Testing the Twin Higgs Mechanism at a Linear Collider

Physics at CLIC Workshop

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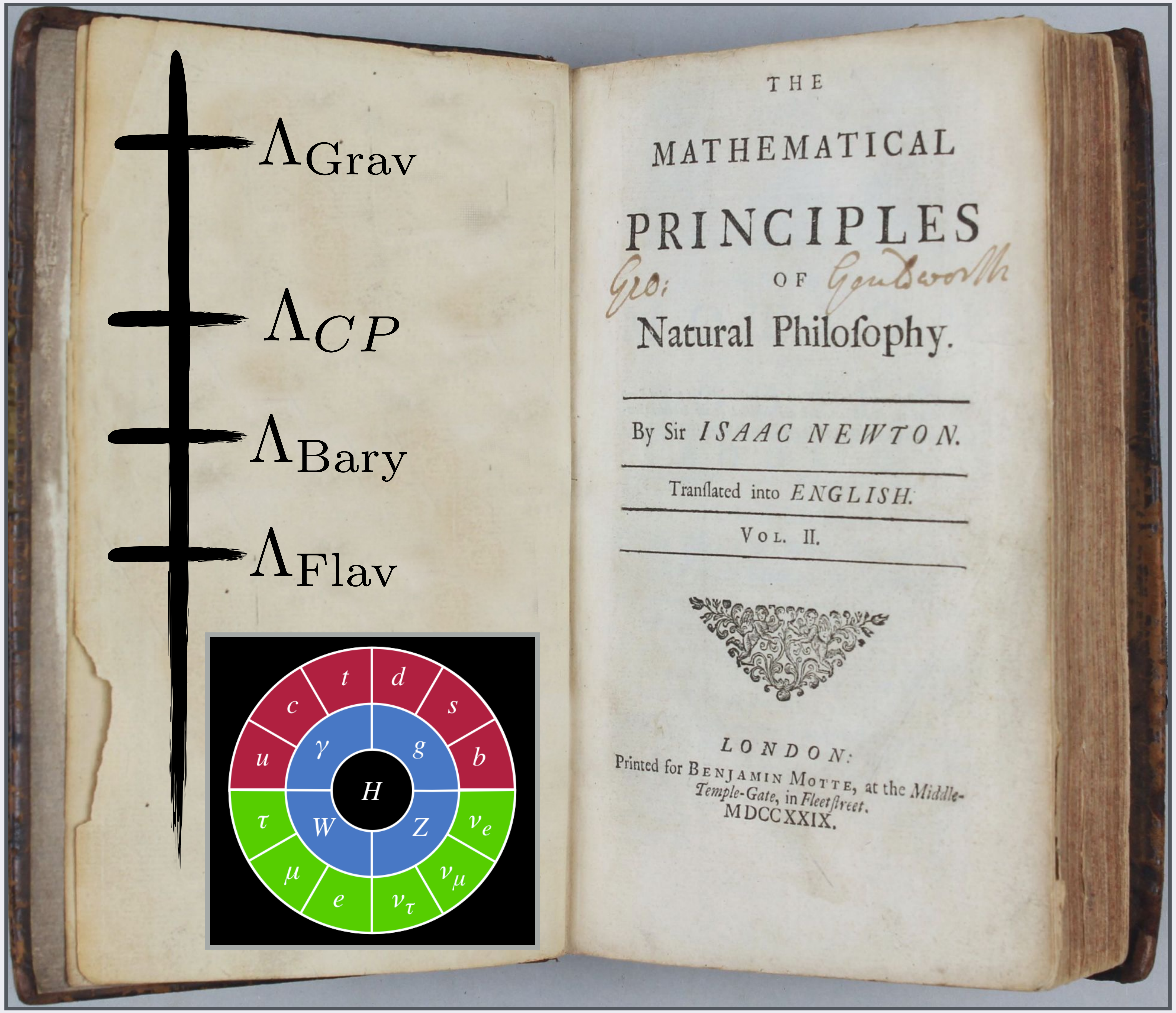
$Q|MAP\rangle$

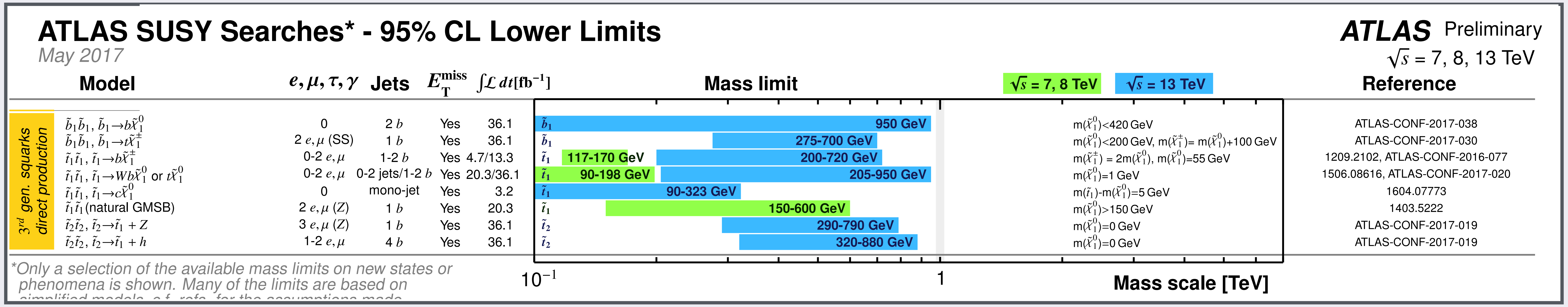
Some Natural Philosophy

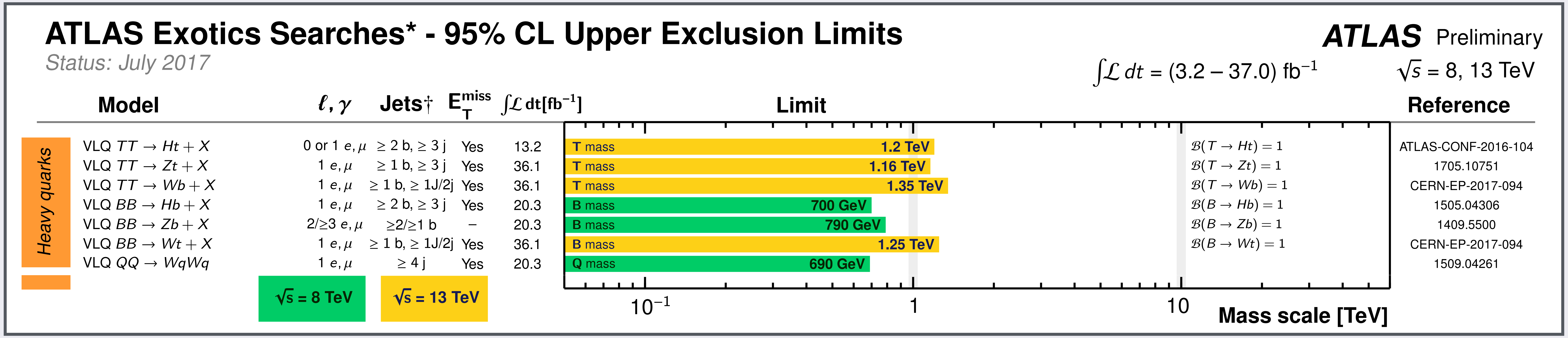
- We still do not understand why the Higgs is light
- We know that the Standard Model is "only" an effective field theory
    - Dark Matter, gravity, etc are not included
- Only experiment can determine what structure, if any, keeps the Higgs naturally light



Results thus far…

- No evidence of compositeness or symmetry partners

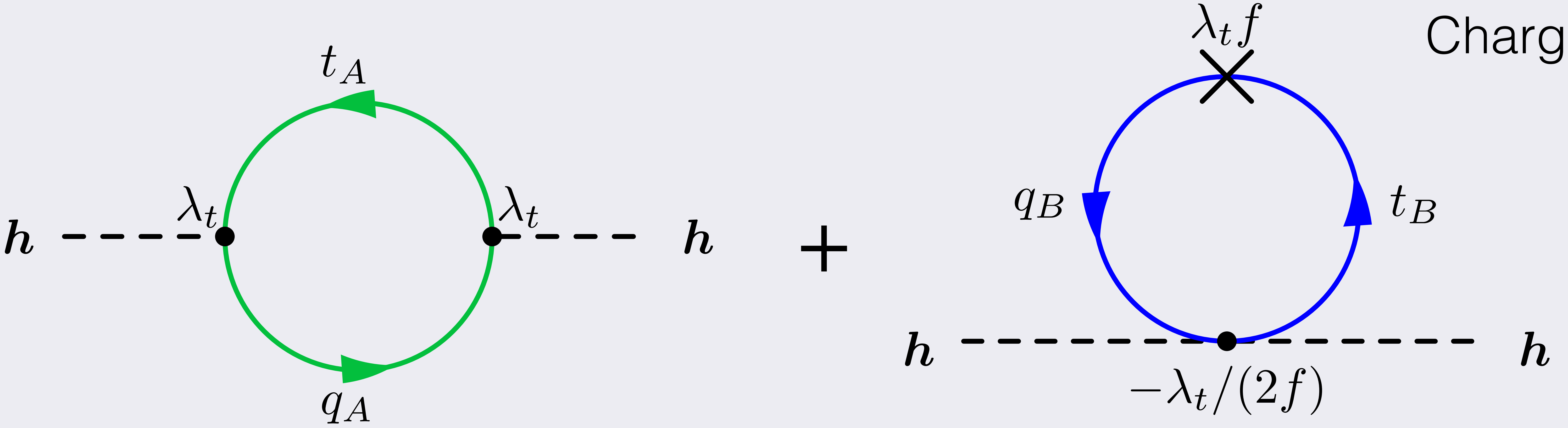




- Looks like symmetry based naturalness is “under stress”

(Color) Neutral Naturalness

- Symmetry based solutions to the hierarchy problem without colored partner particles
- Usually a discrete symmetry plays an important role
- Symmetry partners charged under a "hidden" QCD



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

Your Model Here

Twin Higgs

Chacko, Goh, Harnik, hep-ph/0506256

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

- Make a ‘twin’ copy of the entire SM with $SU(4)$ symmetric Higgs sector
  - Gauge two $SU(2)$ subgroups, *A* for SM and *B* for BSM
  - Exchange symmetry equates *A* and *B* gauge couplings
- H gets a VEV, f , breaks $SU(4)$ to $SU(3)$, gives 7 NGBs
- 6 eaten by *A* and *B* gauge bosons, one physical Higgs
- One loop contributions are $SU(4)$ symmetric, do not affect pNGB Higgs

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

Soft Twin Breaking

- If the Twinning were perfect, the Higgs would have equal VEV in each sector and equal coupling to SM and twin particles

$$v_A^2 = v_B^2 = f^2$$

  - Already ruled out by Higgs measurements

- Reminiscent of SUSY, the discrete symmetry can be softly broken, making the Higgs mostly a SM particle

$$v_B \gg v_A$$

  - This also raising the masses of twin states
  - Constitutes a tuning $$\sim \frac{3\lambda_t^2}{8\pi^2} m_T^2 \ln \frac{\Lambda^2}{m_T^2}$$

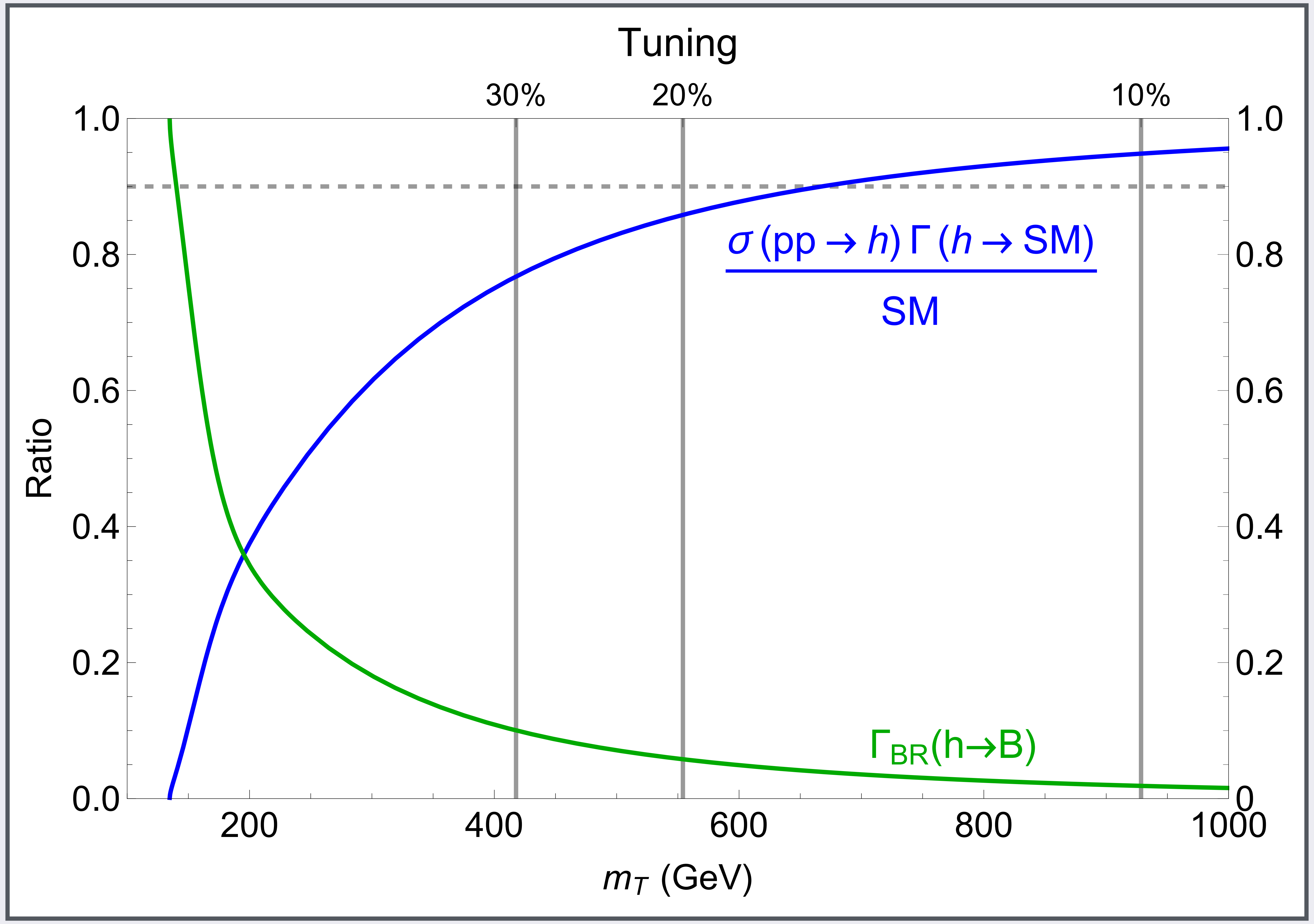
Phenomenology of the Twin Higgs

$$\vartheta = \frac{v}{f\sqrt{2}}$$

- Higgs Couplings are reduced, similar to any pNGB model

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

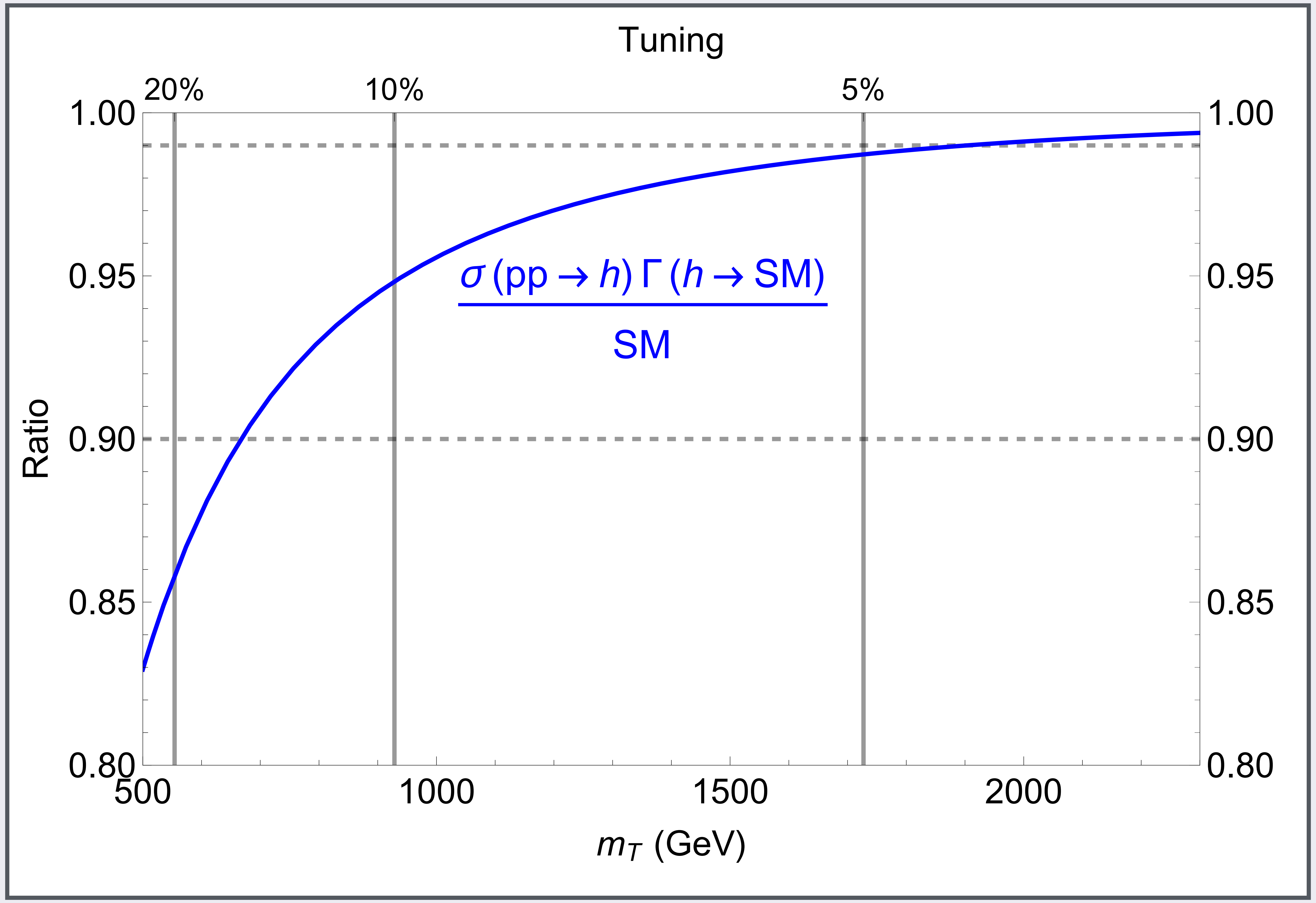
- Larger branching fraction to invisible states
- What can be done at the LHC?
    - Couplings to 10% after HL-LHC



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

Higgs Couplings

- A Linear collider can probe much deeper into the natural parameter space
    - Expect better than 1% precision, corresponding to ~% level tuning
- But coupling deviations arise in many models
- How do we distinguish the Twin Higgs?



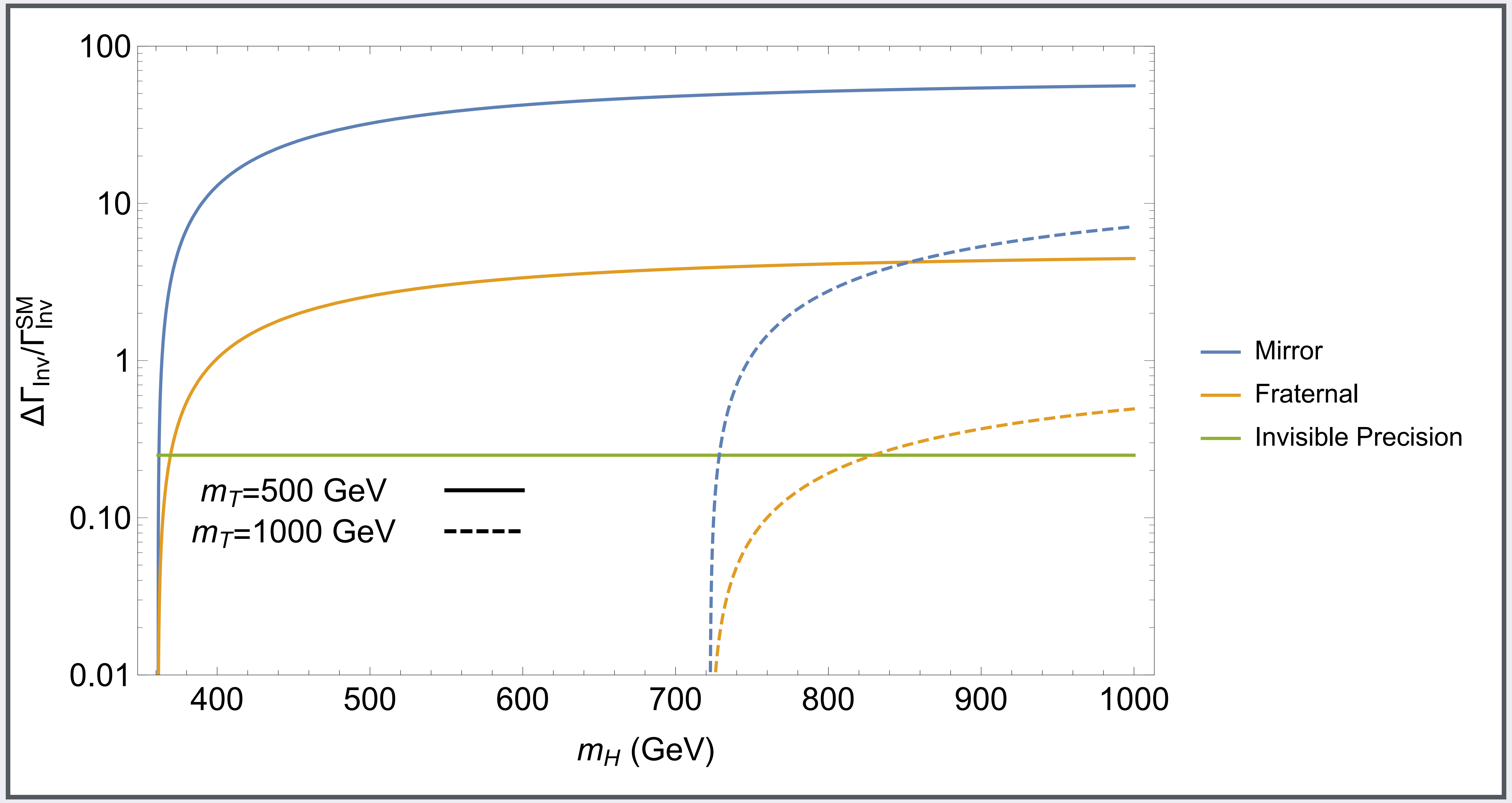
Invisible Higgs Width?

- In the mirror twin Higgs, after Higgs coupling deviations are measured the invisible width is a prediction

- However, cosmological considerations motivate variations in the twin sector spectrum (see e.g. Craig, Katz, Strassler, Sundrum 1501.05310)

  - Preserves the mechanism, spoils this prediction

- There is an irreducible increase to the invisible width, but the total value is model dependent



Radial Mode as Twin Higgs

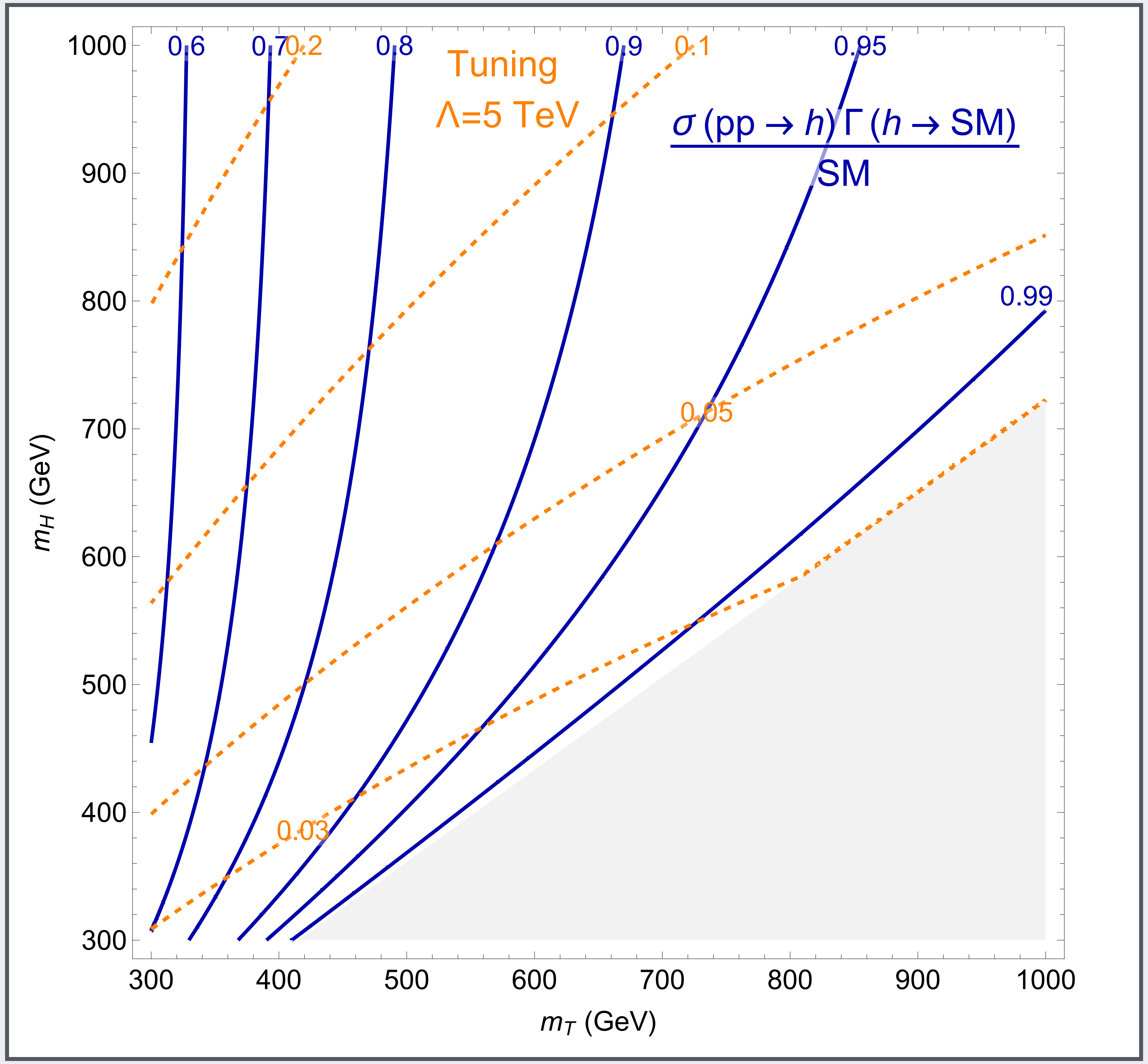
- Expect the radial mode to be close to the cutoff, but a lighter state is only mildly tuned

- Mixes with the light Higgs, with mixing angle θ

- Coupling deviations change

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

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



The Twin Higgs Portal

- Higgs potential is defined by 4 parameters (see Barbieri, Gregoire, Hall hep-ph/0509242)

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

Breaks Z_2 and $SU(4)$ →

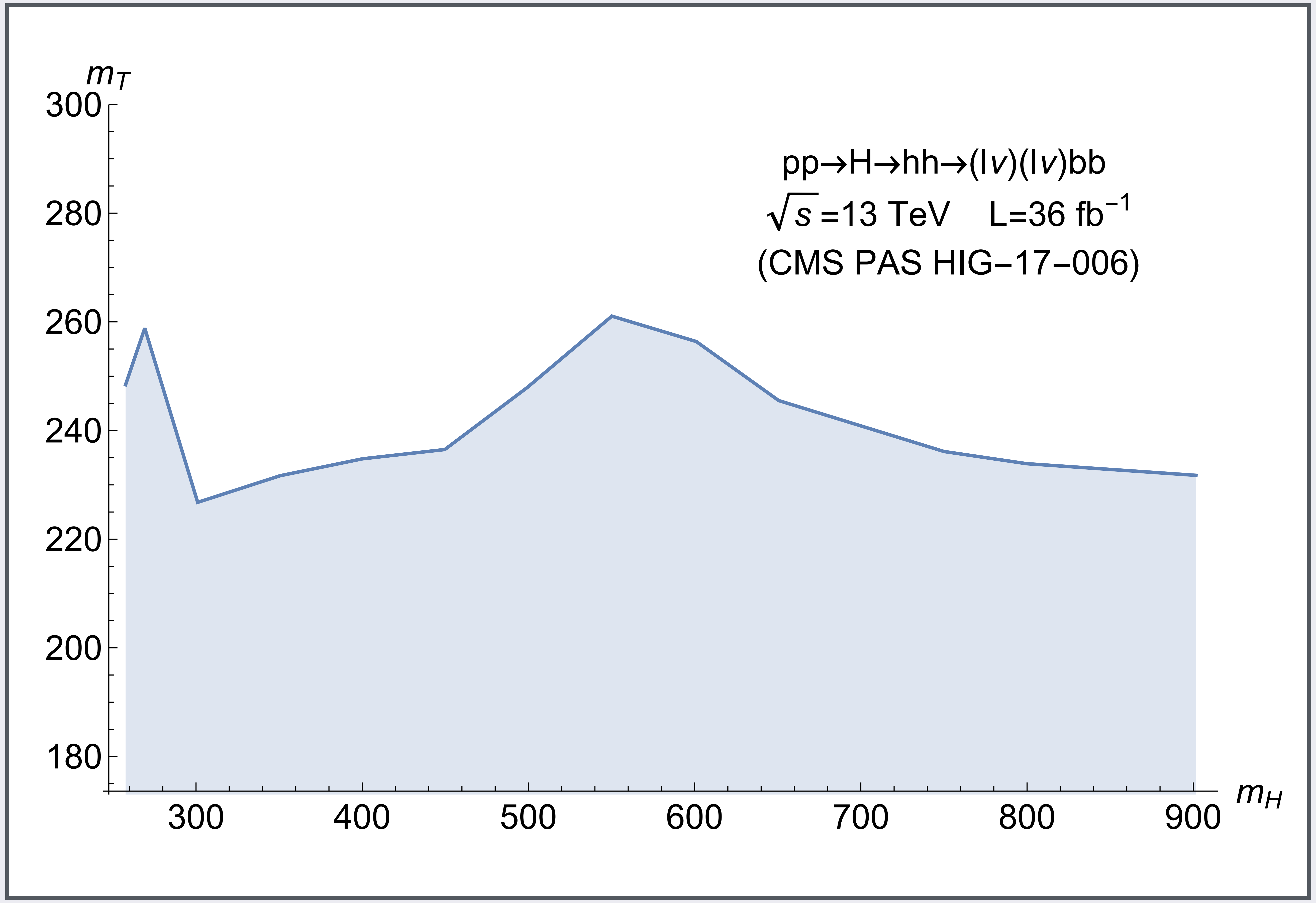
$$+ m^2 \left(H_A^\dagger H_A - H_B^\dagger H_B\right) + \delta \left[\left(H_A^\dagger H_A\right)^2 + \left(H_B^\dagger H_B\right)^2\right]$$

← Breaks $SU(4)$

- For stable vacuum, require $\dfrac{m_H}{m_h} \geq \dfrac{m_T}{m_t} = \cot \vartheta$
- The EW VEV and Higgs mass constrain the potential
- Measurements of Higgs coupling deviations and the mass of the radial mode determine the rest
- All rates are then predictions of the framework

LHC Heavy Higgs Searches

- The LHC has looked for heavy scalars, the best bound come from a CMS resonant di-Higgs search
  - Not nearly as powerful as LHC Higgs coupling probes
- Similar ATLAS search $ggF \to H \to hh \to WW\gamma\gamma$ (ATLAS-CONF-2016-071) gives a weaker bound and extrapolation to higher luminosity appears systematics dominated

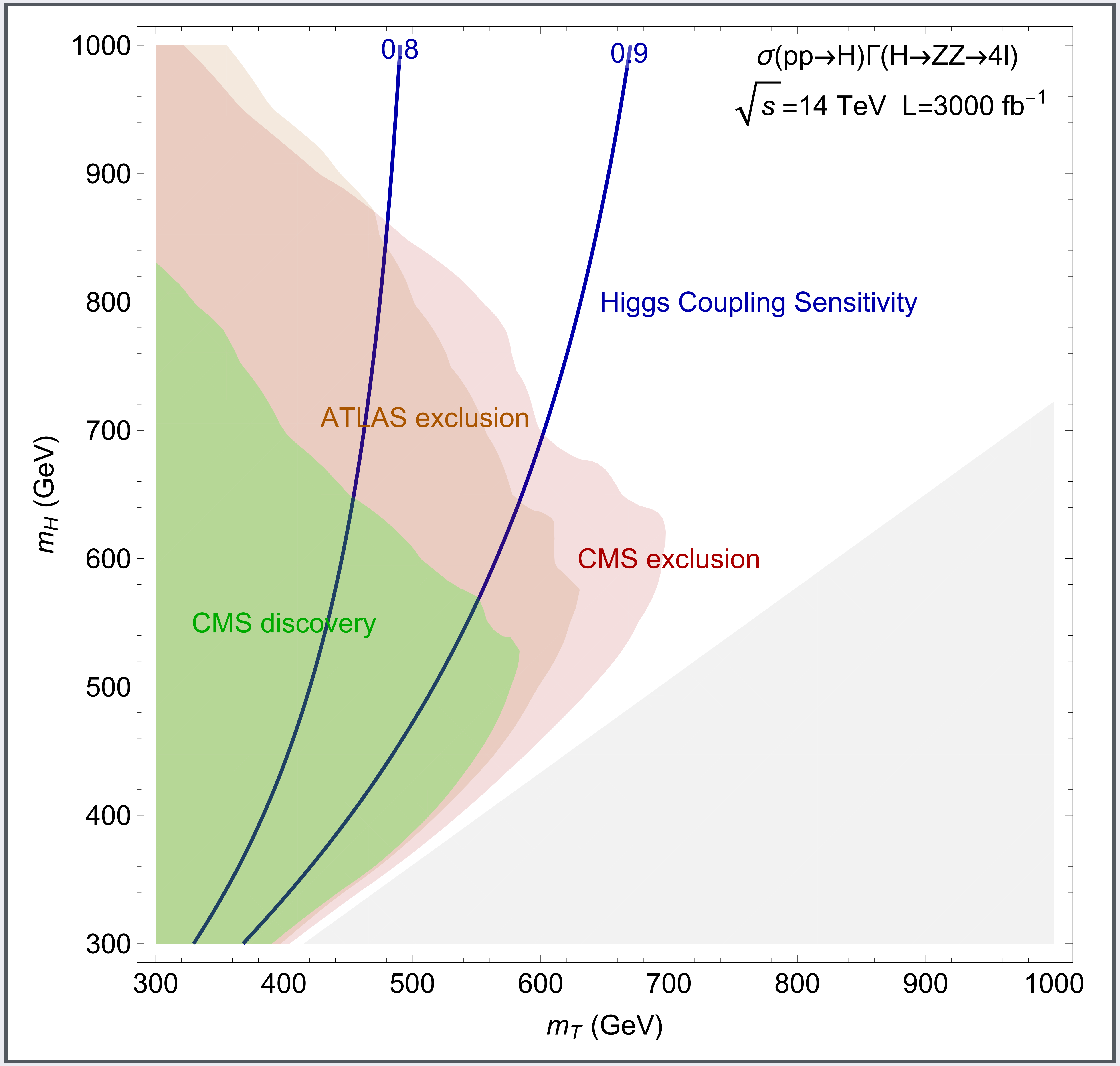


Projected LHC Reach with ZZ

- Using CMS-PAS-FTR-13-024 and ATL-PHYS-PUB-2013-016 we find the projected reach for $pp \to H \to ZZ \to \ell\ell\ell\ell$

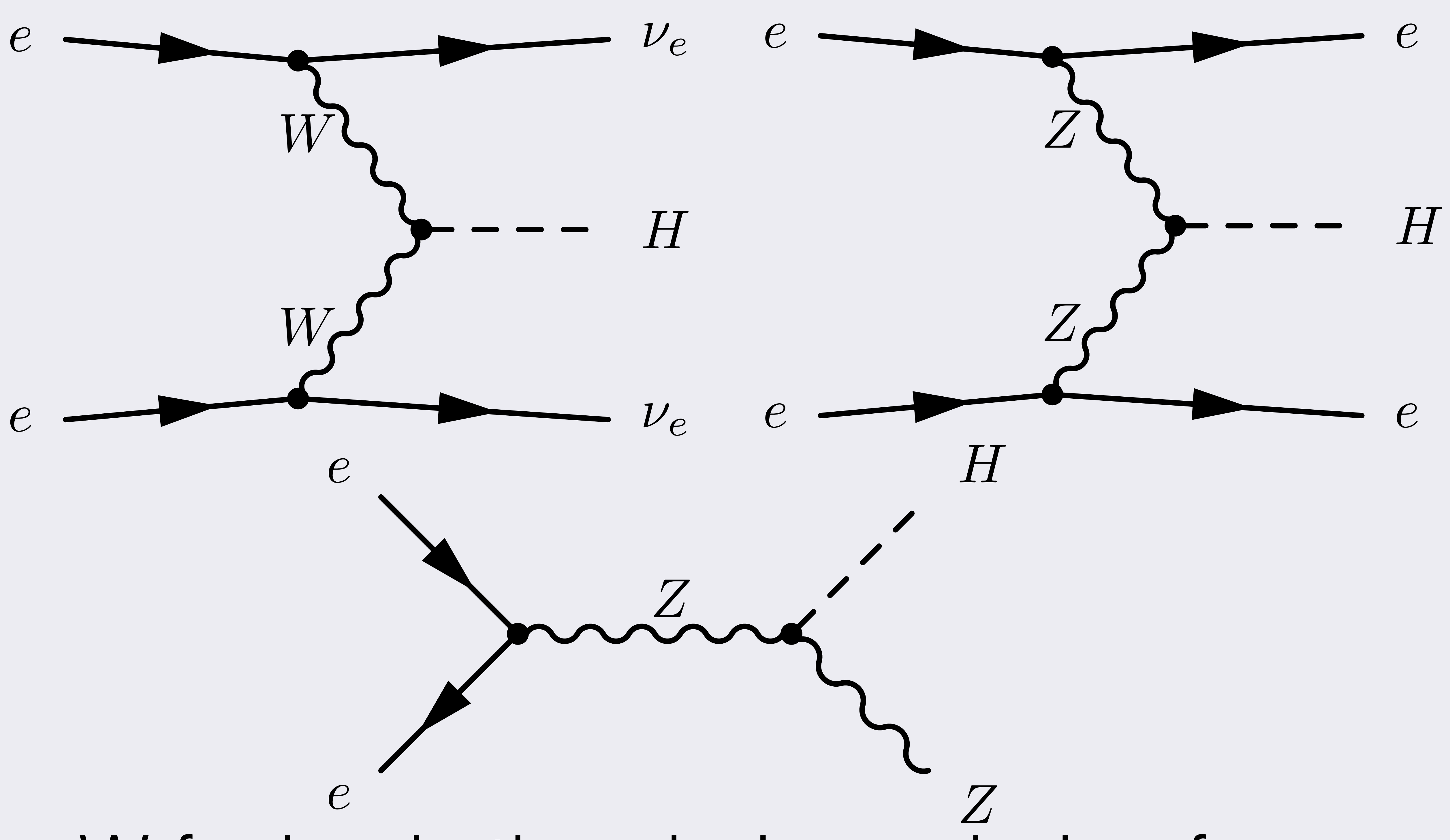
- Clearly, the LHC can test the Twin Higgs for some parameter regions

- How does a linear collider compare?



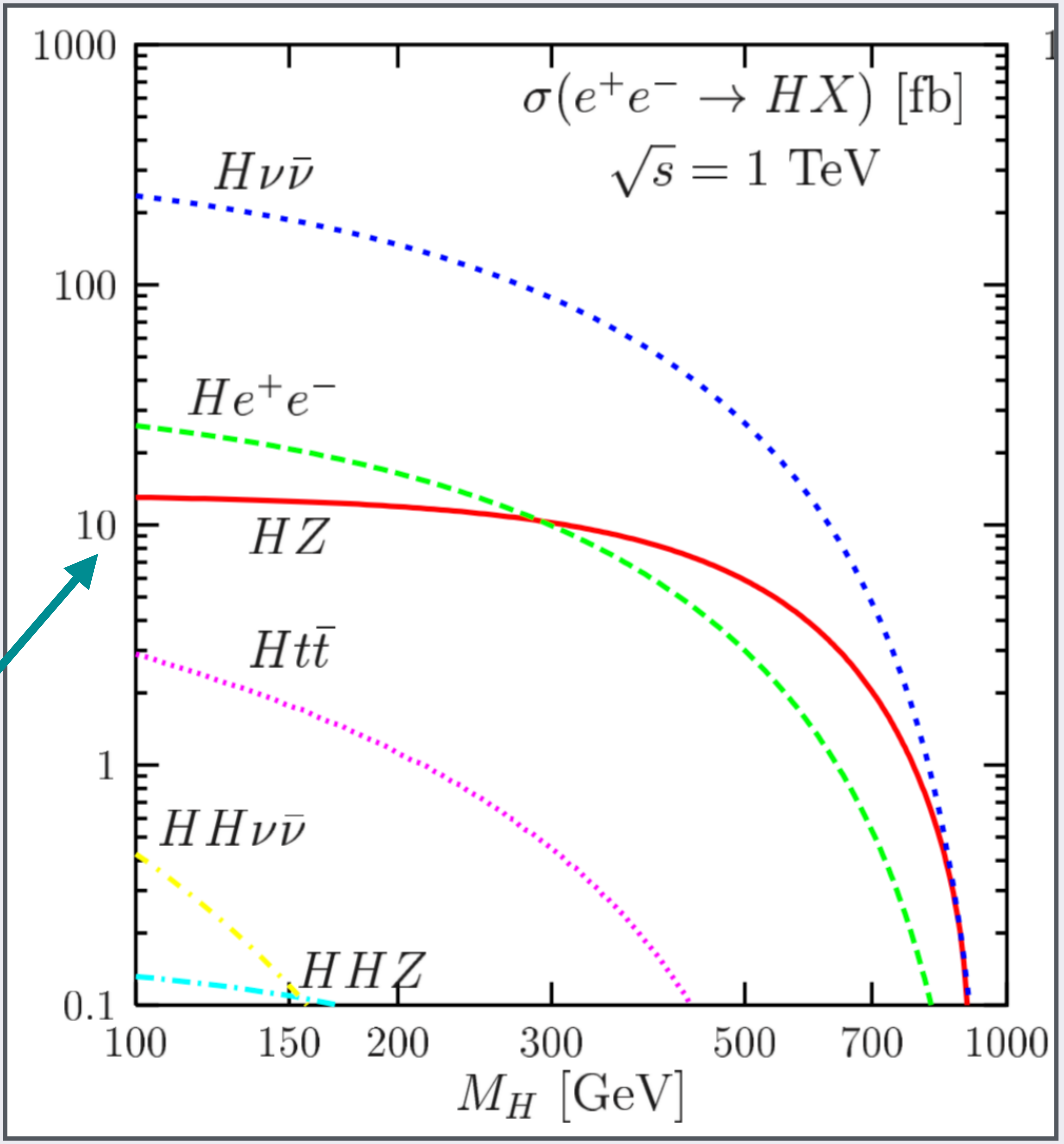
Producing the Twin Higgs

- W fusion, Z fusion, and associated production



- W fusion is the obvious choice for visible decays

Djouadi, hep-ph/0503172

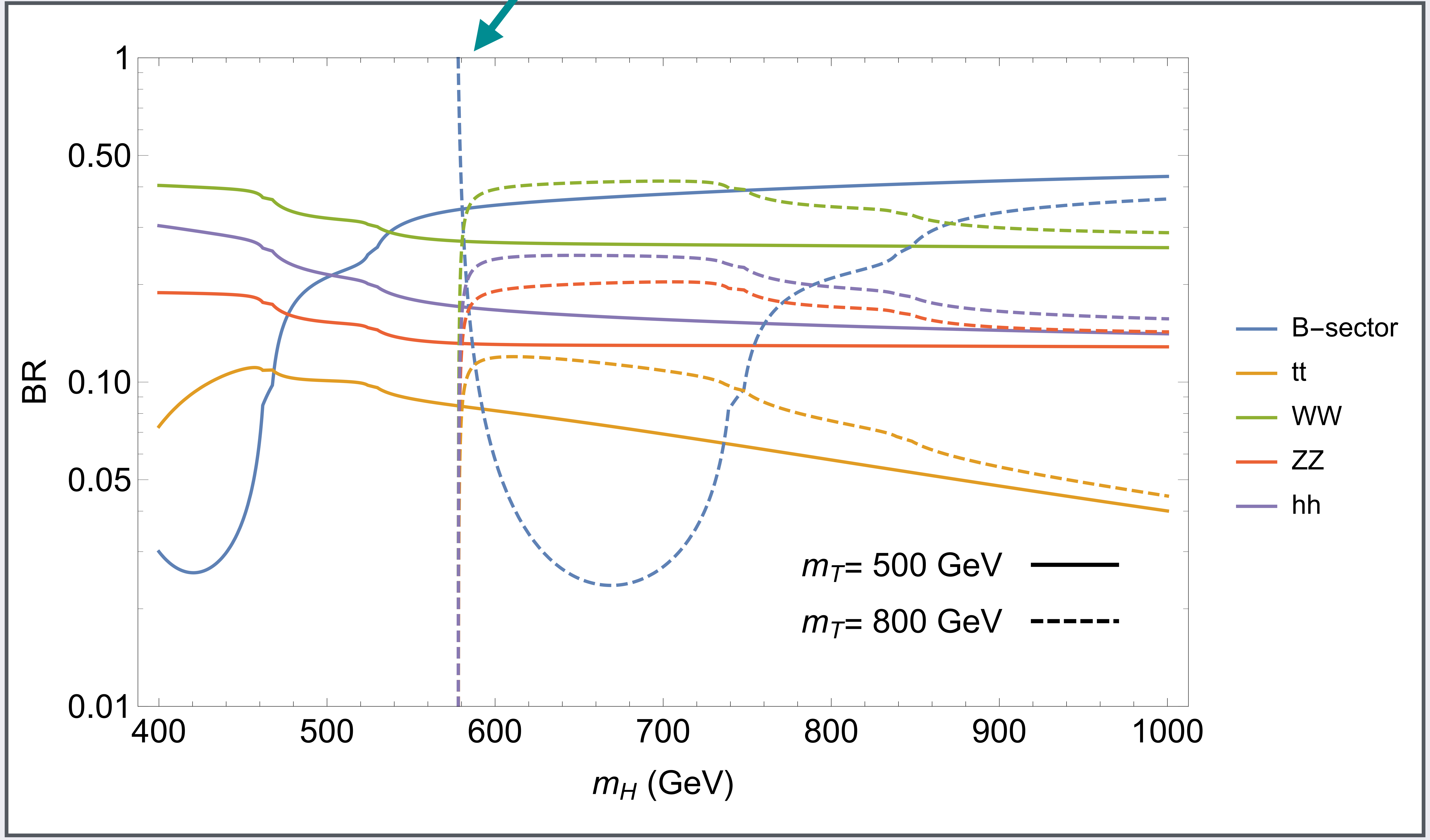


No suppression included!!

Twin Higgs Branching

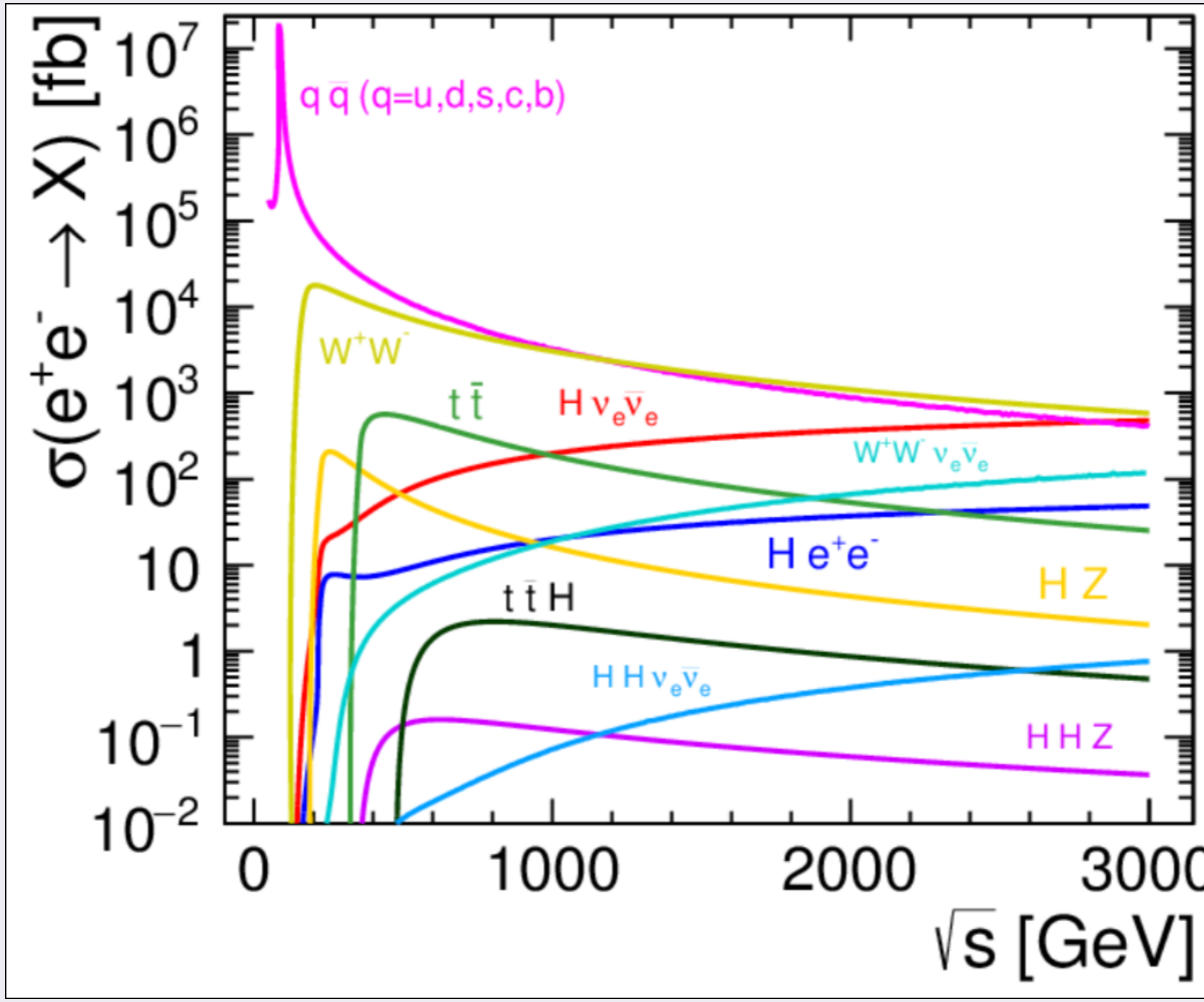
- Branching to EW bosons dominates
  - To the B sector when kinematically allowed
- For heavier twin tops, branching to visible is enhanced
- WW has largest ratio, followed by hh

Edge of stable vacuum



Resonant di-Higgs

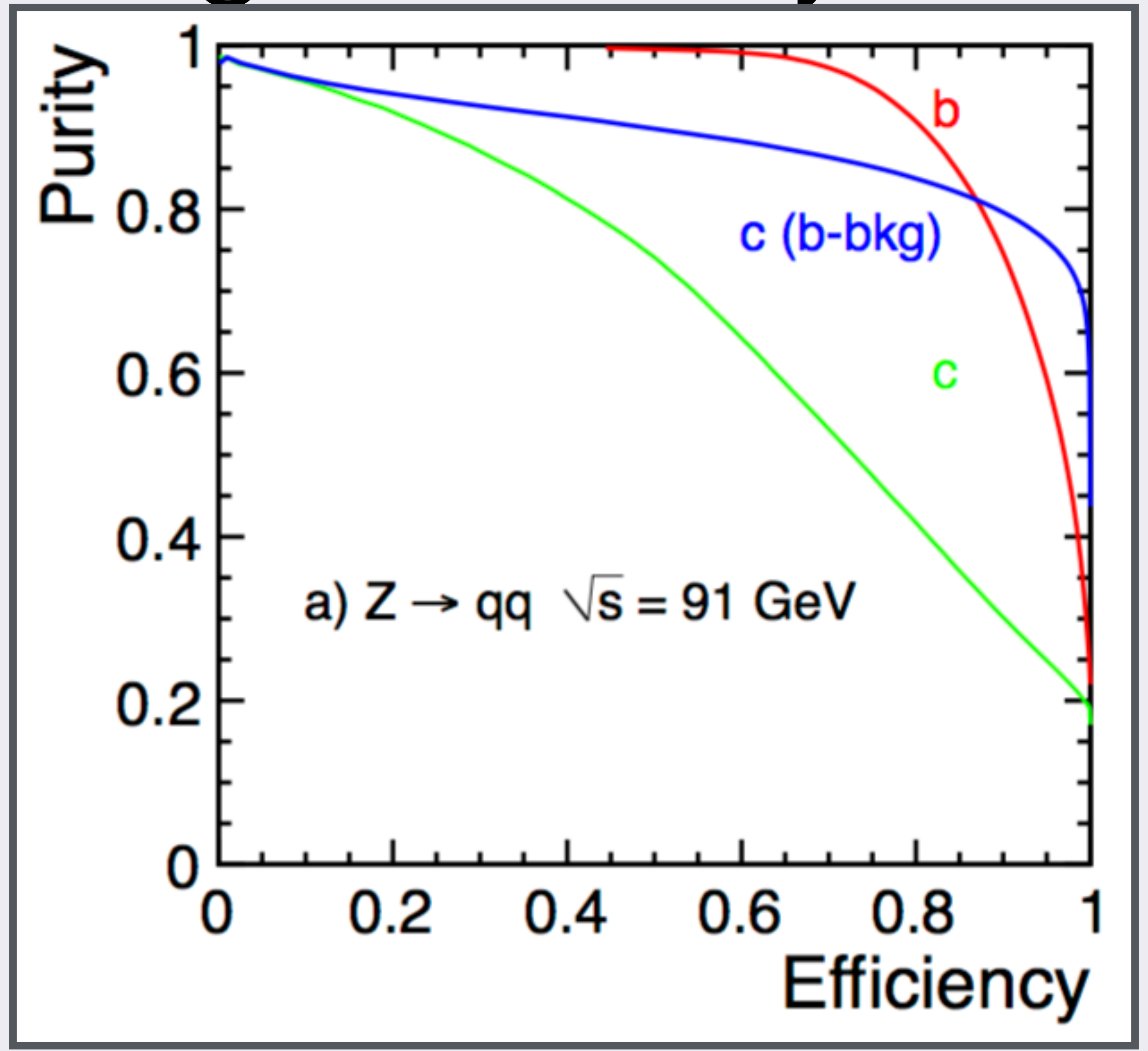
- While the WW rate is largest, the backgrounds overwhelm the signal
- The di-Higgs rate to 4 b's has much smaller background
  - Benefit of using a lepton collider!
- Simply cut the background by requiring the 4 b's reconstruct 2 Higgses
- Require 3 b-tags

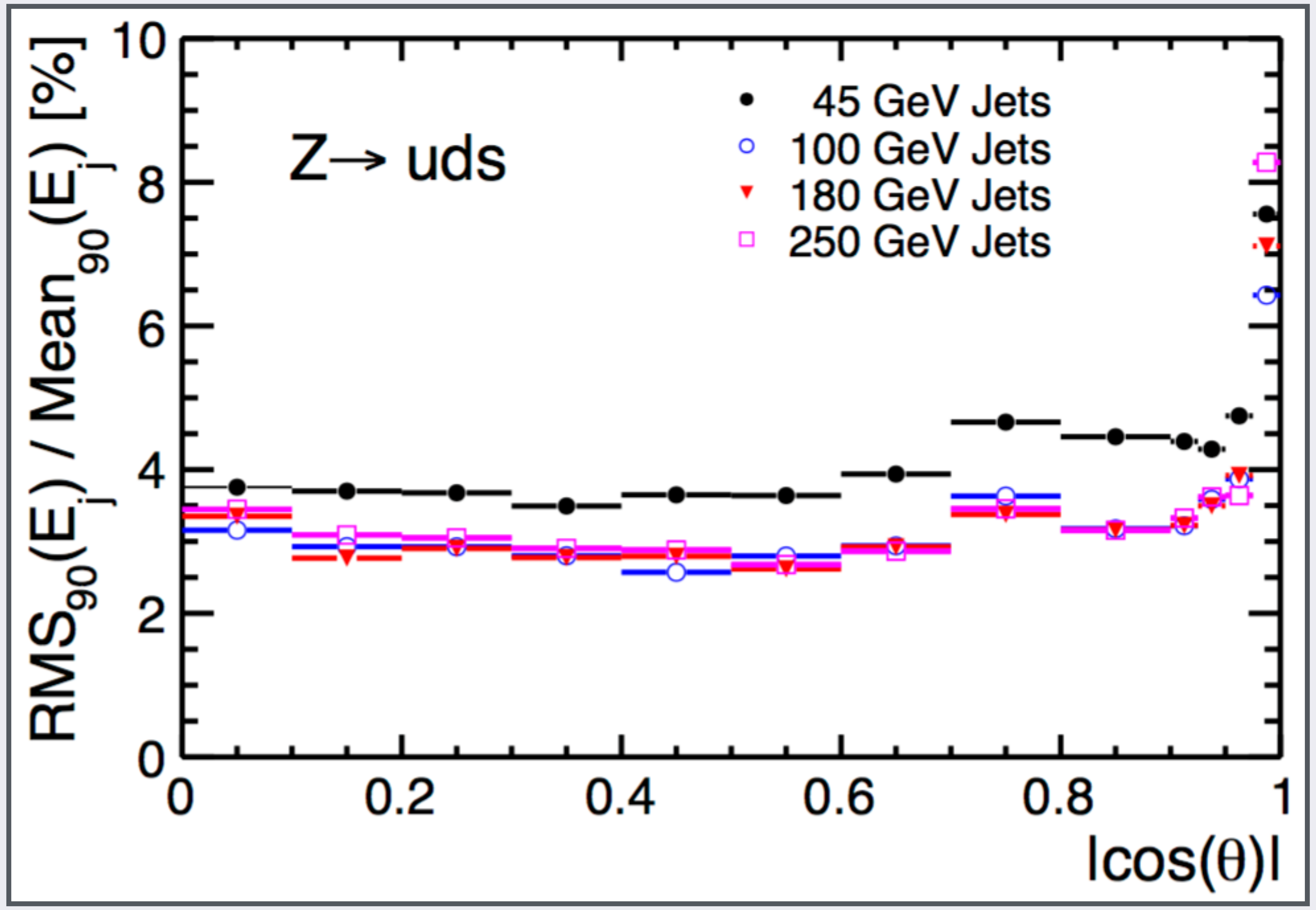


Stolen from Alexander Mitov's talk

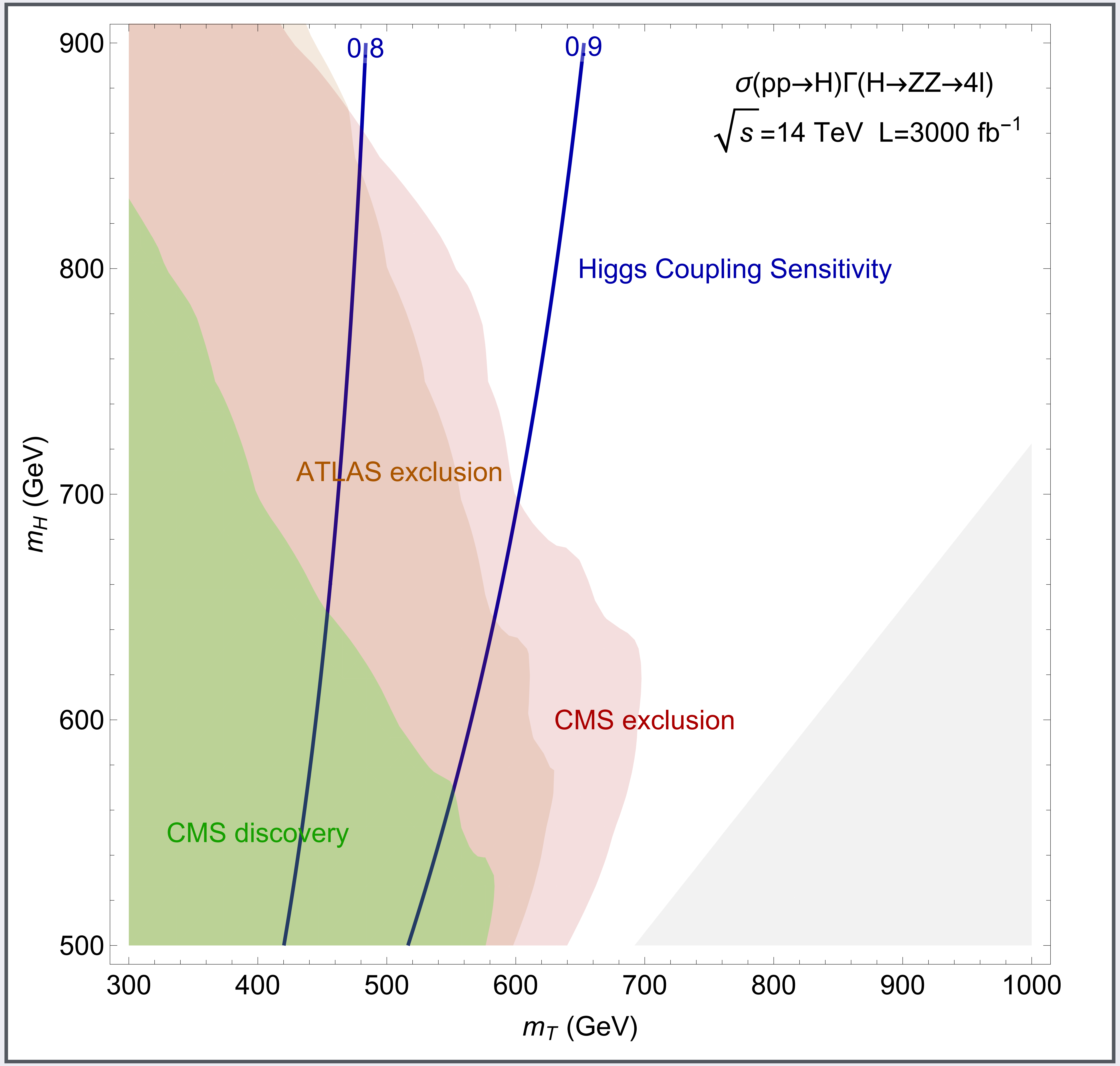
Detector Issues

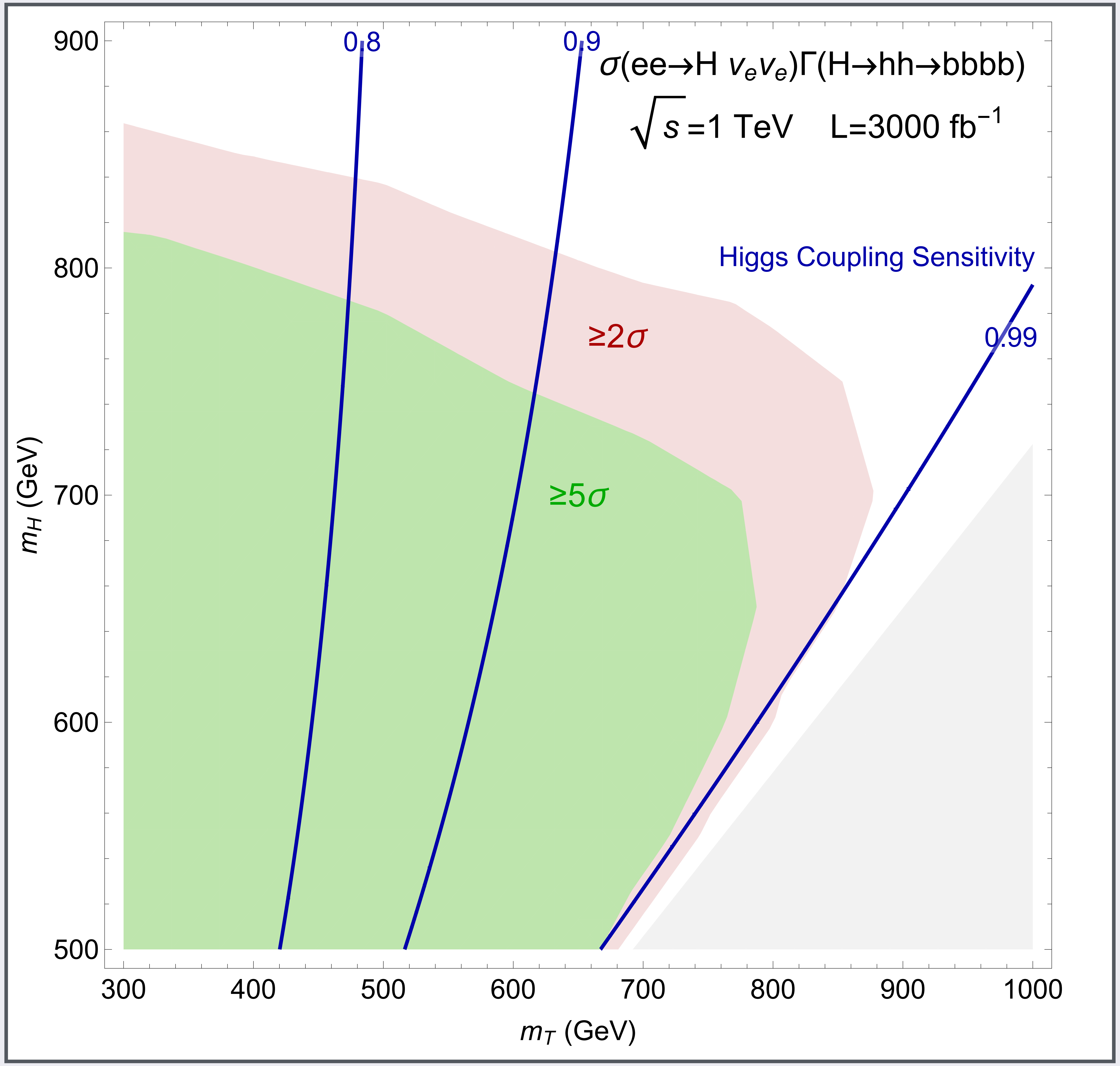
- Use The International Linear Collider Technical Design Report: Vol.4 1306.6329
- Lepton energy resolution $\left(1.1 \oplus \frac{16.6}{\sqrt{E\,(\mathrm{GeV})}}\right)\%$
- Jet energy resolution ~ 3%
- b-tag efficiency ~ 70%





Mass Measurement Comparison





Testing the Twin Higgs

- There are regions in which the LHC and CLIC both can measure Higgs coupling deviations and the mass of the Twin Higgs
  - Heavy Higgs mass is comparable, CLIC generally reaches heavier twin top masses
  - Thus, CLIC gives more complete coverage to natural parameter space
- These two measurements, along with the Higgs mass and EW VEV completely specify the potential parameters
- The total di-Higgs rate is then a prediction of the Twin Higgs framework

Can we do more?

- In this scenario we measure the mass from the di-Higgs signal and the rate into di-Higgs

- We have examined the WW channel and found small excesses

  - These reinforce the explanation, but are not convincing on their own

- Measuring the rate of Twin Higgs to invisible would be much more compelling, signaling the rich hidden sector (Perhaps Ideas from Pedro S. and Michael R. can help…)

- Cannot use W fusion for this channel, associated production does not seem to have large enough cross section relative to backgrounds

Conclusions and Continuations

- The LHC will not be the last word on naturalness
- The precision of a linear lepton collider can detect the irreducible Higgs coupling deviations of many natural Twin Higgs models
- Both the LHC and a linear collider can potentially confirm the Twin Higgs mechanism, but a CLIC like machine provides greater coverage
    - Higher energy machines can probe naturalness more completely
- Still looking into how to determine the invisible Twin Higgs width