(10\%) \left(\frac{400\text{ GeV}}{M_A}\right)^2 .$$

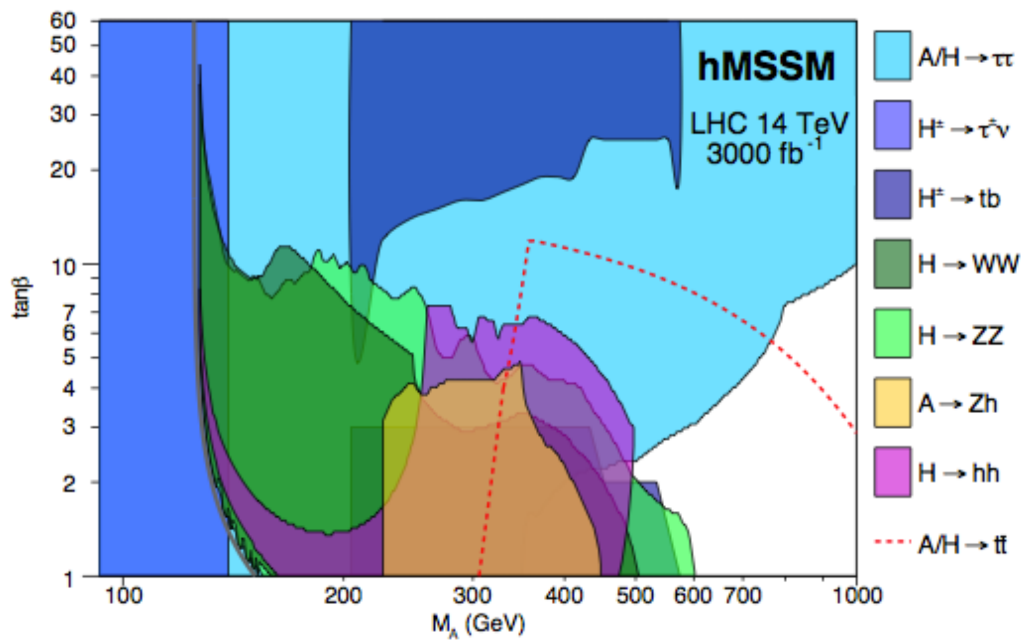
However, corrections can be much smaller in alignment limit → have to do direct searches!

1310.8361 Snowmass Higgs Working Group Report

1207.4835 Craig, Thomas

1305.2424 Craig, Galloway, Thomas

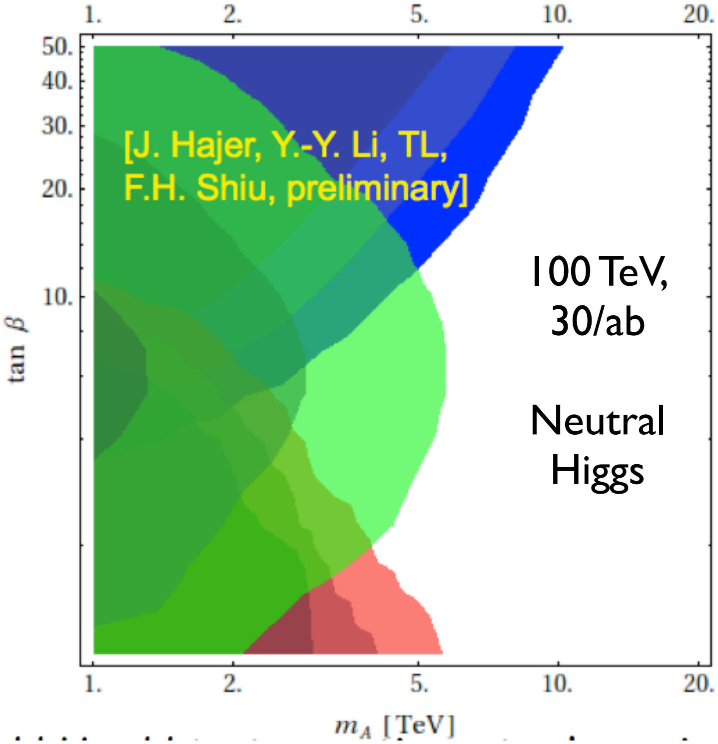
1310.2248 Carena, Low, Shah, Wagner

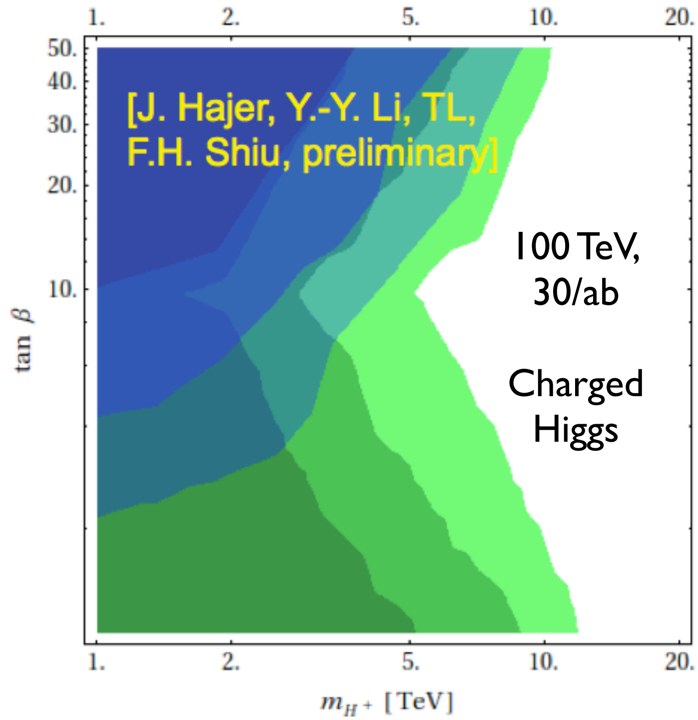


HL-LHC gives ~ TeV mass reach for MSSM (type II).

1502.05653 Djouadi, Maiani, Polosa, Quevillon, Riquer

2HDM (+S)





In MSSM, 100 TeV mass reach is better than 5 TeV.

Exotic Higgs Decays could also reveal light states! Easy to get in 2HDM+S (i.e. NMSSM-like), but also in 2HDM.

Motivates extending NMSSM-like exotic higgs decay searches to full kinematically allowed mass range, and to consider most general Yukawa-ordered h→aa→4f decays

1412.4779 DC, Essig, Zhong
1412.3385 Bernon, Gunion, Jiang, Kraml

Strongly Interacting Light Higgs

Low-energy limit of Composite Higgs or RS-like theories. Assume some new 'strong' sector is responsible for EWSB.

Generically, can be any BSM higgs sector with a perturbative SM-like higgs dof, up to corrections that depend on the strong coupling scale.

$$\delta g \sim \frac{v^2}{f^2}$$

Lepton colliders are sensitive to **f ~ 1 TeV** (expected effect of higgs mixing/coupling deviations at tree-level), or **f ~ 5 TeV** (generic effect of hadron-zoo at mass scale ~ f on EWPO, but could be subject to cancellations).

1411.1054 Fan, Reece, Wang

$$S \sim \frac{4\pi v^2}{m_\rho^2} \sim \frac{N}{4\pi}\frac{v^2}{f^2}$$

Can expect to produce EW resonances with similar mass reach as heavy higgs searches, but more model-dependent. (Also top partners, like in SUSY!)

1402.4431 Pappadopulo, Thamm, Torre, Wulzer

Big Picture

Motivations

Big Picture Motivations

Naturalness

See also Nathaniel Craig's talk!

Solutions to the Hierarchy Problem

A calculable theory of the higgs mass requires top partners to stabilize the weak scale beyond O(500 GeV).

Classify such theories by top partner spin and gauge charge.

This organizes the low-energy signatures of naturalness into a clear pattern.

	scalar	*fermion*
colored	SUSY	CH/RS
EW	Folded SUSY	Quirky Little Higgs
singlet	?	Twin Higgs

hep-ph/0506256 Chacko, Goh, Harnik
hep-ph/0609152 Burdman, Chacko, Goh, Harnik
0812.0843 Cai, Cheng, Terning
1411.7393 Craig, Knapen, Longhi
....

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Strong production of top partners

EW DY production of top partners. Interesting decays....

Chacko, DC, Verhaaren [in preparation]

Tree-level Higgs coupling shifts of $O(v^2/f^2)$ ~ tuning

Exotic Higgs decays to glueballs of mirror QCD

Chacko, DC, Verhaaren [in preparation]

Higgs Portal Observables

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Higgs Portal Observables

(Colored) SUSY

Direct searches for additional Higgs bosons in the MSSM have ~ 1 TeV reach at HL-LHC and ~ 5 TeV reach at 100 TeV (see 2HDM)

Within the MSSM, a 125 GeV Higgs mass requires either very heavy stops (unnatural) or additional tree-level contributions to the Higgs mass:

F-terms (NMSSM etc) → extra singlet scalar

→ Extra Higgs production
Exotic Higgs decays!
EWPO, etc....

D-terms (non-decoupling D-term models) → new gauge group

→ DY production of BSM gauge bosons at a few TeV!

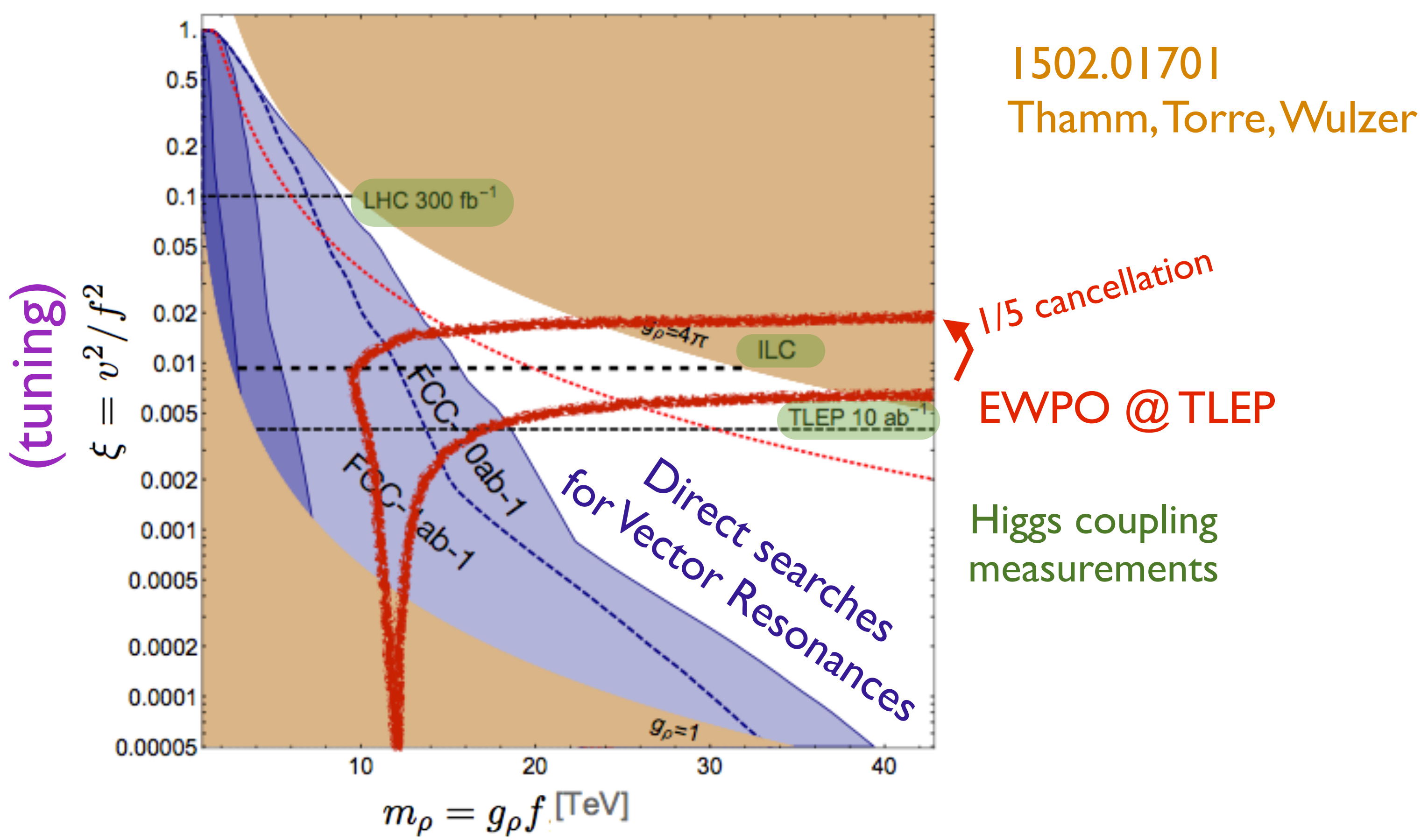
hep-ph/0309149 Batra, Delgado, Kaplan, Tait

Of course, a 100 TeV collider has exquisite reach for colored stops....

Composite Higgs Models

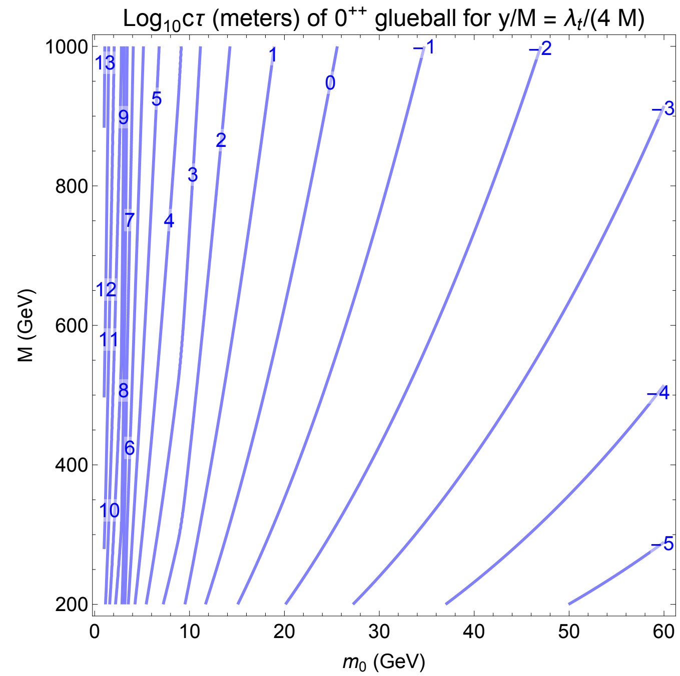
Want Lepton colliders to probe Higgs coupling deviations & EWPO

Want 100 TeV to produce vector resonances of strongly coupled sector (as well as top partners)



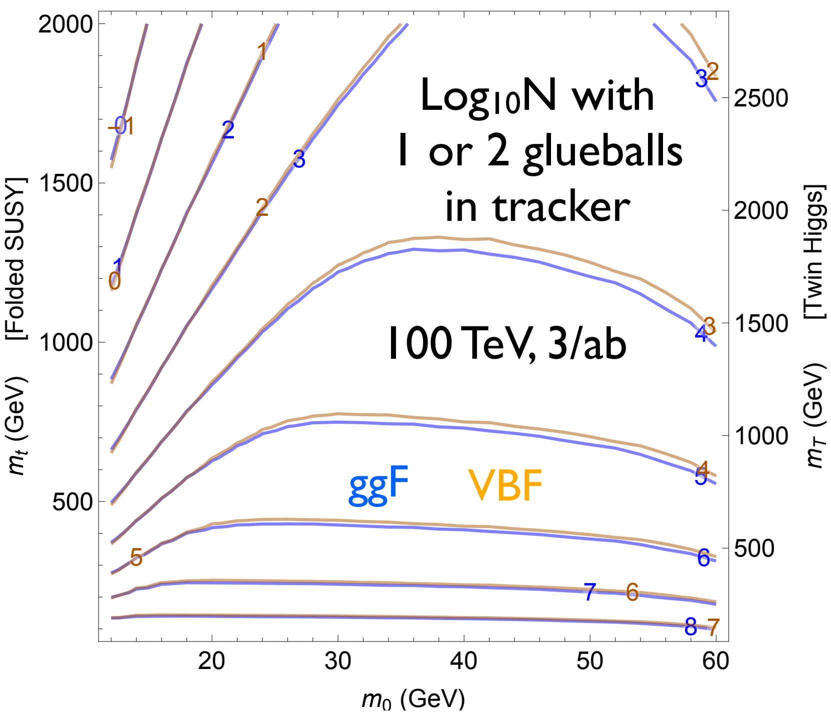
Colorless Electroweak Naturalness

Models with uncolored top partners are usually charged under mirror QCD.
The mirror sector has dark glueballs for EW-charged partners, and also *possibly* for SM singlet partners.



These glueballs have < km decay lengths.
0911.5616 Juknevich; 0903.0883 Juknevich, Melnikov, Strassler

The higgs can decay to these glueballs via a top partner loop, which can constitute the discovery signature for uncolored naturalness!
1501.05310 Craig, Katz, Strassler, Sundrum



These glueballs are naturally in the 10 60 GeV mass range!

⇛ exotic Higgs decays allow the 100 TeV collider to probe ~ 3 TeV uncolored Partners! (~ 1.5 TeV @ HL-LHC)

Chacko, DC, Verhaaren [in preparation]

Singlet Naturalness

Fermionic top partners *without* any SM charge *always* lead to tree-level Higgs coupling shifts. ⇛ Detectable at lepton colliders for partner masses ≲ 1-2 TeV!

What about SM singlet scalar top partners? No theory yet, but can probably write one down....

In that case, would have to rely on *Higgs Portal Observables* at future colliders:

h*→SS production (100 TeV)
σ(Zh) shift by partner loops (ILC/TLEP)
triple higgs coupling shift by partner loops (100 TeV)

Sensitive to singlet scalar top partners at ~ 300 GeV

If there is a mirror QCD, h→invisible decays at lepton colliders *might* be sensitive to ~ 400 GeV

However, the 100 TeV collider can probably access the UV completion of these models directly.

[in preparation] DC, Saraswat, Sundrum

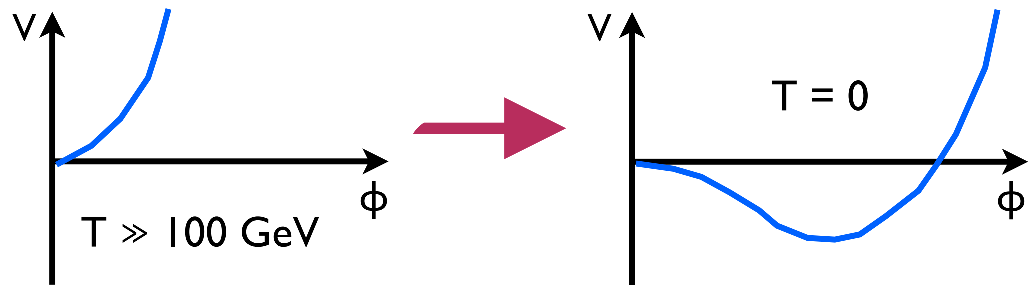
[in preparation] Cohen, Craig, DC

Big Picture Motivations

Electroweak Phase Transition

Electroweak Phase Transition

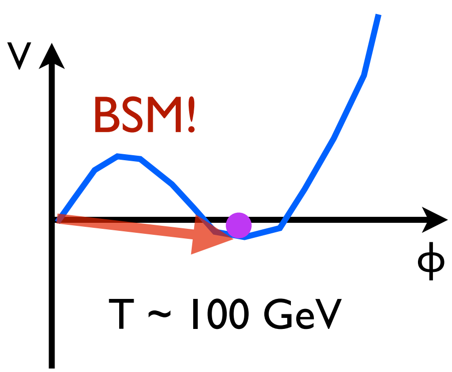
In the early universe at T ≫ 100 GeV, interactions with the plasma stabilize the Higgs boson at the origin.



Many reviews, e.g. Quiros hep-ph/9901312

Understanding this important part of cosmological history requires understanding the Higgs potential away from our current vacuum.

With some BSM ingredients, the EWPT can be made strongly *first order.*



This results in *bubbles* of true vacuum expanding in the universe. The resulting departure from thermodynamic equilibrium can cause **Electroweak Baryogenesis** if there is a new source of CPV in the plasma.

The Electroweak Phase Transition is very difficult to probe at colliders.

Achieving a strong EWPT

Need to modify the Higgs potential to get barrier:

$$V_{\text{eff}}(h,T) = V_0(h) + V_0^{CW}(h) + V_T(h,T)$$

Tree Effects

Add scalars to modify shape of the Higgs potential at tree-level,

Loop Effects

Add particles whose loop interactions reduce the depth of the Higgs potential well.

Thermal Effects

Add new *bosons* with large Higgs couplings to the plasma.

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↓

Mass is < 200 GeV.
Produce directly,
modify Higgs couplings.

Cohen, Morrissey, Pierce 1203.2924,
DC, Jaiswal, Meade 1203.2932

Carena, Nardini, Quiros, Wagner 1207.6330

Katz, Perelstein 1401.1827

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Coh y, Pierce 1203.2924,
DC, Jaiswal, Meade 1203.2932

Carena, Nardini, Quiros, Wagner 1207.6330

Katz, Perelstein 1401.1827

Do *not* require *very* light particles.
Can realize this e.g. in SM+S model.

Many parameters, and many potential Higgs sector experimental observables.

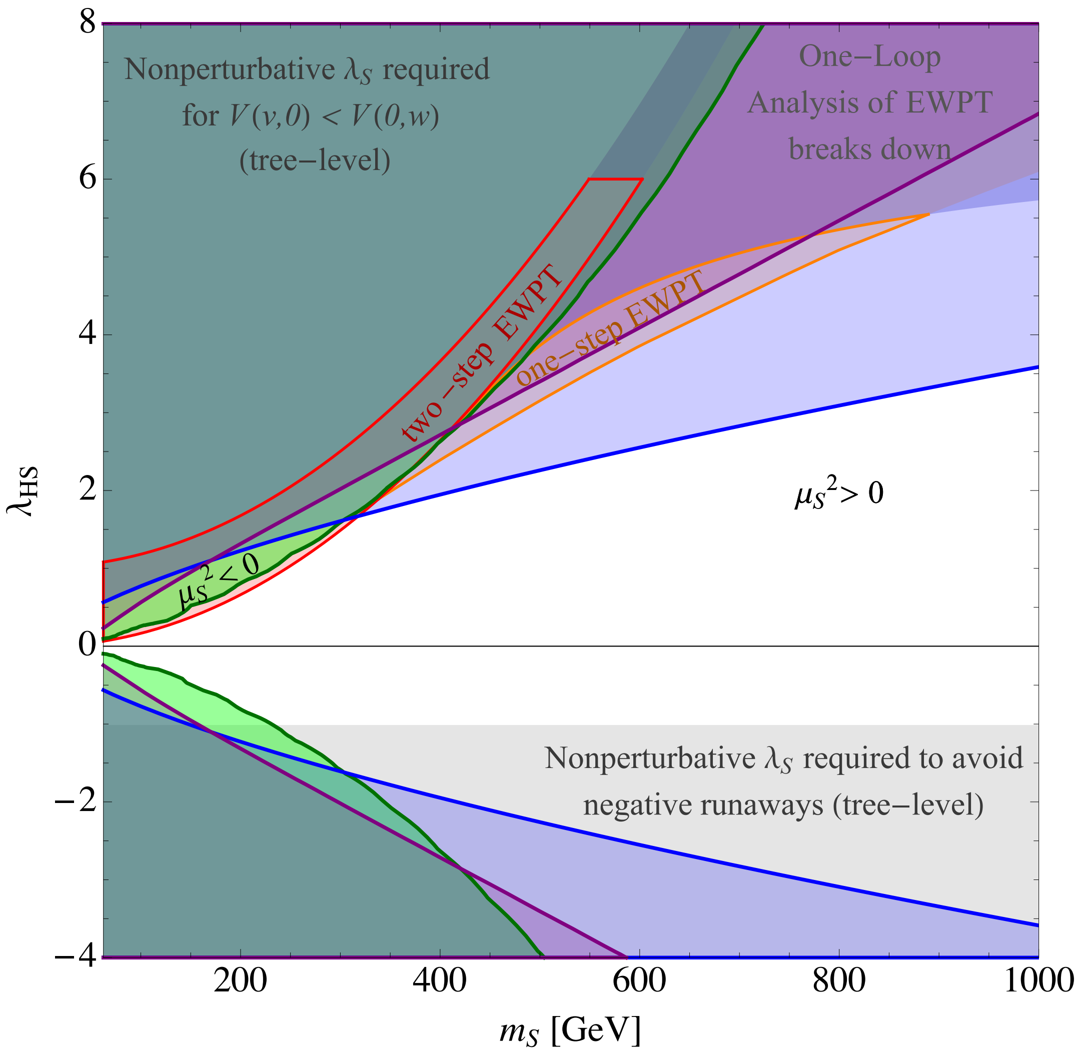
Can a *strong* EWPT be generally excluded?

Need to study a model with *minimal signatures* that we can explore completely.

Minimal stealthy model for a strong EWPT

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

Unmixed SM+S. No exotic higgs decays, no higgs-singlet mixing, no EWPO, ...



Two regions with strong EWPT

Only Higgs Portal signatures:
h*→SS direct production
Higgs cubic coupling
σ(Zh) deviation (> 0.6% @ TLEP)

100 TeV collider could cover *entire* parameter space.

TLEP (super ILC) can cover *some* of parameter space.

Potential complimentarily!

1409.0005 DC, Patrick Meade, Tien-Tien Yu

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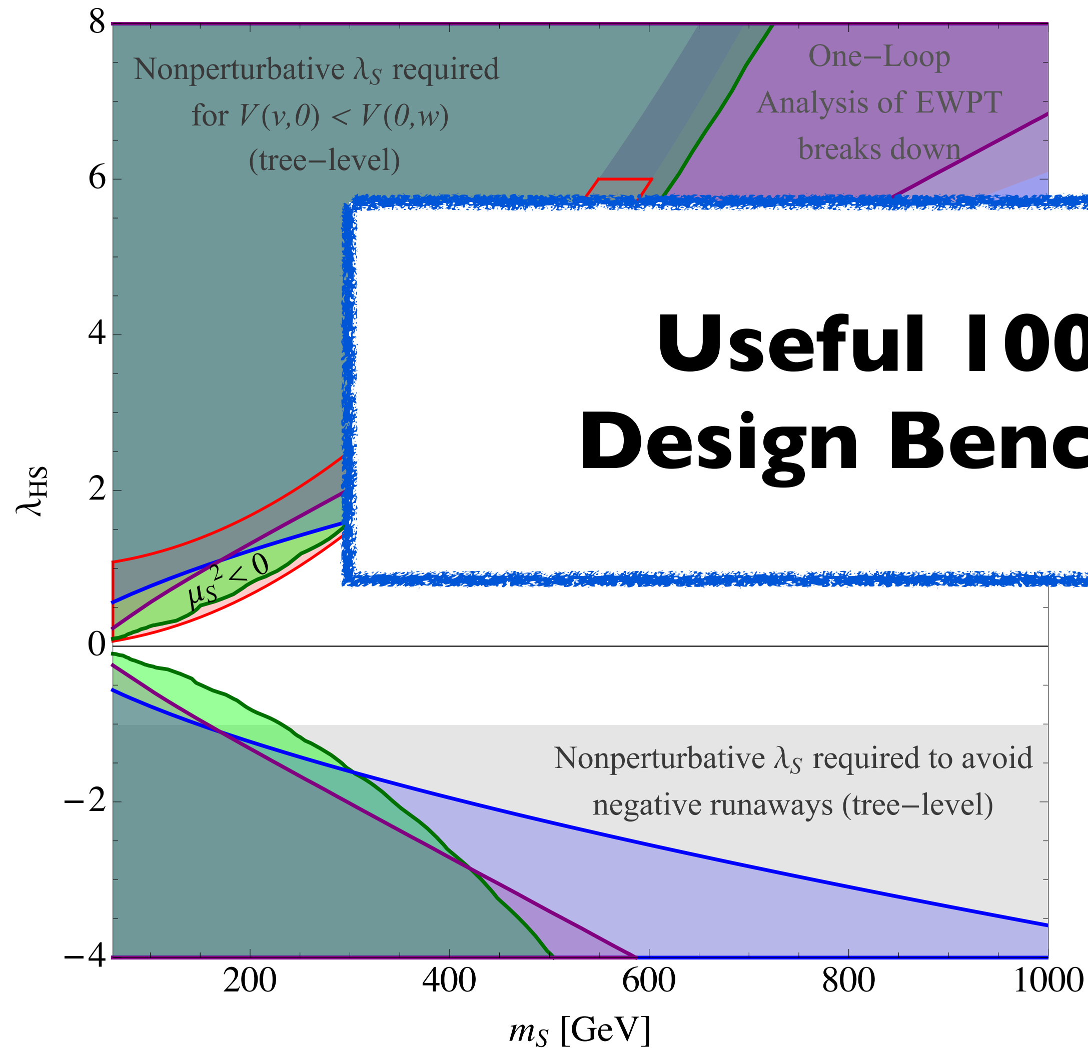

Two regions with strong EWPT

Only Higgs Portal signatures:

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g

0.6% @ TLEP)

Useful 100 TeV Design Benchmark

could cover

ter space.

TLEP (super ILC) can cover *some* of parameter space.

Potential complimentarily!

1409.0005 DC, Patrick Meade, Tien-Tien Yu

Conclusions

Conclusions

- The Higgs program provides enormous experimental challenges and opportunities.
- The resulting information would allow us to constrain or construct the low-energy Higgs sector, *which could easily be very non-SM-like!*
- This is vital to understand whether nature is natural, the electroweak phase transition / baryogenesis, and general BSM via the agnostic Higgs portal.
- Both lepton and 100 TeV pp colliders are vital for this effort!

Observables at Current + Future Colliders	100 TeV	ILC/TLEP
• producing extra higgs states (incl. superpartners)	✓	
• Exotic Higgs Decays	✓	✓
• Electroweak Precision Observables		✓
• Higgs coupling measurements	✓ (grey)	✓
• Higgs portal direct production of new states	✓	
• Higgs self coupling measurements	✓	✓ (grey)
• Zh cross section measurements		✓