Neutral Naturalness

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1st FCC Physics Workshop

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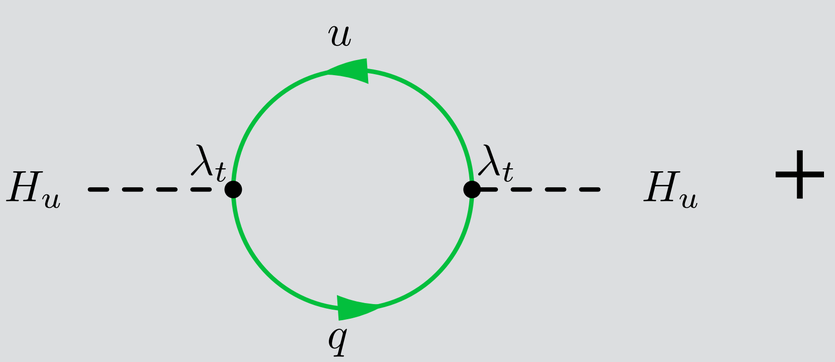
$Q|MAP\rangle$

Naturalness from Symmetry

- The Standard Model successfully accounts for <u>nearly</u> all microphysical phenomena
- If the SM is an EFT, why is the Higgs so light?
- Symmetries may protect the Higgs from large mass corrections
  - Predict symmetry partner fields, usually colored



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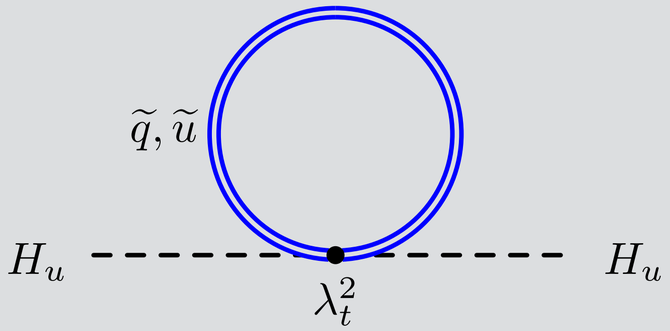


Colorless Top Partners

- One can consider a space of possible top partner gauge charges
- I'll briefly introduce you to the poster children of neutral naturalness
- Then, we'll see how FCCs can be used to discover them

	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

- Make a ‘twin’ copy of the entire SM
- Assume a $SU(4)$ symmetric Higgs field
- Gauge two $SU(2)$ subgroups $\quad H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$
- The A sector is associated with SM, the B sector is BSM
  - Exchange symmetry equates A and B gauge couplings

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

Twin Higgs

- 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 contribution

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

- The exchange symmetry is enough to make a $SU(4)$ invariant

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

- Cannot give mass to the pNGB

Quirky Little Higgs

Cai, Cheng, Terning, 0812.0843

- In QLH, we have $H = \begin{pmatrix} H_A \\ \Phi \end{pmatrix} \Big\downarrow \mathrm{SU}(3)_W$
- The quarks are $Q = \begin{pmatrix} \overrightarrow{\mathrm{SU}(6)} \\ q_L \quad Q_L \\ \chi \quad T \end{pmatrix} \Big\downarrow \mathrm{SU}(3)_W \quad U = \begin{pmatrix} \overrightarrow{\mathrm{SU}(6)} \\ t_R \quad T^c \end{pmatrix}$
- Now, the cancelation happens twice, with the participants charged under two different color groups.
- Now, we project out χ and Q_L from the low energy theory $Q = \begin{pmatrix} \overrightarrow{\mathrm{SU}(6)} \\ q_L \quad \cancel{Q_L} \\ \cancel{\chi} \quad T \end{pmatrix} \Big\downarrow \mathrm{SU}(3)_W$
- One cancellation with color neutral, but hypercharged partner

Folded SUSY

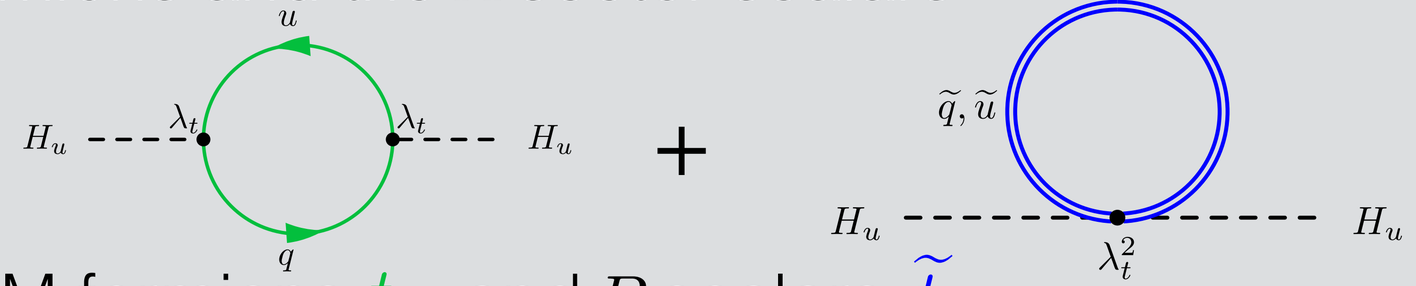
Burdman, Chacko, Goh, Harnik, hep-ph/0609152.

- Double the MSSM matter content and assume exchange symmetry
  - As in QLH the cancellation of divergences happens twice
- Have schematic multiplets

$$\begin{pmatrix} t_A & t_B \\ \widetilde{t}_A & \widetilde{t}_B \end{pmatrix} \xrightarrow{\mathrm{SU}(3)\times\mathrm{SU}(3)} \Big\downarrow \text{SUSY}$$

- Project out the B sector fermions and the A sector scalars

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



- Cancellation occurs with SM fermions t_A and B scalars $\widetilde{t}_B$

Commonalities

- Solve the ‘Little Hierarchy’ Problem
  - Low Cutoff $\lesssim$ 10 TeV
- Hidden $SU(3)$ gauge group needed to match SM color
- New states are tied to the Higgs
  - That’s what it means to be a top partner

Neutral Naturalness at FCCs

- Higgs coupling deviations
  - Tree level vs. loop level
- Probing the UV completion (See Dario's talk for Higgs sector searches)
- Exotic Higgs Decays
- Direct top partner production
  - Higgs Portal
  - Drell-Yan for EW charged partners

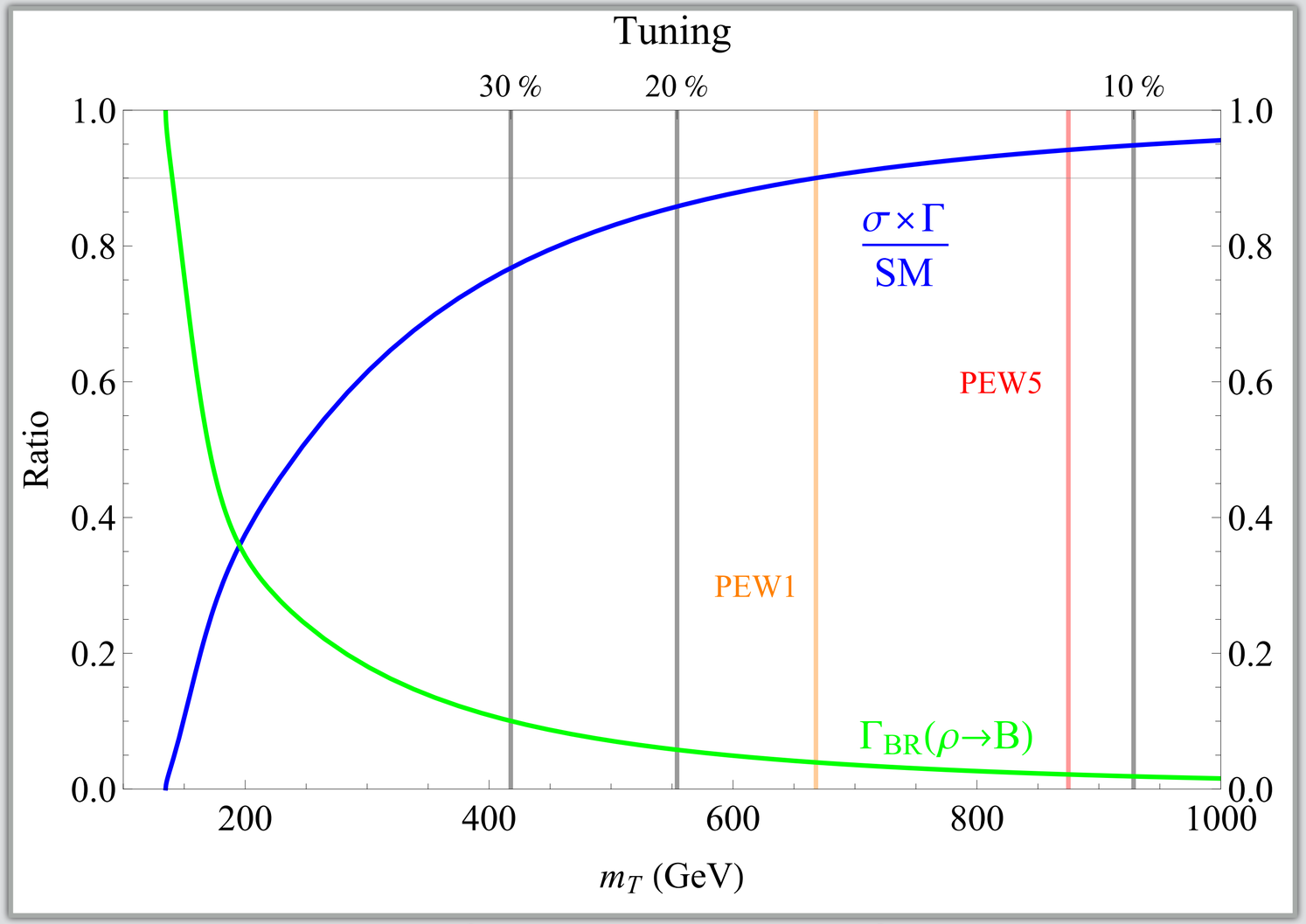
Higgs Couplings

- pNGB Higgs models, like Twin Higgs and Quirky Little Higgs, have modified tree level couplings

$$g = g_{\mathrm{SM}} \cos\left(v/f\right)$$

- FCC-ee can push limits to ~few TeV

- Scalar top partners…less constrained



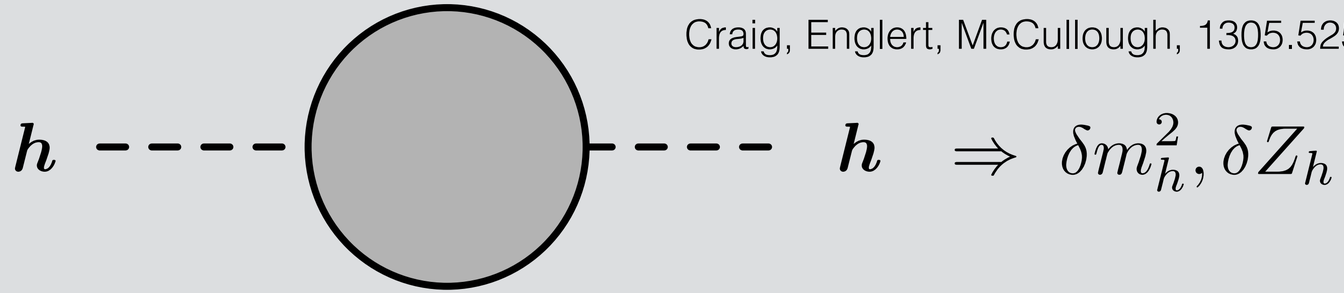
Burdman, Chacko, Harnik, de Lima, CV 1411.3310

Higgs Couplings at FCC

- Even a completely SM neutral top partner from a non-pNGB mechanism leaves its mark on the Higgs (the ??? model)

- Corrections to mass also affect the kinetic term

Craig, Englert, McCullough, 1305.5251



- These loops induce shifts in the Higgs couplings

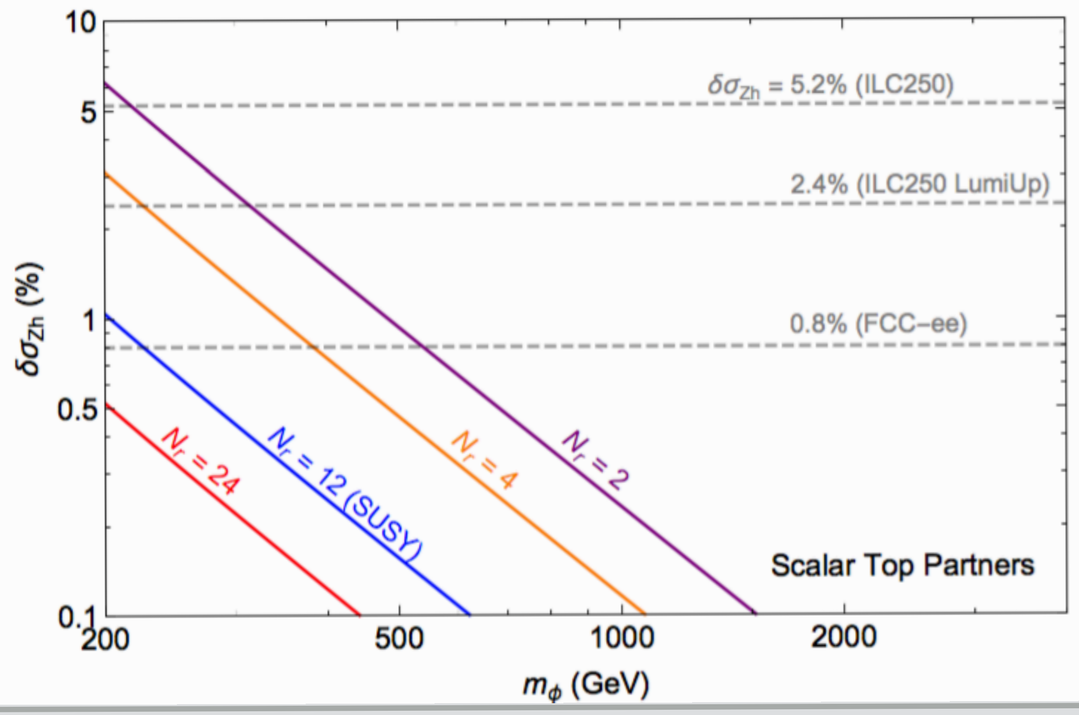
- Can probe σ_{Zh} at FCC-ee and σ_{hh} at FCC-hh

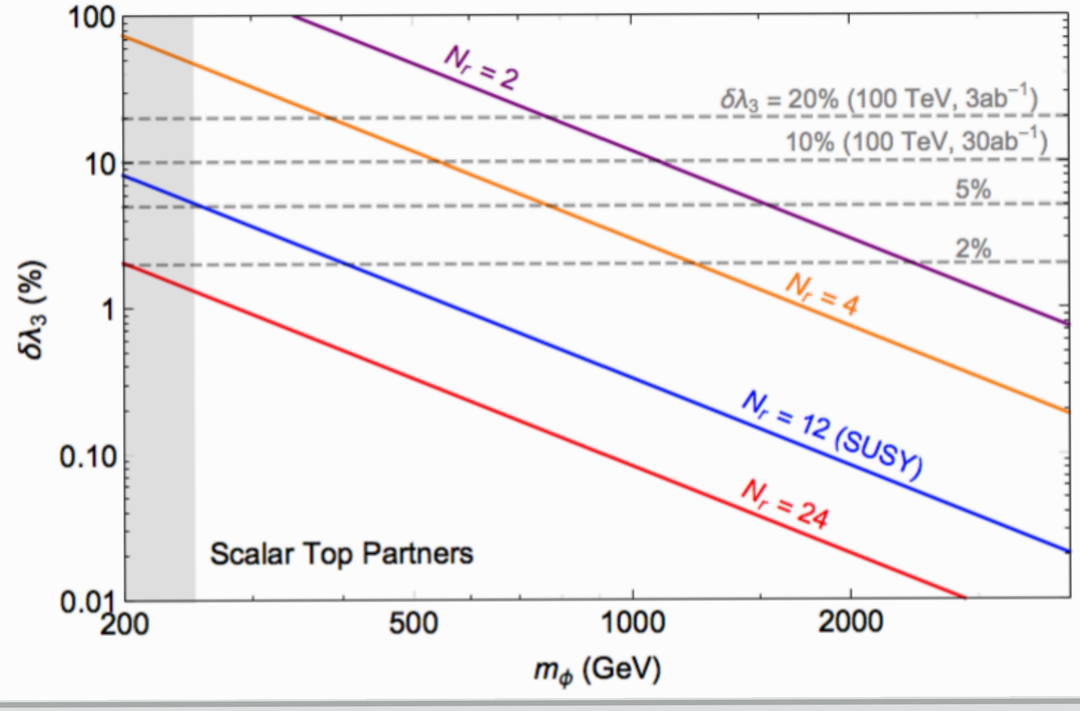
FCC Coupling Results

- The sensitivity of the searches depends on the mass of the top partner and the number of top partners

- Can these probes by strengthened? (FCC-eh to help?)

Curtin, Saraswat, 1509.04284





Probing the UV

- Models address the Little Hierarchy
- Cutoff ~ 10 TeV or less for most natural realizations
- UV completions have colored states
  - Often have states charged under SM and hidden color
- These heavy (~ TeV) colored states can be produced at FCC-hh

Twin Higgs UV Studies

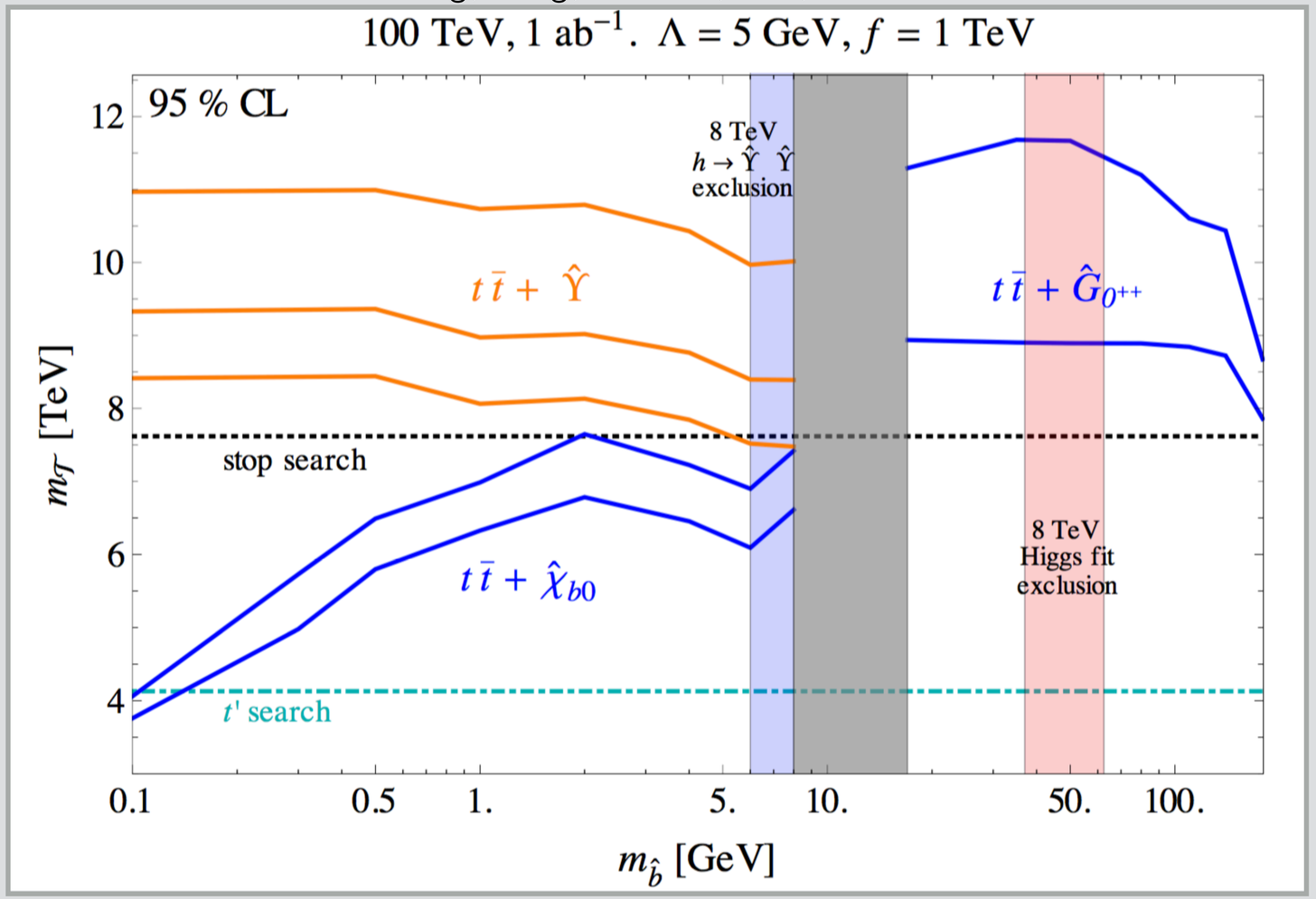
- In the context of the ‘Fraternal’ Twin Higgs

Craig, Katz, Strassler, Sundrum, 1501.05310

  - Only twin third generation, no light hidden states

- Prime signal is $t\bar{t}$ plus a displaced vertex

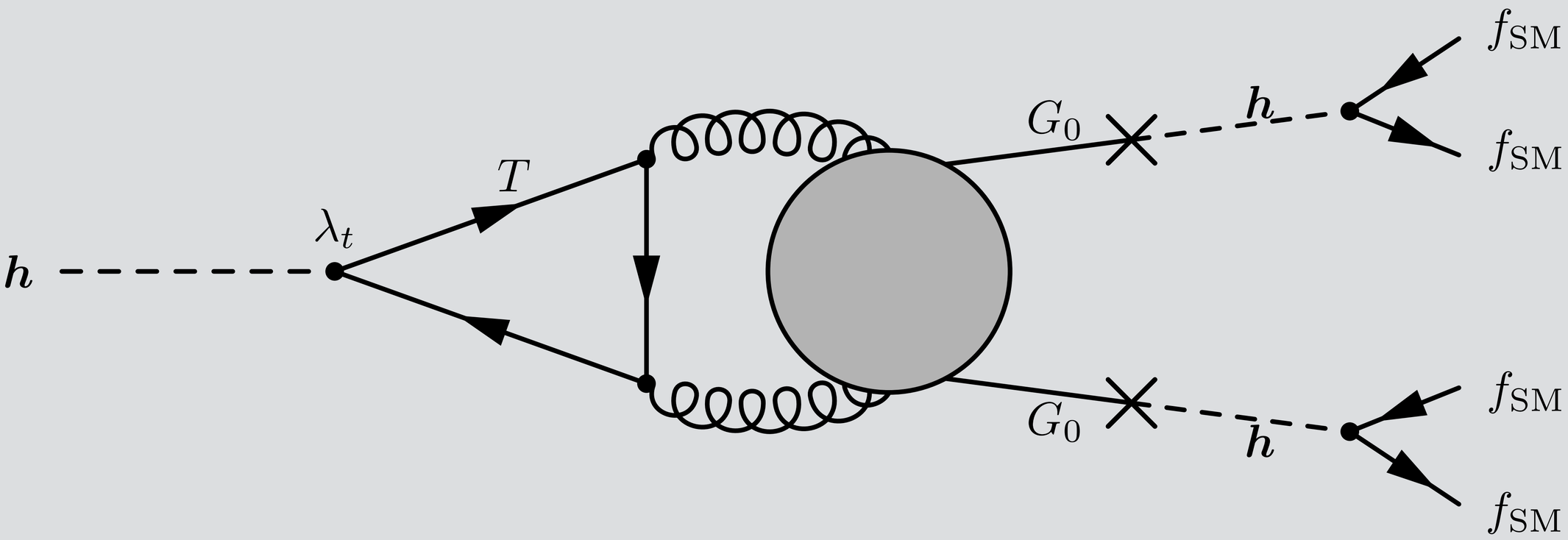
Cheng, Jung, Salvioni, Tsai, 1512.02647



$$pp \to (\mathcal{T} \to tZ_B)(\overline{\mathcal{T}} \to \bar{t}Z_B) \to t\bar{t} + (\text{twin Hadron} \to \text{Displaced Vertex})$$

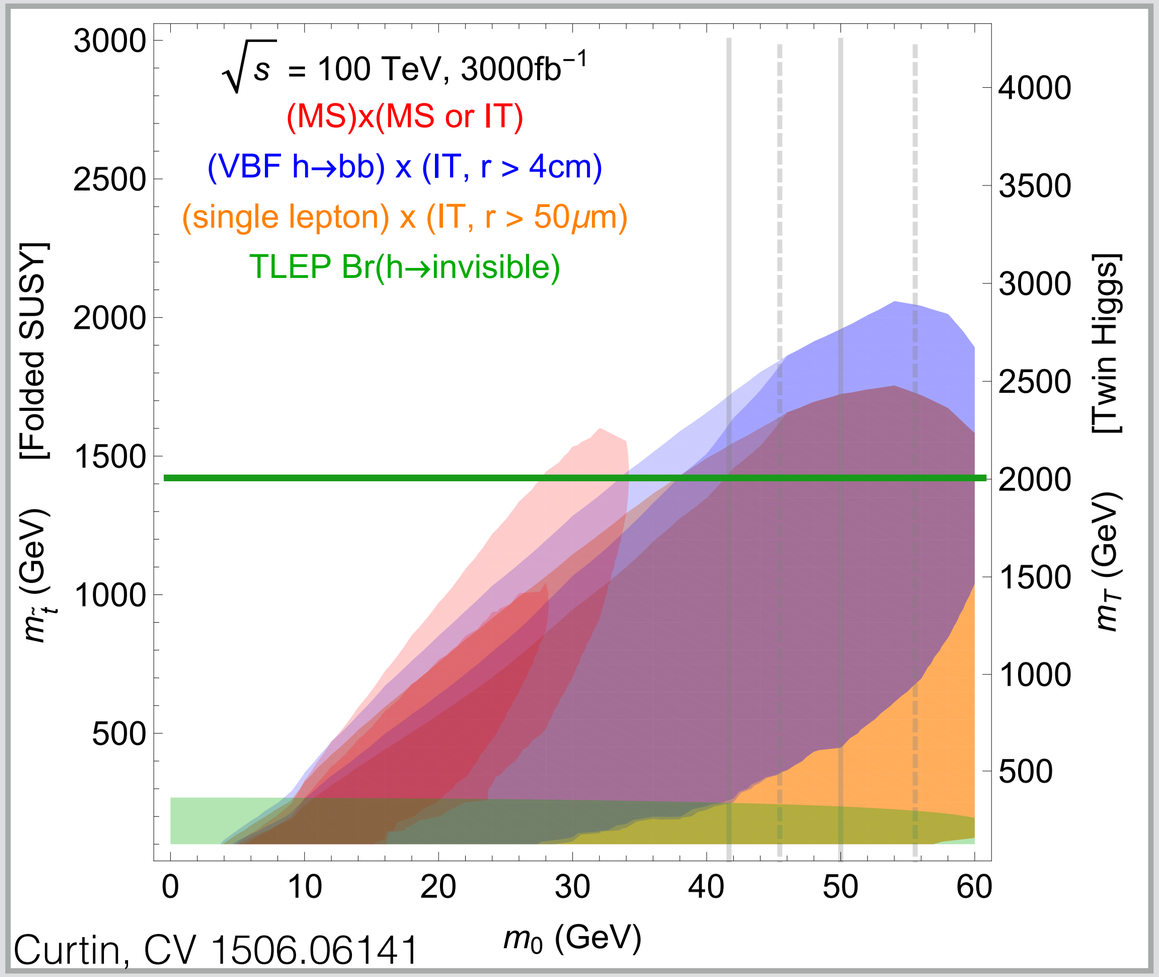
Exotic Higgs Decays

- Occurs whenever the hidden sector does not have light states
  - Guaranteed for EW charged top partners, can occur in Fraternal TH
- Displaced decays on detector length scales



Exotic Higgs Decay Searches

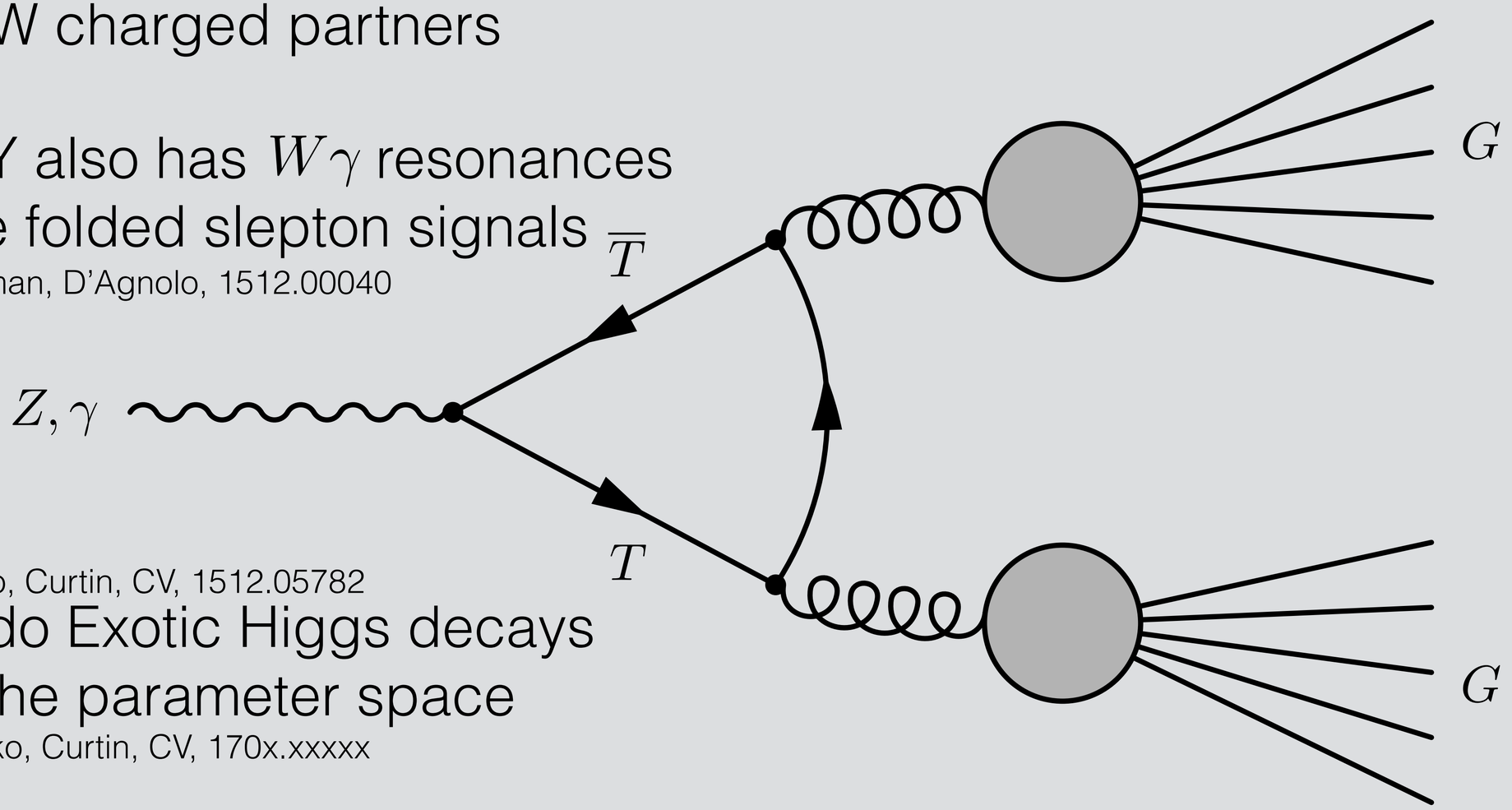
- Reaches into the TeV range of top partner masses!
- Complementarity with FCC-ee Higgs to invisible measurements of the total Higgs to gluballs width
  - And pNGB Higgs couplings
- Assumes current trigger thresholds for displaced vertices



Top Partner Production

- Higgs Portal guaranteed
- Drell-Yan for EW charged partners
  - Folded SUSY also has $W\gamma$ resonances and possible folded slepton signals

    Burdman, D'Agnolo, 1512.00040



  - Likely to outdo Exotic Higgs decays for some of the parameter space

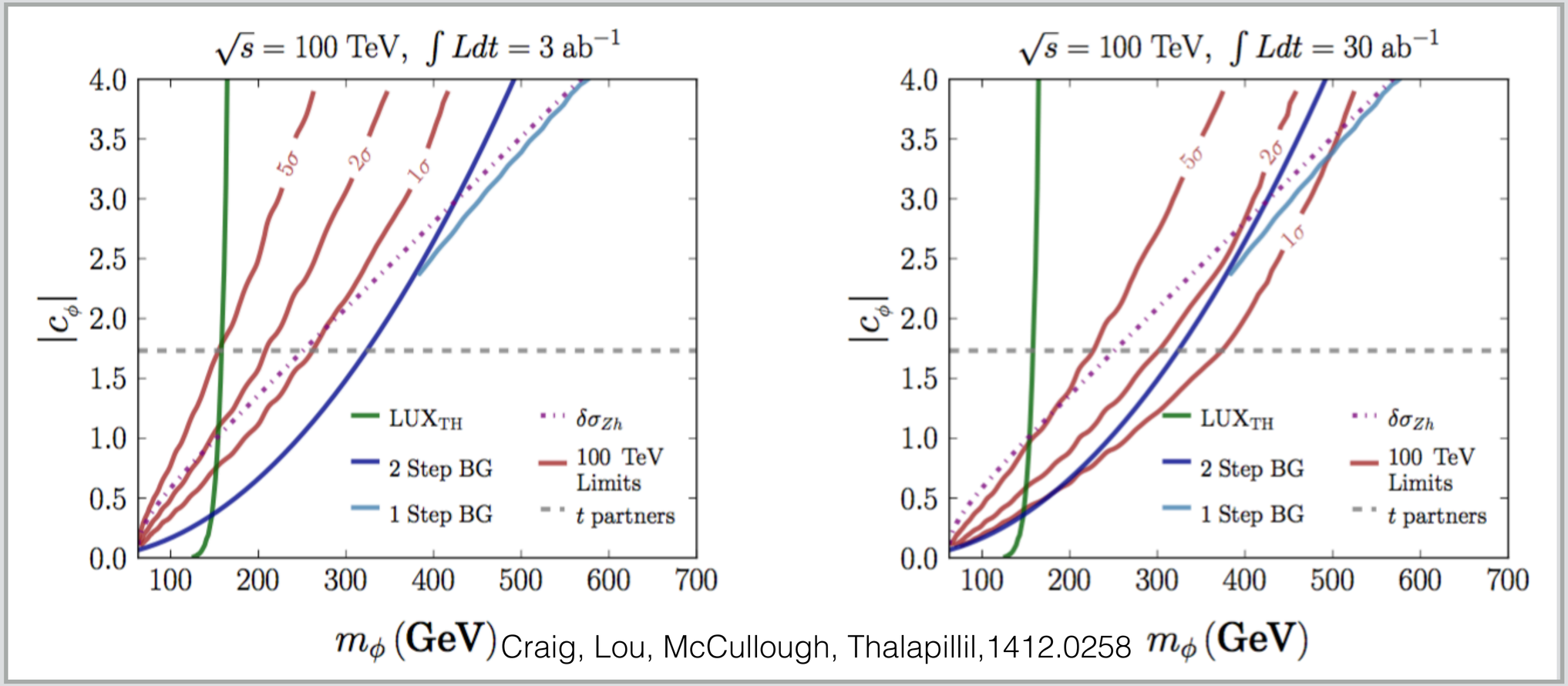
    Chacko, Curtin, CV, 1512.05782

    Chacko, Curtin, CV, 170x.xxxxx

Higgs Portal at FCC

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

- Assuming no Exotic Higgs decays



Craig, Lou, McCullough, Thalapillil,1412.0258

Complementarity

- FCC-ee
  - Tree level Higgs couplings (pNGB Higgs models)
  - Loop level σ_{Zh} (All, best for SM neutral non-pNGB)
- FCC-hh
  - Direct EW production (EW charged)
  - Direct Higgs portal production (All, best for SM neutral)
  - Exotic Higgs Decays (No light states)
  - Higgs Self coupling (All, best for scalar top partners, depends on number)
  - UV states (All known)

Conclusion

- Symmetry based solutions to the hierarchy problem with color neutral top partners will **not** be fully probed at the LHC
- Thorough experimental explorations of neutral naturalness require both FCC-ee and FCC-hh machines
- Even the most hidden models can be meaningfully probed by the combination of these experiments (up to ~300 GeV, can we do better?)
  - Displaced signals are ubiquitous and powerful
- To Do: Find concrete models of a SM neutral scalar top partner and Folded SUSY UV completion and update searches with better detectors