New Physics at the Electroweak Scale and Naturalness (theory)

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A huge subject I will inevitably fail to do justice to in 40 mins. We will hear details of some specific topics in the electroweak sections.

Highlight several aspects of new physics at the weak scale with a focus on possible new experimental signatures at the LHC and suggest a few general lessons to think about in the coming years.

I apologize in advance for omissions—there are many interesting things I don't have sufficient time or knowledge of to include. (I do not talk about new physics related to flavor and neutrino since there are extensive talks on them)

Pursue Naturalness

Electroweak Naturalness

The Higgs is more mysterious than ever given the discovery. So far the Higgs boson looks like an elementary scalar (the **only** elementary scalar found).

At first glance, it looks very simple, just a spin-zero light particle.

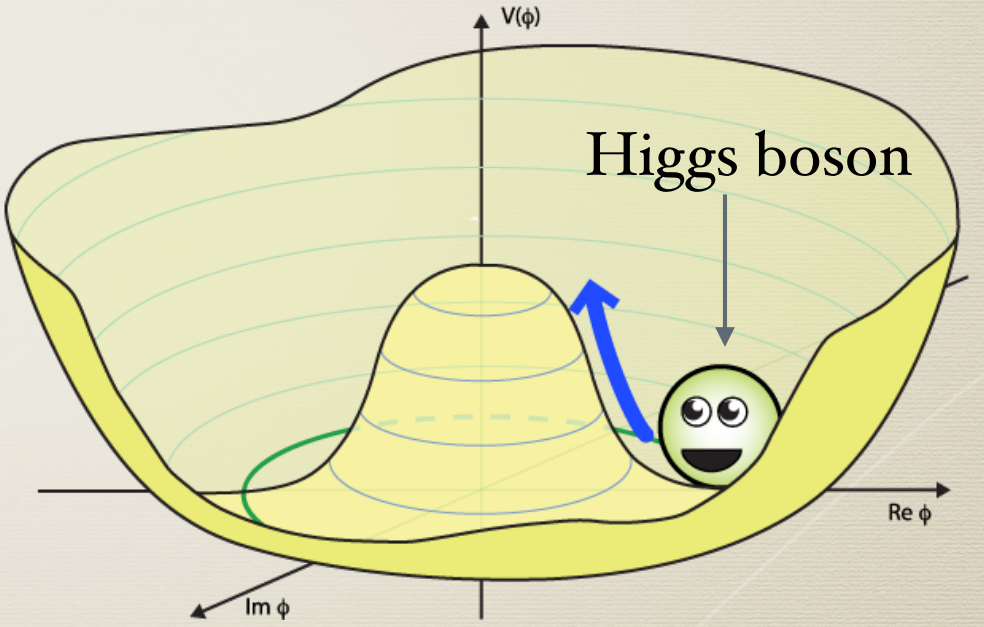
Higgs potential

Higgs is a field that permeates the vacuum. It can store energy, depending on the field value in some region.

The Higgs has a non-zero "**expectation value**": at the minimal of its potential, the field value is non-zero.

The non-zero expectation value is responsible for electroweak symmetry breaking (EWSB).

Higgs potential energy



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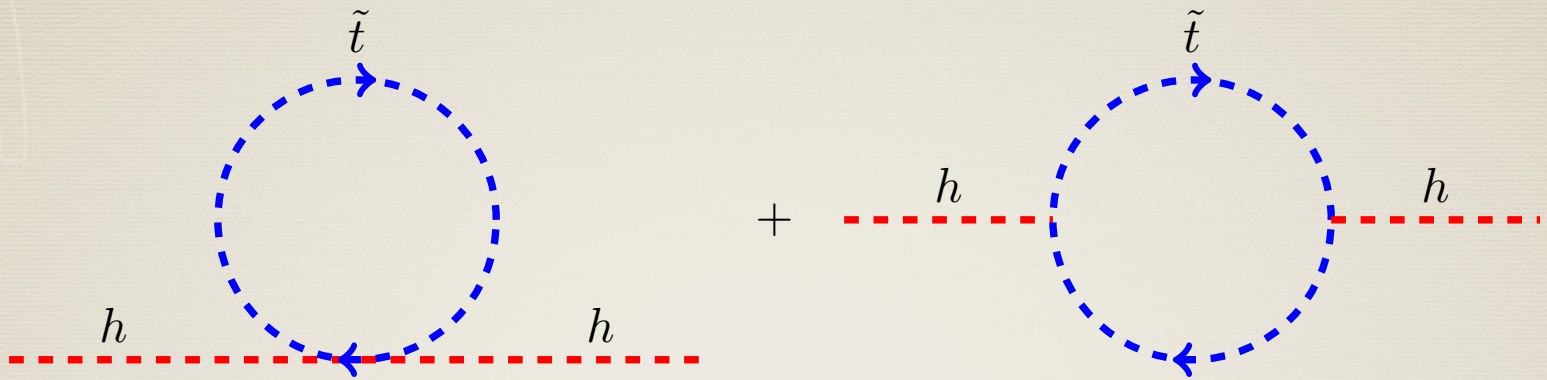
Electroweak Naturalness

The Higgs potential is something we put in by hand in Standard Model.

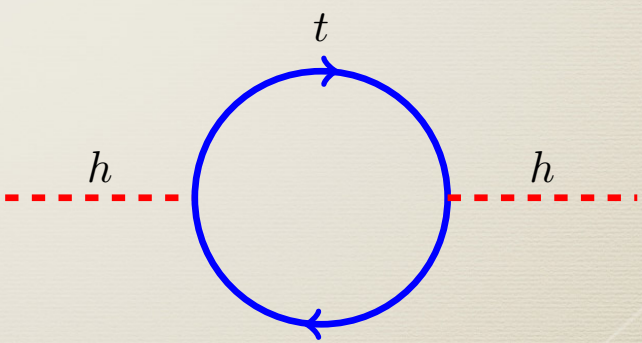
We want to explain it $\longrightarrow$ new physics beyond the SM;

Natural ways to explain it: new physics with colored top partners close to weak scale.
Classic examples: weak-scale SUSY and composite Higgs

Electroweak Naturalness: weak-scale SUSY

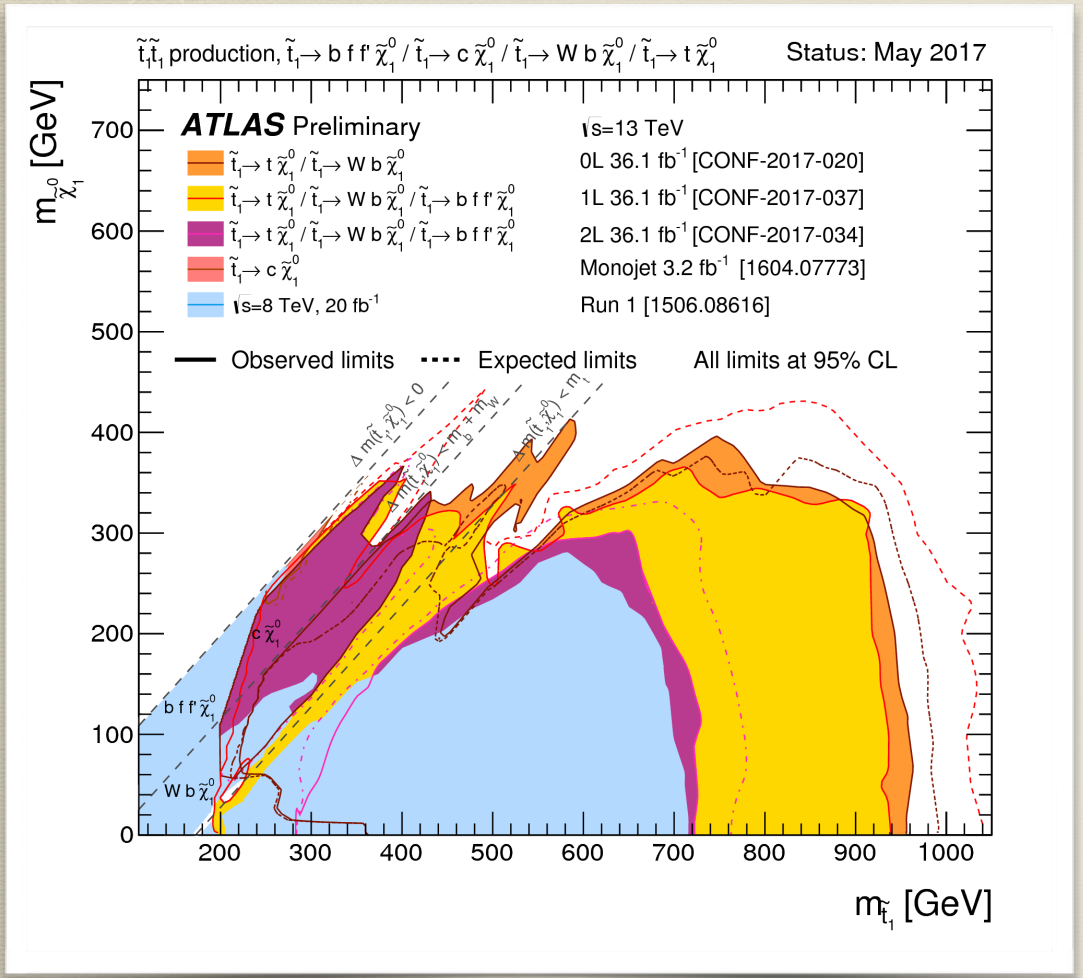


Different-spin pieces combine to cancel large corrections.



"Stop" or "scalar top": cancels the biggest correction from the top loop. ~10% tuned if mass ~ 700 GeV.

Stop Parameter Space



Impressive reach with 13 TeV data for **simplest** stop decays (at both CMS and ATLAS): exclude stop ~ 1 TeV (for neutralino below 400 GeV) and cover the compressed region (stop mass ~ top + heavy neutralino).

Compressed region theory:
Hagiwara, Yamada 1307.1553
An, Wang 1506.00653
Macaluso, Park, Shih, Tweedie 1506.07885

Null results teach us valuable lessons: traditional natural scenarios with electroweak fine-tuning no worse than 10% are very cornered.

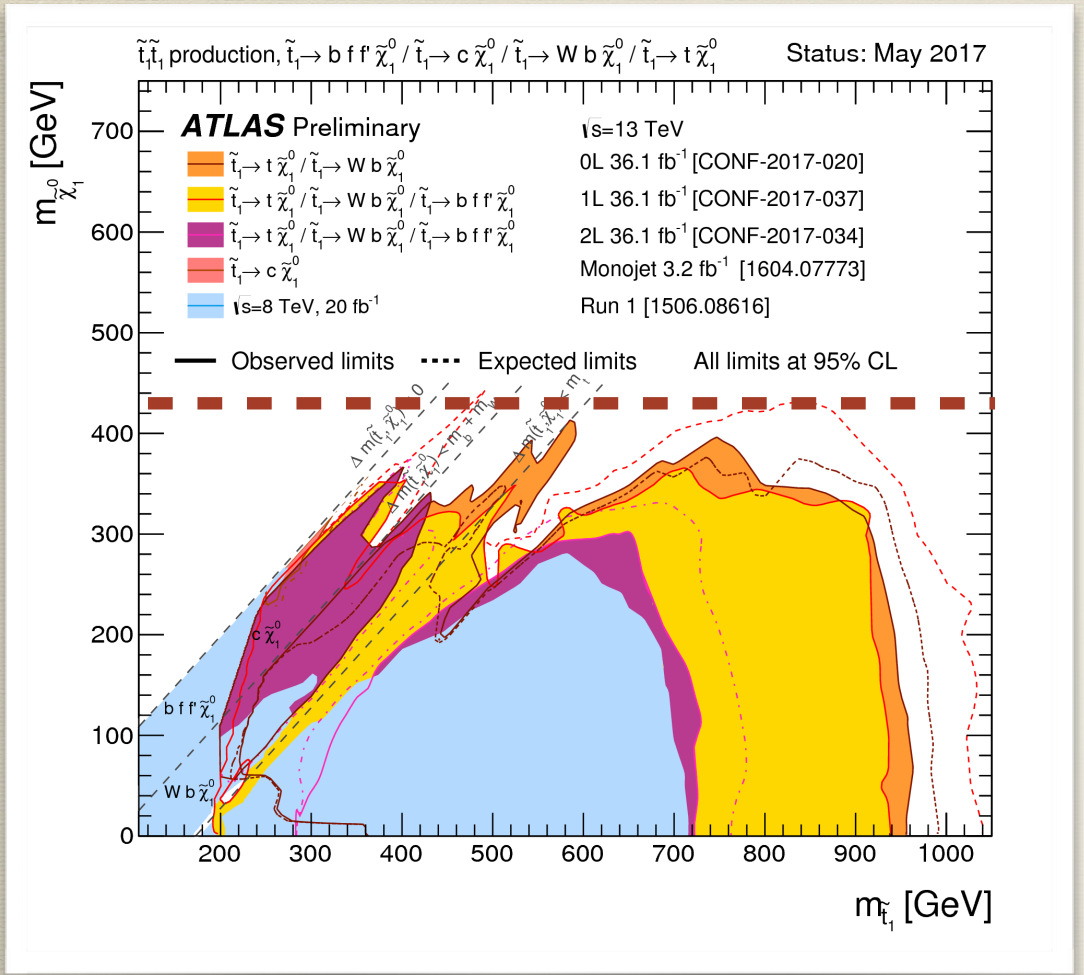
Does it mean paradigm shifting?

Could be. It could be a dramatically new paradigm or a mild paradigm shift: meso-tuning scenario such as heavy SUSY scenario with susy scalars ~ (10 - 100) TeV (sufficient to explain the Higgs mass). Yet the bottom of the spectrum including the gluino and the electroweak sector could still be light and be searched for at the LHC.

But before we abandon the idea of naturalness or in general new physics at the TeV scale, we have to make sure that we cover as much ground as possible and ***explore the full capacity of the LHC***.

There could still be loopholes in existing searches. The theoretical models may look more complicated and the main point is to motivate new experimental signals and searches.

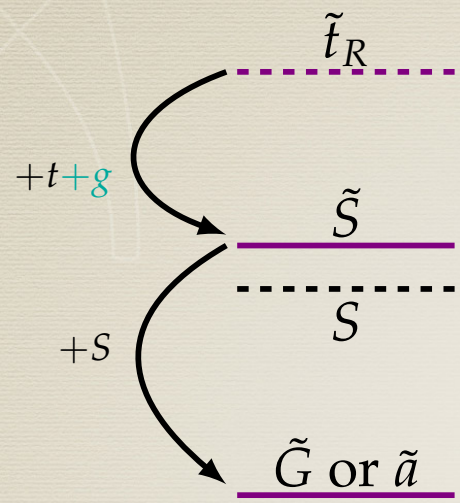
First Caveat: heavy neutralino



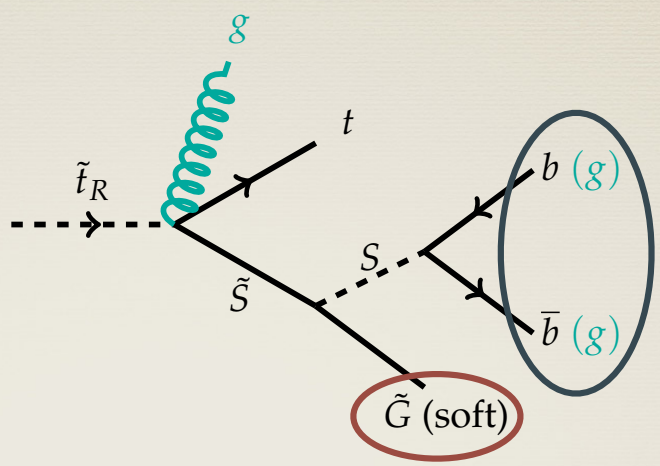
No bound for heavy neutralino.

Theoretically, may prefer light neutralino (higgsino);
yet certainly possible to have a natural scenario with a heavy higgsino
Cohen, Kearney, Luty 2012

Second Caveat: METless stop signals



light invisible fermion

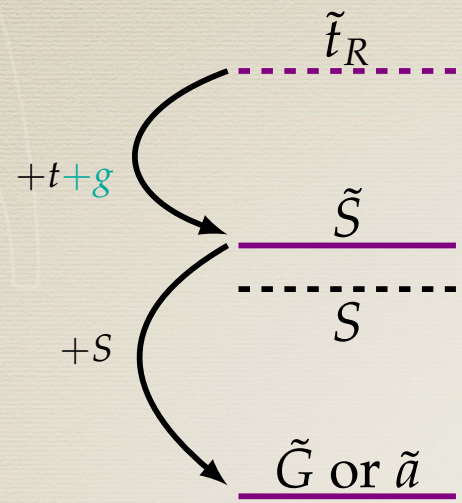


softened in pT

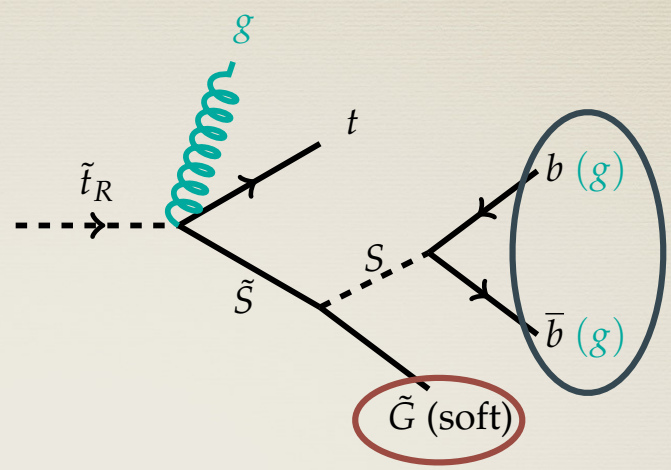
Stealth SUSY:
Approximate SUSY in the hidden sector suppressing missing momentum;
visible particles at the end of long cascades through the hidden sector have less energies

Fan, Krall, Pinner,
Reece, Ruderman, 2015

Second Caveat: METless stop signals



light invisible fermion

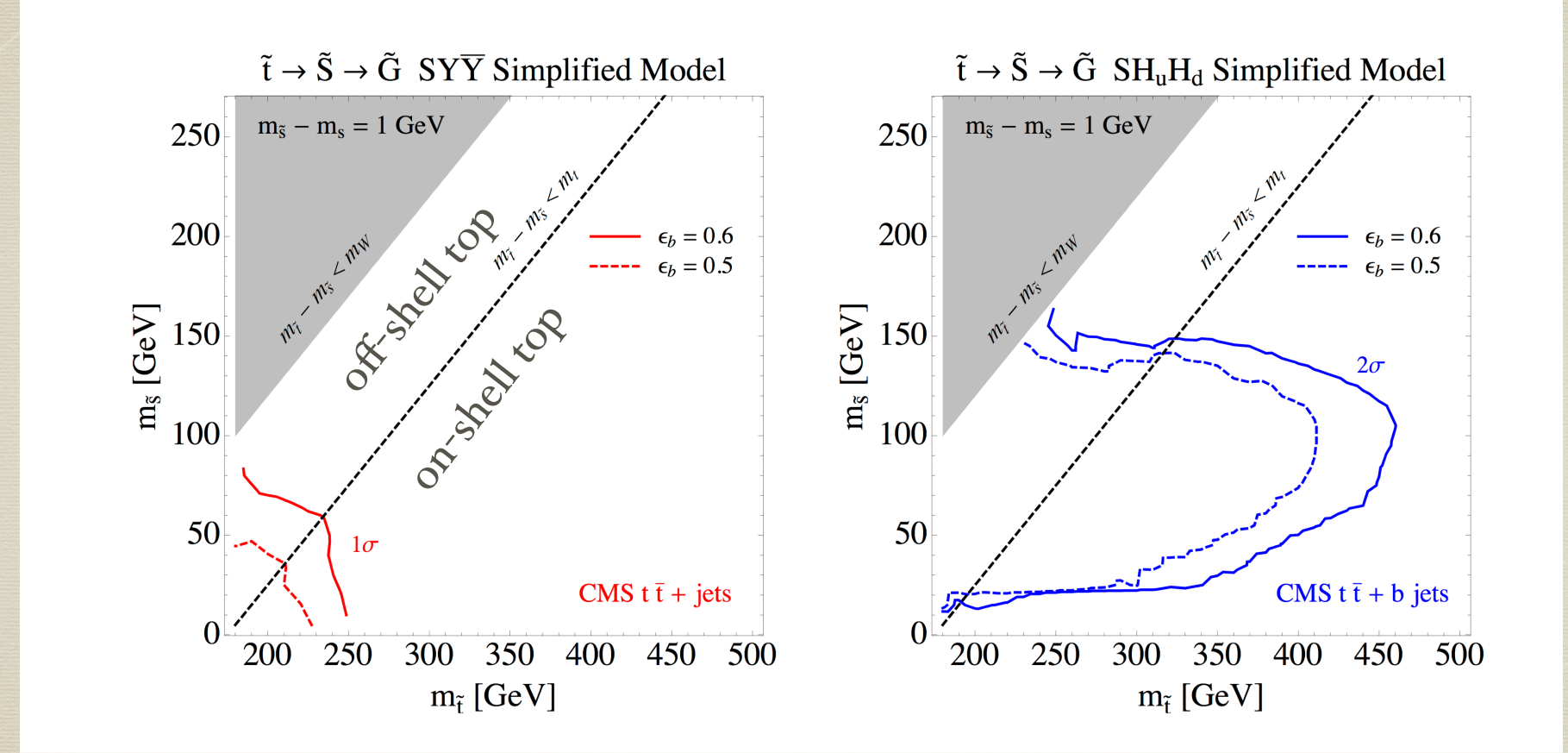


softened in pT

The final state of stop pair production is top pairs + jets (very little additional missing momentum)

similar to SM top pair backgrounds + additional ISR/FSR jets

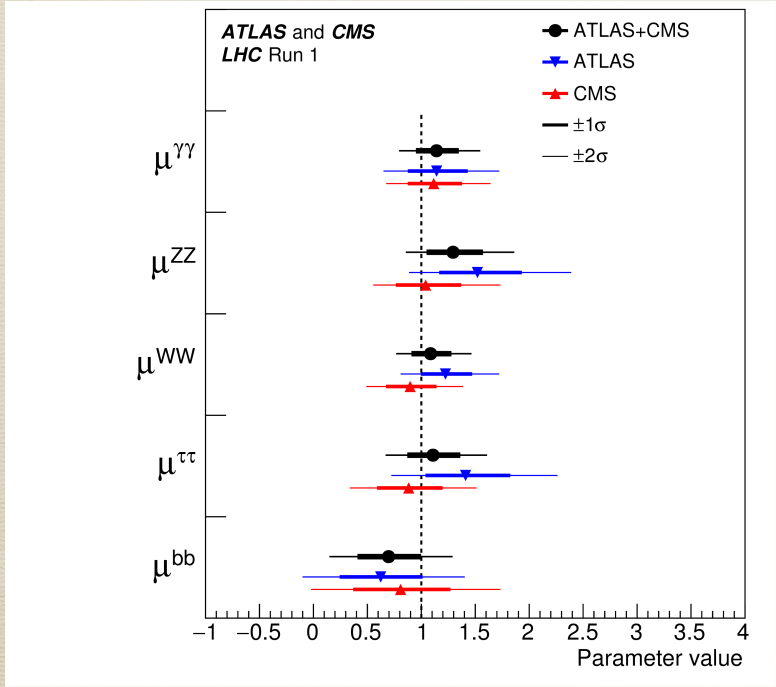
Recast of CMS top measurements: need better understanding of the SM background and even better, a dedicated search for the tt+jets final state

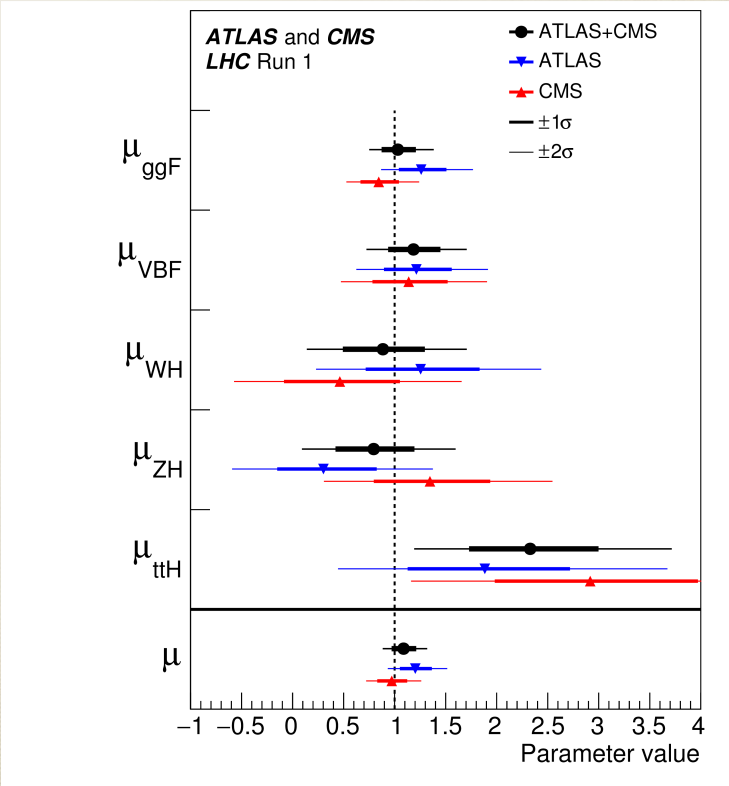


Indirect Probe using Higgs Coupling

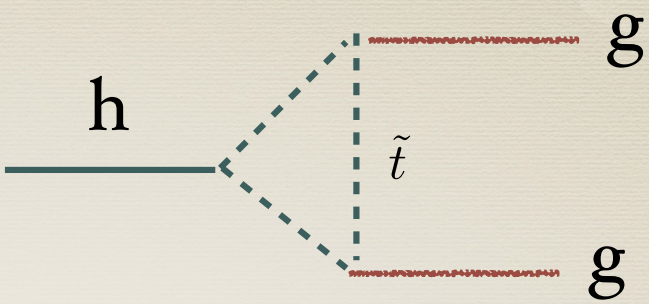
A natural Higgs is **not** a SM Higgs.

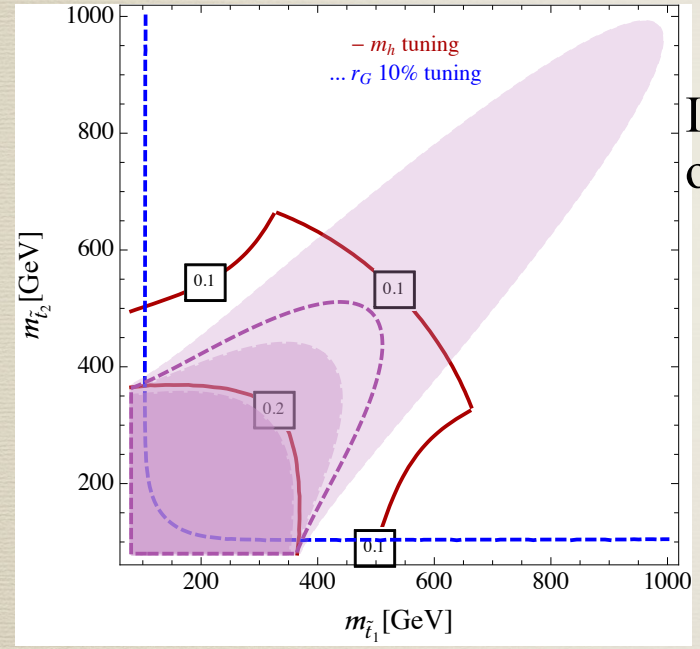
Possible O(10%) or larger deviation in Higgs coupling if we stick to the strict naturalness with light degrees of freedom coupling to Higgs to stabilize its potential.





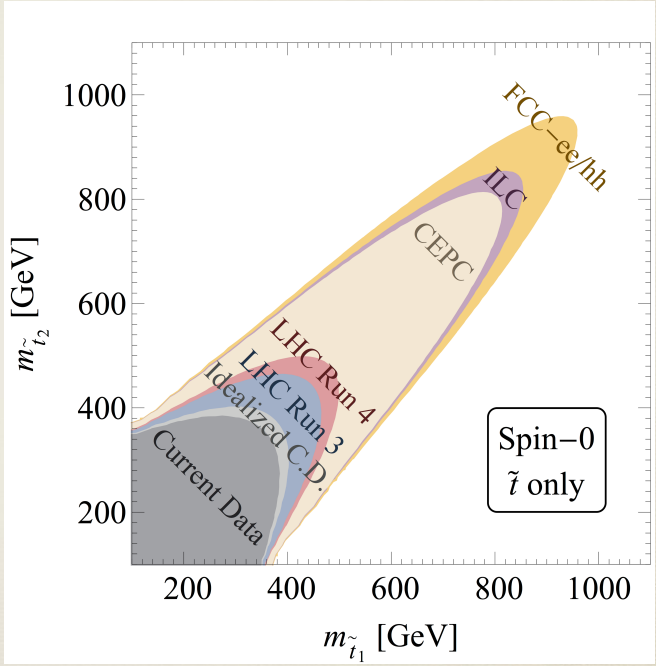
Indirect Probe using Higgs Coupling: stop search





Independent of stop mixing

Fan, Reece 2013



Essig, Meade, Ramani, Zhong, to appear

Two light stops with mass below 400 GeV is ruled out by 8 TeV Higgs data at 95% C.L.

An update with the latest Higgs data and projection of future LHC Runs and possible future collider

Why do we care about them?

Independent of how stops decay and is not susceptible to the loopholes in direct searches.

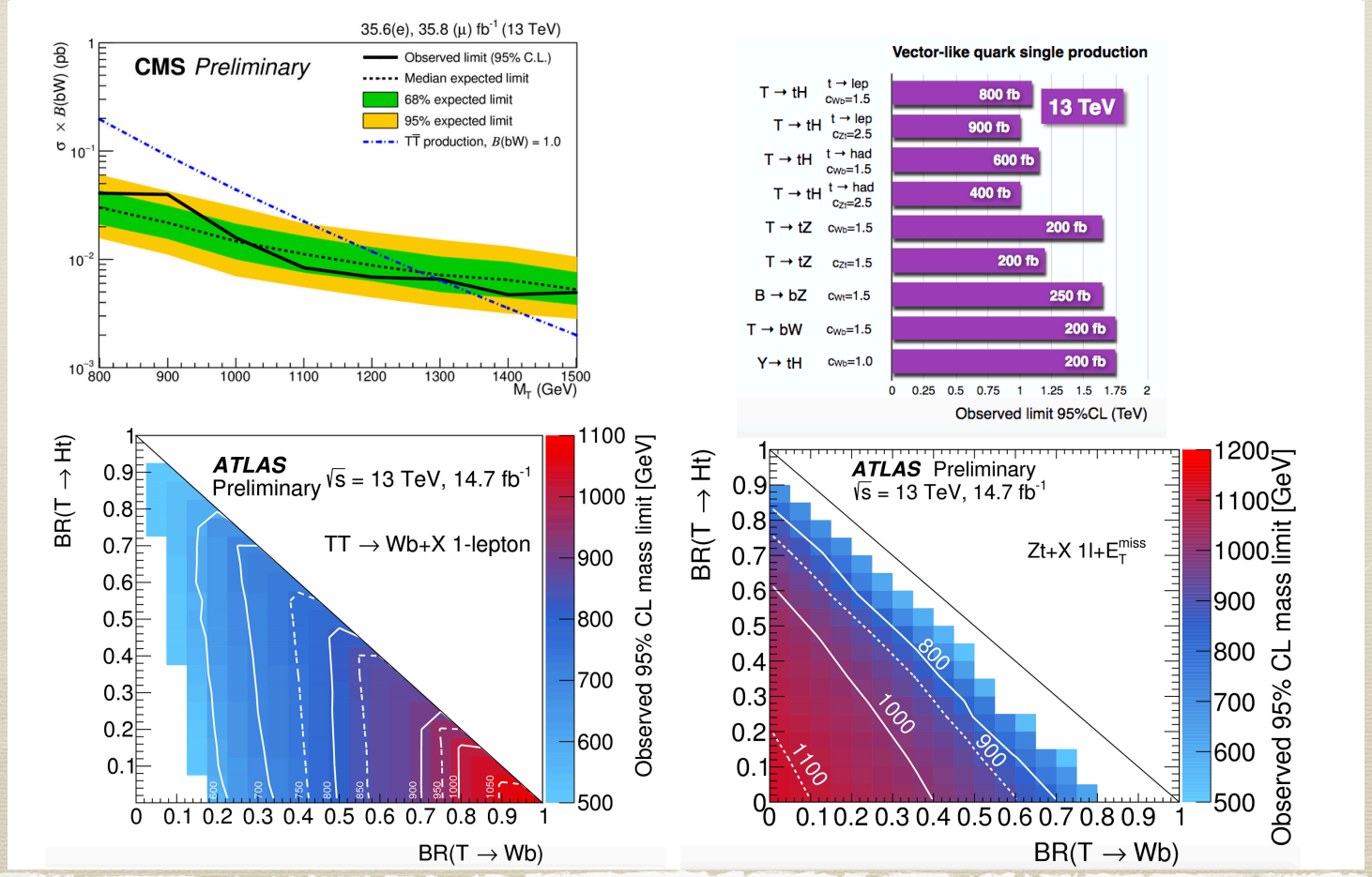
Complementary to the direct searches!

Fermionic Top Partners

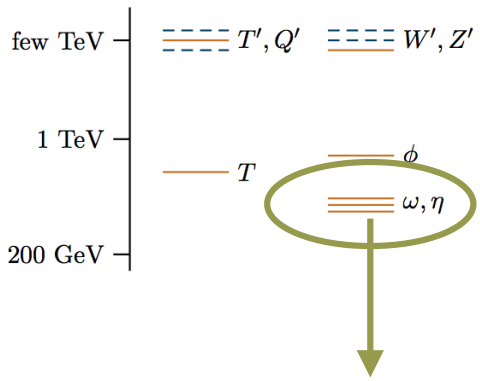
They generically accompany composite Higgs, which could be a (pseudo) Nambu-Goldstone Boson (pNGB) associated to a spontaneously broken symmetry.

Strong exclusion limits **above 1 TeV** are also achieved in standard channels:

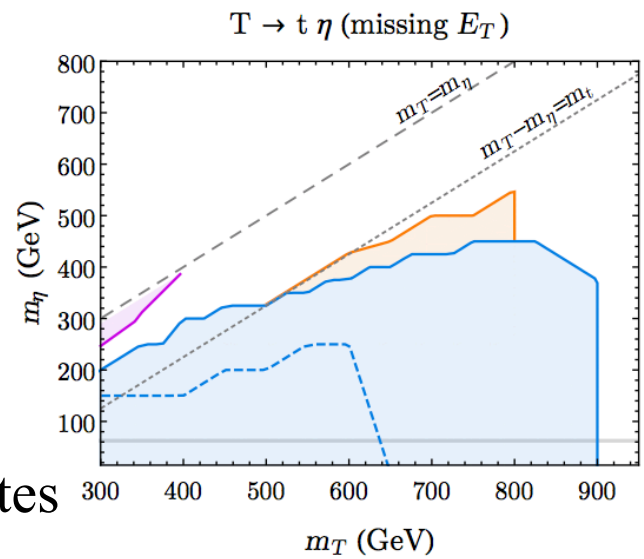
$$T \to th, tZ, bW^+, B \to bh, bZ, tW^-$$

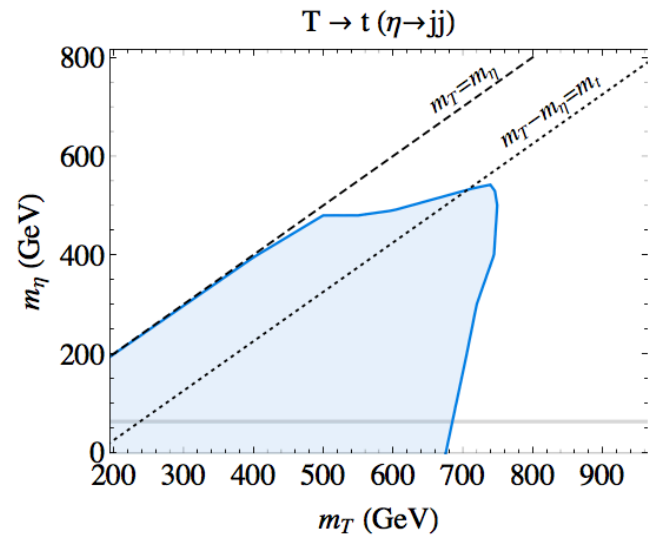


Top partners, less simplified

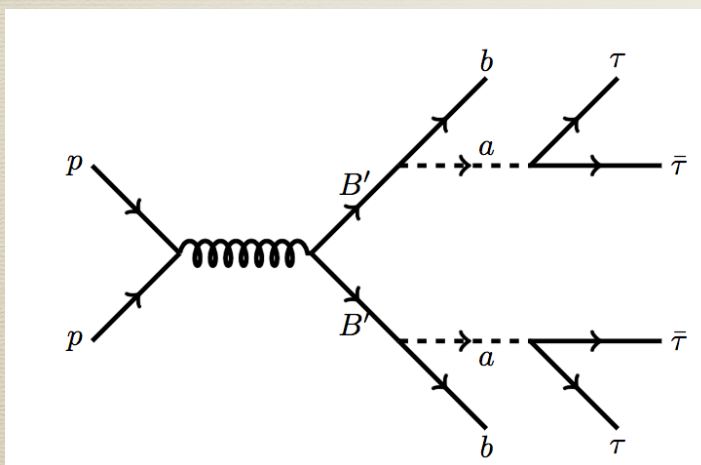


New (pseudo)-scalar states

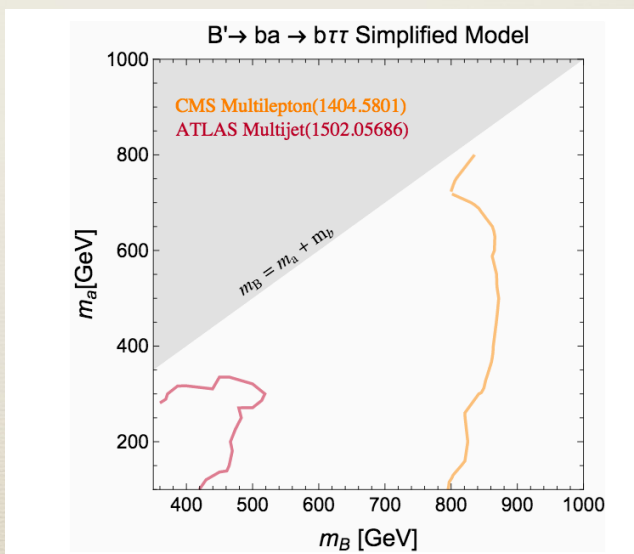




Anandarkrishnan, Collins, Farina, Kuflik, Perelstein; Serra 2015



Fan, Koushiappas, Landsberg 2015



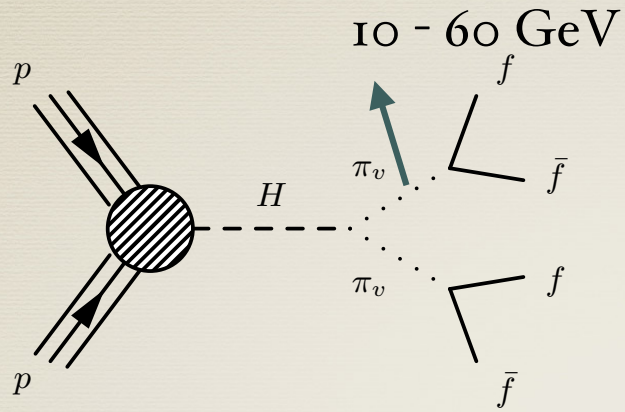
More complicated jetty final states, pretty good coverage already, but could be improved by more targeted searches.

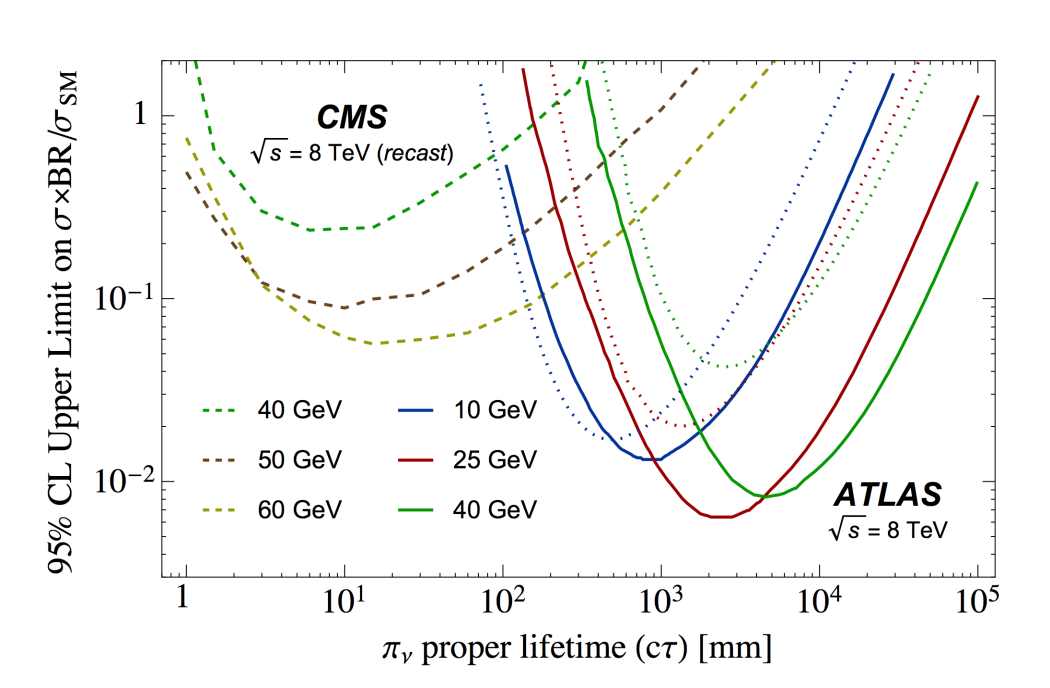
Exotic Higgs decays as a direct probe

Searching for extended Higgs sector including new heavy neutral or charged Higgses are clearly probing new physics.

Yet we should also try to use the lamppost 125 GeV Higgs boson directly to probe new physics: search for exotic Higgs decays.

Exotic Higgs decays: Csaki, Kuflik, Lombardo, Slone 2015





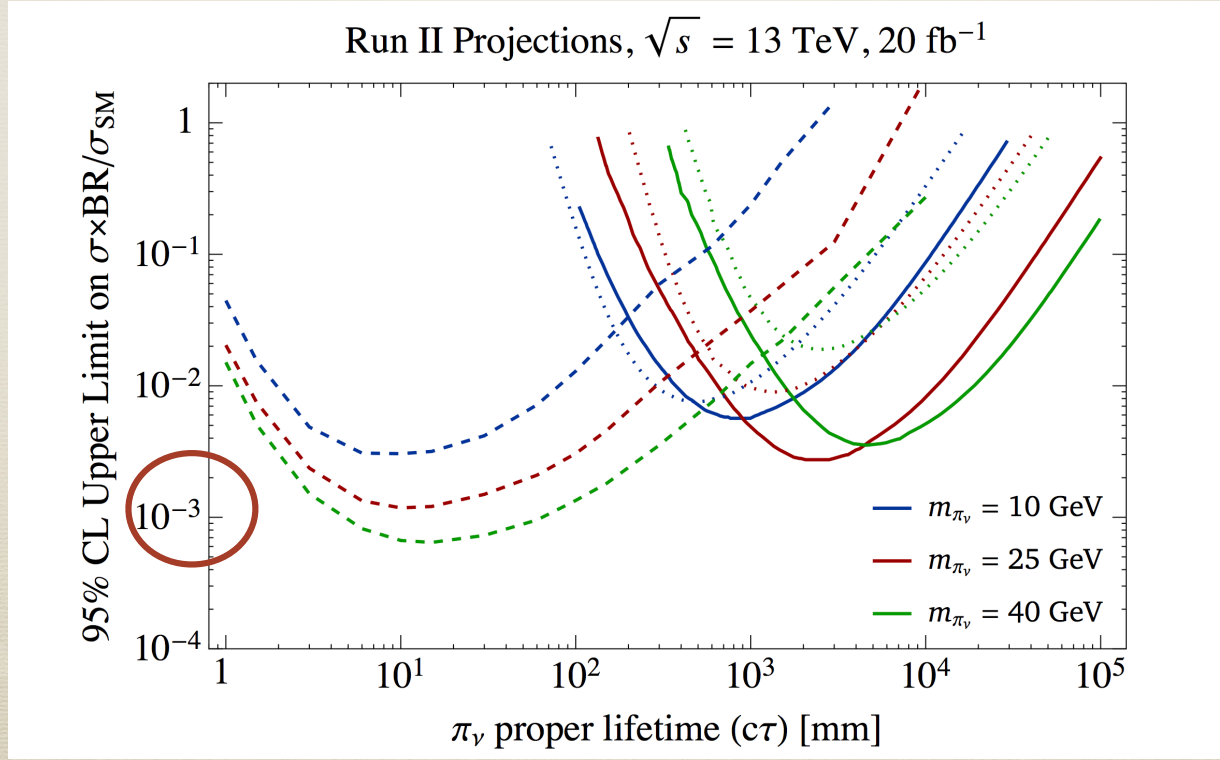
Run 1 triggers were too strong for O(cm) lifetime: required more energy than a typical Higgs event

Displaced vertex

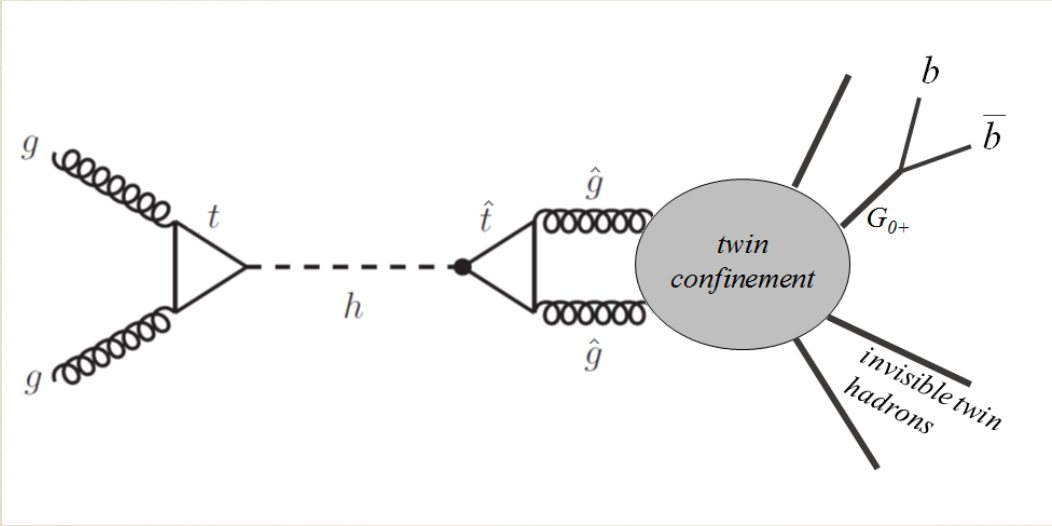
Decay in HCAL or muon chamber

Signal vertices: low invariant mass and low track multiplicity

Strategy: weaken the vertex mass and track requirements; require additional objects associated with the DV or impose other selection requirements (e.g., reconstruct the Higgs and the intermediate particles' masses)



Exotic Higgs decays could be the main signal at the LHC for Neutral Naturalness (rebranding of Twin Higgs by Chacko, Goh, Harnik, 2005 and related ideas; top partners: SM gauge singlets or electroweak doublets)



Craig, Katz, Strassler, Sundrum 2015

Signature: twin glueball decays including displaced vertex

A recent nice report on exotic Higgs decays: Curtin, et.al (13 authors), 1312.4992

Dark Matter (Electroweak States) at the LHC

Dark Matter at the LHC

There has been a well-established DM program at the LHC: mono-X (X = jet, Higgs,….) based on model -independent effective operator parametrization or simplified models.

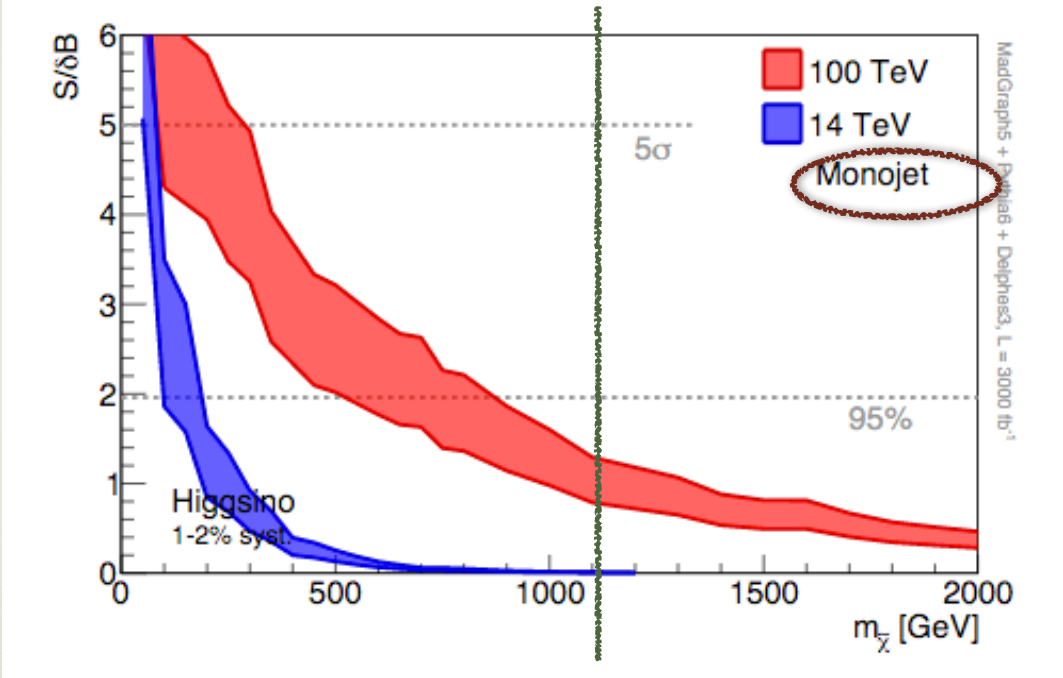
It originates at Irvine with a continuous Irvine input: Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu 2000; summary report: 1506.03116; 1507.00966

Electroweak dark matter benchmark: Higgsino DM

Simple WIMP model still **alive (elusive to all DM detections so far)**: higgsino dark matter, a fermonic electroweak doublet with little mixing with other fermions

Thermal higgsino benchmark

Low, Wang: 2014



Notice **wide bands**: varying background systematics 1-2%. Big exp. challenge is well-characterized background!

Many other work: for example, Ismail, Izaguirre, Shuve 2016

Possible improvements of tracker?

Charged and neutral higgsino nearly degenerate in mass, one-loop induced mass splitting ~ 360 MeV;
nominal decay length of charged higgsino, $c\tau$~ **6.6 mm**

Disappearing charged track: need large boost (~ 100) (more easy to get large forward than transverse boost)
(disappearing charged track (for wino DM) has been proposed by Feng, Moroi, Randall, Strassler, Su 2009)

Increase the tracker granularity below r=10 cm (r: transverse distance from the beamline): need 10 hits at r = 10 cm.

In the future, have a forward tracker covering $2 \leq |\eta| \leq 4$.

Mahbubani, Schwaller, Zurita;
Fukuda, Nagata, Otono, Shirai, 2017

Electroweak Precision

CP even operators with higgses and gauge fields

$$\mathcal{O}_W = \frac{ig}{2}(h^\dagger \sigma^i D_\mu h) D^\nu W^i_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}(h^\dagger D_\mu h)\partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{WW} = g^2 |h|^2 W^i_{\mu\nu} W^{i\mu\nu}$$

$$\mathcal{O}_{WB} = g g' h^\dagger \sigma^i h W^i_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{BB} = g'^2 h^\dagger h B_{\mu\nu} B^{\mu\nu}$$

Peskin-Takeuchi S parameter depends on:

$$S: \quad C_{WB}, C_W, C_B$$

well-constrained by LEP

$$h \to \gamma\gamma, h \to Z\gamma:$$

$$C_{WW}, C_{BB}, C_{WB}$$

Trip gauge coupling:

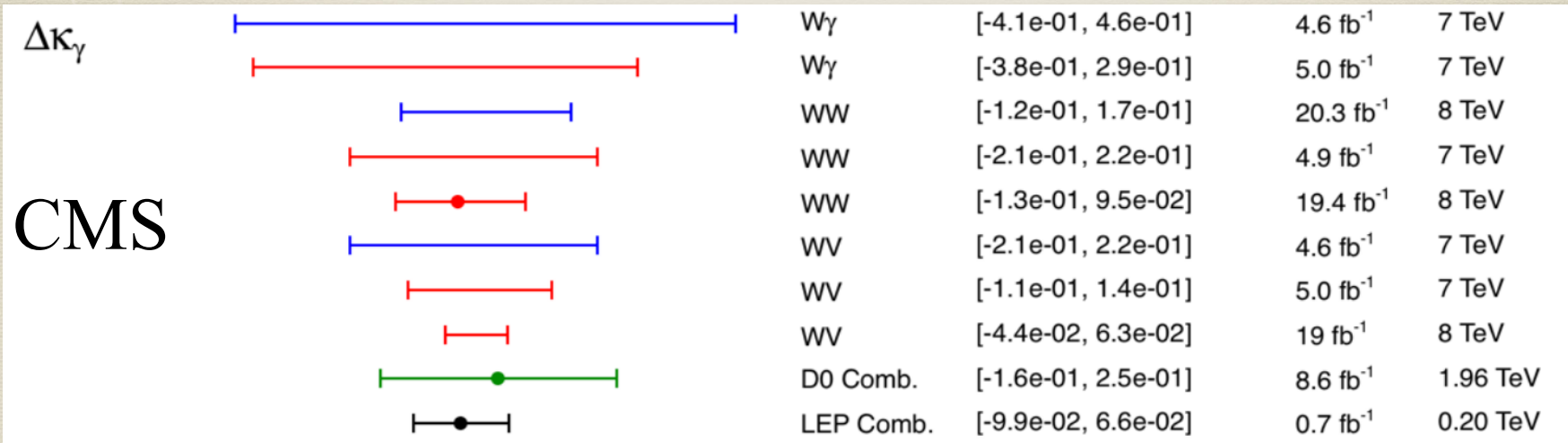
$$ig\cos\theta_W (\Delta g_1^Z) Z^\nu (W^+_{\mu\nu} W^{-\mu} + \text{h.c.}), \quad \Delta g_1^Z \propto C_W$$

$$(\Delta\kappa_\gamma)\sin\theta_W A^{\mu\nu} W^+_\mu W^-_\nu / 2, \quad \Delta\kappa_\gamma \propto C_{WB}$$

many papers, many bases; see e.g.
Elias-Miró, Grojean, Gupta, Marzocca 2013
Wells, Zhang 2015

A full section on Friday on using electroweak precision to probe new physics.

By measuring both Higgs branching ratios and Triple Gauge Couplings (TGC), can try to explore the whole space of these operators. TGCs at the LHC already compete with LEP, e.g:



Other purely-electroweak (no Higgs) operators: for example,

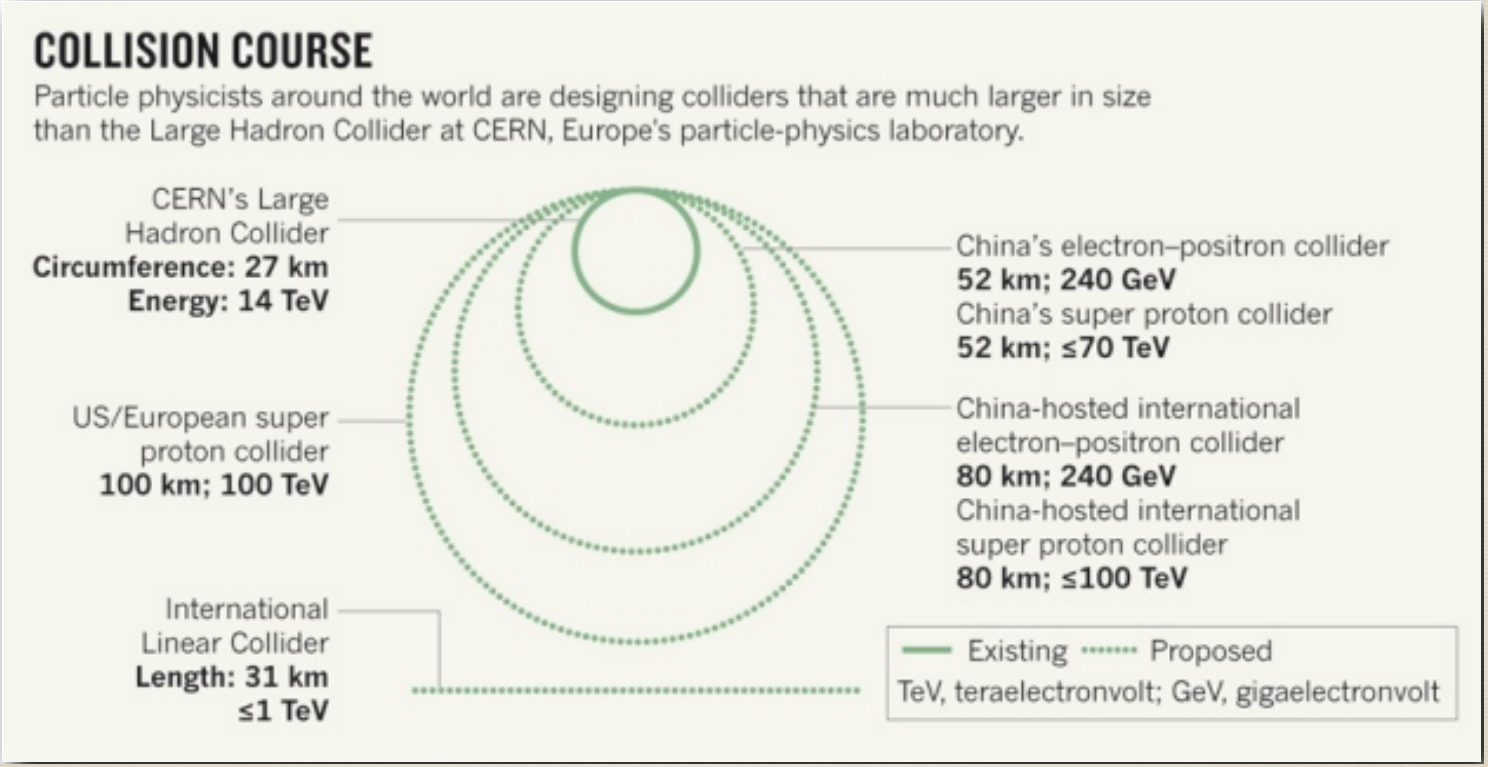
$$(D^\mu W_{\mu\nu})^2 \sim j_{W\mu} j_W^\mu$$

test with Drell-Yan

Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer 2016

Future Colliders

Beyond the near future:
High-energy LHC and future colliders



Nature News (E. Gibney), 2014
http://www.nature.com/news/china-plans-super-collider-1.15603

A lot of questions to address:

What are the physics goals? Naturalness, dark matter, electroweak phase transition...

To achieve the physics goals, what technology developments are needed? And how to achieve them?

For a future hadron collider, can we improve the design upon the LHC design?

Have to think about it from now rather than wait to make future colliders built!

The party is under way already

CEPC-SPPC

Preliminary Conceptual Design Report: Physics and Detector

Physics at a 100 TeV pp collider: beyond the Standard Model phenomena

Editors:
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Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies

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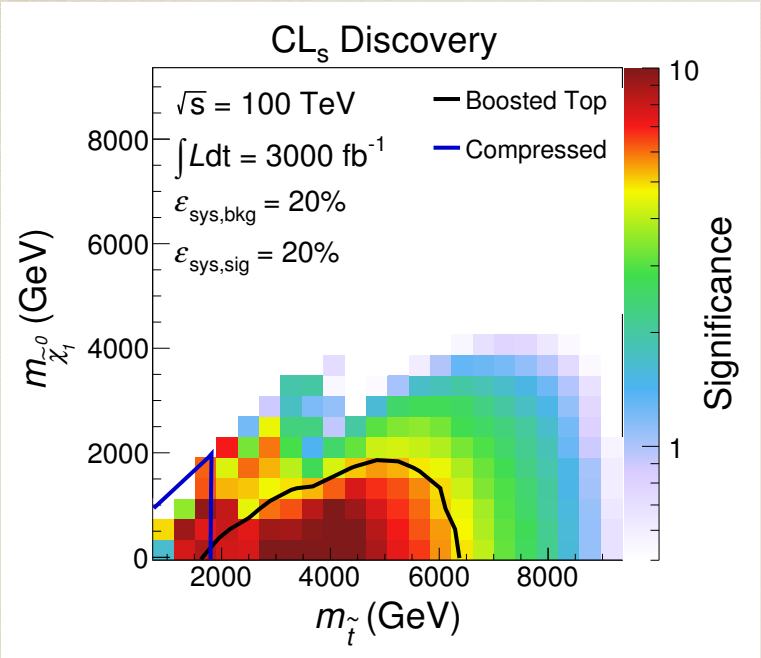
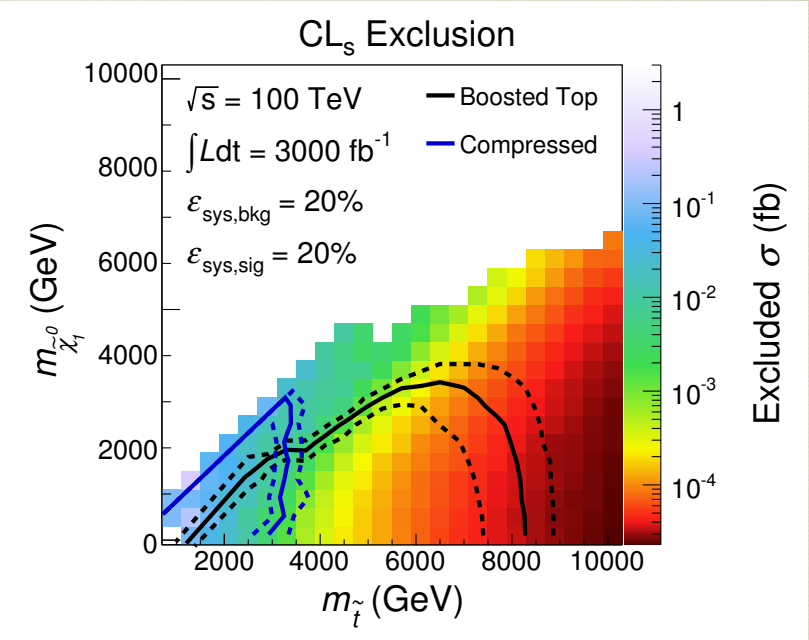
More work are on the way and needed.

Leap in searching for new physics and testing fine-tuning

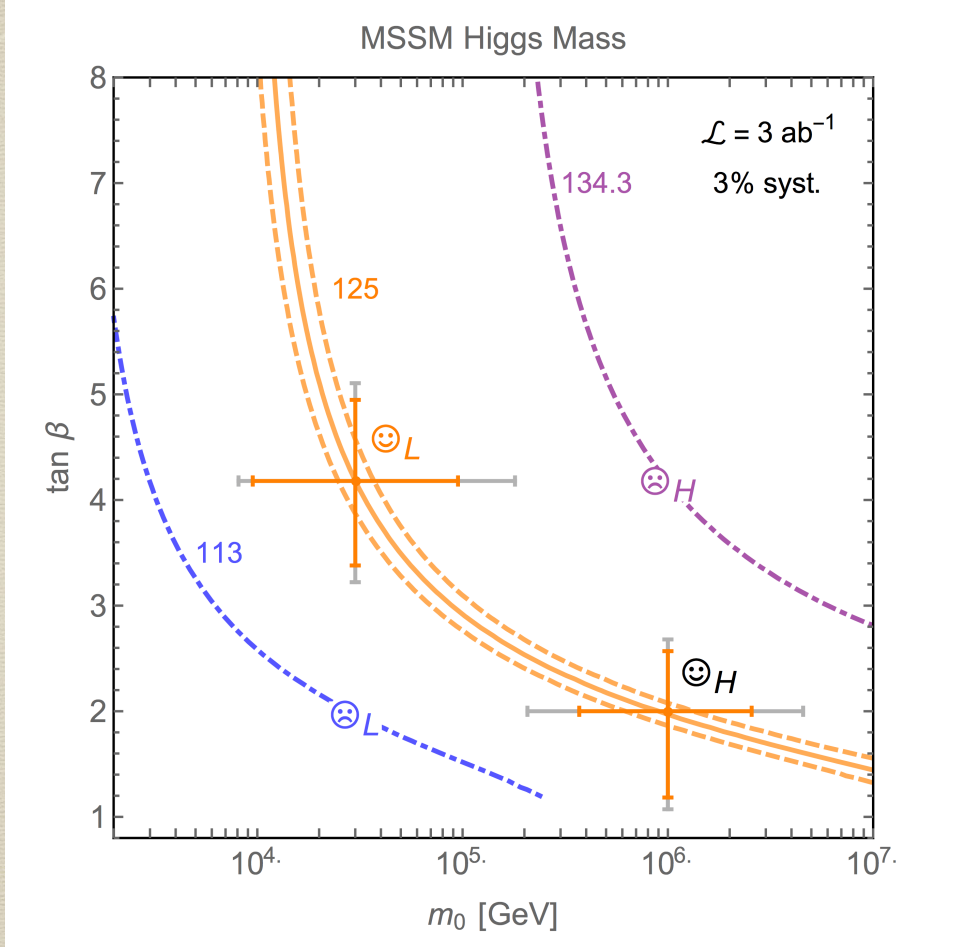




Cohen, D'Agnolo, Hance, Lou, Wacker 2014

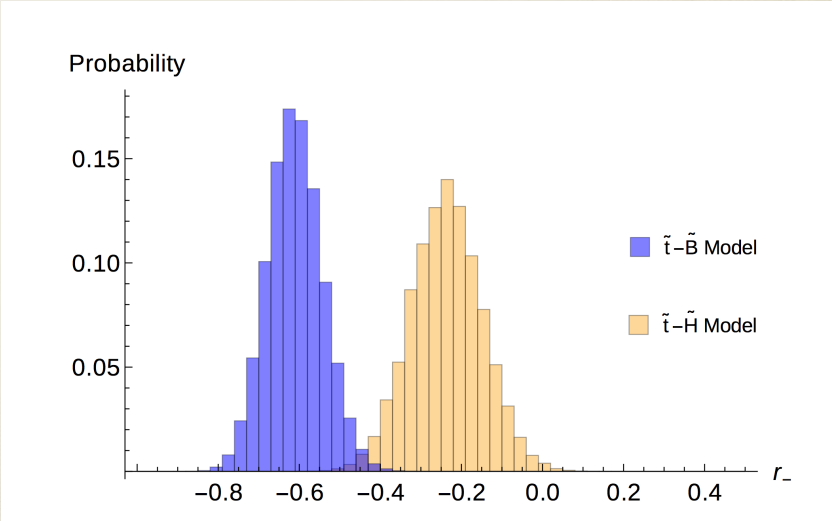
Dramatic Discovery Reach ~ 6 TeV stop! Exclude 8 TeV stops at 95%.
Probe electroweak fine tuning ~ 3000.
(But need to improve compressed spectrum reach!)

Use gluino decay branching ratios to test the MSSM explanation of the Higgs mass



Agrawal, Fan, Reece, Xue 2017

Ideal playground to apply jet substructure tools to discover and distinguish new physics models



Fan, Jaiswal, Leung 2017

Conclusion

No conclusion, keep exploring!

Thank you!