Exotic Quarks in Twin Higgs Models

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

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Twin Higgs

Chacko, Goh, Harnik, hep-ph/0506256

- There exists a “mirror” or “twin” sector related to SM by an (approximate) Z_2 symmetry.
- The quadratic term of the SM Higgs and twin Higgs potential respects an SU(4) symmetry.

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

- SU(4) is spontaneously broken down to SU(3)

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

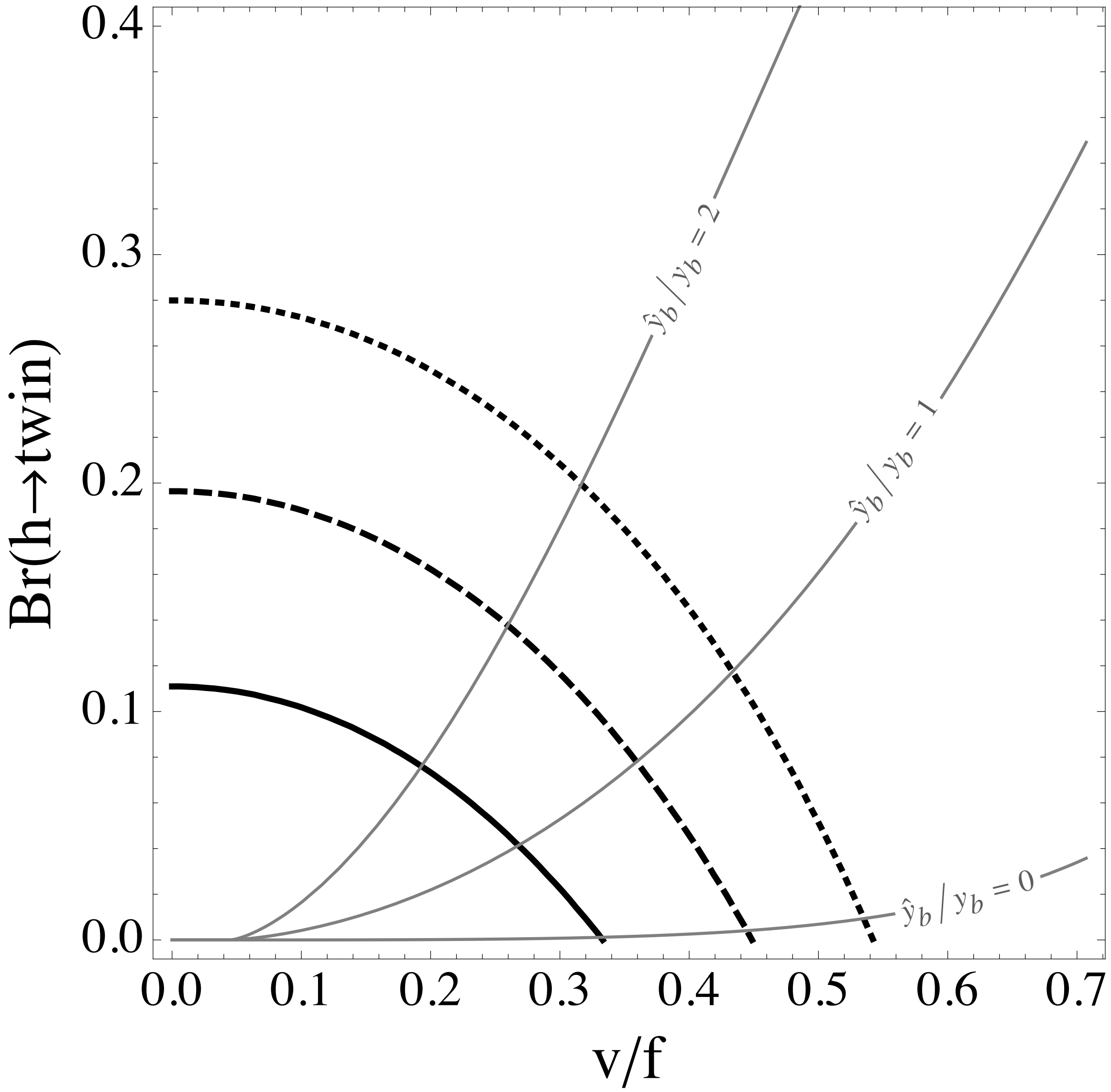
125 GeV Higgs is an PNGB.

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. Its 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.

Twin Higgs Phenomenology

- The current LHC data bound is *f/v* ≳ 3. Future LHC runs won’t improve it by much.



Craig, Katz, Strassler, Sundrum, 1501.05310

UV Completion

- 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.

UV Completion

- New states should appear at or below 5-10 TeV (< 4π*f*) to regularize the logarithmic divergence in the Higgs potential.
- In non-SUSY UV completions, the top sector needs to be extended to form complete SU(6)×SU(4) (⊃[SU(3)×SU(2)]^2) multiplets $\Longrightarrow$

new fermions charged under both SM and twin gauge groups.

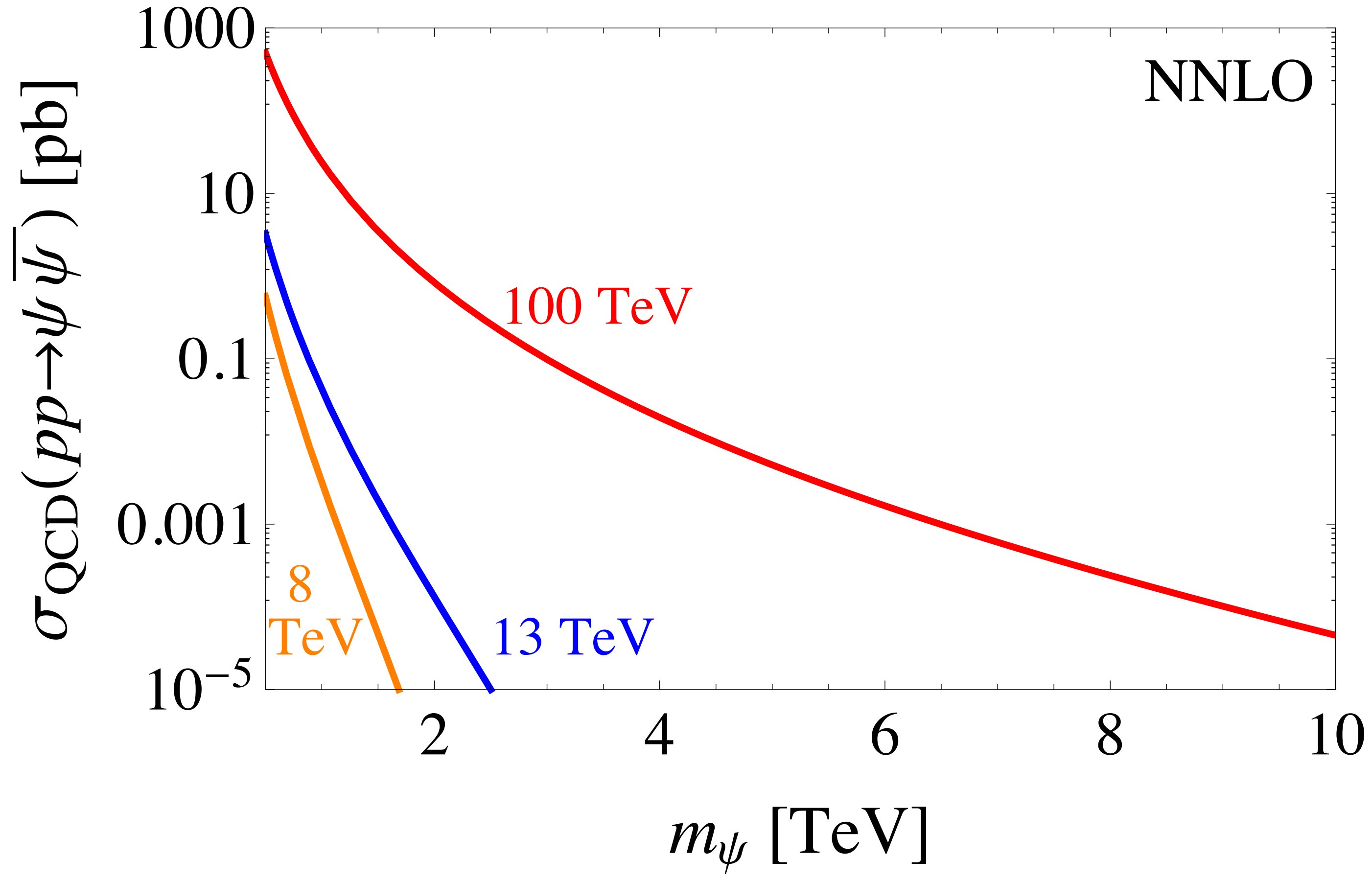
$$y_t \left(H_A^\dagger \quad H_B^\dagger\right) Q \begin{pmatrix} t_A \\ t_B \end{pmatrix} \qquad Q = \begin{array}{cc} \begin{array}{cc} \text{SM } SU(3) & \text{twin } SU(3) \end{array} & \\ \left(\begin{array}{cc} q_A & \tilde{q}_B \\ \boxed{\tilde{q}_A} & q_B \end{array}\right) & \begin{array}{l}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

exotic quarks

Exotic Fermions

- 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 Quarks

- Fermion mass eigenstates:

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

$$-\mathcal{L}_m = \tilde{M}(\overline{\tilde{q}}_{3R}^A \tilde{q}_{3L}^A + \overline{\tilde{q}}_{3R}^B \tilde{q}_{3L}^B) + \text{h.c.}$$

- The top component of the exotic quarks mixes with top quark.

$$\tilde{q}_3^A = \begin{pmatrix} \tilde{u}_3^A \\ \tilde{d}_3^A \end{pmatrix}$$

$$-\begin{pmatrix} \overline{u}_{3R}^A & \overline{\tilde{u}}_{3R}^A \end{pmatrix} \begin{pmatrix} \frac{y_t f}{\sqrt{2}} s_h & \frac{y_t f}{\sqrt{2}} c_h \\ 0 & \tilde{M} \end{pmatrix} \begin{pmatrix} u_{3L}^A \\ \tilde{u}_{3L}^A \end{pmatrix} + \text{h.c.} \quad \Rightarrow \quad \text{mass eigenstates:} \quad \begin{pmatrix} t \\ \mathcal{T} \end{pmatrix}$$

$\tilde{d}_3^A \equiv \mathcal{B}$ (also with electric charge 2/3)

Exotic Quark Decays

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

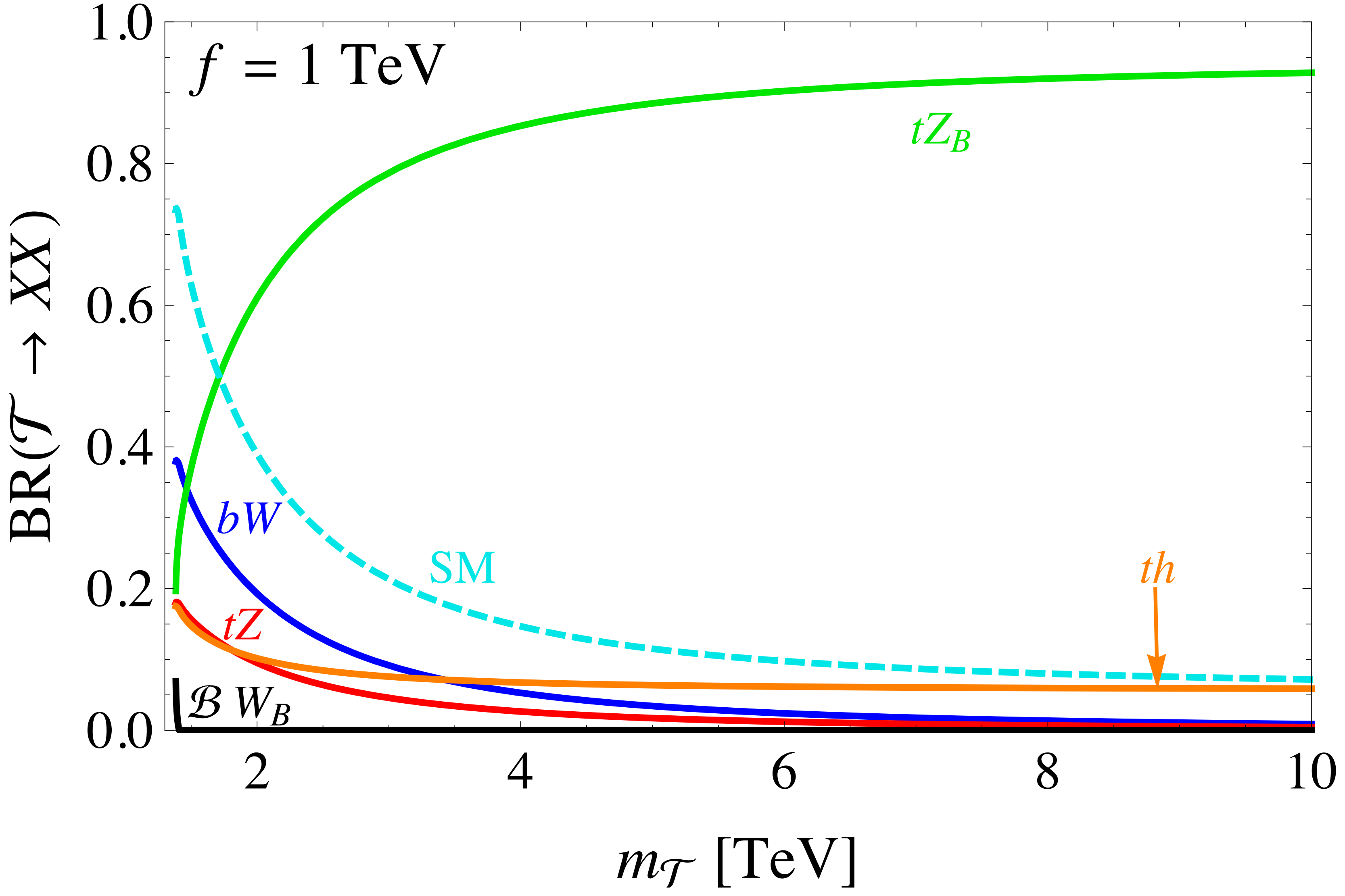
(dominant for large mass)

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

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

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

(due to mixing with top)



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

Traditional Searches

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

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

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

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

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

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

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

Twin Particle Phenomenology

- To discuss collider signals of the twin particles Z_B, W_B, one needs to specify the twin sector. We assume the Fraternal Twin Higgs scenario.

  (Craig, Katz, Strassler, Sundrum, 1501.05310)

  - A minimal approach to the naturalness problem by including only the particles that have large couplings to the Higgs (e.g., top, W/Z) in the twin sector.
  - Avoid cosmological problems caused by the light states in the twin sector.

Similar phenomenology for vector-like Twin Higgs.

(Knapen's talk)

Fraternal Twin Higgs

In the twin sector:

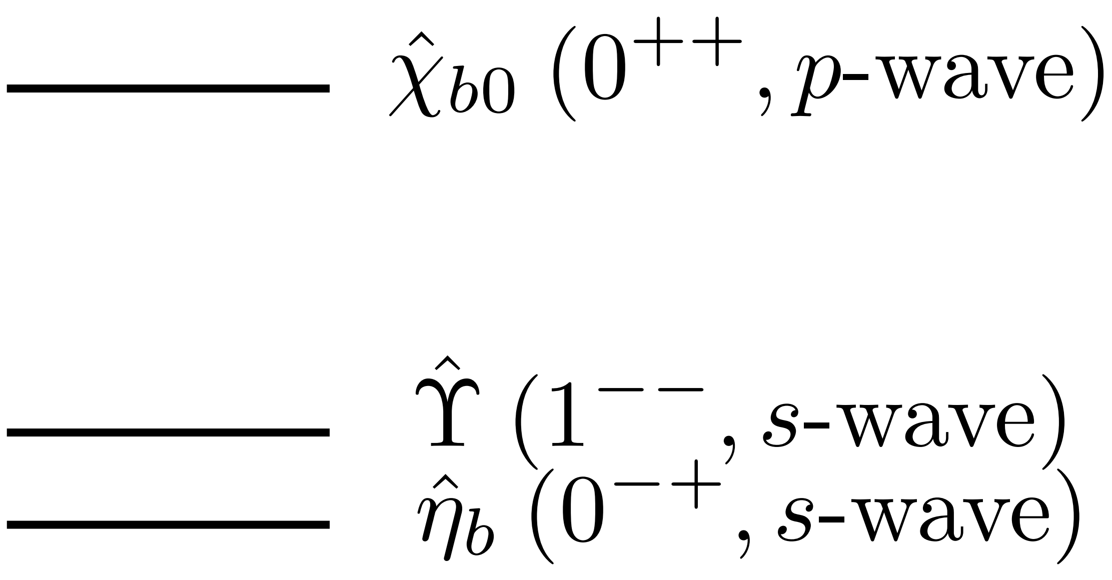
- Only 3rd generation fermions are needed (to cancel anomalies). Only top Yukawas need to respect Z_2. The twin bottom, tau, neutrino masses are free parameters as long as they are much lighter than the twin top.
- SU(2) and SU(3) gauge couplings need to be approximately equal to SM gauge couplings.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

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.



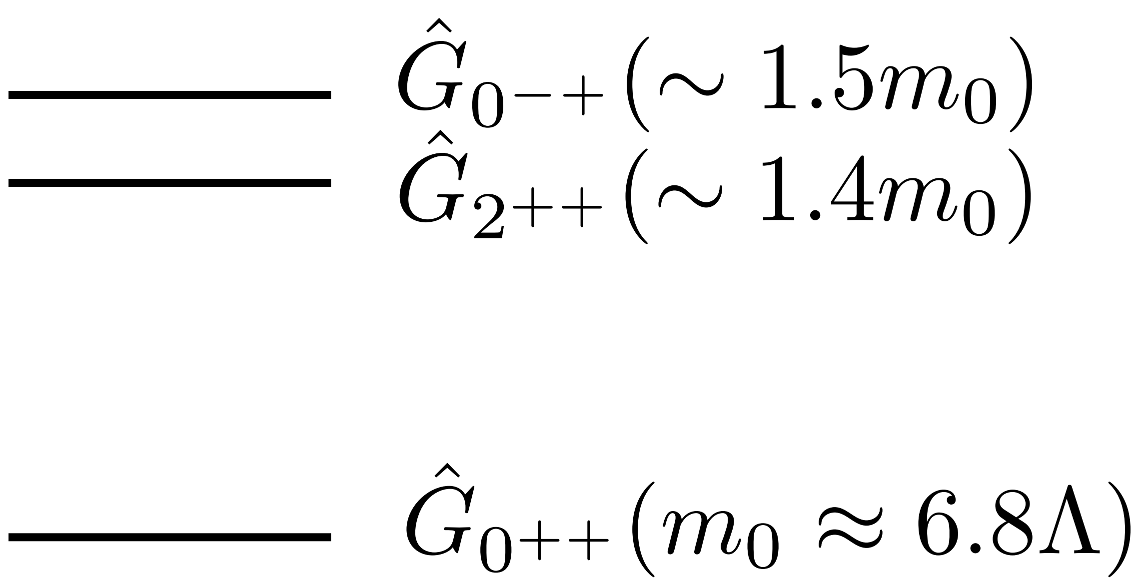
$\hat{\chi}_{b0}\ (0^{++}, p\text{-wave})$

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

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

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

Twin glueball emission from twin b scattering dominates.



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

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

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

Twin Hadron Decays

- Assuming no light twin leptons

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

For the benchmark point:

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

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

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

Twin Hadron Decays

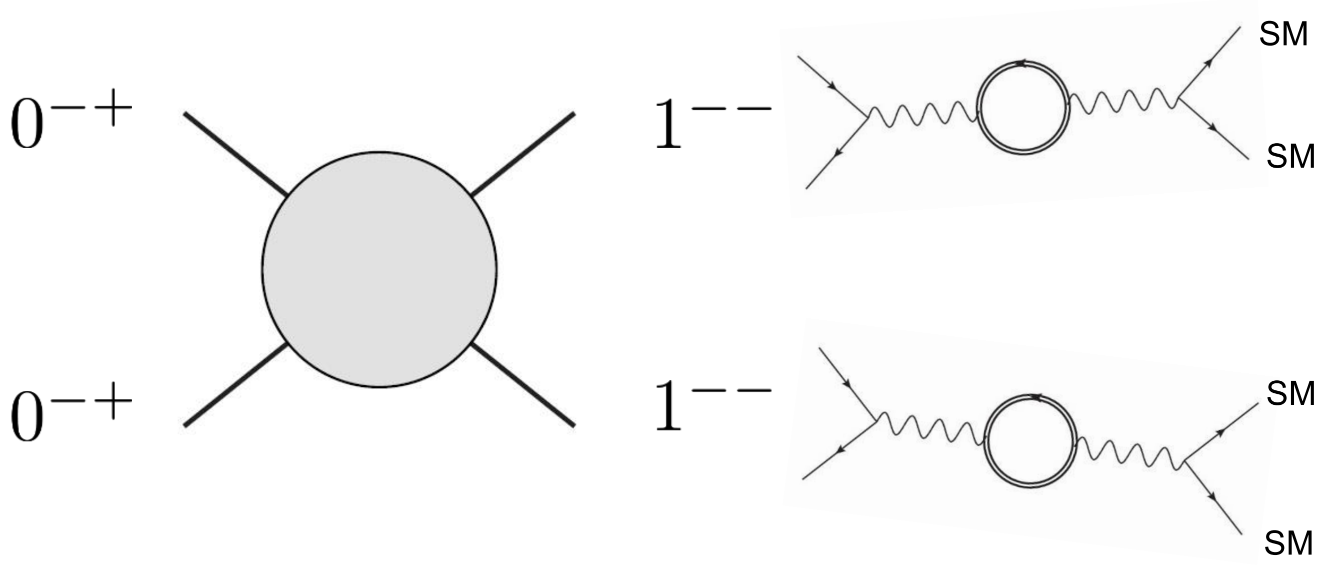
- $\hat{\Upsilon}$ (1^{--}) could decay back to SM through kinematic mixing between the U(1)'s, $-(\epsilon/2)B_{\mu\nu}\hat{B}^{\mu\nu}$

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

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.

Twin Hadron Decays

- 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.



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

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

(See Yuhsin's talk)

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.

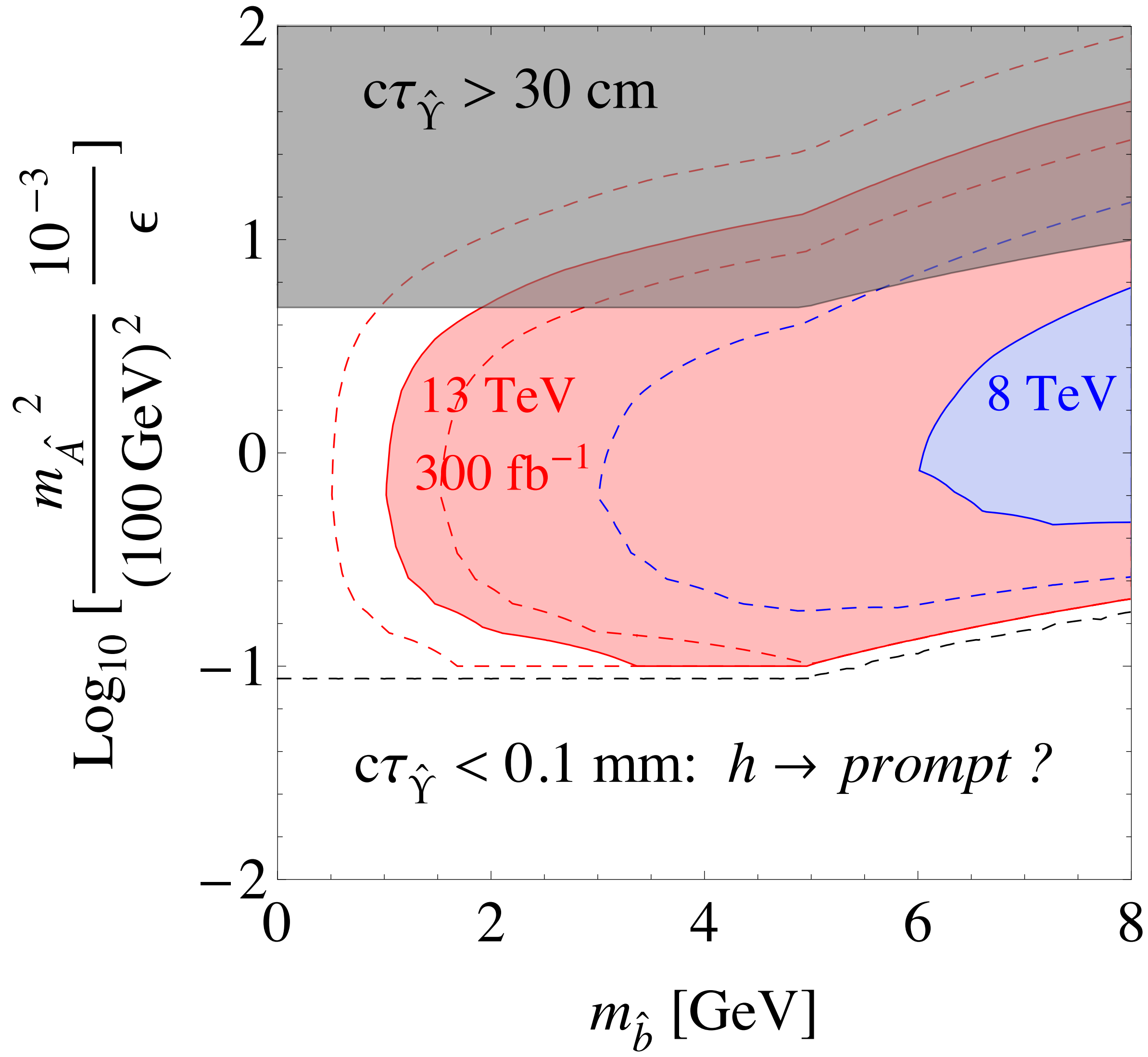
  ▸ There are $4(l{+}1)^2$ states with orbital angular momentum up to l. $\hat{\Upsilon}$ has 3 states.

  ▸ Assuming that all states below l are produced equally:

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

Twin Υ from Higgs Decay

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



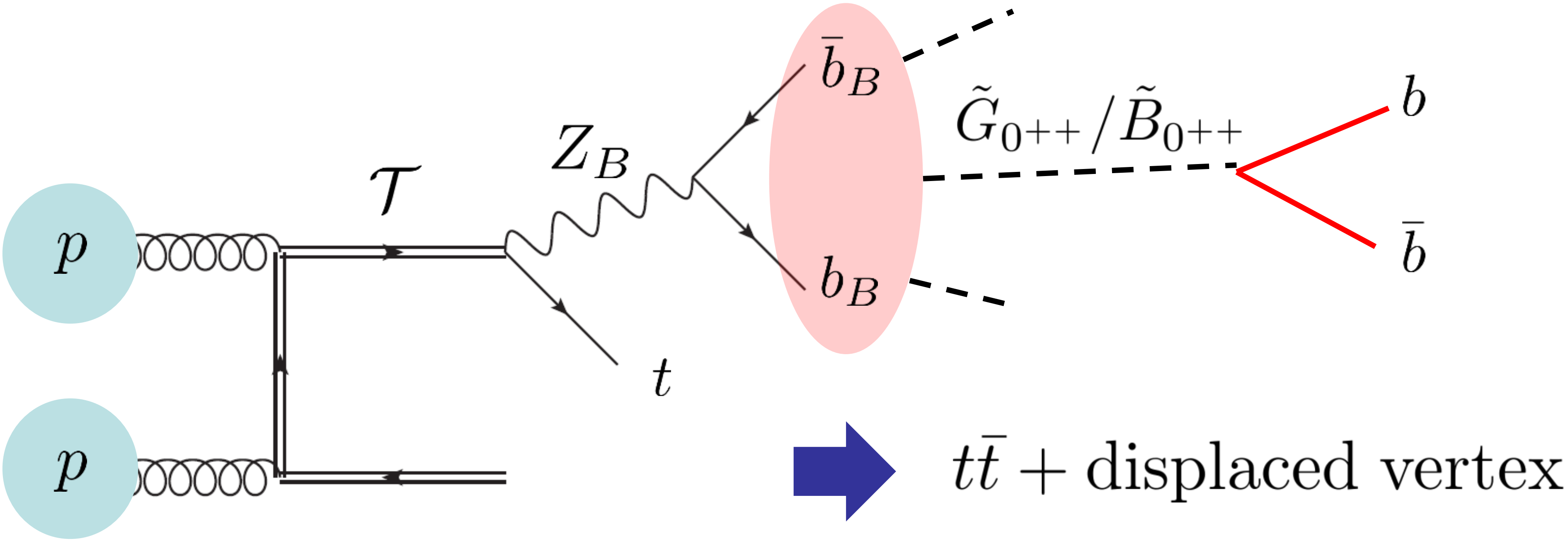
Assuming fraction of twin bottomonia being $\hat{\Upsilon}$, $R_{\hat{\Upsilon}} = 3/16$

Based on CMS search for generic long-lived particles decaying into a lepton pair in the inner detector, 1411.6977.

Exotic Quark Searches

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

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



Easy to trigger from hard objects from top decay.

Combination of displaced vertex and hard objects from prompt top quarks should make it basically 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

- References

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].

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

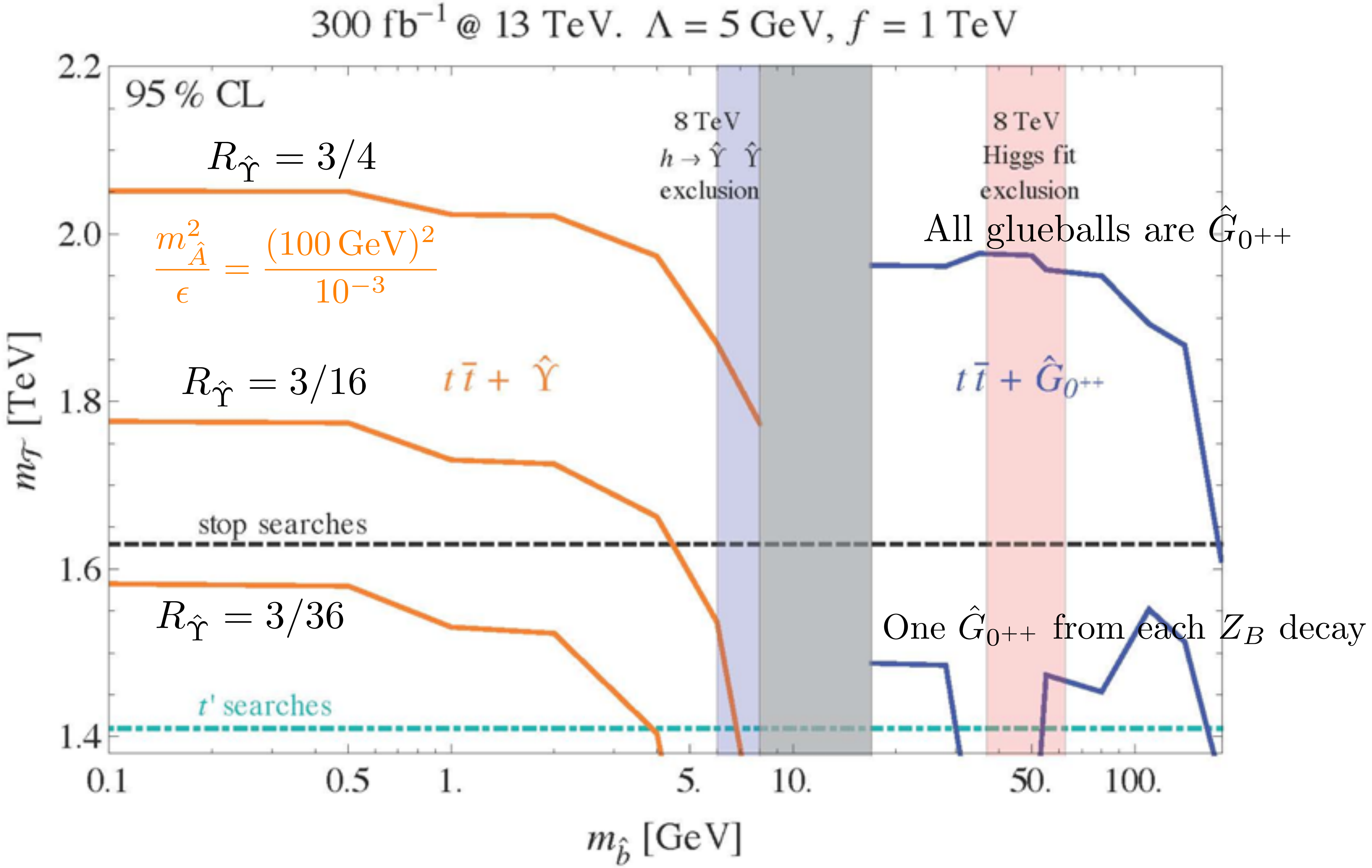
ATLAS Collaboration, "Search for long-lived, weakly interacting particles that decay to displaced hadronic jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," arXiv:1504.03634 [hep-ex].

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].

Hadronic DV in ID, HCAL, MS,

$$1 < r < 28\,\mathrm{cm},\ 200 < r < 750\,\mathrm{cm}$$

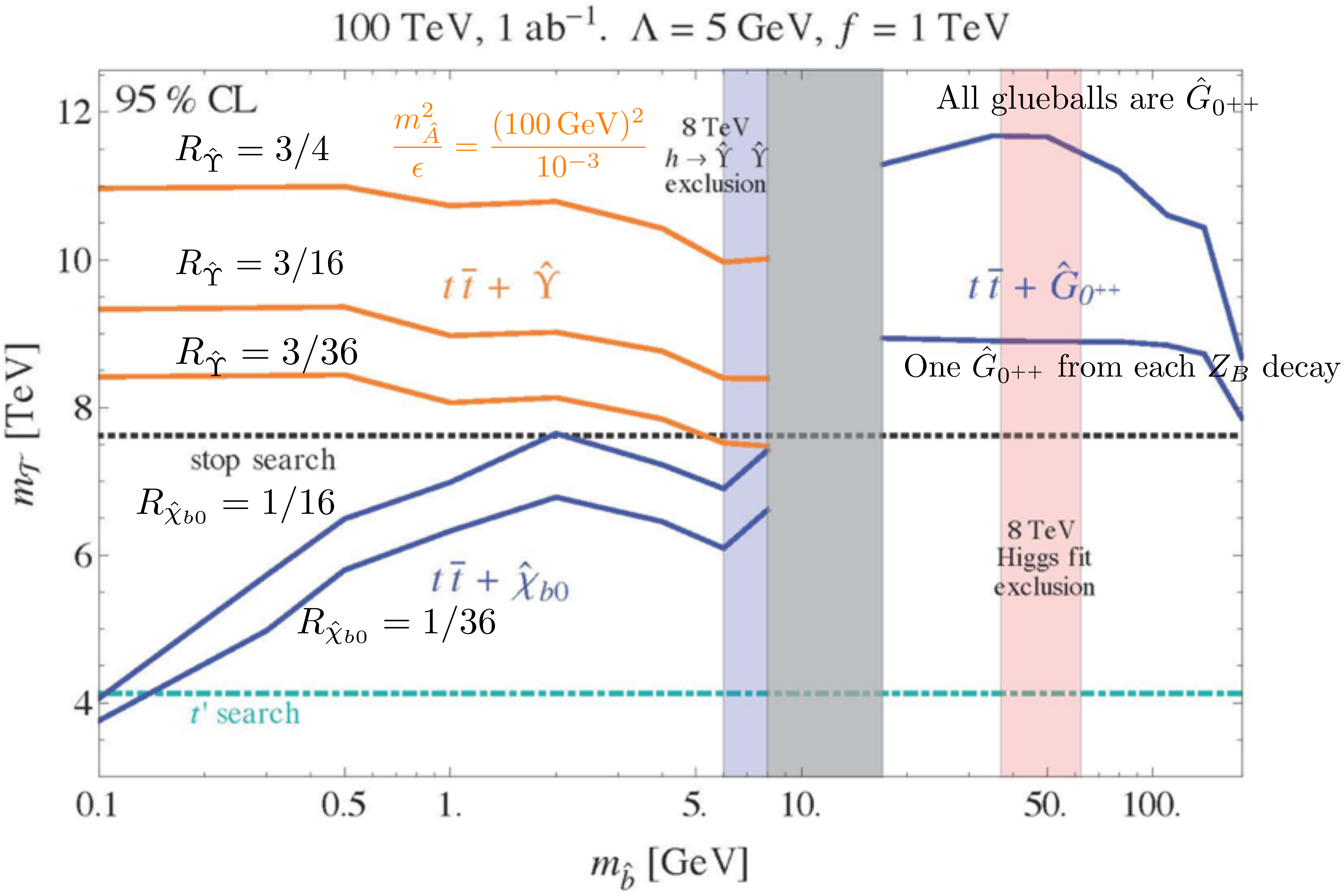
Exotic Quark Searches



Twin bottomonia dominate

Twin glueballs dominate

Exotic Quark Searches



Discussion

- Light twin leptons deplete the twin bottomonium signals (Twin bottomonium decays to twin leptons), but enhance the twin glueball signals (all twin glueballs decays to $\hat{G}_{0++}$+ twin leptons).
- Light twin leptons can overclose the universe if stable.
- They look like sterile neutrinos to us, can mix with SM leptons through higher dimensional operators, then they decay to 3 leptons or 1 lepton+2 quarks. For appropriate parameters they can also give rise to displaced vertices.

Conclusions

- Twin Higgs models will contain new particles charged under SM once it's UV completed. In non-SUSY UV-completion, there are exotic top partners carrying SM color and twin EW. These exotic quarks provide a strong probe to Twin Higgs models.
- Displaced vertex signals are common in Twin Higgs models from the hidden sector. When generated from the exotic quarks, they are typically accompanied by hard objects from top decays, resulting in distinct clean signals, and hence high reaches in UV scales of Twin Higgs models.

Twin Leptons

- The twin tau and twin neutrino are singlets under unbroken gauge symmetries. They behave like sterile neutrinos, may mix with SM neutrinos through higher-dim operators.

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

E.g., if only mixes with tau neutrino,

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & \cos\theta_\nu & -\sin\theta_\nu \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \\ \hat{\ell} \end{pmatrix} \qquad \to \qquad U_{\gamma x} = -\sin\theta_\nu\,\delta_{\gamma\tau}\,.$$

Twin Leptons

- The twin tau and twin neutrino masses are free parameters in the Fraternal Twin Higgs scenario. For suitable masses and mixing angles, a twin lepton may decay inside the detector with a displaced vertex.

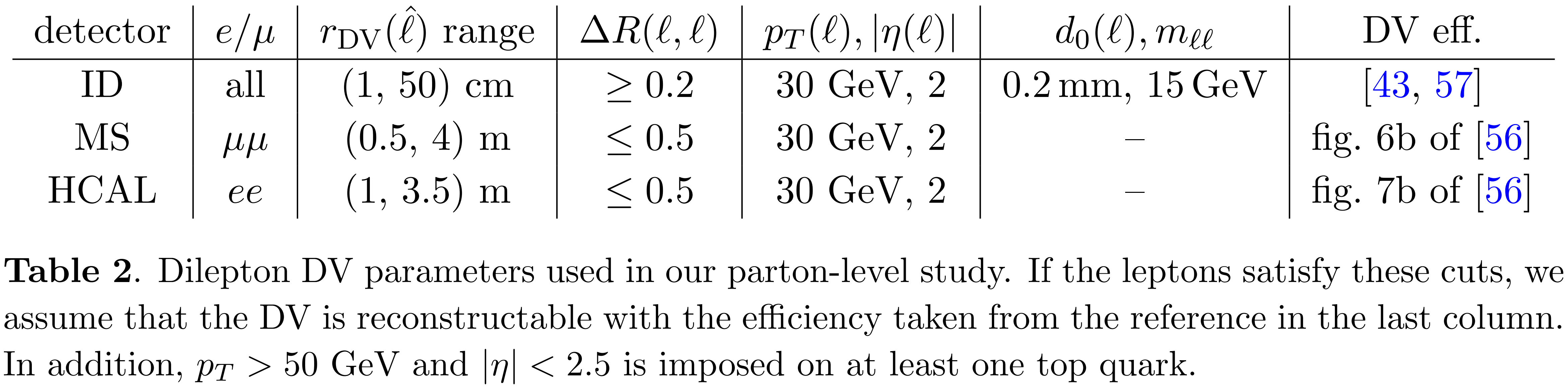
$$\Gamma_{\hat{\ell}} = \frac{G_F^2 m_{\hat{\ell}}^5}{192\pi^3}\left(\frac{51}{4} - 7s_w^2 + 12s_w^4\right)\sin^2\theta_\nu \approx \left(\frac{\sin\theta_\nu}{10^{-3}}\right)^2\left(\frac{m_{\hat{\ell}}}{6\,\mathrm{GeV}}\right)^5\left(\frac{1}{10\ \mathrm{cm}}\right).$$

- Since W_B from $\mathfrak{B}$ exotic quark always decays to twin leptons, we study the following signals:

$$pp \to (\mathcal{B} \to tW_B)(\overline{\mathcal{B}} \to \bar{t}W_B) \to t\bar{t} + \text{twin leptons}\,, \quad \hat{\ell} \to (\ell^+\ell^-)_{\mathrm{DV}} \text{ or } \hat{\ell} \to (q\bar{q}^{(\prime)})_{\mathrm{DV}}\,.$$

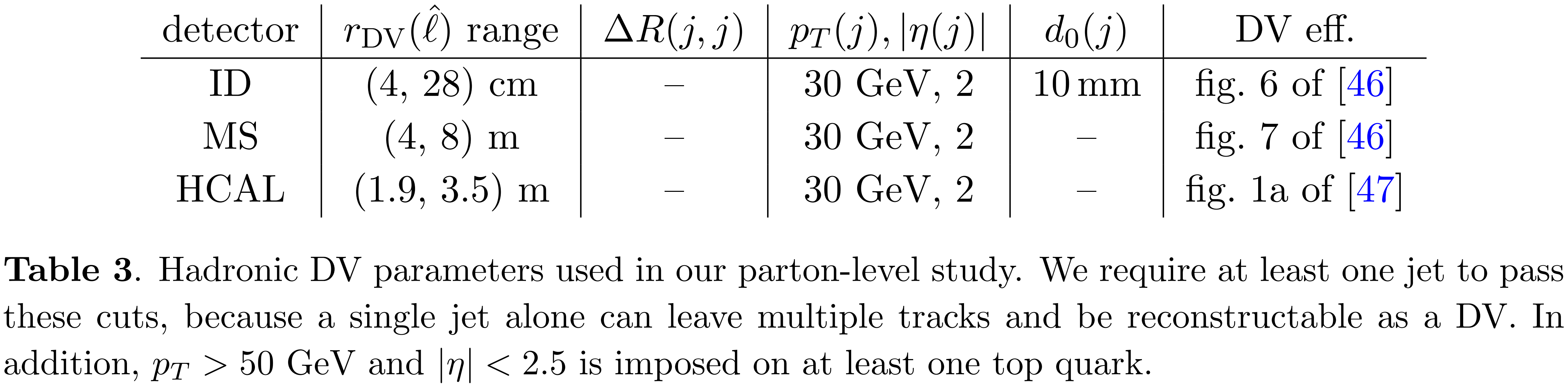
Twin Leptons

- Signal selections based on current ATLAS and CMS studies.



detector	e/μ	$r_{\rm DV}(\hat{\ell})$ range	$\Delta R(\ell, \ell)$	$p_T(\ell), \lvert\eta(\ell)\rvert$	$d_0(\ell), m_{\ell\ell}$	DV eff.
ID	all	(1, 50) cm	≥ 0.2	30 GeV, 2	0.2 mm, 15 GeV	[43, 57]
MS	$\mu\mu$	(0.5, 4) m	≤ 0.5	30 GeV, 2	–	fig. 6b of [56]
HCAL	ee	(1, 3.5) m	≤ 0.5	30 GeV, 2	–	fig. 7b of [56]

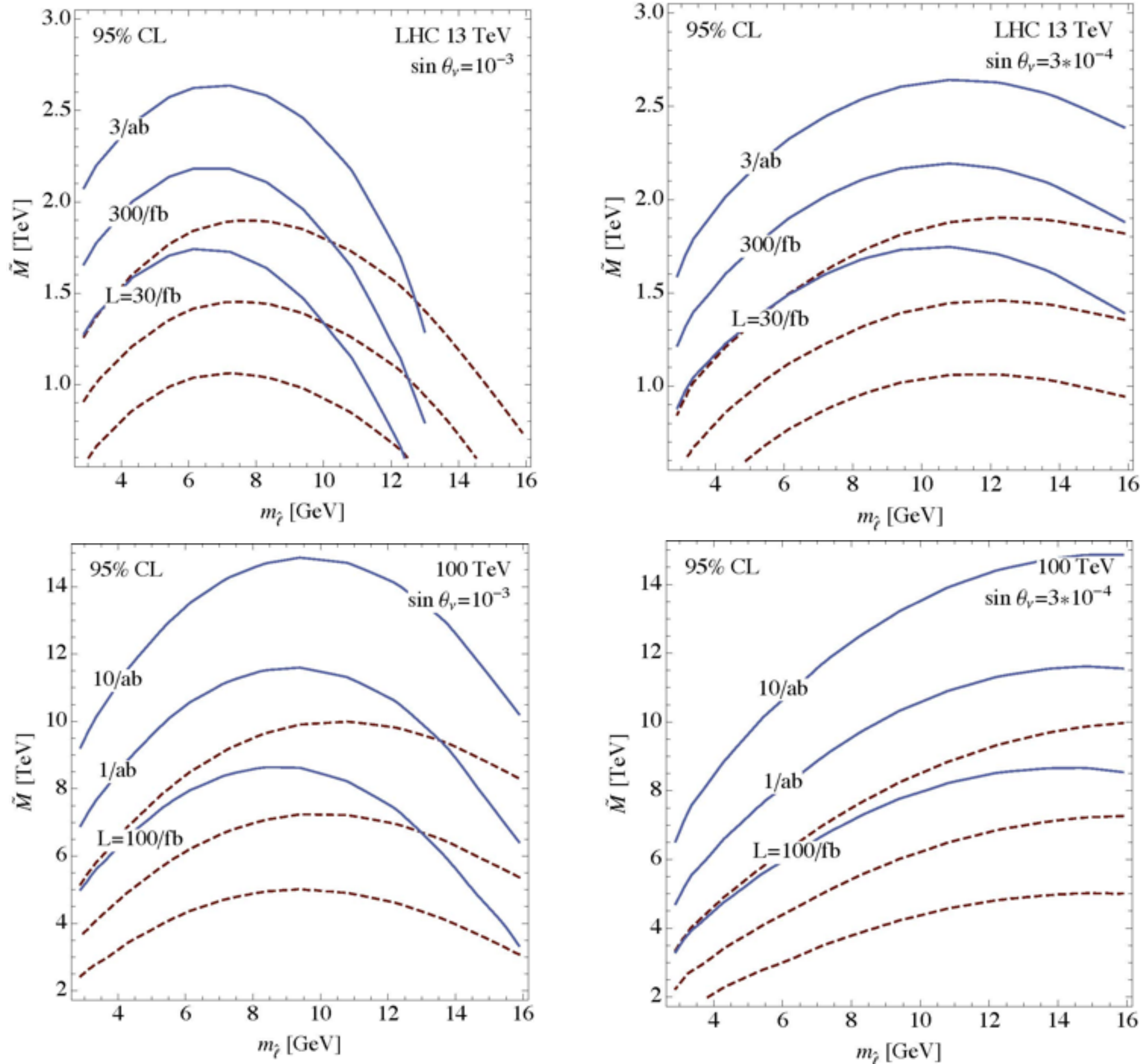
Table 2. Dilepton DV parameters used in our parton-level study. If the leptons satisfy these cuts, we assume that the DV is reconstructable with the efficiency taken from the reference in the last column. In addition, $p_T > 50$ GeV and $|\eta| < 2.5$ is imposed on at least one top quark.



detector	$r_{\rm DV}(\hat{\ell})$ range	$\Delta R(j, j)$	$p_T(j), \lvert\eta(j)\rvert$	$d_0(j)$	DV eff.
ID	(4, 28) cm	–	30 GeV, 2	10 mm	fig. 6 of [46]
MS	(4, 8) m	–	30 GeV, 2	–	fig. 7 of [46]
HCAL	(1.9, 3.5) m	–	30 GeV, 2	–	fig. 1a of [47]

Table 3. Hadronic DV parameters used in our parton-level study. We require at least one jet to pass these cuts, because a single jet alone can leave multiple tracks and be reconstructable as a DV. In addition, $p_T > 50$ GeV and $|\eta| < 2.5$ is imposed on at least one top quark.

Expected reaches:

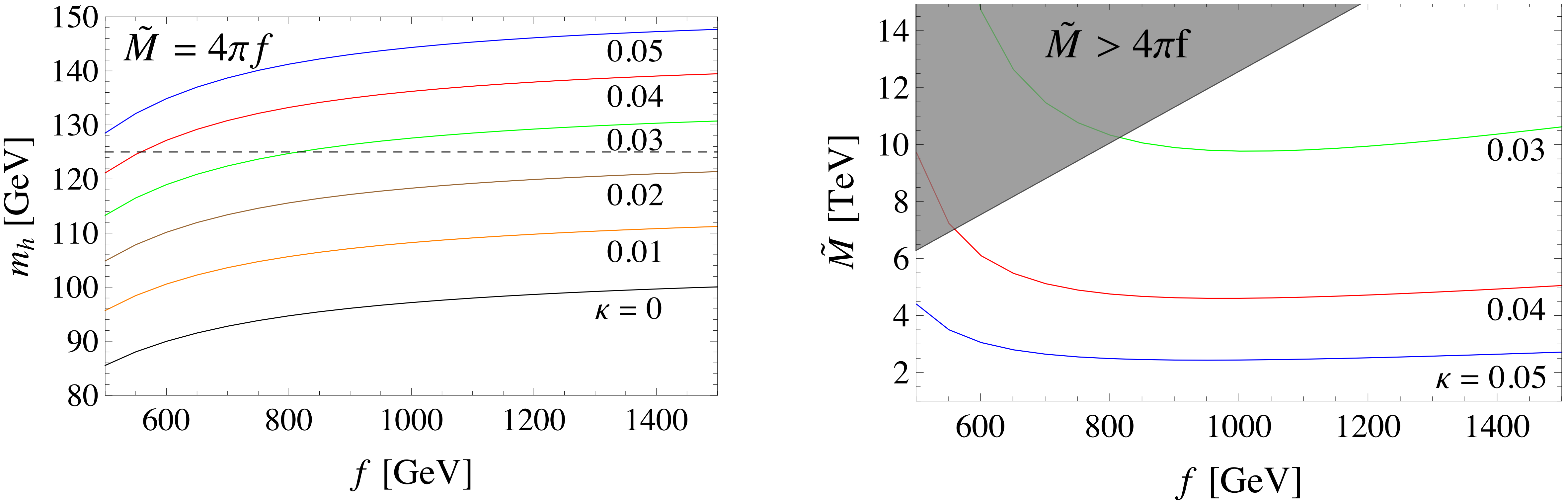


Higgs Potential and Higgs Mass

- 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.



Exotic Quark Searches