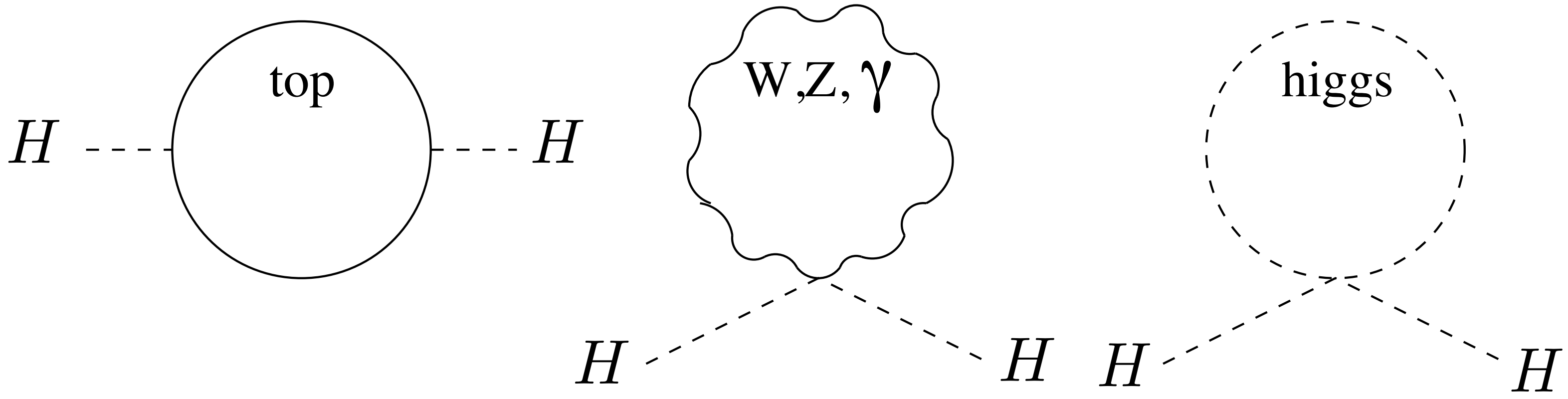
Twin Higgs Models and Their Collider Phenomenology

Hsin-Chia Cheng
University of California, Davis

MC4BSM 2016 UCAS, Beijing, 20-24, July 2016

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

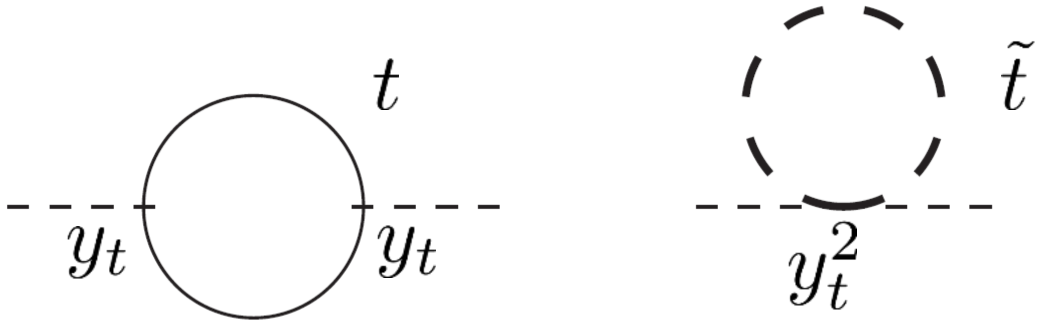
Superpartners have the same gauge quantum numbers as the SM particles, but have the spins differed by 1/2.

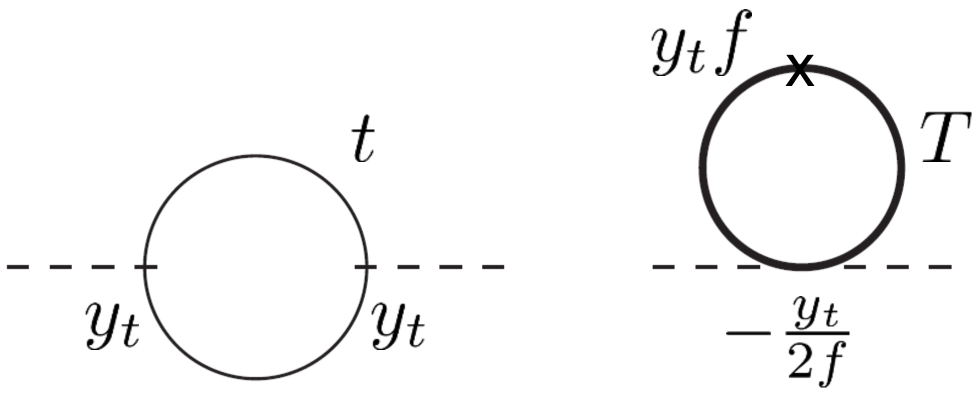
Global symmetry (Higgs as PNGB)

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

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

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

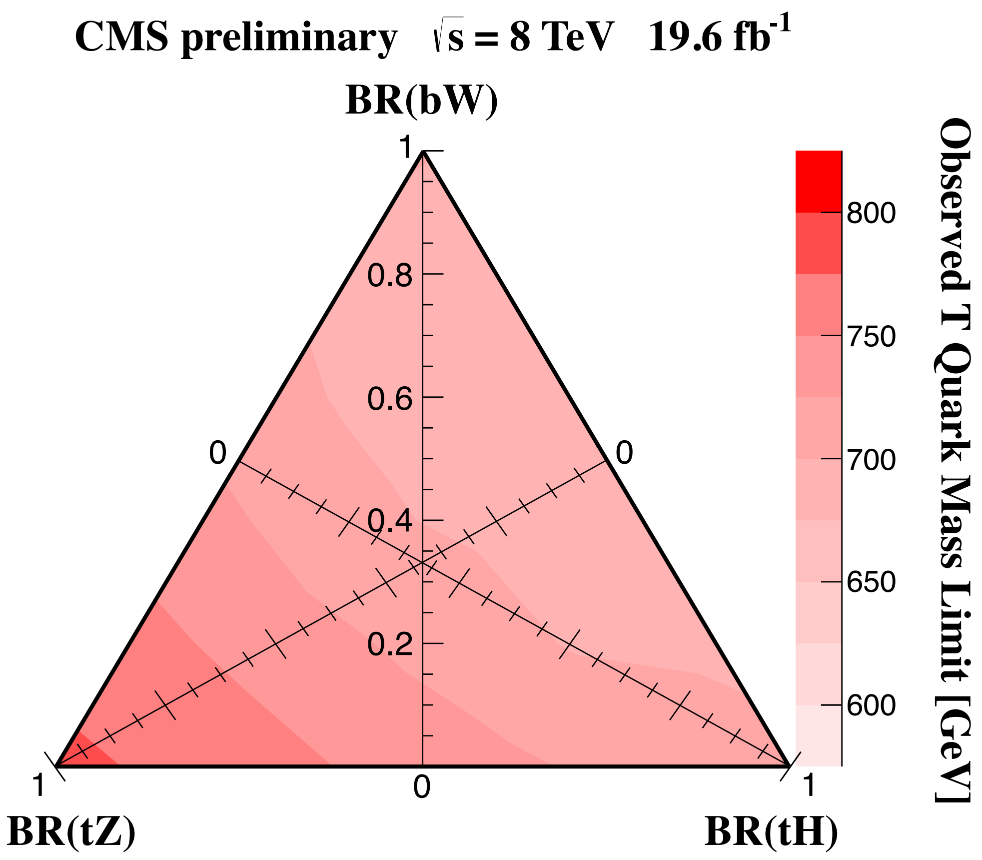




Naturalness of Weak Scale

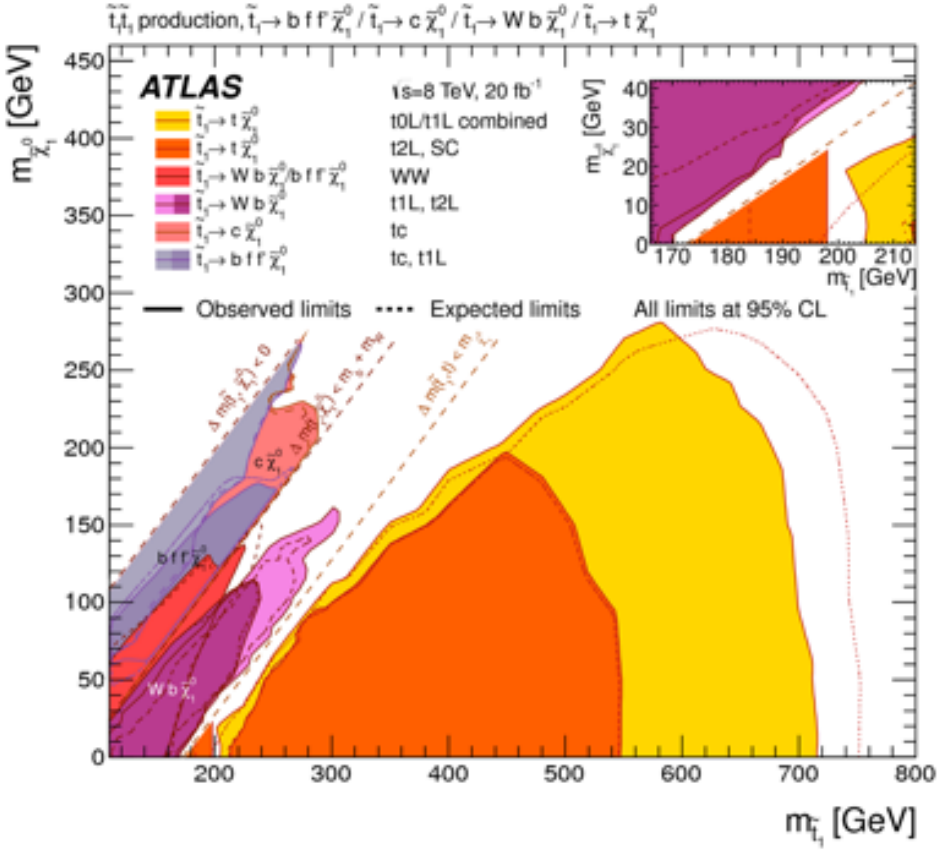
- Top partners are extensively searched at LHC, but nothing was found below 700-800 GeV, which makes the hierarchy problem more prominent.

Global Symmetry



CMS B2G-12-015

Supersymmetry



Neutral Naturalness

- As a result, 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

- Imagine that there is a "mirror" or "twin" sector related to SM by an (approximate) Z_2 symmetry.
- The SM Higgs doublet and twin Higgs doublet have an approximate 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 guaranteed by the Z_2 symmetry. No quadratic divergence for the masses of Goldstone bosons.

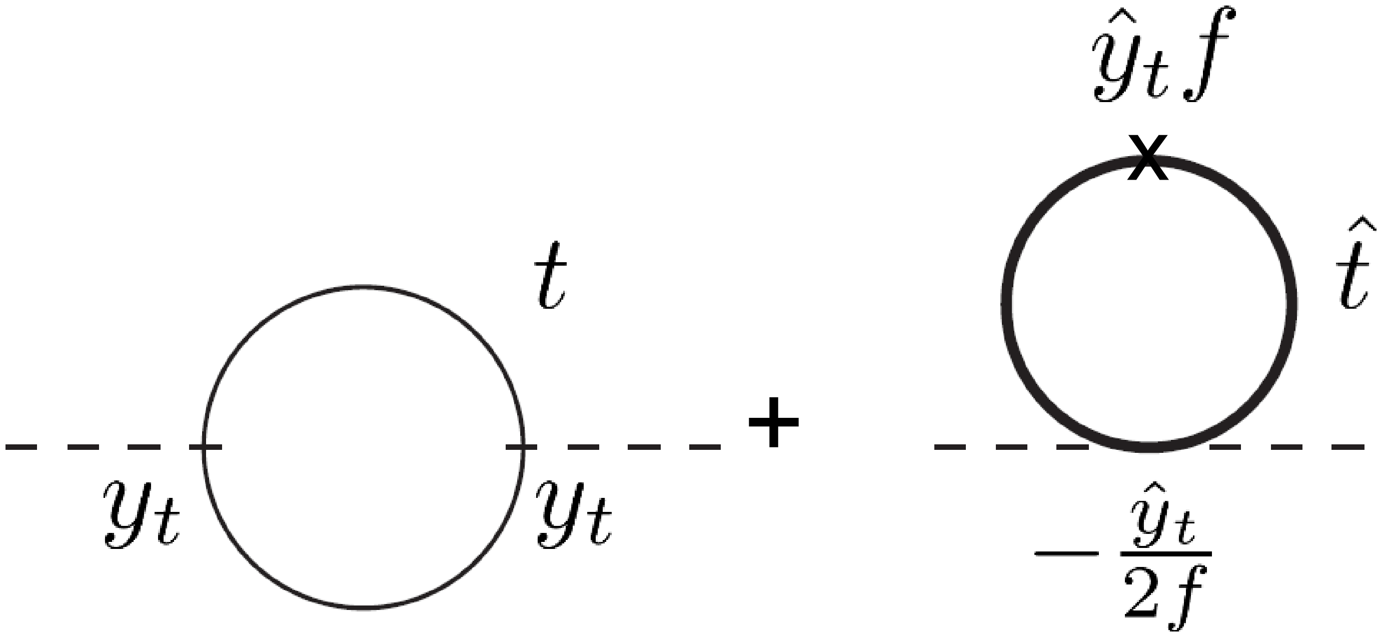
$$V(H) \supset \frac{9}{64\pi^2} g^2 \Lambda^2 \left(|H_A|^2 + |H_B|^2\right)$$

- 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.

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

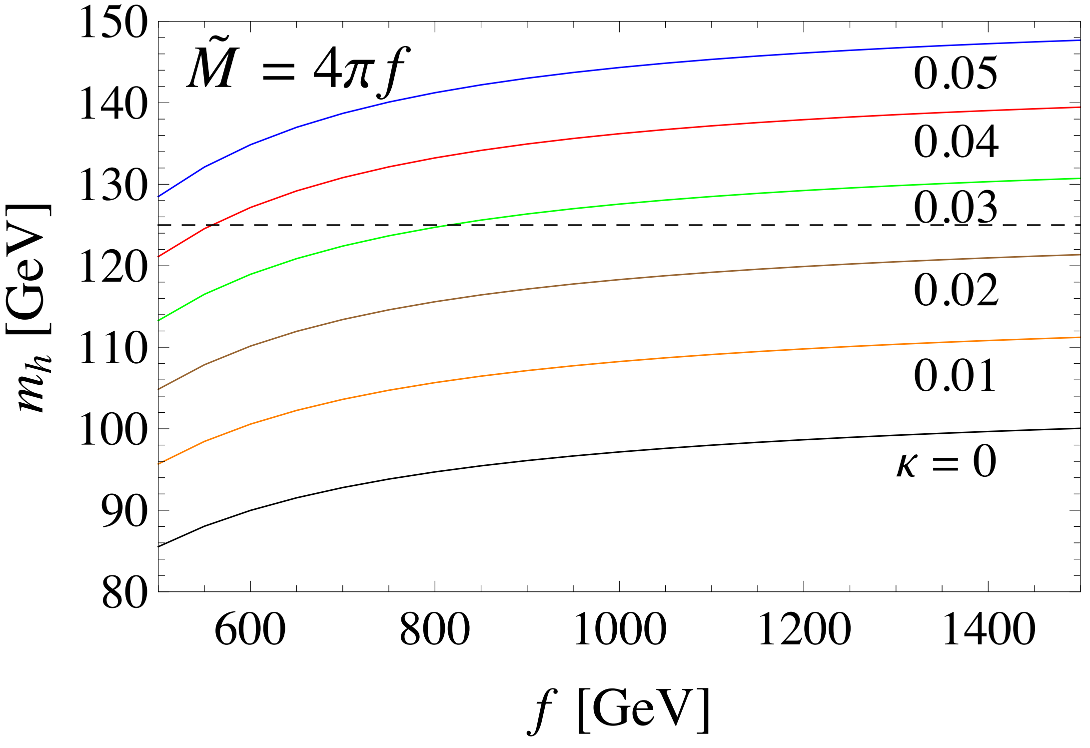
- A UV completion of Twin Higgs should regularize the log divergence, making the Higgs boson mass finite and calculable.

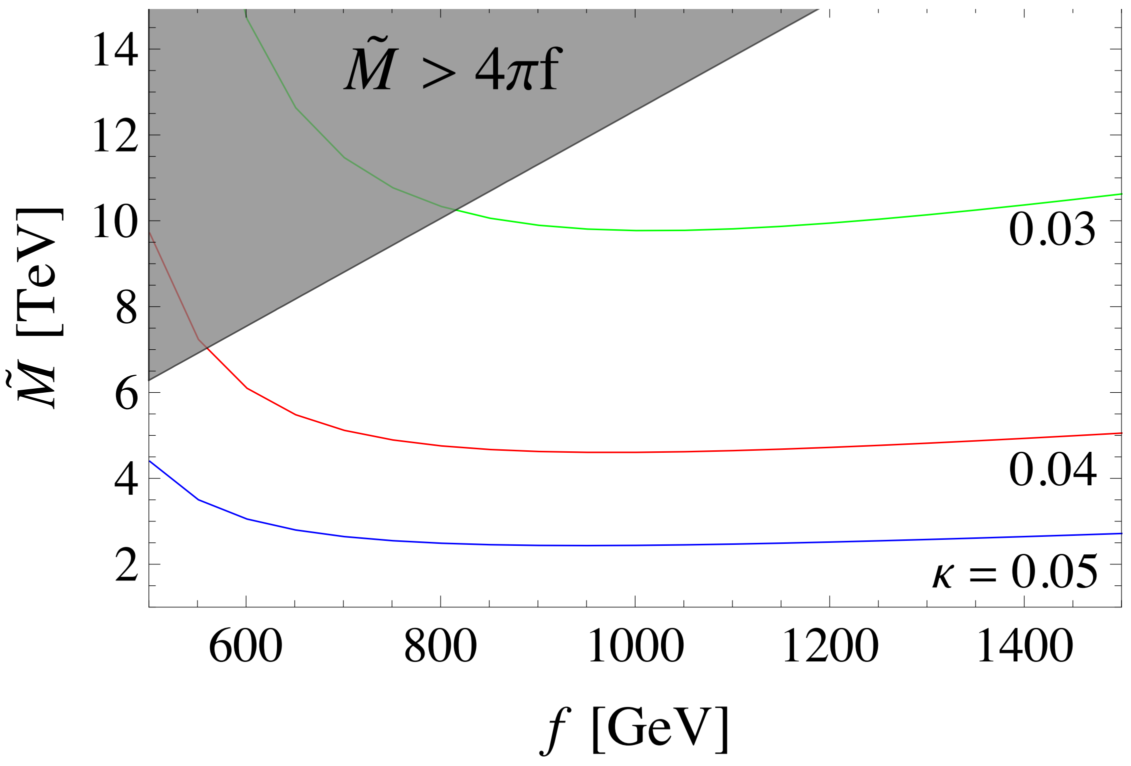
Higgs Potential and Higgs Mass

- Higgs boson mass is determined by the bare quartic term at the UV cutoff of the low energy theory,

$$\kappa\left(|H_A|^4+|H_B|^4\right) = \kappa\frac{f^4}{4}\left(\sin\left(\frac{h}{f}\right)^4+\cos\left(\frac{h}{f}\right)^4\right)$$

plus the radiative corrections to the Higgs potential in the low energy theory.

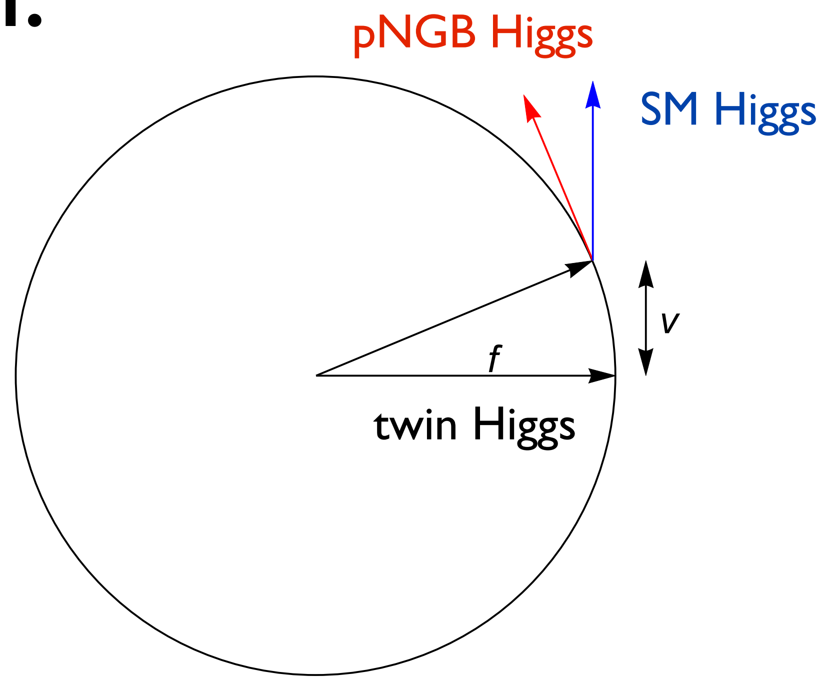




HC, Sunghoon Jung, Ennio Salvioni, and Yuhsin Tsai, arXiv:1512.02647

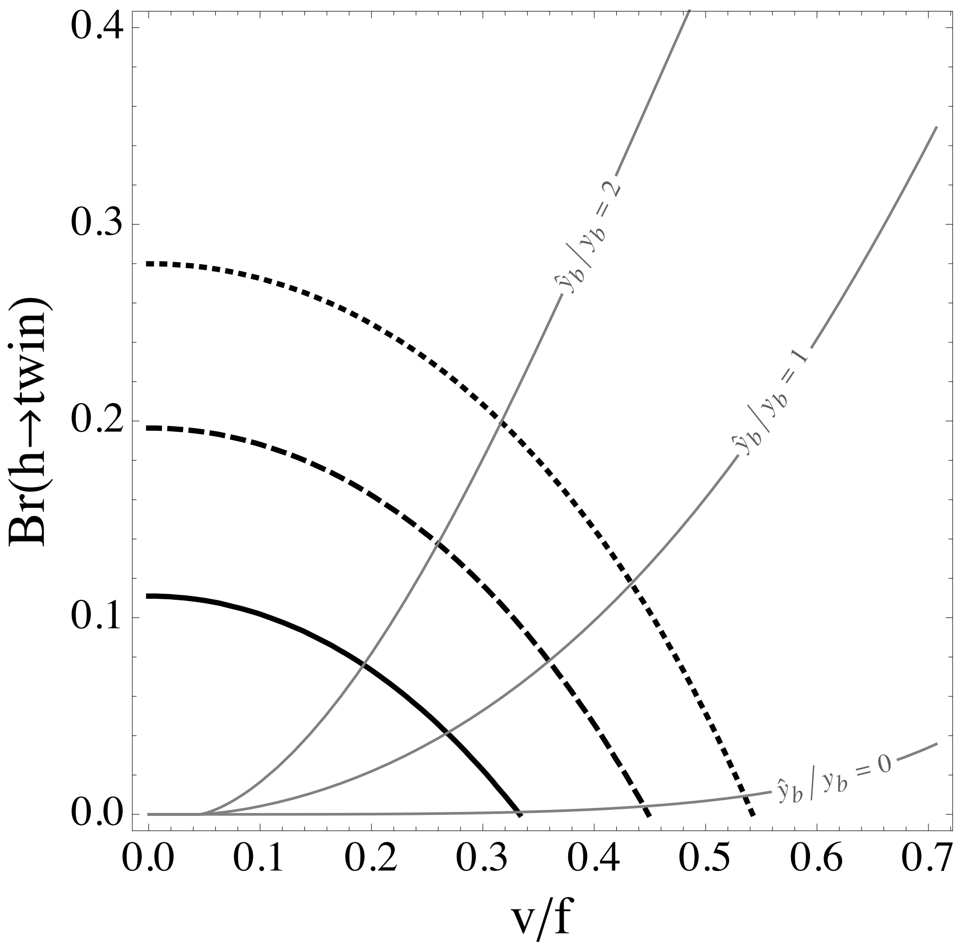
Twin Higgs Phenomenology

- 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.

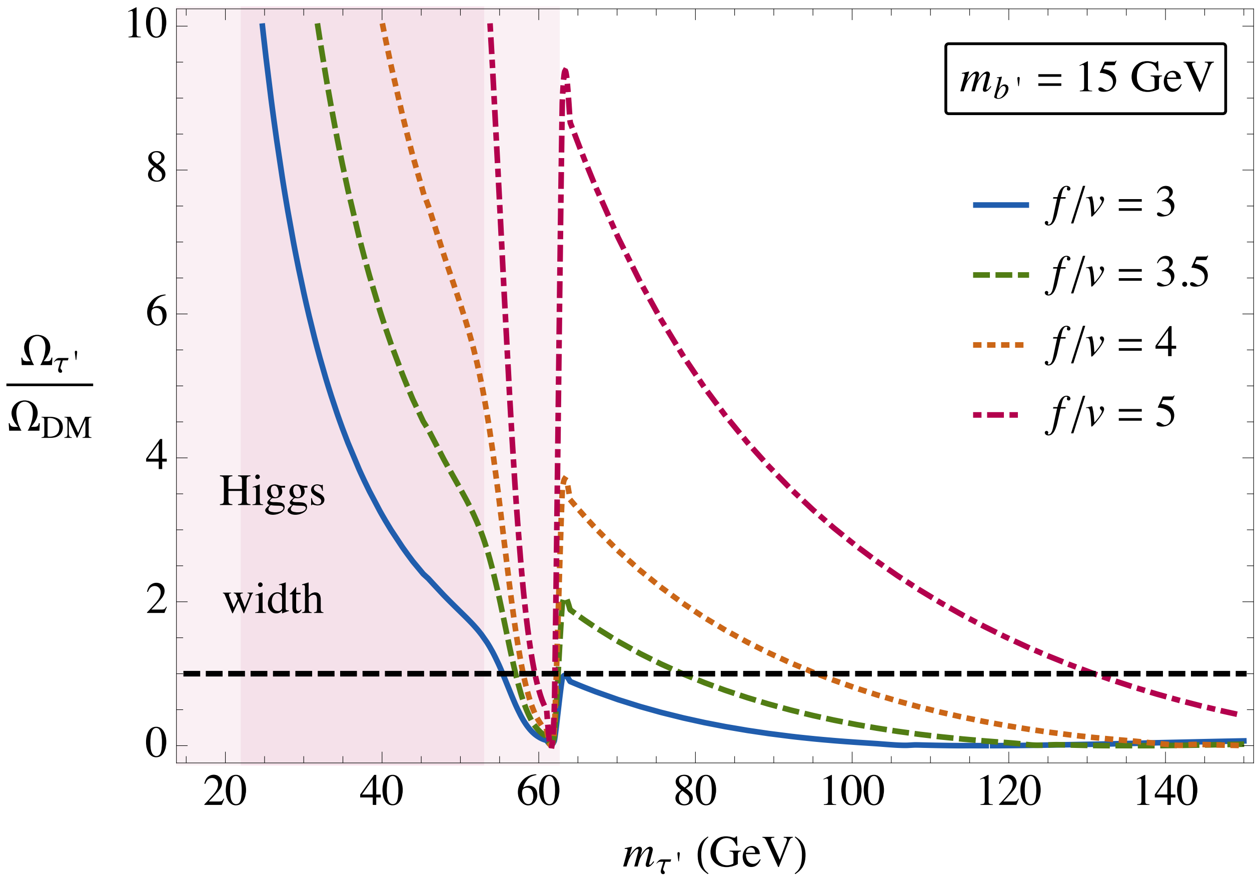
Fraternal Twin Higgs

In the twin sector:

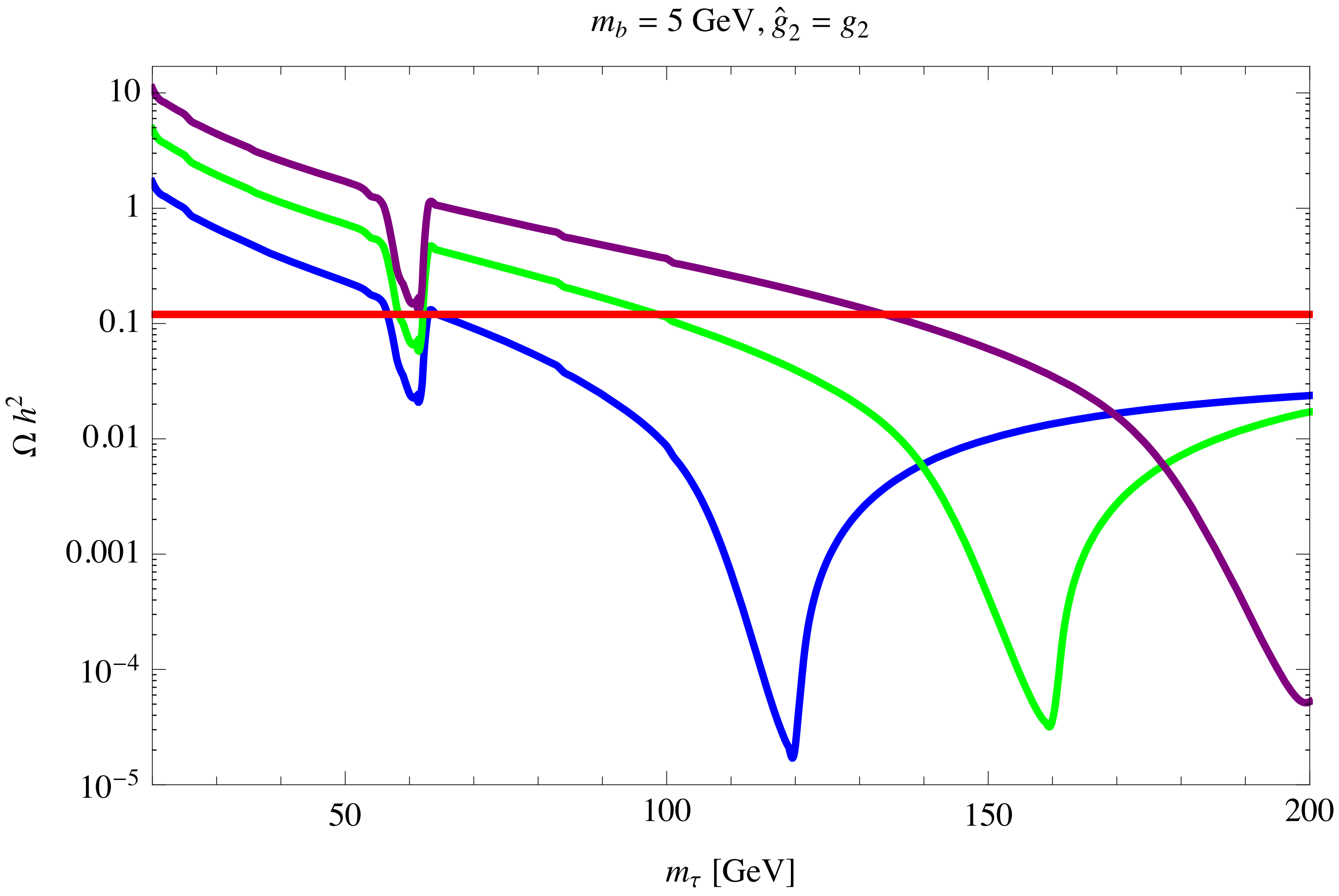
- Only 3rd generation fermions are needed (to cancel anomalies). Only top Yukawas need to respect Z_2. The twin bottom, tau, neutrino masses are free parameters as long as they are much lighter than the twin top.
- SU(2) and SU(3) gauge couplings need to be approximately equal to SM gauge couplings.
- 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.



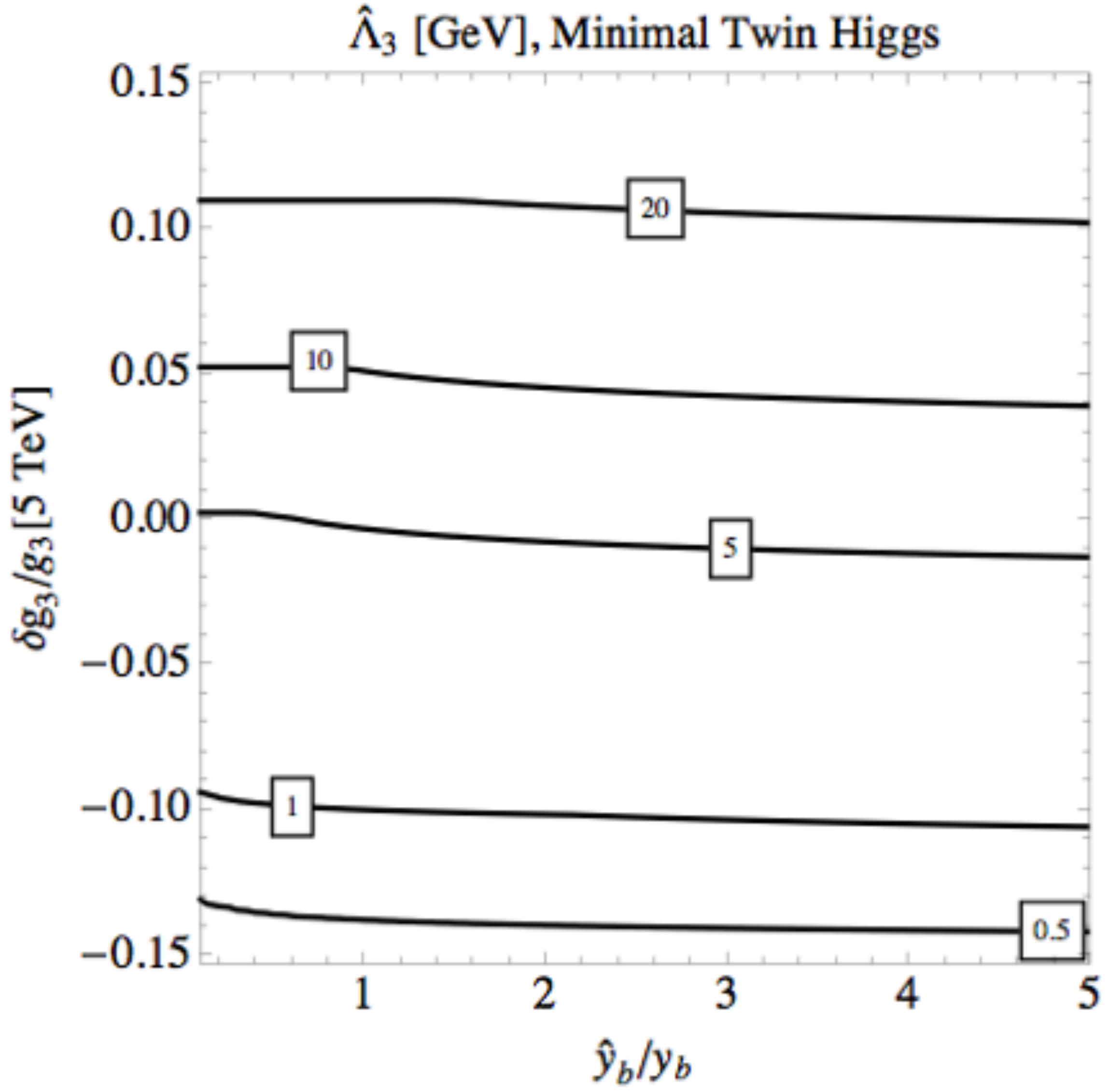
Garcia Garcia, Lasenby, March-Russell, 1505.07109

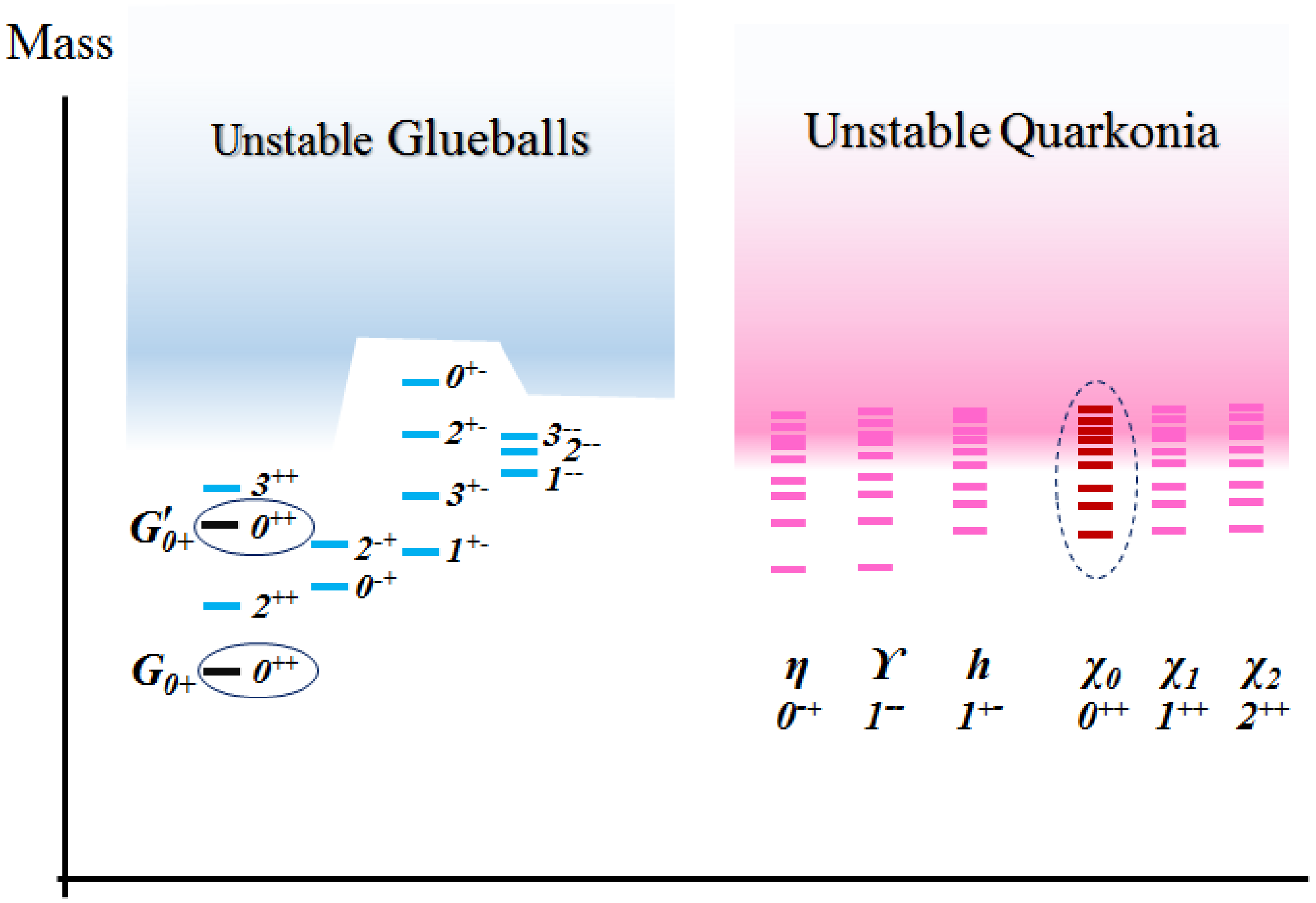


Craig, Katz, 1505.07113

Fraternal Twin Higgs

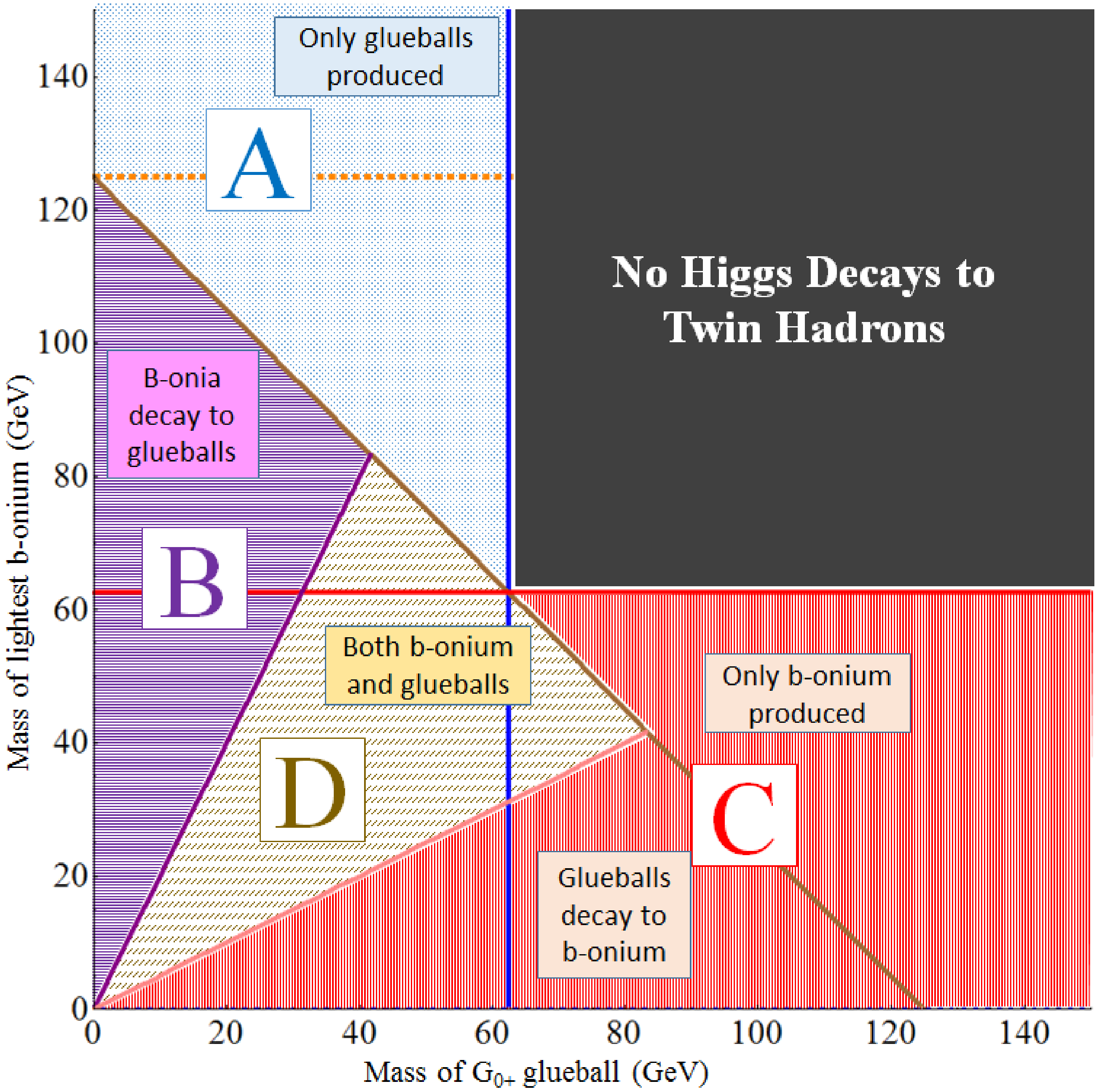
- With no light twin quarks, the lightest twin hadrons are twin glueballs or bottomonia, depending on the twin QCD scale and the twin bottom quark mass.





Fraternal Twin Higgs

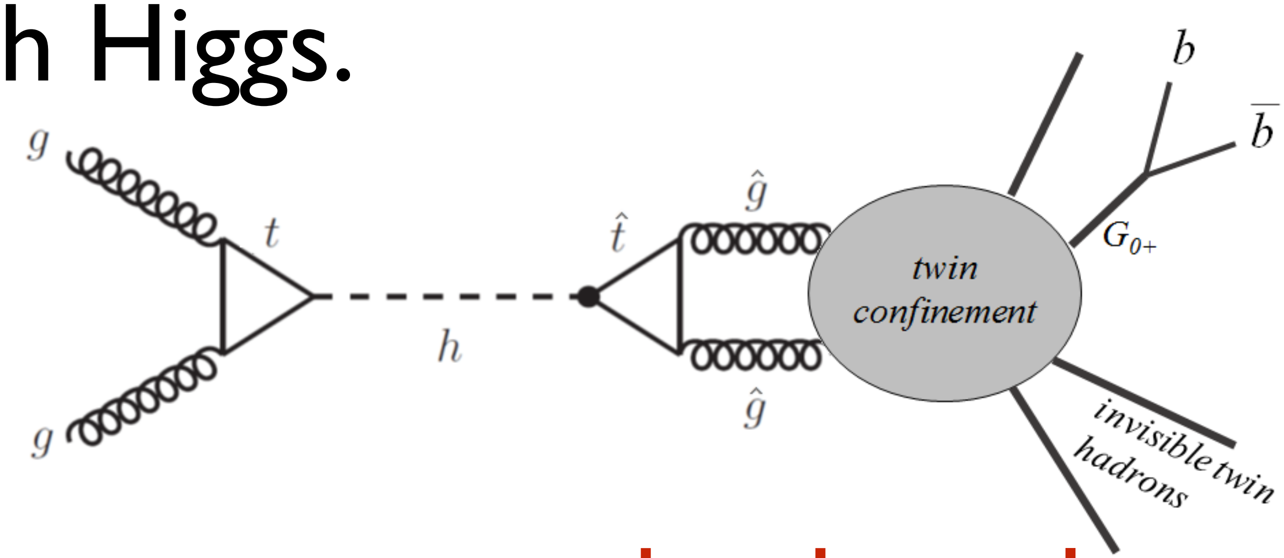
- Twin glueballs or bottomonia may be produced in Higgs decays for interesting regions of parameter regions.



Craig, Katz, Strassler, Sundrum, 1501.05310

Scalar Twin Hadron Decays

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



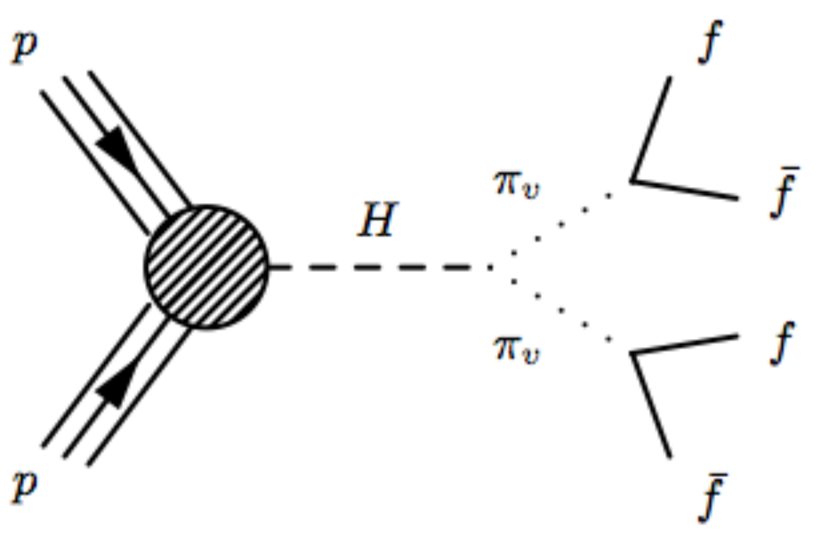
- For typical parameters, the decay lengths are macroscopic, giving rise to displaced vertices in Higgs decays.

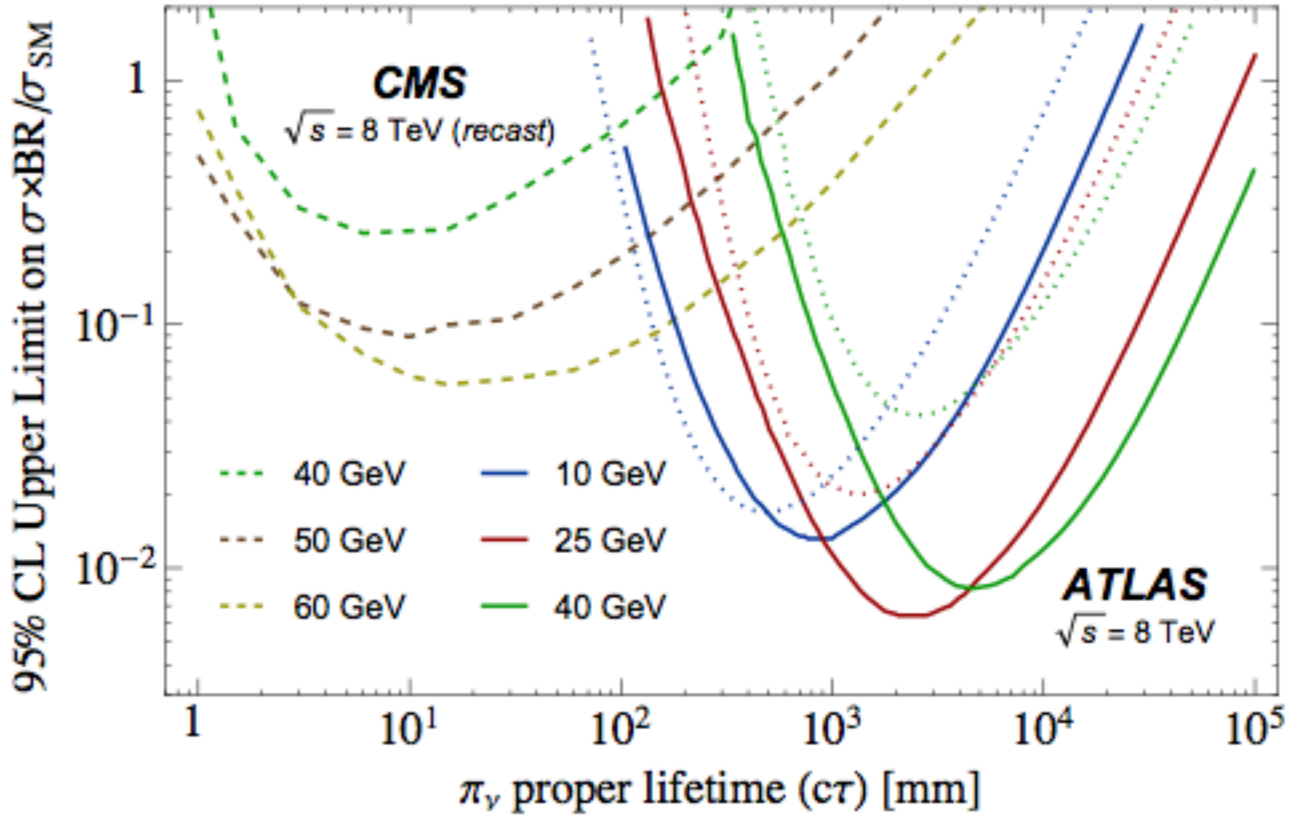
E.g., for benchmark $f = 1\ \text{TeV}, \quad \Lambda = 5\ \text{GeV}, \quad m_{Z_B} = 360\ \text{GeV}.$

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

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

LHC Searches for Displaced Higgs Decays





- References

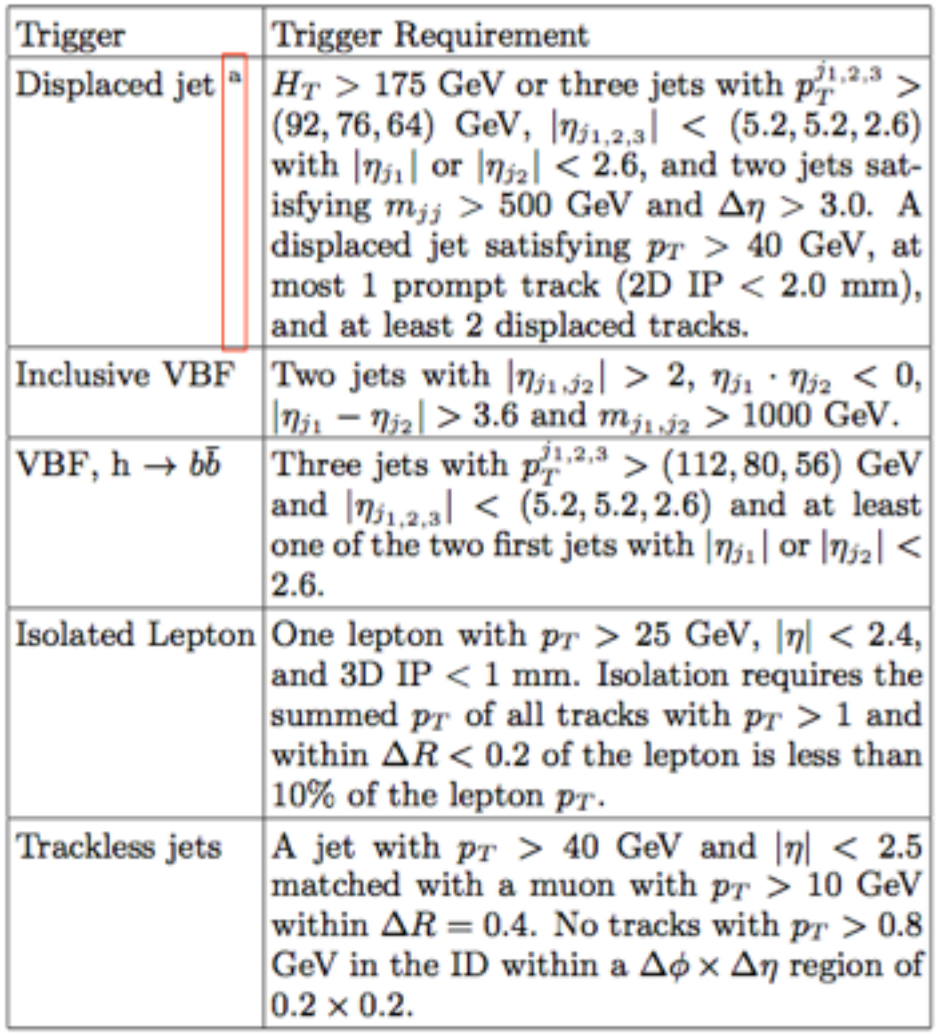
ATLAS Collaboration, "Search for long-lived, weakly interacting particles that decay to displaced hadronic jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," arXiv:1504.03634 [hep-ex].

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].

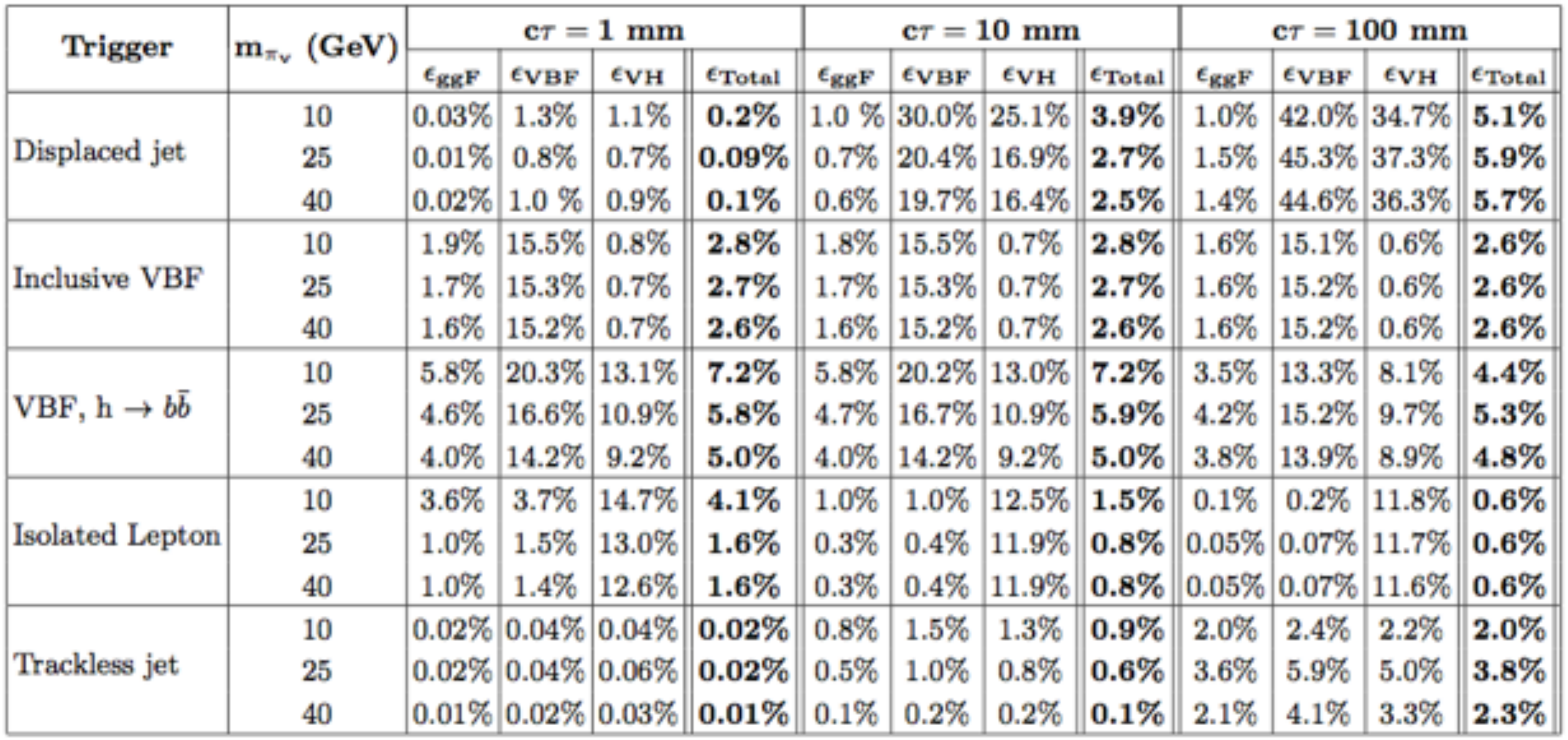
LHC Searches for Displaced Higgs Decays

- 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, $\lvert\eta_{j1,2,3}\rvert < (5.2, 5.2, 2.6)$ with $\lvert\eta_{j1}\rvert$ or $\lvert\eta_{j2}\rvert < 2.6$, 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 $\lvert\eta_{j1,j2}\rvert > 2$, $\eta_{j1} \cdot \eta_{j2} < 0$, $\lvert\eta_{j1} - \eta_{j2}\rvert > 3.6$ and $m_{j1,j2} > 1000$ GeV.
VBF, h → $b\bar{b}$	Three jets with $p_T^{j1,2,3} > (112, 80, 56)$ GeV and $\lvert\eta_{j1,2,3}\rvert < (5.2, 5.2, 2.6)$ and at least one of the two first jets with $\lvert\eta_{j1}\rvert$ or $\lvert\eta_{j2}\rvert < 2.6$.
Isolated Lepton	One lepton with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.4$, 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 $\lvert\eta\rvert < 2.5$ 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.

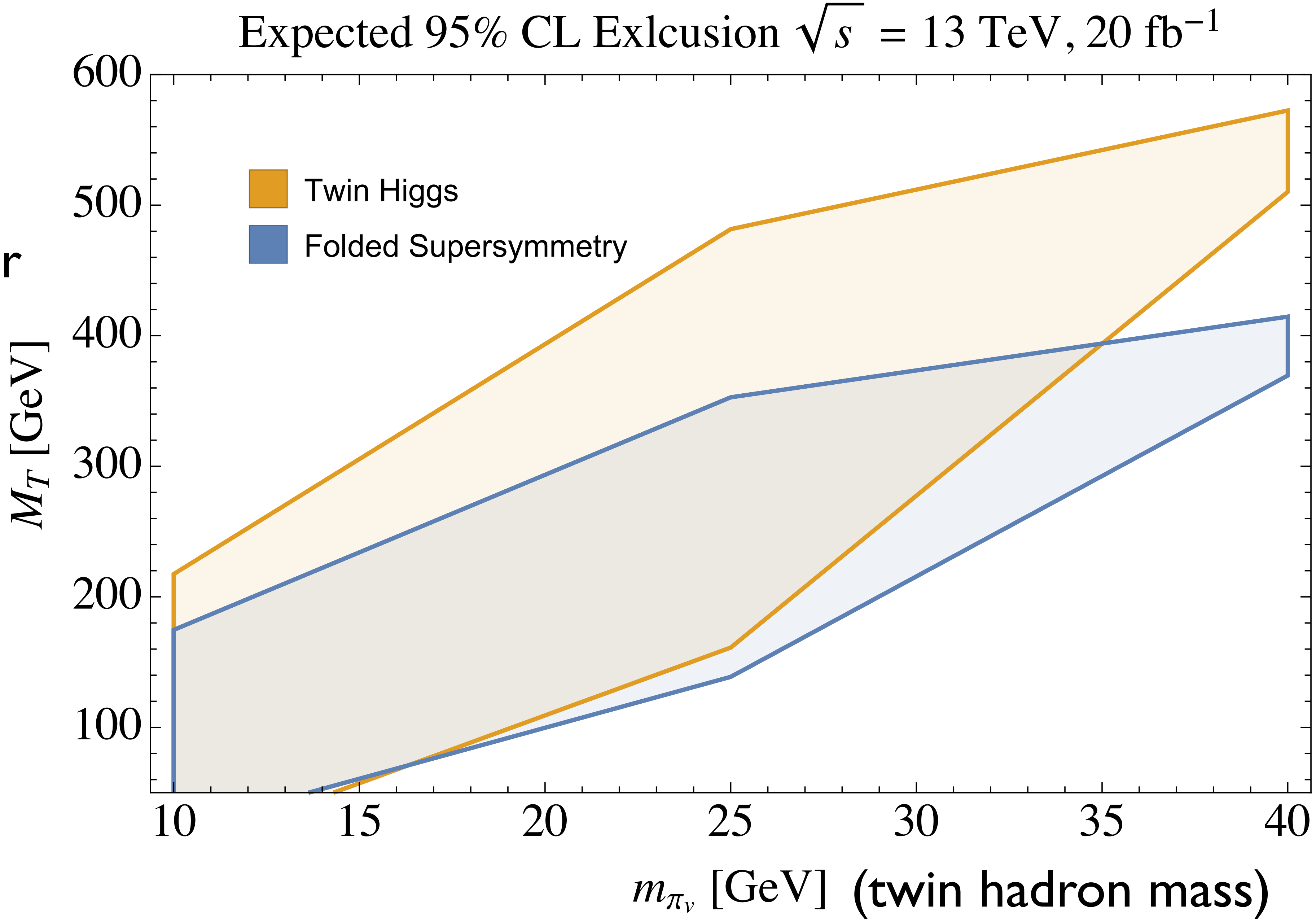


Trigger	m_{π_v} (GeV)	$c\tau = 1$ mm				$c\tau = 10$ mm				$c\tau = 100$ mm			
		ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}
Displaced jet	10	0.03%	1.3%	1.1%	**0.2%**	1.0 %	30.0%	25.1%	**3.9%**	1.0%	42.0%	34.7%	**5.1%**
	25	0.01%	0.8%	0.7%	**0.09%**	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 → $b\bar{b}$	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

LHC Searches for Displaced Higgs Decays

- Expected Run 2 reaches:



(top partner mass)

(twin hadron mass)

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, $-(\epsilon/2)B_{\mu\nu}\hat{B}^{\mu\nu}$

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

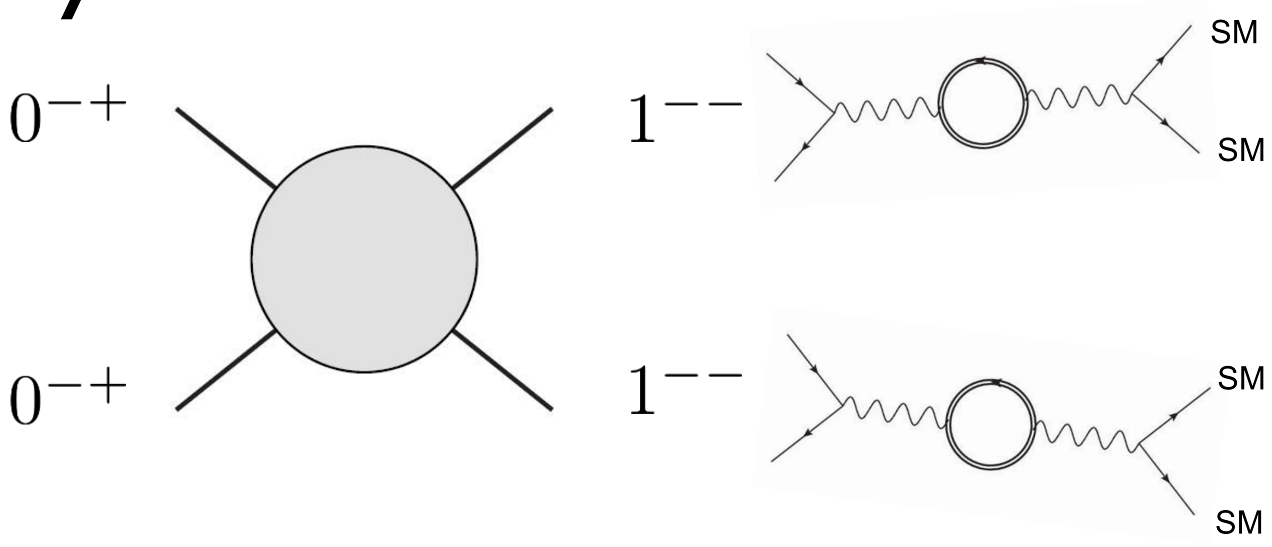
(assuming that twin leptons are heavy).

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

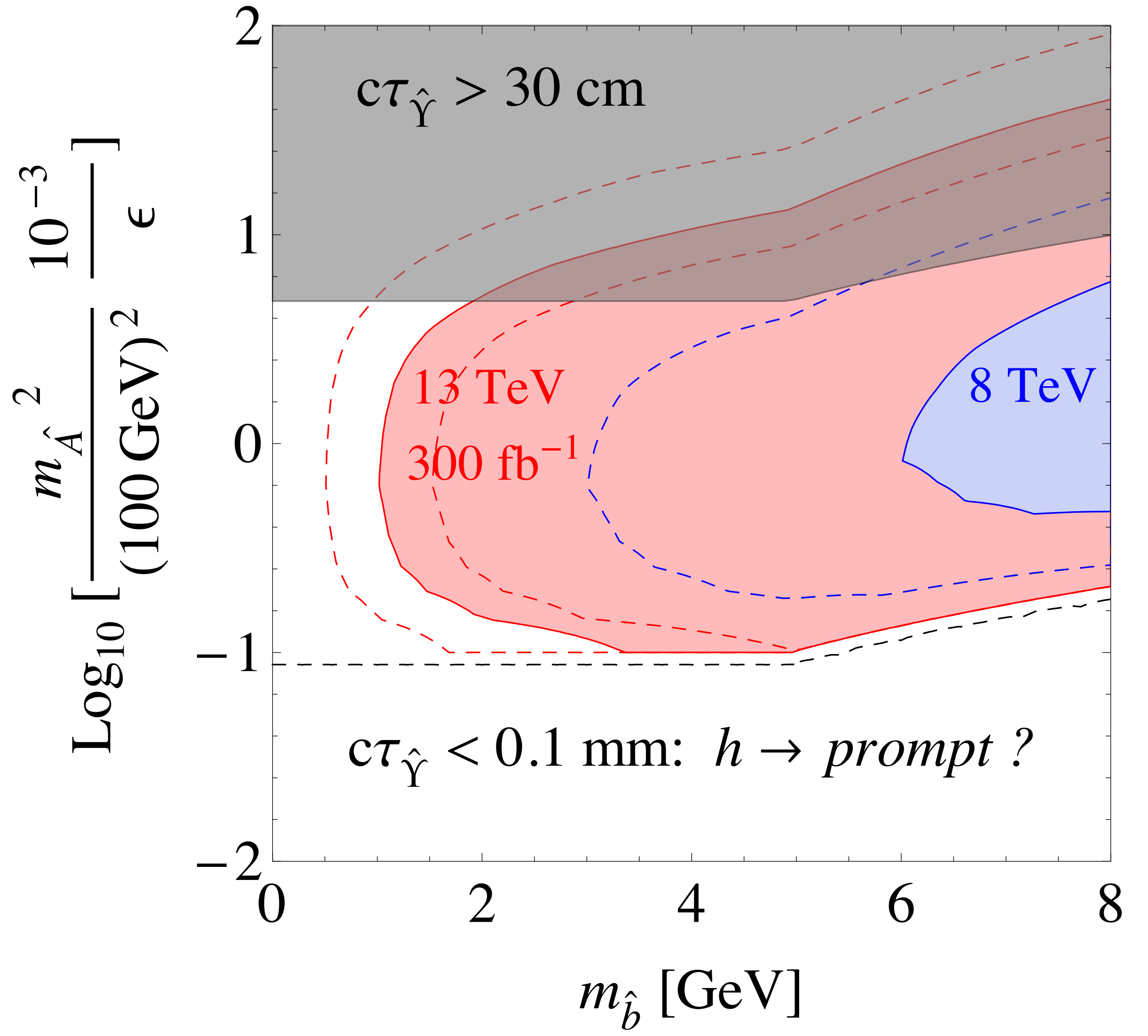
- It depends on the fraction $R_{\hat{\Upsilon}}$ of the twin bottomonia being $\hat{\Upsilon}$.

  - 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:

$$
\begin{aligned}
R_{\hat{\Upsilon}} \;=\; & \; 3/4, \quad\;\; 3/16, \quad\;\; 3/36 \\
& (l=0) \;\; (l \leq 1) \;\; (l \leq 2)
\end{aligned}
$$

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.

$$y_t \left(H_A^\dagger \quad H_B^\dagger\right) Q \begin{pmatrix} t_A \\ t_B \end{pmatrix} \qquad Q = \begin{array}{cc} \begin{array}{cc} \text{SM } SU(3) & \text{twin } SU(3) \end{array} & \\ \begin{pmatrix} q_A & \tilde{q}_B \\ \boxed{\tilde{q}_A} & q_B \end{pmatrix} & \begin{array}{l} \text{SM } SU(2) \\ \text{twin } SU(2) \end{array} \end{array}$$

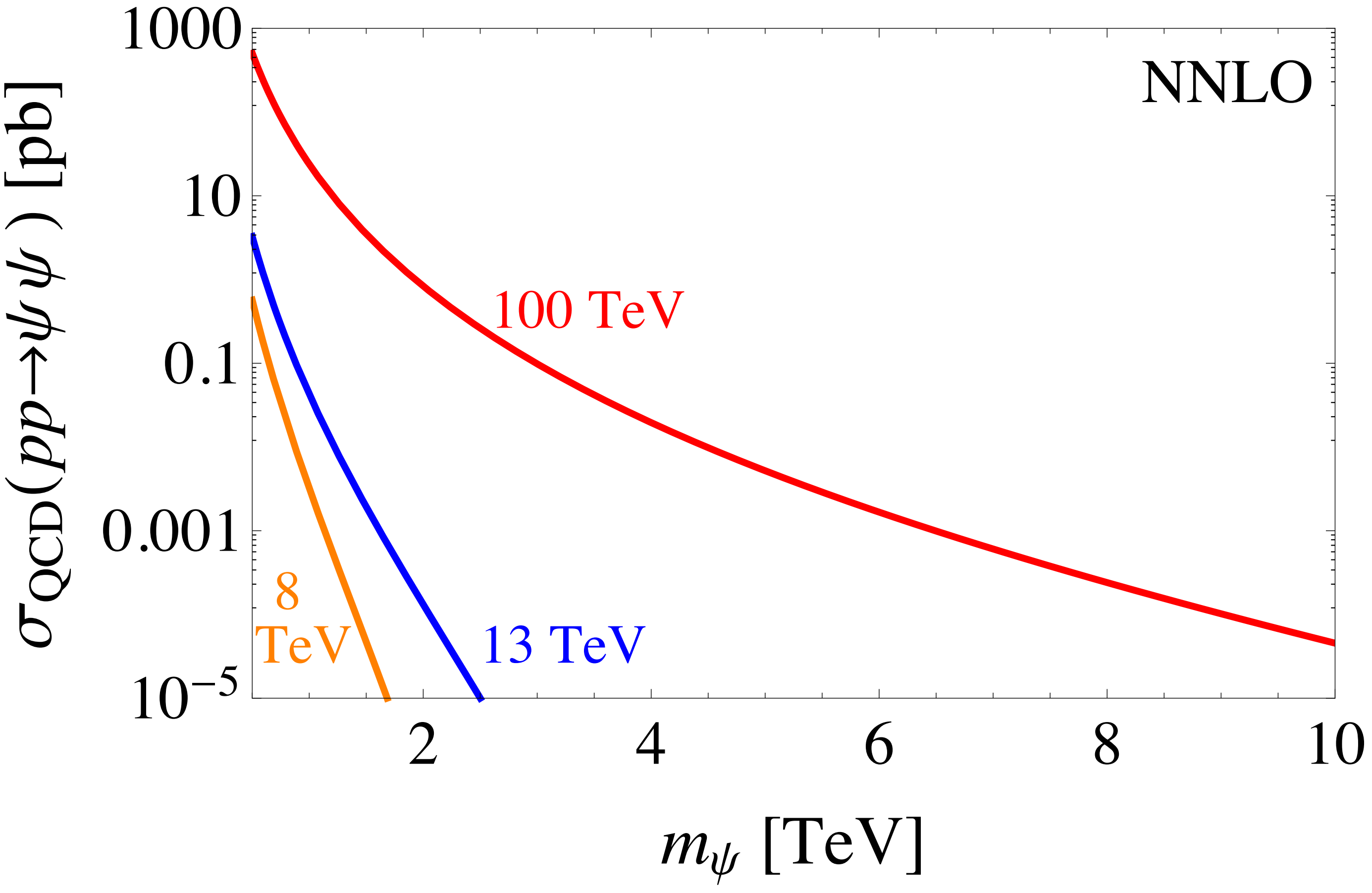
exotic quarks

Exotic Fermions

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

- In composite models, these new fermions are resonances of composite dynamics. In extra dimensional models, they are KK excitations.

- The exotic quarks (carrying SM color) can be copiously produced at hadron colliders if their masses are within reach.



Exotic Quark Decays

- The top component of the exotic quarks mixes with top quark: $- \begin{pmatrix} \overline{u}^A_{3R} & \overline{\tilde{u}}^A_{3R} \end{pmatrix} \begin{pmatrix} \frac{y_t f}{\sqrt{2}} s_h & \frac{y_t f}{\sqrt{2}} c_h \\ 0 & \tilde{M} \end{pmatrix} \begin{pmatrix} u^A_{3L} \\ \tilde{u}^A_{3L} \end{pmatrix} + \text{h.c.}$

$$\Rightarrow \text{ mass eigenstates: } \begin{pmatrix} t \\ \mathcal{T} \end{pmatrix} \qquad \tilde{d}^A_3 \equiv \mathcal{B} \text{ (also with electric charge } 2/3\text{)}$$

- Main decay modes:

$\mathcal{T} \to t\, Z_B$

(dominant for large mass)

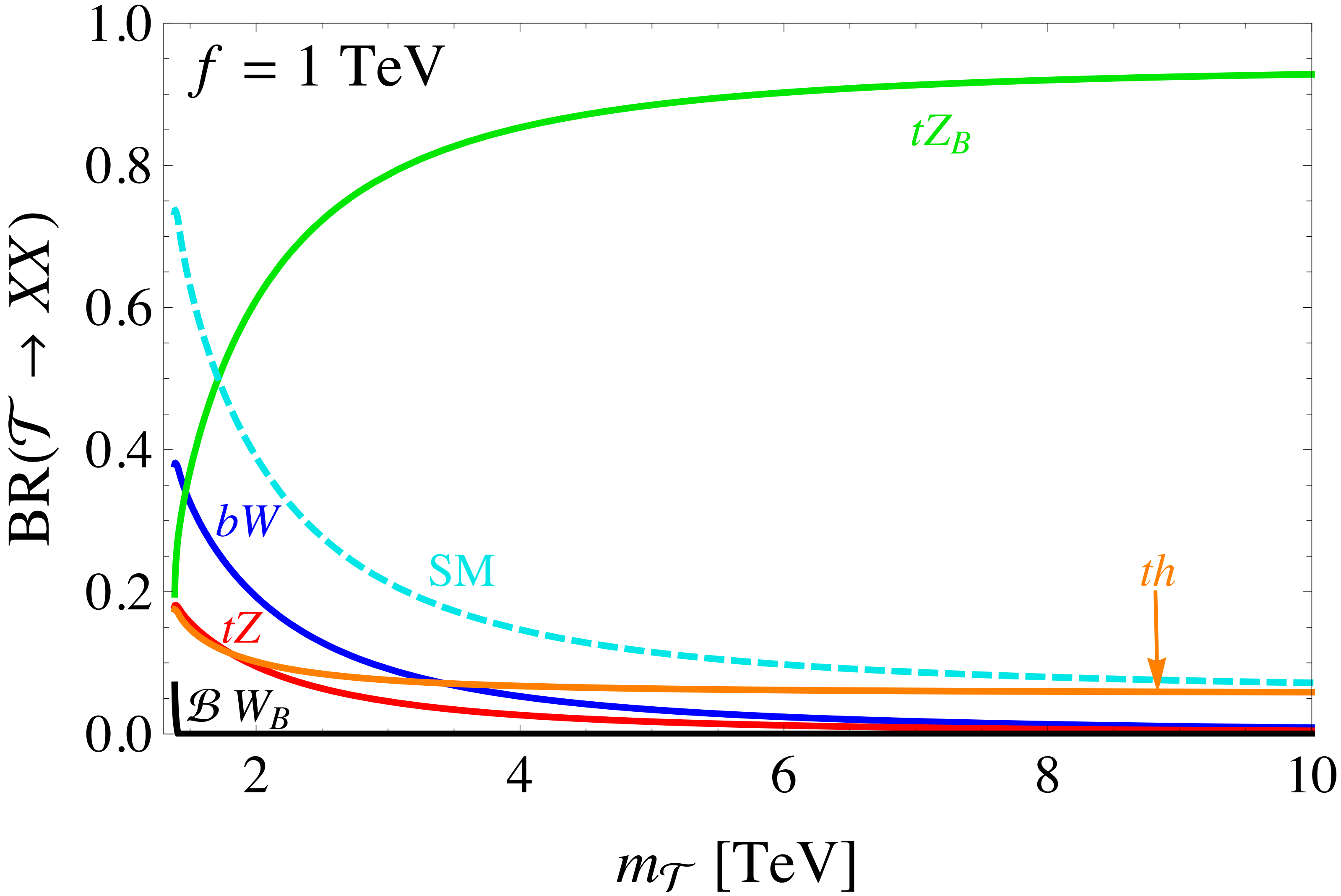
$\mathcal{T} \to t\, h$

$\mathcal{T} \to b\, W$

$\mathcal{T} \to t\, Z$

(due to mixing with top)

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



Traditional Searches

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

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

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

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

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

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

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

Twin Hadronizations

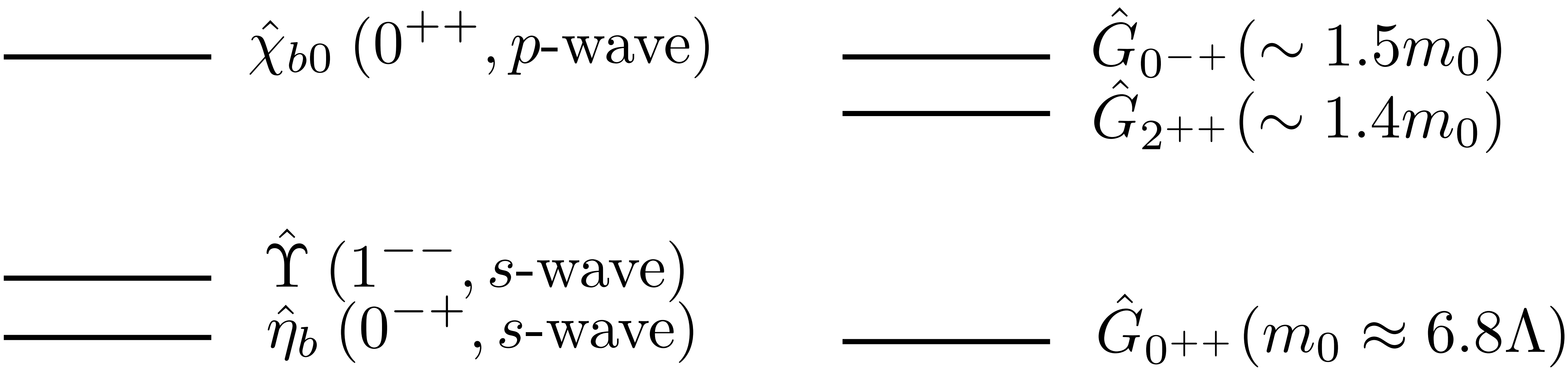
- The twin b's from Z_B decay form a long string.

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

String breaking dominates, producing multiple twin bottomonia.

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

Twin glueball emission from twin b scattering dominates.



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

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

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

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

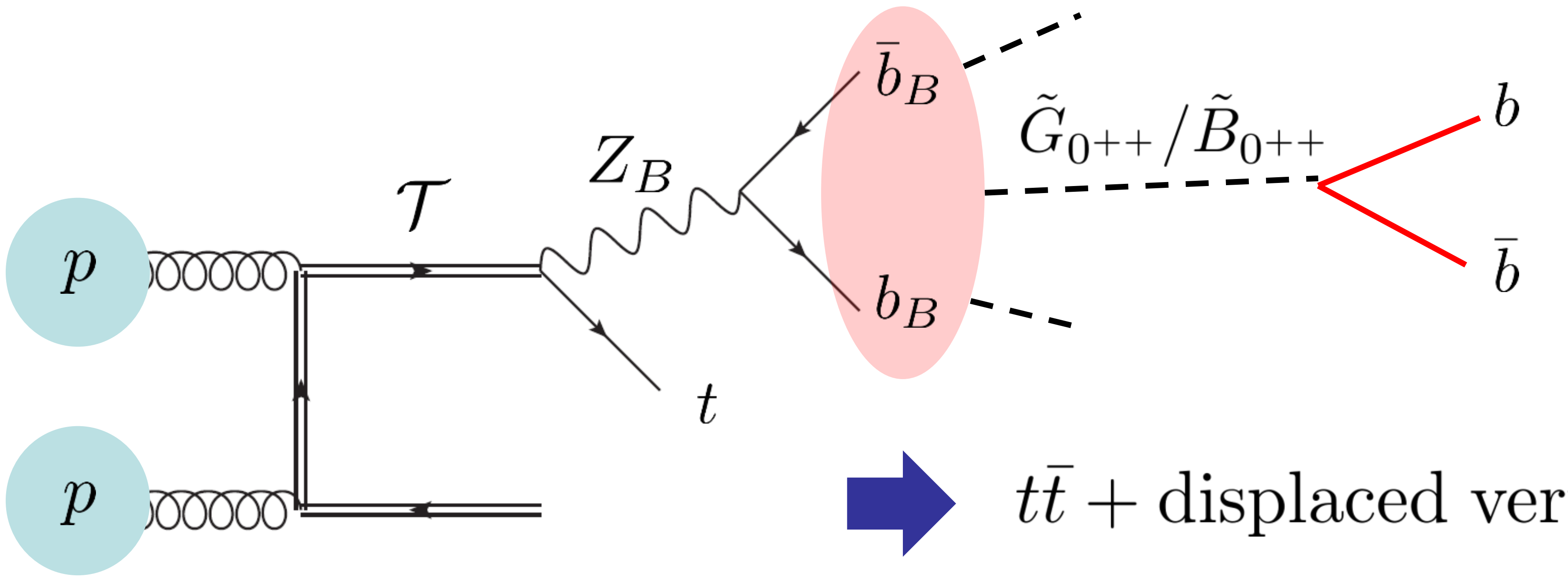
$\hat{G}_{2^{++}}(\sim 1.4 m_0)$

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

Exotic Quark Searches

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

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



➡ $t\bar{t}$ + displaced vertex

Easy to trigger from hard objects from top decay.

Combination of displaced vertex and hard objects from prompt top quarks makes it essentially background free.

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.

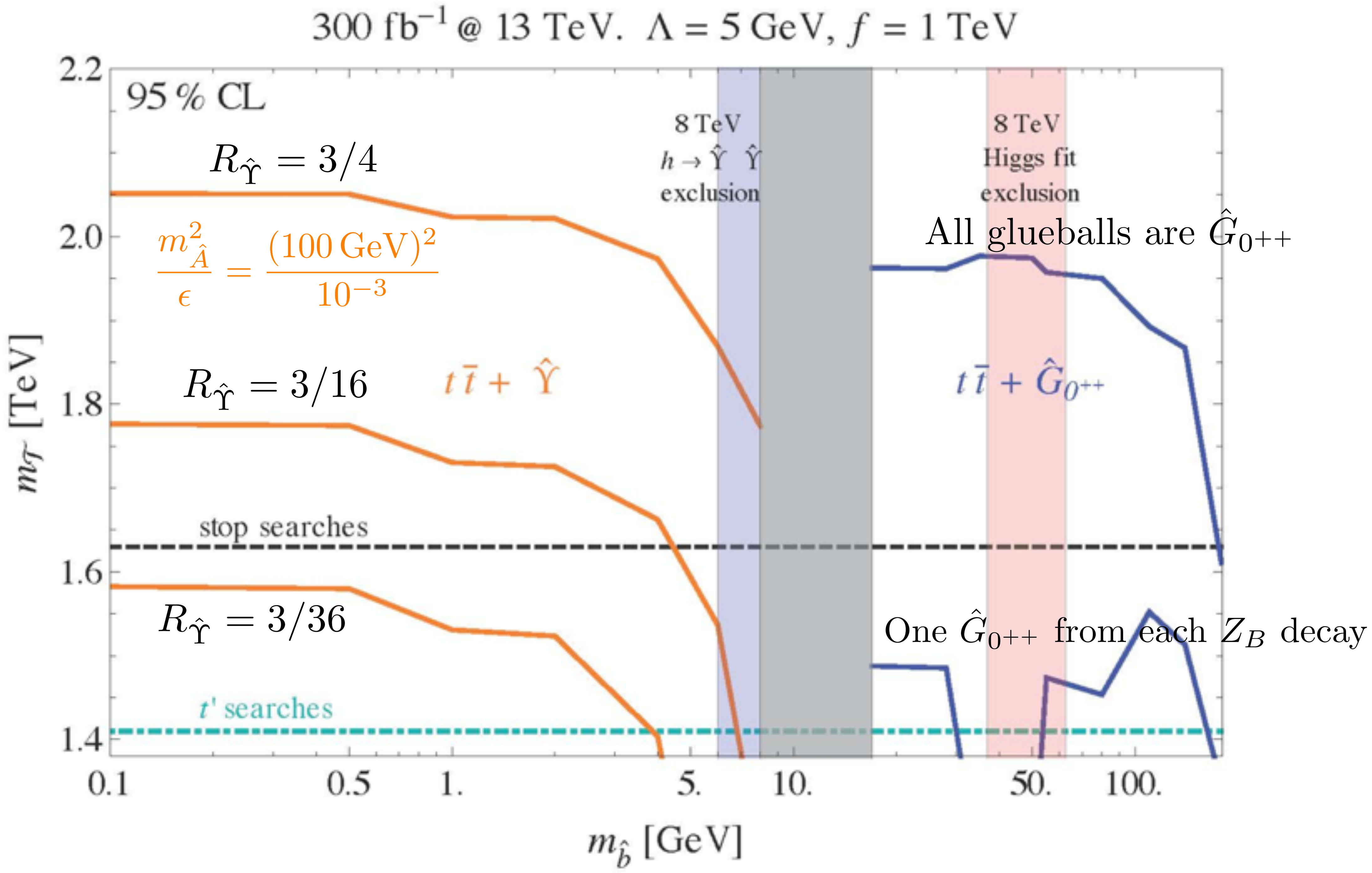
Twin glueball emission dominates for $m_{\hat{b}} \gtrsim 17\,\mathrm{GeV}$

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



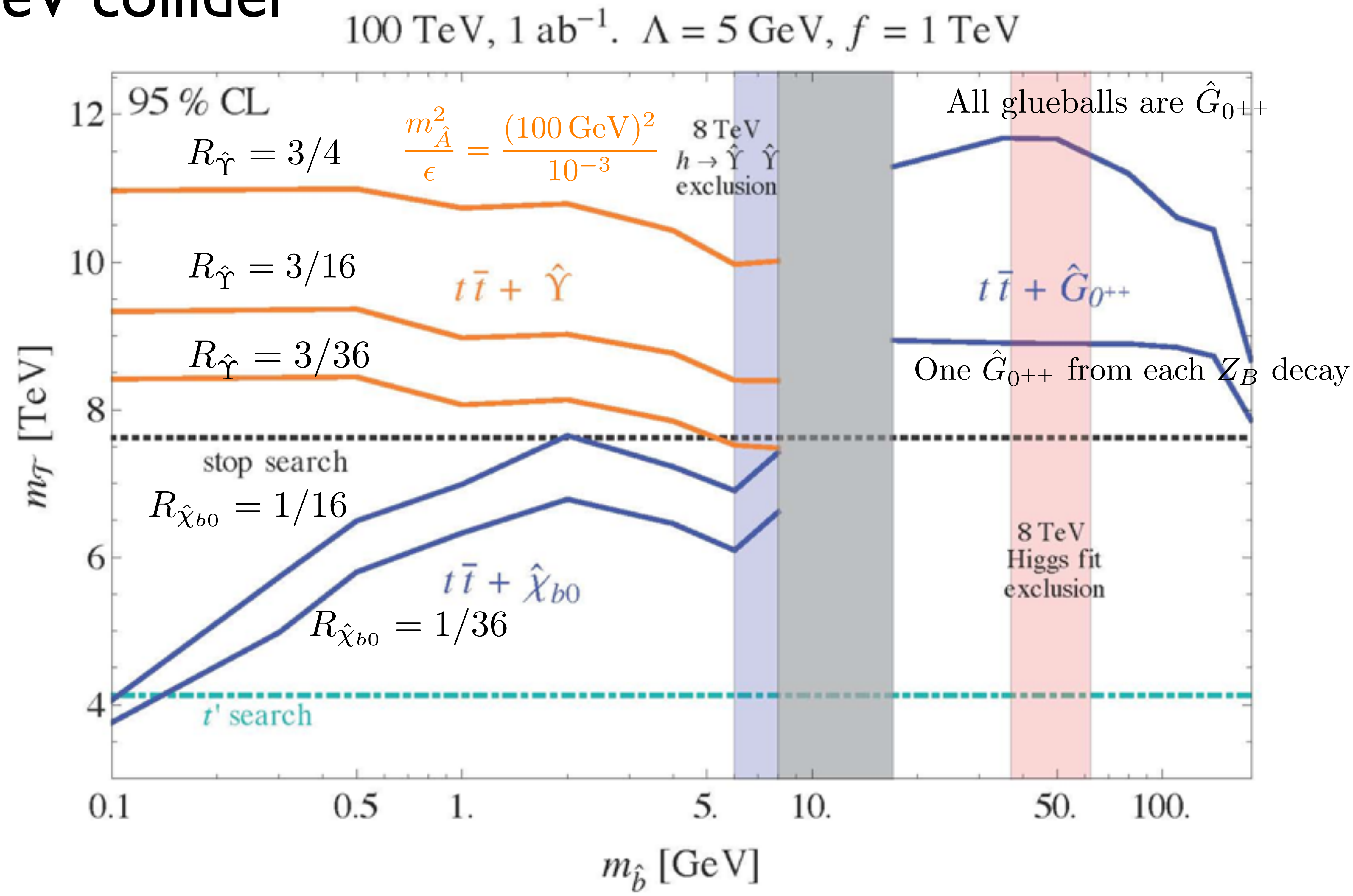
Twin bottomonia dominate

Twin glueballs dominate

Based on a simplified model of hadronization

Exotic Quark Searches

100 TeV collider



Twin Leptons

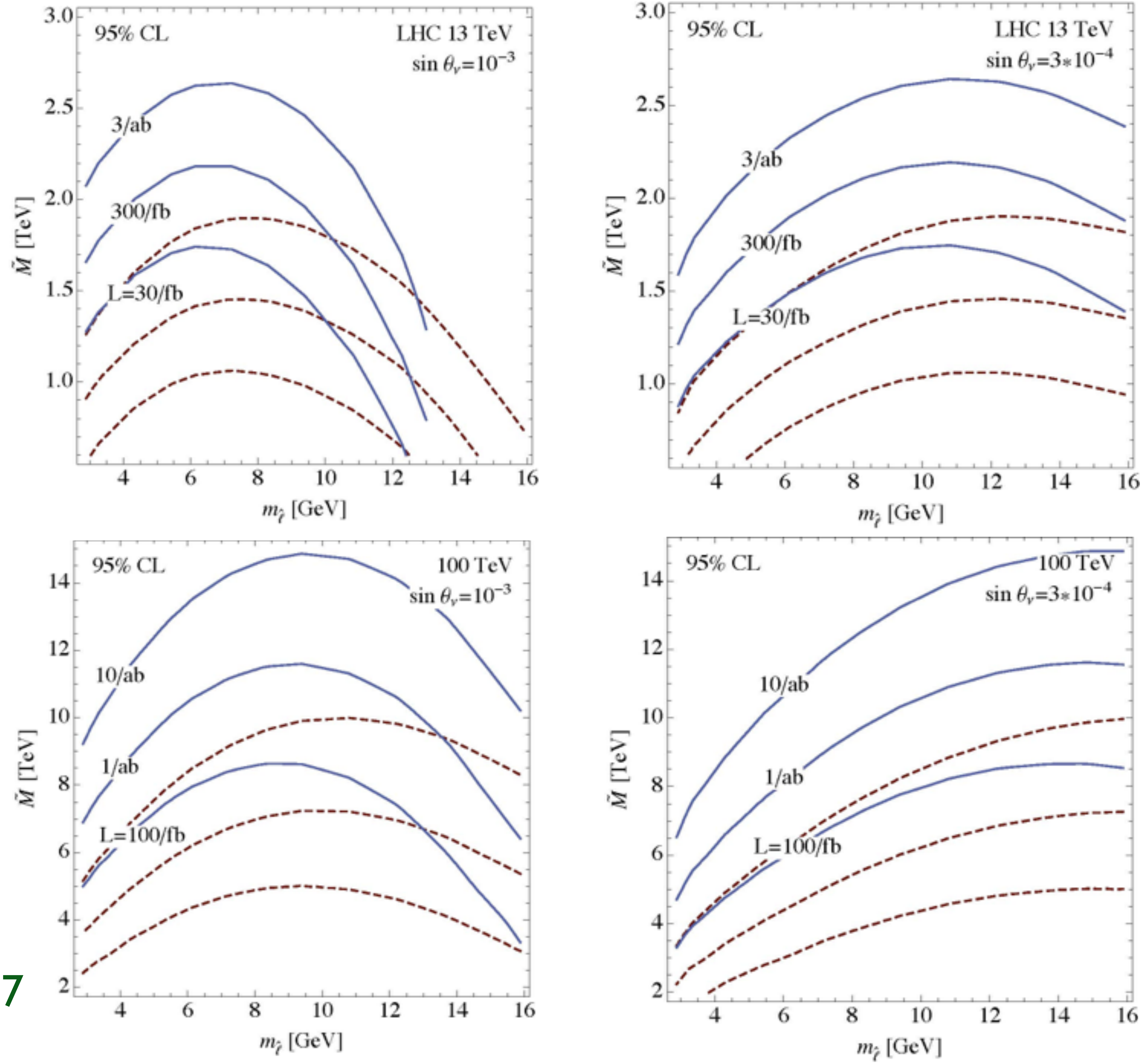
- If the twin leptons (τ and ν) are light (< 50 GeV) and stable, they may over-close the universe.
  $\Rightarrow$ They need to decay back to SM.
- They are singlets under unbroken gauge groups, behaving like sterile neutrinos. They may mix with SM neutrinos through higher-dim operators.

$$\mathcal{O}_{\hat{\nu}\mathrm{SM}} = \frac{1}{M_1}(H_B^\dagger \ell_{3L}^B)(H_A^\dagger \ell_{3L}^A), \qquad \mathcal{O}_{\hat{\tau}\mathrm{SM}} = \frac{\langle\phi\rangle}{M_2}\overline{\tau}_{3R}^B H_A^\dagger \ell_{3L}^A,$$

- For some range of parameters, they can also give rise to displaced decay. The future collider reaches are similar to twin hadrons.

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

Expected reaches for twin lepton:



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

Ultra-Long-Lived Particles

- For particles decaying outside the detector but before the BBN bound (~0.1 sec), there is a proposal by J.P. Chou, D. Curtin, H.J. Lubatti (1606.06298) for a surface detector (MATHUSLA) at HL-LHC and a dedicated detector at a future 100 TeV collider.

FIG. 1. Possible geometric configurations for the MATHUSLA surface detector at the HL-LHC. Gray shading indicates areas assumed to be sensitive to LLP decays. The surface detector in (a) is a 200m square building, centered along the beam line; (b) shows an alternative distributed arrangement of surface detectors.

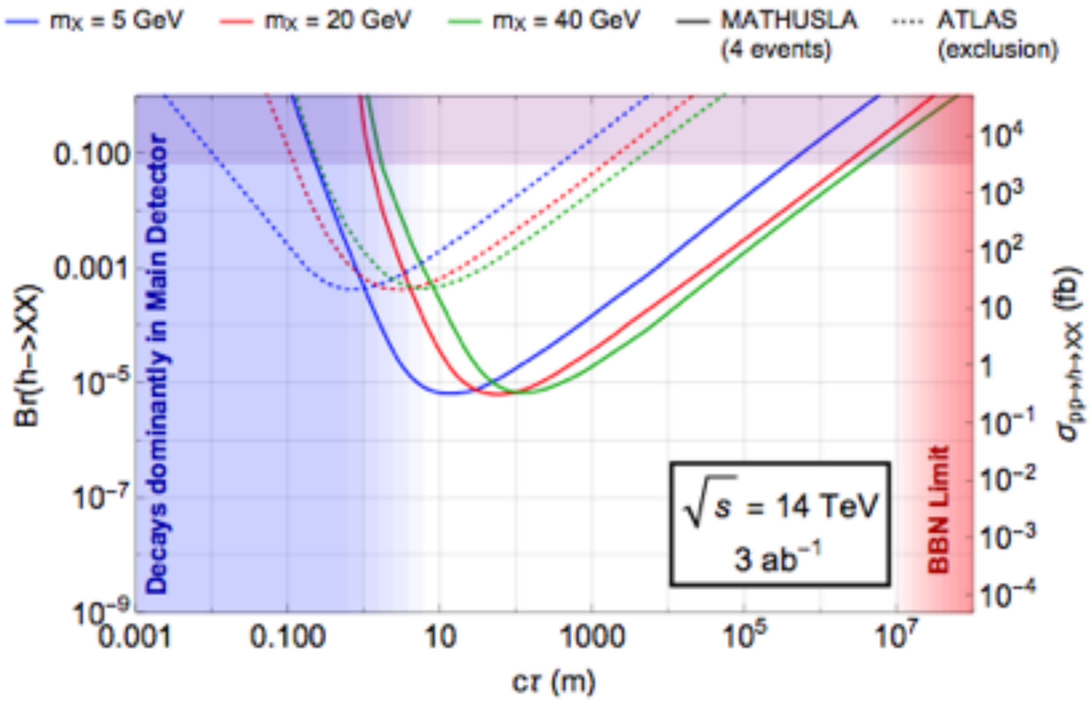


FIG. 4. HL-HLC sensitivity to LLP production in exotic Higgs decays. Solid lines: Required $\mathrm{Br}(h \to XX)$ required to see 4 events in MATHUSLA. Dotted lines: projected ATLAS $\mathrm{Br}(h \to XX)$ exclusions [69]. Purple shading: projected CMS $\mathrm{Br}(h \to \text{invis})$ exclusion [60], which applies roughly beyond the blue shaded region.

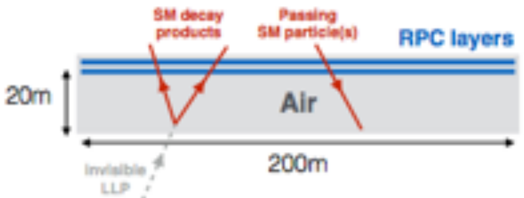


FIG. 2. Schematic of an RPC design for MATHUSLA.

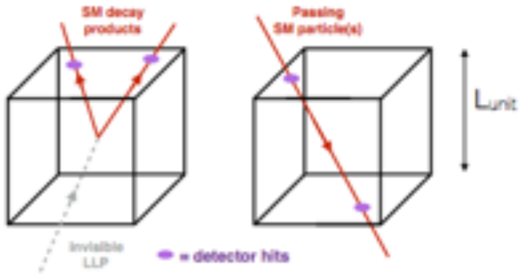


FIG. 3. Schematic of a scintillator design for MATHUSLA.

Conclusions

- The Twin Higgs model provides an elusive natural theory of EW symmetry breaking. However, it cannot be completely hidden.
- There are novel experimental signatures associated with the twin sector to be explored, such as displaced vertices from hidden sector decays.
- Better understanding and more realistic simulations of hadronization of the hidden (twin) QCD sector (and detector responses to displaced decays) can improve the predictions of the collider signals associated with the hidden sector.