Gaps in New Higgs Searches

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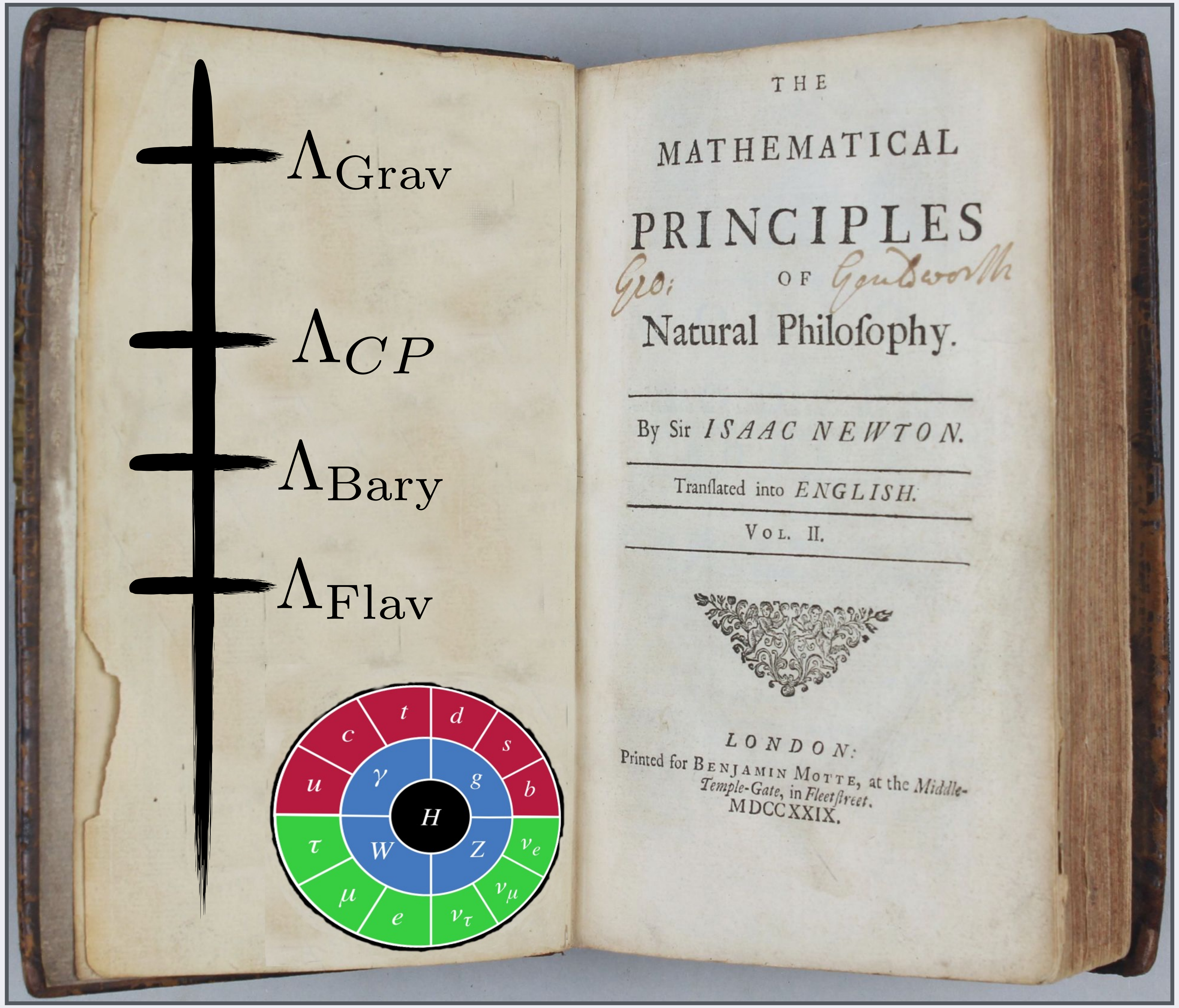
Searching for New Higgses

Lots of new scalars in SUSY, but most not Higges

Let's focus on pNGB Higgs models

Higgs in here

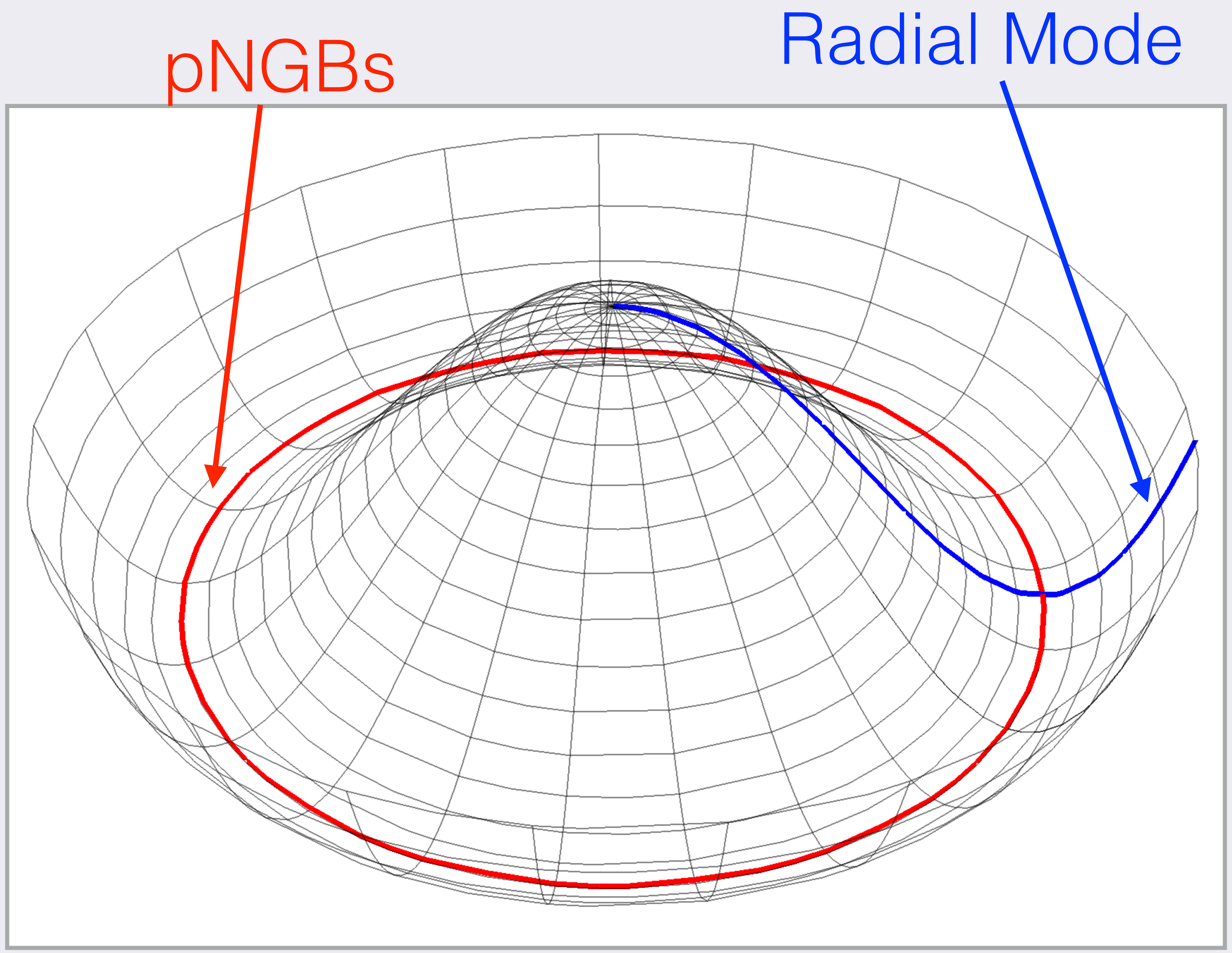
$$\Phi = e^{i\frac{\Pi}{f}} \begin{pmatrix} \mathbf{0} \\ f \end{pmatrix}$$



Radial Modes and pNGBs

If the UV completion is weakly coupled, a radial mode may appear in the low energy spectrum

$$\Phi = e^{i\frac{\Pi}{f}} \begin{pmatrix} \mathbf{0} \\ f + \frac{1}{\sqrt{2}} R \end{pmatrix}$$



Strongly coupled completions may include a dilaton, the pNGB of scale symmetry

Behaves similarly to a radial mode

Radial Mode as Dilaton

Why are the radial mode and dilaton similar?

The classical SM, with no Higgs potential, is scale symmetric

When the Higgs gets a VEV, this symmetry is spontaneously broken, with the Higgs as a dilaton

Hence, the classical Higgs couplings, other than self-couplings (which are related to its potential) are dictated by the scale symmetry

The same can be true of

$$\Phi = e^{i\frac{\Pi}{f}} \begin{pmatrix} \mathbf{0} \\ f + \frac{1}{\sqrt{2}} R \end{pmatrix}$$

Dilaton Couplings

Under rescaling $x \to e^{-\omega}x$ the dilaton shifts $\sigma \to \sigma + F\omega$ where F is the scale of conformal symmetry breaking

It is useful to define $\chi = Fe^{\sigma/F}$ with $\chi \to e^{\omega}\chi$

Any operator $\mathcal{O}$ transforms as $\mathcal{O} \to e^{\omega\Delta_{\mathcal{O}}}\mathcal{O}$ where $\Delta_{\mathcal{O}}$ is the scaling dimension of the operator

For instance, $d^4x\, m_W^2 W_\mu W^\mu \to d^4x e^{-2\omega} m_W^2 W_\mu W^\mu$

We compensate with powers of $\frac{\chi}{F}$, and obtain the dilaton coupling

$$\left(\frac{\chi}{F}\right)^2 m_W^2 W_\mu W^\mu \Rightarrow 2\frac{\sigma}{F} m_W^2 W_\mu W^\mu$$

Couplings to Massless Bosons

While $-\frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu}$ has dimension 4, the running of g leads to

$$\frac{b_< - b_>}{32\pi^2}\ln\left(\frac{\chi}{F}\right)F_{\mu\nu}F^{\mu\nu} \Rightarrow \frac{b_< - b_>}{32\pi^2}\frac{\sigma}{F}F_{\mu\nu}F^{\mu\nu}$$

where $b_>(b_<)$ is the 1-loop beta function coefficient above (below) F

All of these couplings are modified by the explicit breaking of scale symmetry that gives the dilaton a mass

However, these corrections scale like $\sim \frac{m_\sigma^2}{(4\pi F)^2}$, and are small for a light dilaton

A Natural Test Case

The strong sector scale violation that gives mass to the dilaton contributes to the (composite) Higgs potential

Tuning the potential to give a light Higgs mass does not imply similar cancellation in the Higgs couplings to the dilaton

This makes the dilaton coupling to the Higgs, and all other pNGBs (W,Z in both sectors) ambiguous

The Twin Higgs framework is the natural choice to explore these ideas, as the tuning may be better than 10%, even if there is no sign at the HL-LHC

Chacko, Goh, Harnik, hep-ph/0506256

The Twin Higgs

Copy the SM matter and gauge structure and assume a exchange Z_2 symmetry between the SM and its twin

Let the Higgs sector realize a global $SU(4)$ symmetry, then gauge two $SU(2)$ subgroups

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

When H gets a VEV, $SU(4)$ breaks to $SU(3)$, producing 7 pNGBs
6 are eaten by the A and B sector $SU(2)$ gauge bosons

Left with one physical pNGB, the Higgs

Twin Higgs Pheno

$$\frac{v}{f} \equiv \vartheta$$

The Z_2 symmetry predicts equal VEV in A and B sectors

$$v_A = f \sin\vartheta,\ v_B = f\cos\vartheta \quad m_B = m_A \cot\vartheta$$

The pNGB structure implies the Higgs couplings to A sector states is

$$g_{\rm A} = g_{\rm SM}\cos\vartheta$$

This already in tension with Higgs measurements for exact Z_2

However, the Z_2 can be softly broken, without reintroducing divergences, to make

$$v_B \gg v_A$$

Lifting the twin top mass does reintroducing tuning $\sim \frac{3\lambda_t^2}{8\pi^2} m_T^2 \ln\frac{\Lambda^2}{m_T^2}$

The Potential

The radial mode has a mass set by f

This state provides more information about the Higgs potential

$$V = -\mu^2 \left(H_A^\dagger H_A + H_B^\dagger H_B\right) + \lambda \left(H_A^\dagger H_A + H_B^\dagger H_B\right)^2$$

Breaks Z_2 and $SU(4)$ →

$$+ m^2 \left(H_A^\dagger H_A - H_B^\dagger H_B\right) + \delta \left[\left(H_A^\dagger H_A\right)^2 + \left(H_B^\dagger H_B\right)^2\right]$$

← Breaks $SU(4)$

For stable vacuum require $\dfrac{m_H}{m_h} \geq \dfrac{m_T}{m_t} = \cot\vartheta$

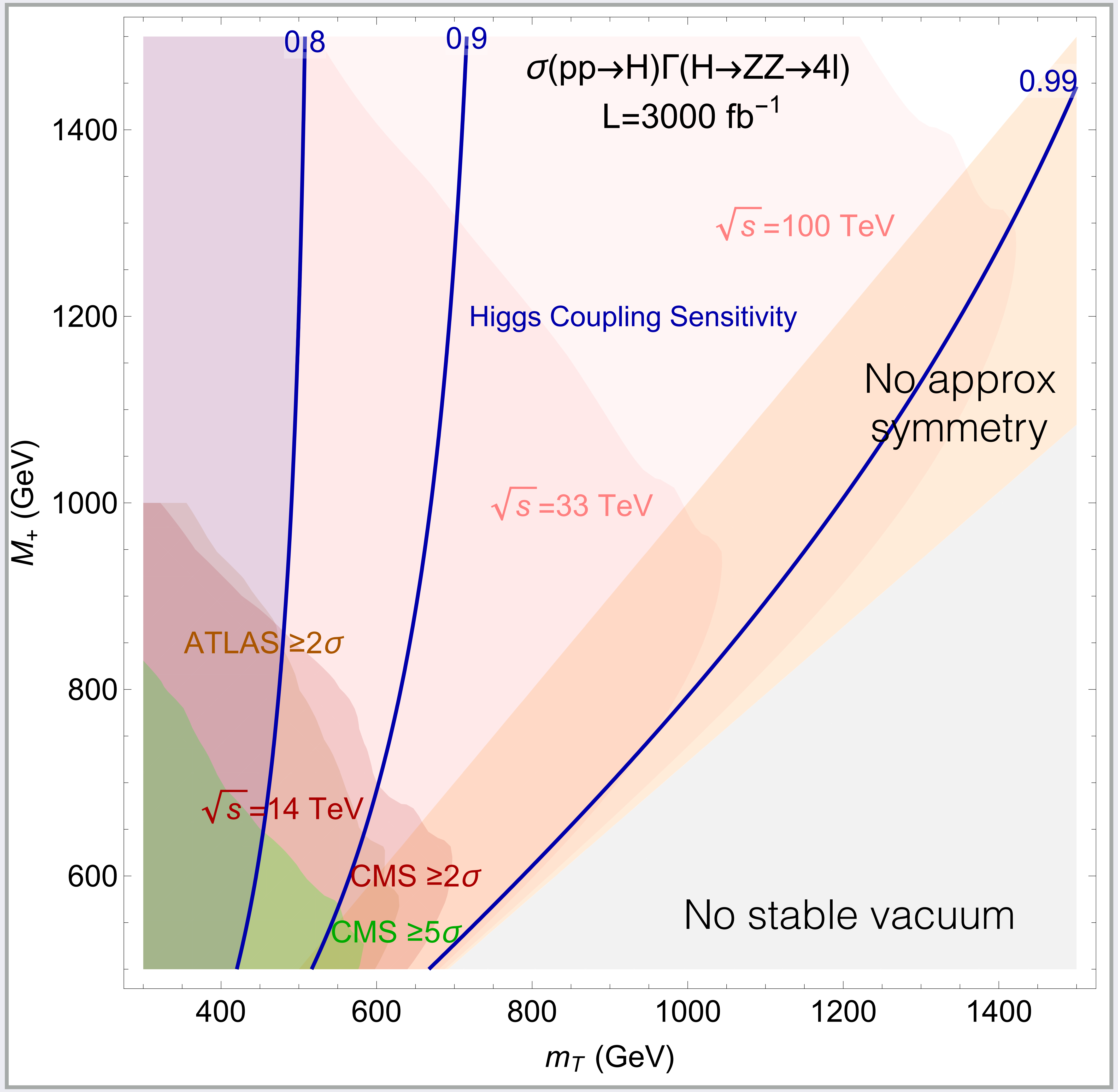
Four parameter potential, with the requirement that $SU(4)$ breaking terms are much smaller than preserving terms

Discovering the Twin Higgs

The LHC can discover in $H \to ZZ$
LHC-HL results from
ATL-PHYS-PUB-2013-016
CMS-PAS-FTR-13-024

Extrapolation to 33 (100) TeV uses
D. Buttazzo, F. Sala, and A. Tesi 1505.05488,
where the background is assumed to be primarily $\overline{q}q$ initiated

Measured values of
$v_{\rm EW}, m_h, m_H$, and ϑ
completely specify the
4 parameter Higgs potential



See Chacko, Kilic, Najjari, CV 1711.05300

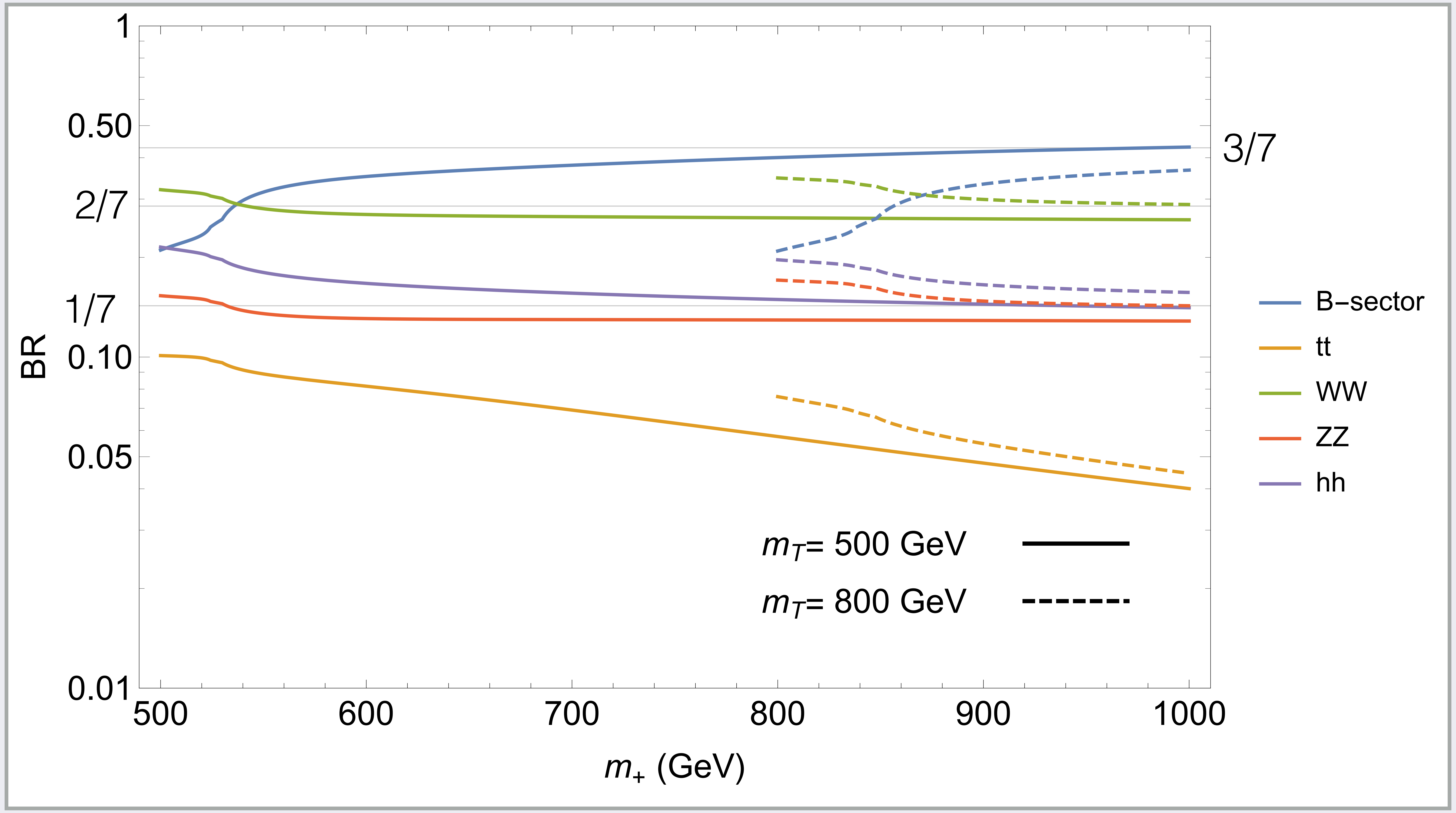
Confirming the Twin Higgs

The $H \to ZZ$ also determines the Heavy Higgs mass and the rate to ZZ

The symmetry breaking pattern of the Twin Higgs predicts

$$BR(H \to ZZ) \sim \frac{1}{7}$$

A test of the Twin Higgs symmetry breaking pattern!

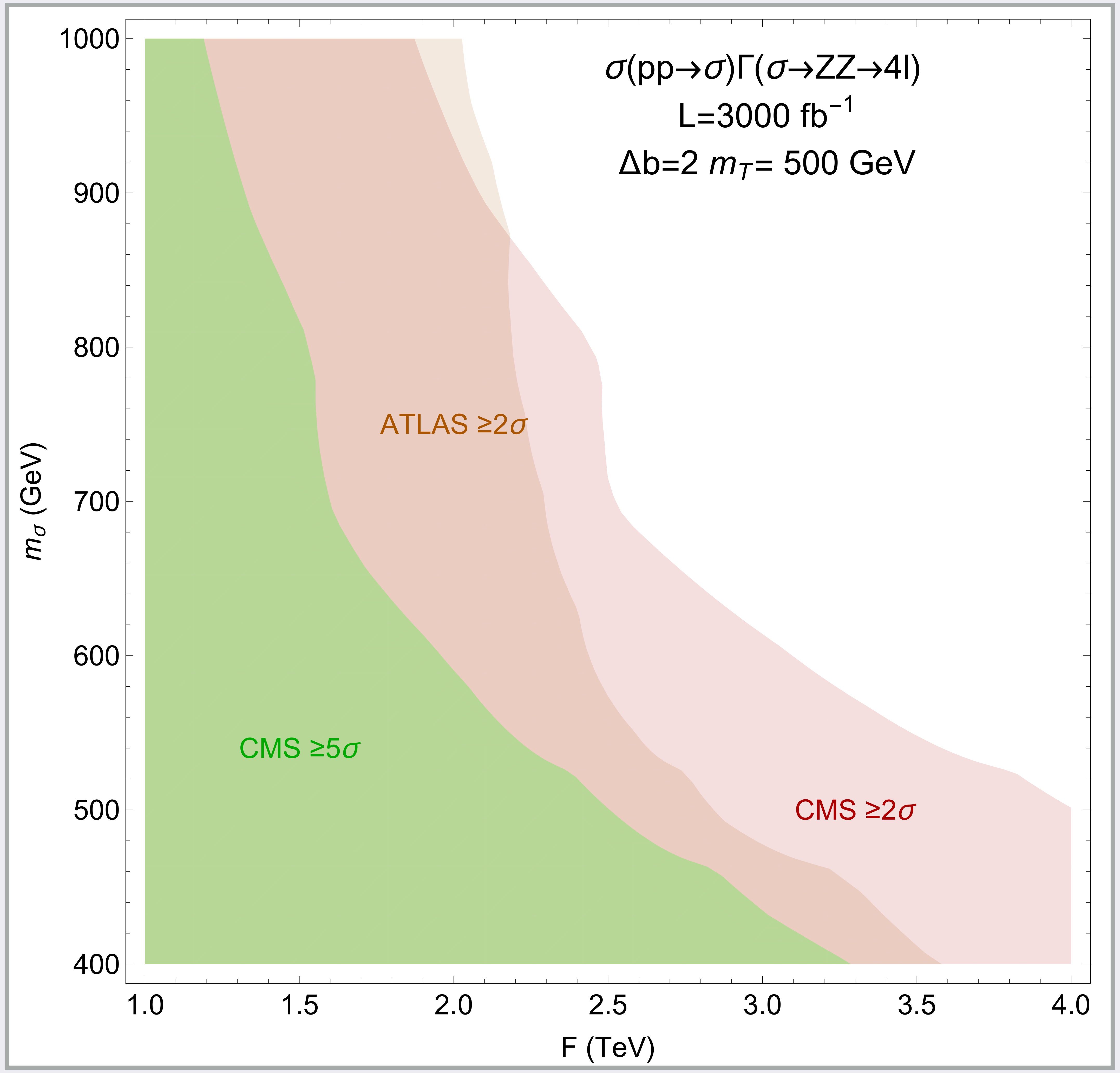


Discovering Dilatons

A dilaton may be easier to produce than a radial mode because the coupling to gluons is larger

The LHC can discover in $\sigma \to ZZ$

LHC-HL results from
ATL-PHYS-PUB-2013-016
CMS-PAS-FTR-13-024

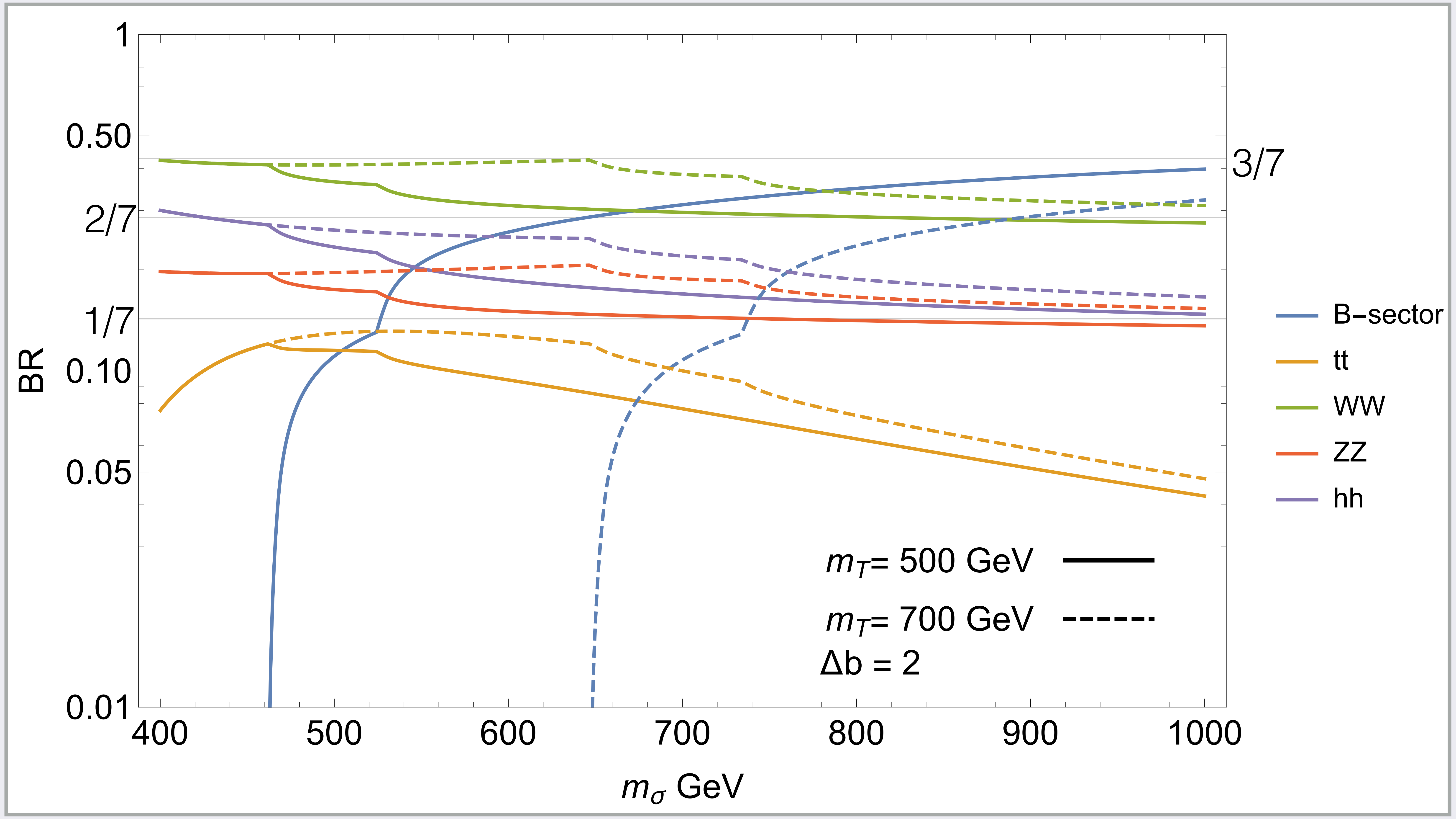


Confirming the Twin Higgs

As with the Heavy Higgs, the dilaton's branching fractions are shaped by the global symmetry of the Higgs potential

However, the F scale is distinct from the Higgs VEV and ϑ

Need to measure the rate to invisible



Conclusions

New Higgs-like particles are discoverable by HL/HE LHC

Beyond discovery, these new particles can be used to determine symmetries of the Higgs potential, e.g. Twin Higgs structure

Need to understand backgrounds at HE-LHC to determine discovery reach

Measuring the heavy Higgs/Dilaton rate to invisible can give powerful insights

$+ 50m_h$

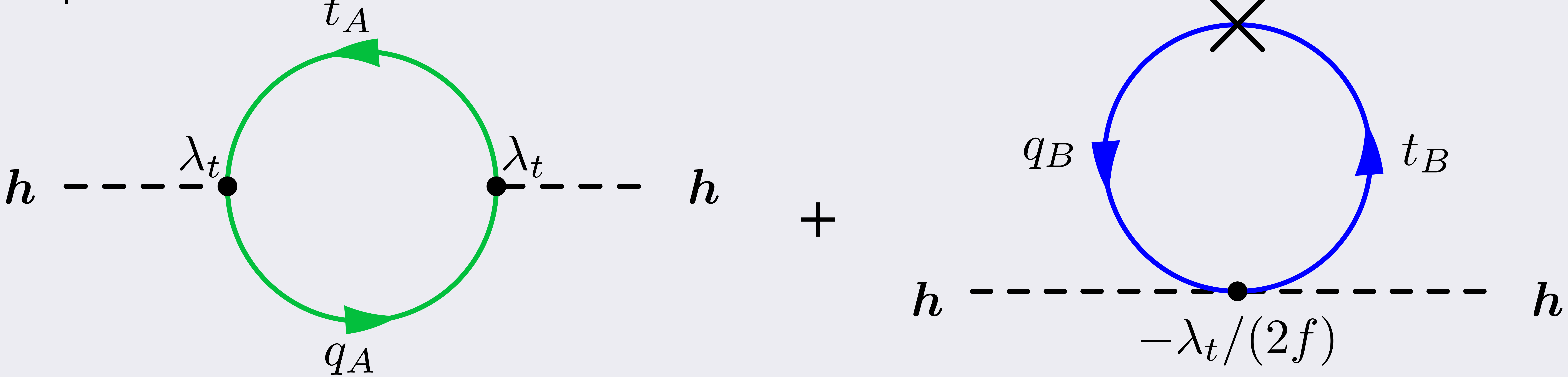
Beyond the Standard Slides

Twin Higgs Protection

The 1-loop top quark corrections to the Higgs mass

$$\frac{3\Lambda^2}{8\pi^2}\left(\lambda_{t_A}^2|H_A|^2+\lambda_{t_B}^2|H_B|^2\right)=\frac{3\lambda_t^2\Lambda^2}{8\pi^2}\left(|H_A|^2+|H_B|^2\right)=\frac{3\lambda_t^2\Lambda^2}{8\pi^2}|H|^2$$

The Z_2 makes the total contribution $SU(4)$ symmetric, cannot affect the pNGB mass



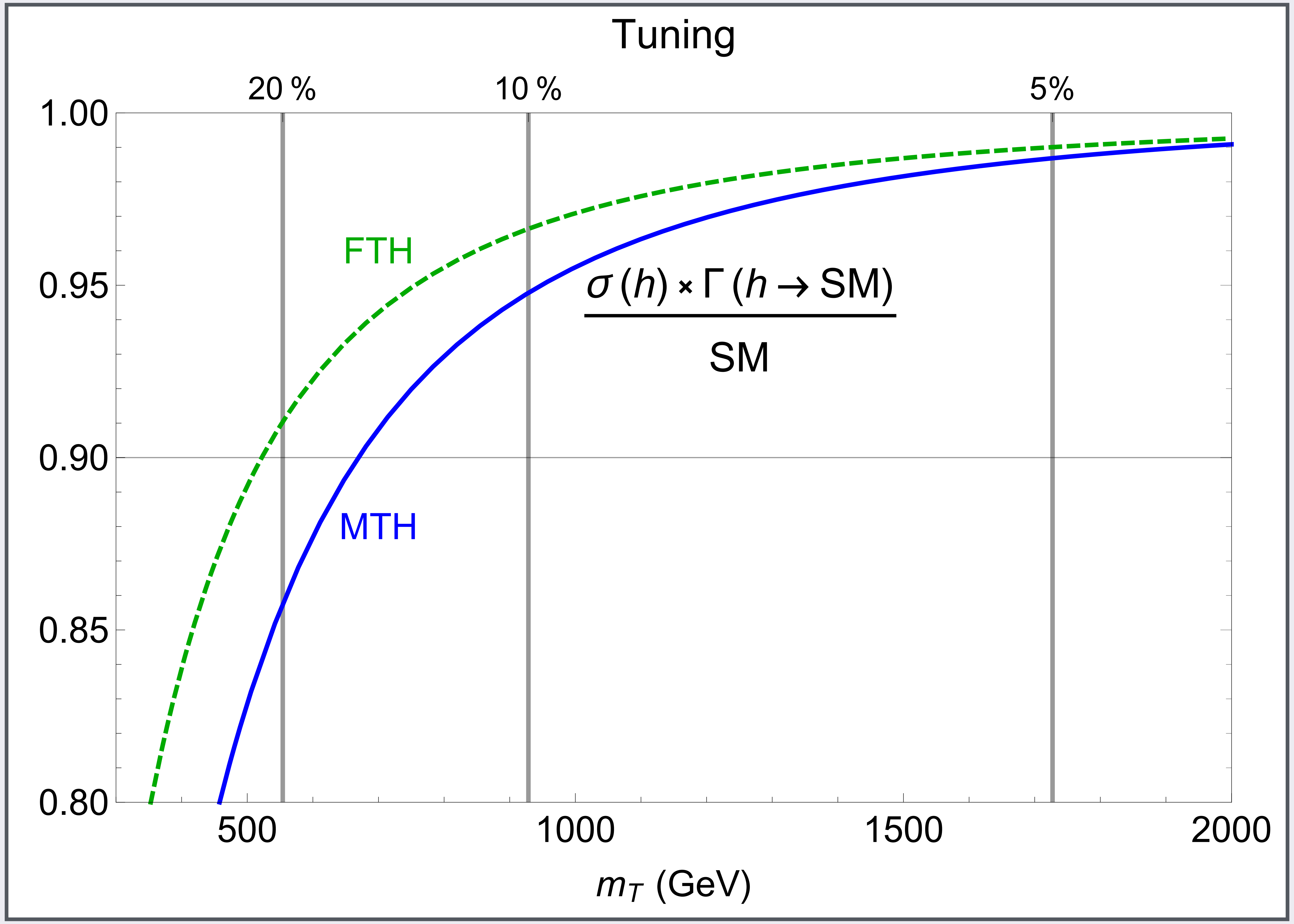
Higgs Couplings

Recall that Higgs couplings are reduced $g_{\mathrm{A}} = g_{\mathrm{SM}} \cos\vartheta$

This reduces Higgs rates to SM states

The HL-LHC is expected to measure these rates to 10%

Probes~500-700 GeV twin tops



See Burdman, Chacko, de Lima, Harnik, CV 1411.3310

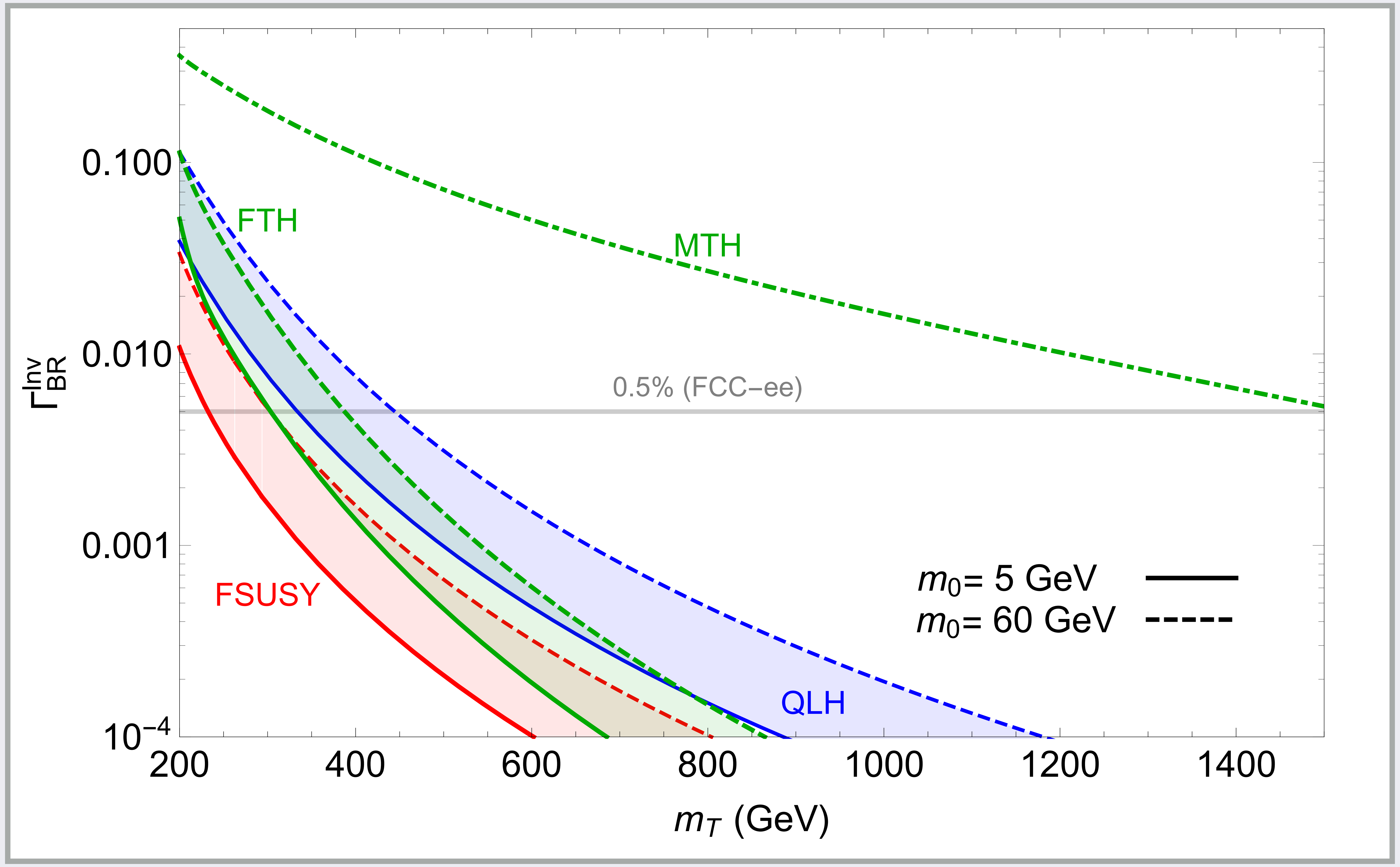
Invisible Higgs Width

It is unlikely that the LHC will be able to measure the Higgs invisible width

Currently, about 20% invisible branching is allowed

However, future lepton machines will measure down to ~1% invisible branching fractions

This has great potential to probe hidden sectors of all types, and the whole spectrum of TH models



Twin Higgs Pheno

The radial mode and Higgs mix by θ

The couplings now satisfy

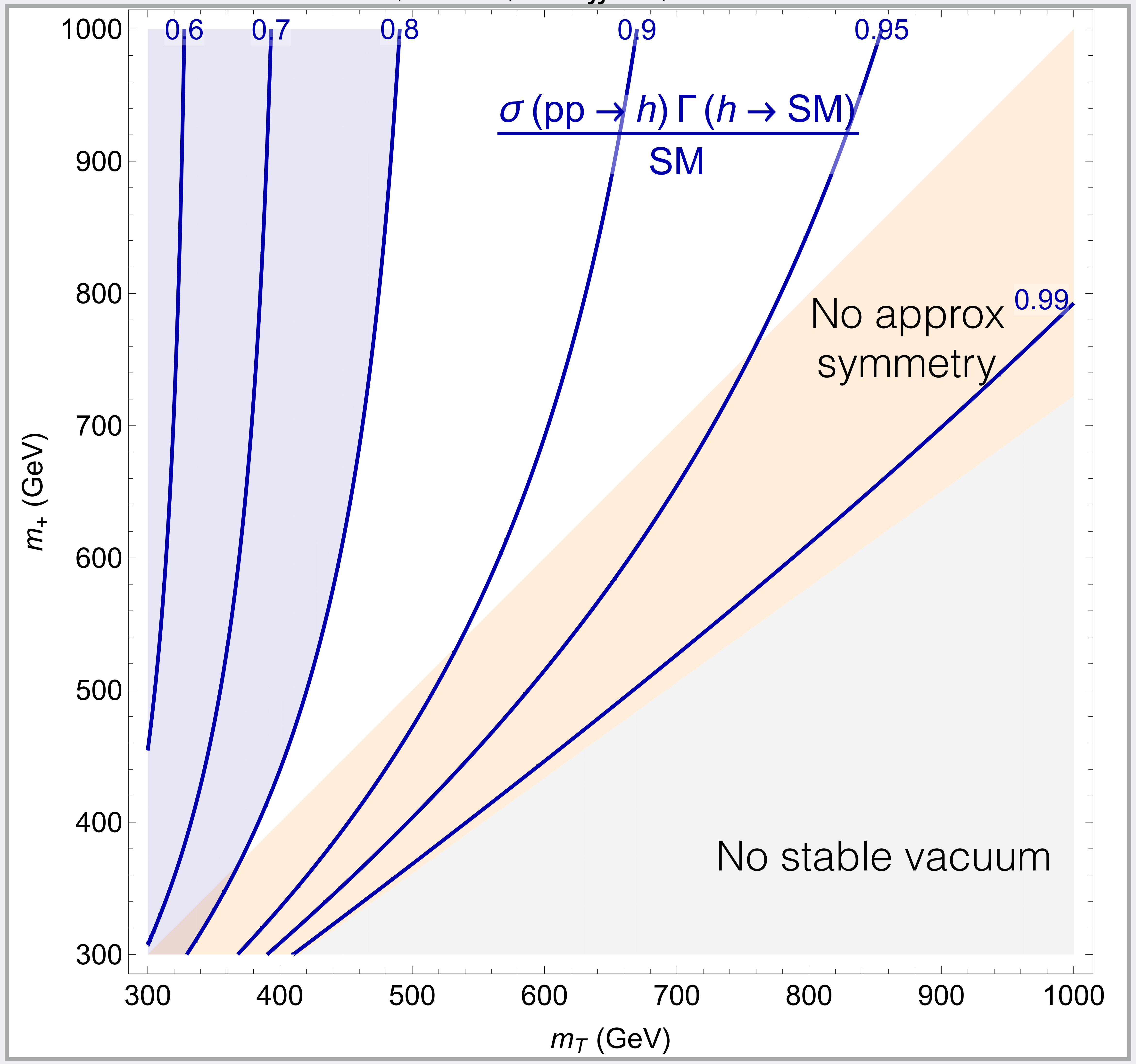
$$g_{hA} = g_{\rm SM} \cos\left(\vartheta - \theta\right)$$

$$g_{HA} = g_{\rm SM}(m_H) \sin\left(\vartheta - \theta\right)$$

HL-LHC expected to measure couplings to 0.9

Can this be improved?

See Chacko, Kilic, Najjari, CV 1711.05300



Hard Breaking

Small hard breaking, like in the Fraternal Twin Higgs, follows the Mirror analysis for larger masses