Collider Signals for the Twin Higgs Model and Its UV Completion

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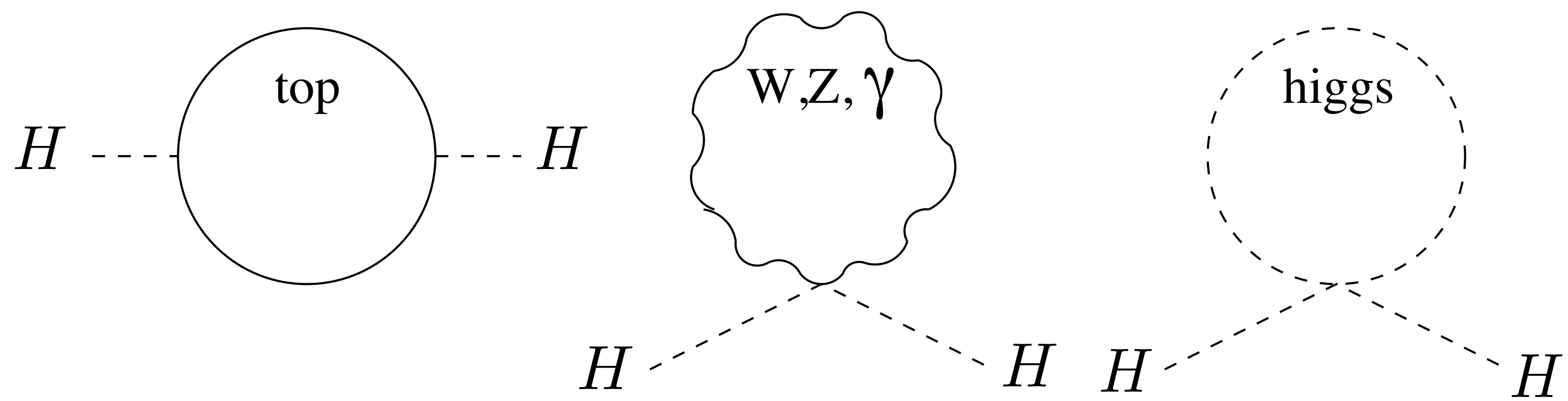
HC, Sunghoon Jung, Ennio Salvioni, and Yuhsin Tsai, arXiv:1512.02647
HC, Ennio Salvioni, and Yuhsin Tsai, arXiv:1612.03176

IAS Program on High Energy Physics, HKUST, Jan 17, 2017

Naturalness of Weak Scale

- The hierarchy problem has been a main driving force in searching for new physics beyond SM.



$$-\frac{3y_t^2}{8\pi^2}\Lambda^2 \qquad \frac{9g^2}{64\pi^2}\Lambda^2 \qquad \frac{\lambda^2}{16\pi^2}\Lambda^2$$

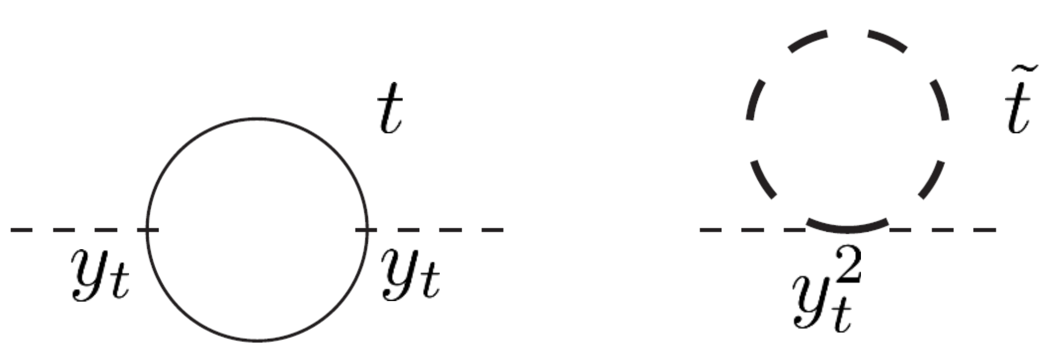
- The solutions based on symmetry principles require new states (top partners) below TeV scale to cancel the quadratically divergent contribution from the top quark to m_H^2 .

Naturalness of Weak Scale

- In common frameworks, e.g., supersymmetry (SUSY), composite Higgs (including little Higgs), the top partners carry color charge just as the SM top quark.

SUSY

Superpartners have the same gauge quantum numbers as the SM particles, but have the spins differed by 1/2.

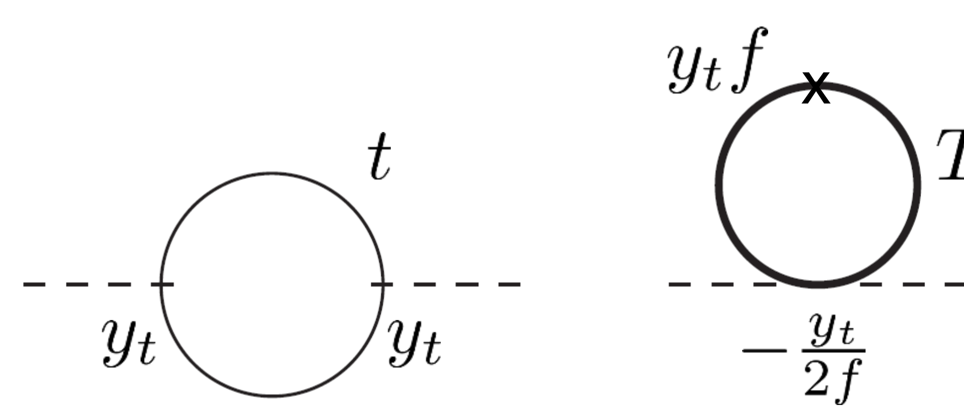


Global symmetry (Higgs as PNGB)

E.g., SU(3)/SU(2):

$$y_t\, \overline{(t_L,\, b_L,\, T_L)}\, \Phi\, t_R + M_T \overline{T_L}\, T_R + \text{h.c.}$$

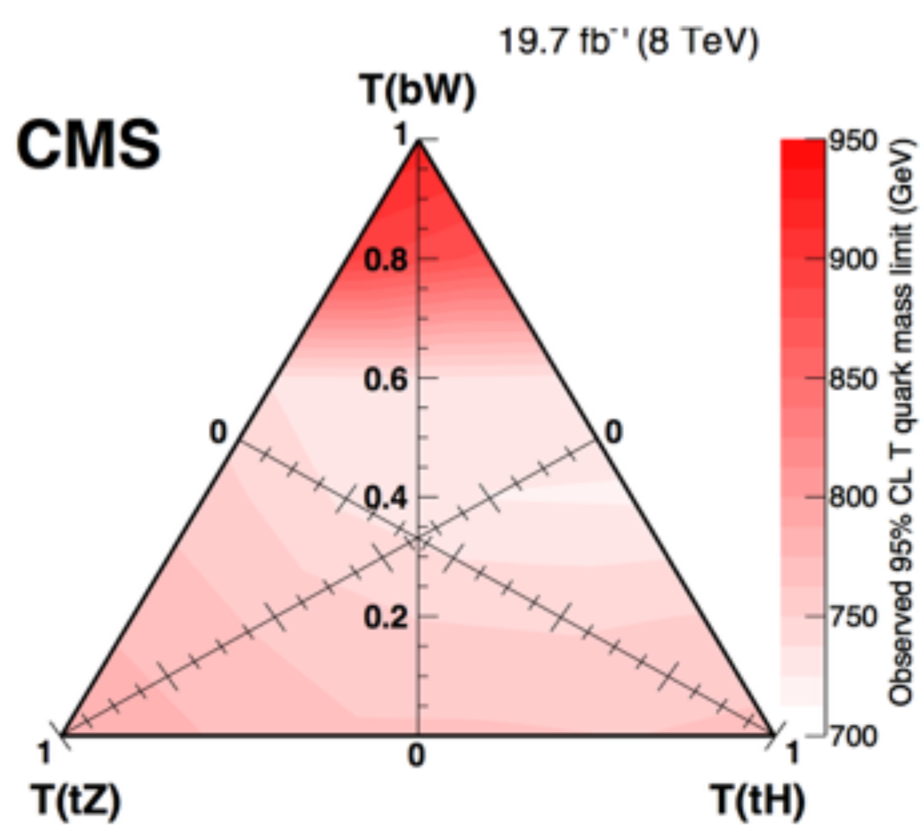
$$\Phi = \exp\left(\frac{i2\Pi}{f}\right)\begin{pmatrix} 0 \\ 0 \\ f/\sqrt{2} \end{pmatrix} \qquad \Pi \supset \begin{pmatrix} & & H \\ & & \\ & H^\dagger & \end{pmatrix}$$



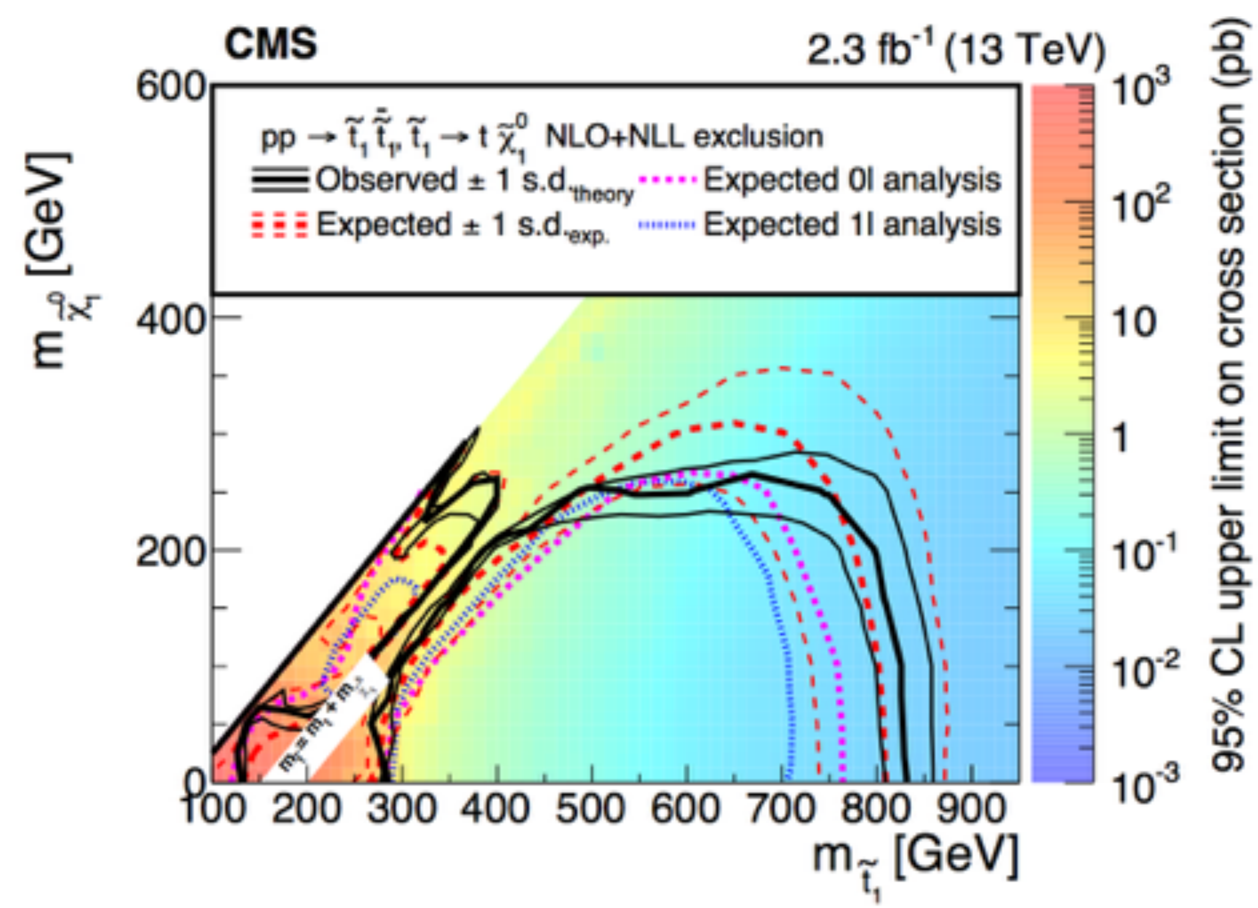
Naturalness of Weak Scale

- Top partners are extensively searched at LHC, but nothing was found below 700-800 GeV, which makes the hierarchy problem more prominent.

Global symmetry



Supersymmetry



Neutral Naturalness

- There is a surge of interests in models where the top contribution to the Higgs mass is cut off by states that do not carry color.

Partner quantum #s	Global dim-6 mixing	SUSY dim-8 mixing
QCD x EWK	CHM, Little Higgs	MSSM
Neutral x EWK	Quirky Little Higgs Cai, HC, Terning	Folded SUSY Burdman, Chacko, Goh, Harnik
Neutral x Neutral	Twin Higgs Chacko, Goh, Harnik	????

Table borrowed from David Curtin/Nathaniel Craig

Twin Higgs

Chacko, Goh, Harnik, hep-ph/0506256

- Assume a “mirror” or “twin” sector related to SM by an (approximate) Z_2 symmetry.
- The SM Higgs doublet and twin Higgs doublet have an approximately SU(4) invariant potential.

$$V(H) = -m^2|H|^2 + \lambda|H|^4 \qquad H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \begin{matrix} \leftarrow SU(2)_A \\ \leftarrow SU(2)_B \end{matrix}$$

- SU(4) is spontaneously broken down to SU(3) by the H VEV, producing 7 Goldstone modes.

$$|\langle H \rangle|^2 = \frac{m^2}{2\lambda} \equiv \frac{f^2}{2}$$

Twin Higgs

- The SU(4) invariance of the quadratic term is a consequence of the Z_2 symmetry. No quadratic divergence for the masses of Goldstone bosons.

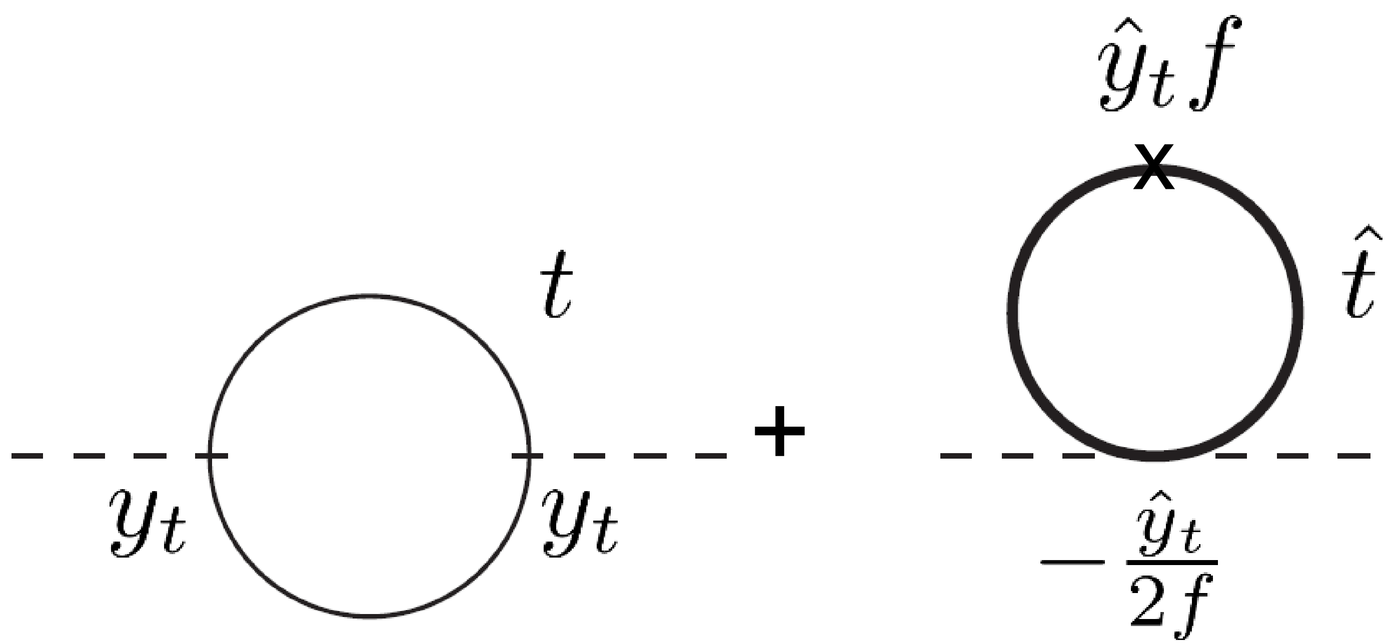
$$V(H) \supset \frac{9}{64\pi^2} g^2 \Lambda^2 \left(|H_A|^2 + |H_B|^2 \right)$$

- To obtain a realistic model, a soft Z_2 breaking term is needed to make the twin Higgs VEV larger than the SM VEV, $f \gg v$.

$$\mu^2 H_A^\dagger H_A \quad \Rightarrow \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \\ 0 \\ f\sqrt{1 - v^2/f^2} \end{pmatrix}$$

Twin Higgs

- 6 of 7 Goldstones are eaten by the W, Z bosons of the SM and twin sectors, leaving one as the observed light Higgs boson.



Cancelation of top quadratic divergence to Higgs mass

Twin Higgs

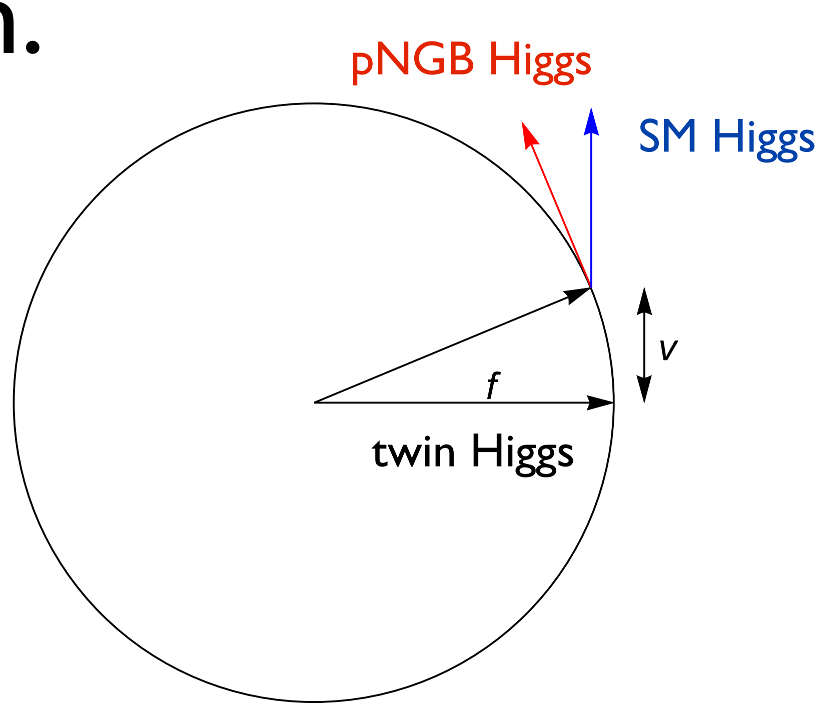
- The Z_2 does not imply SU(4) invariance of the quartic term.
- $|H_A|^4+|H_B|^4$ will be generated by radiative corrections, but only has logarithmic sensitivity to the cutoff. Such a term is needed to give the physical Higgs boson a mass.

$$\delta V = \frac{3y_t^4}{8\pi^2} \log\Lambda\left(|H_A|^4 + |H_B|^4\right)$$

- A UV completion of Twin Higgs should regularize the log divergence, making the Higgs boson mass finite and calculable.

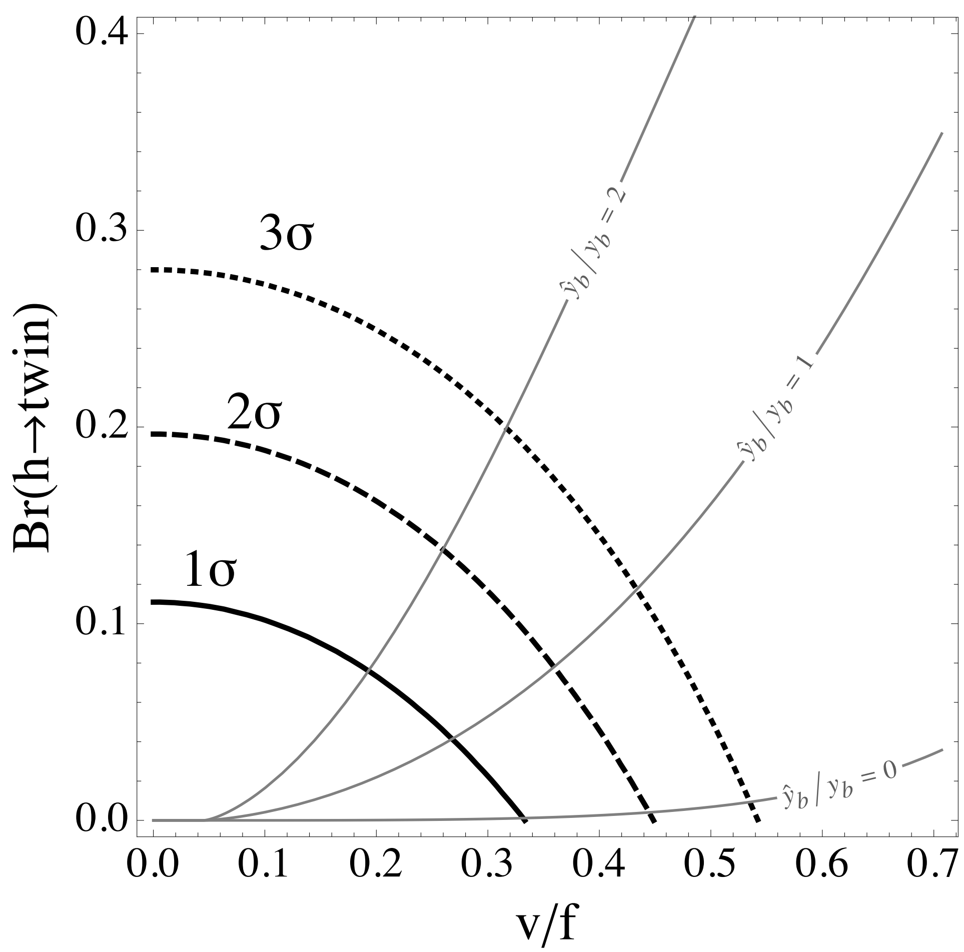
Twin Higgs Phenomenology

- The twin sector particles do not carry SM gauge charges and hence are difficult to find.
- The only bridge in the low energy theory between the SM and twin sectors is through the mixing of the Higgses. The physical Higgs boson has a small component ~v/f in the twin sector direction.



Twin Higgs Phenomenology

- Higgs coupling to SM particles is universally reduced by $(1-v^2/f^2)^{1/2}$. It can have a small invisible decay width to the twin sector.
- The current LHC data bound is $f/v \gtrsim 3$. Future LHC runs won't improve it by much.



Craig, Katz, Strassler, Sundrum, 1501.05310

Fraternal Twin Higgs

Craig, Katz, Strassler, Sundrum, 1501.05310

- Existence of many light states in the twin sector may cause cosmological problems.
- To address the naturalness problem, Z_2 symmetry is only needed for particles that have large couplings to the Higgs (e.g., top, W/Z). One can take a minimal approach to include only necessary ingredients.

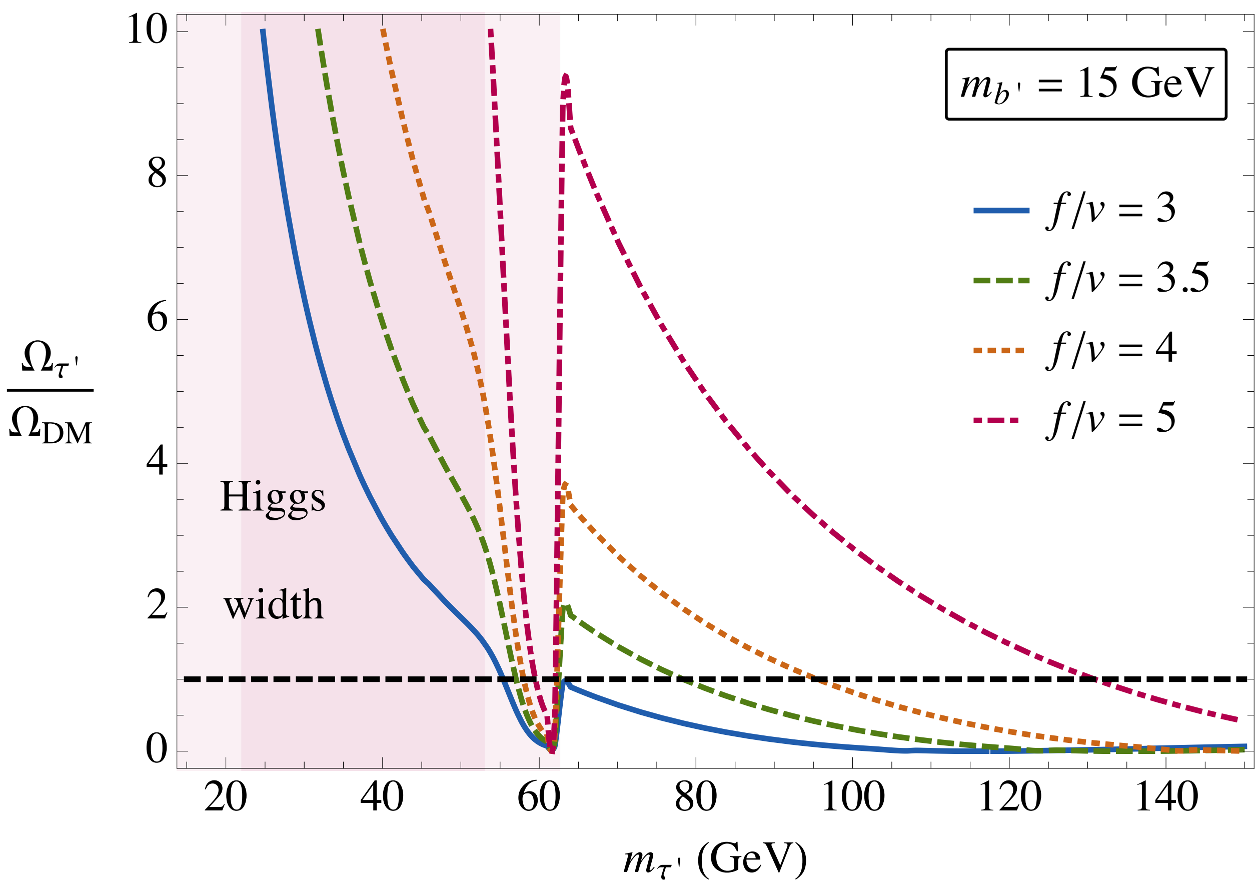
Fraternal Twin Higgs

In the twin sector:

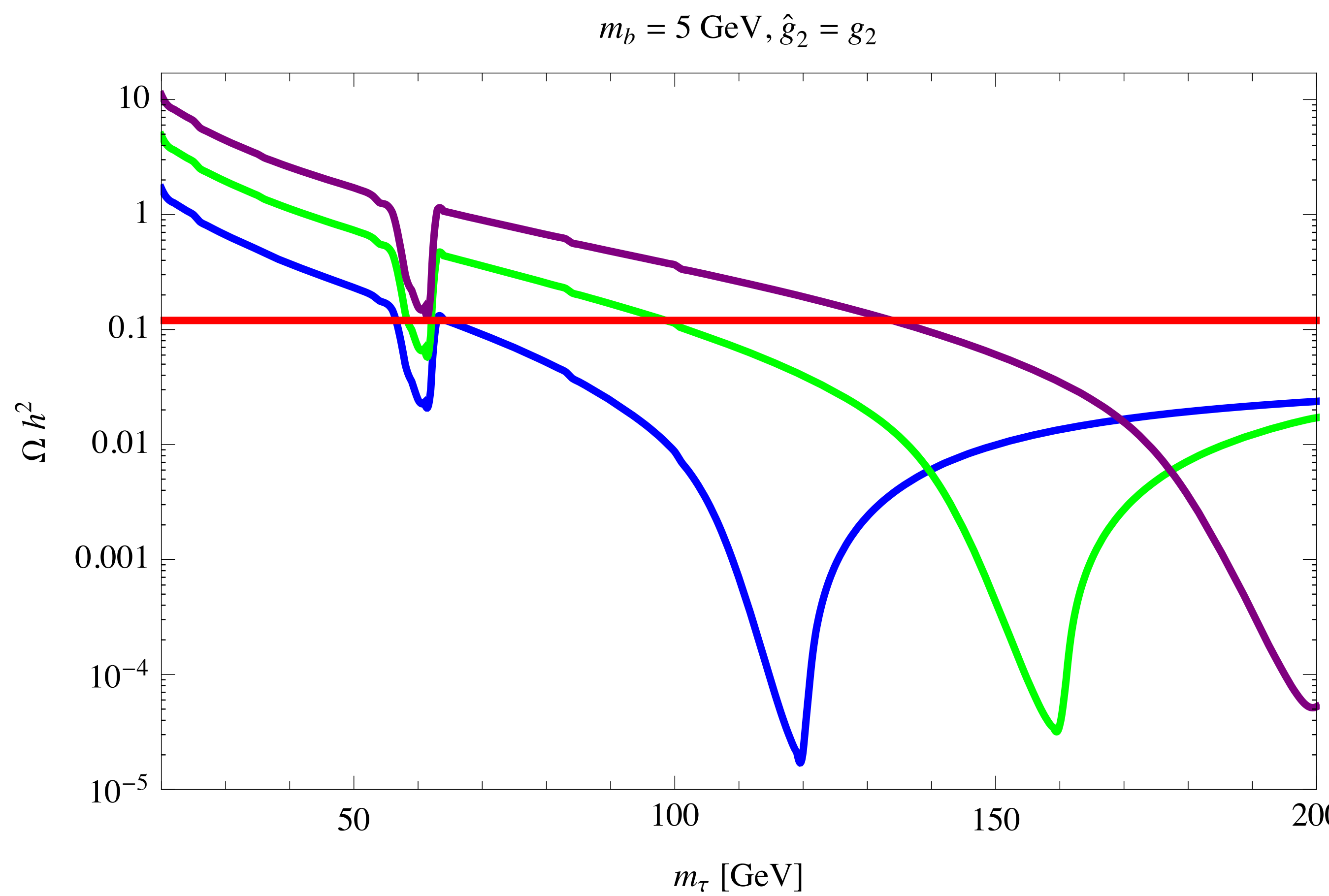
- Only 3rd generation fermions are needed (to cancel anomalies). Only top Yukawas need to respect Z_2. The twin bottom, tau, neutrino masses are free parameters as long as they are much lighter than the twin top.
- SU(2) and SU(3) gauge couplings need to be approximately equal to SM gauge couplings.
- Twin U(1) is not needed (or twin photon can be heavy).

Fraternal Twin Higgs

- Twin leptons, if stable and heavy enough, could be good thermal dark matter candidates.



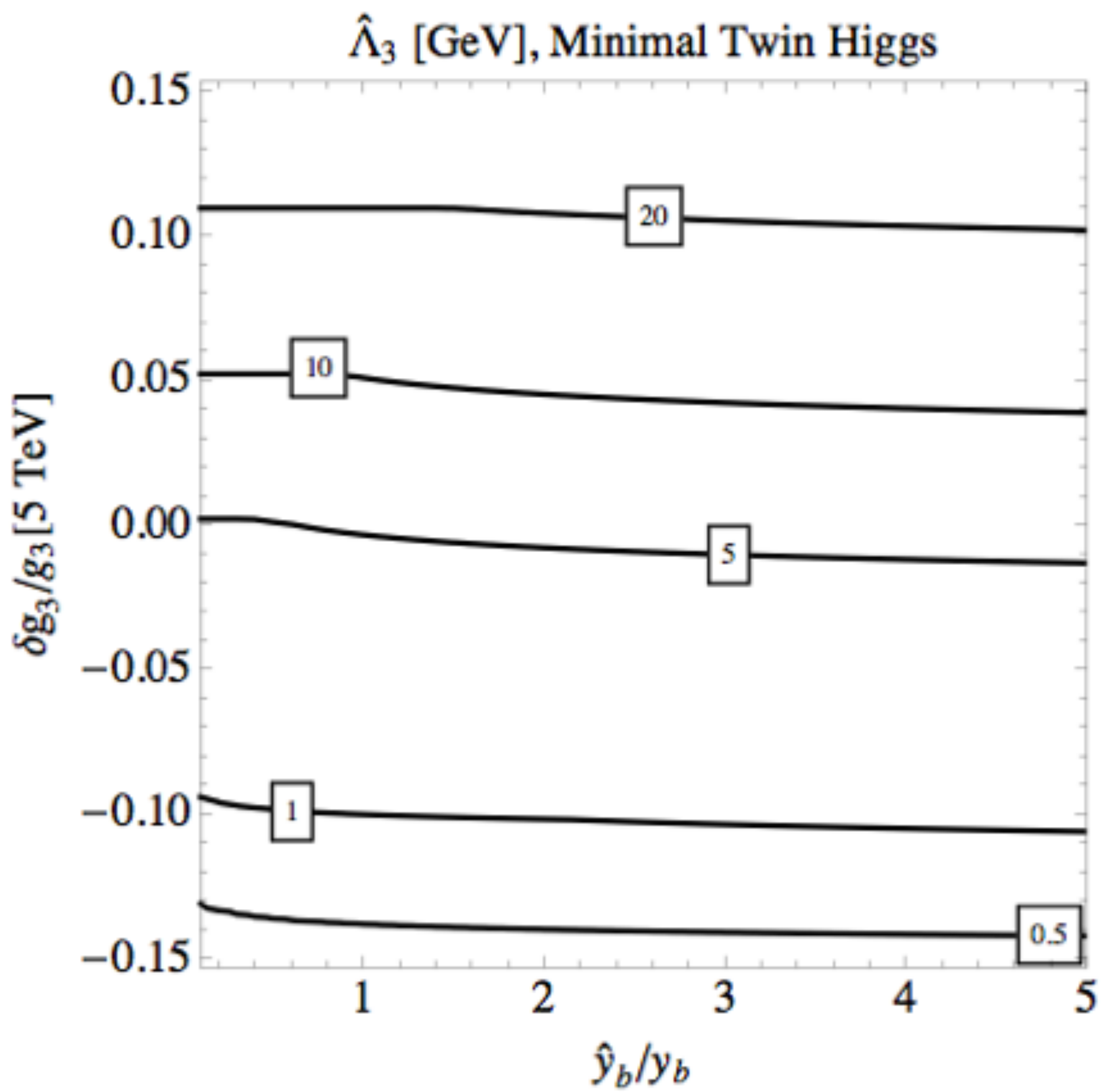
Garcia Garcia, Lasenby, March-Russell, 1505.07109

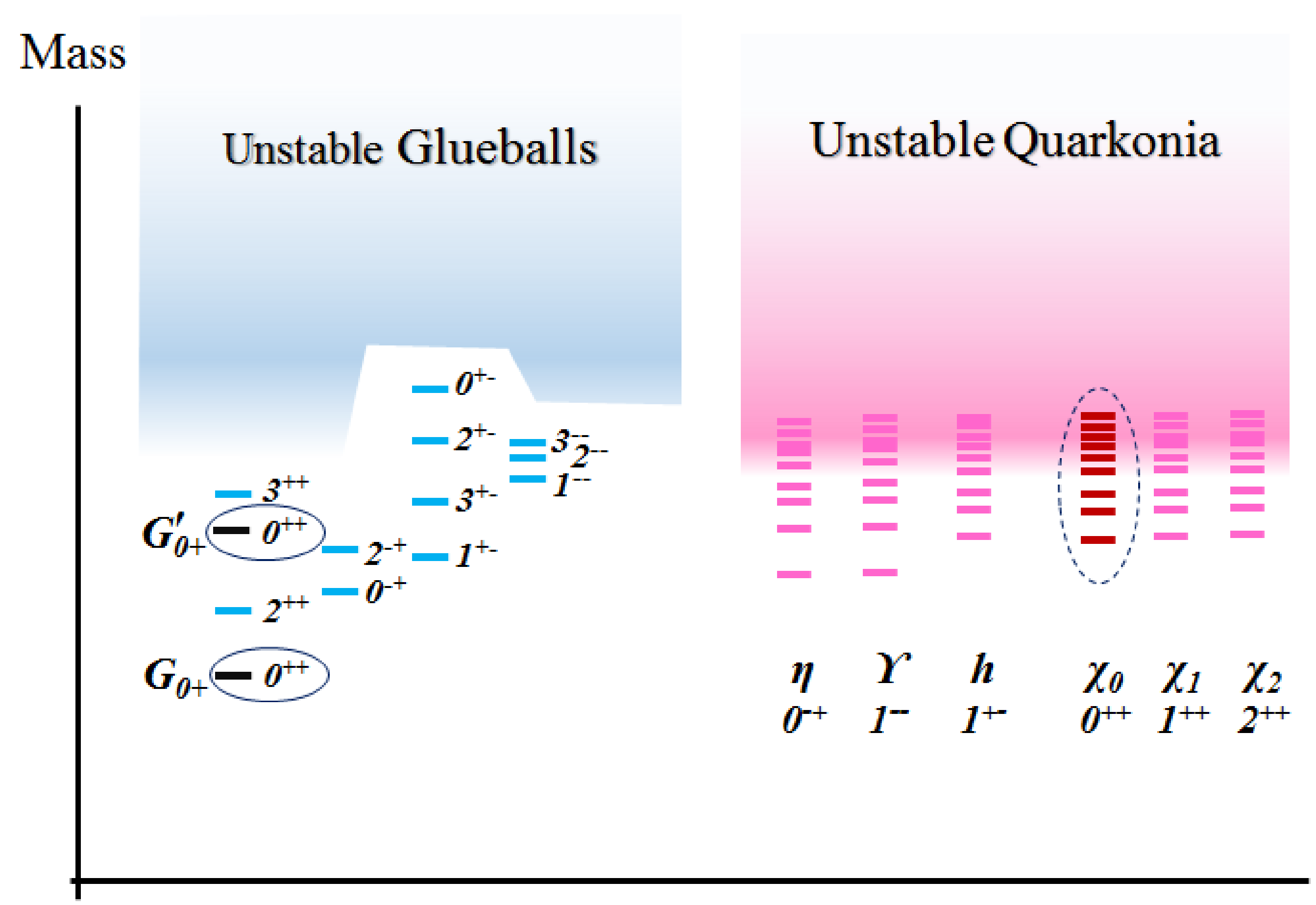


Craig, Katz, 1505.07113

Fraternal Twin Higgs

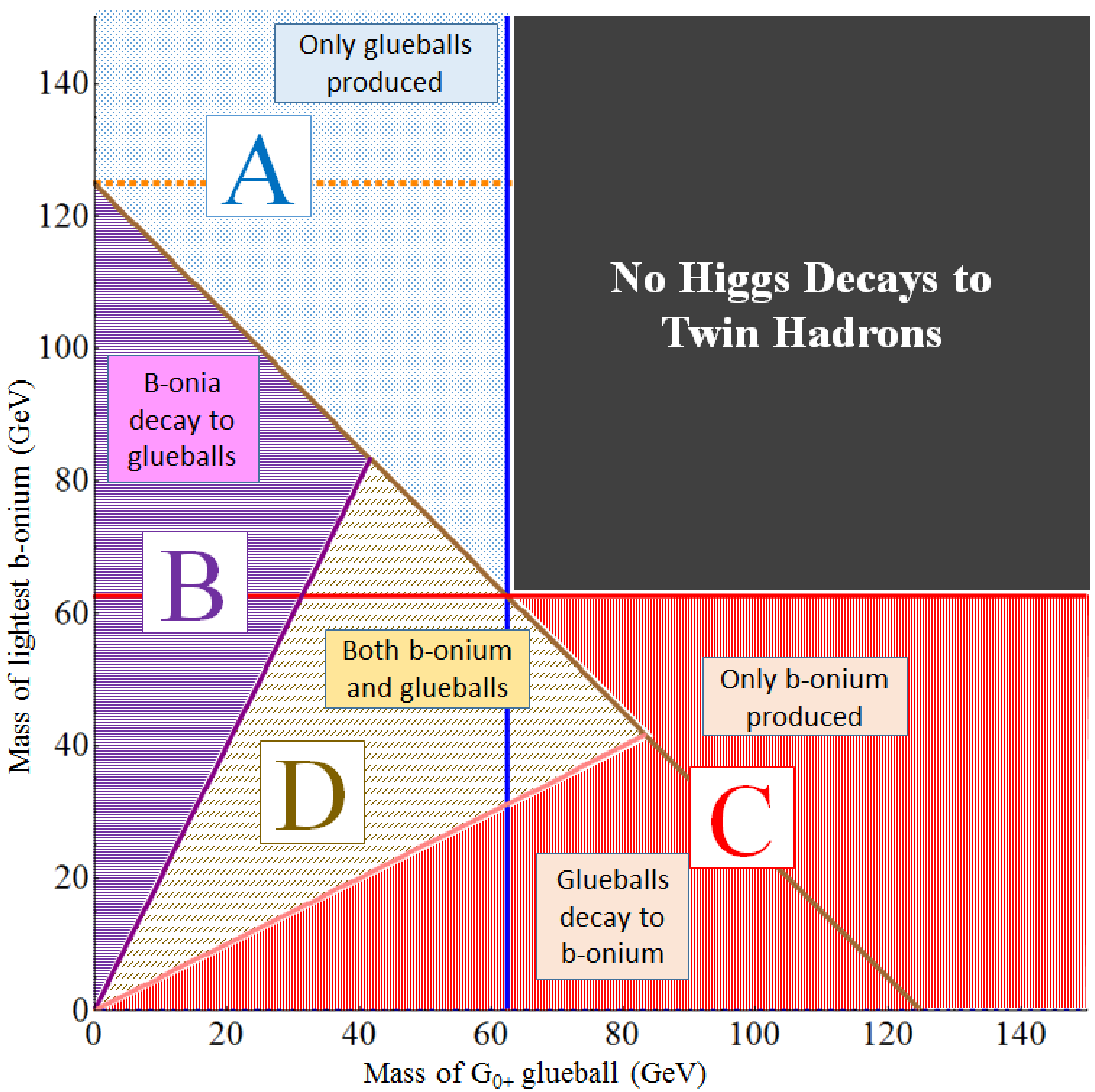
- With no light twin quarks, the lightest twin hadrons are twin glueballs or bottomonia, depending on the twin QCD scale and the twin bottom quark mass.





Fraternal Twin Higgs

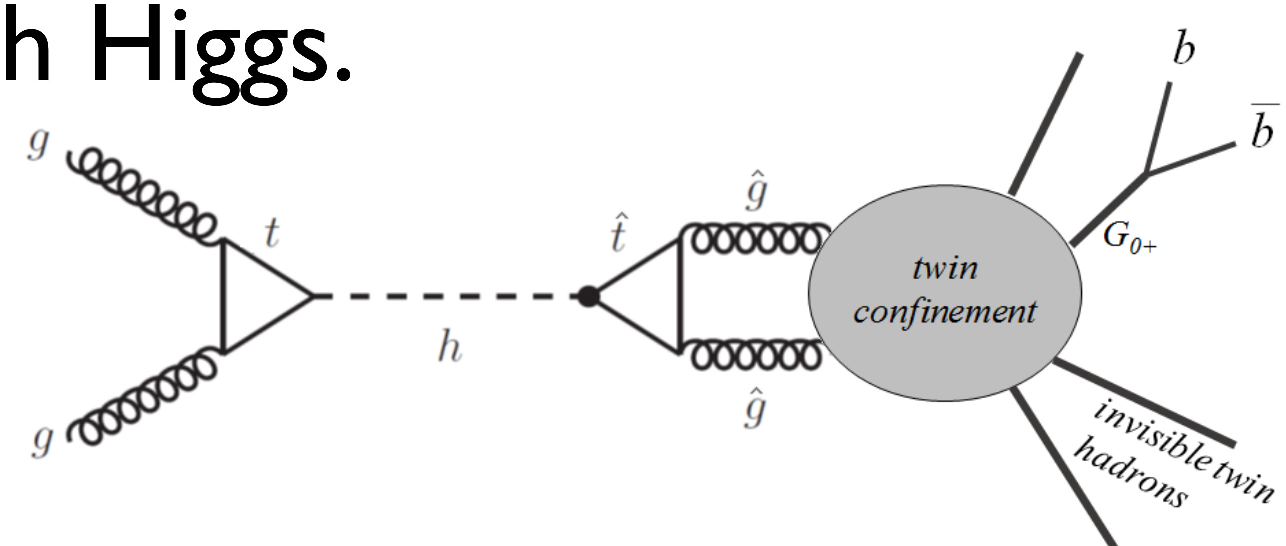
- Twin glueballs or bottomonia may be produced in Higgs decays for interesting regions of parameter regions.



Craig, Katz, Strassler, Sundrum, 1501.05310

Scalar Twin Hadron Decays

- The 0^{++} states can decay back to SM through mixing with Higgs.



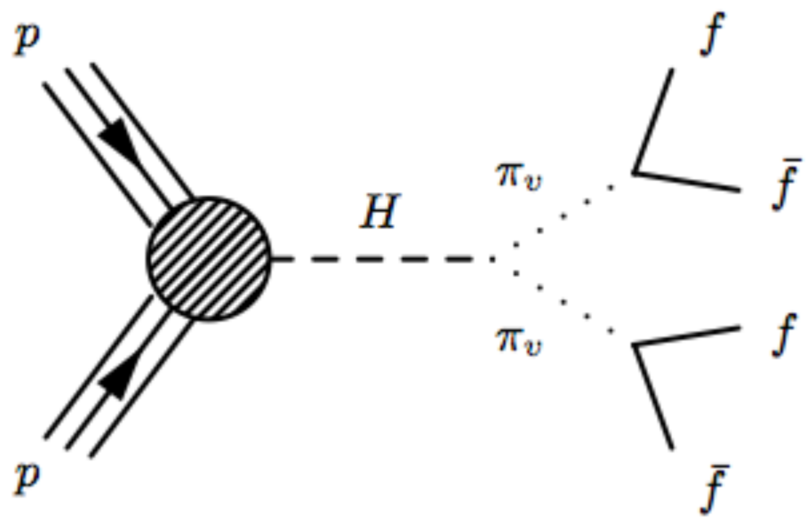
- For a typical range of parameters, the decay lengths can be macroscopic, giving rise to displaced vertices in Higgs decays.

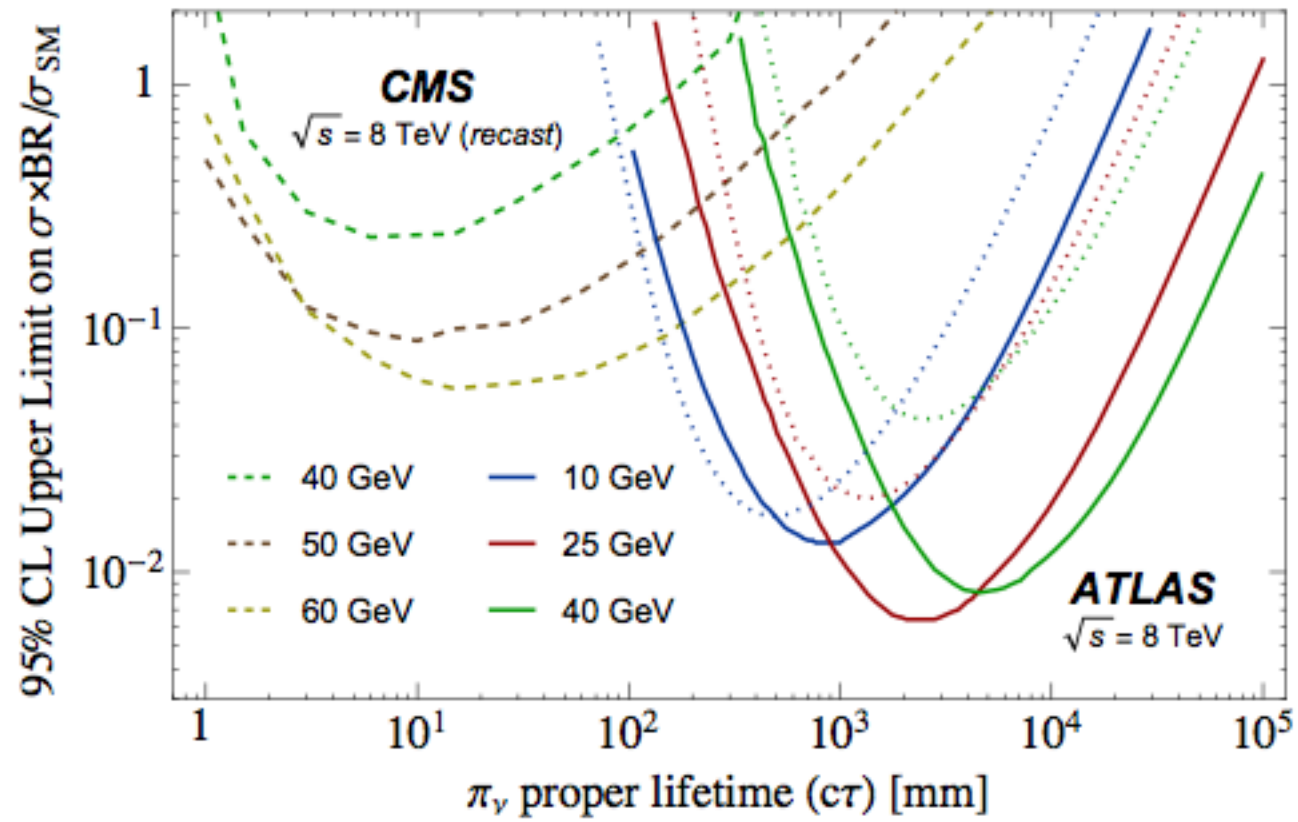
E.g., for benchmark $f = 1\ \text{TeV}, \quad \Lambda = 5\ \text{GeV}, \quad m_{Z_B} = 360\ \text{GeV}.$

$$c\tau_{\hat{G}_{0++}} \simeq 1\ \text{cm} \left(\frac{5\ \text{GeV}}{\Lambda}\right)^7 \left(\frac{f}{1\ \text{TeV}}\right)^4 .$$

$$c\tau_{\hat{\chi}_{b0}} \simeq 3.8\,\text{cm} \left(\frac{m_b}{m_{\hat{b}}}\right)^2 \left(\frac{f}{1\ \text{TeV}}\right)^4 \left(\frac{5\,\text{GeV}}{\Lambda}\right)^5 \left(\frac{\sqrt{s}}{3\Lambda}\right)^{-2} \qquad m_{\hat{b}} \lesssim \Lambda$$

Displaced Higgs Decays Searches





- References

ATLAS Collaboration, "Search for long-lived, weakly interacting particles that decay to displaced hadronic jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," arXiv:1504.03634 [hep-ex].

ATLAS Collaboration, "Search for pair-produced long-lived neutral particles decaying in the ATLAS hadronic calorimeter in pp collisions at $\sqrt{s} = 8$ TeV," Phys. Lett. B **743**, 15 (2015), arXiv:1501.04020 [hep-ex].

CMS Collaboration, "Search for long-lived particles that decay into final states containing two electrons or two muons in proton-proton collisions at $\sqrt{s} = 8$ TeV," arXiv:1411.6977 [hep-ex].

Displaced Higgs Decays Searches

- It's not easy to trigger without a hard object for a relatively light twin hadron. The 7-8 TeV LHC data give no meaningful constraint. Future LHC runs could probe some interesting parameter regions.

Trigger	Trigger Requirement
Displaced jet [a]	$H_T > 175$ GeV or three jets with $p_T^{j1,2,3} >$ (92, 76, 64) GeV, $\vert\eta_{j_{1,2,3}}\vert <$ (5.2, 5.2, 2.6) with $\vert\eta_{j_1}\vert$ or $\vert\eta_{j_2}\vert < 2.6$, and two jets satisfying $m_{jj} > 500$ GeV and $\Delta\eta > 3.0$. A displaced jet satisfying $p_T > 40$ GeV, at most 1 prompt track (2D IP < 2.0 mm), and at least 2 displaced tracks.
Inclusive VBF	Two jets with $\vert\eta_{j_1,j_2}\vert > 2$, $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\vert\eta_{j_1} - \eta_{j_2}\vert > 3.6$ and $m_{j_1,j_2} > 1000$ GeV.
VBF, $h \to b\bar{b}$	Three jets with $p_T^{j1,2,3} > (112, 80, 56)$ GeV and $\vert\eta_{j_{1,2,3}}\vert <$ (5.2, 5.2, 2.6) and at least one of the two first jets with $\vert\eta_{j_1}\vert$ or $\vert\eta_{j_2}\vert <$ 2.6.
Isolated Lepton	One lepton with $p_T > 25$ GeV, $\vert\eta\vert < 2.4$, and 3D IP < 1 mm. Isolation requires the summed p_T of all tracks with $p_T > 1$ and within $\Delta R < 0.2$ of the lepton is less than 10% of the lepton p_T.
Trackless jets	A jet with $p_T > 40$ GeV and $\vert\eta\vert < 2.5$ matched with a muon with $p_T > 10$ GeV within $\Delta R = 0.4$. No tracks with $p_T > 0.8$ GeV in the ID within a $\Delta\phi \times \Delta\eta$ region of 0.2×0.2.

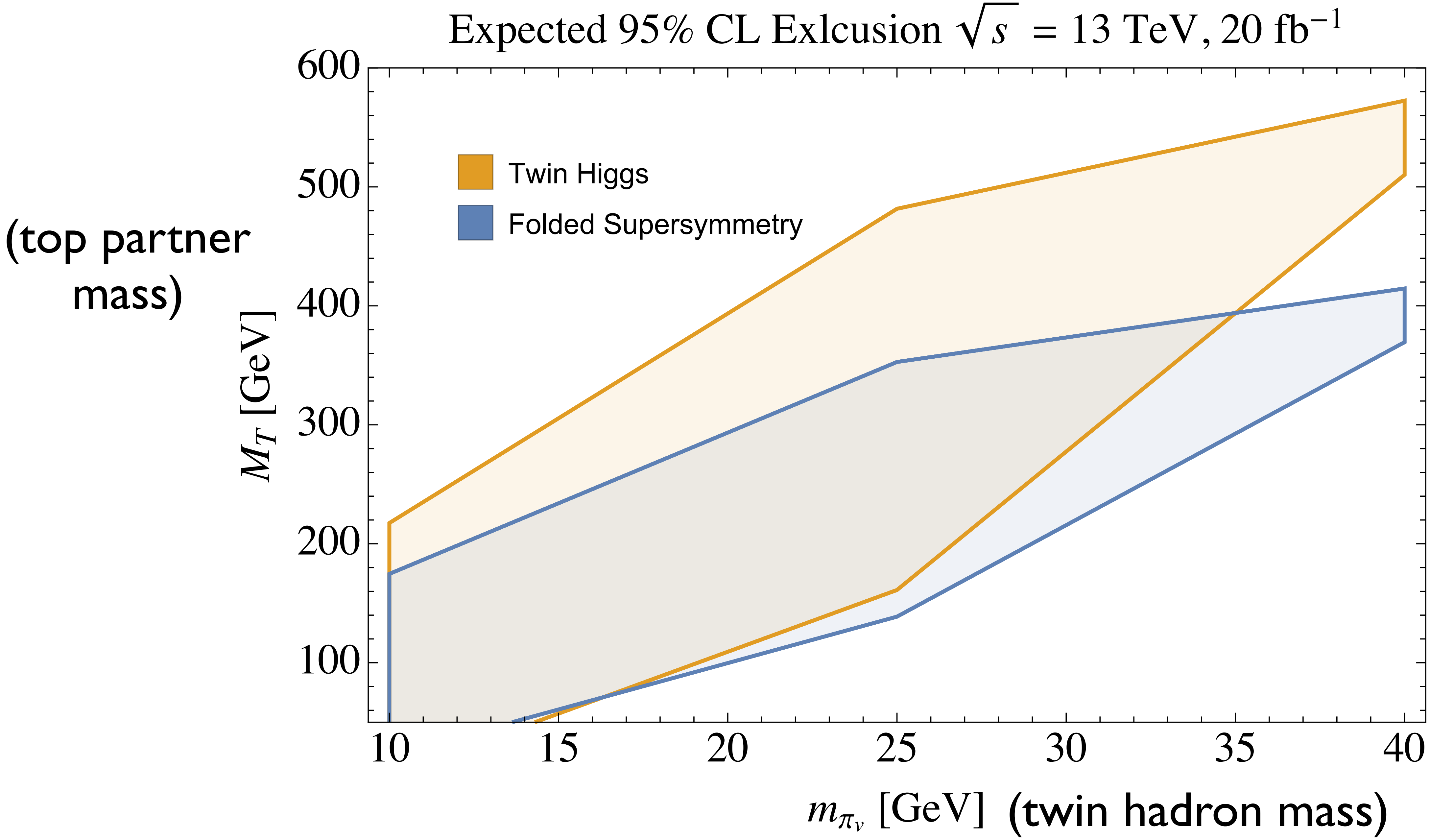
TABLE I. Triggers for Run II which may be sensitive to displaced Higgs decays.

Trigger	m_{π_v} (GeV)	$c\tau = 1$ mm				$c\tau = 10$ mm				$c\tau = 100$ mm			
		ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}
Displaced jet	10	0.03%	1.3%	1.1%	**0.2%**	1.0 %	30.0%	25.1%	**3.9%**	1.0%	42.0%	34.7%	**5.1%**
	25	0.01%	0.8%	0.7%	**0.09%**	0.7%	20.4%	16.9%	**2.7%**	1.5%	45.3%	37.3%	**5.9%**
	40	0.02%	1.0 %	0.9%	**0.1%**	0.6%	19.7%	16.4%	**2.5%**	1.4%	44.6%	36.3%	**5.7%**
Inclusive VBF	10	1.9%	15.5%	0.8%	**2.8%**	1.8%	15.5%	0.7%	**2.8%**	1.6%	15.1%	0.6%	**2.6%**
	25	1.7%	15.3%	0.7%	**2.7%**	1.7%	15.3%	0.7%	**2.7%**	1.6%	15.2%	0.6%	**2.6%**
	40	1.6%	15.2%	0.7%	**2.6%**	1.6%	15.2%	0.7%	**2.6%**	1.6%	15.2%	0.6%	**2.6%**
VBF, $h \to b\bar{b}$	10	5.8%	20.3%	13.1%	**7.2%**	5.8%	20.2%	13.0%	**7.2%**	3.5%	13.3%	8.1%	**4.4%**
	25	4.6%	16.6%	10.9%	**5.8%**	4.7%	16.7%	10.9%	**5.9%**	4.2%	15.2%	9.7%	**5.3%**
	40	4.0%	14.2%	9.2%	**5.0%**	4.0%	14.2%	9.2%	**5.0%**	3.8%	13.9%	8.9%	**4.8%**
Isolated Lepton	10	3.6%	3.7%	14.7%	**4.1%**	1.0%	1.0%	12.5%	**1.5%**	0.1%	0.2%	11.8%	**0.6%**
	25	1.0%	1.5%	13.0%	**1.6%**	0.3%	0.4%	11.9%	**0.8%**	0.05%	0.07%	11.7%	**0.6%**
	40	1.0%	1.4%	12.6%	**1.6%**	0.3%	0.4%	11.9%	**0.8%**	0.05%	0.07%	11.6%	**0.6%**
Trackless jet	10	0.02%	0.04%	0.04%	**0.02%**	0.8%	1.5%	1.3%	**0.9%**	2.0%	2.4%	2.2%	**2.0%**
	25	0.02%	0.04%	0.06%	**0.02%**	0.5%	1.0%	0.8%	**0.6%**	3.6%	5.9%	5.0%	**3.8%**
	40	0.01%	0.02%	0.03%	**0.01%**	0.1%	0.2%	0.2%	**0.1%**	2.1%	4.1%	3.3%	**2.3%**

Csaki, Kuflik, Lombardo, Slone, 1508.01522v3

Displaced Higgs Decays Searches

- Expected Run 2 reaches:



Csaki, Kuflik, Lombardo, Slone, 1508.01522v3

Vector Twin Hadron Decays

- $\hat{\Upsilon}$ (1^{--}) could decay back to SM through kinematic mixing between the U(1)'s, $-(\epsilon/2)B_{\mu\nu}\hat{B}^{\mu\nu}$

$$c\tau_{\hat{\Upsilon}} \simeq 1.3\,\text{cm}\left(\frac{m_{\hat{A}}}{100\,\text{GeV}}\right)^4\left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{5\,\text{GeV}}{\Lambda}\right)^5\left(\frac{\sqrt{s}}{3\Lambda}\right)^{-2} \quad m_{\hat{b}} \lesssim \Lambda$$

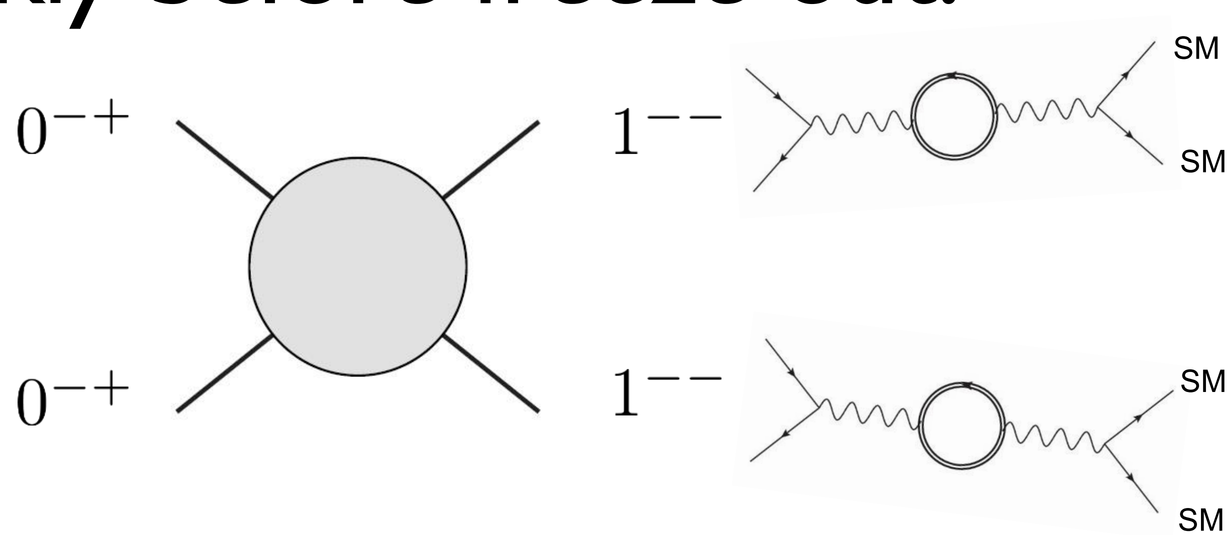
(assuming that twin leptons are heavy).

If twin photon is heavy and/or the kinematic mixing is small, $\hat{\Upsilon}$ could decay outside the detector, leaving only missing energy signals. However, cosmological constraints motivate that $\hat{\Upsilon}$ should decay fast enough to occur inside the detector.

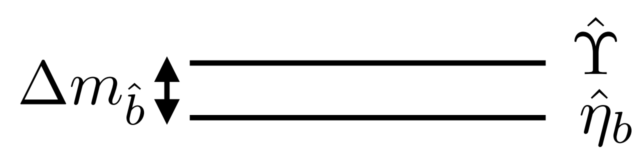
Cosmological Constraints

HC, Sunghoon Jung, Ennio Salvioni, and Yuhsin Tsai, arXiv:1512.02647

- The lightest twin bottomonium $\hat{\eta}_b(0^{-+})$ is long-lived, decaying after BBN, could cause cosmological problems. Only way to get rid of them is to have them annihilate to slightly heavier $\hat{\Upsilon}$, then to have $\hat{\Upsilon}$ decay quickly before freeze out.



$$\Gamma/H \gtrsim 1 \text{ when } T > \Delta m_{\hat{b}}$$



$$\Rightarrow c\tau_{\hat{\Upsilon}} \lesssim 10^{-9} \text{ sec, or } \lesssim 30 \text{ cm.}$$

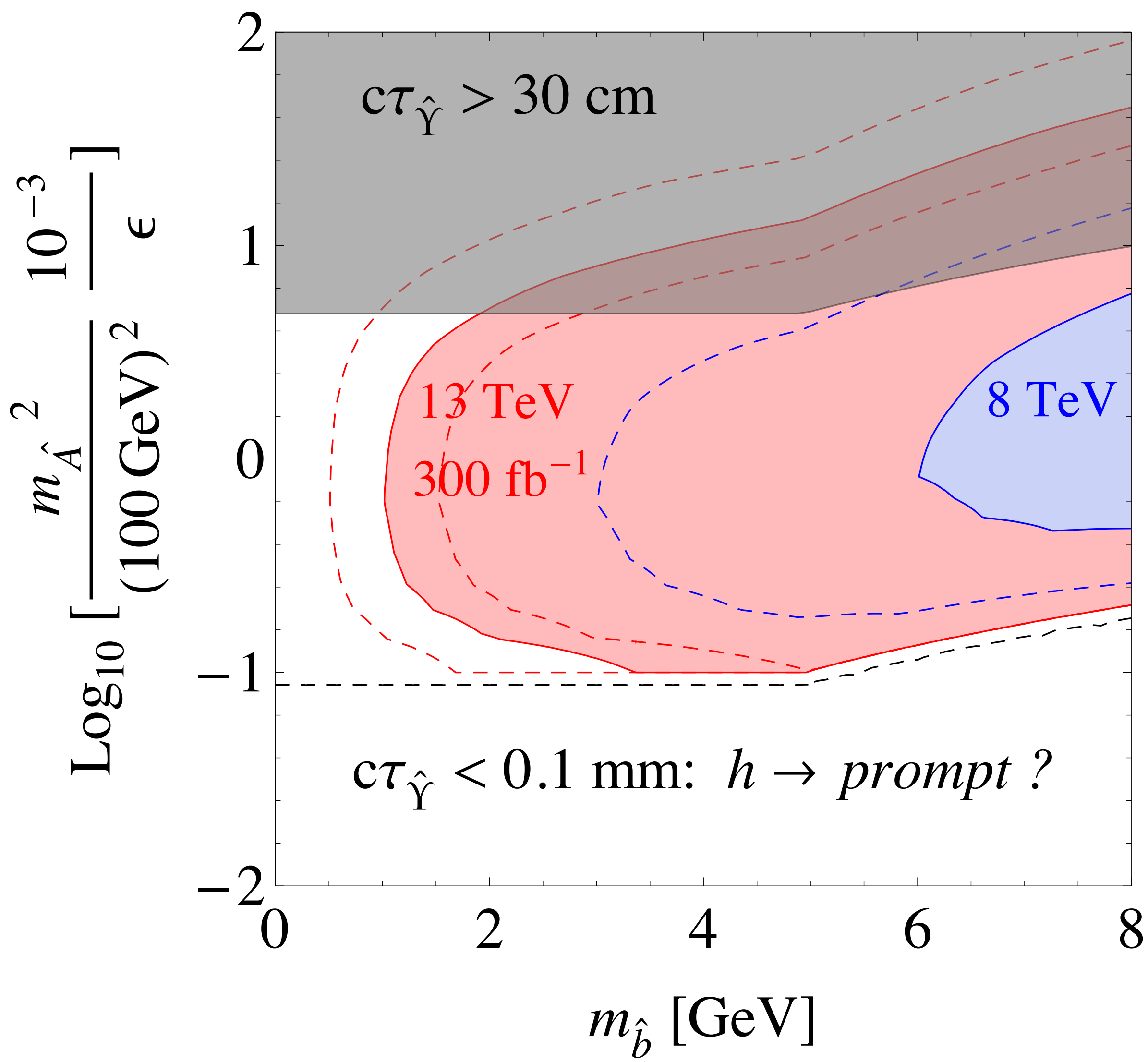
Collider Constraints on Twin Υ

- It depends on the fraction $R_{\hat{\Upsilon}}$ of the twin bottomonia being $\hat{\Upsilon}$.
  - Most twin bottomonia should have low l.
  - There are $4(l{+}1)^2$ states with orbital angular momentum up to l. $\hat{\Upsilon}$ has 3 states.
  - Assuming that all states below l are produced equally:

$$R_{\hat{\Upsilon}} \;=\; 3/4, \quad 3/16, \quad 3/36$$
$$(l=0) \;\; (l\le 1) \;\; (l \le 2)$$

Twin Υ from Higgs Decay

$$pp \to h \to \hat{\Upsilon}\hat{\Upsilon}, \qquad \hat{\Upsilon} \to (\mu^+\mu^-)_{\rm DV}$$



Assuming fraction of twin bottomonia being $\hat{\Upsilon}$, $R_{\hat{\Upsilon}} = 3/16$

HC, Sunghoon Jung, Ennio Salvioni, and Yuhsin Tsai, arXiv:1512.02647

Reference:

CMS Collaboration, "Search for long-lived particles that decay into final states containing two electrons or two muons in proton-proton collisions at $\sqrt{s} = 8$ TeV," Phys. Rev. D **91** 052012 (2015), arXiv:1411.6977 [hep-ex].

$(\mu^+\mu^-)_{\rm DV}$ in inner detector (ID), $1 < r < 50\,\mathrm{cm}$

UV Completion

- Twin Higgs models need to be UV completed at 5-10 TeV ($< 4\pi f$), with new states regularizing the log divergence in the Higgs potential.
- In non-SUSY UV completions, the top sector needs to be extended to complete multiplets of SU(6)×SU(4) (⊃[SU(3)×SU(2)]^2) $\Longrightarrow$ new fermions charged under both SM and twin gauge groups.

twin SU(3) SM SU(3)

twin SU(2)

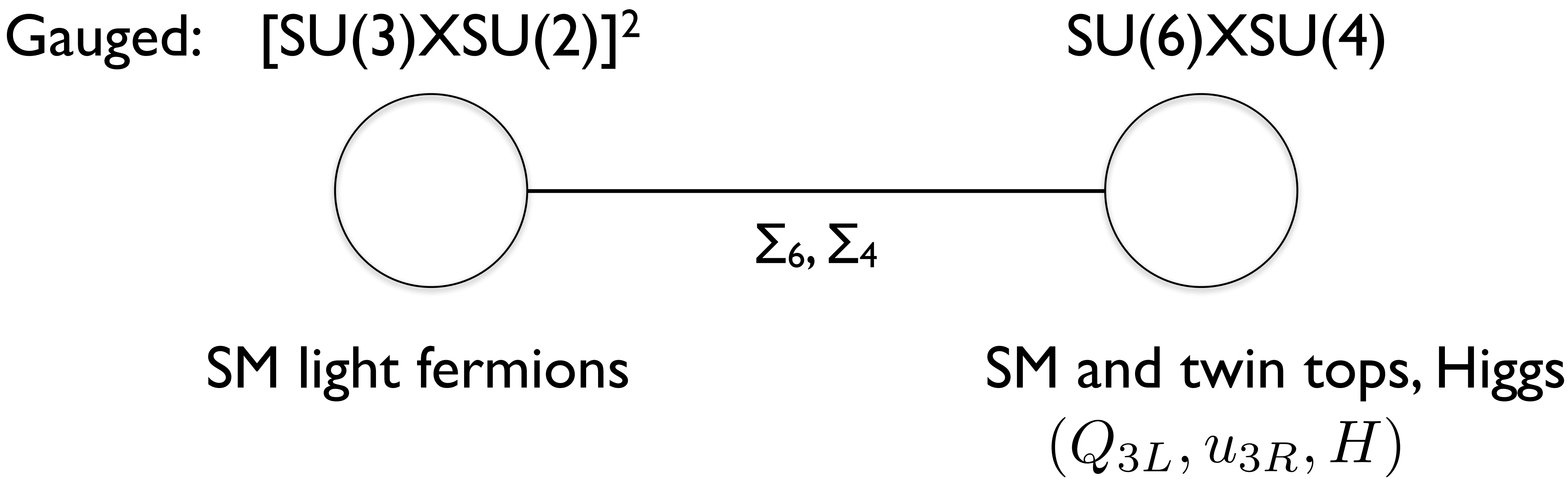
SM SU(2)

$$-\mathcal{L}_t = y_t H^\dagger Q_{3L}\bar{u}_{3R} + \text{h.c.} = y_t \begin{pmatrix} H_B^\dagger & H_A^\dagger \end{pmatrix} \begin{pmatrix} q^B_{3L} & \tilde{q}^A_{3L} \\ \tilde{q}^B_{3L} & q^A_{3L}\end{pmatrix}\begin{pmatrix}\bar{u}^B_{3R}\\ \bar{u}^A_{3R}\end{pmatrix} + \text{h.c.},$$

$$-\mathcal{L}_m = \tilde{M}_A \bar{\tilde{q}}^A_{3R}\tilde{q}^A_{3L} + \tilde{M}_B \bar{\tilde{q}}^B_{3R}\tilde{q}^B_{3L} + \text{h.c.}.$$

Two-site Model

- The exotic states can be described by a two-site model.



Exotic States

- Exotic fermions: $\tilde{q}_3^A$ SM colored, twin EW charges (exotic quarks)
  $\tilde{q}_3^B$ SM EW charges, twin colored
- Exotic vectors: $\mathcal{W}$ bi-doublet under SM SU(2) and twin SU(2)
  $\mathcal{X}$ bi-fund. under SM SU(3) and twin SU(3)

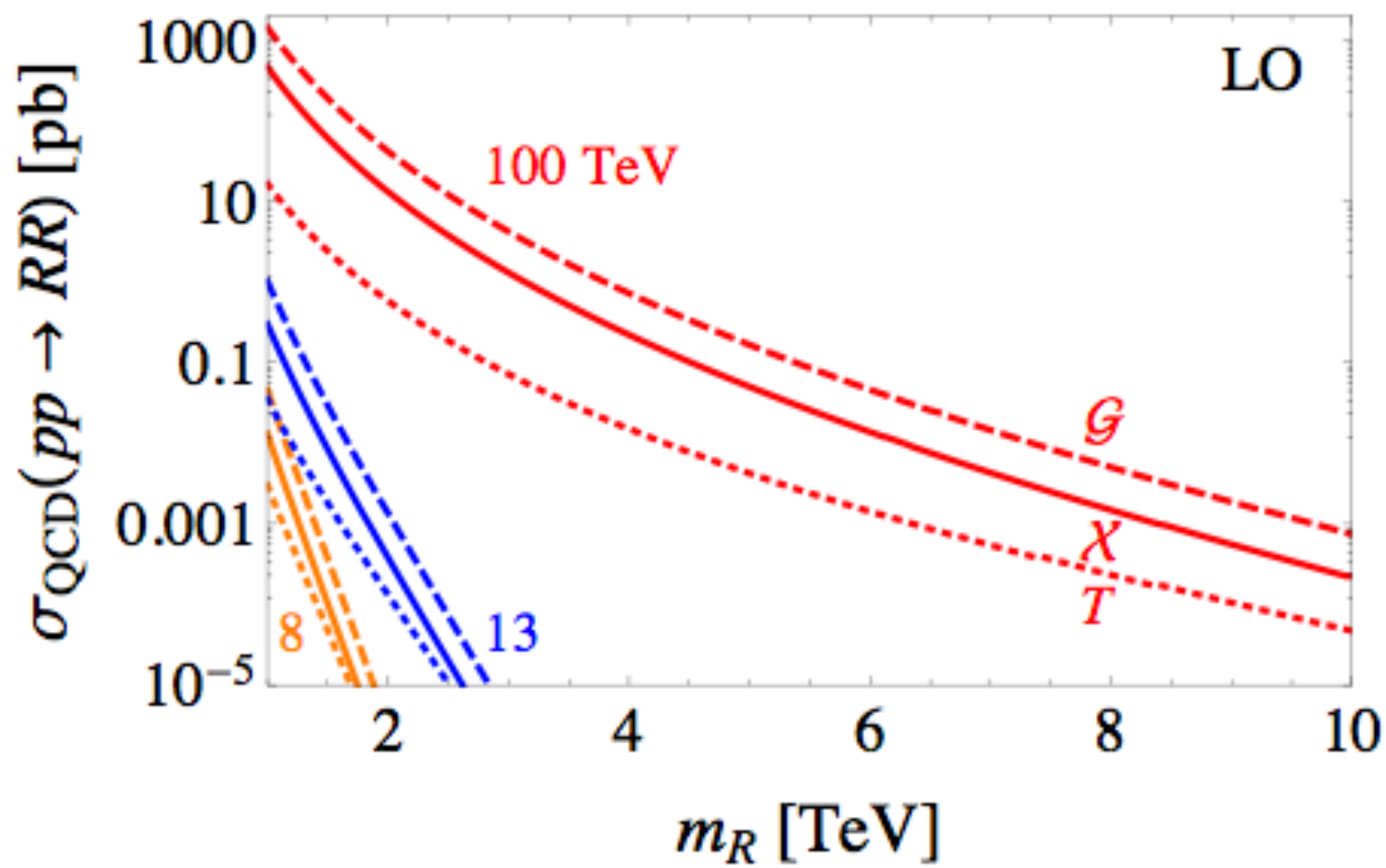
mixed with SM top ($\mathcal{T}$)

mixed with twin top ($\mathcal{K}^0$)

	$SU(3)$		$SU(2)$		$U(1)$		$U(1)_{\rm em}$	
	A	B	A	B	Y	D	SM	Twin
$\tilde{q}_3^A = \begin{pmatrix} \tilde{u}_3^A \approx \mathcal{T} \\ \tilde{d}_3^A = \mathcal{B} \end{pmatrix}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$2/3$	$-1/2$	$\begin{pmatrix} 2/3 \\ 2/3 \end{pmatrix}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
$\tilde{q}_3^B = \begin{pmatrix} \tilde{u}_3^B \approx \mathcal{K}^0 \\ \tilde{d}_3^B = \mathcal{K}^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{1}$	$-1/2$	$2/3$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$	$\begin{pmatrix} 2/3 \\ 2/3 \end{pmatrix}$
$\mathcal{X}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$2/3$	$-2/3$	$2/3$	$-2/3$
$\mathcal{W} = \begin{pmatrix} \mathcal{W}_1^0 & \mathcal{W}_1^+ \\ \mathcal{W}_2^0 & \mathcal{W}_2^+ \end{pmatrix}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$1/2$	$-1/2$	$\begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 \\ -1 & -1 \end{pmatrix}$

Production of Exotic States

- Colored exotic states may be copiously produced at the hadron colliders if their masses are within reach.



- $\tilde{q}_3^B$, $\mathcal{W}$ are produced by EW interactions. $\tilde{q}_3^B$ may also be produced in $\mathcal{X}$ decays.

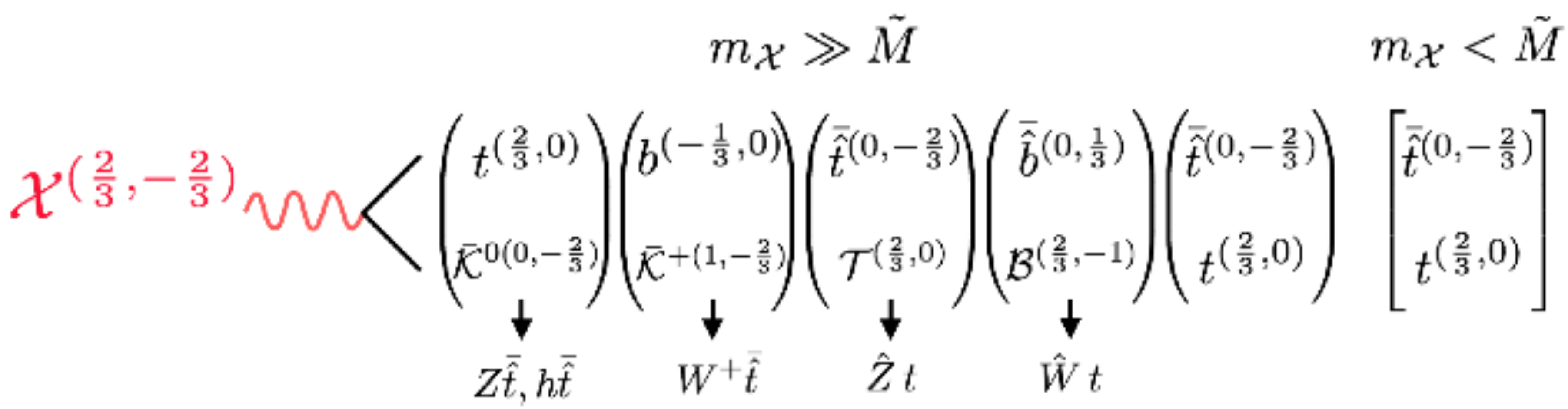
Colored Exotic State Decays

- Exotic quark decays

  $\mathcal{T} \to t\, Z_B$ (dominant for large mass), $th,\ bW,\ tZ$ (due to mixing with top)

  $\mathcal{B} \to t\, W_B \quad (100\%)$

- $\mathcal{X}$ decays



- Most final states contain t (or bW) + twin sector particles. If twin particles give missing energies ⇒ Stop-like signals.

Exotic Quark Reaches from Stop or t' searches

- Stop search reaches: $t\bar{t} + \not{E}_T$ if twin sector is invisible

$$m_{\mathcal{B}} \gtrsim 1.43\text{TeV} \quad (13\text{TeV}, 300\text{fb}^{-1})$$
$$m_{\mathcal{B}} \gtrsim 7.58\text{TeV} \quad (100\text{TeV}, 1\text{ab}^{-1})$$

- t' search reaches from $\mathcal{T} \to b\,W + t\,Z + t\,h$

$$m_{\mathcal{T}} \gtrsim 1.41\text{TeV} \quad (13\text{TeV}, 300\text{fb}^{-1})$$
$$m_{\mathcal{T}} \gtrsim 4.13\text{TeV} \quad (100\text{TeV}, 1\text{ab}^{-1})$$

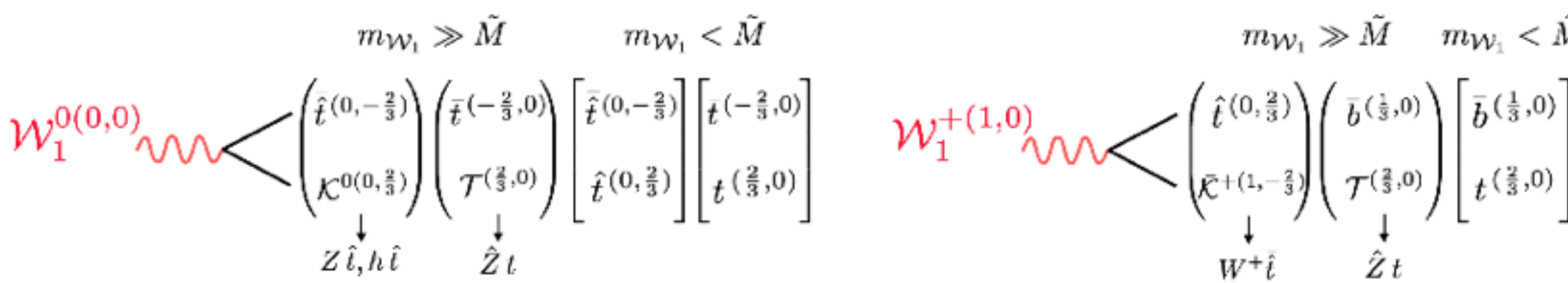
Based on Collider Reach method, Salam & Weiler,
http://collider-reach.web.cern.ch/collider-reach/

EW Exotic States

- $\mathcal{W}$ masses strongly constrained by EW precision S and T parameters.

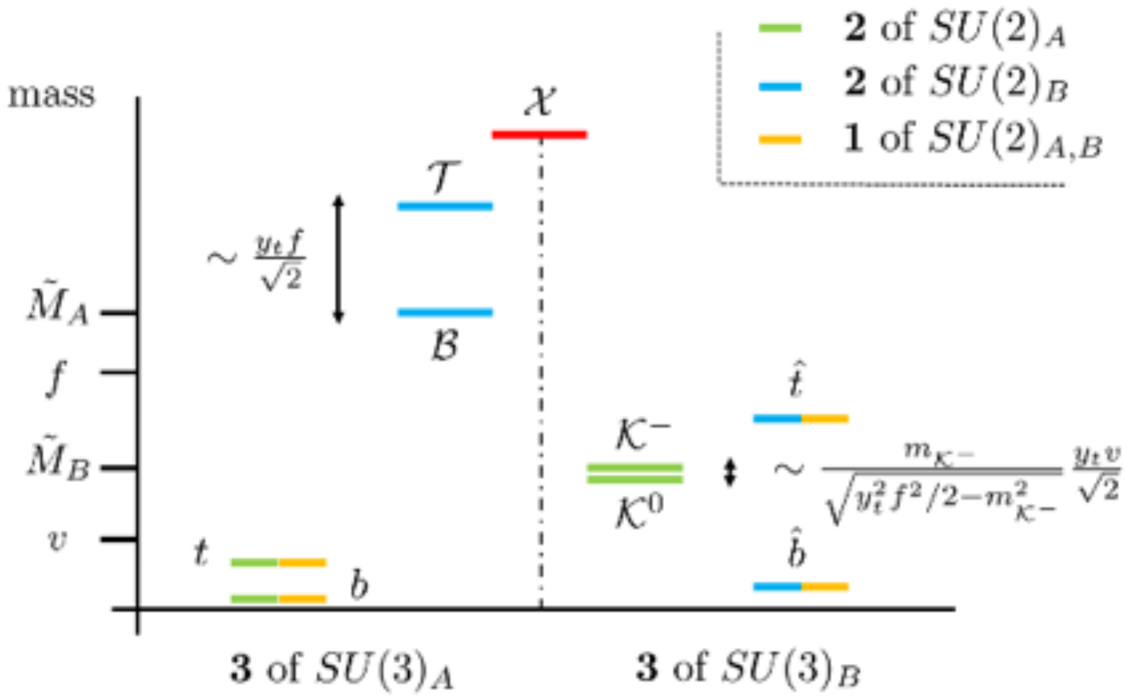
  From S parameter $m_{\mathcal{W}_1} \gtrsim 3.3$ TeV and $m_{\mathcal{W}_2} \gtrsim 2.1$ TeV
  T parameter constant is even stronger but can be removed by a custodial extension to SO(8).

- $\mathcal{W}_1$ mixes with SM W and Z, can be singly produced, but not likely to be seen at LHC due to the mass constraints, maybe possible at a 100 TeV collider.



EW Exotic States

- EW production of $\tilde{q}_3^B(\mathcal{K}^0, \mathcal{K}^-)$ can only be appreciable if they are light (violating Z_2 softly).
- For $\tilde{m}_B < f$, they form bound states by twin color force after production because their decay widths are small.



$$\mathcal{K}^- \to \mathcal{K}^0 + (W^* \to f f')$$

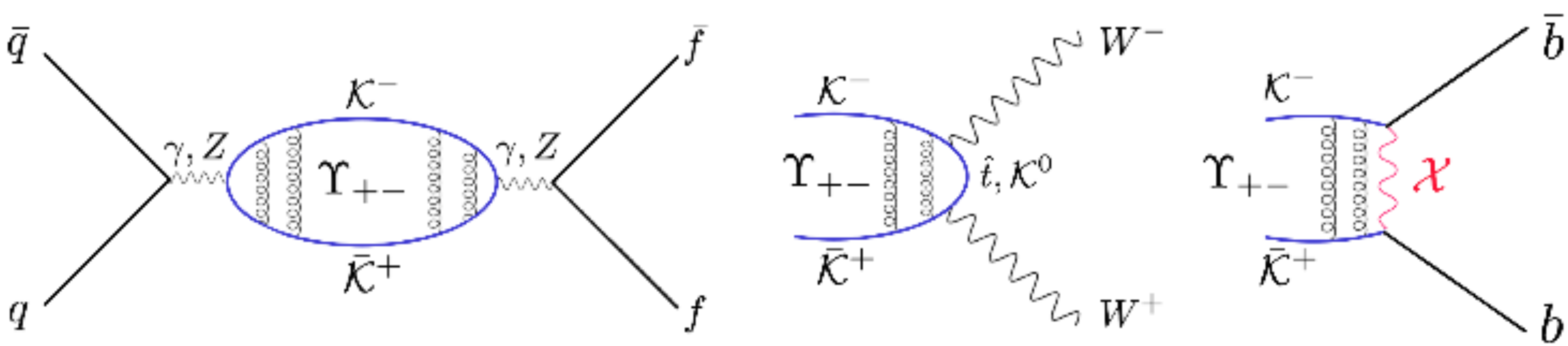
3-body, small phase space

$$\mathcal{K}^0 \to \hat{W}^{(*)} \hat{b}$$

thru mixing with twin top, 2 or 3-body

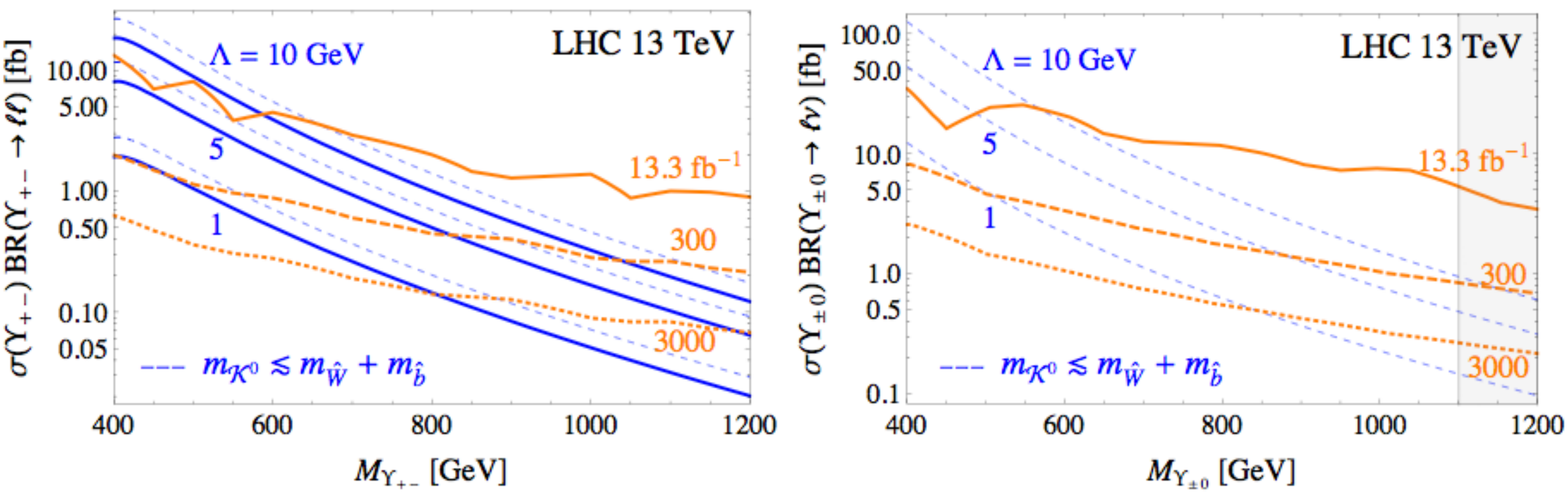
EW Exotic States

- $\Upsilon_{+-}(\mathcal{K}^+\mathcal{K}^-)$ decays dominantly by annihilating to SM fermion pair.
- The decays of $\Upsilon_{00}, \Upsilon_{\pm 0}$ depend on $\mathcal{K}^0 \to \hat{W}^{(*)}\hat{b}$ decay rate compared to the annihilation rate.
- The pseudoscalar bound state production rates are too small to be interesting.



EW Exotic Fermion Bound States

- Decays by annihilating to lepton pair provide the best way to search for these resonances made of exotic fermions.



Λ: twin QCD scale

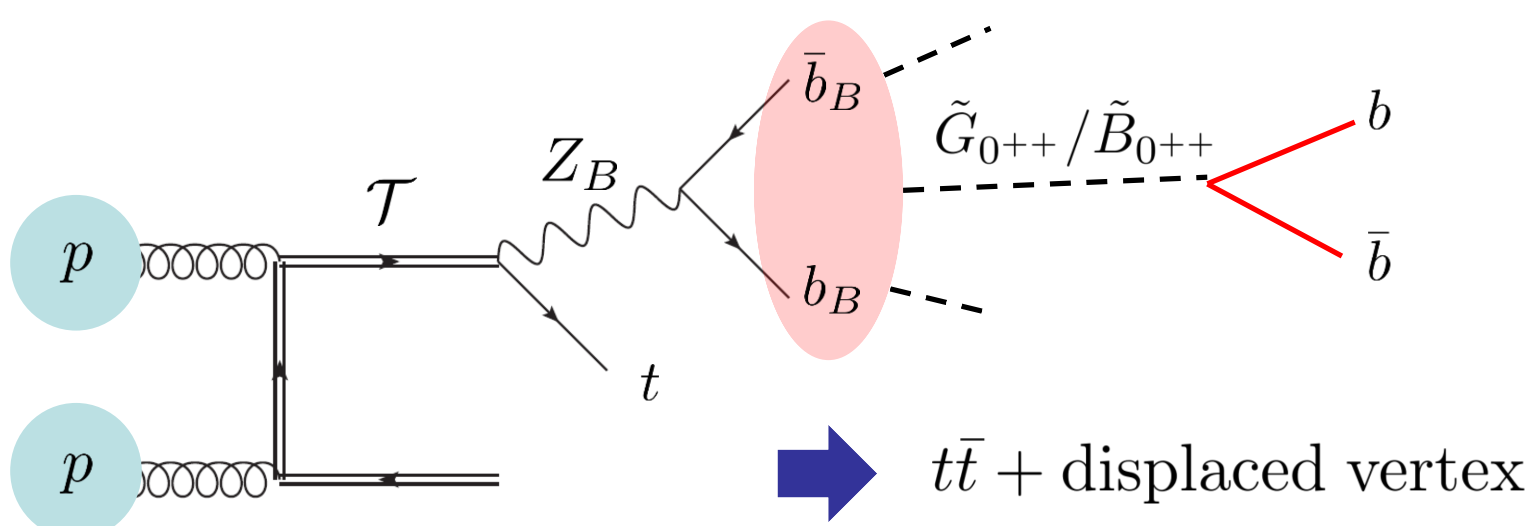
Signals from the Twin Sector

- If the twin particles from the exotic state decays can decay back to SM particles (with displaced vertices), there are more distinctive signals.

  Ex: The exotic quark search with displaced vertices can be triggered from hard objects from top decay, which makes it essentially background free.

$$pp \;\to\; (\mathcal{T} \to tZ_B)(\overline{\mathcal{T}} \to \bar{t}Z_B) \;\to\; t\bar{t} \;+\; \text{twin hadrons}\,,$$

$$\text{twin hadron} \;\to\; \text{displaced vertex.}$$



Twin Hadronizations

- The twin b's from Z_B decay form a long string.

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

String breaking dominates, producing multiple twin bottomonia.

$\hat{\chi}_{b0}\ (0^{++}, p\text{-wave})$

$\hat{\Upsilon}\ (1^{--}, s\text{-wave})$

$\hat{\eta}_b\ (0^{-+}, s\text{-wave})$

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

Twin glueball emission from twin b scattering dominates.

$\hat{G}_{0^{-+}} (\sim 1.5 m_0)$

$\hat{G}_{2^{++}} (\sim 1.4 m_0)$

$\hat{G}_{0^{++}} (m_0 \approx 6.8\Lambda)$

Exotic Quark Searches

- For the benchmark Λ=5 GeV,

String breaking dominates for $m_{\hat{b}} \lesssim 8\,\mathrm{GeV}$

Typically 10 − 4 twin bottomonia are produced for $m_{\hat{b}} \in (0,\, 8)\,\mathrm{GeV}$

Can produce various excited states, collider searches depend on their fractions.

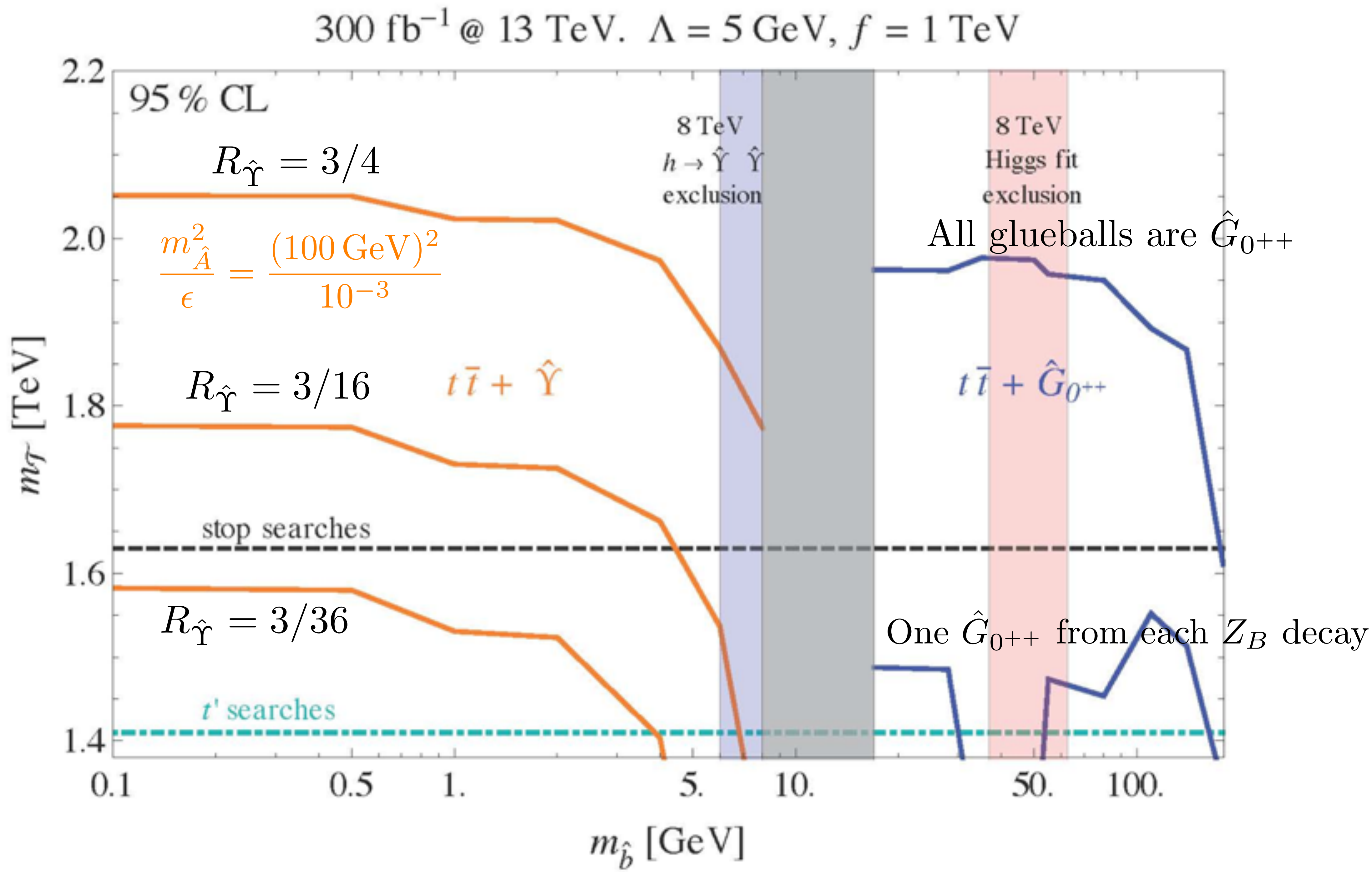
Twin glueball emission dominates for $m_{\hat{b}} \gtrsim 17\,\mathrm{GeV}$

Typically 8 − 2 twin glueballs are produced for $m_{\hat{b}} \in (17,\, 180)\,\mathrm{GeV}$

Presumably dominated by the lightest $\hat{G}_{0^{++}}$

Exotic Quark Searches

LHC



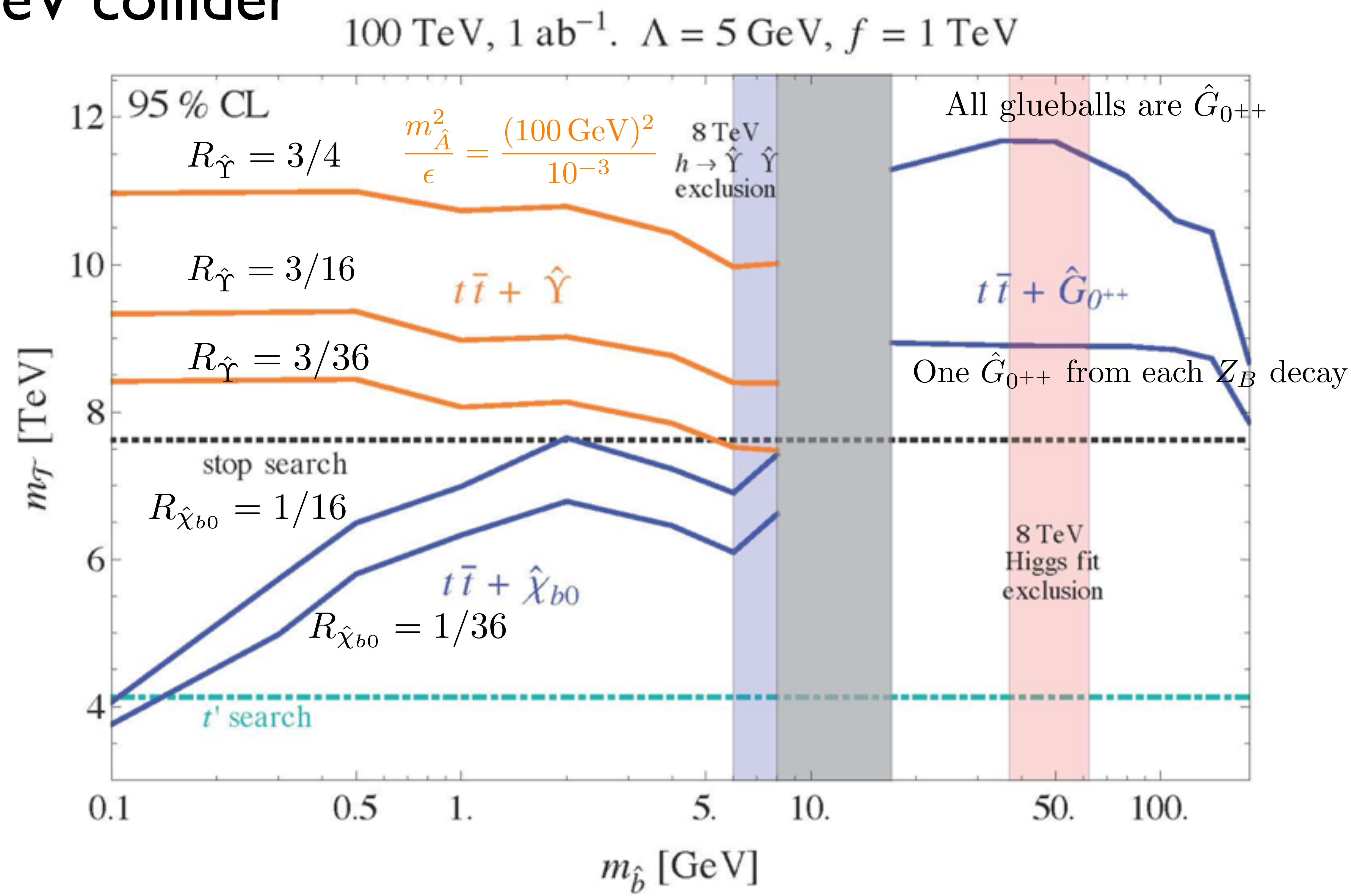
Twin bottomonia dominate

Twin glueballs dominate

Based on a simplified model of hadronization

Exotic Quark Searches

100 TeV collider



Conclusions

- The Twin Higgs model provides an elusive natural theory of EW symmetry breaking.
- In low energy theory, the experimental reaches from modification of Higgs couplings and invisible Higgs decay are limited.
- However, it needs UV completion below 5-10 TeV, the exotic states carrying both SM and twin charges provide additional probes of the model.
- There can be novel experimental signatures associated with exotic states, such as displaced vertices from hidden sector decays, or resonance signals from bound states formed by twin color.