NEUTRAL NATURALNESS AT THE LHC

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based on: JHEP 02 (2018) 048 [arXiv:1711.03107]

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NEUTRAL NATURALNESS

- Solution to the *Electroweak Hierarchy Problem* is one of the main theoretical motivations to search for new physics 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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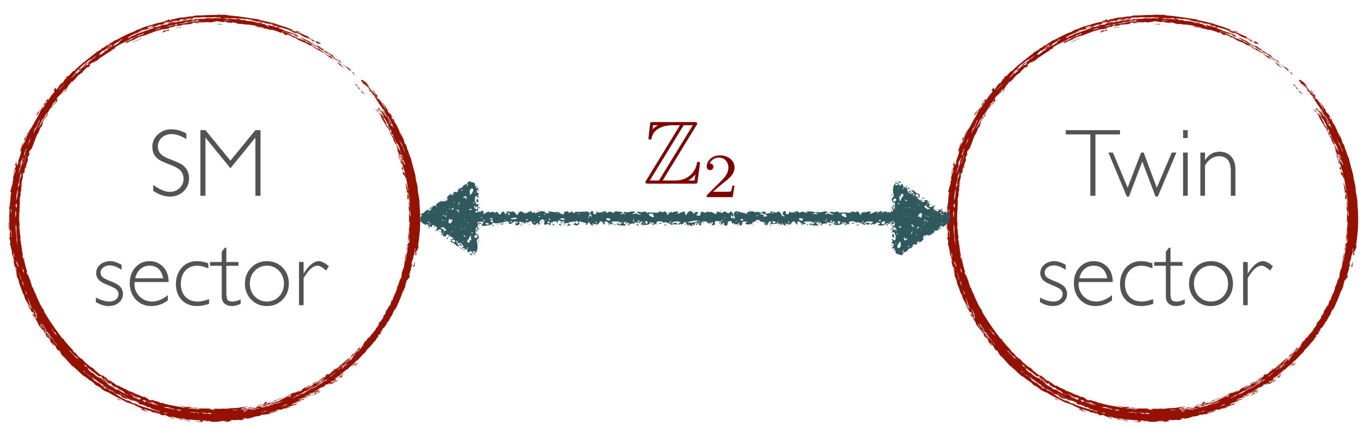
focus of this talk

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 partner'.

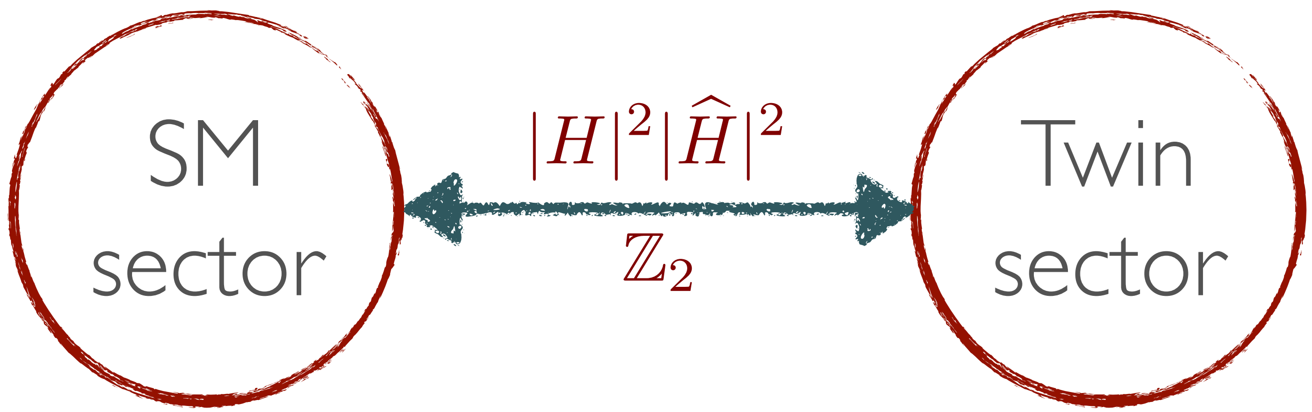
- Twin Higgs model extends the SM by its "twin/mirror" copy.



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

- Mirror SM is related to the SM by a discrete $\mathbb{Z}_2$ symmetry.

TWIN HIGGS MODEL



- The SM Higgs doublet H and the twin Higgs doublet $\widehat{H}$ have an $SU(4)$ global symmetry.

$$V(\mathbb{H}) = \lambda\left(\mathbb{H}^\dagger\mathbb{H} - f_0^2/2\right)^2 \qquad \mathbb{H} = \begin{pmatrix} H \\ \widehat{H} \end{pmatrix}$$

- Spontaneous symmetry breaking:

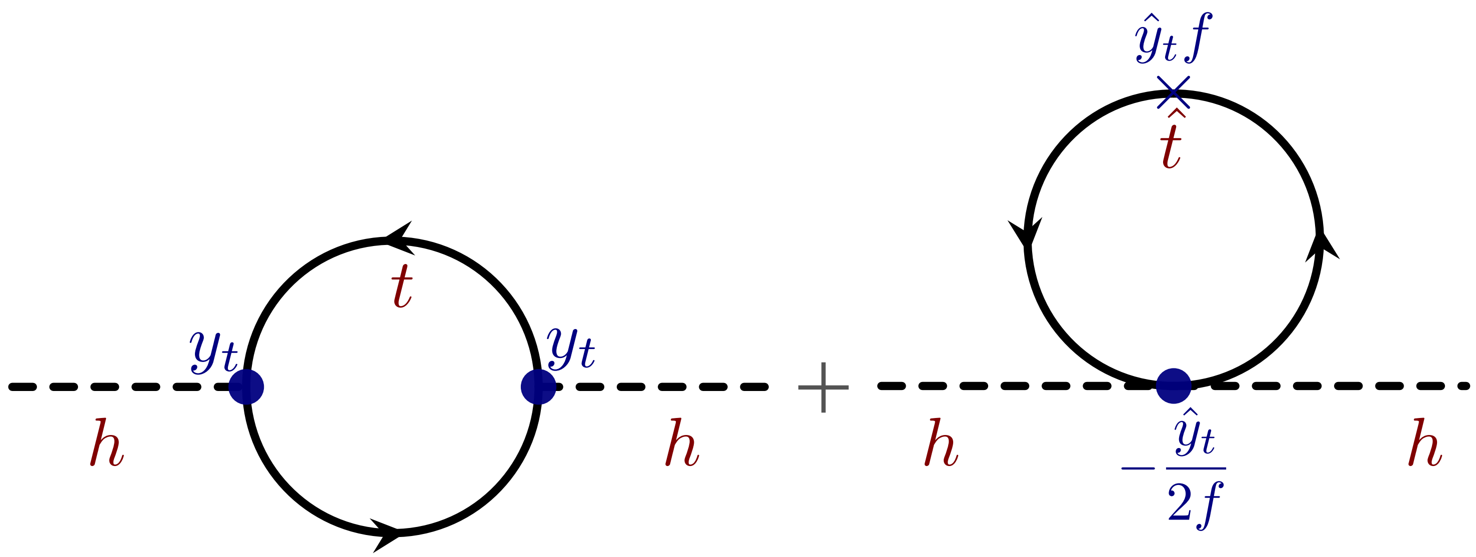
$$SU(4) \to SU(3) = 7 \text{ Goldstone bosons}$$

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

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

SM weak gauge bosons — Twin weak gauge bosons

✦ Cancellation of quadratic divergences in the Twin Higgs models



$$\sim \frac{y_t^2}{8\pi^2} N_c \Lambda^2 \left(|H|^2 + |\widehat{H}|^2\right)$$

$$\sim \frac{y_t^2}{8\pi^2} N_c \Lambda^2 |\mathbb{H}|^2$$

$$\hat{y}_t \simeq y_t$$

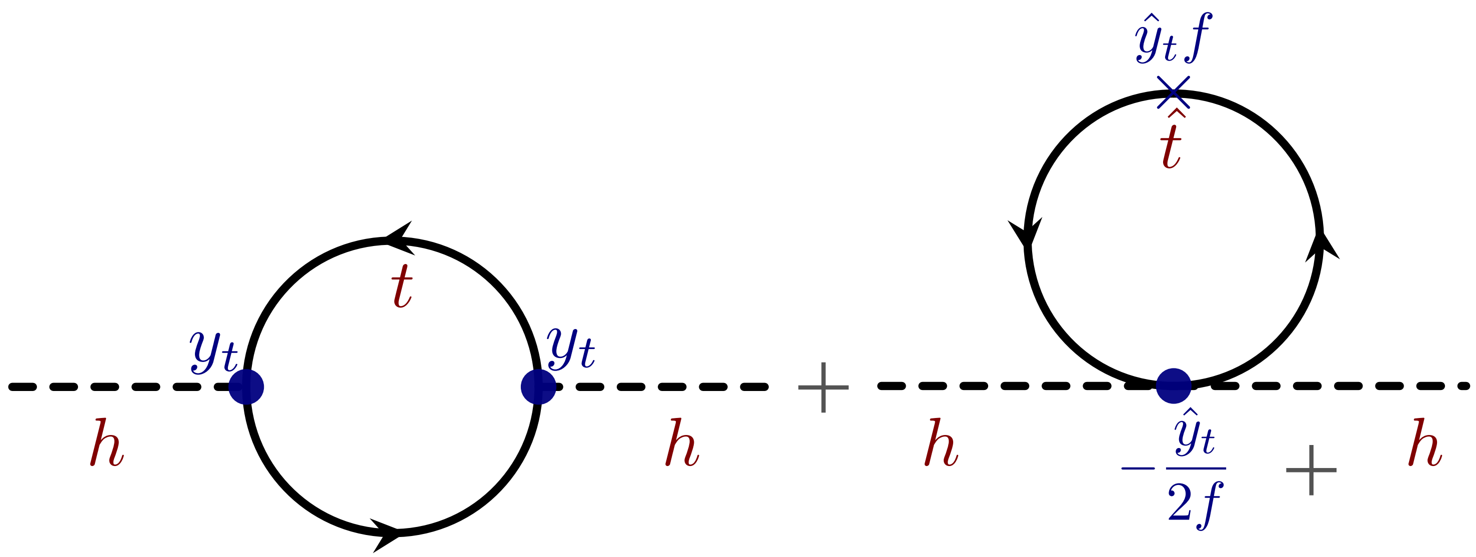
$SU(4)$ invariant

→ $m_{h_0} = 0$

✦ Note, since the 'top partners' $\hat{t}$ are SM colorless, therefore, they are elusive at the LHC.

TWIN TOP-PARTNER CANCELATION

✦ Cancellation of quadratic divergences in the Twin Higgs models



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$\longrightarrow \; m_{h_0} = 0$

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The SM Higgs mass is induced by the $SU(4)$ and $\mathbb{Z}_2$ explicit symmetry breaking terms.

TWIN HIGGS POTENTIAL

- ✦ Twin Higgs effective potential

see e.g. Craig, Katz, Strassler, Sundrum: 1501.05310
Katz, Mariotti, Pokorski, Redigolo, Ziegler: 1611.08615

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

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

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Invariant under $\mathbb{Z}_2$ and $SU(4)$ symmetries, and source of spontaneous symmetry breaking.

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Invariant under $\mathbb{Z}_2$ and $SU(4)$ symmetries, and sources the spontaneous symmetry breaking.

Invariant under $\mathbb{Z}_2$ but breaks $SU(4)$ symmetry explicitly.
This generates SM Higgs VEV,

$$v = \hat{v} = \frac{f_0}{\sqrt{(2\lambda+\kappa)}}$$

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Softly breaks both $\mathbb{Z}_2/SU(4)$ symmetries. It generates misalignment in the two VEVs

$$v \ll \hat{v}$$

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

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$$v \leq \hat{v}$$

Hardly breaks $\mathbb{Z}_2/SU(4)$ symmetries. It Introduces misalignment and potentially reduces fine-tuning.

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

TWIN HIGGS PHYSICAL BASIS

- Twin Higgs effective potential has 5 parameters

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

- Twin Higgs physical basis

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

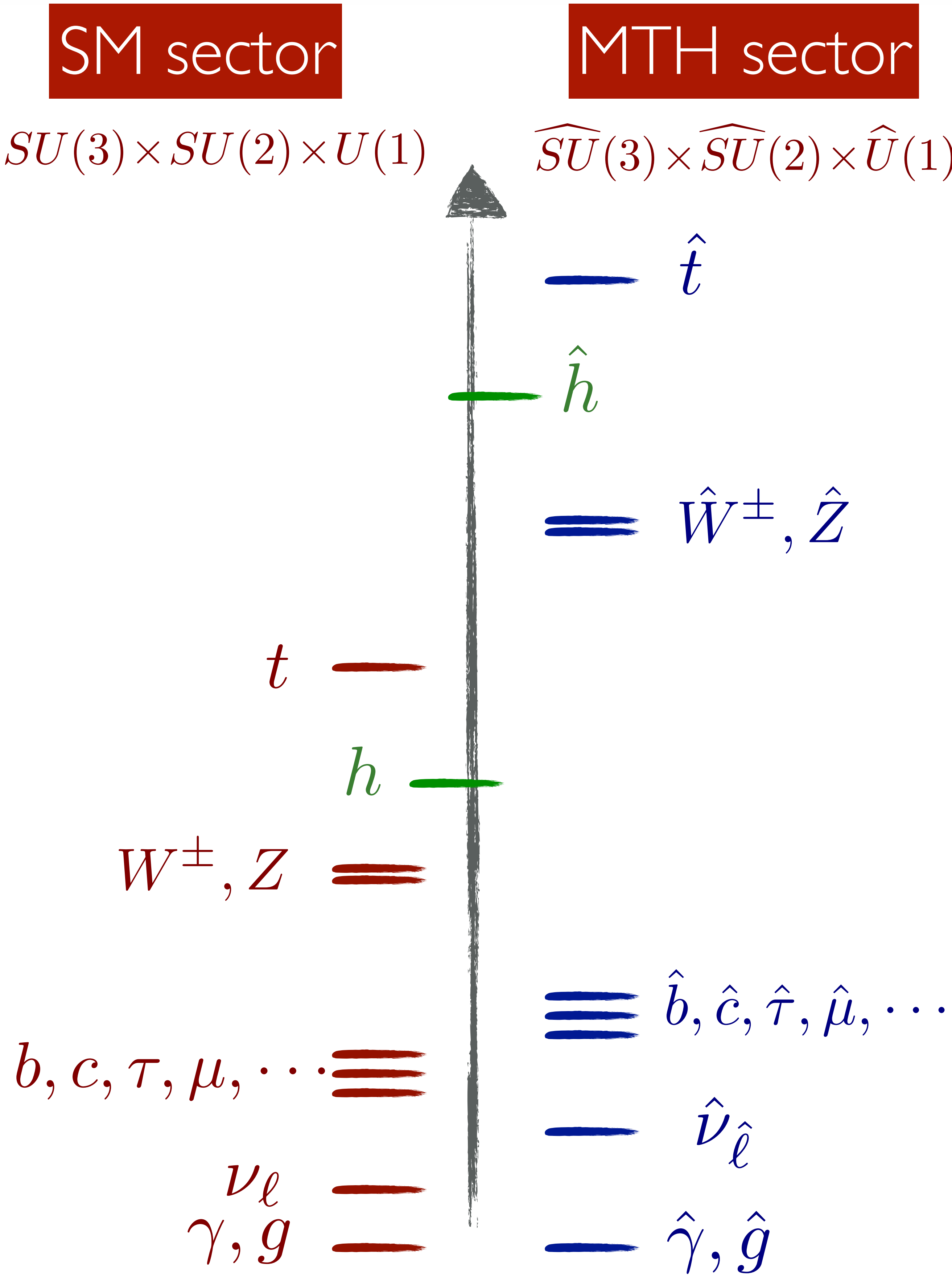
- SM Higgs mass $m_h = 125\,\mathrm{GeV}$ and SM vev $v = 246\,\mathrm{GeV}$ are fixed.

- Twin Higgs mass $m_{\hat{h}}$ and twin 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

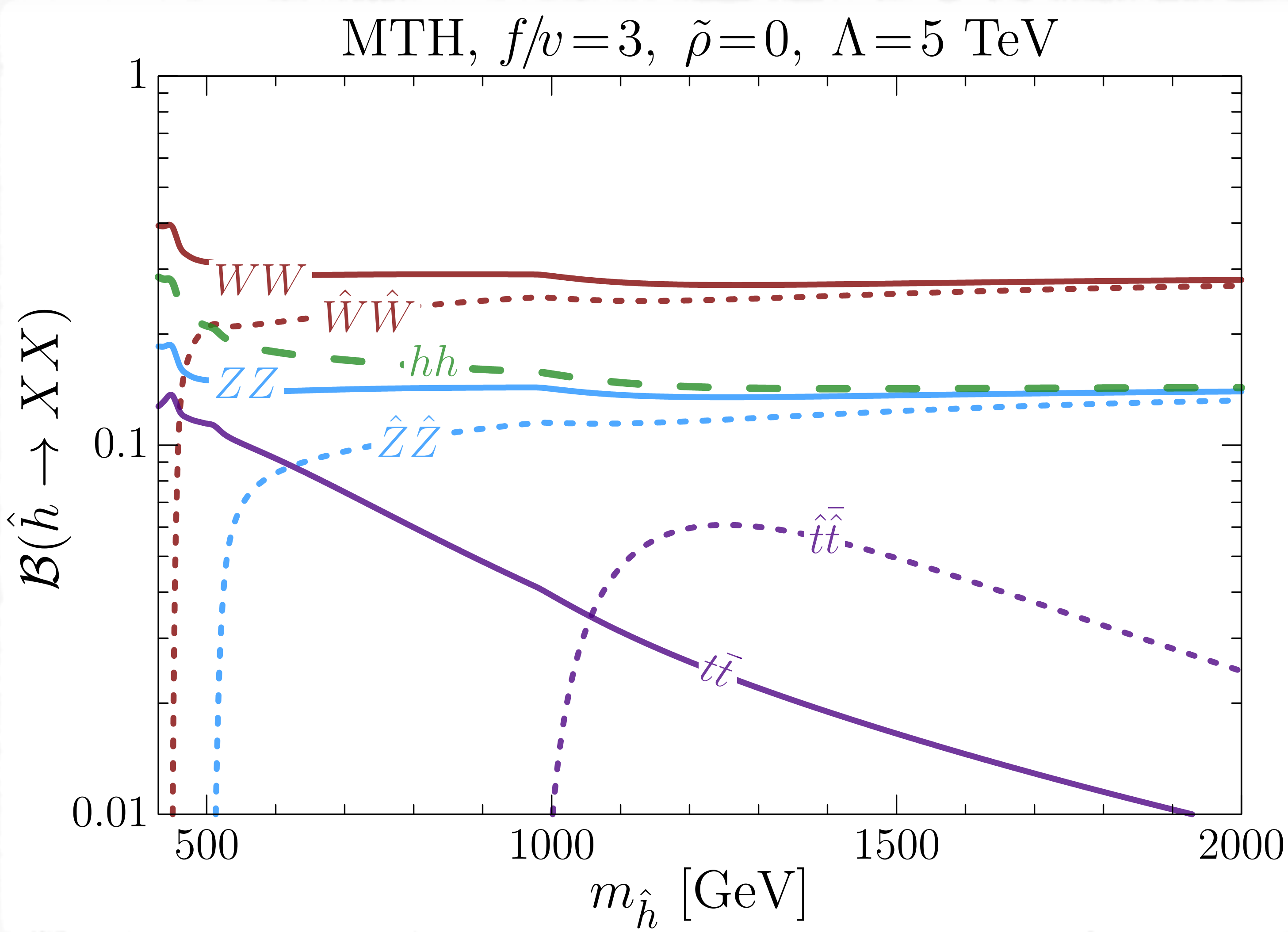


Twin sector is an exact copy of SM.

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

MIRROR TWIN HIGGS BRANCHING RATIOS

- Twin Higgs (radial mode) decays dominantly into SM and twin sector gauge bosons, and to the SM Higgs.
- Prediction for the twin Higgs branching fractions (due to Goldstone boson equivalence theorem)

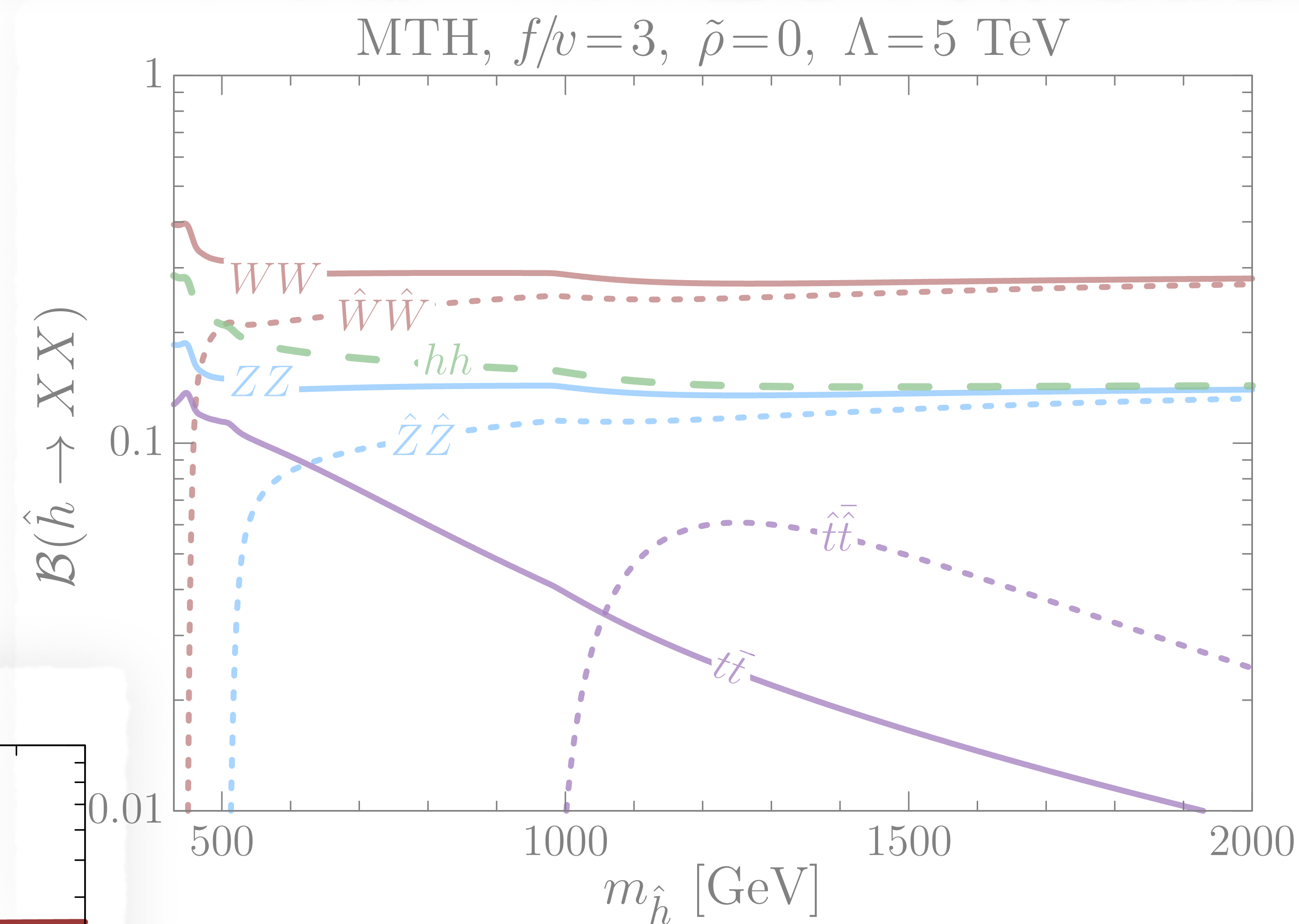


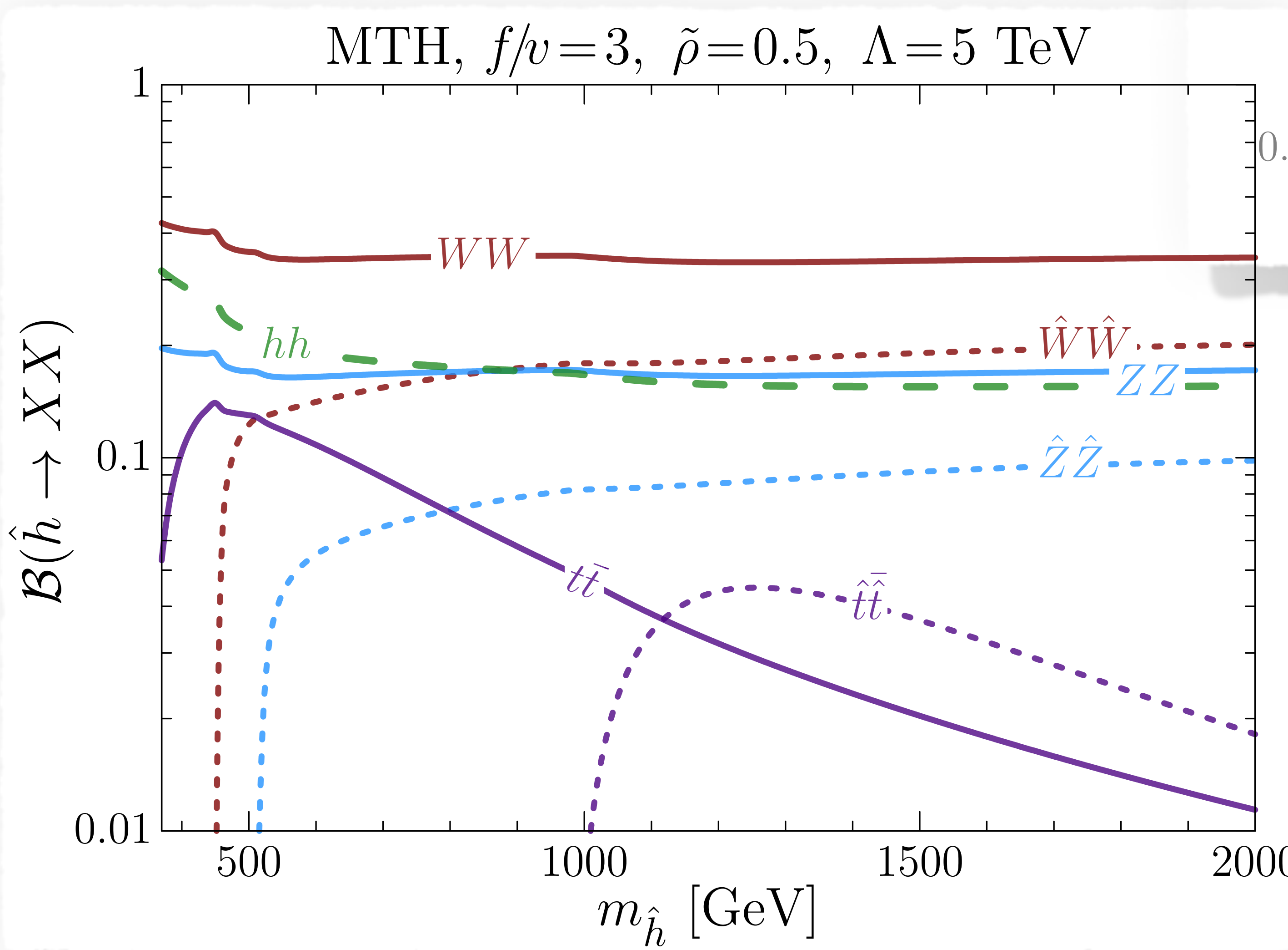
$$\mathcal{B}(\hat{h} \to hh) \simeq \mathcal{B}(\hat{h} \to ZZ) \simeq \tfrac{1}{2}\mathcal{B}(\hat{h} \to WW)$$
$$\simeq \mathcal{B}(\hat{h} \to \hat{Z}\hat{Z}) \simeq \tfrac{1}{2}\mathcal{B}(\hat{h} \to \hat{W}\hat{W})$$

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

MIRROR TWIN HIGGS BRANCHING RATIOS

★ In the presence of $\mathbb{Z}_2$ hard breaking term $\tilde{\rho}|H|^4$



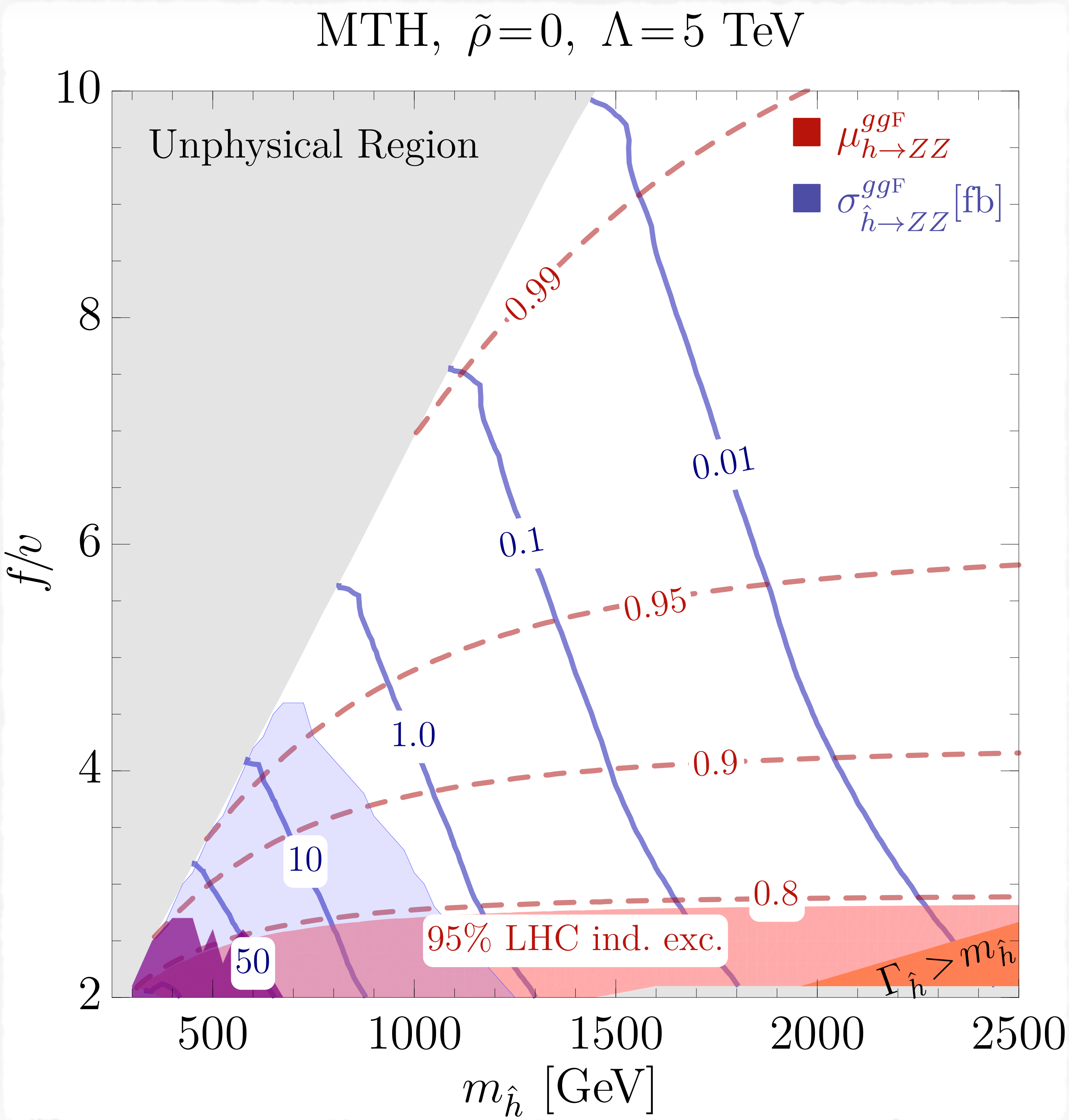


★ For $\tilde{\rho}>0$

$$\mathcal{B}(\hat{h}\to VV) > \mathcal{B}(\hat{h}\to \hat{V}\hat{V})$$

$$\mathcal{B}(\hat{h}\to VV) \approx \mathcal{B}(\hat{h}\to hh)$$

MIRROR TWIN HIGGS PHENOMENOLOGY



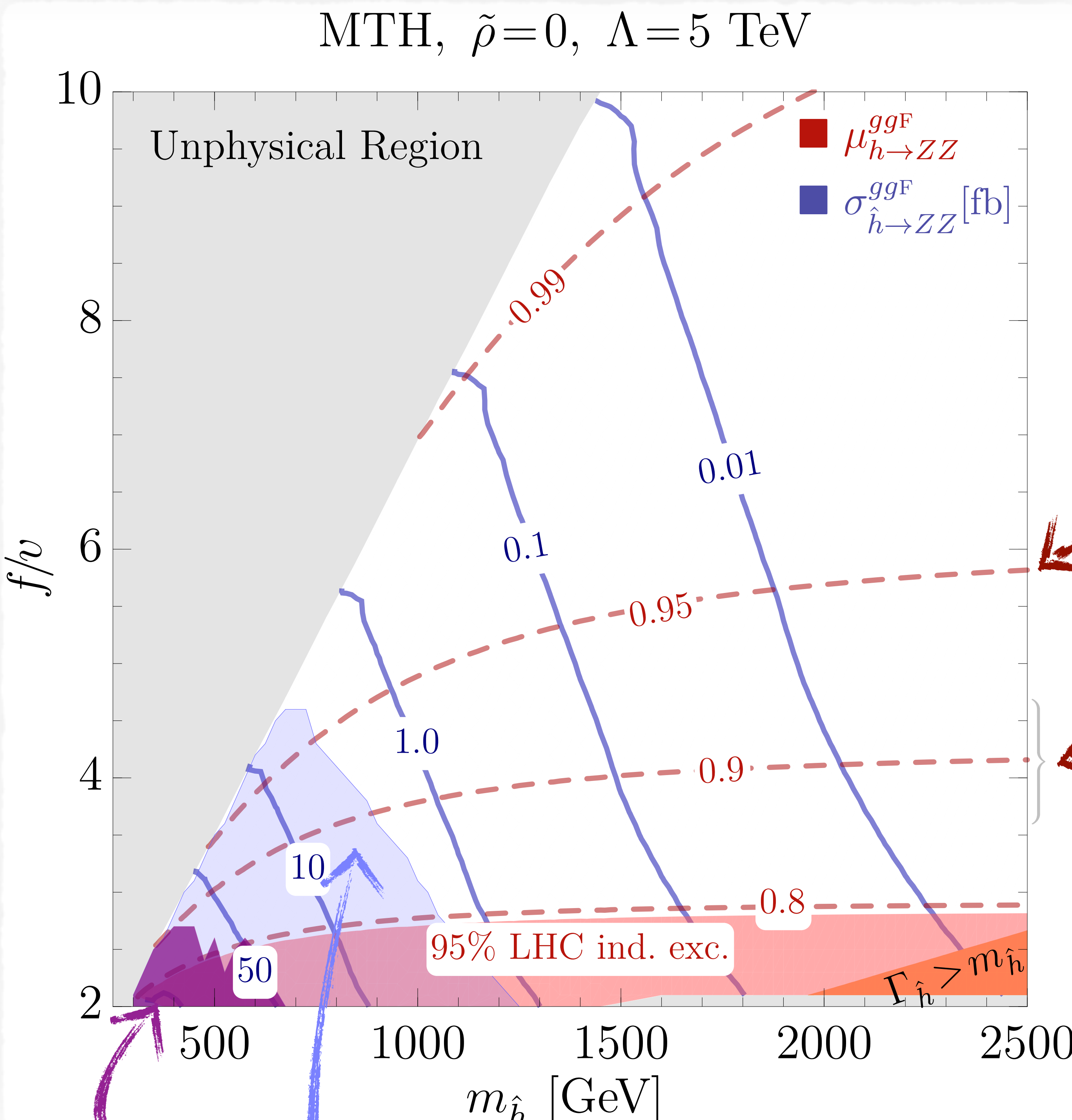
★Contours of twin Higgs cross-sections to SM gauge bosons at the LHC with $\sqrt{s}=14\,\text{TeV}$

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

★Contours of Higgs signal strength

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

MIRROR TWIN HIGGS PHENOMENOLOGY



see also: Buttazzo, Sala, Tesi: 1505.05488
Chacko, Kilic, Najjari, Verhaaren: 1711.05300

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

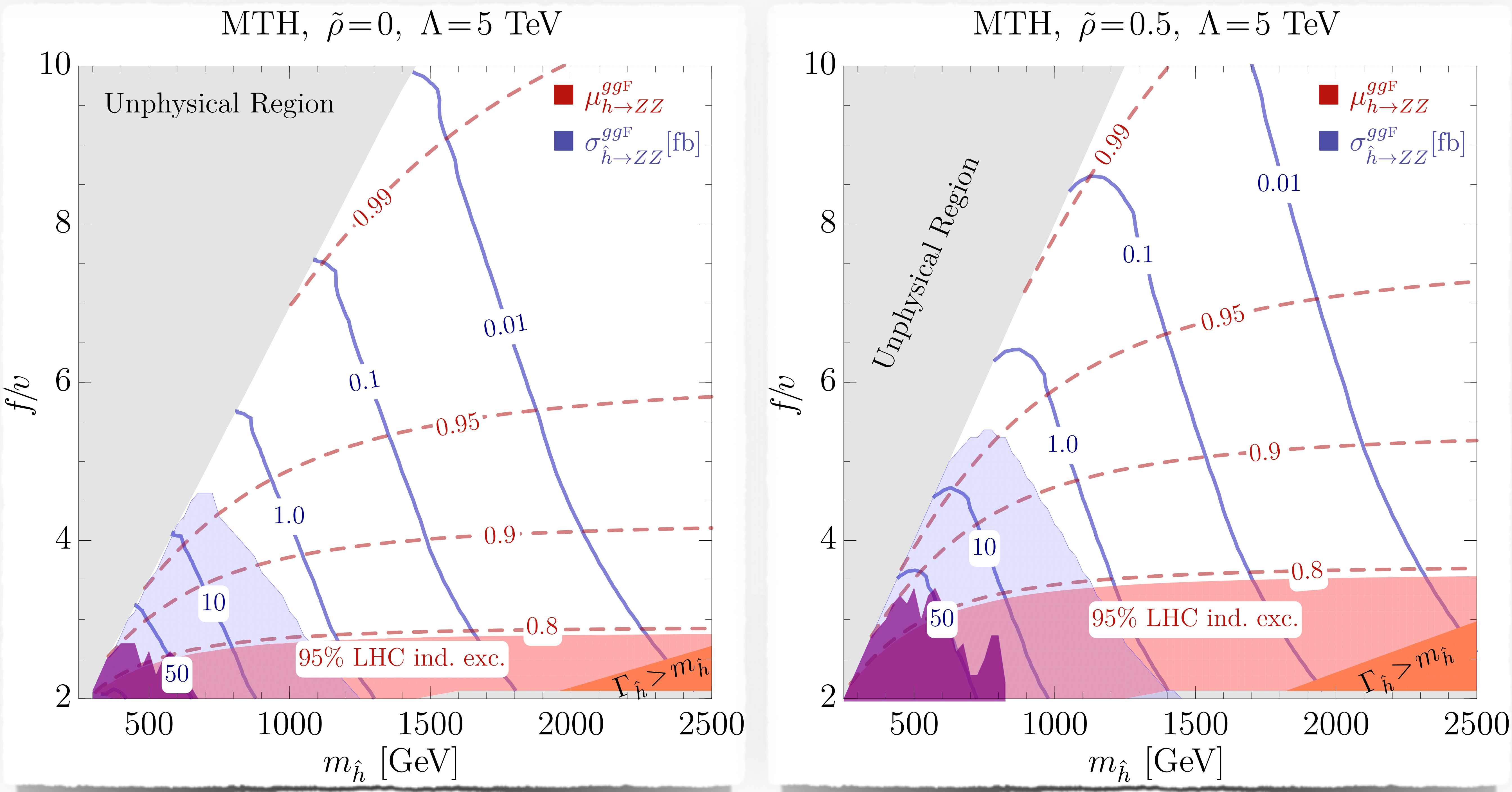
HL-LHC will reach sensitivity of Higgs signal strength measurements up to 8~10 %.

Excluded by ATLAS @ 95% C.L.

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

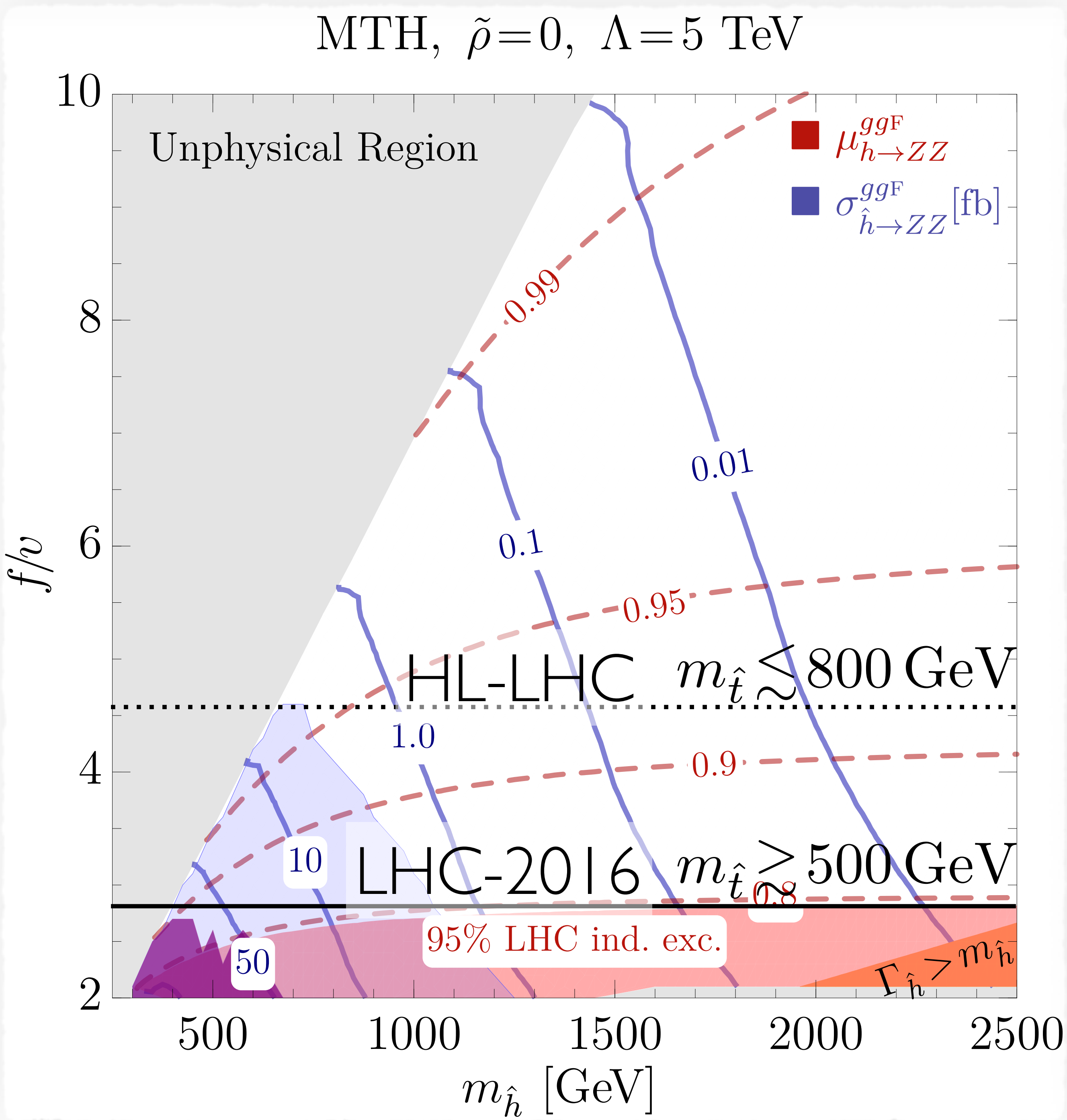
Heavy Higgs searches

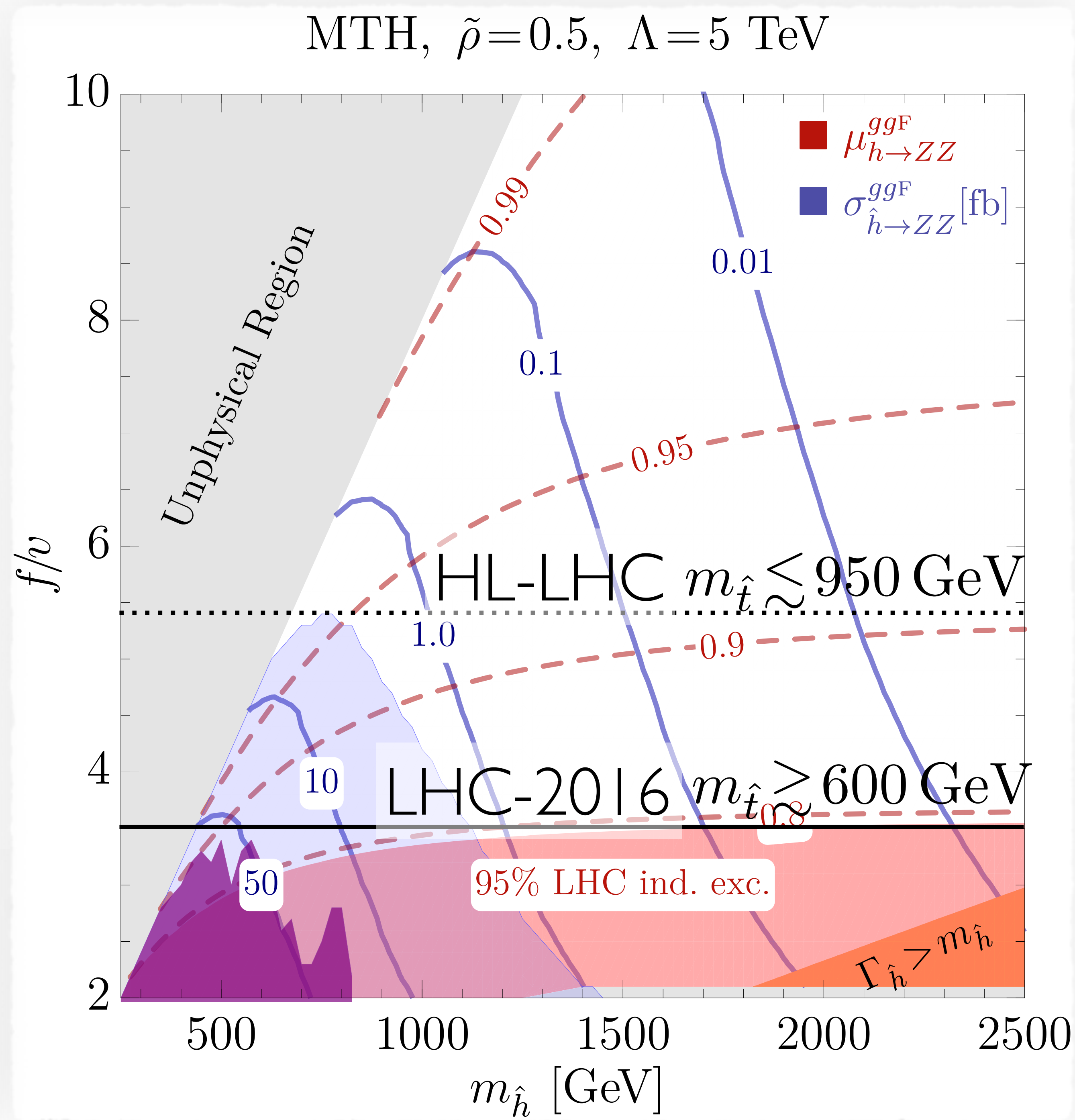
MIRROR TWIN HIGGS PHENOMENOLOGY



★ For explicit $\mathbb{Z}_2$ hard breaking parameter $\tilde{\rho} > 0$, the twin Higgs rates to the SM states increase, hence larger parameter space can be probed at the LHC.

MIRROR TWIN HIGGS PHENOMENOLOGY





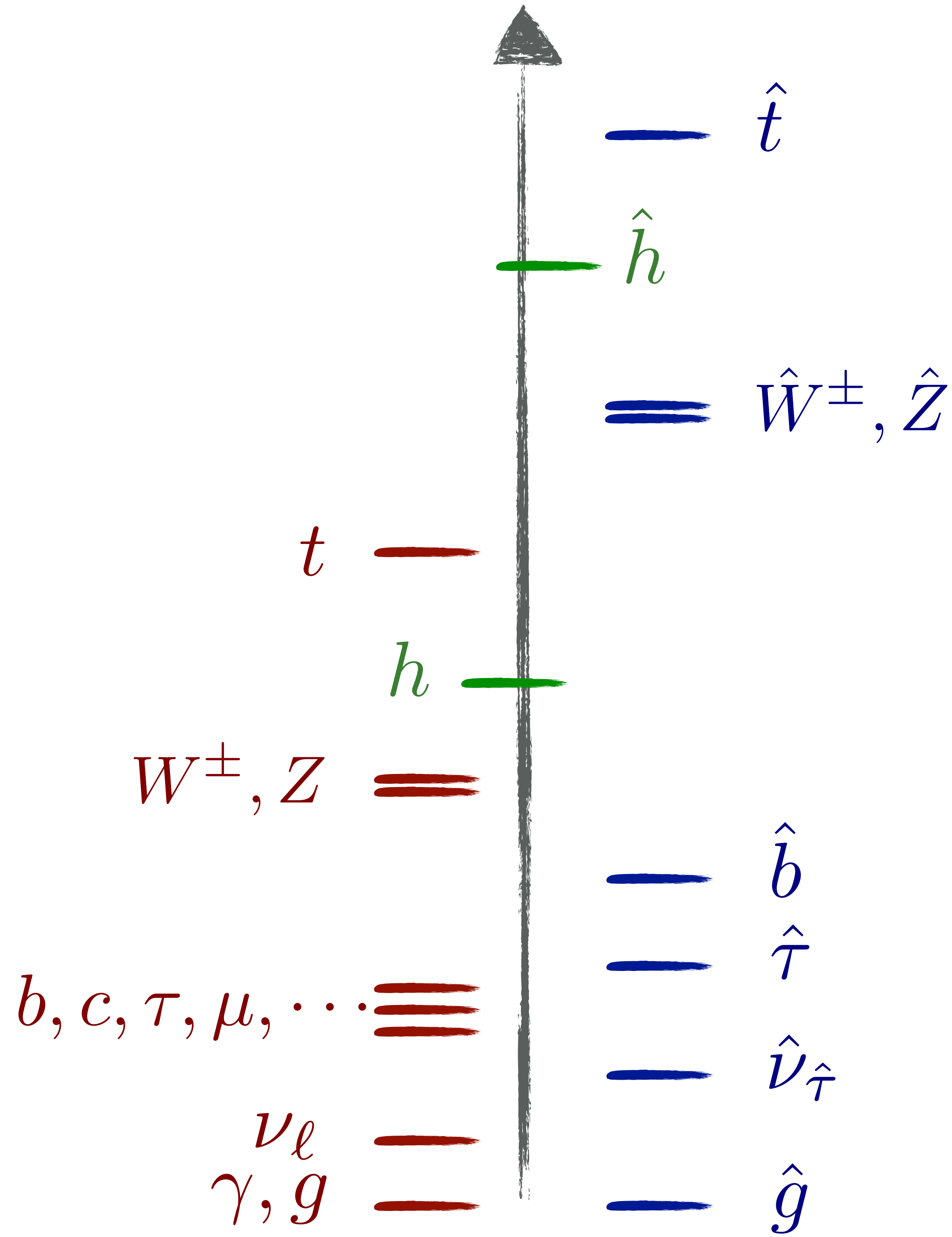
LHC can explore the MTH model for $500 \text{ GeV} \lesssim m_{\hat{t}} \lesssim 900 \text{ GeV}$ via direct and indirect search of heavy (radial) Higgs!

FRATERNAL TWIN HIGGS

Craig, Katz, Strassler, Sundrum: 1501.05310

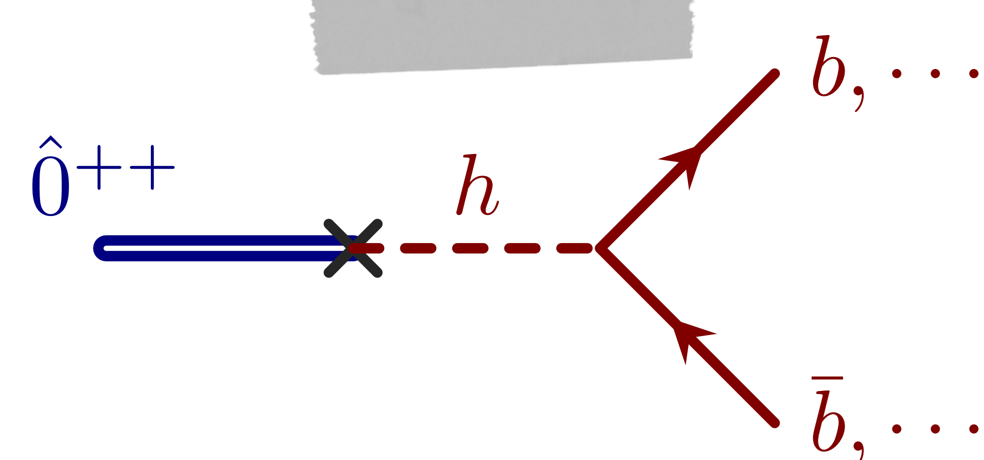
SM sector $SU(3)\times SU(2)\times U(1)$

FTH sector $\widehat{SU}(3)\times\widehat{SU}(2)$



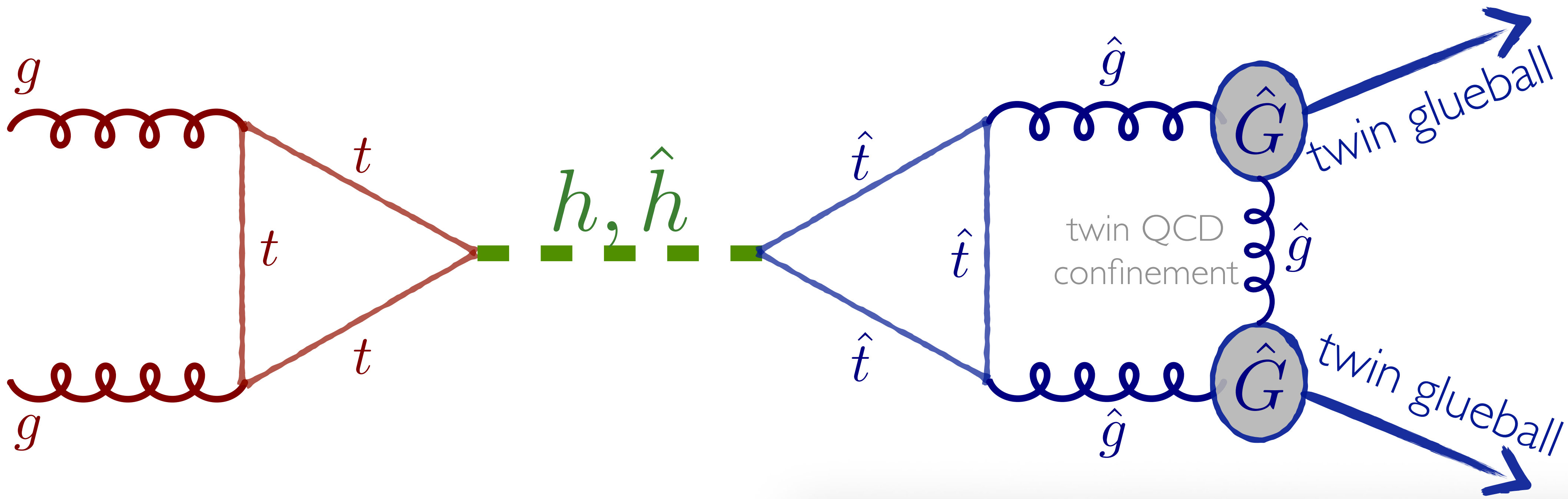
FTH require minimal twin sector particles to cancel radiative corrections.

- ★No light twin quarks, implies large twin QCD confinement scale.
- ★Light twin hadrons are twin glueball/bottomonium states.
- ★$\hat{0}^{++}$ twin hadrons mix with the SM Higgs, implies exotic decays!

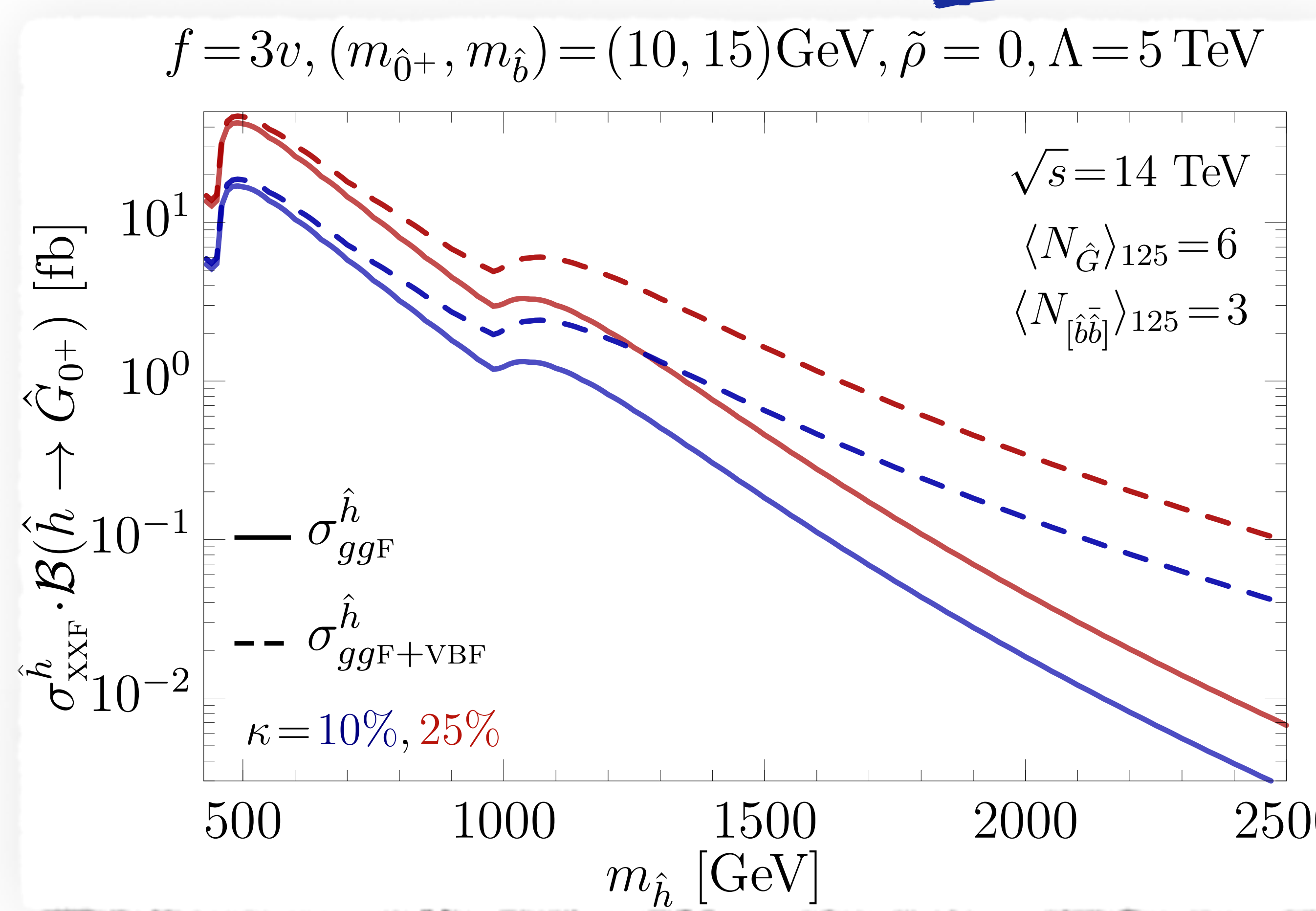


TWIN GLUEBALL PRODUCTION

- 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

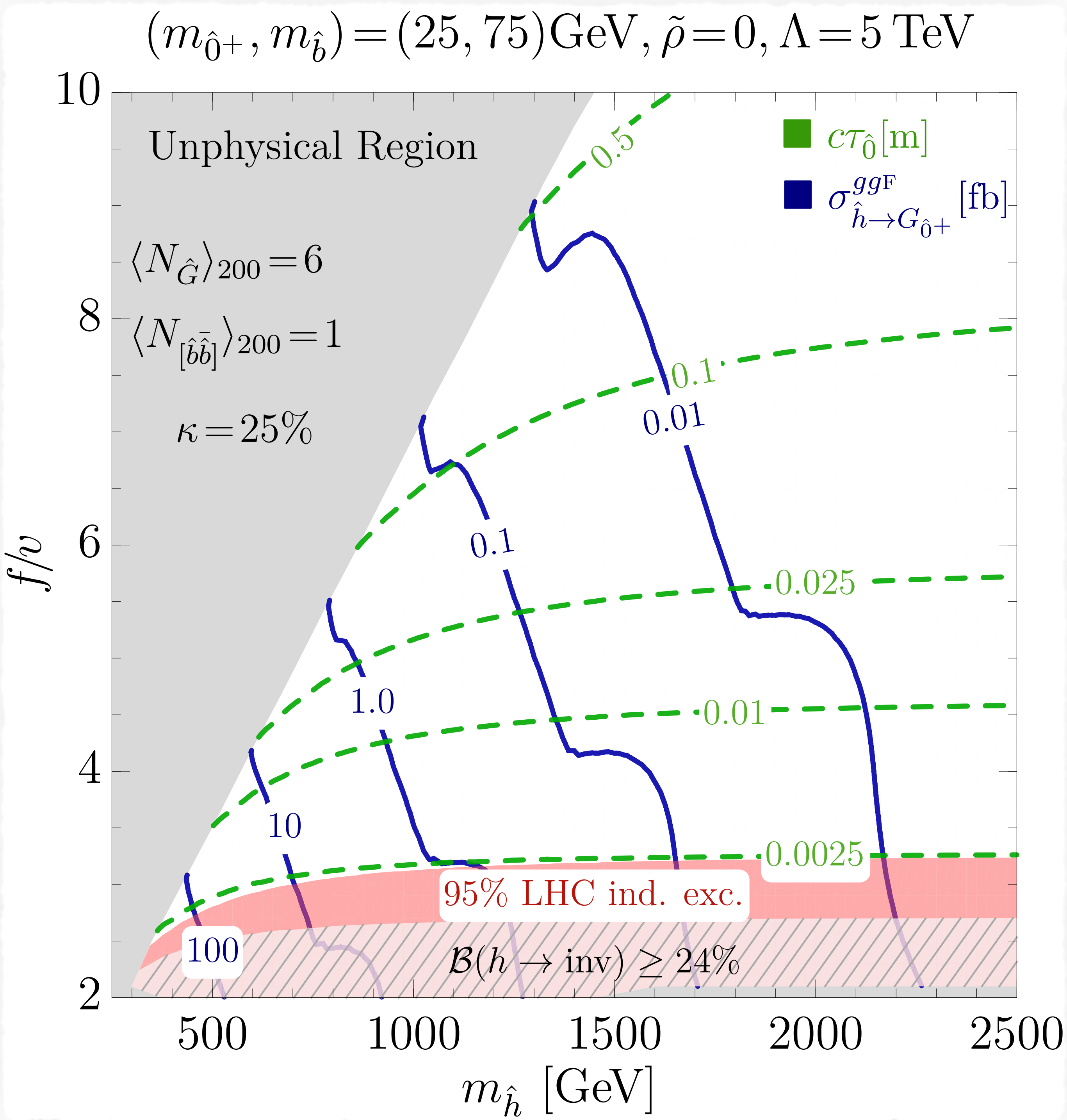


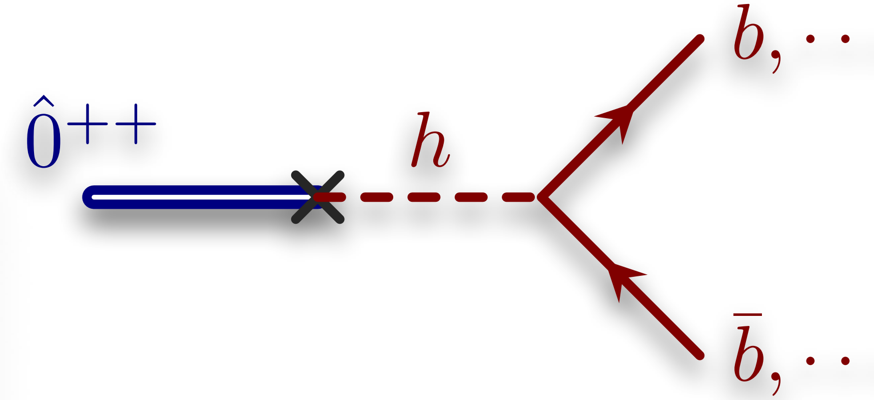
- Lightest twin glueball $\hat{G}_{0^+}$

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

TWIN HADRON PHENOMENOLOGY

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





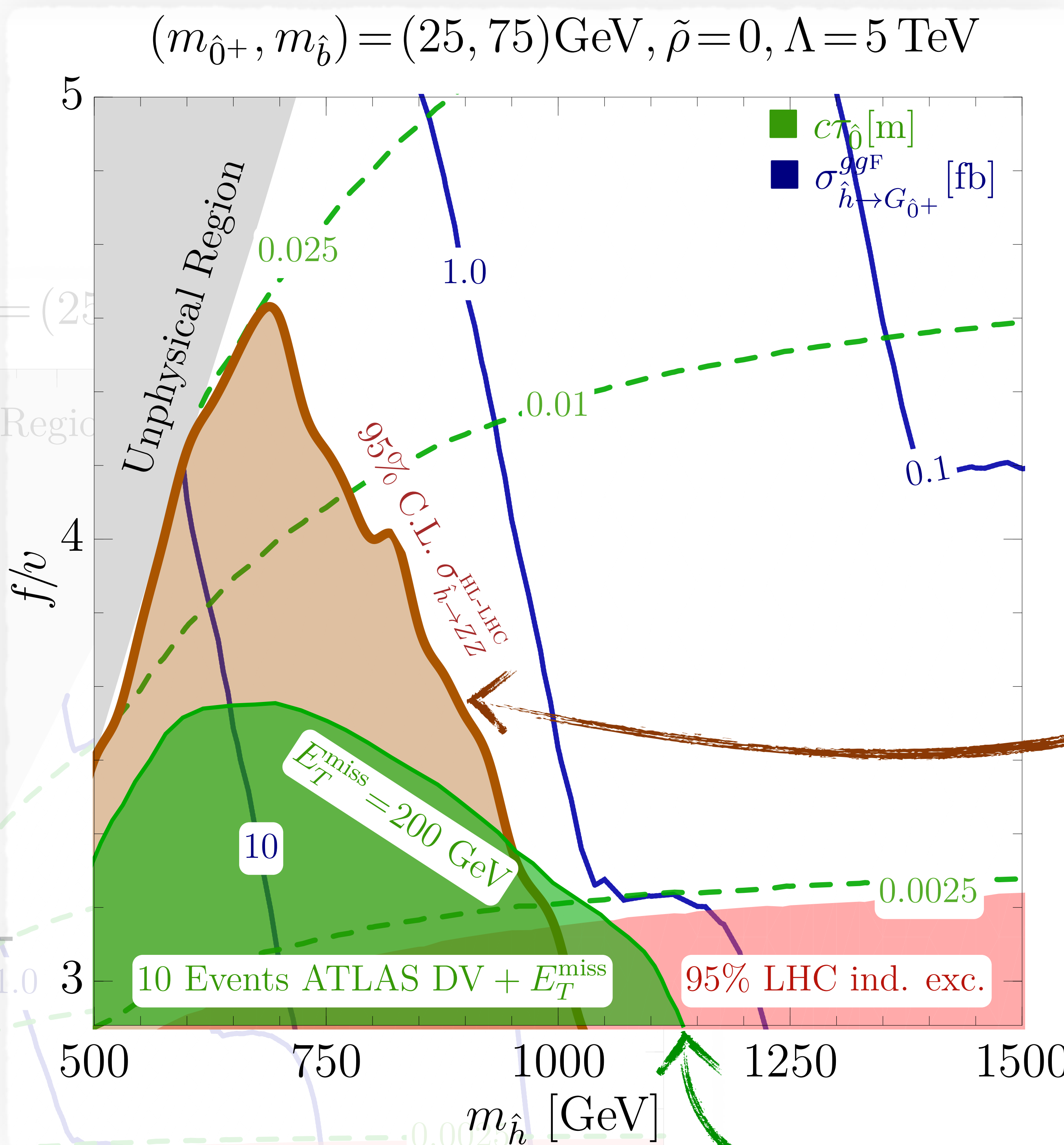
★ decay-length $c\tau_{\hat{0}} \lesssim 10\,\mathrm{m}$ is accessible at the LHC.

★ 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.nnnn

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 model gives novel discovery potential via the exotic decays of twin hadrons to the SM light fermions.
- ✦ HL-LHC and the future colliders have the potential to discover (or refute) the twin Higgs mechanism.