NEUTRAL NATURALNESS AT THE LHC

Aqeel Ahmed

Vrije Universiteit Brussel

based on: JHEP 02 (2018) 048 [arXiv:1711.03107]
and
arXiv:1906.xxxx [with B. Dillon & S. Najjari]

PLANCK 2019 Granada — June 4, 2019

NEUTRAL NATURALNESS

- Solution to the *Electroweak Hierarchy Problem* is one of the main theoretical motivations to go beyond the SM.

- There are many plausible solutions to the EW hierarchy problem and most of them predict new physics close to the EW scale.

	top-partners	Scalar	Fermion
Strong direct production	QCD	SUSY	Composite Higgs/ Extra Dimensions
DY direct production	EW	Folded SUSY	Quirky Little Higgs
Higgs portal production	SM Neutral	Hyperbolic Higgs	Twin Higgs

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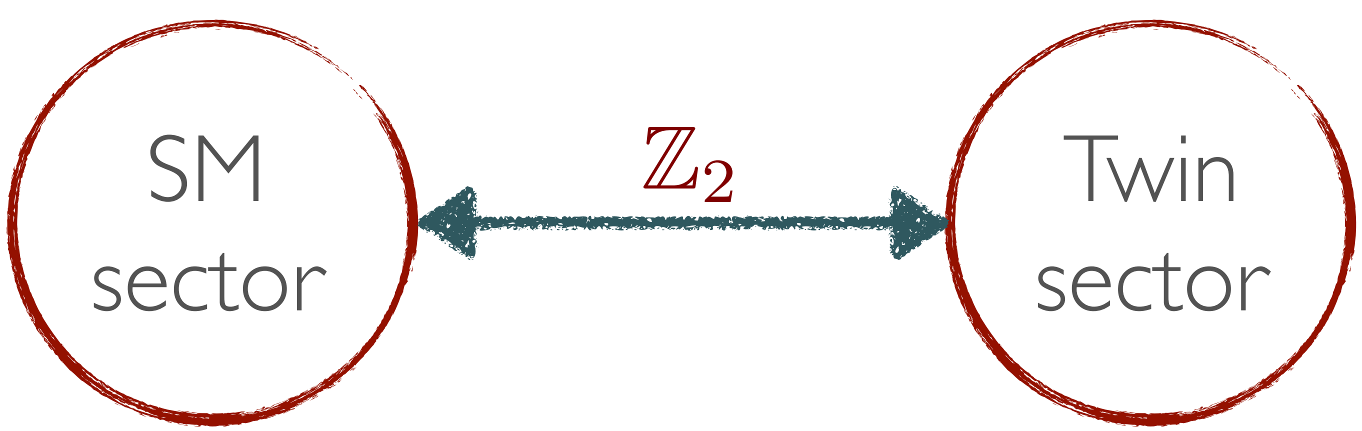
focus of this talk

TWIN HIGGS MODEL

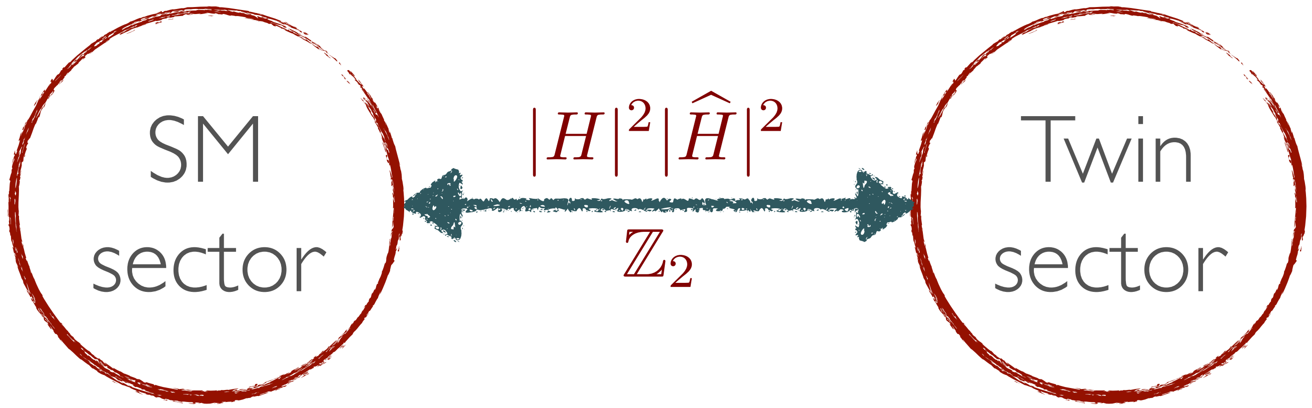
Chacko, Goh, Harnik: hep-ph/0506256

- Twin Higgs model is the prime example of *Neutral Naturalness*, where the *Hierarchy Problem* is solved by SM neutral 'top partners'.
- Twin Higgs model extends the SM by its "twin/mirror" copy.
- Mirror SM is related to the SM by a discrete $\mathbb{Z}_2$ symmetry.



$SU(3)_c \times SU(2)_L \times U(1)_Y$ $\qquad$ $\widehat{SU}(3)_c \times \widehat{SU}(2)_L \times \widehat{U}(1)_Y$

TWIN HIGGS MODEL



- Twin Higgs model employs an $SU(4)$ approximate global symmetry in the scalar sector

$$\mathbb{H} = \begin{pmatrix} H \\ \widehat{H} \end{pmatrix}$$

H SM Higgs doublet

$\widehat{H}$ twin Higgs doublet

- Spontaneous symmetry breaking:

$$SU(4) \to SU(3) = 7 \text{ Goldstone bosons}$$

$7\,\mathrm{GBs} - 3\,(W^{\pm}, Z) - 3\,(\hat{W}^{\pm}, \hat{Z}) = 1\,\mathrm{GB}$, the SM Higgs h_0

+ the radial mode $\hat{h}_0$

SM weak gauge bosons   Twin weak gauge bosons

TWIN HIGGS RADIAL MODE

- Assuming twin Higgs symmetry breaking is triggered by a strongly coupled UV dynamics one can integrate out the twin radial mode from the low energy effective theory.

- However, a weakly coupled UV completion of a twin Higgs model would require a relatively light twin radial mode $\hat{h}_0$.

- In the following, I will discuss phenomenological implications of a light radial mode in the Mirror and Fraternal Twin Higgs scenarios, when the twin Higgs symmetry is linearly realized.

TWIN HIGGS POTENTIAL

- We parametrize the twin potential as

see also Katz, Mariotti, Pokorski, Redigolo, Ziegler:1611.08615

$$V_{\text{eff}}(H,\widehat{H}) = \lambda\left(|H|^2 + |\widehat{H}|^2 - \frac{f_0^2}{2}\right)^2 + \kappa\left(|H|^4 + |\widehat{H}|^4\right) - \sigma f_0^2 |H|^2 + \rho |H|^4$$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h_0 \end{pmatrix}, \quad \widehat{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \hat{v} + \hat{h}_0 \end{pmatrix}$$

- Twin Higgs physical basis

$$\underbrace{f_0,\ \lambda,\ \kappa,\ \sigma,\ \rho}_{\text{TH gauge basis}} \longleftrightarrow \underbrace{v,\ f,\ m_h,\ m_{\hat{h}},\ \tilde{\rho}}_{\text{TH physical basis}}$$

- SM Higgs mass $m_h = 125\ \text{GeV}$ and VEV $v = 246\ \text{GeV}$ are fixed.
- Twin Higgs mass $m_{\hat{h}}$ and VEV $f \equiv \sqrt{v^2 + \hat{v}^2}$ are free parameter, along with hard breaking term

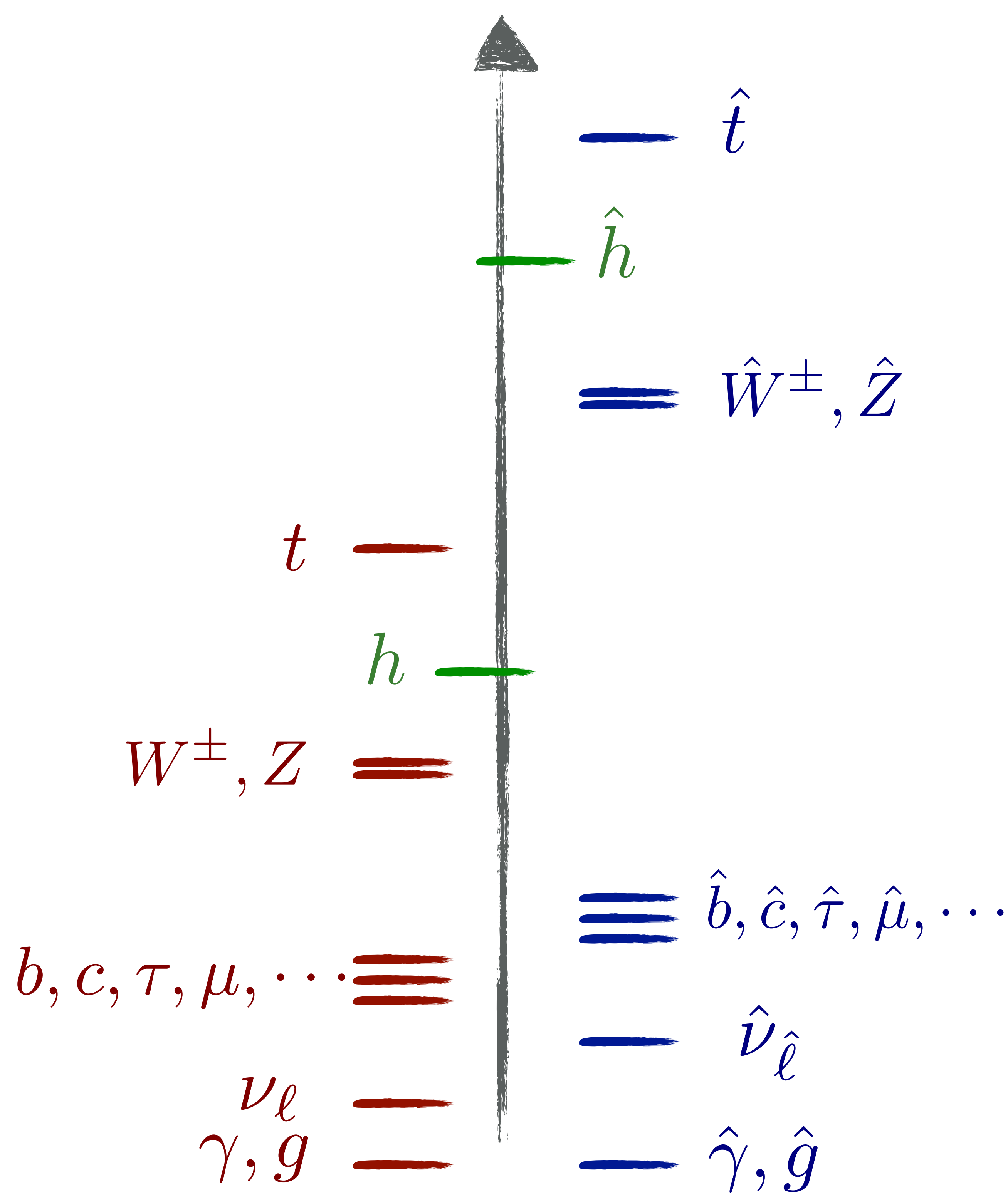
$$|\tilde{\rho}| \equiv \left|\frac{\rho}{\lambda}\right| < 1$$

MIRROR TWIN HIGGS

Chacko, Goh, Harnik: hep-ph/0506256

SM sector

Mirror sector

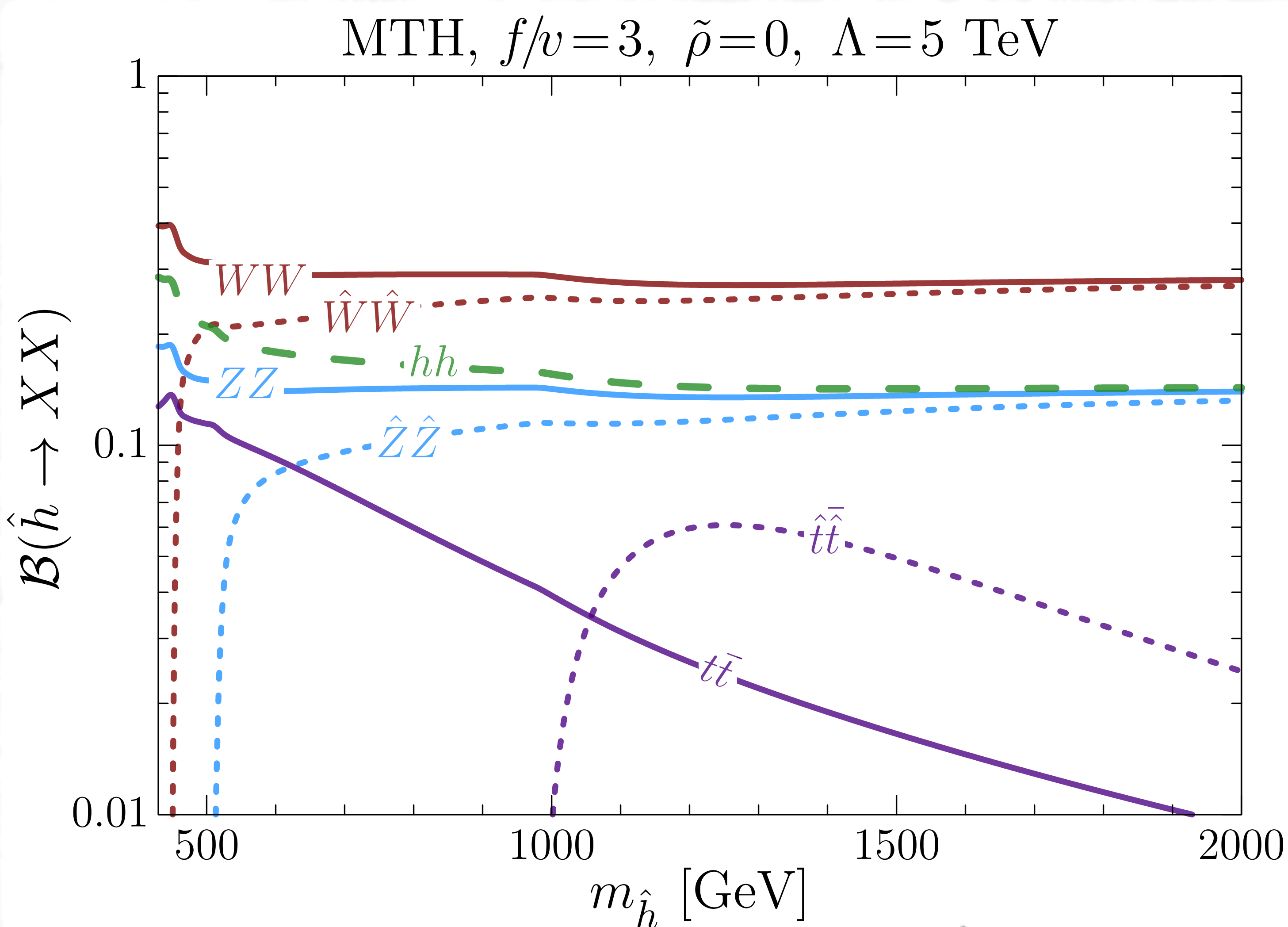


Twin sector is an exact copy of SM

$$\hat{m}_{\text{twin}} = \frac{\hat{v}}{v} m_{\text{SM}} \simeq \frac{f}{v} m_{\text{SM}}$$

MIRROR TWIN HIGGS BRANCHING RATIOS

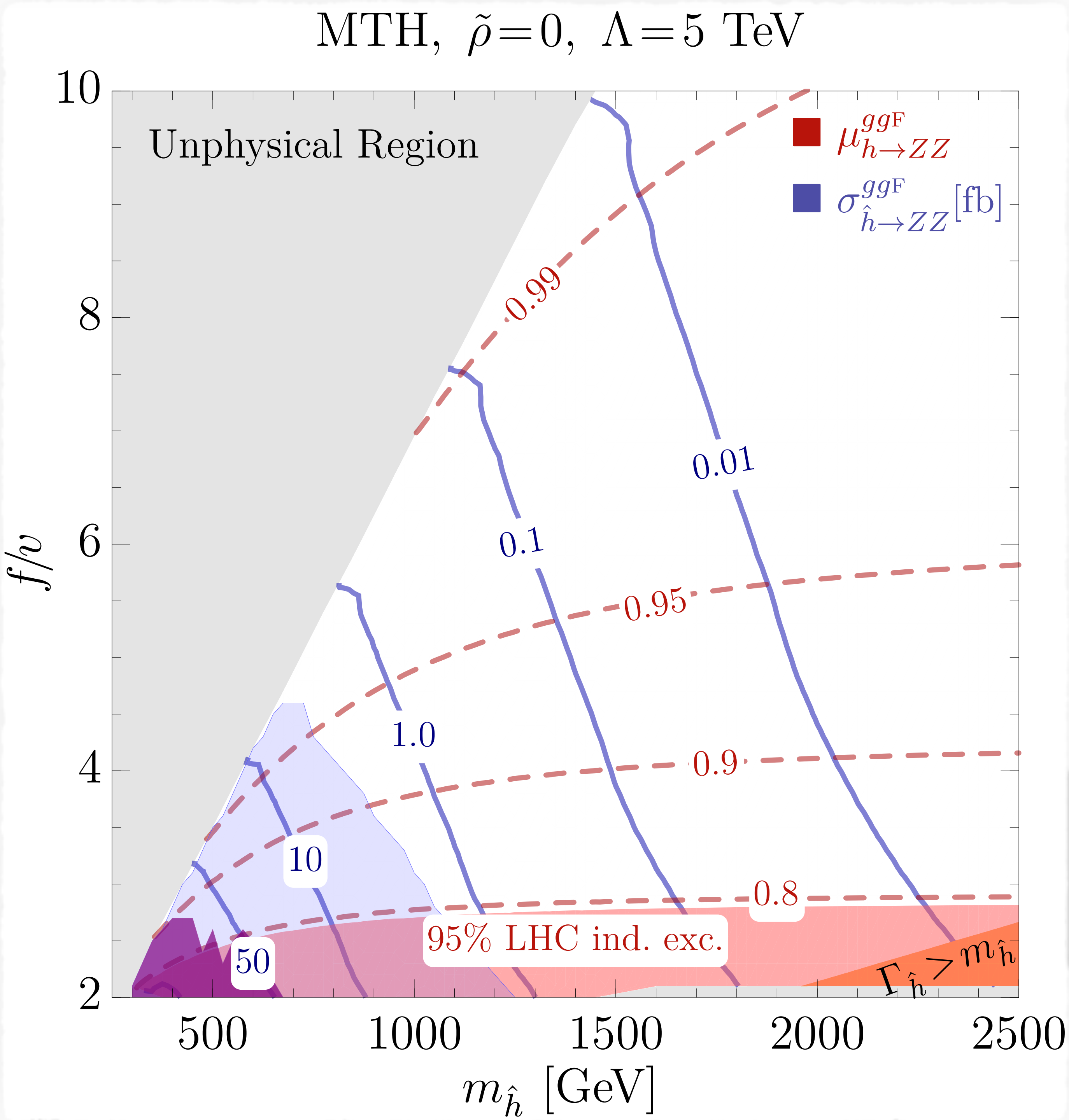
- Twin Higgs (radial mode) decays dominantly into SM and twin sector gauge bosons, and to the SM Higgs.
- The branching fractions of the twin radial mode to the would-be Goldstone bosons are predicted:



$$\mathcal{B}(\hat{h}\to hh) \simeq \mathcal{B}(\hat{h}\to ZZ) \simeq \tfrac{1}{2}\mathcal{B}(\hat{h}\to WW)$$
$$\simeq \mathcal{B}(\hat{h}\to \hat{Z}\hat{Z}) \simeq \tfrac{1}{2}\mathcal{B}(\hat{h}\to \hat{W}\hat{W})$$

$$\mathcal{B}(\hat{h}\to \text{SM}) \simeq \frac{4}{7}, \qquad \mathcal{B}(\hat{h}\to \text{inv.}) \simeq \frac{3}{7}$$

MIRROR TWIN HIGGS PHENOMENOLOGY



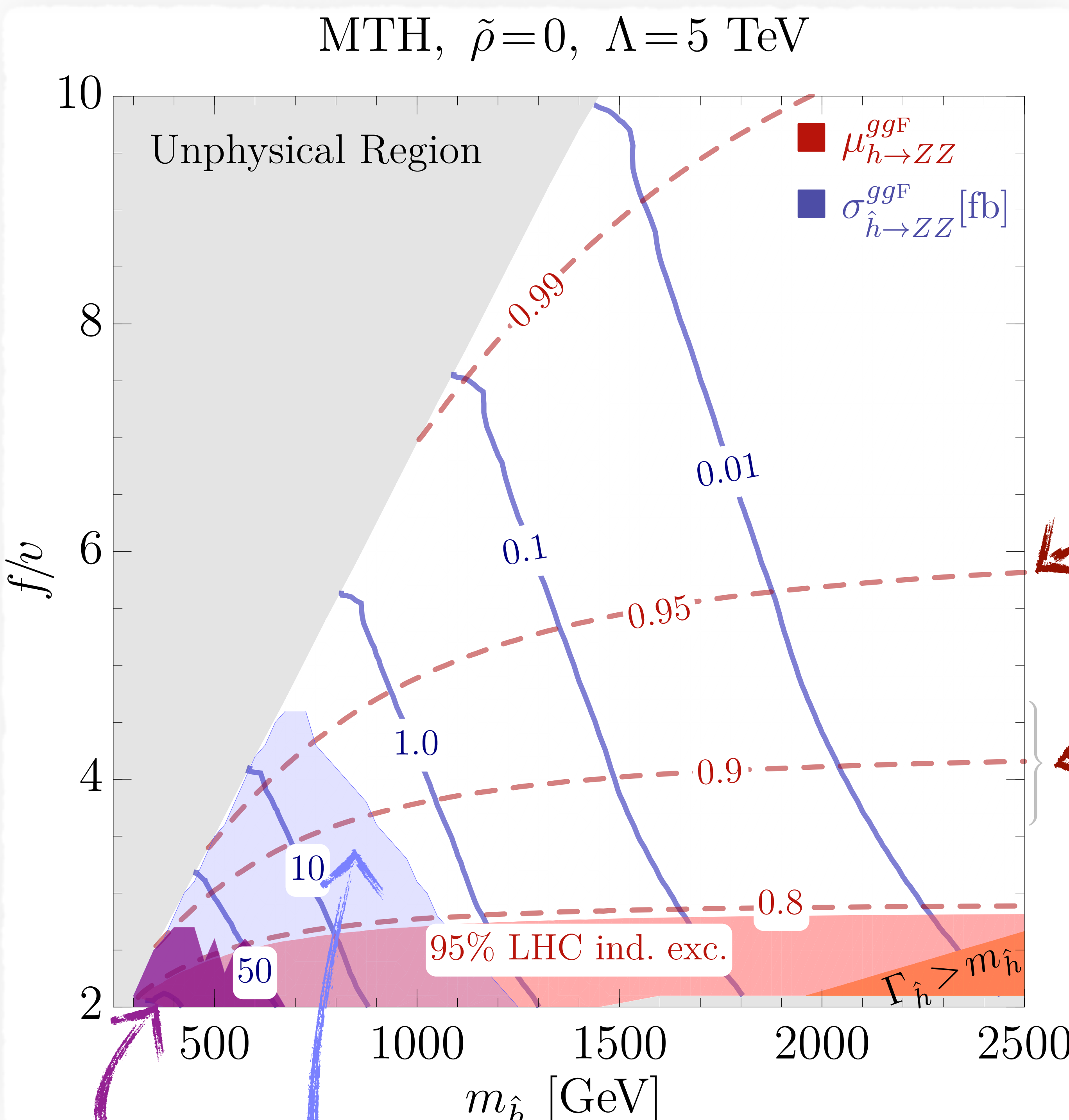
★Twin Higgs cross-sections to SM gauge bosons at the LHC

$$\sigma^{ggF}_{\hat{h}\to ZZ} \equiv \sigma(gg\to\hat{h})\cdot\mathcal{B}(\hat{h}\to ZZ)$$

★Higgs signal strength

$$\mu^{ggF}_{h\to ZZ} \equiv \frac{\sigma(gg\to h)\cdot\mathcal{B}(h\to ZZ)}{\sigma^{SM}(gg\to h)\cdot\mathcal{B}^{SM}(h\to ZZ)}$$

MIRROR TWIN HIGGS PHENOMENOLOGY



see also: Buttazzo, Sala, Tesi: 1505.05488
Chacko, Kilic, Najjari, Verhaaren: 1711.05300
Saereh Najjari's talk@PLANCK2019

ILC can reach sensitivity of Higgs signal strength measurements up to ~5 %.

HL-LHC will reach sensitivity of Higgs signal strength measurements up to 8~10 %.

Excluded by ATLAS @ 95% C.L.

HL-LHC projected reach @ 95% C.L.

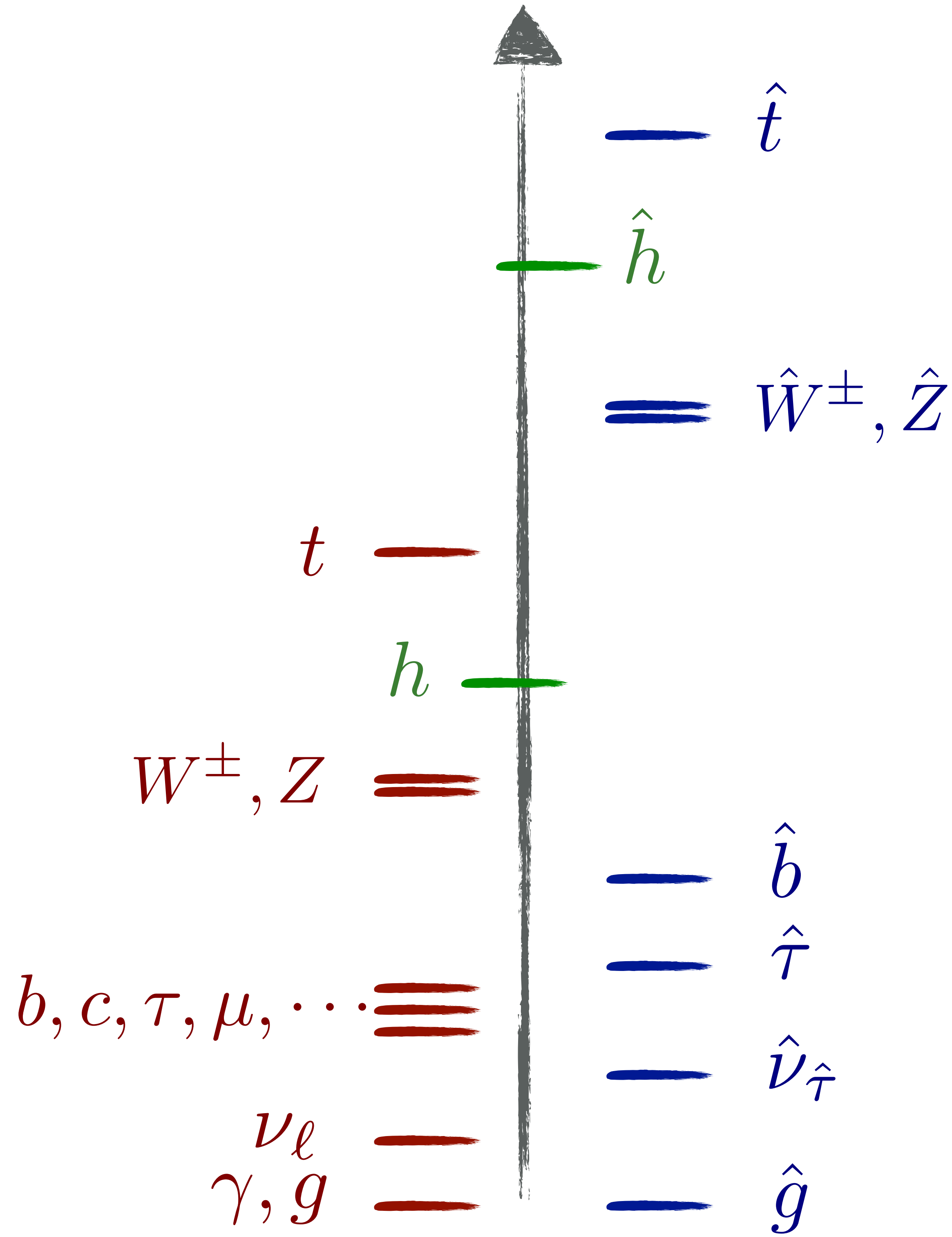
} Heavy Higgs searches

FRATERNAL TWIN HIGGS

Craig, Katz, Strassler, Sundrum: 1501.05310

SM sector $SU(3)_c \times SU(2)_L \times U(1)_Y$

Fraternal sector $\widehat{SU}(3)_c \times \widehat{SU}(2)_L$

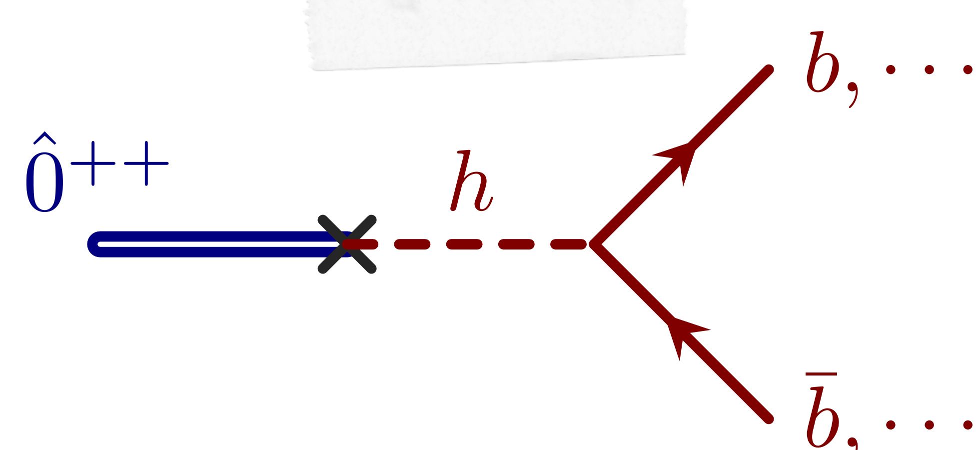


FTH requires minimal twin sector particles to cancel radiative corrections

★No light twin quarks, implies large twin QCD confinement scale.

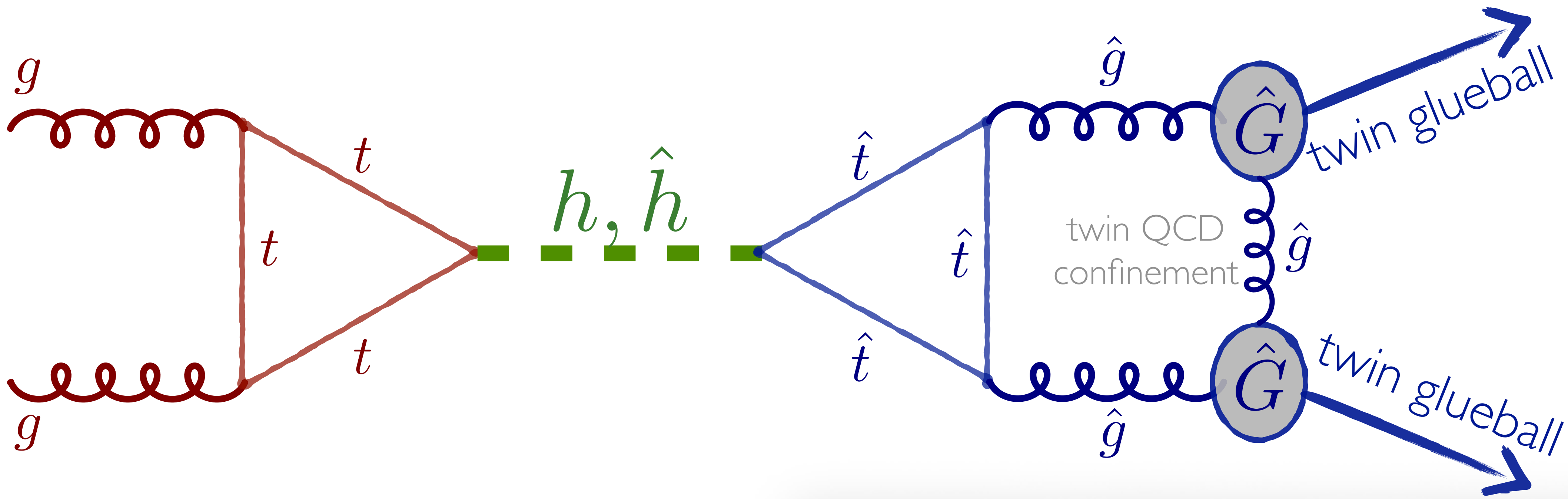
★Light twin hadrons are twin glueball/bottomonium states.

★$\hat{0}^{++}$ twin hadrons mix with SM Higgs and lead to exotic decays!



TWIN GLUEBALL PRODUCTION

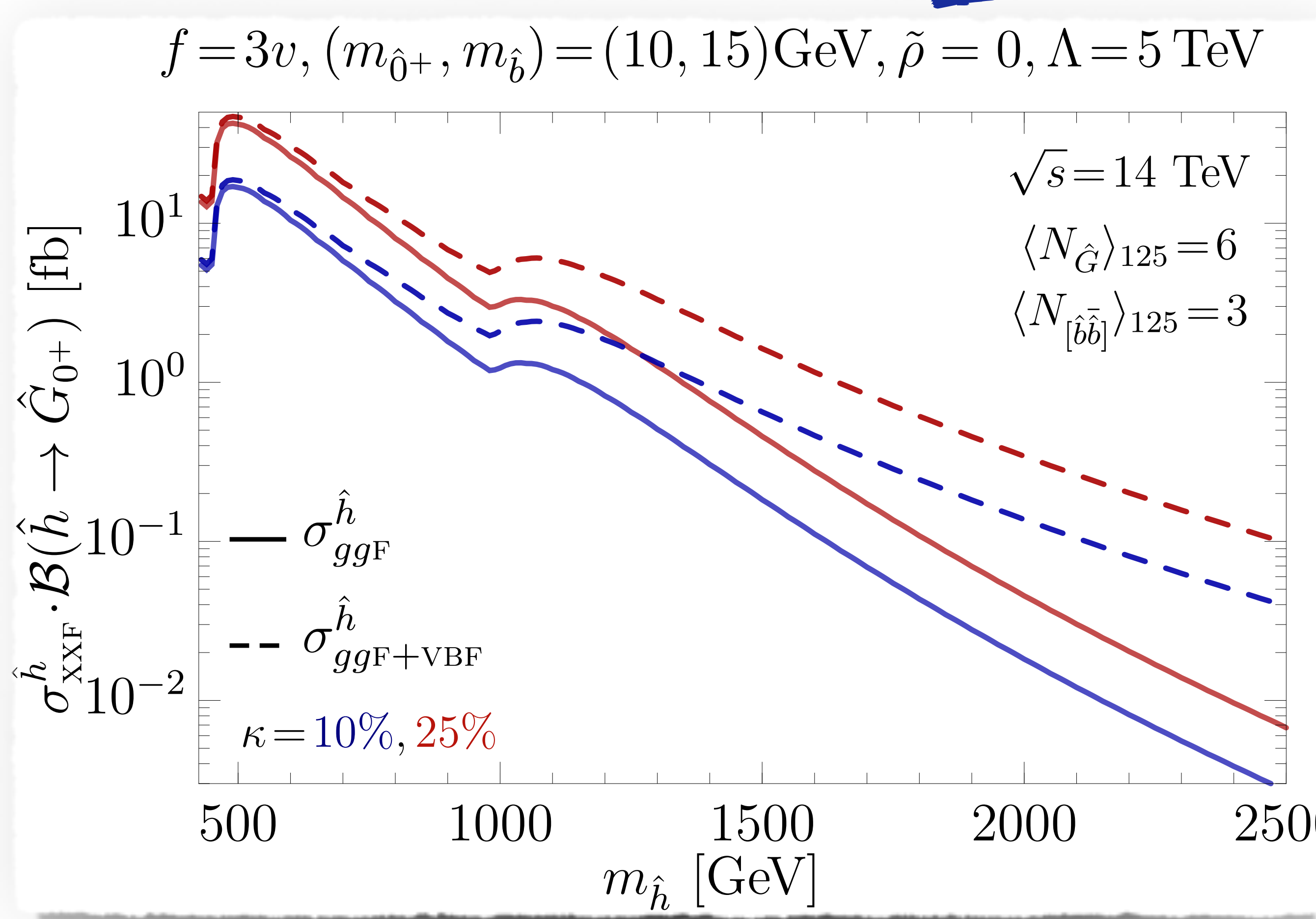
- Twin hadrons (glueball) are produced via SM Higgs and twin Higgs



- Twin hadron production via heavy Higgs
  - ★ Large hadronic multiplicities
  - ★ heavy twin hadron states accessible

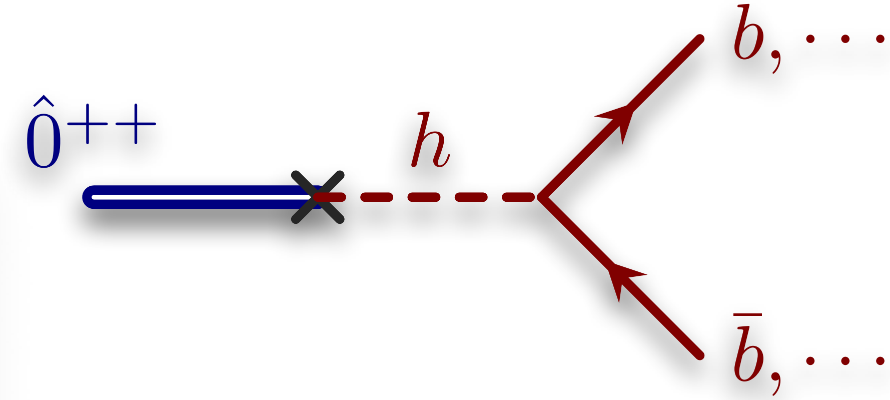
- Lightest twin glueball $\hat{G}_{0+}$

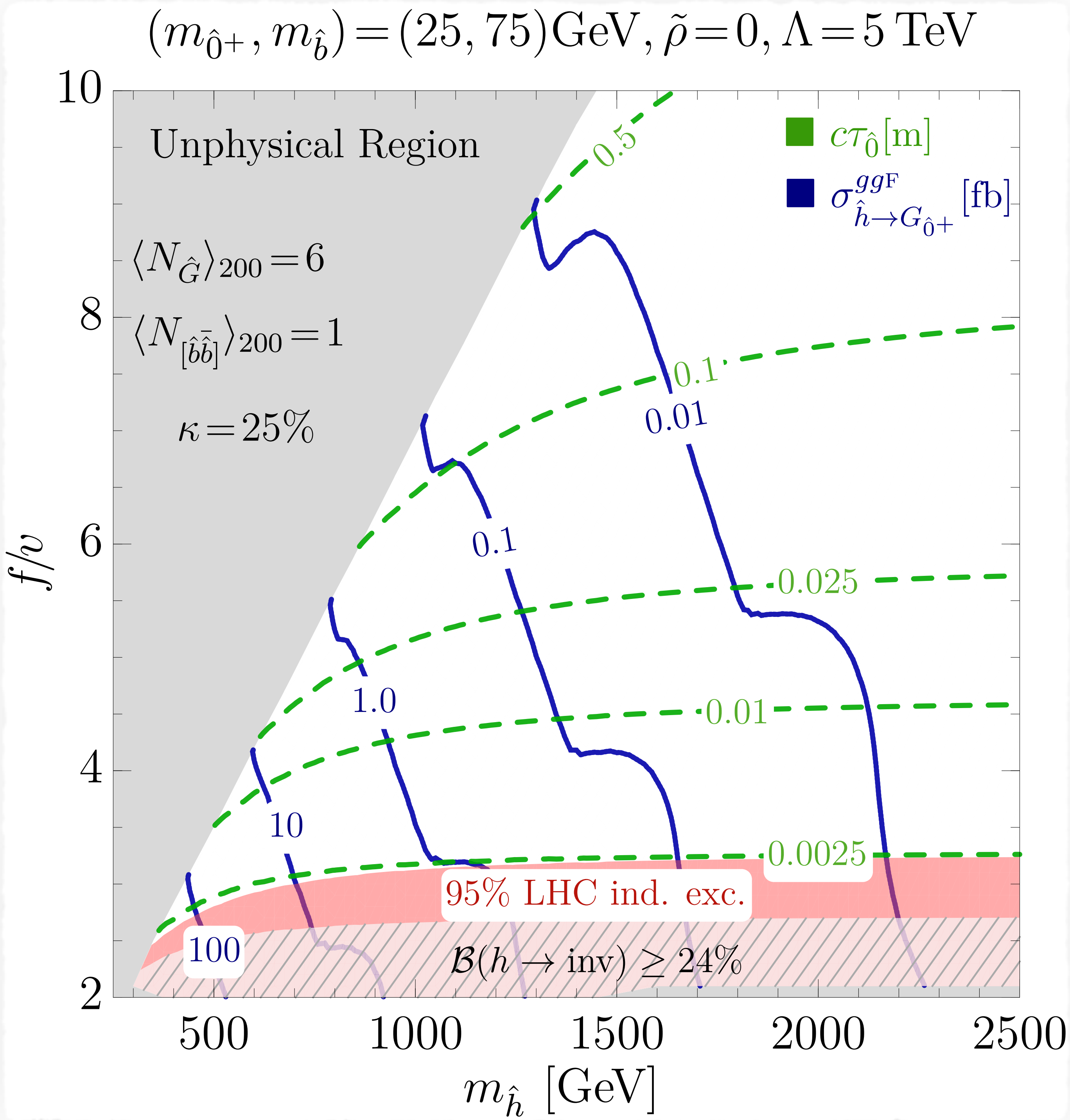
$$m_{\hat{0}+} \simeq 6.8\hat{\Lambda}_{\rm QCD}$$



TWIN HADRON PHENOMENOLOGY

- $\hat{0}^{++}$ twin glueball mix with the Higgs and decays to SM light fermions with displaced vertices.





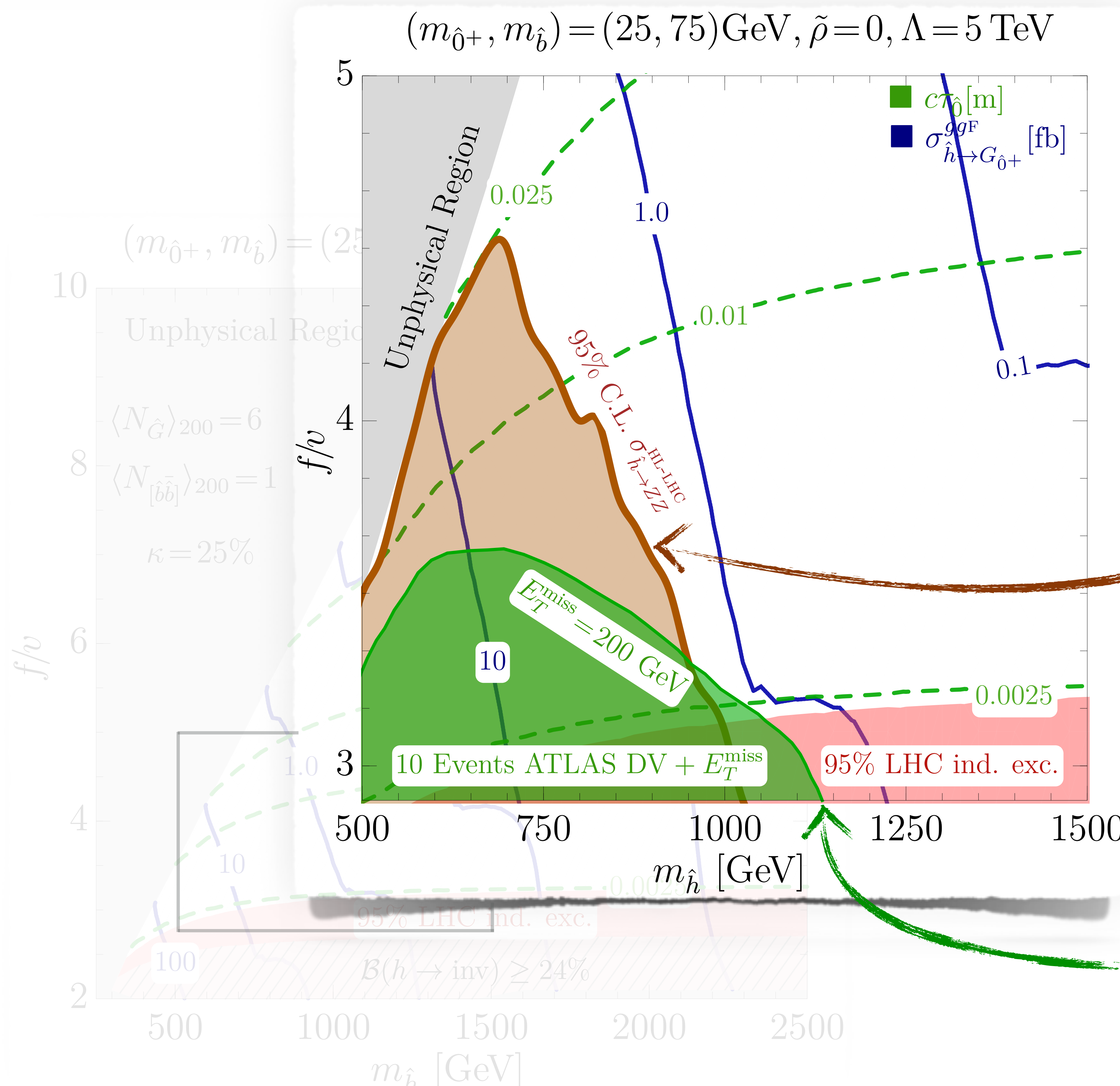
★ decay-length $c\tau_{\hat{0}} \lesssim 10\,\mathrm{m}$ is accessible at the LHC.

★ glueball cross-sections via twin Higgs are comparable to that of SM gauge bosons

$$\sigma^{ggF}_{\hat{h}\to\hat{G}_{0+}} \approx \sigma^{ggF}_{\hat{h}\to ZZ}$$

This makes a strong case to discover Twin Higgs at the LHC

FRATERNAL TWIN HIGGS AT THE HL-LHC



HL-LHC projected reach @ 95% C.L. $\hat{h} \to ZZ \to \ell\ell\ell\ell$

10 Events at HL-LHC with DV+*missing Energy*

Kilic, Najjari, Verhaaren: 1812.08173

TWIN DILATON PORTAL

AA, Dillon, Najjari:1906.xxxx

- Most of the UV completions of twin Higgs mechanism employ strongly coupled theories, e.g. composite Higgs model or extra dimensional embeddings via holography, which imply radial mode is at or above the symmetry breaking scale, hence it can be integrated out.

see e.g. Geller-Telem:1411.2974
Barbieri-Greco-Rattazzi-Wulzer:1501.07803
Low-Tesi-Wang:1501.07890

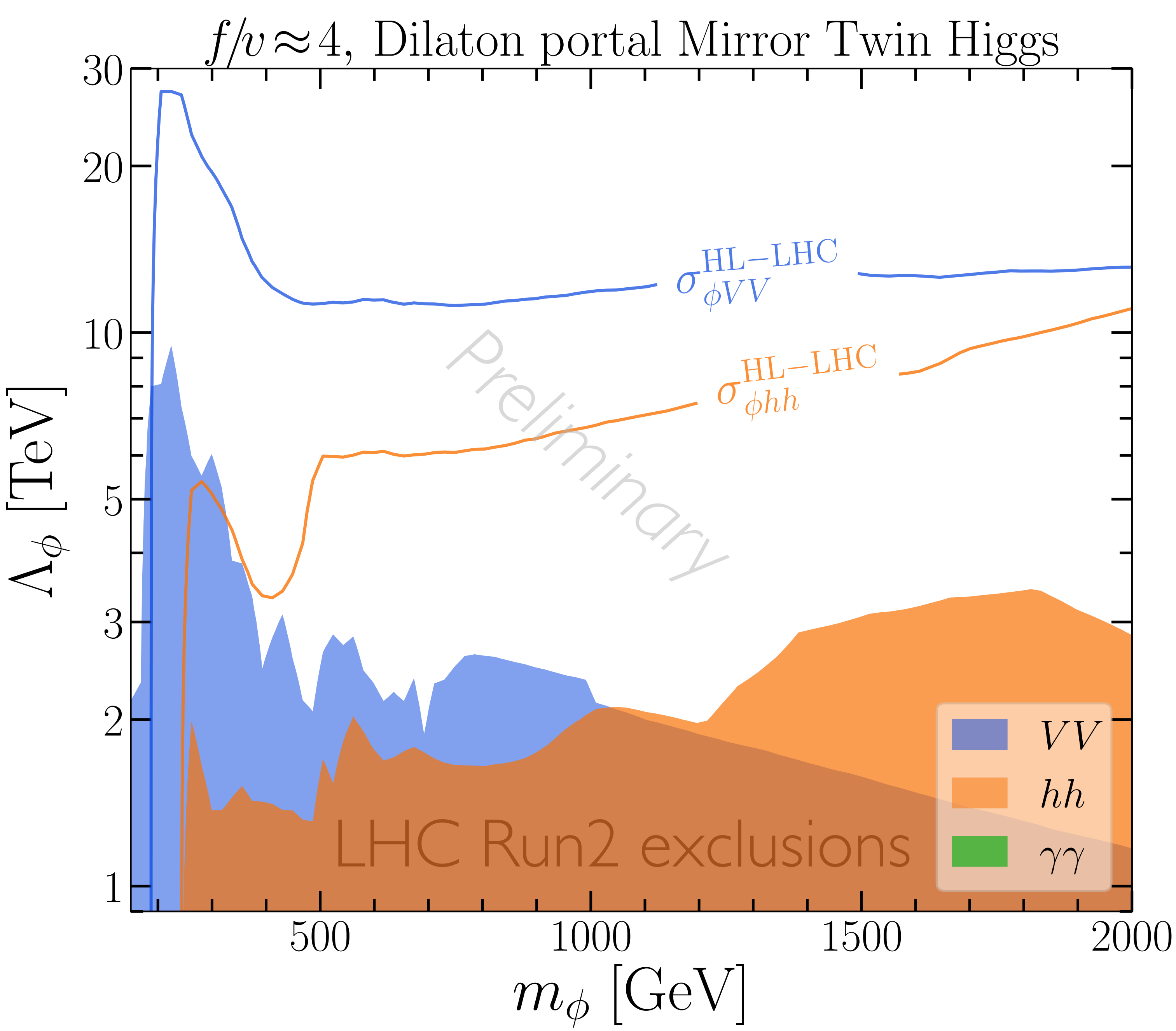
- On the other hand strongly coupled/5D theories naturally involve a light scalar, the Dilaton/Radion.

- Hence, a light Dilaton/Radion can also provide a natural scalar portal between the SM and twin sectors.

TWIN DILATON PORTAL AT THE LHC

AA, Dillon, Najjari: 1906.xxxx

✦ Twin dilaton couples to the SM and twin sectors via their energy-momentum tensors



$$\mathcal{L}_{\mathrm{TD}}^{\mathrm{int}} = \frac{\phi}{\Lambda_\phi}\left[T_\mu^\mu + \hat{T}_\mu^\mu\right]$$

HL-LHC projected reach @ 95% C.L.

CONCLUSIONS

- ✦ Twin Higgs Models are the prime illustration of "Neutral Naturalness".
- ✦ Scalar sector of the Twin Higgs model provides a portal between the visible (SM) and dark (Twin) sectors.
- ✦ Twin Higgs mechanism can be confirmed by measuring the mass and VEV of the heavy twin Higgs, along with its predicted rates to SM.
- ✦ Fraternal Twin Higgs gives novel discovery potential via the exotic decays of twin hadrons to the SM light fermions.
- ✦ Twin Dilaton portal provides another avenue to probe the twin/hidden sector.
- ✦ HL-LHC and the future colliders have the potential to discover (or refute) the twin Higgs mechanism.