The Twin Higgs & Neutral Naturalness

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The Standard Model

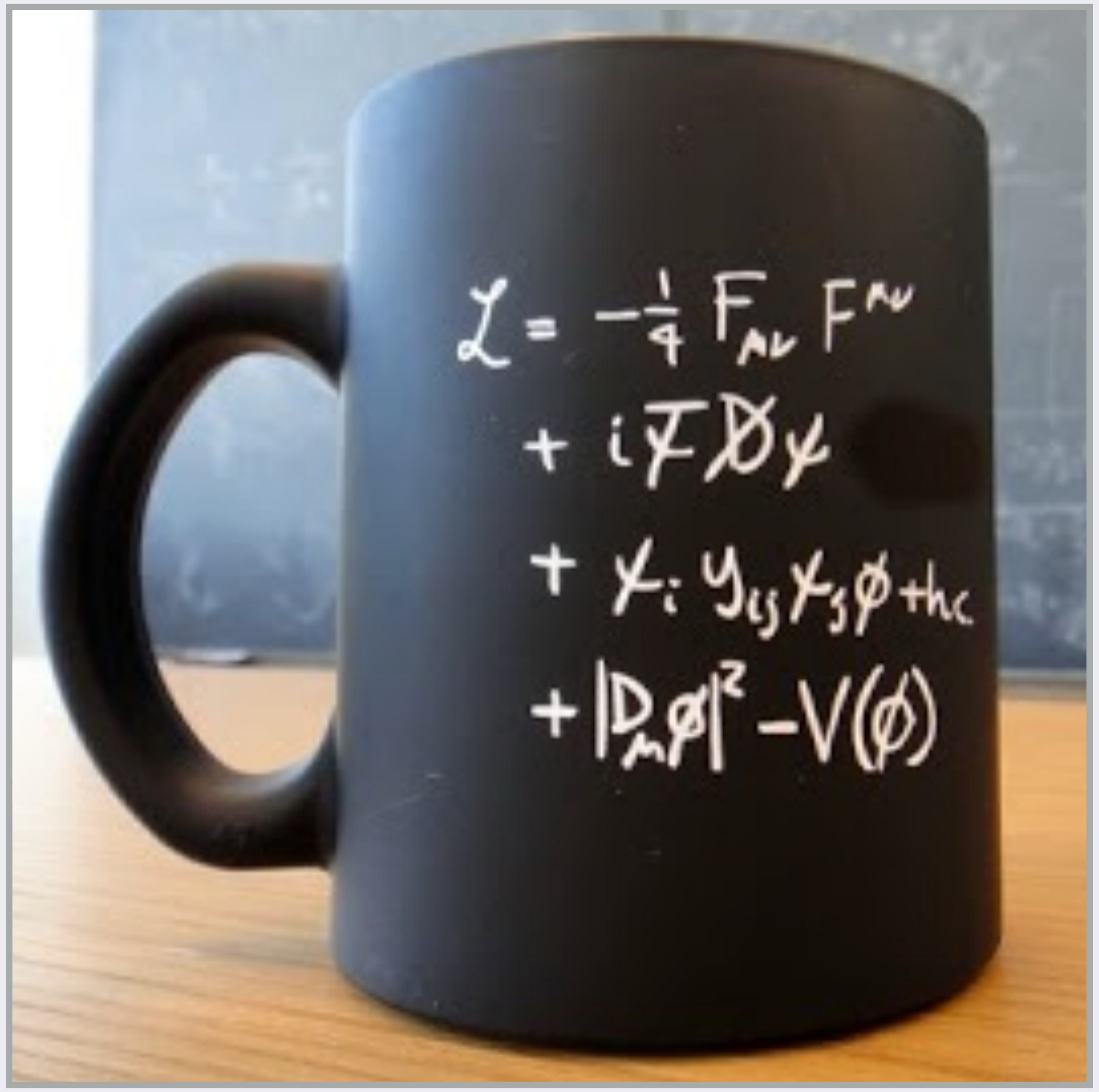
The Standard Model is a wonderfully successful and predictive model of much of particle physics

However, we know it is not all there is:

Does not include: dark matter, neutrino masses, baryogenesis, gravity

Does not explain: Flavor structure, Strong CP, Higgs Mass

Therefore, the SM is an **effective field theory**

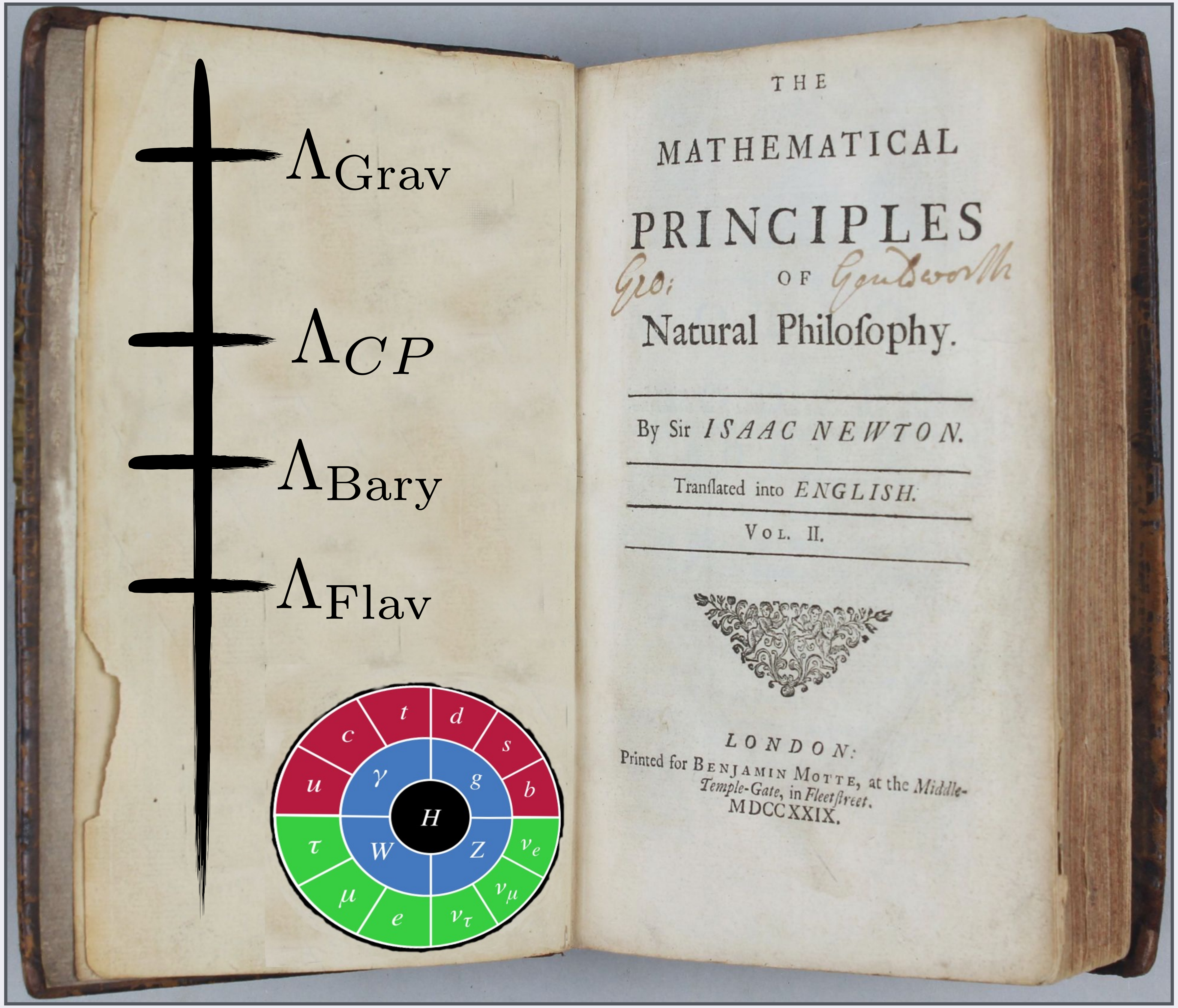


Some Natural Philosophy

With the Higgs a scalar in an EFT, the mass is generically set by the heaviest scales

An elementary Higgs "should" have a Planck scale mass

If gravity is somehow different, the mass scales associated with every other new physics scale lead to similar sensitivity



Paths to a Natural Higgs Mass

If the Higgs is not an elementary scalar, then there is no problem. The Higgs mass is set by confining scale of the new force (See Ramona's talk)

Morally equivalent to warped extra dimension and clockwork (See Dave's Talk)

There may be a symmetry that prevents large quantum corrections to the Higgs mass

If the Higgs coupling to the top quark breaks this symmetry we have not gained anything, need symmetry partner(s)

There may be some historical reason, in the cosmic sense, that leads to a light Higgs mass

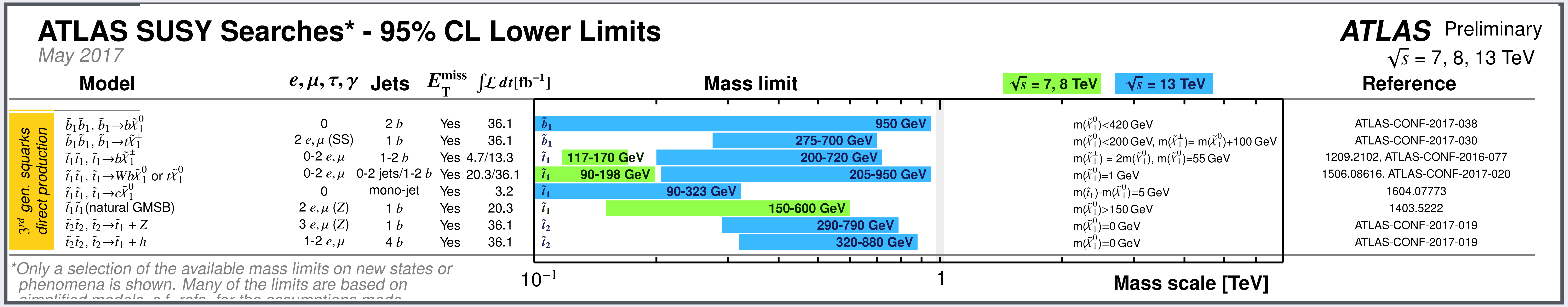
The Higgs may relax to the EW scale (See Elina's Talk)

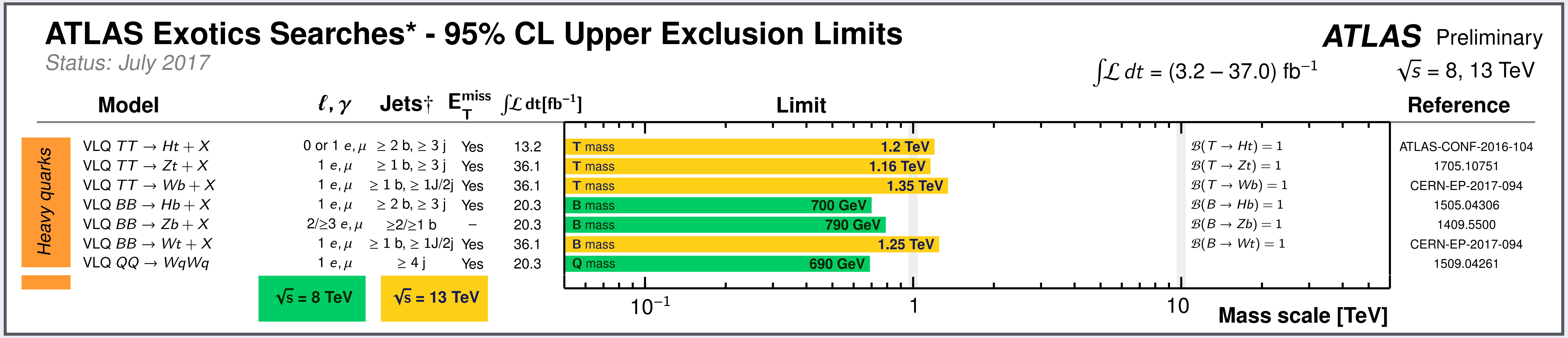
The LHC Weighs In

No evidence of compositeness or symmetry partners, so far

Already a hierarchy between the search limits and the Higgs mass

Is naturalness ruled out, or “under stress”? (Hint: No)





(Color) Neutral Naturalness

Beginning in 2005, a class of symmetry based solutions the the Higgs mass hierarchy problem have been introduced

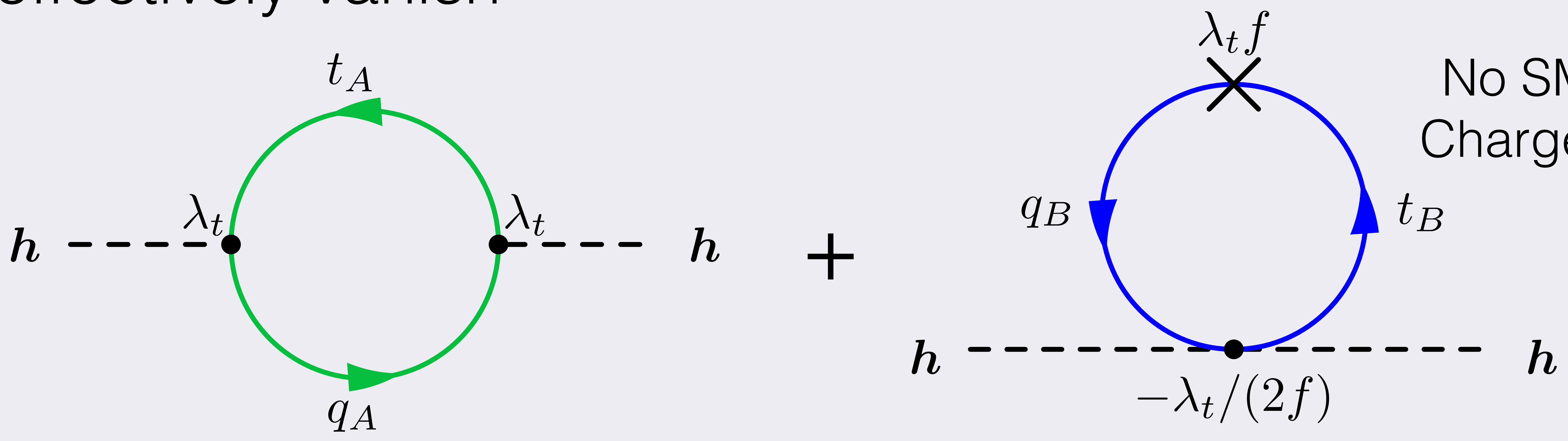
These models do have symmetry partners of the top quark, but these partners are color neutral

Bounds from direct colored production effectively vanish

	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY	pNGB/RS
EW Charges	Folded SUSY	Quirky Little Higgs
No SM Charges	Tripled Top/ Hyperbolic Higgs	Twin Higgs

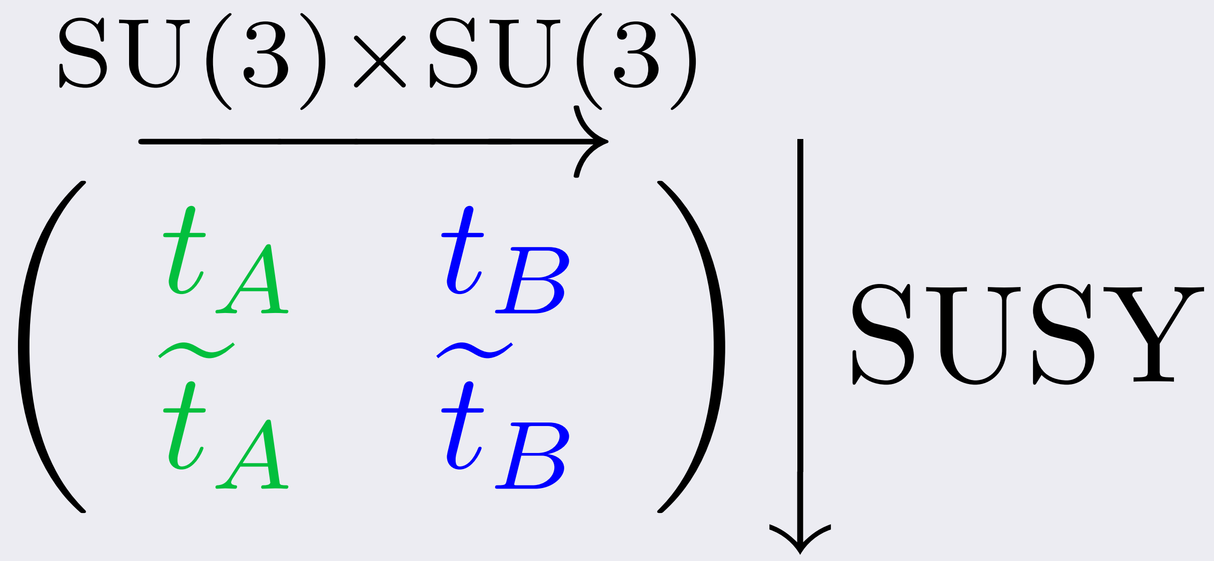
↑ (Tripled Top/ Hyperbolic Higgs)

Brand New!
See Ennio's Talk



Folded-SUSY

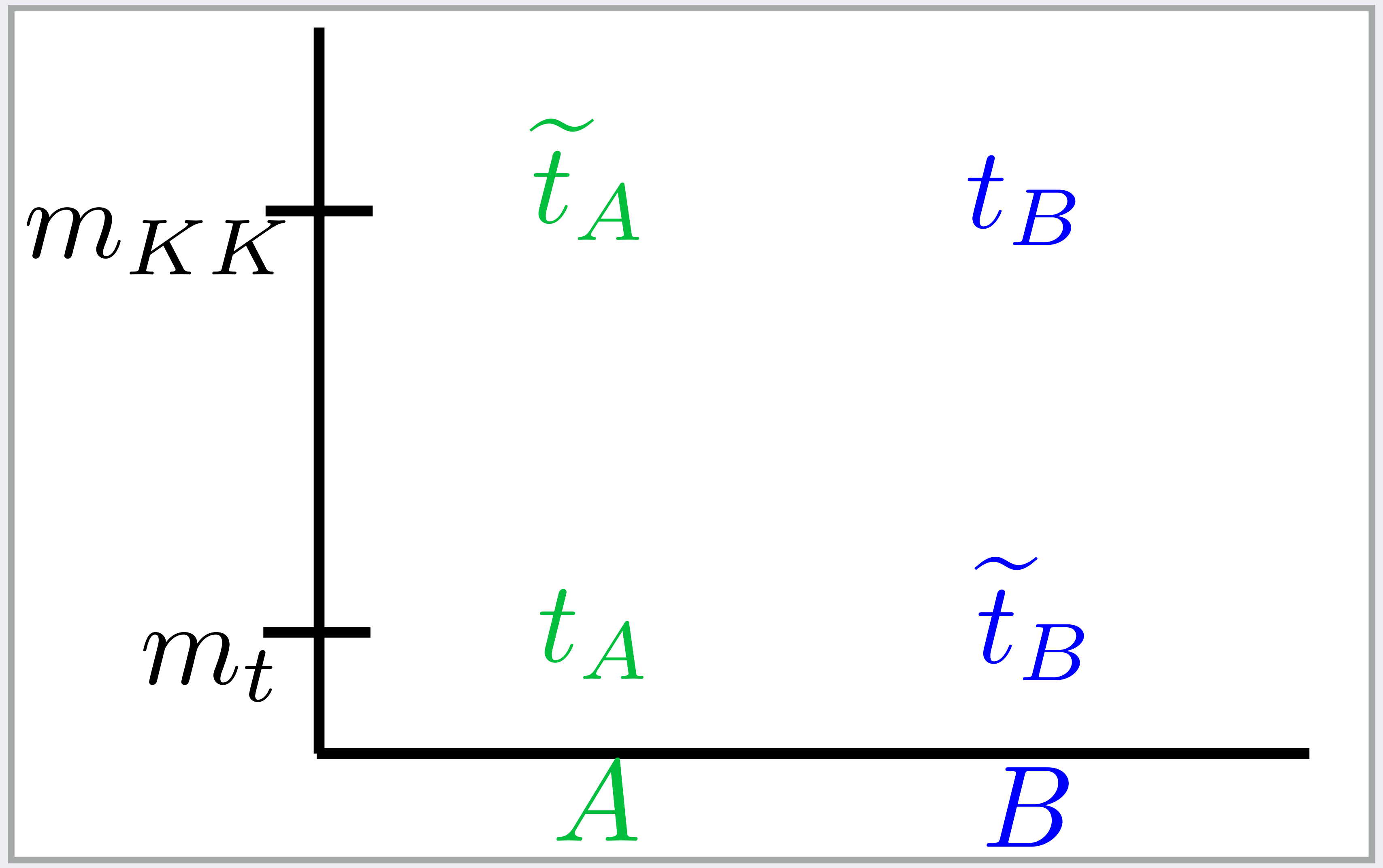
Burdman, Chacko, Goh, Harnik, hep-ph/0609152



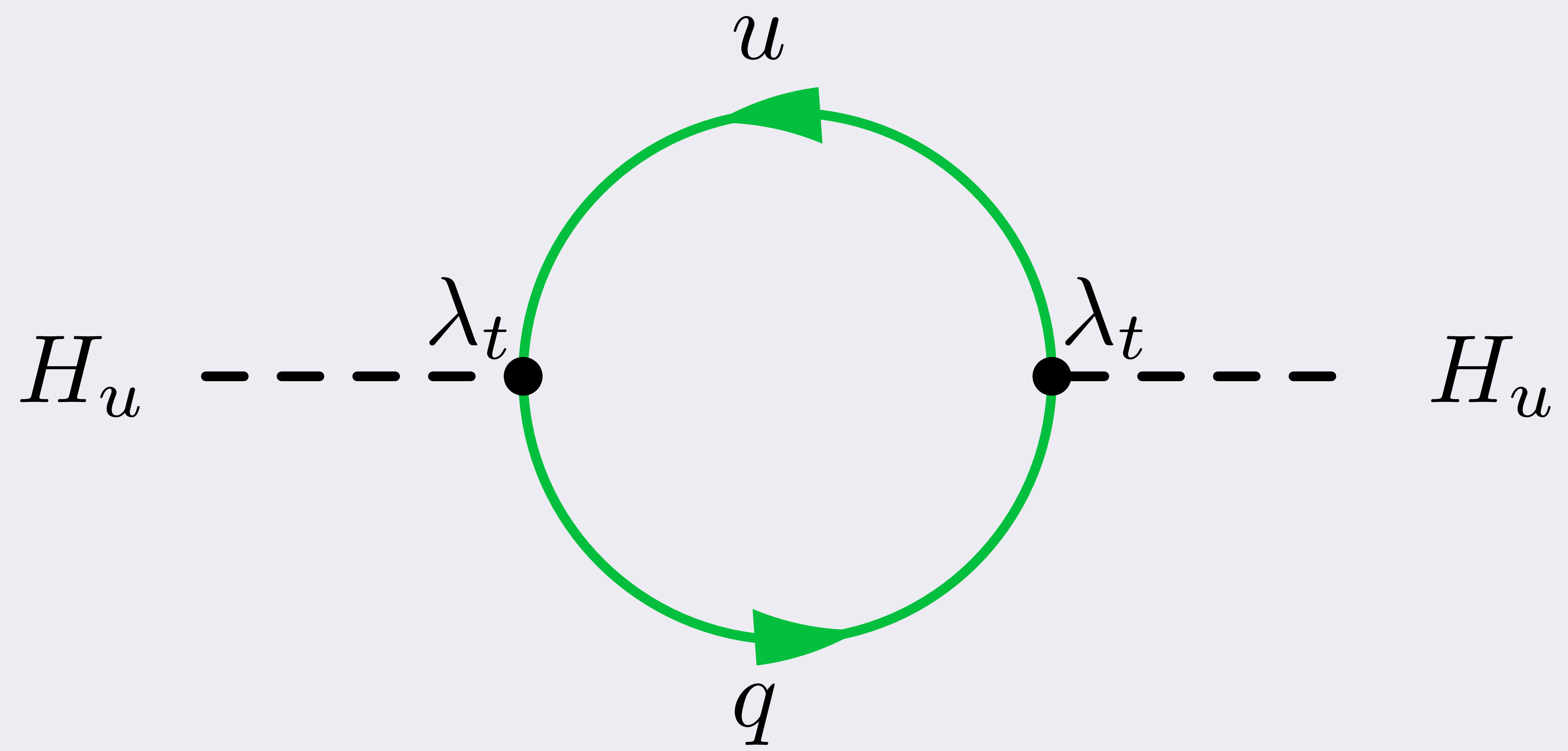
The usual SUSY multiplets are extended by a new $SU(3)$

The colored scalars folded fermions are projected out of the low energy theory through boundary conditions in 5D

$$\Rightarrow \begin{pmatrix} t_A & \cancel{t_B} \\ \cancel{\tilde{t}_A} & \tilde{t}_B \end{pmatrix}$$



The cancelation proceeds with the SM fermions t_A and folded scalars $\tilde{t}_B$



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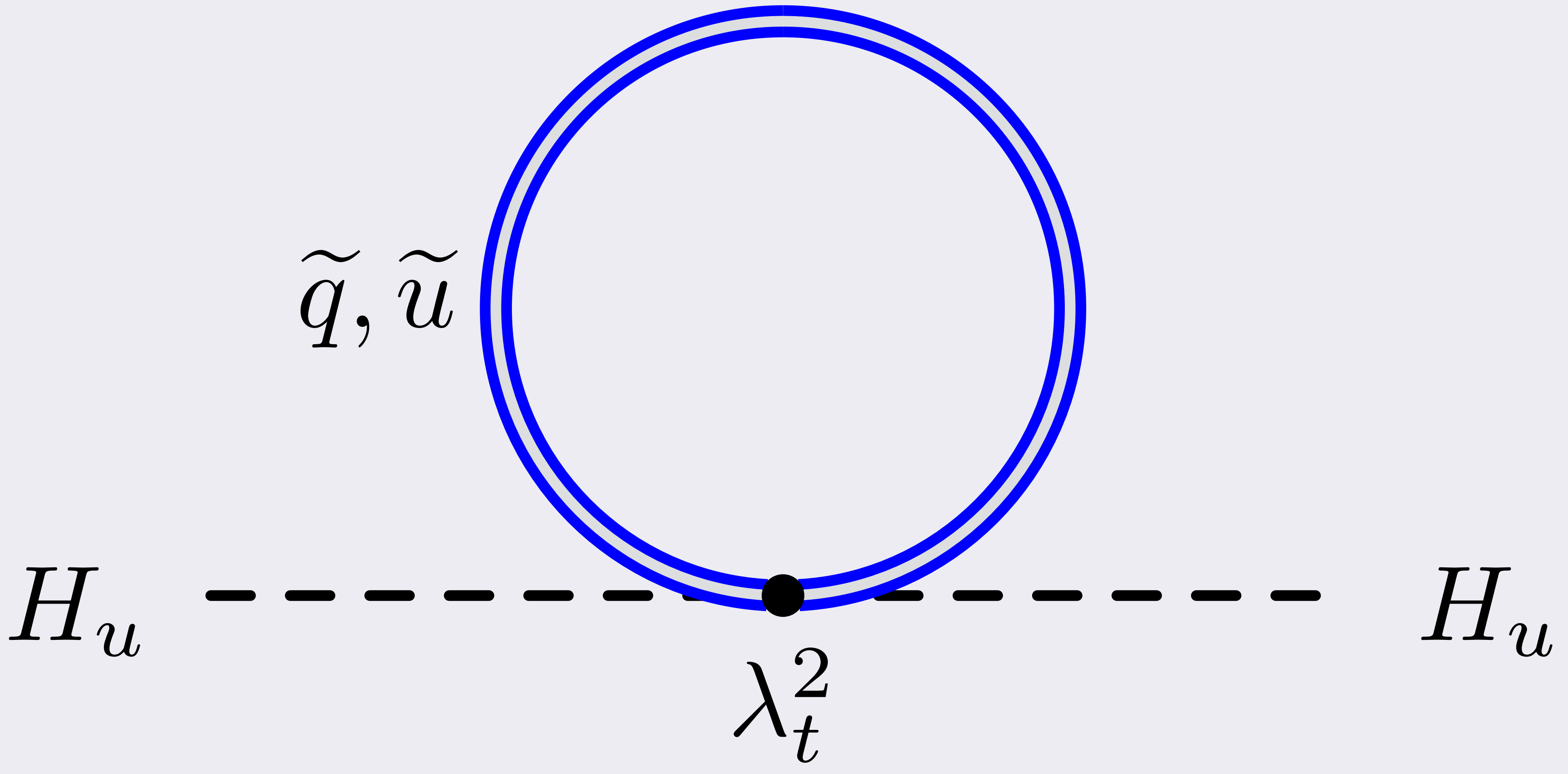


Folded SUSY Pheno

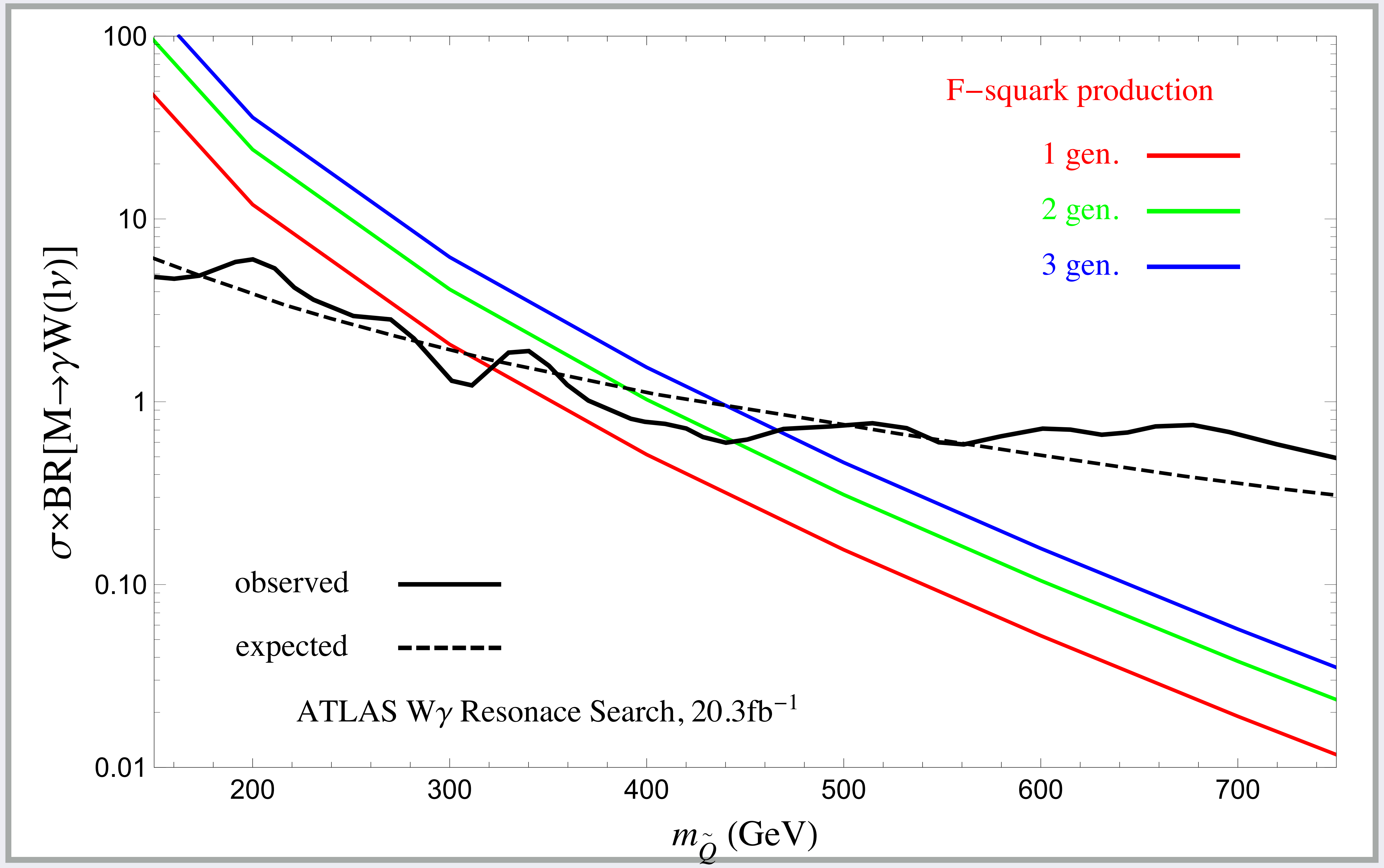
In the alignment limit the deviations from SM Higgs couplings can be very small

Phenomenology driven by new EW states

There are no light states charged under the hidden color, so the particles are linked by a ‘string’ of gauge flux

Quirky Dynamics, Kang, Luty 0805.4642

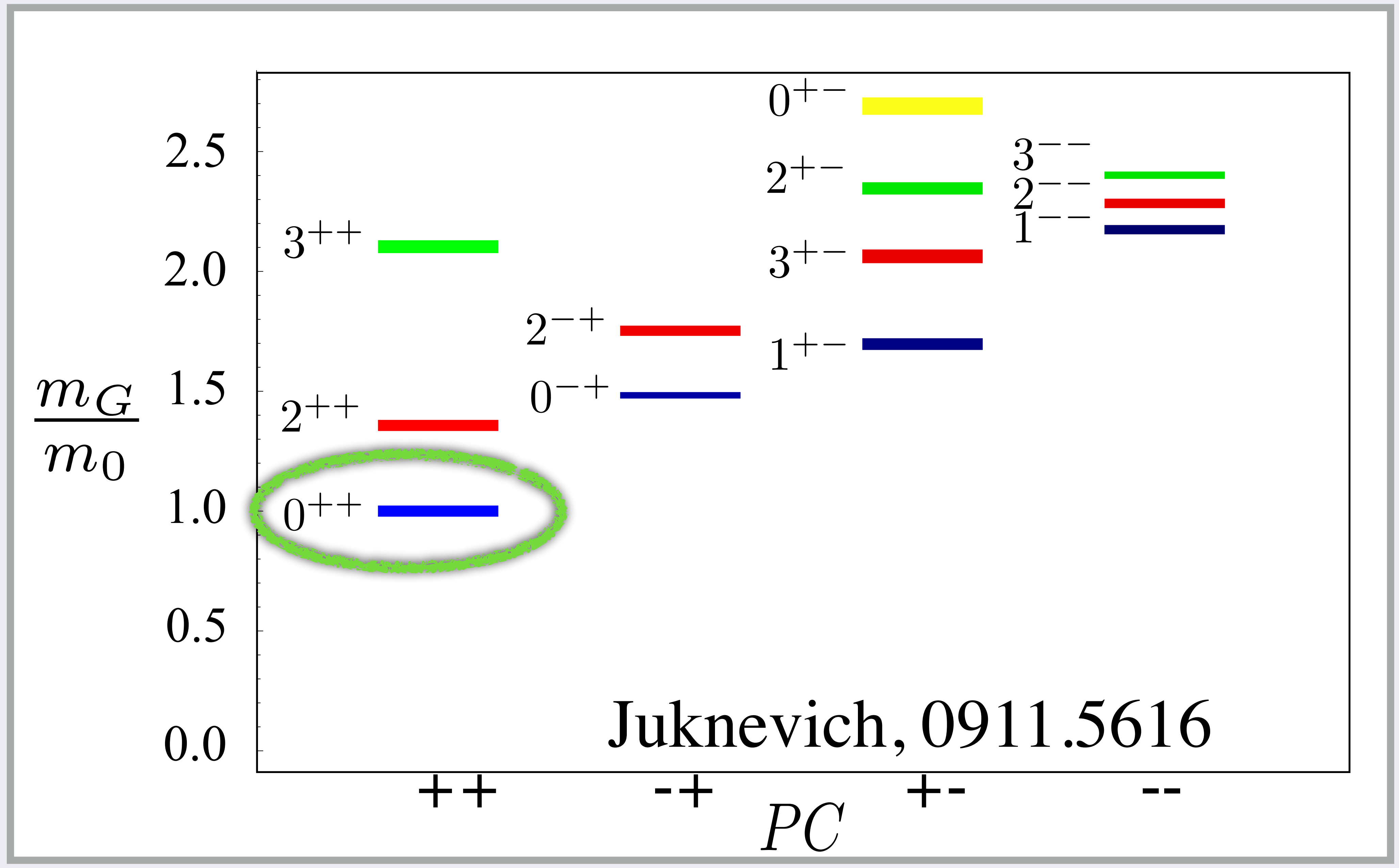
Produce an up-down pair through Drell-Yan. It cannot shower, so must annihilate. Can give a $W\gamma$ resonance



Burdman, Chacko, de Lima, Harnik, CV 1411.3310

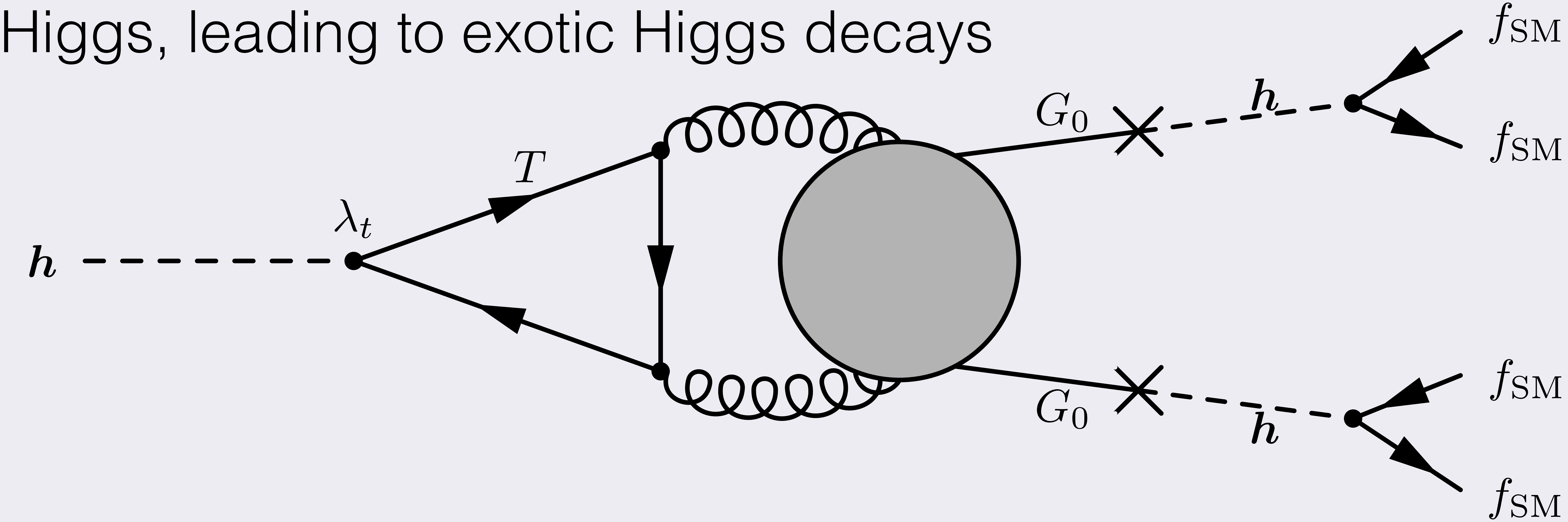
Exotic Higgs Decays

Because the top parters are EW charged, LEP bounds require they have masses of at least 100 GeV



Therefore, the lightest hidden states are glueballs of the new $SU(3)$

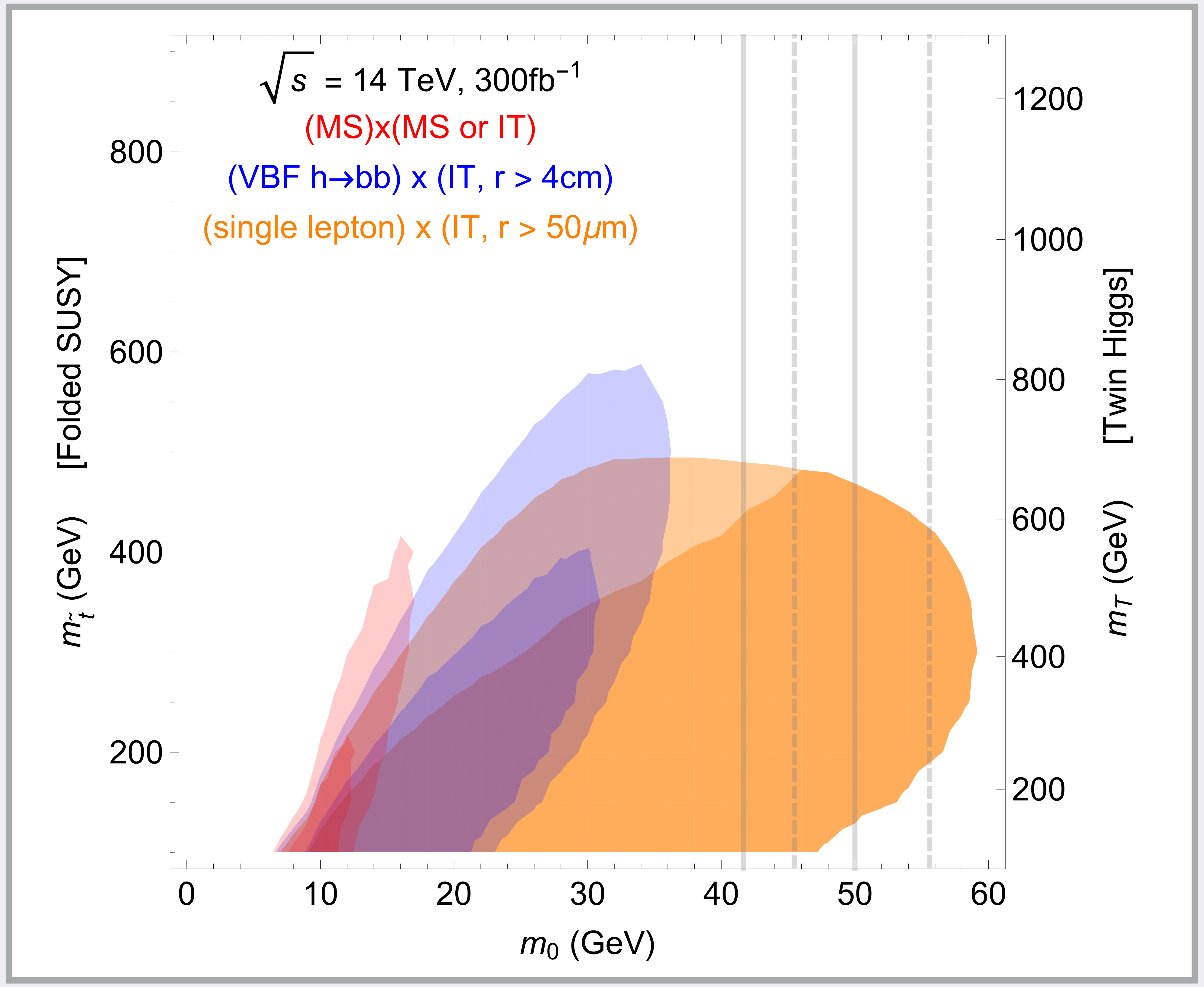
The lightest glueball, the 0^{++}, mixes with the Higgs, leading to exotic Higgs decays

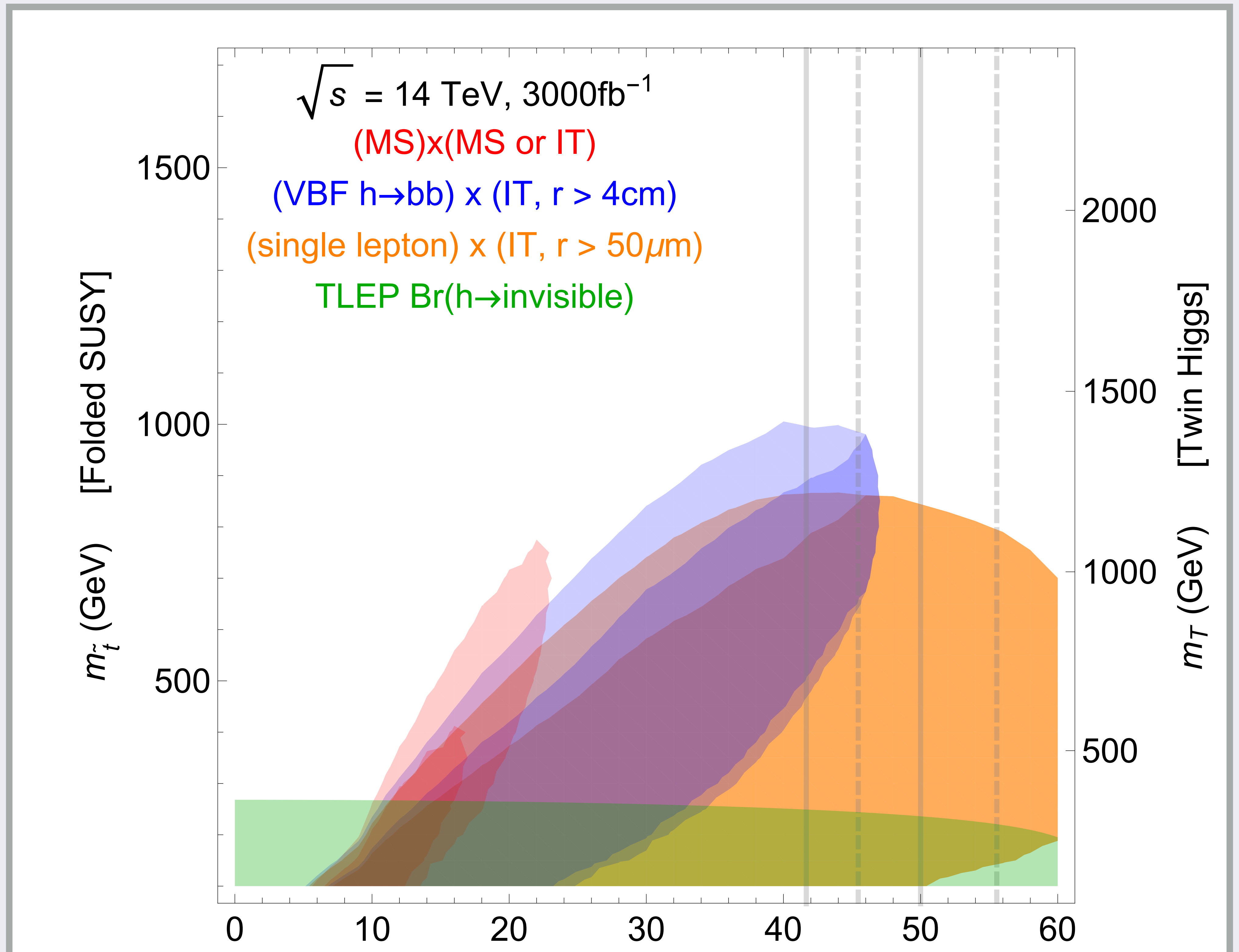


Exotic Higgs Decays

These decays are suppressed by the small mixing between the Higgs and the lightest glueball, the 0^{++}

The resulting displaced vertices provide a powerful probe of Folded SUSY





Curtin, CV 1506.06141

Similar phenomenology in Tripled Top and Folded SUSY (see Ennio's talk)

Twin Higgs

Chacko, Goh, Harnik, hep-ph/0506256

Make a twin copy of the SM matter and gauge structure and assume a Z_2 exchange symmetry between the SM and its twin

In the Higgs sector, assume global $SU(4)$ symmetry, with two $SU(2)$ subgroups gauged

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

When $\mathcal{H}$ gets a VEV f , $SU(4)$ breaks to $SU(3)$, yielding 7 pNGBs
6 of these are eaten by the A and B sector $SU(2)$ gauge bosons

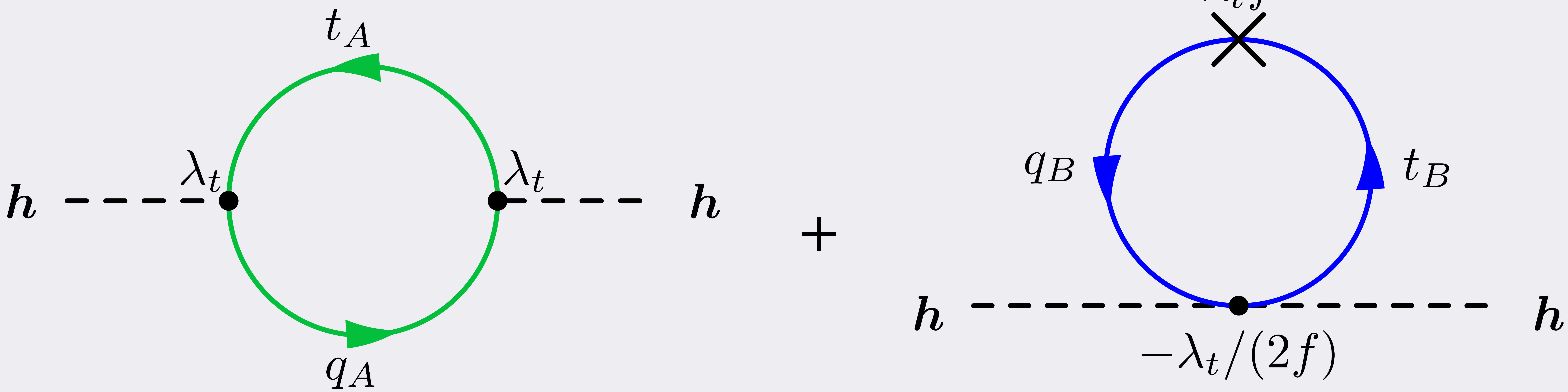
We are left with one physical pNGB, the Higgs

Twin Higgs Protection

The 1-loop top quark corrections to the Higgs mass

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

The Z_2 makes the total contribution $SU(4)$ symmetric, does not affect the pNGB of broken $SU(4)$



Twin Higgs Physics

The Z_2 symmetry predicts equal VEV in A and B sectors $\quad \frac{v}{f} \equiv \vartheta$

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

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

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

This already in tension with Higgs measurements…

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 $\sim \frac{3\lambda_t^2}{8\pi^2} m_T^2 \ln\frac{\Lambda^2}{m_T^2}$

Twin Higgs Variations

The twin sector need not be a perfect copy. The Fraternal twin Higgs includes only the minimal third generation Craig, Katz, Strassler, Sundrum, 1501.05310

The bottom and tau Yukawas can also depart from the exact Z_2

These variations can address cosmological issues and lead to viable dark matter (FTH not *required*, see Chacko, Craig, Fox, Harnik 1611.07975)

The FTH model may provide a much smaller invisible Higgs width

This in turn makes Higgs rates more SM-like

But it also has the potential for exotic decays of the Higgs with displaced vertices

Higgs Couplings

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

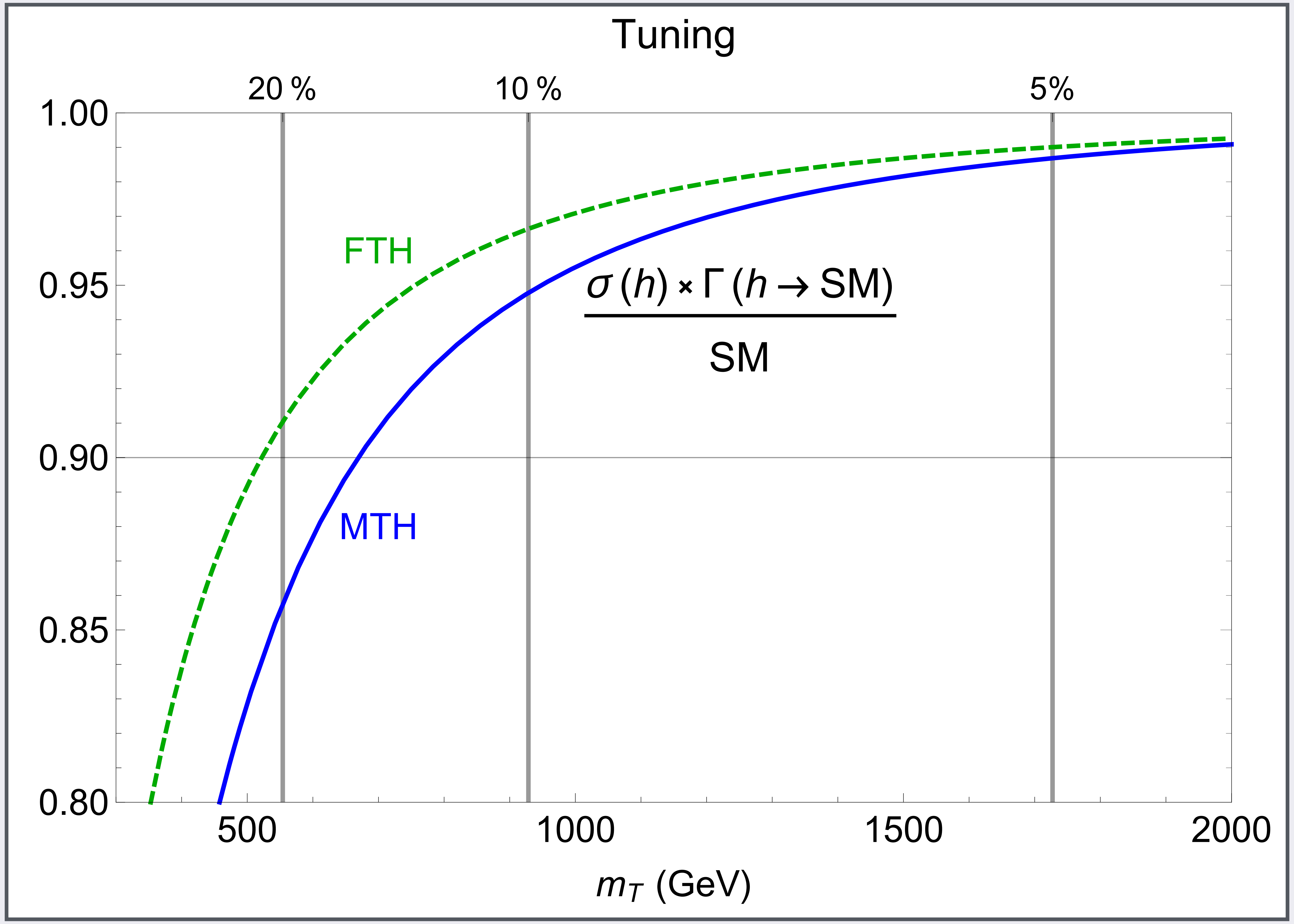
This reduces Higgs rates to SM states

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

Probes~500-700 GeV twin tops

Future lepton colliders can reach multi-TeV masses

Can we find more direct signals?



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

Twin Higgs Portal

So far we have only considered the pNGBs of the broken $SU(4)$

There may also be a radial mode, with mass set by f

This state provides information about the Higgs sector directly

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

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 $\dfrac{m_H}{m_h} \geq \dfrac{m_T}{m_t} = \cot\vartheta$

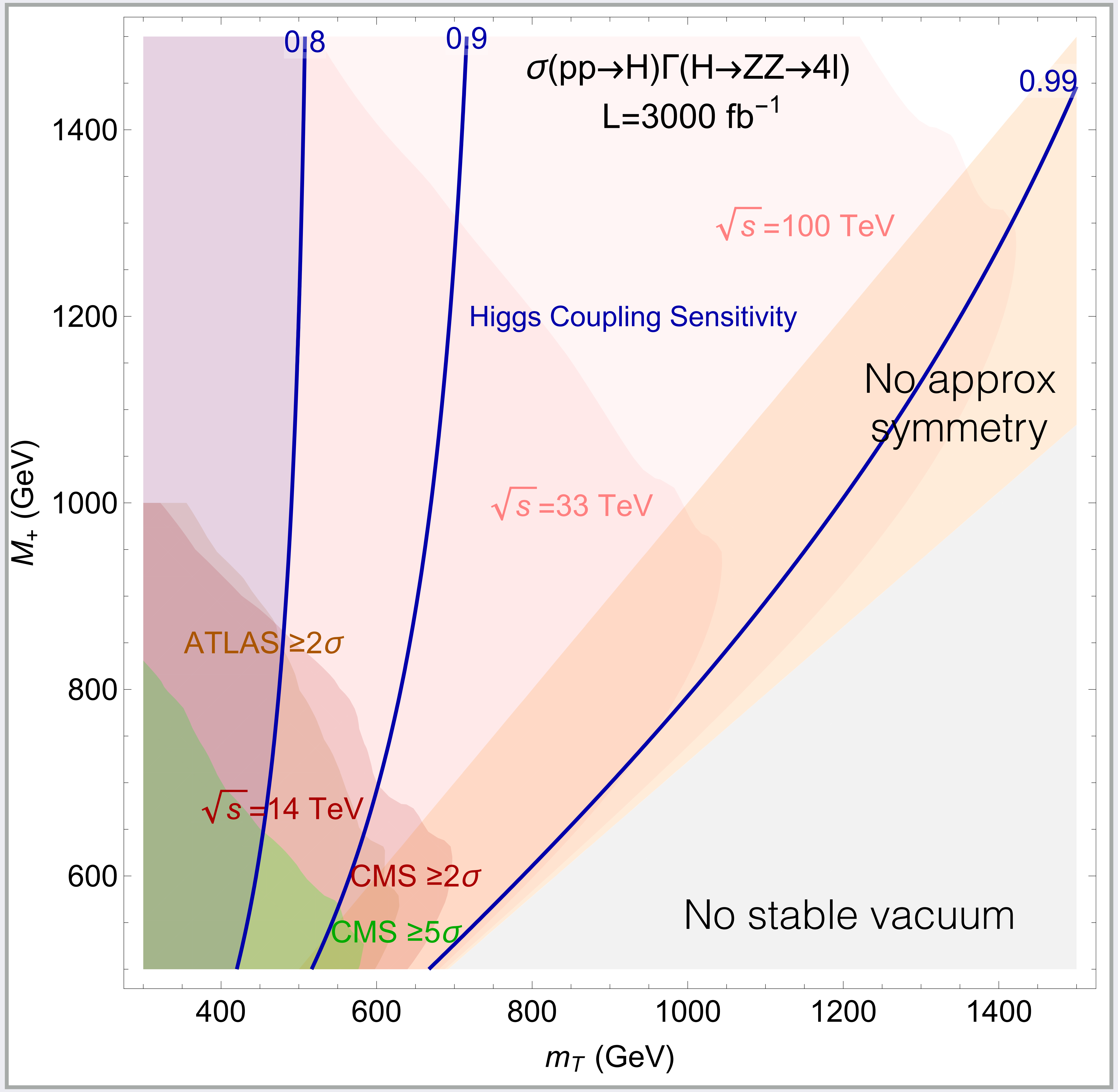
Four parameter potential, with the requirement that $SU(4)$ breaking terms are smaller than preserving terms

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
$v_{\mathrm{EW}}, m_h, m_H$, and ϑ
completely specify the
4 parameter Higgs potential



Chacko, Kilic, Najjari, CV 1711.05300

Confirming the Twin Higgs

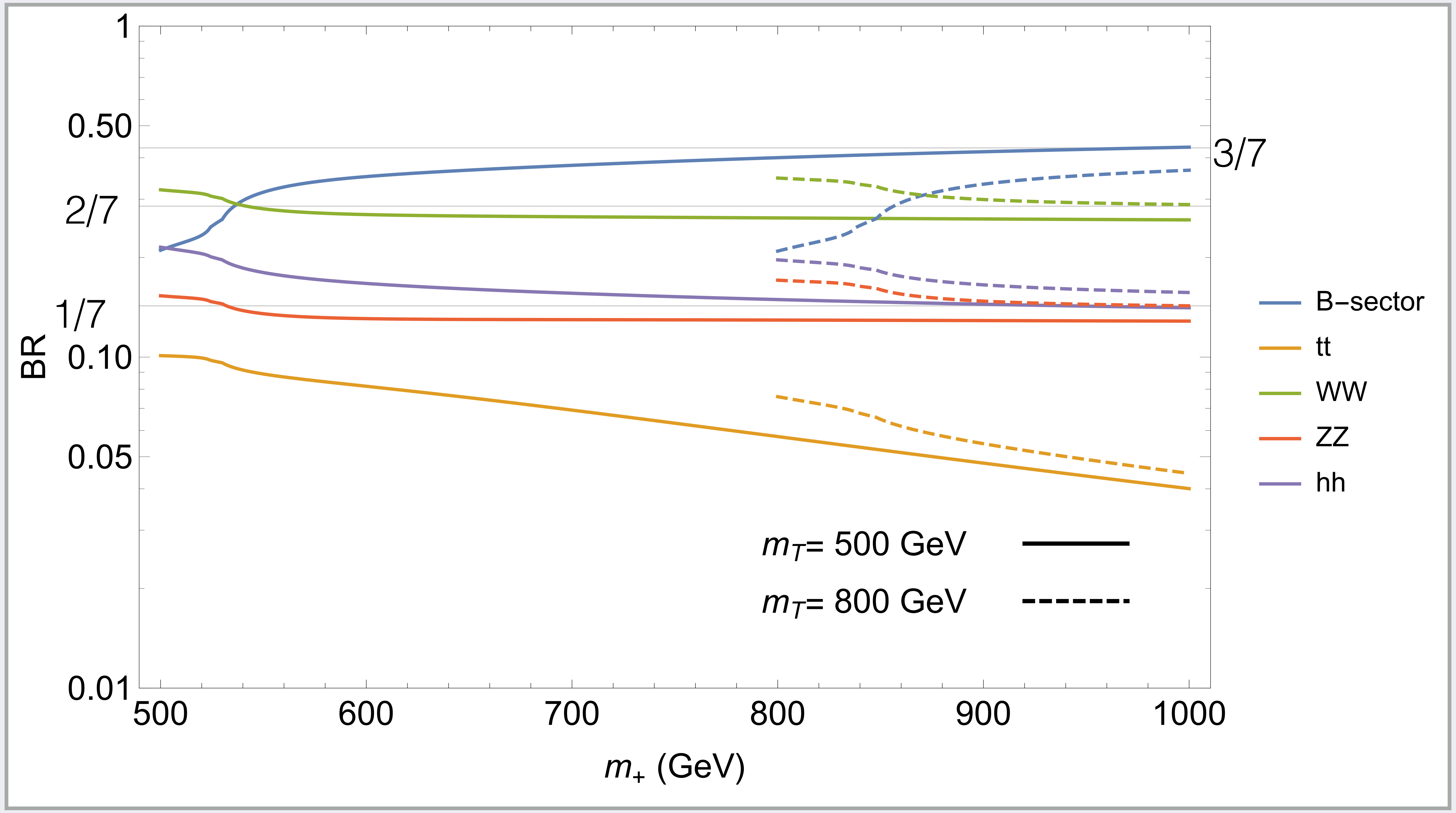
The $H \to ZZ$ discovery determines the Heavy Higgs mass and the rate to ZZ

The specified potential predicts production and widths to EW gauge bosons

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!



Where Did $\frac{1}{7}$ Come From?

From the symmetry preserving quartic, the leading radial mode decays are

$$\lambda \left|\mathcal{H}\right|^4 \Rightarrow \sim \lambda f H \left(\sum_{\text{pNGBs}} \phi_i \phi_i \right)$$

Which dominates the width, as λ is order one and f is large

Then, to leading order

$$\Gamma_{\text{BR}} \left(H \rightarrow \phi_i \phi_i \right) \sim \frac{1}{N_{\text{pNGB}}}$$

Much more general that the Twin Higgs!

Linear Collider Discovery

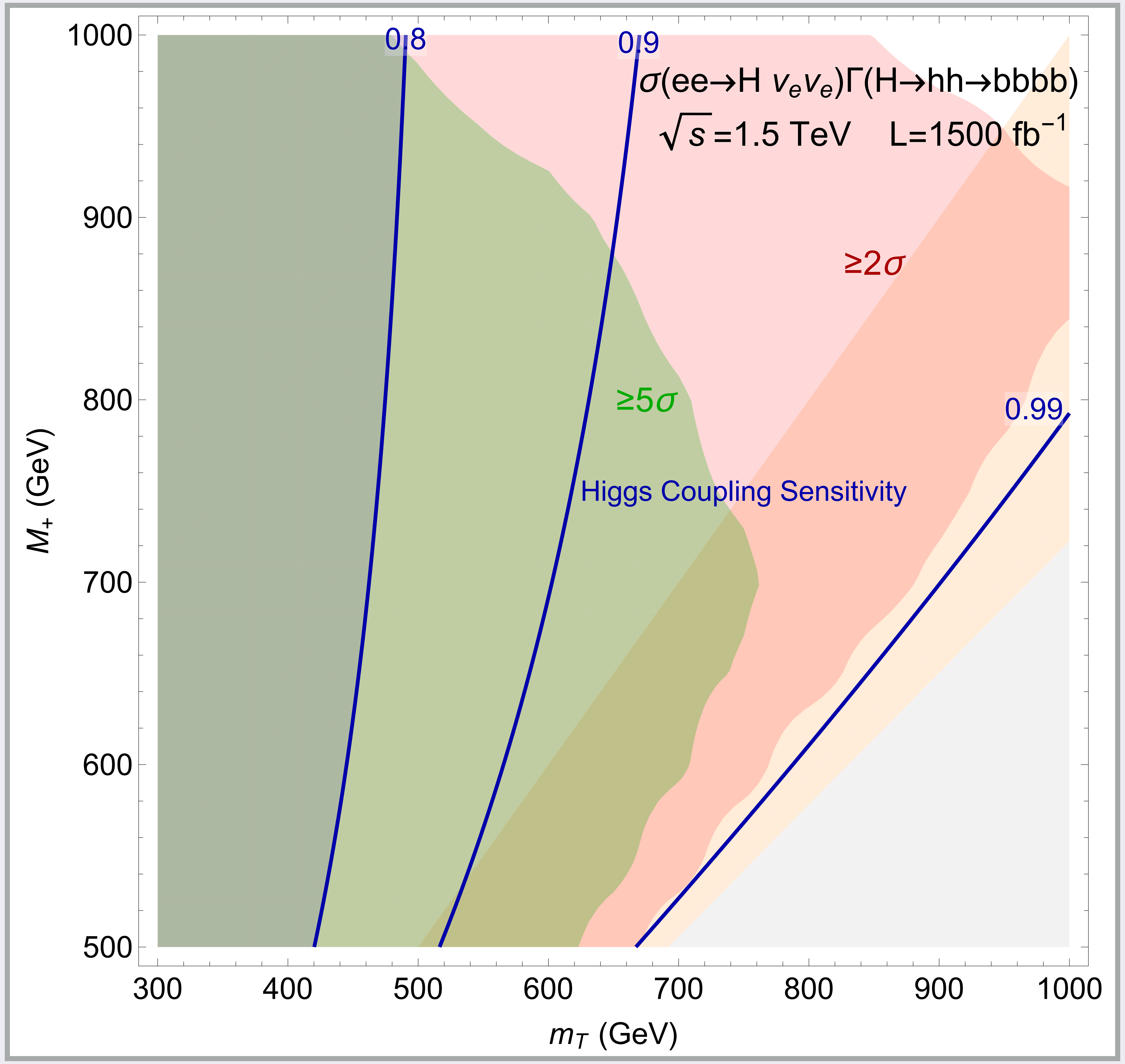
Linear colliders can measure Higgs couplings more precisely

At high energy, they can also discover the twin Higgs through

$$H \to hh$$

Such a machine can discover and test the twin Higgs framework over much of the natural parameter space

It might also probe the invisible twin Higgs width to detect the hidden sector spectrum

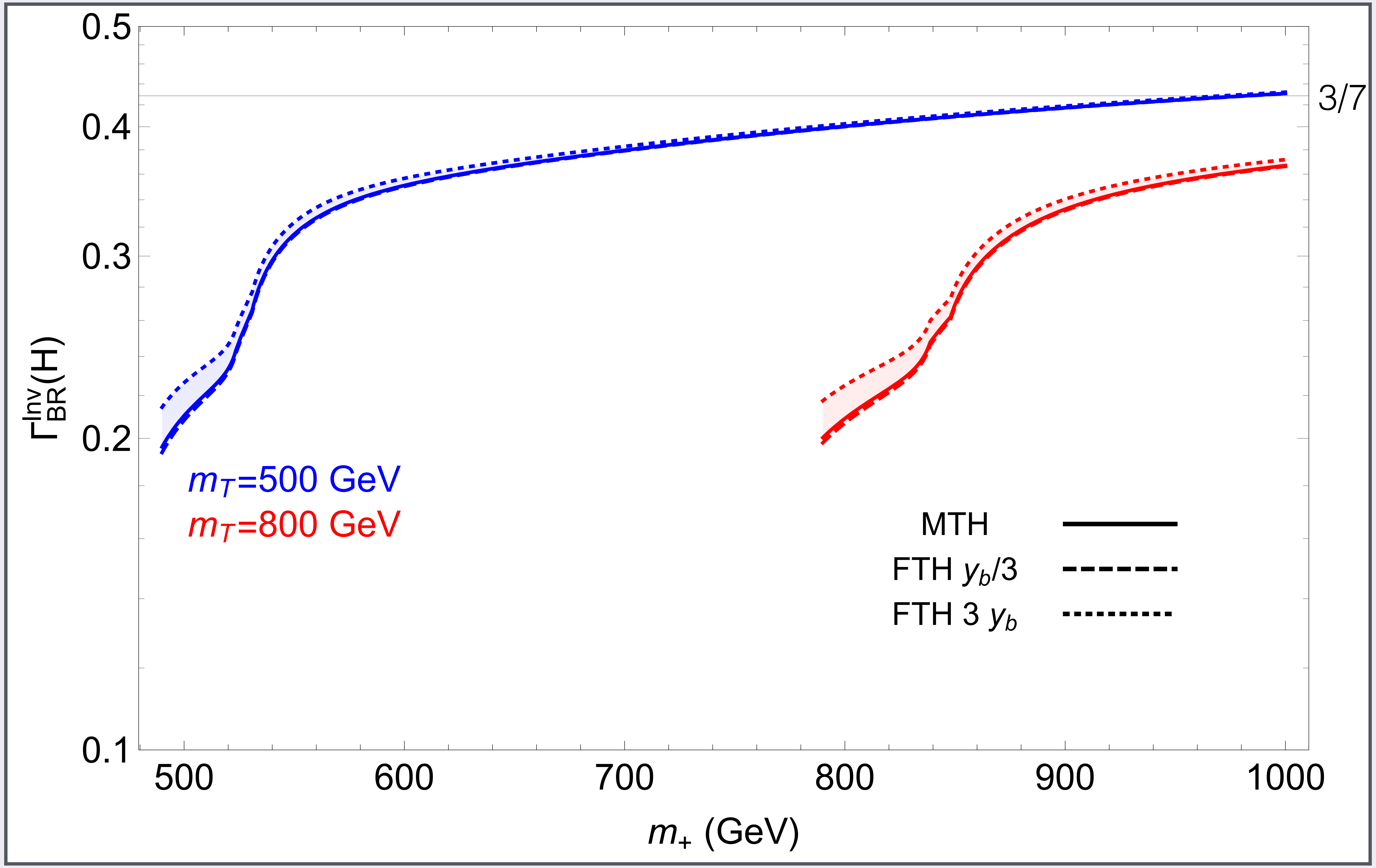


Chacko, Kilic, Najjari, CV 1711.05300

Hard Breaking

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

The symmetry breaking pattern is still a prediction when decays to hidden gauge bosons are open



MC for NN

Showering in hidden QCD sector, often pure glue shower into glueballs, glueball hadronization model

Of course, different QCD running in the hidden sector…

Modeling of quirky dynamics, de-excitation and decays

Within the larger quirk framework, NN motivated quirks have sort strings, a more targeted class

Conclusions

Symmetry based solutions to the hierarchy problem with color neutral top partners provide concrete examples of Higgs naturalness in the LHC era

These models provide interesting phenomenology at the LHC and future colliders

These frameworks can be tested, but may require novel search strategies

There is still a lot of exploring to do!