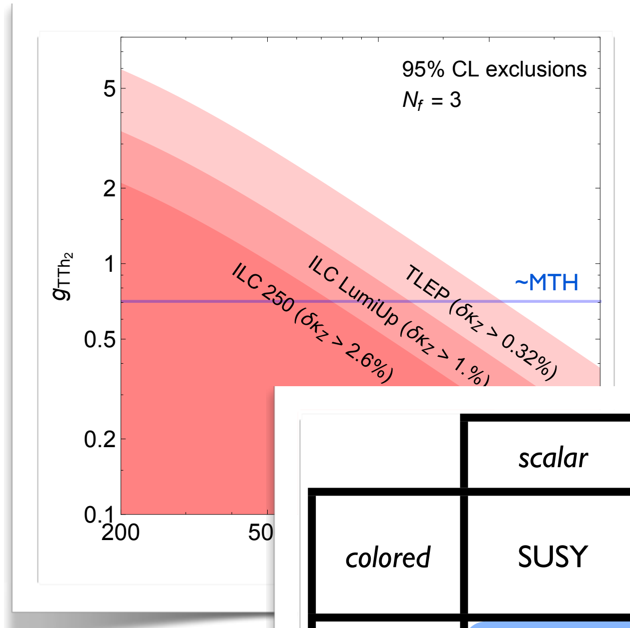
Probing Colorless Naturalness

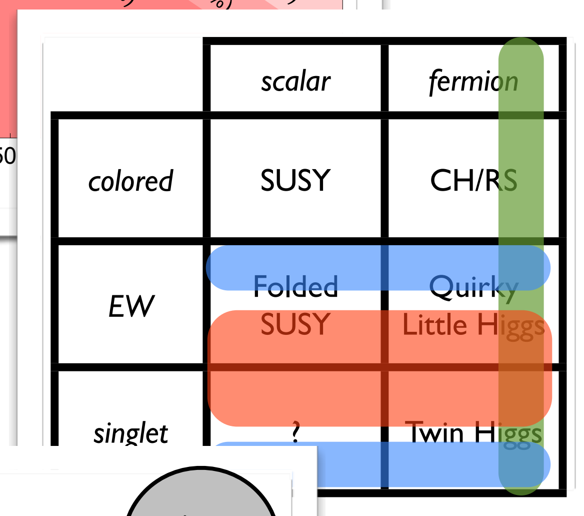
CERN-CKC Theory Institute on
Neutral Naturalness

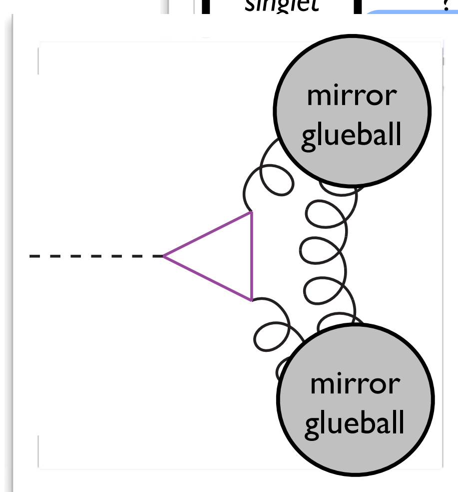
CERN, Geneva
27 April 2015

David Curtin
University of Maryland

based on
DC, Verhaaren [in preparation]
DC, Saraswat, Sundrum [in preparation]







Solving the Hierarchy Problem

Classic Approach: some continuous symmetry (SUSY or shift) protects the Higgs mass. Leads to new colored states ~ TeV.

New(ish) Possibility:* continuous ⊗ discrete symmetry, with only even states in low-energy spectrum. Top Partners without color charge!

See many talks at this workshop for model details.

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

Very rich world of models, which we are still exploring.
$\Rrightarrow$ Old theory biases have to go!

Need a new way to organize our thinking about phenomenology of naturalness.

Bottom-Up Phenomenology

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 will organize low-energy signatures of naturalness into a clear pattern.

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

Other important considerations:

Structure of hidden sector? (Mirror QCD? Glueballs?)

Scale of UV completion?

hep-ph/0506256 Chacko, Goh, Harnik
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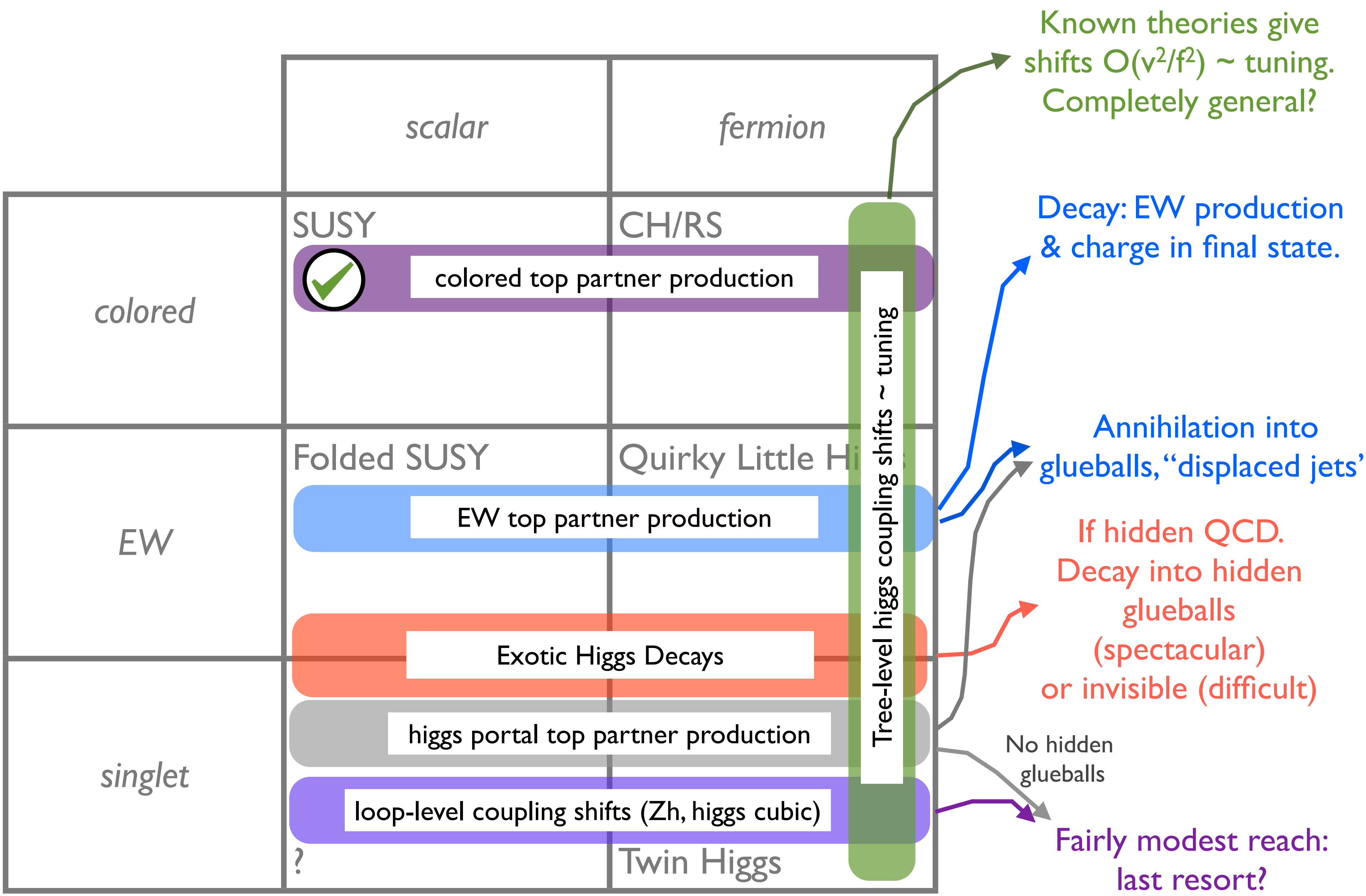
Bottom-Up Phenomenology

- We want to think about the bare-bones signatures of uncolored naturalness as model-independently as possible.
- Concentrate on the signatures due to top partners. Other aspects of the theories will also produce signatures (1,2 gen, EWPO of full hidden sector, etc..)
- Structure of hidden sector will have important consequences. Hidden QCD' is theoretically motivated, reduces tuning (higher Λ_{UV}). In absence of light QCD' matter get *hidden glueballs!*
- Think about signatures in the context of future collider capabilities. What can humanity probe in a lifetime?

Bottom-Up Phenomenology



Bottom-Up Phenomenology

Always some signatures.

Can gain further insight by splitting discussion according to structure of hidden sector.

Hidden QCD with Glueballs

Hidden QCD

Almost all theories with uncolored top partners feature an gauge symmetry G, which is broken at some multi-TeV scale

$$G \rightarrow G_1 \otimes G_2 \otimes Y$$

where

$G1 \supset$ 'our' $SU(3)_{cA}$,

$G2 \supset$ 'mirror' $SU(3)_{cB}$,

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....

Y is a discrete symmetry which ensures that top (sector A) and top partner (sector B) quadratic m_h^2 corrections cancel.

This mirror QCD is also preferred in the presence of any (discrete) symmetry which relates the higgs couplings of the top and a top partner. Without mirror QCD, RG effects in the hidden sector impose at least ~10% tuning.

1501.05310 Craig, Katz, Strassler, Sundrum

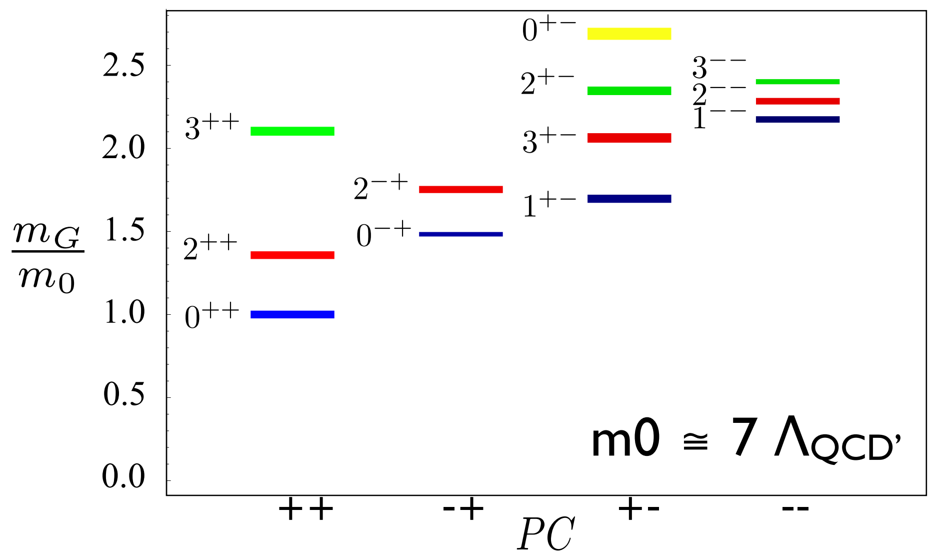
Hidden QCD with Glueballs

The most general hidden sector is some hidden valley with baryons at the bottom of the spectrum.

However, if the hidden sector shares SM EW charge, then no states lighter than ~100 GeV can exist (LEP).

If $g_{3A} \sim g_{3B}$ and there are is no light hidden matter
$\Rrightarrow$ glueballs of mirror QCD are the lightest states in mirror sector!

Spectrum of pure SU(3) known to ~10% from lattice studies. Can calculate some glueball decays, including the lightest state 0^{++}.



hep-lat/9901004 Morningstar ; 0903.0883 Juknevich, Melnikov, Strassler; 0911.5616 Juknevich

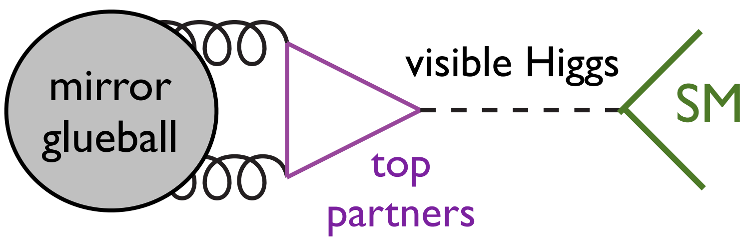
Hidden QCD with Glueballs

0903.0883 Juknevich, Melnikov, Strassler; 0911.5616 Juknevich

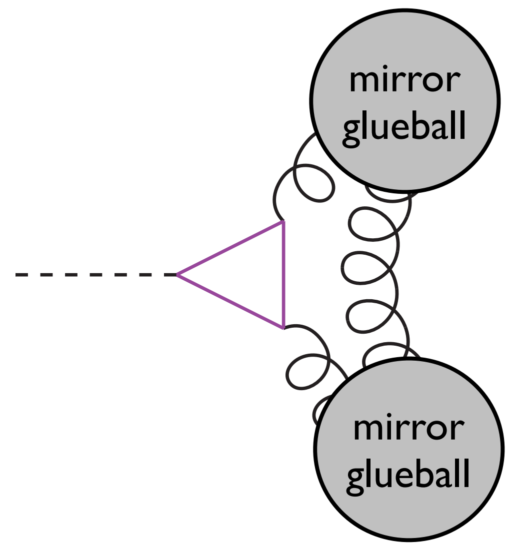
Top partners connect our Higgs sector to the mirror QCD:

$$\mathcal{L}^{(6)} = \frac{\alpha_v\, y^2}{3\pi\, M^2} H^\dagger H \,\mathrm{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}$$

Glueballs mix with the Higgs via top partner loop.
Will decay back to SM!



The Higgs can also decay to these glueballs:
exotic displaced decays!



Key signature of uncolored naturalness!

1501.05310 Craig, Katz, Strassler, Sundrum

Hidden QCD with Glueballs

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

These models are guaranteed* to have glueballs.

These models *could* have hidden glueballs (e.g. MTH) but don't *have* to.

MTH: 1501.05310 Craig, Katz, Strassler, Sundrum

Mirror glueballs lead to two important signatures:
- exotic higgs decays to glueballs
- annihilation of produced top partners into glueball jets

Hidden QCD with Glueballs

	scalar	*fermion*
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Investigate these benchmark models.

These models are guaranteed* to have glueballs.

These models *could* have hidden glueballs (e.g. MTH) but don't *have* to.

MTH: 1501.05310 Craig, Katz, Strassler, Sundrum

Mirror glueballs lead to two important signatures:
- exotic higgs decays to glueballs
- annihilation of produced top partners into glueball jets

Benchmark Models

Folded SUSY

Twin Higgs

EW-charged uncolored stops

SM-singlet fermionic top partners

$$m_T = m_t \cot\left(\frac{1}{\sqrt{2}}\frac{v}{f}\right)$$

$$\mathcal{L}^{(6)} = \frac{\alpha_v\, y^2}{3\pi\, M^2} H^\dagger H \,\mathrm{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}$$

$$\frac{y}{M} = \frac{1}{2\sqrt{2}}\,\frac{m_t}{v\ m_{\tilde{t}}}$$

(for ~ degenerate stops)

$$\frac{y}{M} = \frac{1}{2}\,\frac{m_t}{v\ m_T}$$

Glueball properties given by two parameters:
0^{++} mass m_0 and top partner mass(es) "M"

DY stop production

Higgs Portal top partner production

Quirky Little Higgs: same higgs coupling as TH, but with DY T production.

Benchmark Models

Folded SUSY

EW-charged uncolored stops

Twin Higgs

SM-singlet fermionic top partners

$\left(1 \quad v \right)$

Can serve as placeholders for general uncolored top partner theories by imagining different top partner charges.

Glueball properties given by two parameters:
0^{++} mass m_0 and top partner mass(es) "M"

DY stop production

Higgs Portal top partner production

Quirky Little Higgs: same higgs coupling as TH, but with DY T production.

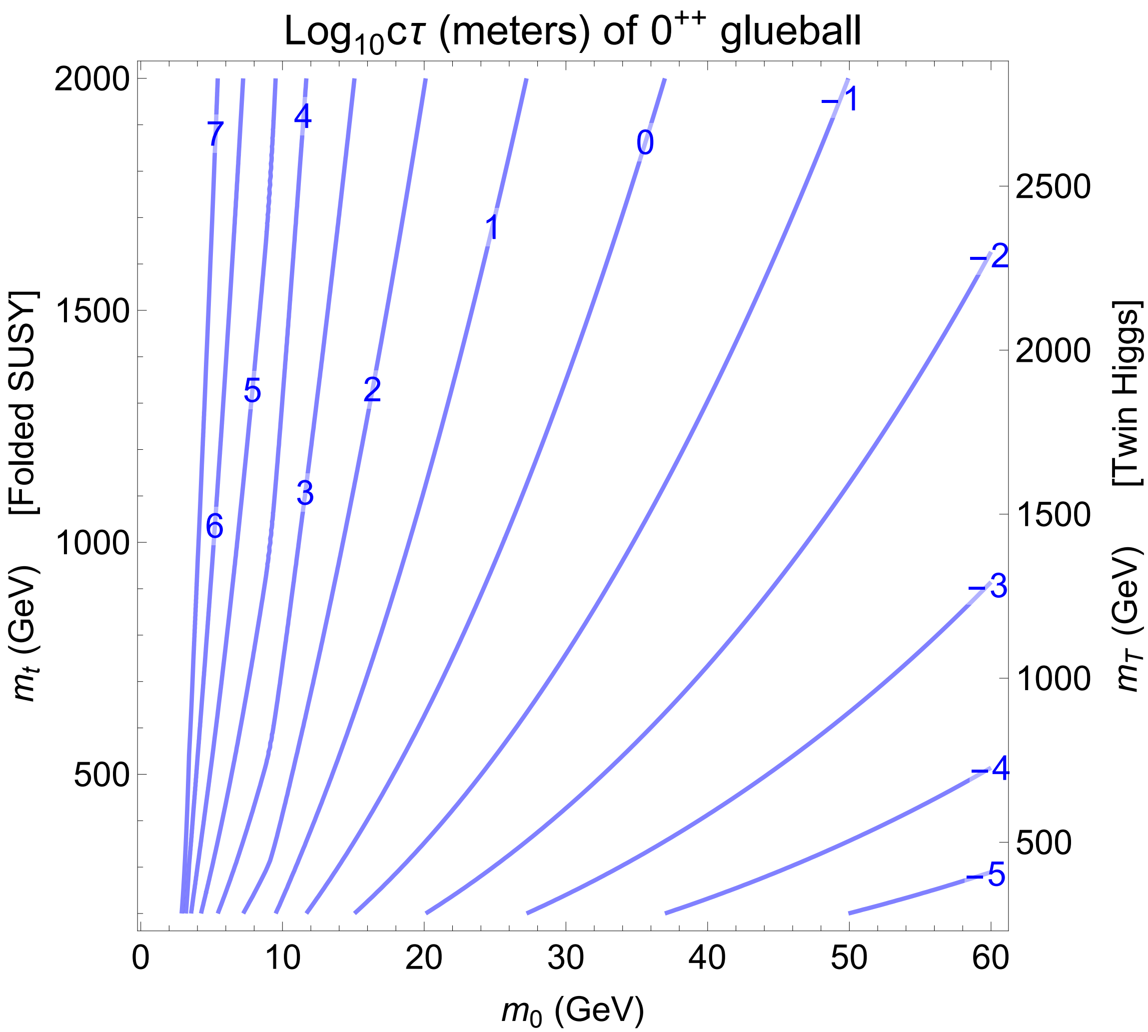
Hidden QCD with Glueballs

Exotic Higgs Decays

Properties of Mirror Glueballs

Glueball Lifetime

0911.5616 Juknevich



Only consider lightest glueball state with mass m_0.

Displaced decays at colliders!

Properties of Mirror Glueballs

Glueball Spectrum

To estimate the plausible range of glueball masses:

Assume QCD = QCD' at some multi-TeV scale.

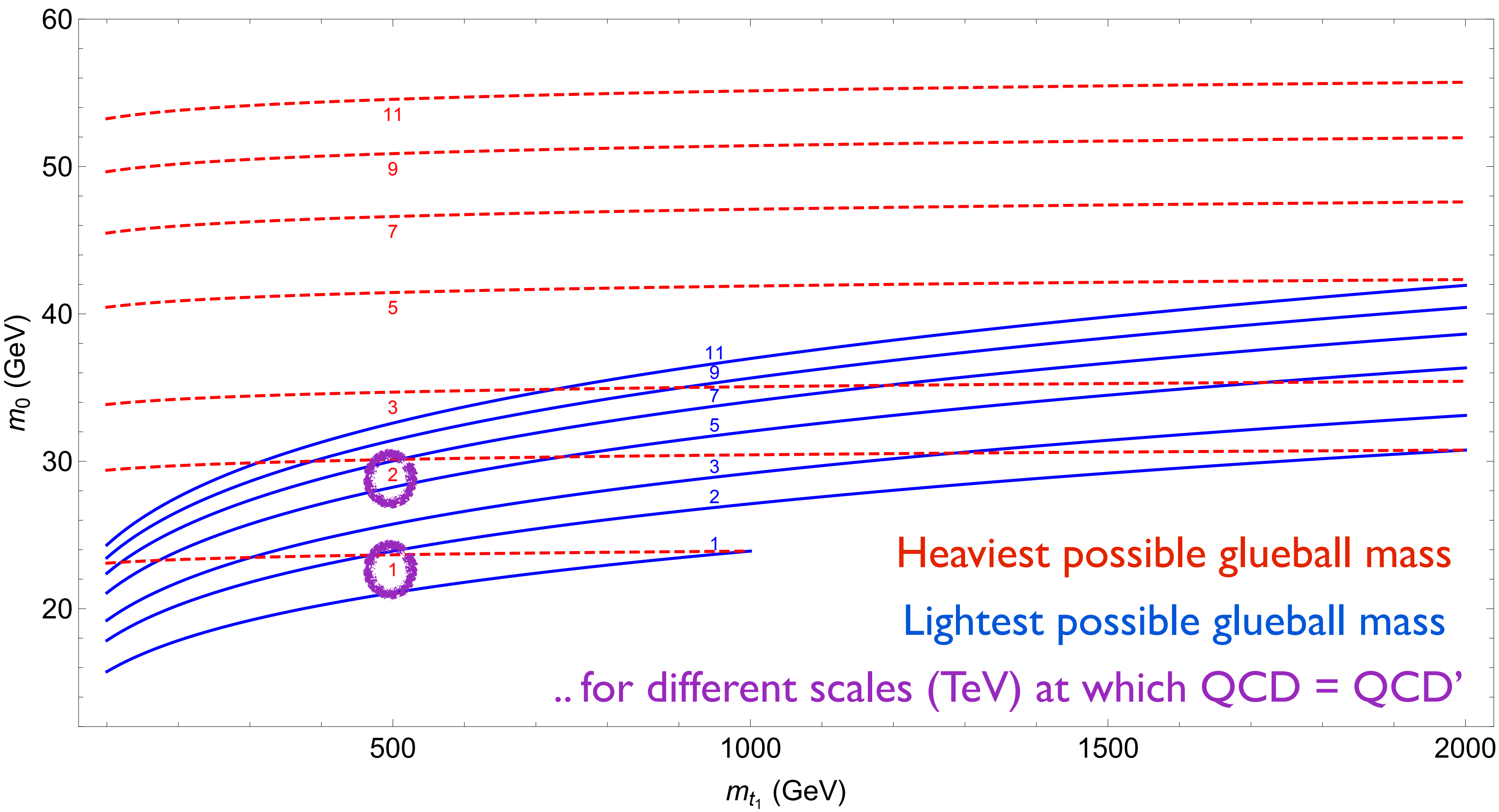
Evolve $\alpha_{QCD'}$ to find $\Lambda_{QCD'} \sim m_0/7$.

More QCD' matter gives lighter glueballs.

Evolve with 'lightest' and 'heaviest' hidden spectra to get m_0 range as function of lightest hidden sector particle.

Properties of Mirror Glueballs

Glueball Spectrum Folded Susy



plausible 0^{++} mass range ~ 15 - 55 GeV

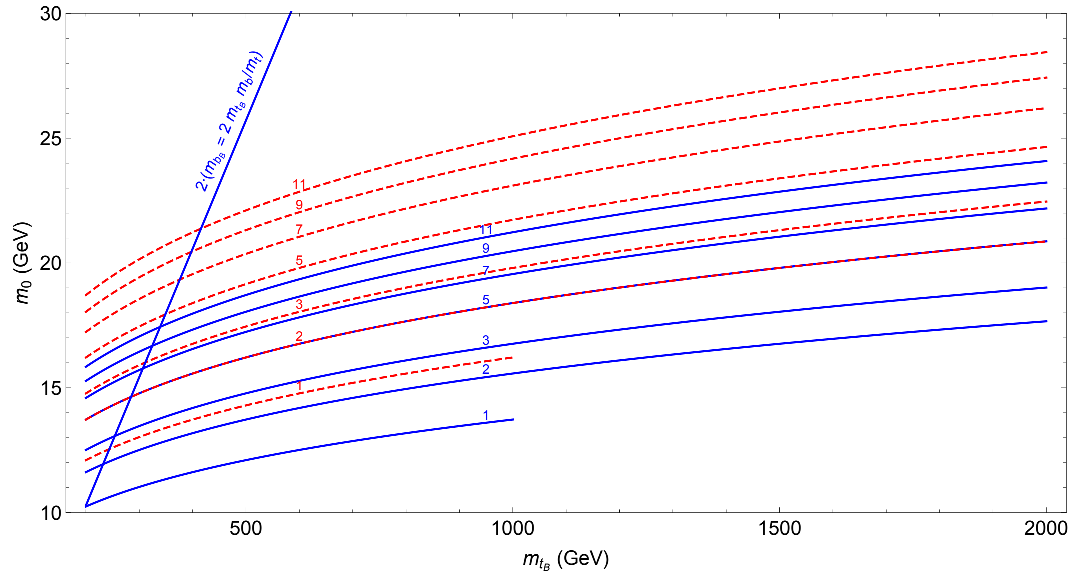
Properties of Mirror Glueballs

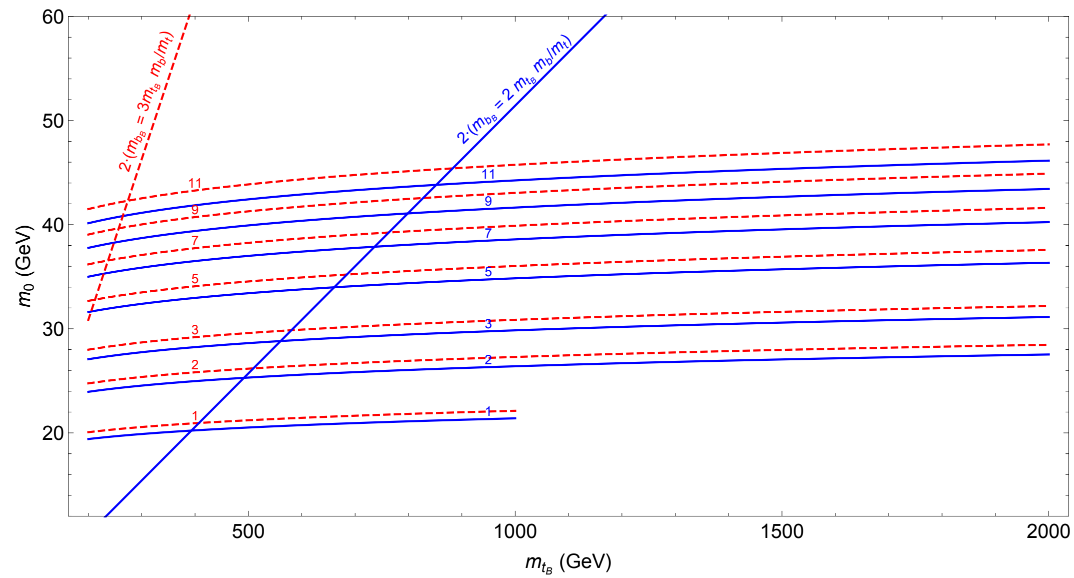
Glueball Spectrum Twin Higgs

Glueballs in TH require mirror symmetry to be broken.

Different possibilities: heavy 1,2 gen, or all gens close to bottom.

plausible 0^{++} mass range ~ 10 - 45 GeV





Properties of Mirror Glueballs

Glueball Spectrum   Twin Higgs

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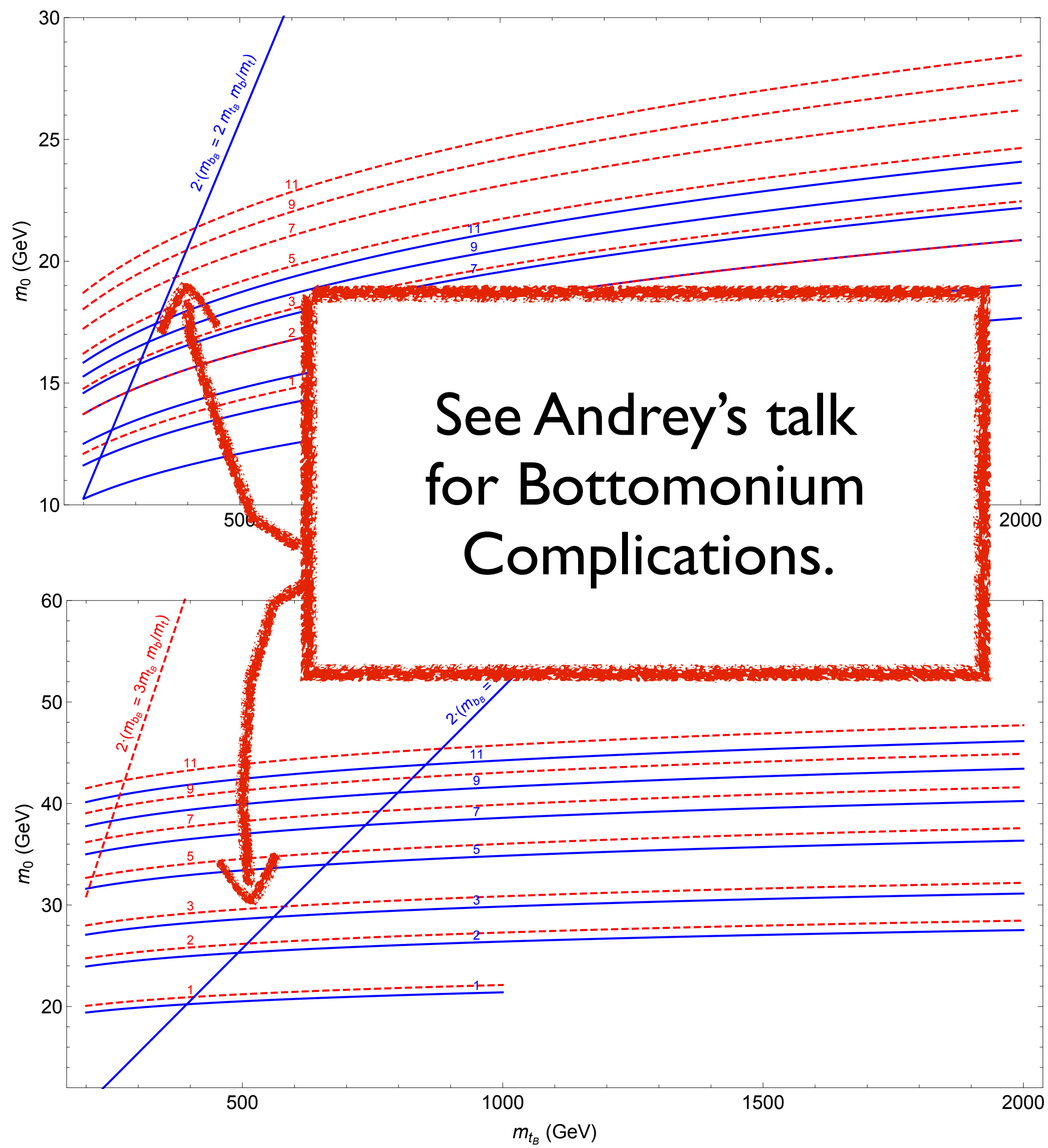


See Andrey's talk for Bottomonium Complications.

Properties of Mirror Glueballs

Summary

Plausible hidden sector with UV-completion scales up to ~10 TeV give glueball masses in 10 - 60 GeV range.

Lifetimes of those glueballs are are μm - km.

⇛ **Spectacular Exotic Higgs Decays!**

Exotic Higgs Decays

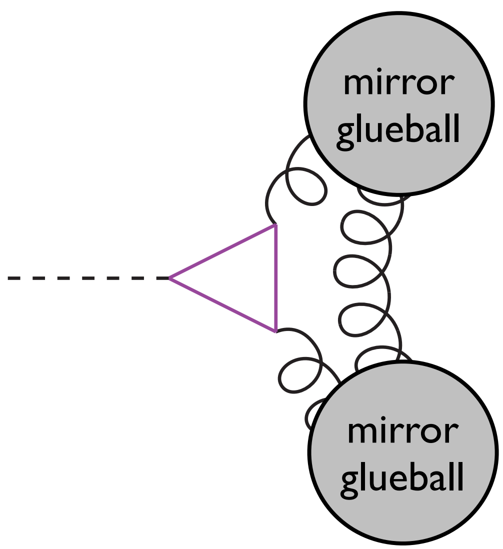
Can use SM Br($h \to gg$) ~ 8% to *estimate* $h \to 0^{++}0^{++}$.

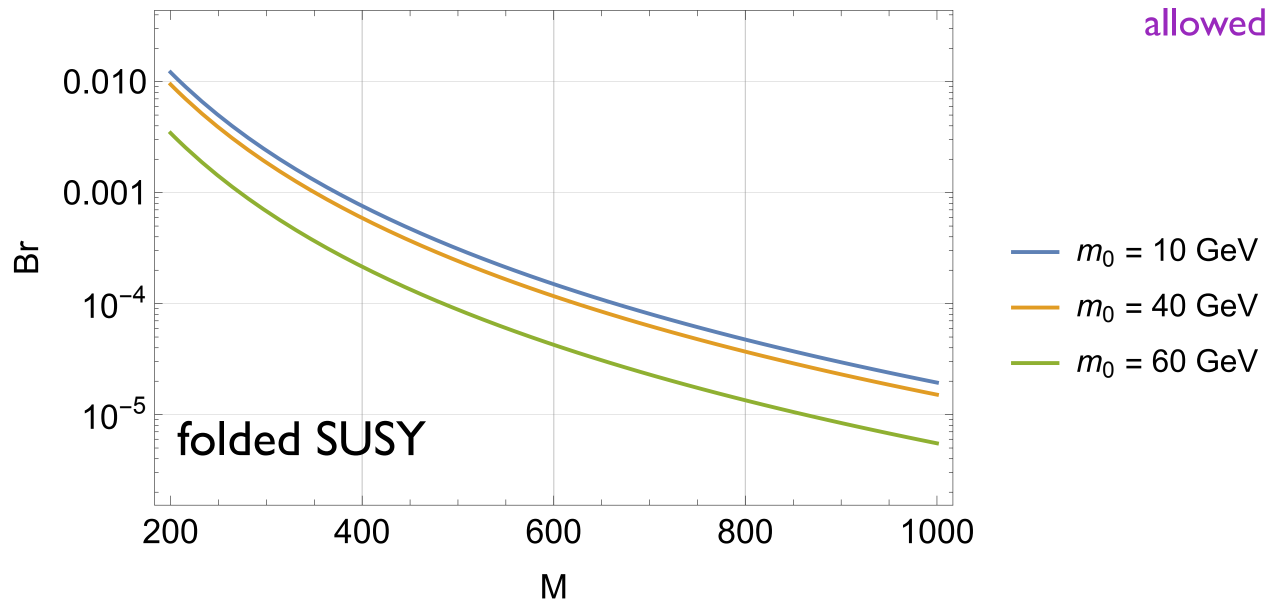
For the spectra we consider, $1.05 \lesssim \dfrac{\alpha_{\mathrm{QCD}'}(m_h)}{\alpha_{\mathrm{QCD}}(m_h)} \lesssim 1.5$

so to be slightly pessimistic set $\alpha_{\mathrm{QCD}'} = \alpha_{\mathrm{QCD}}$.

$$\mathrm{Br}(h \to 0^{++}0^{++}) \approx \mathrm{Br}(h \to gg) \;\times\; \left(4v^2 \, \frac{y^2}{M^2}\right)^2 \times \sqrt{1 - \frac{4m_0^2}{m_h^2}}$$

Assume 0++ always preferred. Modest reduction in Br if all glueball final states are allowed.)





Recall HL-LHC will make ~ 10^8 Higgses.

Exotic Higgs Decays

Estimate expected signal yield of

$h \to 0^{++}\, 0^{++} \to 4b$ (displaced)

For displaced decays, backgrounds very minor.

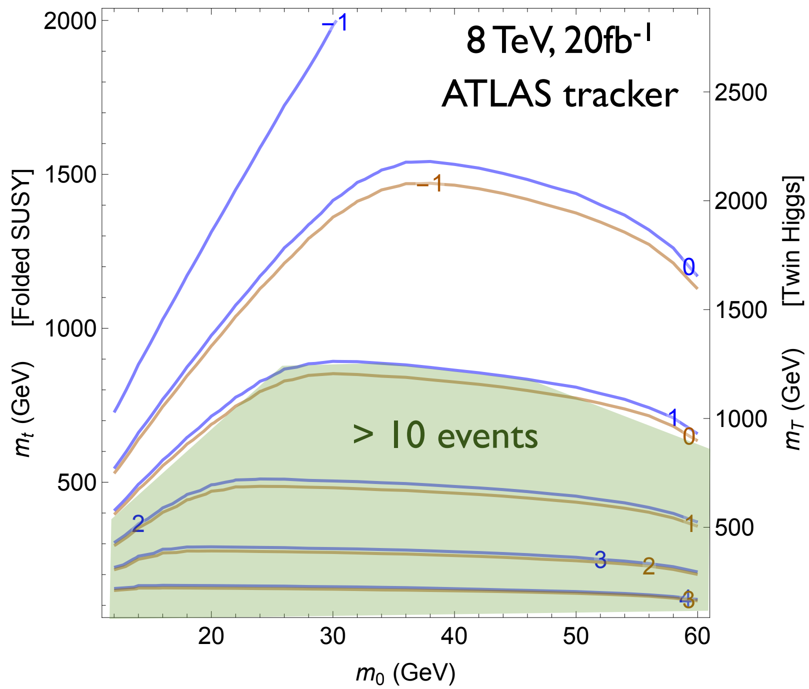
Signal yield will give good idea of sensitivity.*

*Triggers!?

To estimate signal at LHC, HL-LHC and 100 TeV pp collider:

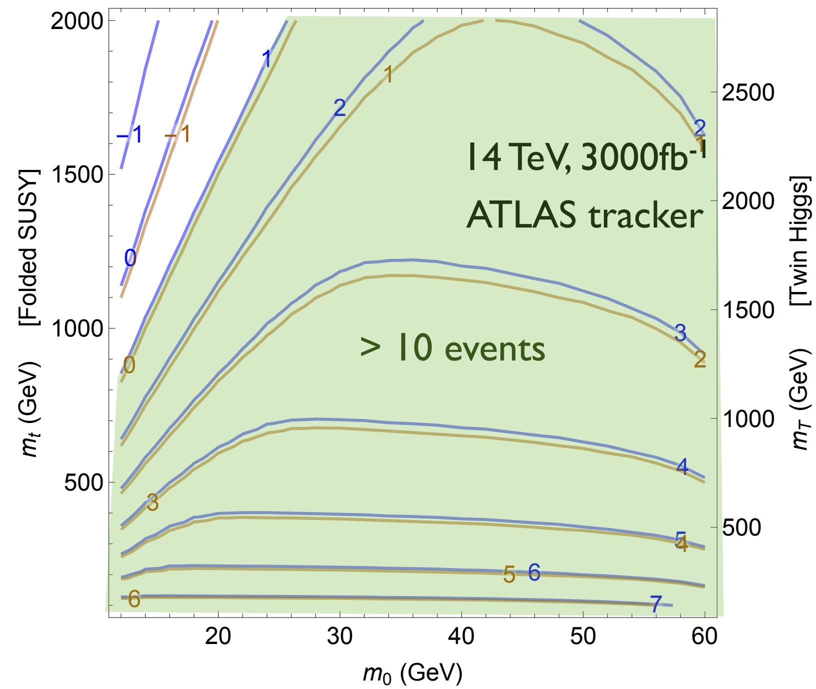
- in MG + Pythia + PGS, simulate $pp \to h + X$, with $h \to ss \to 4b$.
  - ⇛ correctly captures kinematics of h → glueballs → SM
  - ⇛ Use detector-objects from PGS to compute efficiency of various triggers.
- Use known NLO higgs xsec, Br(h→glueballs), Br(glueball→bb) to get signal xsec.
- use truth-level info on s (glueballs) to find likelihood of decaying in given detector subsystem event-by-event.

Compare LHC, HL-LHC, 100 TeV signal in Tracker



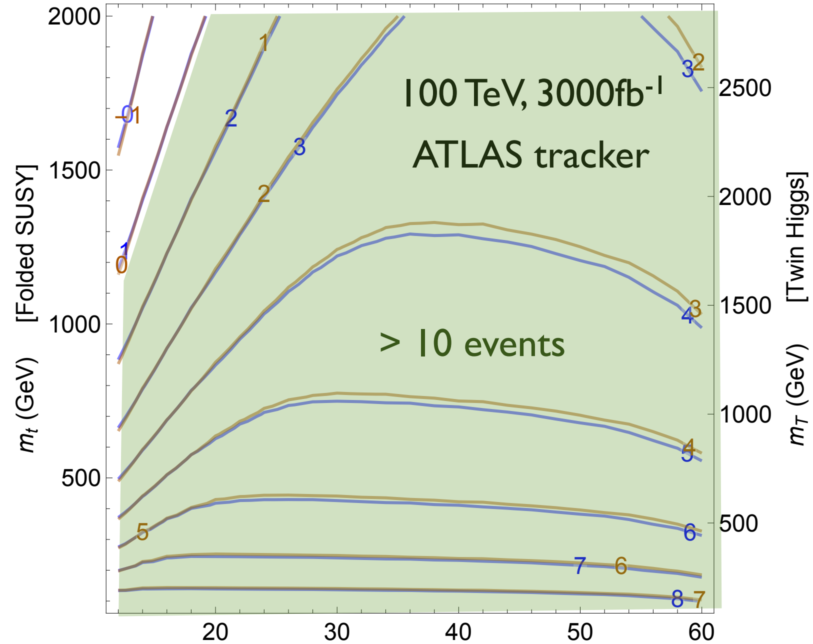
Log10N

ggF
VBF

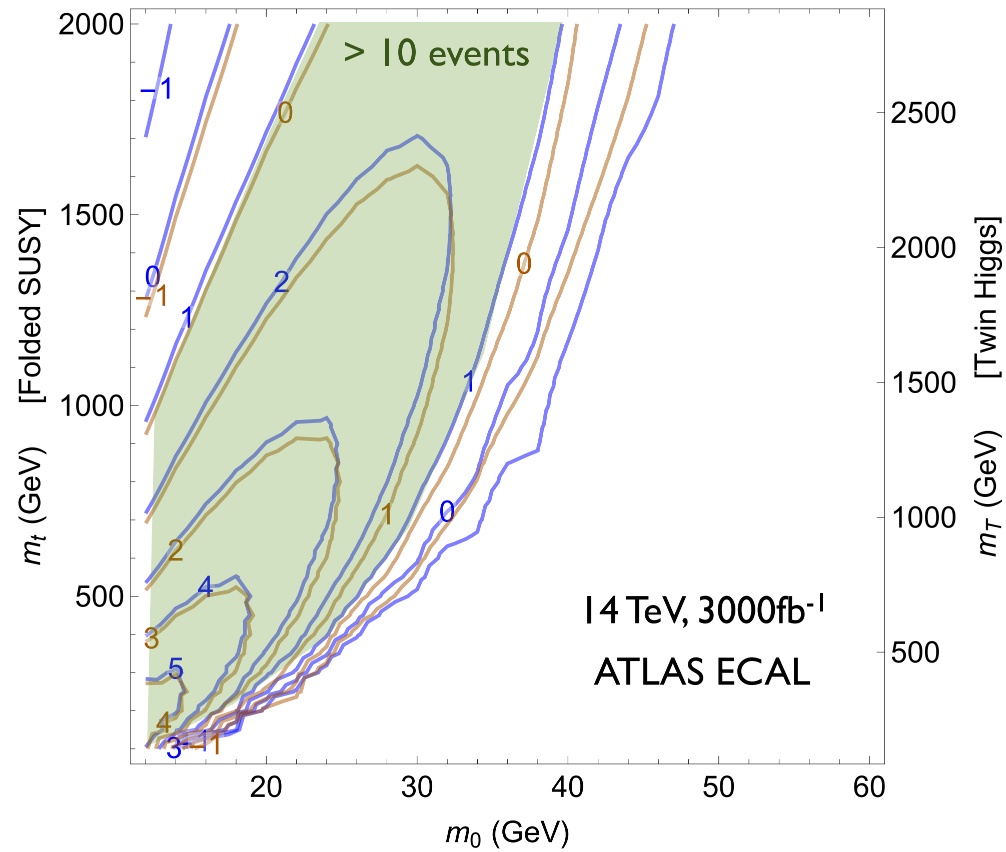


- LHC8 might be sensitive to 200 GeV top partners.
- HL-LHC will cover most of parameter space for M < 2 TeV.
- 100 TeV: M ~3 TeV?

Trigger?



What about other detector systems?

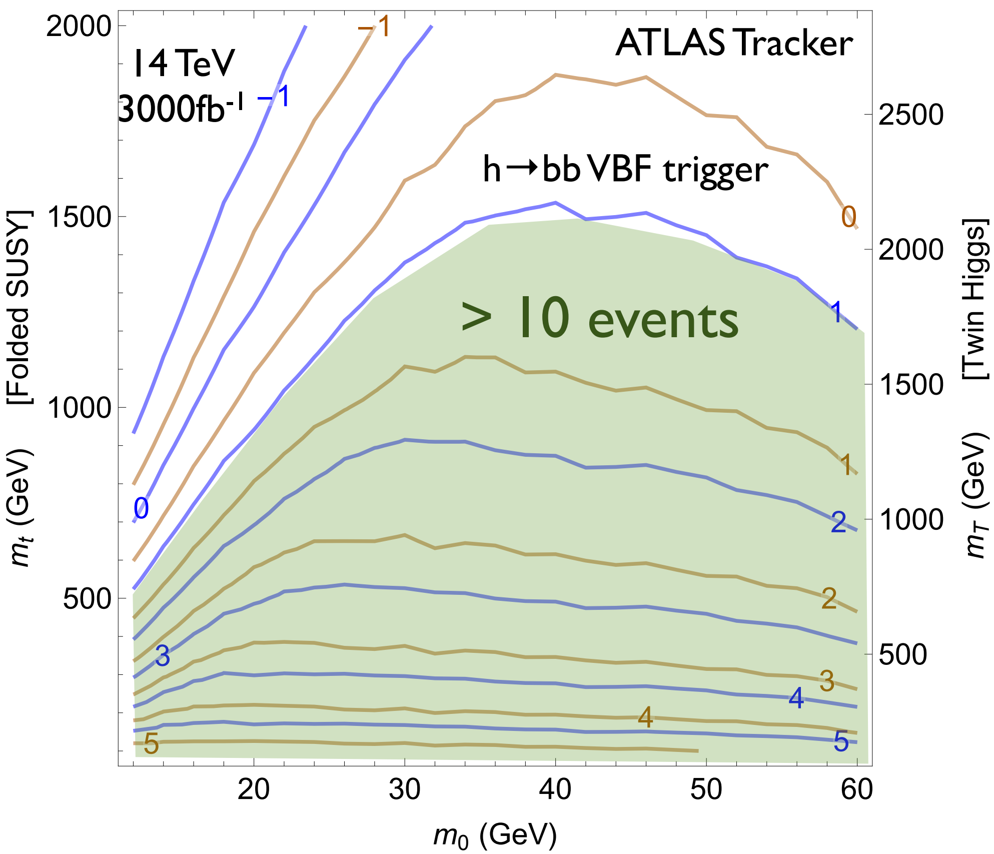


Loose a lot of sensitivity if we can't use decays in tracker!

How to trigger at LHC?

Triggering on Exotic Higgs Decays

Trigger	8 TeV	14 TeV
1 jet	$p_T^{j_1} > 180$ GeV	$p_T^{j_1} > 290$ GeV
inclusive VBF	$\lvert\eta_{j_1,j_2}\rvert > 2$ $\eta_{j_1}\eta_{j_2} < 0$ $\lvert\eta_{j_1} - \eta_{j_2}\rvert > 3.6$ $m_{j_1 j_2} > 600$ GeV	same $m_{j_1 j_2} > 1000$ GeV
$h \to \bar{b}b$ VBF	$p_T^{j_{1,2,3}} > (70, 50, 35)$ GeV $\lvert\eta_{j_{1,2,3}}\rvert < (5.2, 5.2, 2.6)$ $\lvert\eta_{j_1}\rvert$ or $\lvert\eta_{j_2}\rvert < 2.6$	$p_T^{j_{1,2,3}} > (112, 80, 56)$ GeV same



With VBF triggers, maintain sensitivity to ~ 1.5 - 2TeV top partners at HL-LHC

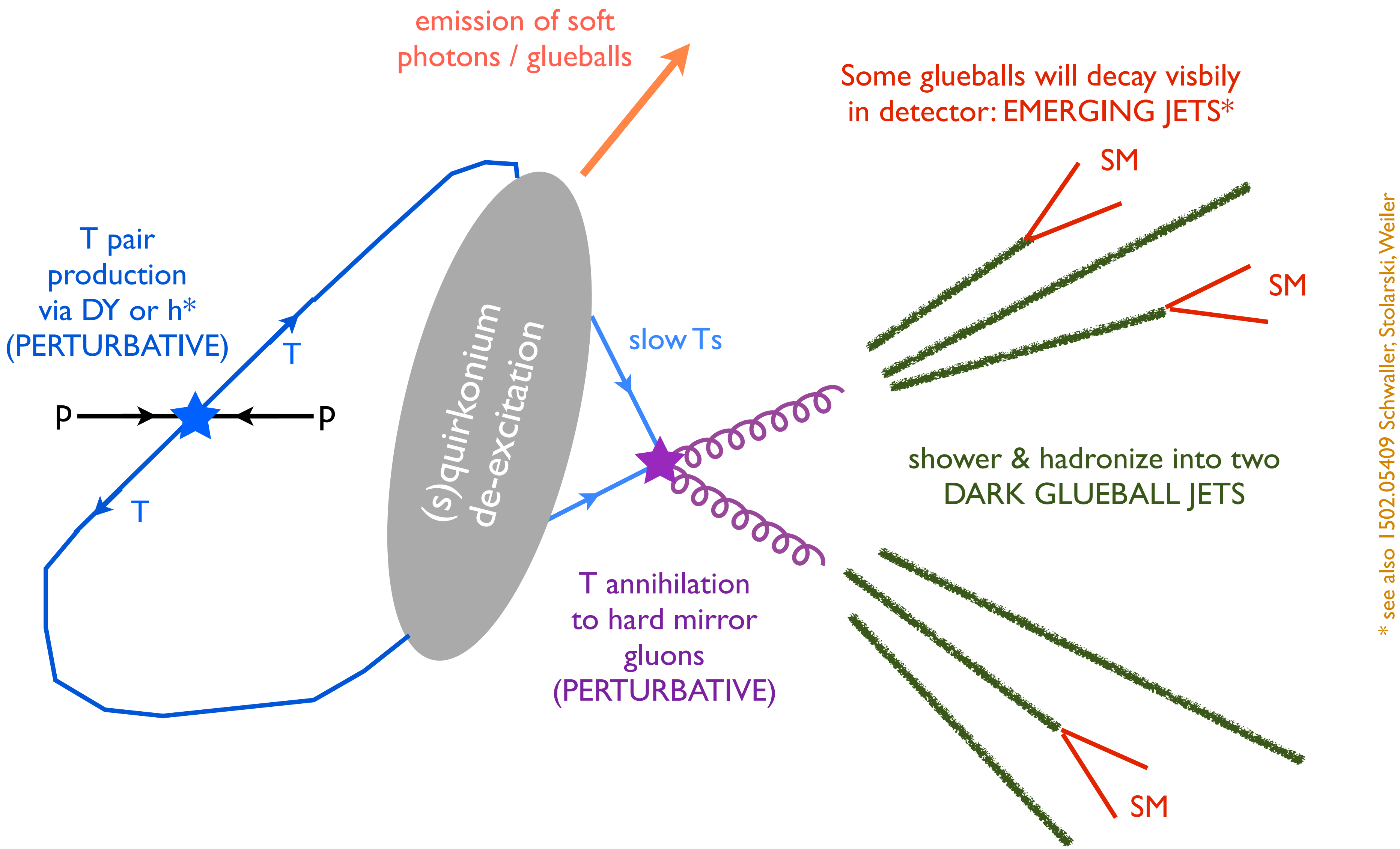
	scalar	*fermion*
colored	SUSY	CH/RS
EW	Folded SUSY	Quirky Little Higgs
singlet	?	Twin Higgs

Hidden QCD with Glueballs

Top Partner Annihilation

PRELIMINARY **PRELIMINARY**

Uncolored (s)quirkonium and Glueball Jets



This might allow measurement of top partner masses & couplings.

PRELIMINARY

Rough Signal Estimate

PRELIMINARY

- Many aspects of the process are calculable perturbatively
  - T pair production xsec via DY or h*
  - for given T velocity distribution, hard mirror gluon spectrum from annihilation
  - Ignore possible hard decays of T partners for now (OK in e.g. folded SUSY with t_l LSP)
- Can attempt to compute velocity spectrum after (s)quirkonium de-excitation, but process is poorly understood. But T's are non-relativistic when they annihilate, so don't need details for first estimate.
- Could parton shower mirror gluons in pure QCD, but 'hadronization' is completely unknown. For *first estimate*, assume average number of glueballs per dark jet is **$\langle N_{GB} \rangle = 1/2\ m_T/m_0$**.
- For a single glueball, we can estimate chance of detection as

$$\xi_{\mathrm{GB}} = r_{0^{++}} \times P_L \times \epsilon_{\mathrm{detect}}$$

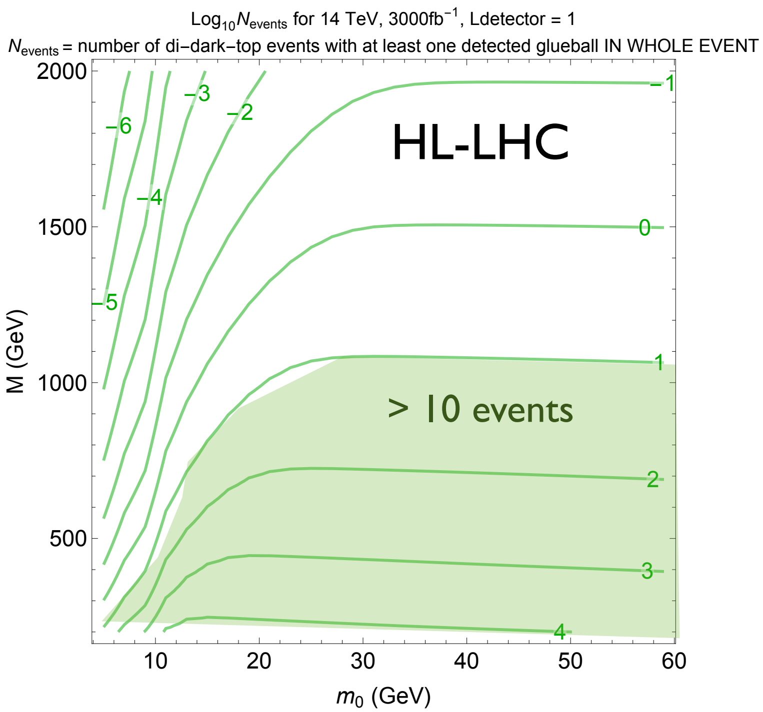
fraction of glueballs that are lightest state (~1/4)

Chance of decay within detector volume (boost ~ 1)

Efficiency of detecting decayed glueball (~ 1/2)

Can estimate number of T production & annihilation events with n detected glueballs per event or per 'dark jet'.

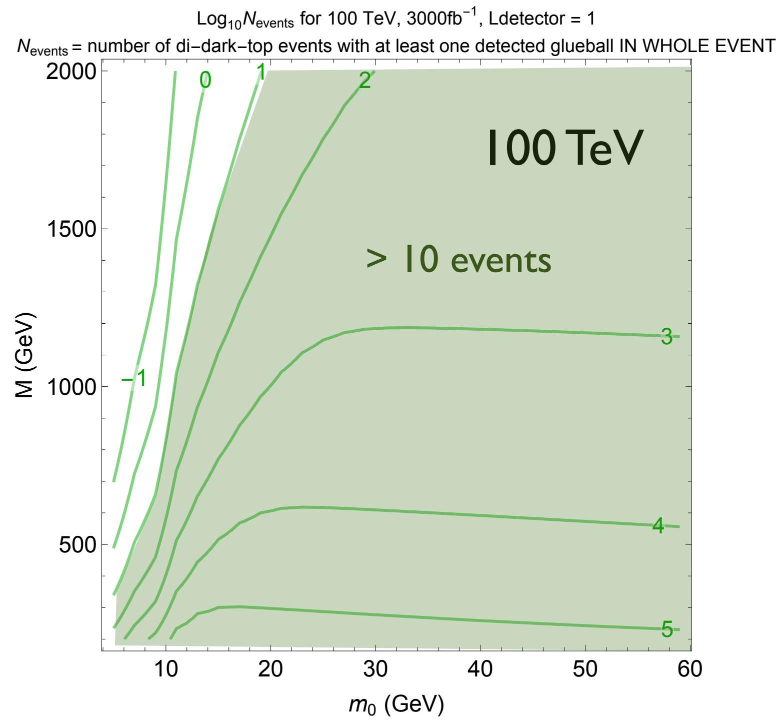
Scalar Top Partners: Detection

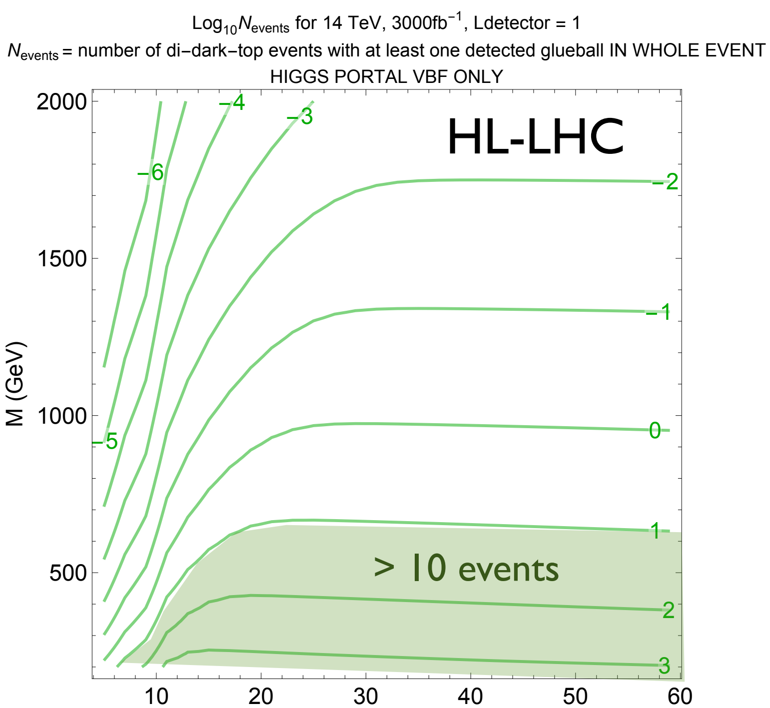


DY production
one detected
glueball
per event.

reach (N>10):
1 TeV @ HL-LHC
2+ TeV @ 100 TeV

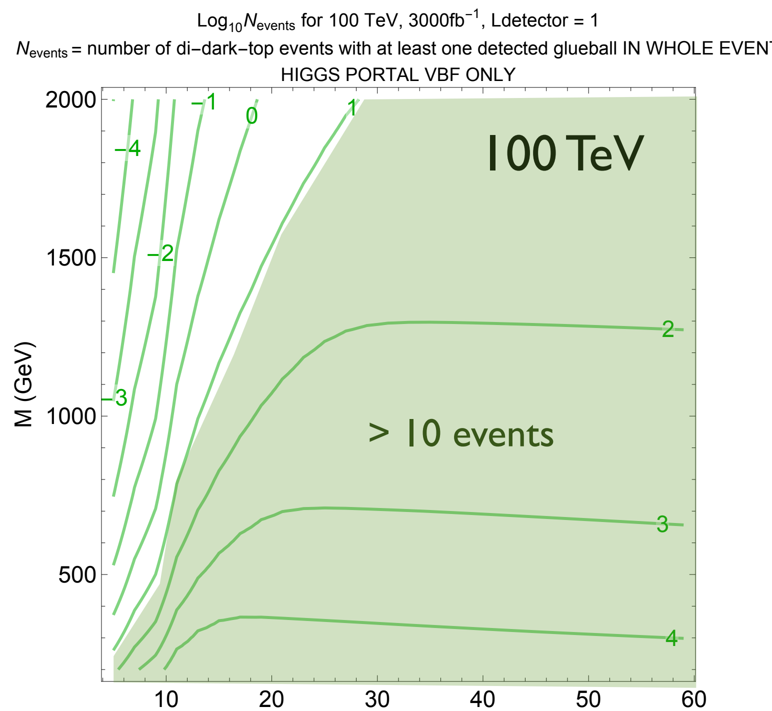
TRIGGER?



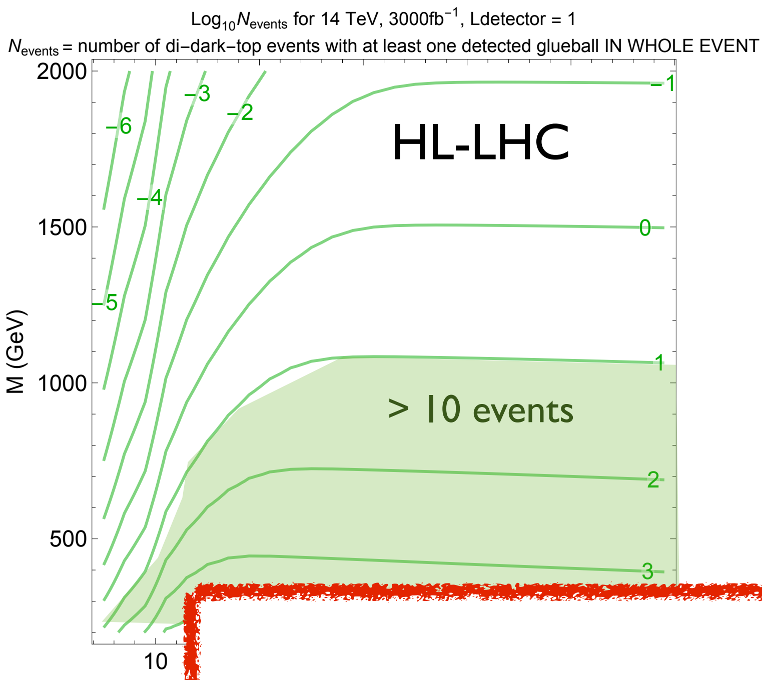


h* + VBF production
one detected
glueball
per event

reach (N>10):
0.6 TeV @ HL-LHC
2+ TeV @ 100 TeV



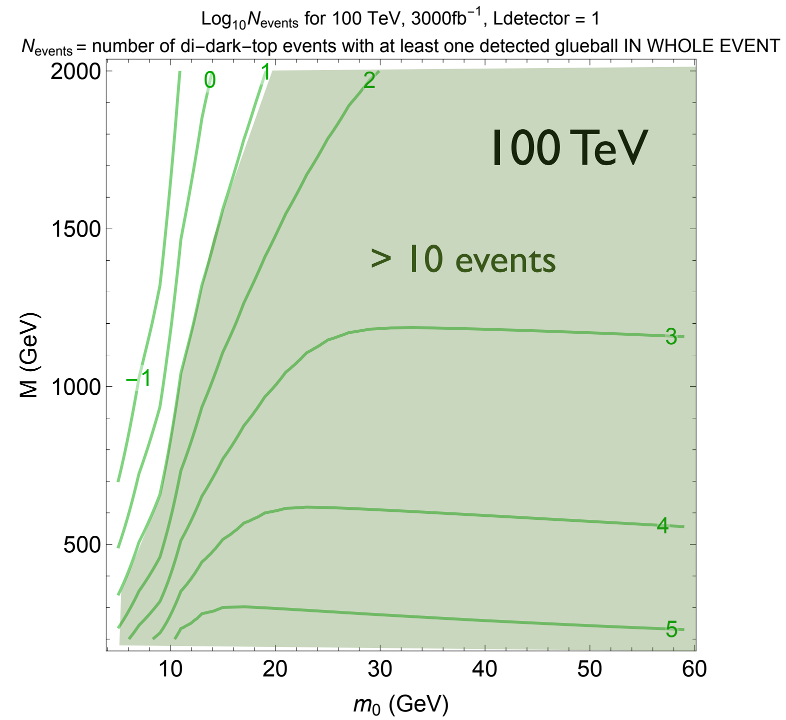
Scalar Top Partners: Detection



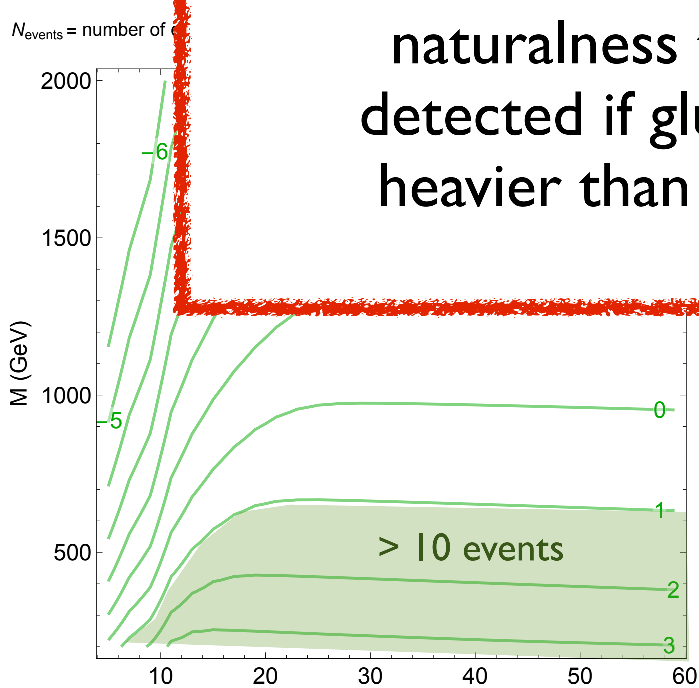
DY production
one detected
glueball
per event.

reach (N>10):
1 TeV @ HL-LHC
2+ TeV @ 100 TeV

ER?



Also allows colorless
naturalness to be
detected if glueballs
heavier than $m_h/2$!



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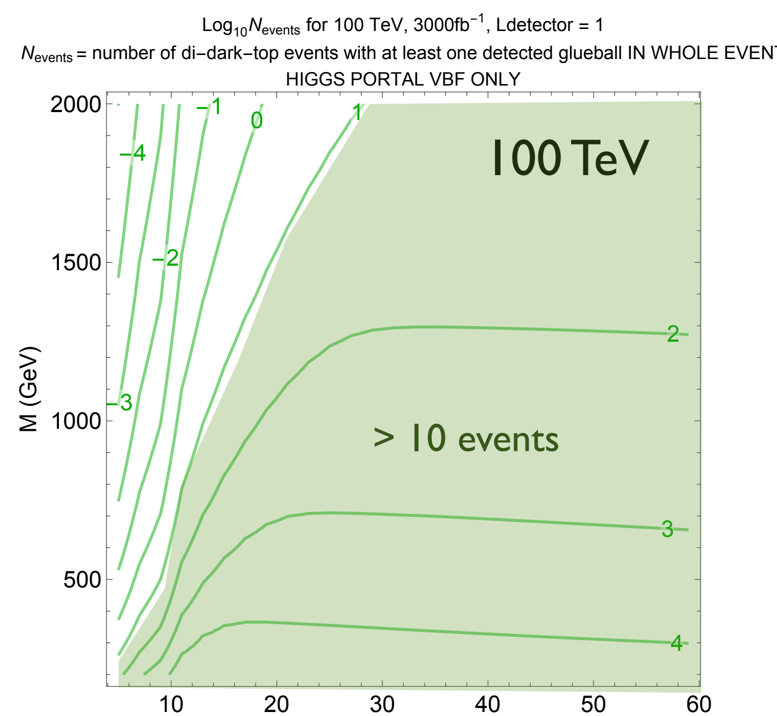
ll
per event

reach (N>10):
0.6 TeV @ HL-LHC
2+ TeV @ 100 TeV



Measurement

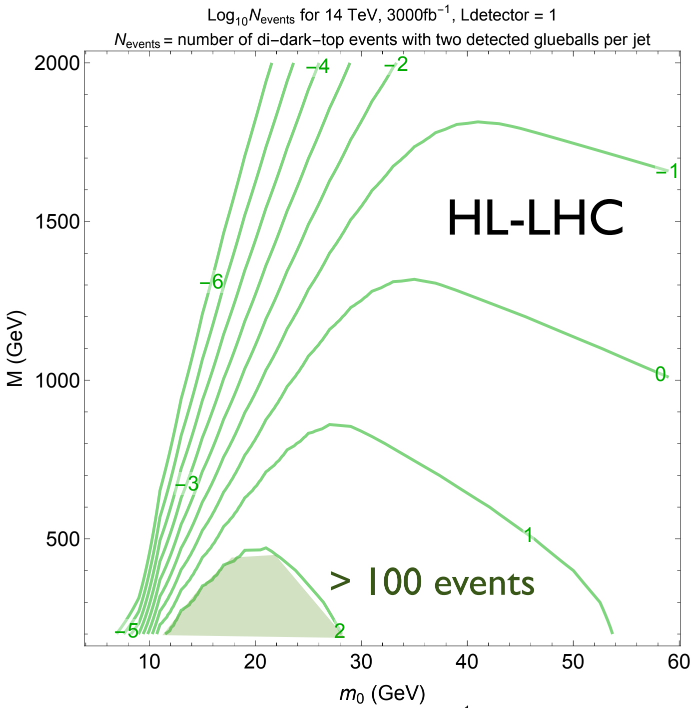
- Annihilation into dark glueball jets allows top partner masses to be measured:
  - Treat glueball jets as 'displaced jets' with unknown (but, on average, constant) fraction of 'hadrons' being invisible.
  - Measure missing fraction event-by-event using ISR pT, then reconstruct missing jet 4-momenta and **measure T mass** (with enough statistics)
  - Could also use MET & other kinematic methods see e.g. 1503.0009 Cohen, Lisanti, Lou

- If T partners undergo visible beta-decay before annihilation, lepton spectrum could reveal more information about hidden sector spectrum.

- In principle, with known T-partner masses and known glueball mass, Br($h \to$glueballs) reveals T-partner coupling to Higgs.

If we're lucky, we might be able to experimentally verify the cancellation of higgs mass quadratic divergences.

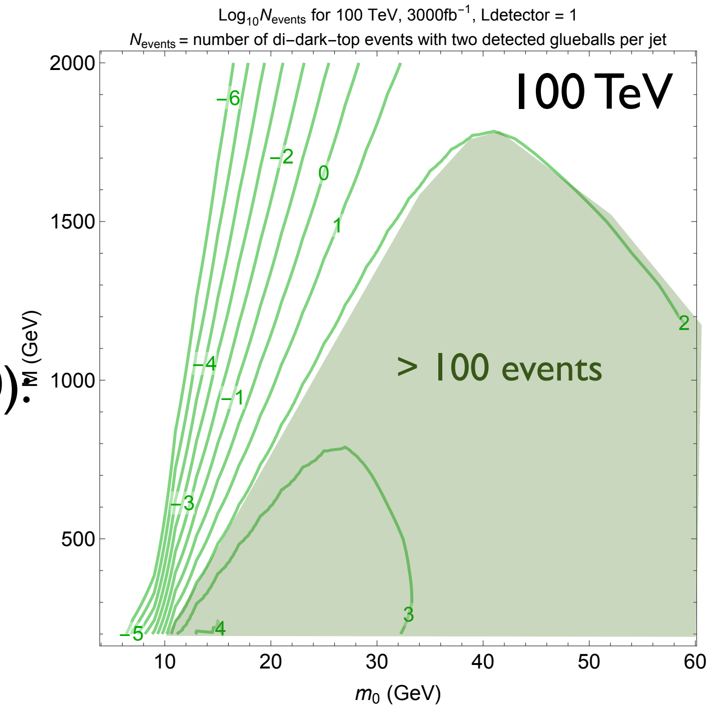
Scalar Top Partners: Measurement

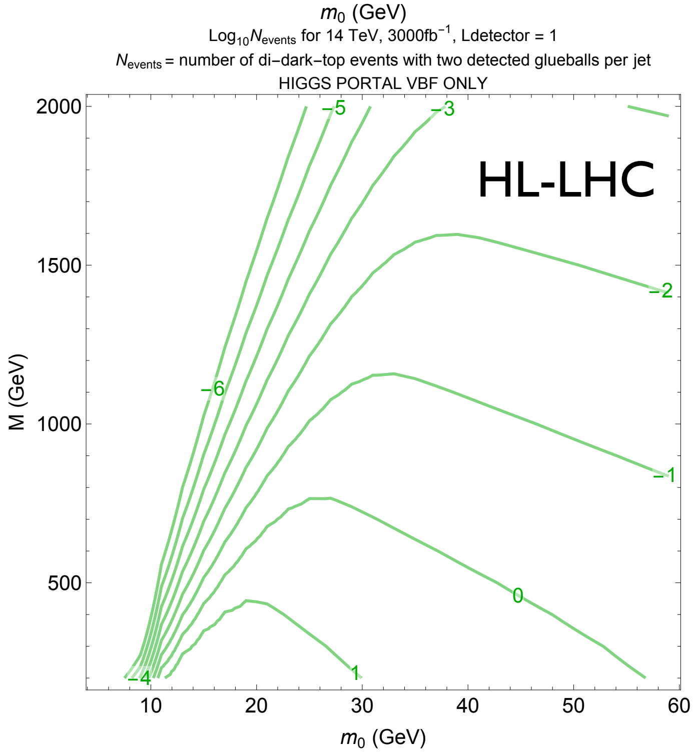


DY production
two detected
glueballs
per dark jet.

measurement (N>100):
0.5 TeV @ HL-LHC
1.7 TeV @ 100 TeV

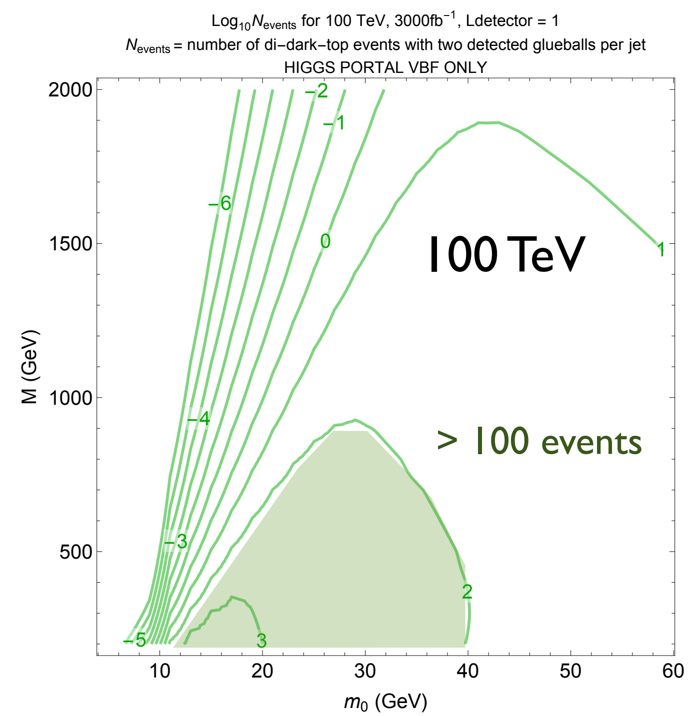
TRIGGER
should be ok





h* + VBF production
two detected
glueballs
per dark jet.

measurement (N>100):
--- @ HL-LHC
0.8 TeV @ 100 TeV



No Hidden QCD

No Hidden QCD

Without hidden QCD, most theories give UV completions that seem very accessible to a 100 TeV collider or even the HL-LHC.

e.g. 0808.1290 Thaler, Poland

Also, if top partners have EW charge, probably have multi-TeV reach due to DY production and EW charge in decay final state.

What about neutral top partners without hidden QCD?

What can we learn about such top partners, without assumptions about the UV completion or even IR-theory bias?

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

Tree-level higgs coupling shifts ~ tuning

higgs portal top partner production

coupling shifts (Zh, higgs cubic)

Some models here have exciting signatures (see e.g. Brian's talk), but we look at 'worst case scenarios' here.

No Hidden QCD

Neutral Scalar

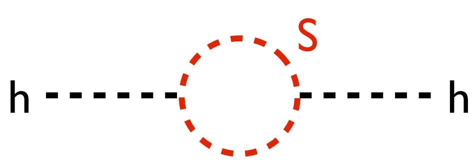
Top Partners

Neutral Scalar Top Partners

Imagine a set of (wlog real) scalars that solve the little hierarchy problem.

$$\mathcal{L} \supset -\frac{\lambda_i}{2}|H|^2 S_i^2 \qquad\qquad N_r \lambda = 12|y_t|^2$$

These scalars must have experimental consequences:

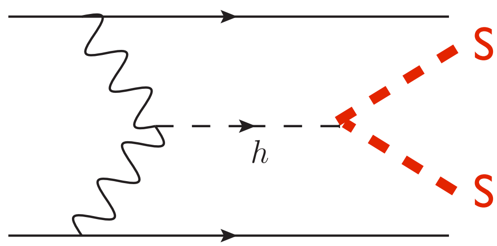


Craig, Englert, McCullough, 1305.5251

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

1310.8361 Snowmass Higgs Working Group Report
1312.4974 Peskin

	ILC	ILC Lumi Up	TLEP
excludable $\delta\sigma_{Zh}$	4%	2%	0.6%
m_S (GeV) for 12 real scalars (SUSY)	113	149	259



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

$N_r = 1$	625 GeV
$N_r = 2$	520 GeV
$N_r = 4$	430 GeV
$N_r = 8$	355 GeV
→ $N_r = 12$	320 GeV
$N_4 = 24$	260 GeV

Probing Naturalness via h^3 coupling

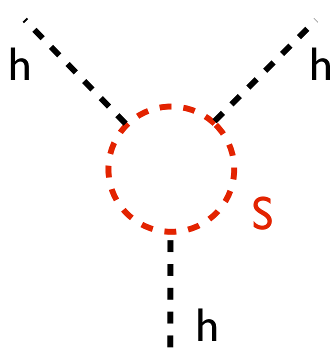
The h^3 coupling is emerging as one of the 'holy grails' of a possible 100 TeV collider. Precision measurement at the % level allows sensitive probe of higgs potential, EW phase transition, extra states coupling to higgs ...

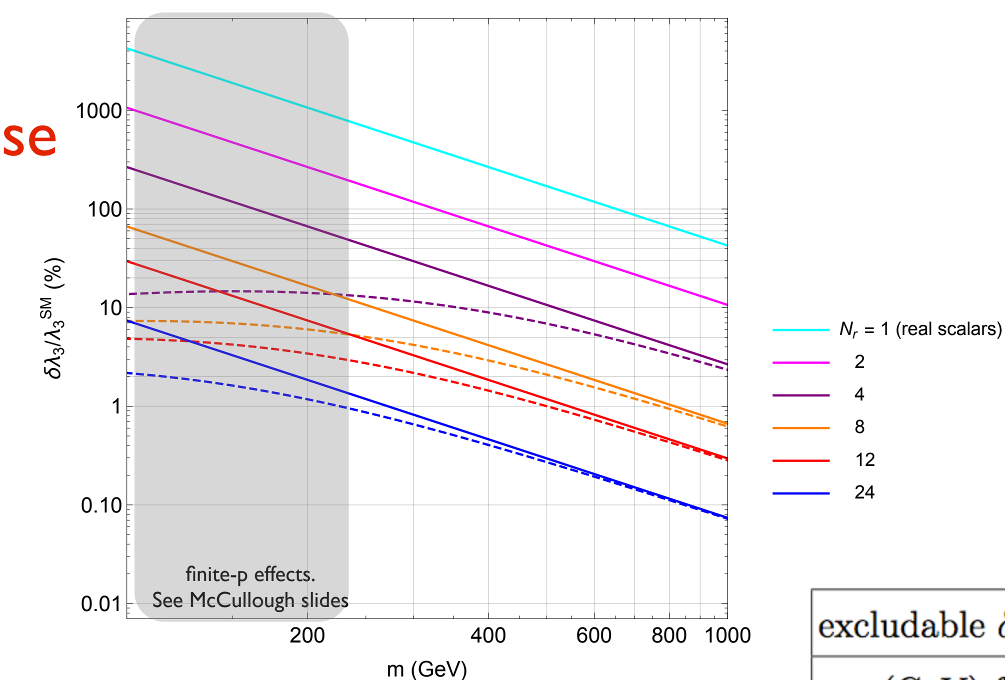
100 TeV with 30/ab can *exclude* 10% shift in λ_3.
(5% 1σ precision)

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

Existing studies point towards exciting possible precision, *but this might even be conservative!*

Top partners also cause shift in h^3 coupling!





Might end up as most sensitive probe?

excludable $\delta\lambda_3$	10%	5%	2%
m_S (GeV) for $N_r = 12$	170	240	380

Neutral Scalar Top Partners

Imagine a set of (wlog real) scalars that solve the little hierarchy problem.

$$\mathcal{L} \supset -\frac{\lambda_i}{2}|H|^2 S_i^2 \qquad\qquad N_r \lambda = 12|y_t|^2$$

These scalars must have experimental consequences:

$\delta\sigma_{Zh}$

	ILC	ILC Lumi Up	TLEP
excludable $\delta\sigma_{Zh}$	4%	2%	0.6%
m_S (GeV) for 12 real scalars (SUSY)	113	149	259

h^3

excludable $\delta\lambda_3$	10%	5%	2%
m_S (GeV) for $N_r = 12$	170	240	380

$h^* \to SS$

$N_r = 1$	625 GeV
$N_r = 2$	520 GeV
$N_r = 4$	430 GeV
$N_r = 8$	355 GeV
$\longrightarrow$ $N_r = 12$	320 GeV
$N_4 = 24$	260 GeV

Motivates more work on h^3.

Also $h^* \to SS$ production.

Even best-case reach seems a bit bleak. Have to probe UV theory?

No Hidden QCD

Neutral Fermionic

Top Partners

Neutral Fermion Top Partners

Same higgs portal measurements available as for the scalar, *with same or slightly better mass reach!*

However: for fermionic top partners, we're used to seeing tree-level higgs coupling corrections ~ tuning. i.e. "v^2/f^2" in CH/MTH/... theories

TLEP gives m_T = 2.2 TeV *exclusion* for e.g. Minimal Twin Higgs model.

(corresponds to ~ 1% tuning)

Higgs coupling measurements seem much more powerful than Higgs Portal observables.

Is this ***completely*** model-independent?

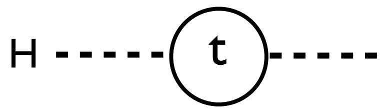
PRELIMINARY

PRELIMINARY

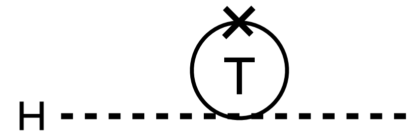
UV completion for Fermionic T

Imagine a set of fermions that solve the little hierarchy problem.

$$\mathcal{L} \supset \lambda \left(M - \frac{|H|^2}{2M'} \right) T\bar{T} \qquad \lambda^2 \frac{M}{M'} = \frac{3}{N_f} y_t^2 \qquad m_T = \lambda \left(M - \frac{v^2}{4M'} \right)$$



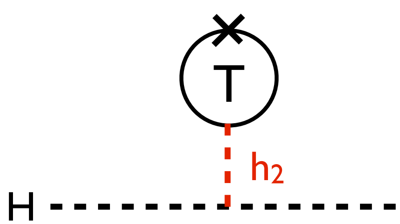
is cancelled by



By itself, this does not imply tree-level higgs coupling shift. However, consider the two possible UV completions:

Bosonic UV Completion

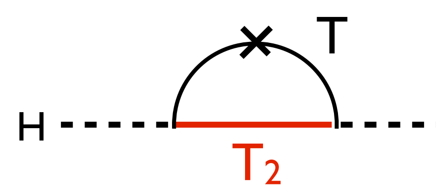
$$\mathcal{L} \supset \mu_{HHh_2} |H|^2 h_2 + g_{TTh_2} h_2 T\bar{T} + \frac{1}{2} m_{h_2}^2 h^2$$



Leads to higgs coupling shifts

Fermionic UV Completion

$$\mathcal{L} \supset m_{T_2} \bar{T}_2 T_2 + (g_{h12} H \bar{T} T_2 + h.c.)$$

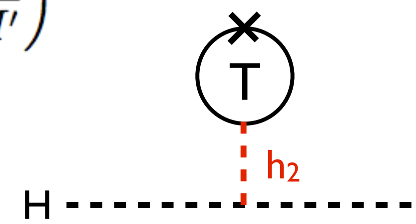


Leads to EW T or T_2 production

Bosonic UV completion for Fermionic T

$$\mathcal{L} \supset \lambda \left(M - \frac{|H|^2}{2M'} \right) T\bar{T} \qquad \boxed{\lambda^2 \frac{M}{M'} = \frac{3}{N_f} y_t^2} \qquad m_T = \lambda \left(M - \frac{v^2}{4M'} \right)$$

$$\mathcal{L} \supset \mu_{HHh_2} |H|^2 h_2 + g_{TTh_2} h_2 T\bar{T} + \frac{1}{2} m_{h_2}^2 h^2$$



Bosonic UV completion necessarily leads to SM higgs mixing with new dof.

$$\sin\theta_h \approx \frac{|\mu_{HHh_2}| v}{m_{h_2}^2} \longrightarrow \sin\theta_h \approx 2 \left(\frac{3}{N_f} \right) \left(\frac{y_t}{\sqrt{2} g_{TTh_2}} \right) \left(\frac{m_t}{m_T} \right) \frac{1}{1 + \sqrt{1 + \frac{6}{N_f} \frac{m_t^2}{m_T^2}}}$$

matching,
cancellation condition

For given Nf and mT, mixing angle is determined up to unknown h_2 TT coupling

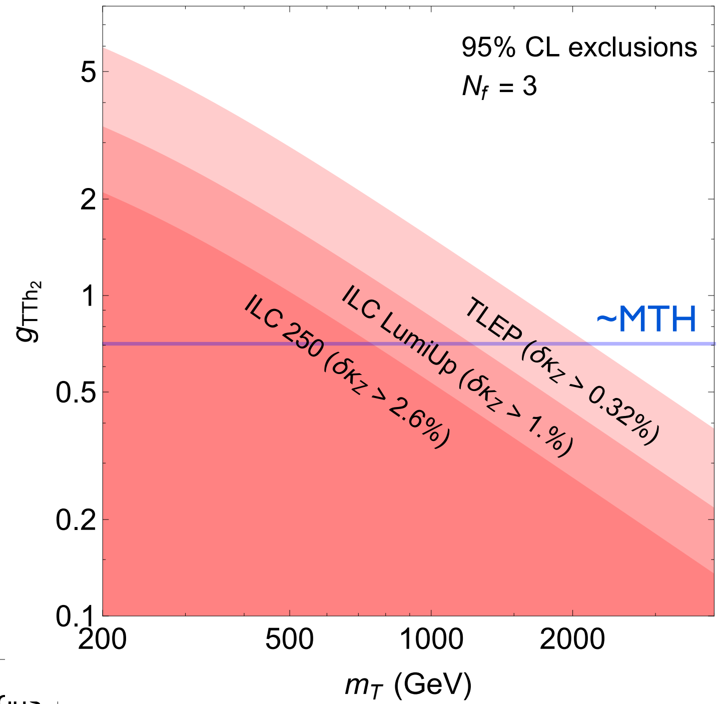
PRELIMINARY **PRELIMINARY**

PRELIMINARY

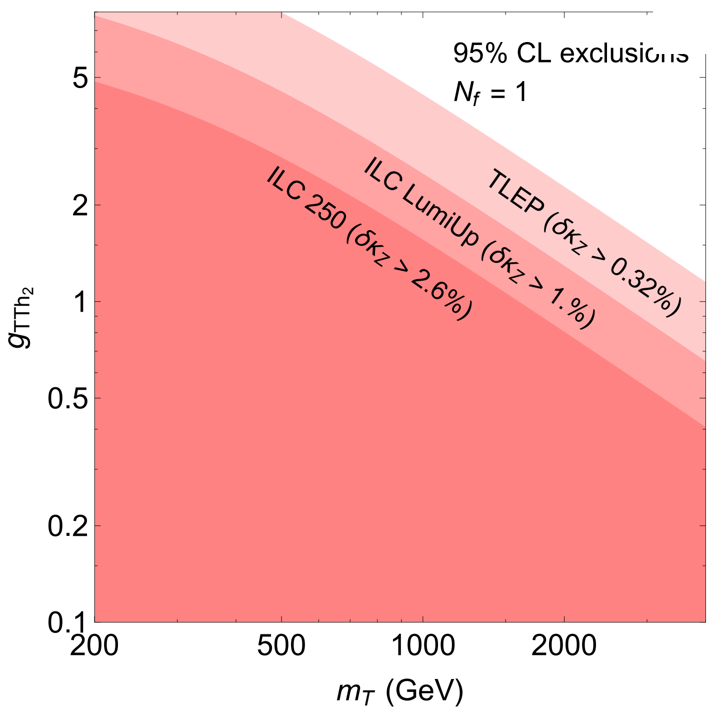
PRELIMINARY

Bosonic UV completion for Fermionic T

Exclusions on neutral fermionic top partners can now be expressed model-independently in the (m_T-g_{TTh2}) plane

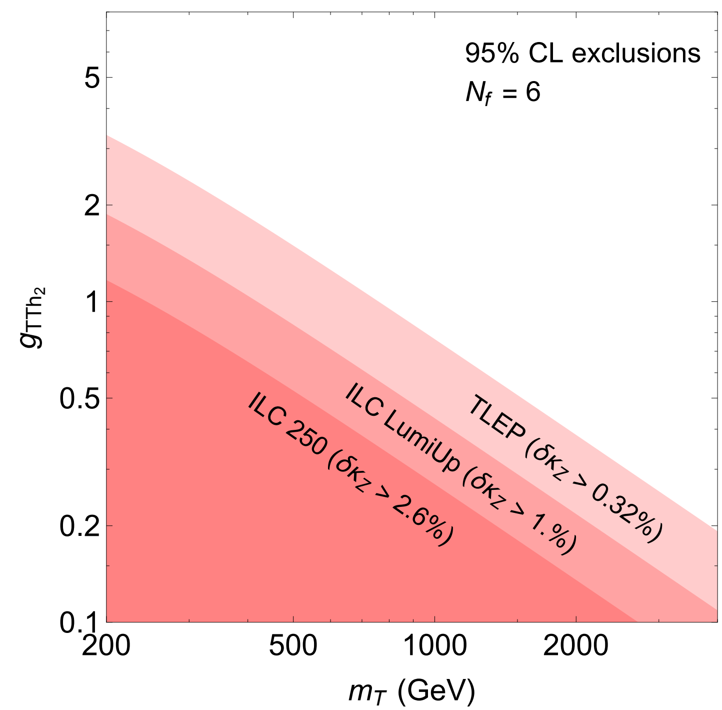


Specific models are curves in this plane, e.g. Twin Higgs.



For arbitrary perturbative UV completions, even light fermionic T can escape detection.

Is this plausible? Scale of UV? Other sources of tuning?



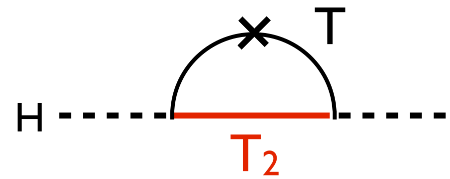
PRELIMINARY

PRELIMINARY

Fermionic UV completion for Fermionic T

$$\mathcal{L} \supset \lambda\left(M - \frac{|H|^2}{2M'}\right) T\bar{T} \qquad \lambda^2 \frac{M}{M'} = \frac{3}{N_f} y_t^2 \qquad m_T = \lambda\left(M - \frac{v^2}{4M'}\right)$$

$$\mathcal{L} \supset m_{T_2} \bar{T}_2 T_2 + (g_{h12} H \bar{T} T_2 + h.c.)$$

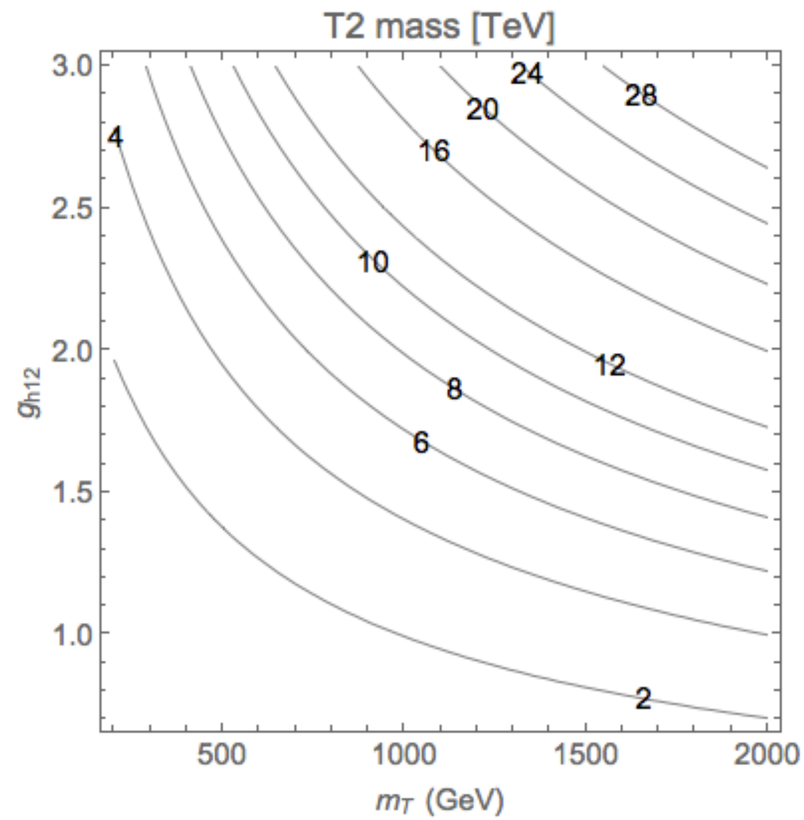


(Much more UV structure above m_{T2}!)

T, T_2 or both must carry EW charge.
Since we assume T is SM-neutral, T_2 is an SU(2) doublet.

Matching & imposing cancellation again fixes observable (T2 mass) up to unknown coupling g_{h12}.

Large parts of this parameter space should be excludable by $T\,T_2$ (h^*) or $T_2\,T_2$ (DY) production.



Investigation in progress....

Hidden QCD without Glueballs

Hidden QCD without Glueballs

Mostly identical phenomenology to case without hidden QCD.
Scale of UV completion might be higher for same 'tuning'.

For EW charged top partners, hidden sector would have to be very non-mirror-SM-like to avoid LEP limits (light QCD' matter < 100 GeV).

Only qualitatively different signature: invisible Higgs decays $h \to g_B g_B$.

TLEP can exclude
$Br(h \to \text{invis}) = 0.4\%$

→

$m_{stop} < 270$ GeV (folded SUSY)
$m_T < 380$ GeV (TH)
Can be most sensitive probe.

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

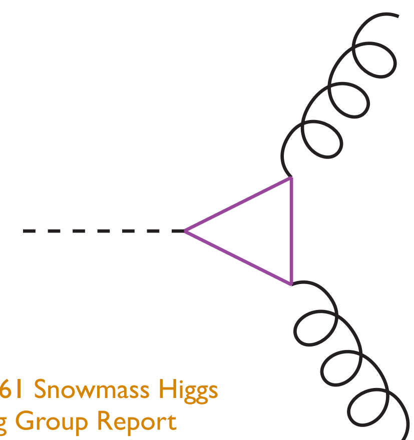
Tree-level higgs coupling shifts ~ tuning

EW top partner production & decay

NEW: Exotic Higgs Decays

higgs portal top partner production

coupling shifts (Zh, higgs cubic)



1310.8361 Snowmass Higgs Working Group Report

1312.4974 Peskin

Conclusions

Conclusions

Uncolored Naturalness $\neq$ avoiding LHC signatures!

$=$ considering most general ways that Naturalness could manifest itself experimentally.

$\Rrightarrow$ could we ever 'experimentally exclude' naturalness to a reasonable degree?

Existing models provide valuable guidance, but much can be gained by considering phenomenology in a model-independent way.

Organize theories by physical properties of top partners to understand pattern of minimal experimental signatures.

For worst-case scenario (singlet top partners), can try to study indirect constraints in a model-independent way.

Twin Higgs smoking gun: Higgs couplings

Folded SUSY smoking gun: glueball signatures!

Summary: Top Partner Mass Reach

With Hidden Glueballs

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

Tree-level higgs coupling shifts ~ tuning. TLEP reach ~ 2 TeV but theories could be more general?

Exotic Higgs Decays to Glueballs: HL-LHC reach ~ 2 TeV, 100 TeV reach ~ 3+ TeV for most glueball masses

Smoking Gun of Folded SUSY!

top partner production & annihilation: HL-LHC, 100 TeV reach (TeV)

	detection (most m_0)	measurement (some m_0)
DY:	1 , 2+	0.5 , 1.5
h*:	0.6 , 2+	--- , 0.8

No Hidden Glueballs

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

Tree-level higgs coupling shifts. TLEP reach ~ 2 TeV, but theories could be more general, some UV completions escape detection at TLEP even for small m_T. *Express constraints in UV completion parameter plane!*

DY partner production & decay: EW final state, multi-TeV reach. (*Studies needed!*)

Exotic Higgs Decays (invisible) (if hidden QCD): ~300 - 400 GeV reach @ TLEP*, but depends on hidden sector.

h* top partner production (invisible): ~300 GeV reach @ 100 TeV*

σ_{Zh} shift @ TLEP: ~ 260 GeV reach*
***h^3 shift** @ 100 TeV: 200 GeV with current estimated precision, but might be as high as ? 400 GeV ?. More studies needed!*

*for 'standard' top partner multiplicities

Summary: Top Partner Mass Reach

With Hidden Glueballs

	scalar	fermion
colored	SUSY	CH/RS
EW		
singlet		

Great Outlook even @ LHC! Probe ~ 2 TeV top partners.

Tree-level higgs coupling shifts ~ tuning. TLEP reach ~ 2 TeV but theories could be more general?

Exotic Higgs Decays to Glueballs: HL-LHC reach ~ 2 TeV, 100 TeV reach ~ 3+ TeV for most glueball masses

Smoking Gun of Folded SUSY!

top partner production & annihilation: HL-LHC, 100 TeV reach (TeV)

nt (some m_0)

DY: 5

h*: .8

Most plausible theories discoverable at LHC & lepton colliders

No Hidden Glueballs

	scalar	fermion
colored	SUSY	CH/RS
EW	Great Outlook even @ LHC!	
singlet	Maybe only O(100) GeV reach...	TLEP probes ~ 2 TeV top partners

Tree EP reach ~ 2 TeV, but theories could be more general, some UV completions escape detection at TLEP even for small m_T. *Express constraints in UV completion parameter plane!*

DY partner production & decay: EW final state, multi-TeV reach. (*Studies needed!*

Exotic Higgs Deca :

~300 - 400 GeV reach ector.

h* top partner pr reach @ 100 TeV*

σ_{Zh} shift @ TLEP: ~

h^3 shift *@ 100 TeV:* *on, but might be as high as ? 400 GeV ?. More studies needed!*

Will be able to probe many UV completions @ 100 TeV.

*for 'standard' top partner multiplicities