Exotic quarks in Twin Higgs models

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based on **H.-C.Cheng, S.Jung, E.Salvioni and Y.Tsai**

to appear

Twin Higgs as solution to little hierarchy
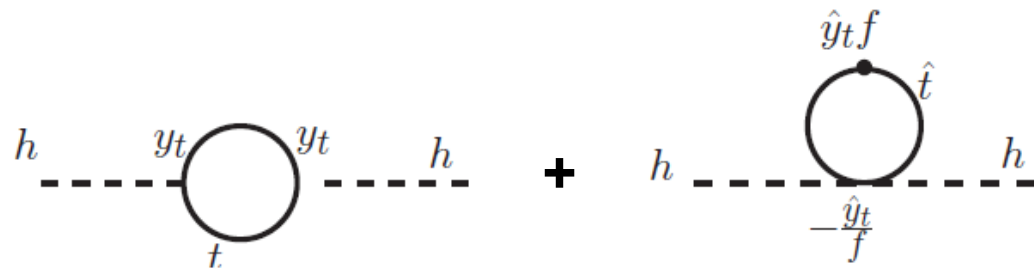
- Naturalness requires the top loop to be cut-off by **top partners** at ~ 500 GeV.

- Bounds on stops and *t*'s are already beyond this level, as these particles carry SM color.

- Can the top partners be color-less? Yes, e.g. folded SUSY and **Twin Higgs**

$$SU(4)/SU(3)$$

$$y_t H_A q t + \hat{y}_t H_B \hat{q} \hat{t}$$ twin top

$$\left\langle \begin{pmatrix} H_A \\ H_B \end{pmatrix} \right\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

- Z_2 symmetry ensures $y_t = \hat{y}_t$ and thus the cancellation of quadratic divergences from top (and gauge) loops. 2-loop tuning ⟹ gauge twin color

- Residual log sensitivity to the cutoff $\Lambda \lesssim 4\pi f \sim 10 \text{ TeV}$

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Twin Higgs pheno

- Top partners are color-less by construction, production rates are suppressed.

- Higgs couplings modified at order v^2/f^2 (Higgs is a Goldstone).

  Linked to EW tuning, which scales the same way.

  Robust signature, but if measured, it would have no unique interpretation.

  e.g. Burdman et al, 2014

- Decays of SM-like h into twin particles can give rise to striking signals,

  prime example displaced vertices from twin glueballs.

  Craig, Katz, Strassler, Sundrum 2015
  Curtin and Verhaaren, 2015

- **What else?** Theory exploration of all signatures of the Twin Higgs idea is

  paramount, to guide searches at colliders (and beyond).

UV completion with exotic quarks

- In non-SUSY UV completions, expect fermionic states charged under both the visible and mirror worlds. E.g. extending the symmetry of the top Yukawa to $\underline{SU(6)} \times \underline{SU(4)}$ makes the potential fully calculable,

  color   weak

$$y_t \begin{pmatrix} H_A^\dagger & H_B^\dagger \end{pmatrix} Q \begin{pmatrix} t_A \\ t_B \end{pmatrix}, \qquad Q = \begin{pmatrix} q_A & \tilde{q}_A \\ \tilde{q}_B & q_B \end{pmatrix}$$

$\tilde{q}_A$ has SM color and twin EW charge

- What can we say on its *mass M* ?

  Depends strongly on extra Z_2 symmetric quartic $V \ni \kappa \left(|H_A|^4 + |H_B|^4 \right)$

$$\lambda \sim \kappa + \frac{3 y_t^4}{4\pi^2} \log(M/m_{\tilde{t}}), \qquad \kappa \geq 0 \qquad \Longrightarrow \qquad M < 6 \text{ TeV}$$

- I will show that even the upper bound is within reach of future colliders, by searching for $\tilde{q}_A$

Exotic quark decays

- For $M \gg f$ symmetry breaking is negligible and decays are controlled by

$$y_t \bar{t}_R^A \tilde{q}_A H_B^\dagger \big) \ni Z_B, W_B, \frac{v}{f} h$$

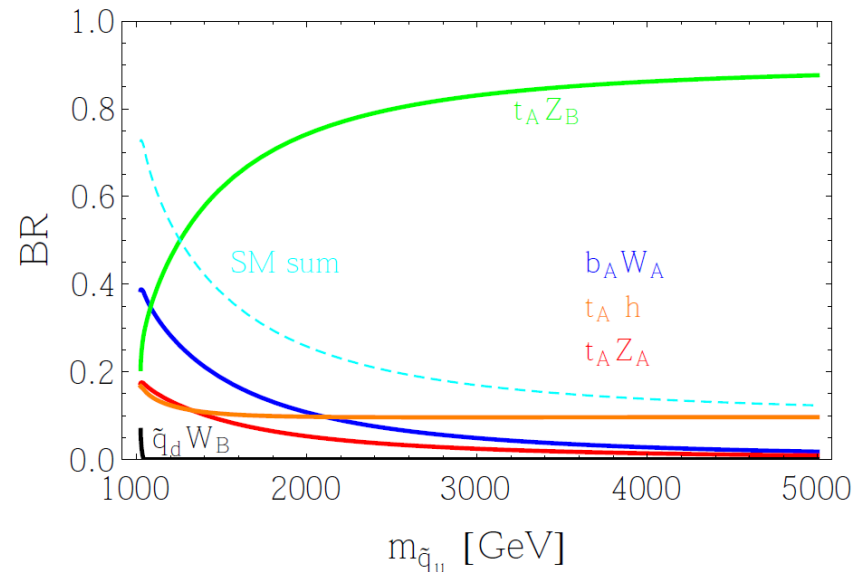- $\tilde{q}_A^u \to t Z_B$ **dominates**, $\tilde{q}_A^u \to th$ suppressed by $\frac{v^2}{f^2} \lesssim 0.1$

Assume twin leptons are ~ 100 GeV.
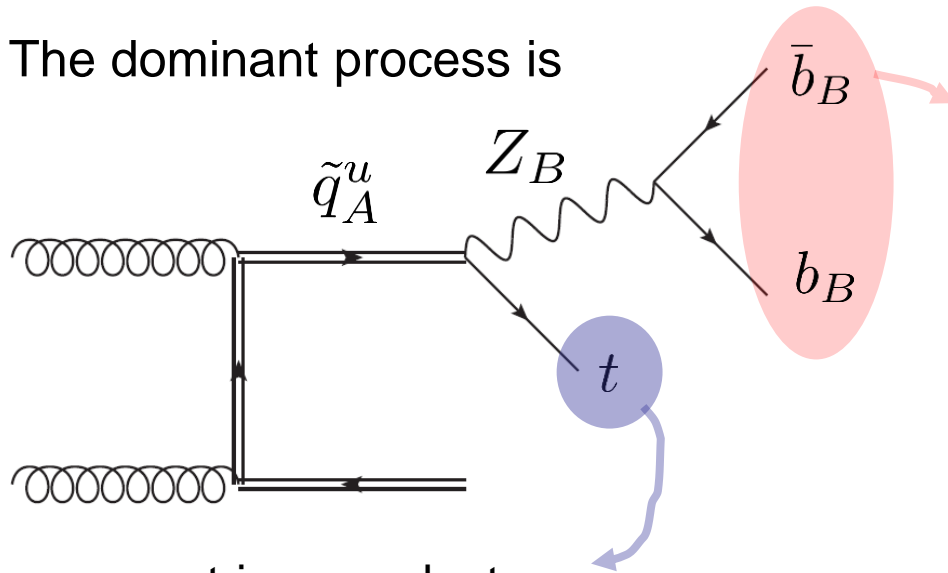
$Z_B \to b_B \bar{b}_B$ is the dominant decay

because

$$\frac{m_{t_B}}{m_{Z_B}} = \frac{m_t}{m_Z} \sim 2$$

- $\tilde{q}_A^d \to t W_B$ only, $W_B \to \tau_B \nu_B$

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Collider signatures

- The dominant process is

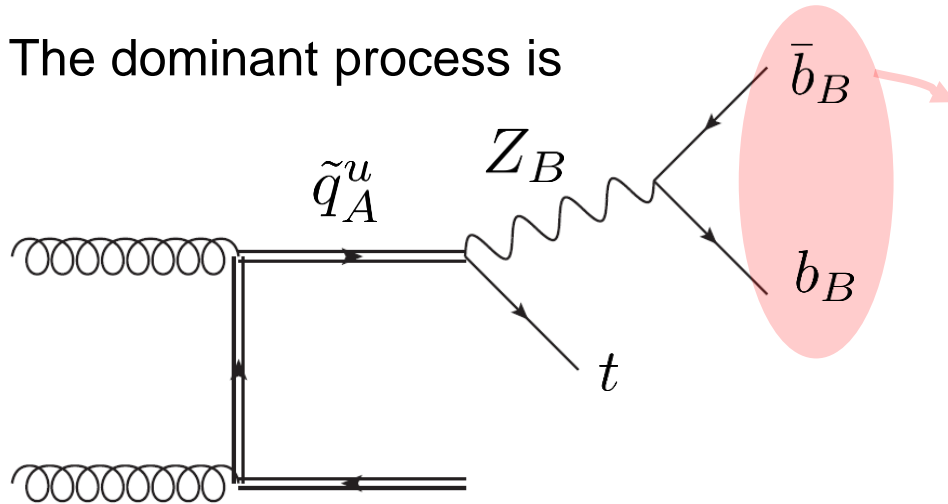$\tilde{q}_A^u$

Z_B

$\bar{b}_B$

b_B

t

easy trigger on leptons

highly excited bound state, connected by twin QCD flux tube

the dynamics that follows depends on ratio

$$\frac{m_{\hat{b}}}{\Lambda}$$

Λ confinement scale of (1-flavor) twin QCD

Collider signatures

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highly excited bound state, connected by twin QCD flux tube

the dynamics that follows depends on ratio

$$\frac{m_{\hat{b}}}{\Lambda}$$

Λ confinement scale of (1-flavor) twin QCD

Kang, Luty 2008

- Two competing mechanisms:

scattering with glueball emission

$$\tau_{\text{scatter}} \sim \left(\frac{m_{Z_B}}{\Lambda^2}\right) \left(\frac{\Lambda^{-2}}{\sigma_{\tilde{B} \to \tilde{B} + \tilde{G}}}\right)$$

dominates for

$$m_{\hat{b}} \gg \Lambda$$

string breaking

$$\tau_{\text{break}} \sim \frac{4\pi^3}{m_{Z_B}} e^{m_{\hat{b}}^2/\Lambda^2}$$
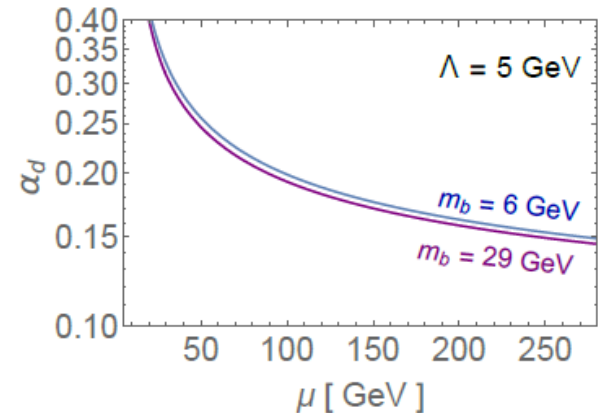
dominates for

$$m_{\hat{b}} \lesssim 2\Lambda$$

$m_{\hat{b}} \gg \Lambda$: **quirk scattering**

- Model radiative process $[\hat{b}\bar{\hat{b}}]^* \to [\hat{b}\bar{\hat{b}}] + \tilde{G}$ as perturbative emission of gluon

  in soft/collinear approximation:

$$P(r) \simeq 1 - \exp\left[-\frac{\alpha_s^B}{\pi}\log^2(r^2)\right], \qquad r \equiv \frac{E_1}{m_{Z_B}}$$

  probability to emit a gluon with energy $E_1 < E < m_{Z_B}$

- Find $\langle r \rangle \sim 1/4$, by iterating process

  find maximum number of glueballs emitted

- Take $\Lambda = 5\ \text{GeV}, f = 750\ \text{GeV}$ as benchmark. $m_{\hat{G}} \sim 34\ \text{GeV}$

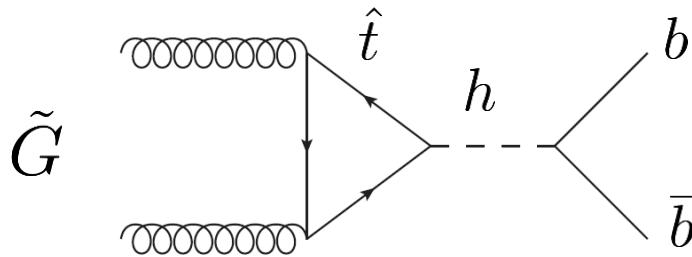 String scattering dominates for $m_{\hat{b}} \gtrsim 18\ \text{GeV}$

  emit $\lesssim 6$ glueballs (depends mildly on $m_{\hat{b}}$)

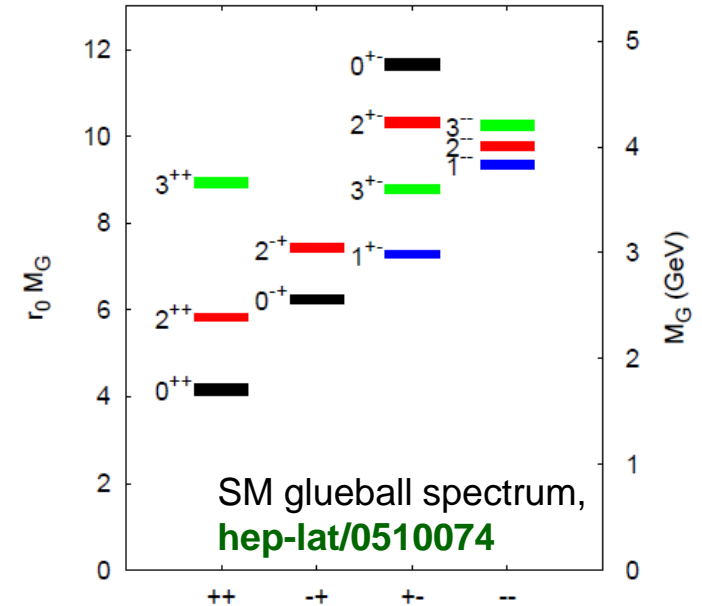**Kang, Luty 2008**
Burdman et al. 2008
(folded SUSY)

Glueball signal

A (not easy to estimate) fraction of the emitted glueballs is 0^{++} and can **decay back to SM via the Higgs portal**, **with lifetime**

$$c\tau_{0^{++}} \sim 3 \text{ mm} \left(\frac{5 \text{ GeV}}{\Lambda}\right)^7 \left(\frac{f}{750 \text{ GeV}}\right)^4$$
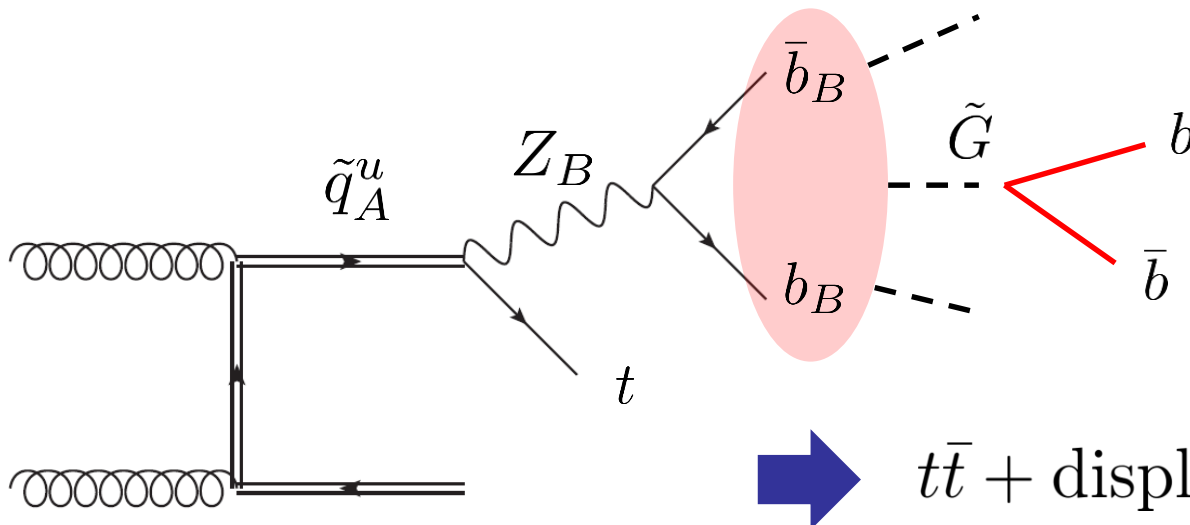
Craig, Katz, Strassler, Sundrum 2015

SM glueball spectrum, **hep-lat/0510074**

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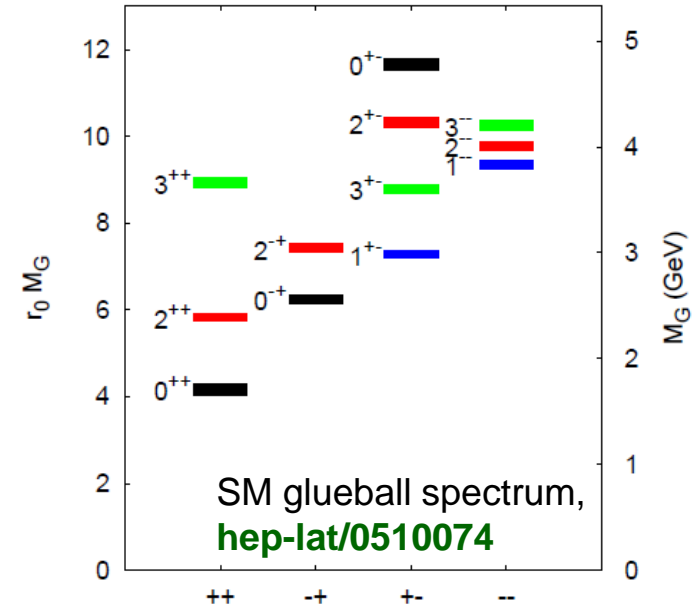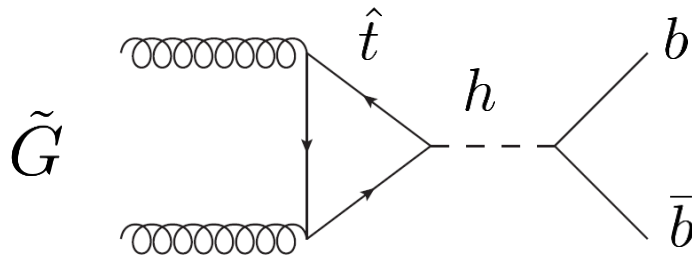

SM glueball spectrum, **hep-lat/0510074**


$t\bar{t} + \text{displaced vertex}$

$m_{\hat{b}} \lesssim 2\Lambda$: string breaking

- For $m_{\hat{b}} \lesssim 2\Lambda$ the string undergoes a series of splittings into less excited $[\hat{b}\bar{\hat{b}}]$ mesons

- By a simplified model where the string breaks at the center, we find

  < 8 mesons for $m_{\hat{b}} \lesssim 9 \text{ GeV} \ (\Lambda = 5 \text{ GeV})$

- **What fraction of the mesons is 0^{++} ?**

  The first breaking produces a large angular momentum $\Delta L \sim \frac{m_{Z_B}}{\Lambda}$,

  but most of it goes into orbital *L* between different mesons
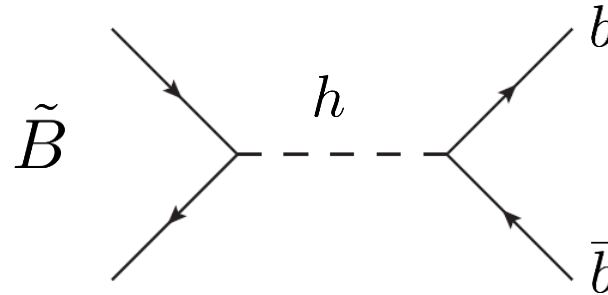
  In later steps, typically $\Delta L \sim m_{\hat{b}}/\Lambda \lesssim 2$

  ➡️ simple counting of dof gives a fraction between $\frac{1}{36}$ and $\frac{1}{16}$
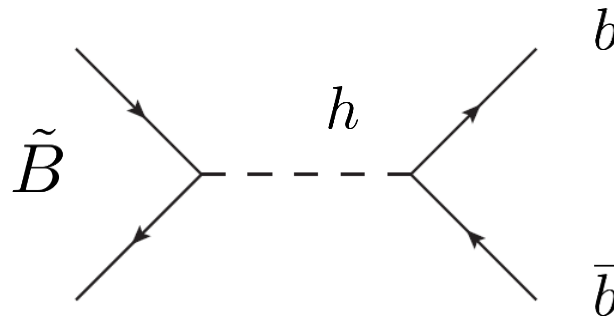
Bottomonium signal

- For $\Lambda \lesssim m_{\hat{b}} \lesssim 2\Lambda$, decay of mesons is suppressed by wavefunction overlap. Classical picture:

Kang, Luty 2008

$$\Gamma(\tilde{B} \to b\bar{b}) = \frac{\mathrm{Prob}(r \leq r_0)}{\frac{4}{3}\pi r_0^3}(\sigma_{\hat{b}\hat{b}\to bb} v_{rel})\,, \qquad r_0 \sim \frac{1}{m_{\hat{b}}}$$

$$\mathrm{Prob}(r \leq r_0) \sim \frac{r_0}{r_{max}}\,, \qquad r_{max} \sim \frac{m_{\hat{b}}}{\Lambda^2}$$

- This works well for highly excited $c\bar{c}$ bound states in the SM
- **Lifetimes from millimeter to meter** (strongly suppressed by SM b Yukawa)

Summary

$(m_{Z_D}, \Lambda) = (262, 5)$ GeV	Decay	Decay Prod.	$\ell_{\tilde{G}_{0++} \to b\bar{b}}$ [mm]	$\ell_{\tilde{B}_{0++} \to b\bar{b}}$ [mm]
$m_{\hat{b}} > 80$ GeV	scatter	$2\,\tilde{G}$	3	prompt
$80 > m_{\hat{b}} > 35$ GeV	scatter	$4\,\tilde{G}$	3	prompt
$35 > m_{\hat{b}} > 29$ GeV	scatter	$6\,\tilde{G}$	3	prompt
$18 < m_{\hat{b}} < 29$ GeV	scatter	$4\,\tilde{G}$	3	prompt
$5 < m_{\hat{b}} < 9$ GeV	break	$4\,\tilde{B}$	(3)	$13 \div 0.5$
$1 < m_{\hat{b}} < 5$ GeV	break	$8\,\tilde{B}$	(3)	$250 \div 10$

Results
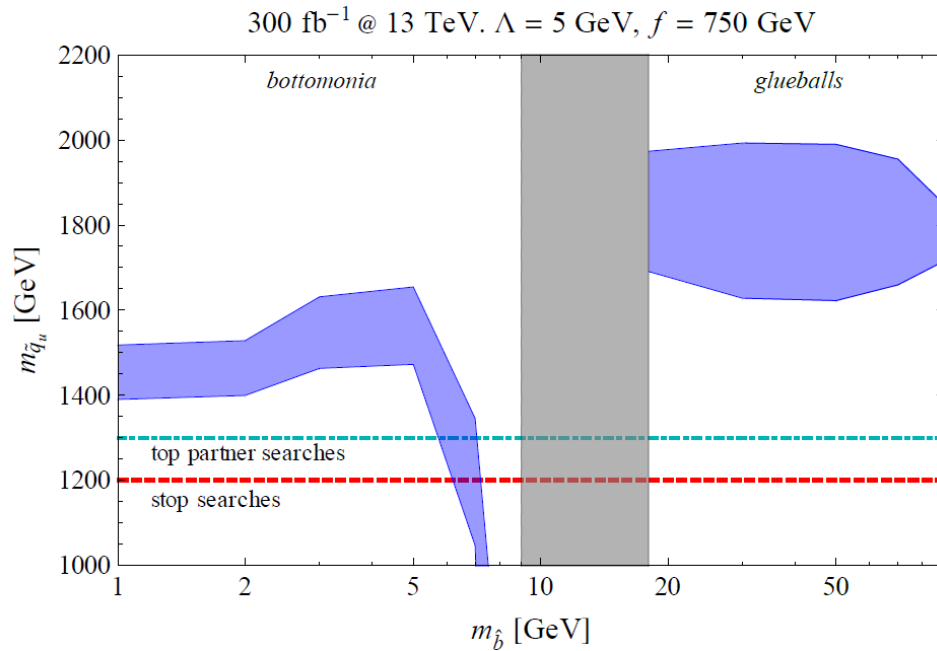
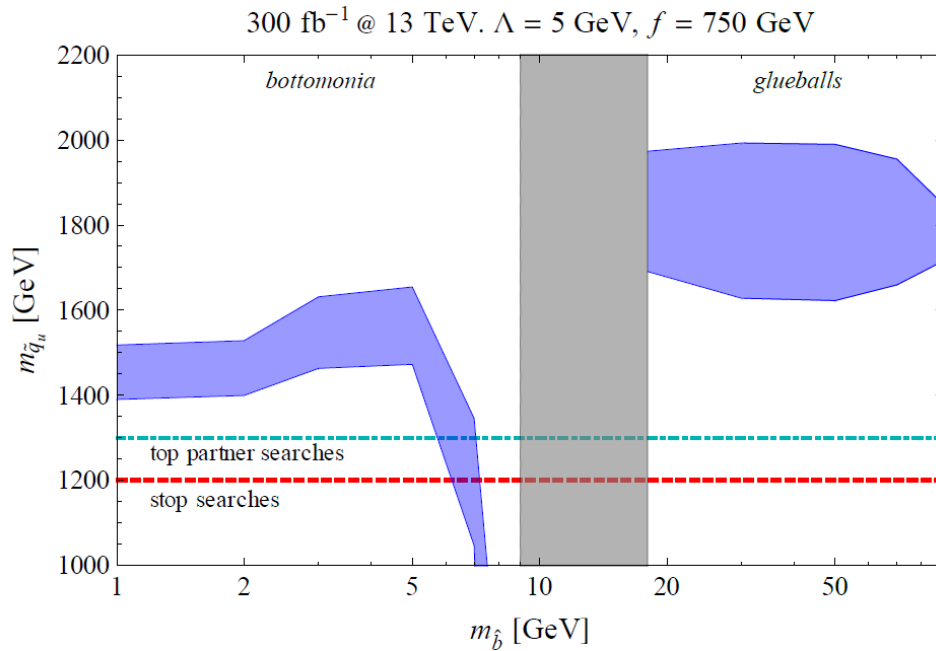300 fb^{-1} @ 13 TeV. $\Lambda = 5$ GeV, $f = 750$ GeV

Assume no background, 95% CL exclusion requires 3 events

Grey area: string scattering and breaking comparable, no theoretical control

Blue bands: optimistic and conservative assumptions on the number of 0^{++} twin hadrons produced

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Results

300 fb^{-1} @ 13 TeV. $\Lambda = 5$ GeV, $f = 750$ GeV

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Grey area: string scattering and breaking comparable, no theoretical control

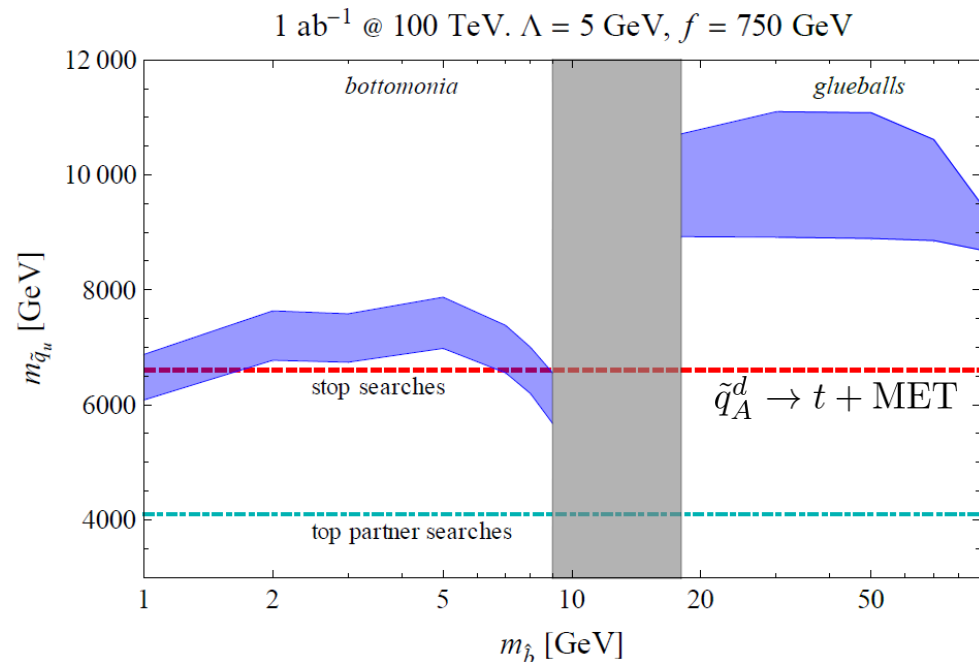**Blue bands:** optimistic and conservative assumptions on the number of 0^{++} twin hadrons produced

1 ab^{-1} @ 100 TeV. $\Lambda = 5$ GeV, $f = 750$ GeV

Summary

- Twin Higgs mechanism can stabilize weak scale up to ~10 TeV.

  Top partners are SM singlets, their direct discovery is challenging.

- New exotic quarks with twin EW charge can appear in UV completions.

  Once produced, they decay into tops + twin glueballs or mesons.

- The twin hadrons can decay back to the SM, typically with long lifetimes

  ➡️ signals display a combination of prompt and displaced objects

- Projected reach exceeds that of searches for stop-like and top partner

  signatures. 100 TeV collider can fully cover the interesting mass range, up to

  $M \sim 10$ TeV.

Thanks!
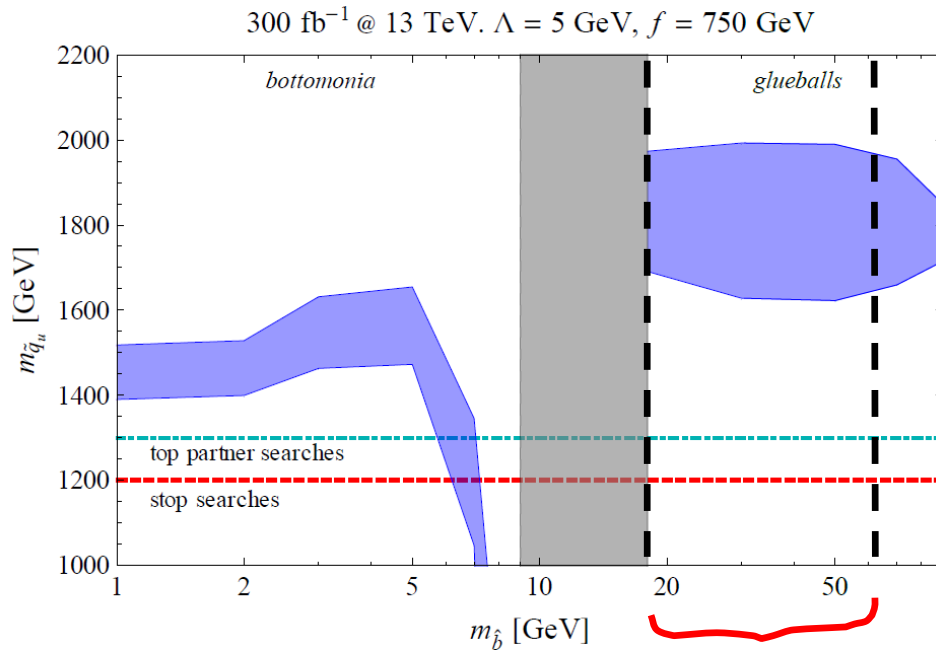
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Backup

Results/2

300 fb^{-1} @ 13 TeV. $\Lambda = 5$ GeV, $f = 750$ GeV

Assume no background, 95% CL exclusion requires 3 events

perturbative exclusion from Higgs coupling measurement, $h \rightarrow \hat{b}\hat{b}$ (relaxed for larger f)

Grey area: string scattering and breaking comparable, no theoretical control

Blue bands: optimistic and conservative assumptions on the number of 0^{++} twin hadrons produced

Craig, Katz, Strassler, Sundrum 2015