

Non-SUSY BSM Theory

Markus Luty
UC Davis

Introduction

Reasons to believe in new physics accessible to LHC:

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Independent of SUSY!

"The SUSY train is late."
— G. Altarelli, 2001

Naturalness

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- “Naturalness” is the requirement that m_h is not the result of a large unexplained cancelation.

$$\begin{aligned} m_h^2 &= 44848354663004959003564458711382292 \text{ GeV}^2 \\ &\quad - 44848354663004959003564458711366667 \text{ GeV}^2 \\ &= (125 \text{ GeV})^2 \end{aligned}$$

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Example: $m_{\tilde{t}} \sim 100 \text{ TeV}$

\Rightarrow threshold correction $\Delta m_h^2 \sim 10^5 \times (125 \text{ GeV})^2$

Is Naturalness Physical?

S. Chang, ML, unpublished

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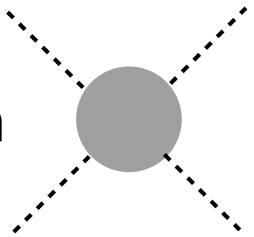
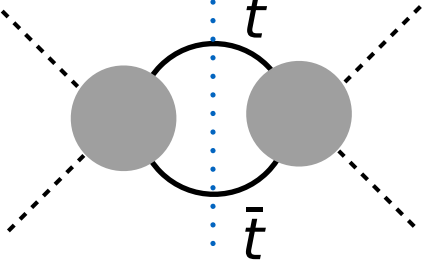
Compute loop effects in terms of observable quantities
⇒ no quadratic dependence on heavy masses.

Is Naturalness Physical?

Example: loop corrections to $hh \rightarrow hh$

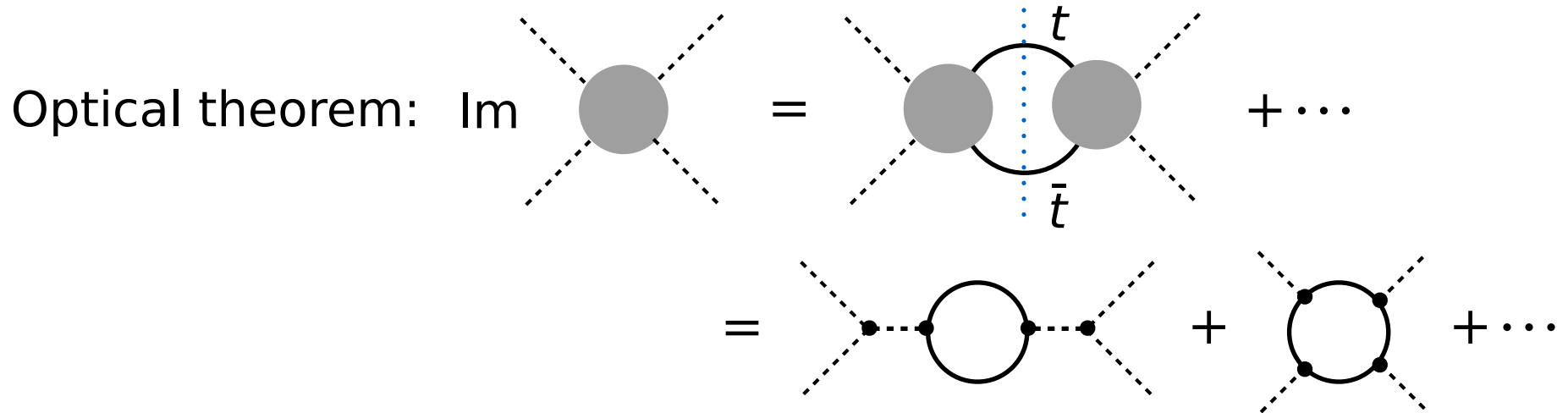
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Optical theorem: Im  =  + ...

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$\sim \frac{y_t^2 m_h^2}{s}$

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$$= \text{[Tree-level vertex with top quark loop]} + \dots$$
$$= \underbrace{\text{[Bubble diagram with top quark loop]}}_{\sim \frac{y_t^2 m_h^2}{s}} + \underbrace{\text{[Bubble diagram with Higgs boson loop]}}_{\sim y_t^4} + \dots$$

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Optical theorem: Im

$$= \text{Im} \left[\text{Tree-level vertex} \right] = \text{Im} \left[\text{Top quark loop} + \dots \right]$$

$$= \underbrace{\text{Bubble diagram with } H_h \text{ lines}}_{\sim \frac{y_t^2 m_h^2}{s}} + \underbrace{\text{Bubble diagram with } t \text{ lines}}_{\sim y_t^4} + \dots$$

Use to compute loop corrections to $hh \rightarrow hh$:

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Use to compute loop corrections to $hh \rightarrow hh$:

$$t \rightarrow 0 : \quad \mathcal{A}(s) = \frac{1}{\pi} \int_0^\infty ds' \frac{\text{Im} \mathcal{A}(s')}{s' - s} = \log \text{ UV divergent}$$

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\Rightarrow can write once-subtracted dispersion relation

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My conclusion: think harder!

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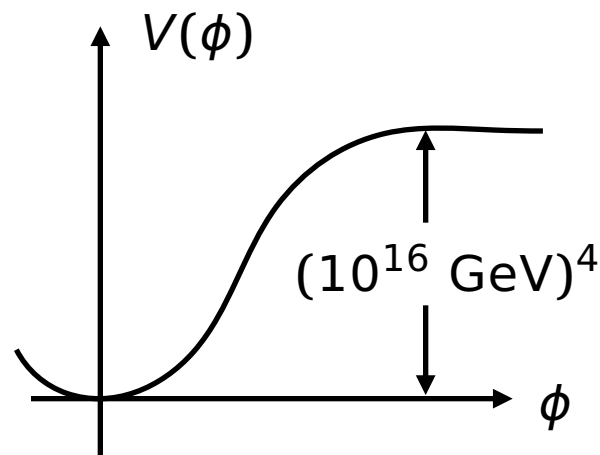
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The strongest evidence for new physics at high scales is tensor modes observed by BICEP2.*

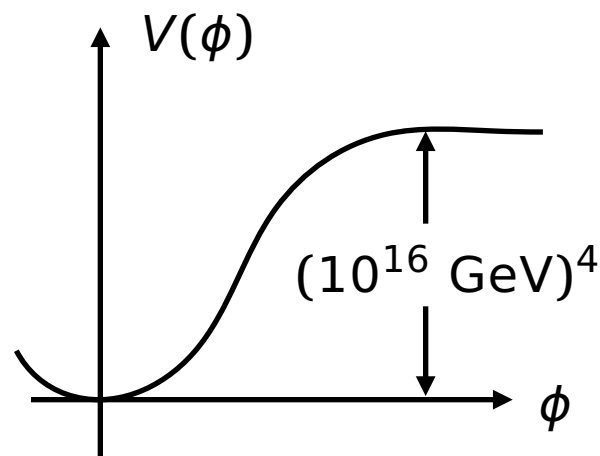


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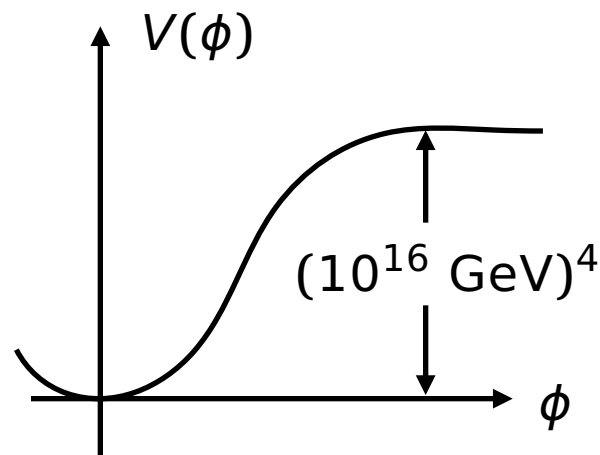
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Gauge unification, ν masses, flavor, ... have *simplest* explanation in terms of physics at scales \gg TeV.

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Implications of Naturalness

Naturalness requires a mechanism to prevent physics at high scales from contributing to m_h^2 .

$$\Delta m_h^2 = \text{---}\diagup\text{---}\bullet\text{---}\bigcirc\text{---}\bullet\text{---}\diagdown\text{---} \sim \frac{\lambda^2 m_X^2}{16\pi^2}$$

The diagram shows a circular loop with an 'X' above it. Dashed lines with arrows indicate external interactions at two points on the circle.

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A diagrammatic representation of a one-loop correction to the Higgs mass. It shows a central circle with a dot at each end, connected to dashed lines extending outwards. Above the circle is the letter 'X'. The circle represents a loop of X particles.

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X \tilde{X}

$$\text{Compositeness: } \Delta m_h^2 = \text{---} \bullet \text{---} \bigcirc \text{---} \bullet \text{---} \text{---} \sim \frac{\lambda \Lambda^2}{16\pi^2}$$

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$\Lambda =$ scale of form factors

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Motivates $\Lambda \sim \text{TeV}$

Compositeness

$$m_h = 125 \text{ GeV}$$

$$\frac{g_{hVV}}{g_{hVV}^{(SM)}} = 1 + O(10\%)$$

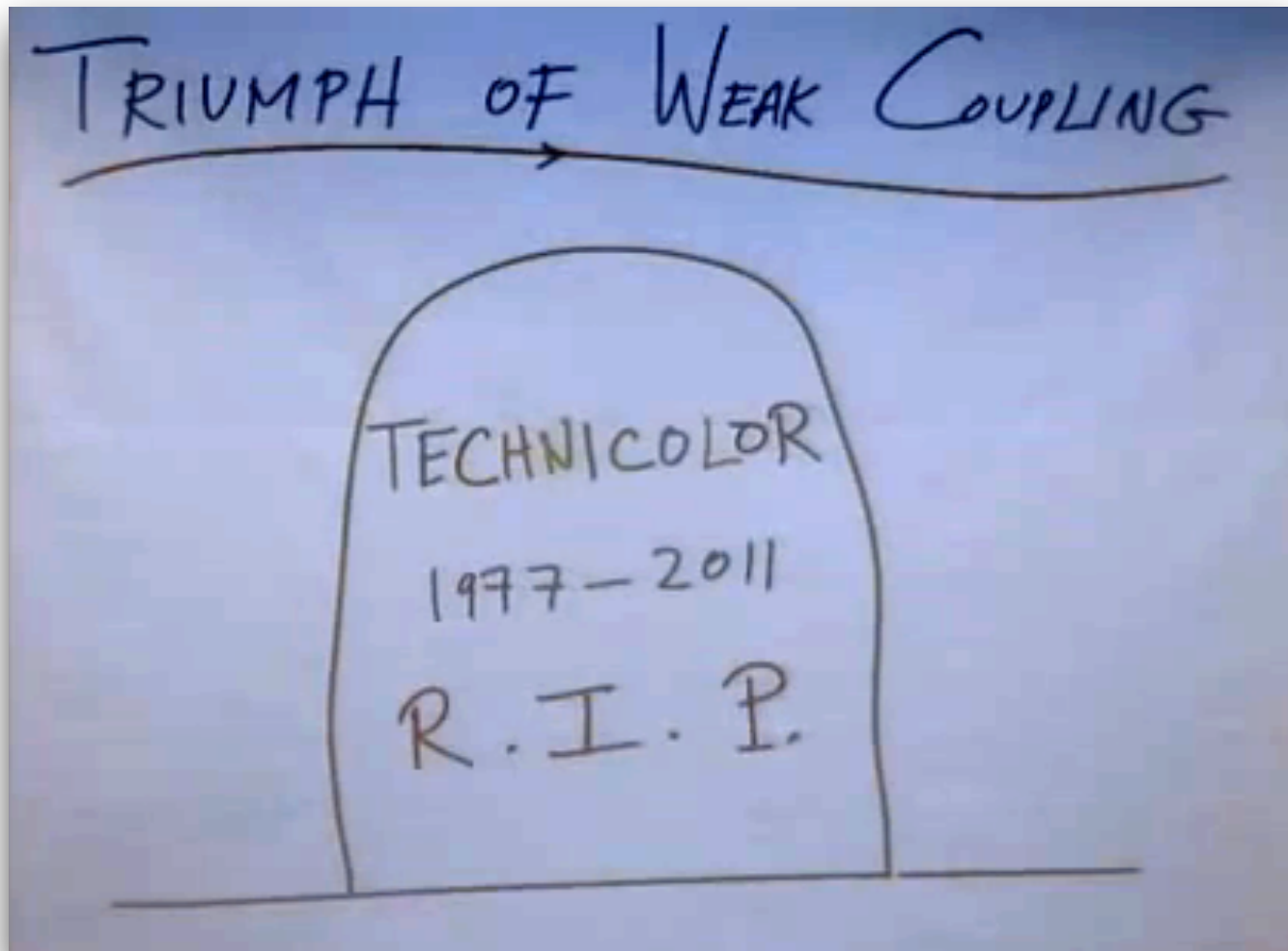
⇒ Higgs VEV dominates
electroweak symmetry breaking

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PNGB Higgs

Georgi, Kaplan, 1984

⋮

Contino, Nomura, Pomarol, 2003

⋮



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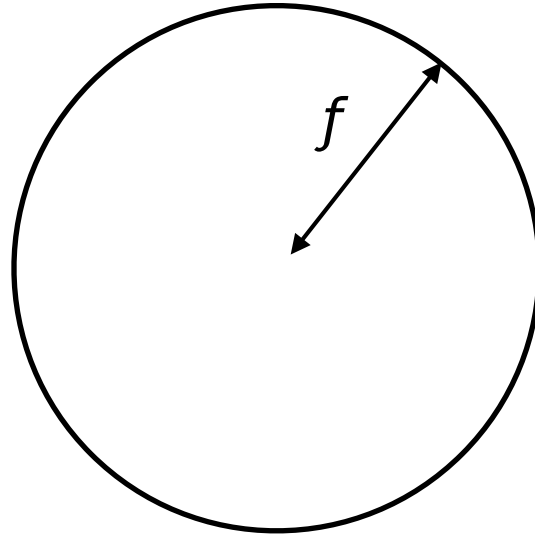
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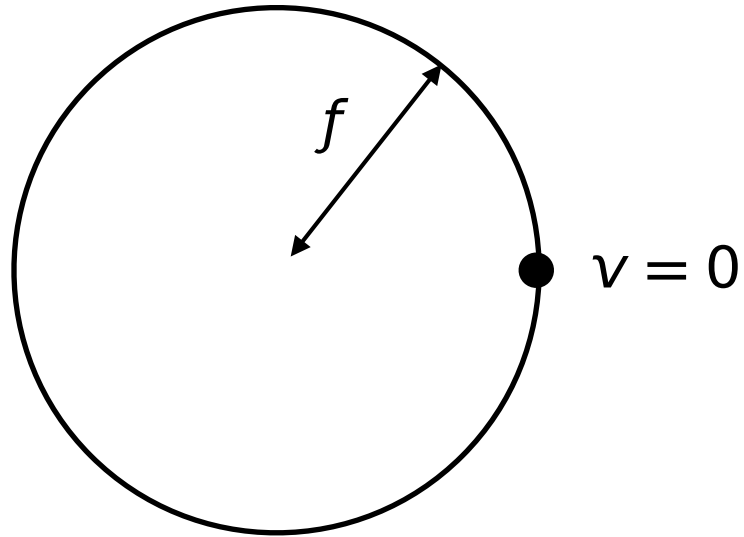
PNGB Higgs

Space of vacua:



PNGB Higgs

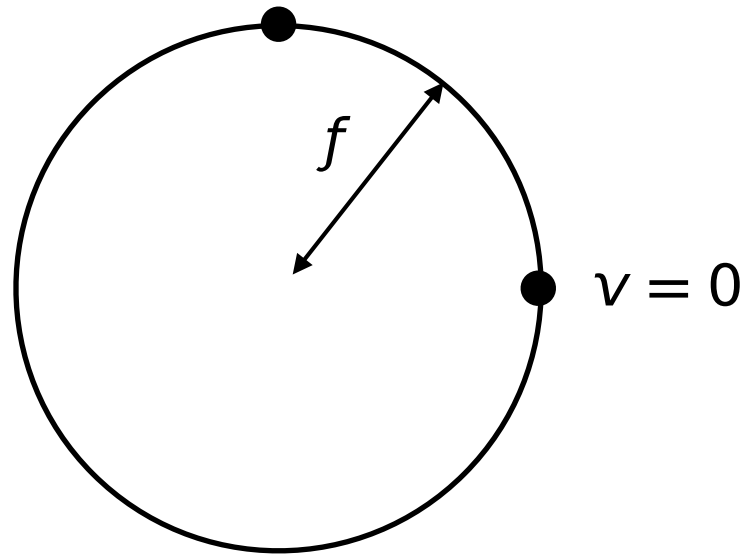
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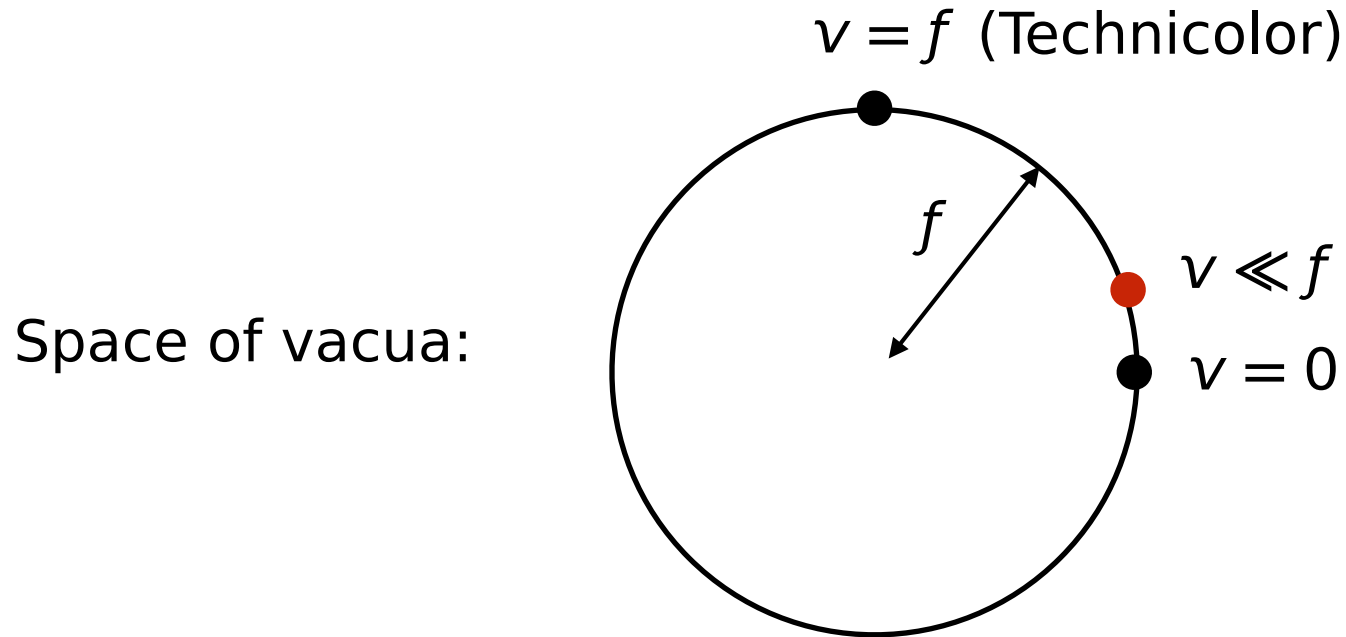
PNGB Higgs

$v = f$ (Technicolor)

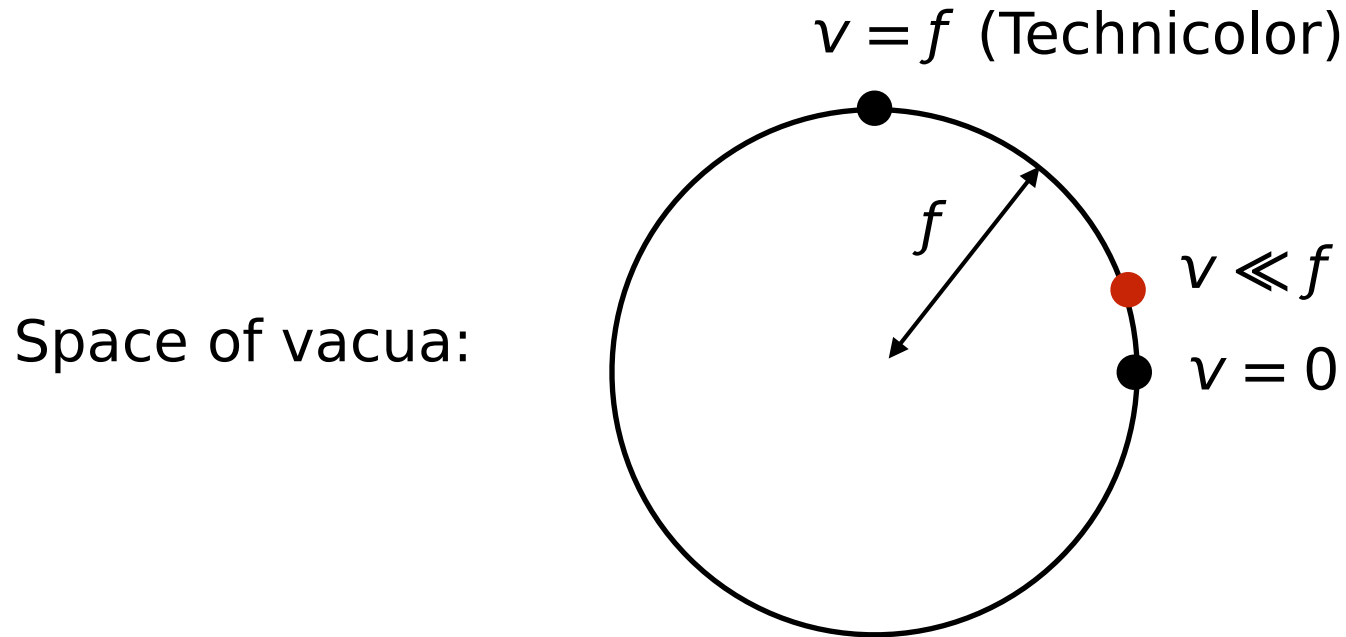
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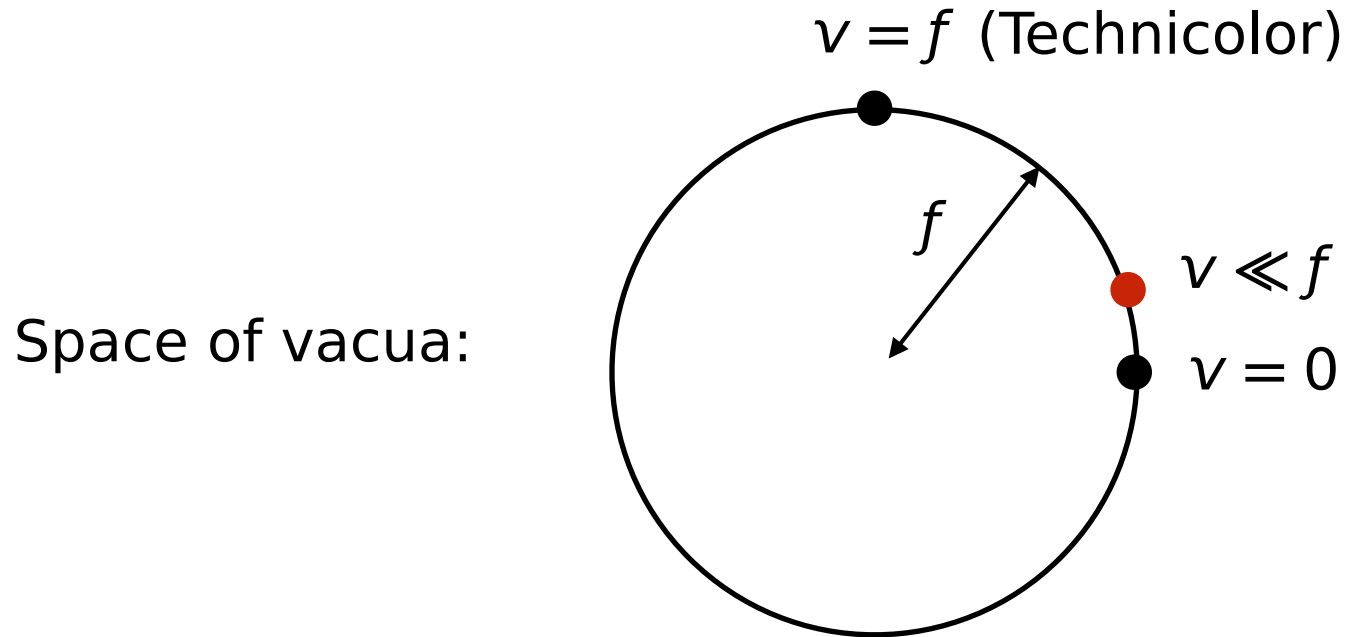


PNGB Higgs



$$\frac{g_{hVV}}{g_{hVV}^{(SM)}} = 1 + O(10\%) \quad \Rightarrow \quad \frac{v^2}{f^2} < 10\%$$

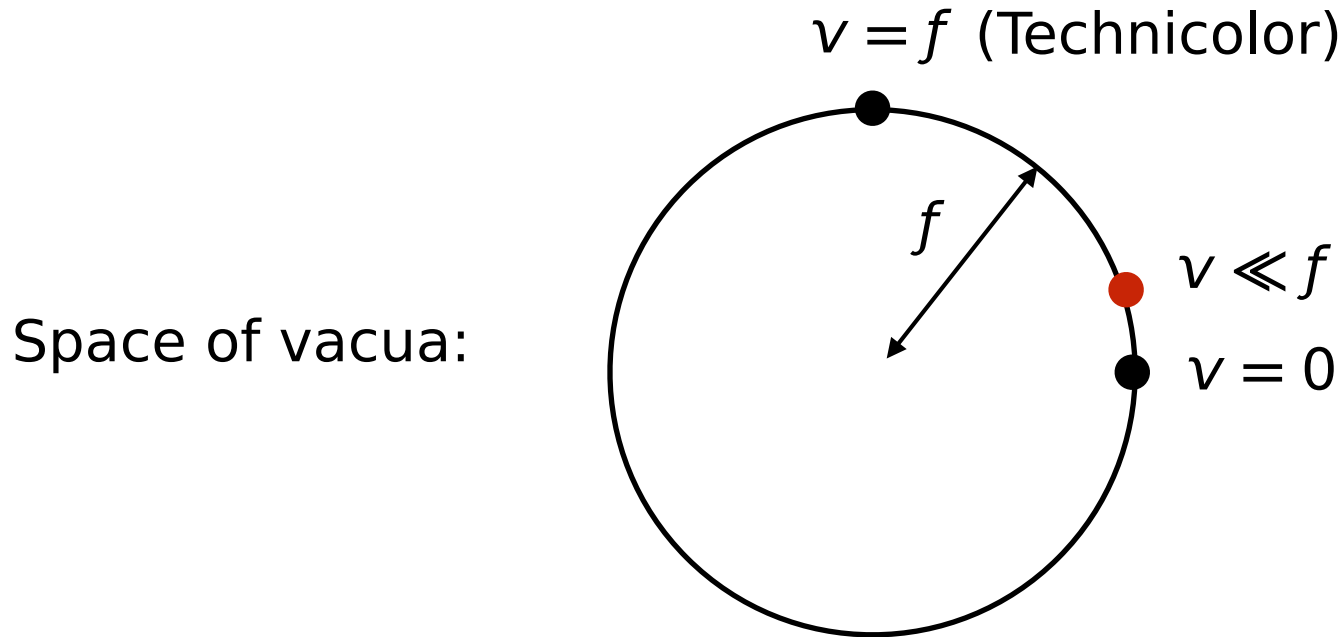
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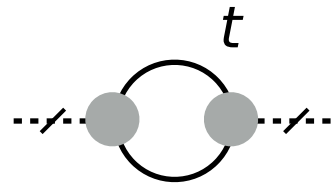
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\Rightarrow precision Higgs coupling measurements directly probe tuning in PNGB Higgs models

PNGB Higgs

Top quark is a potential additional source of tuning:

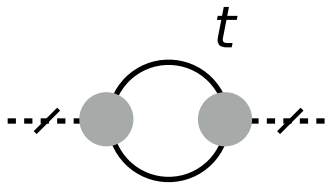


The diagram shows a top quark loop. Two external dashed lines with slashes represent top quarks, entering from the left and exiting to the right. They are connected by a circular loop. Two grey circular nodes are placed on the loop, one at each vertex where an external line meets the loop. The label 't' is positioned above the loop.

$$\sim \frac{y_t^2 \Lambda^2}{16\pi^2} \quad \Lambda \sim 4\pi f$$

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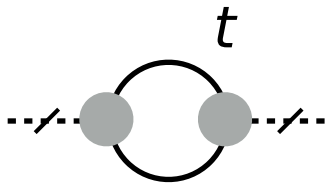
A Feynman diagram showing a top quark loop. Two external dashed lines with slashes represent top quarks, each ending in a grey circular vertex. These vertices are connected by a solid circular loop. The top of the loop is labeled with the letter 't'.

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$\Rightarrow \sim 1\%$ tuning

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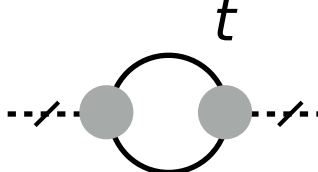
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(PNGB Higgs would have preferred $m_h \sim 300$ GeV...)

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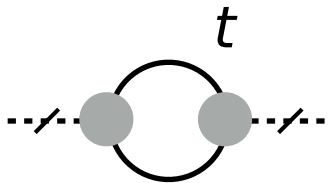
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Naturalness requires additional light states

PNGB Higgs

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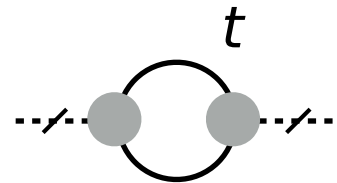
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\Rightarrow top partners

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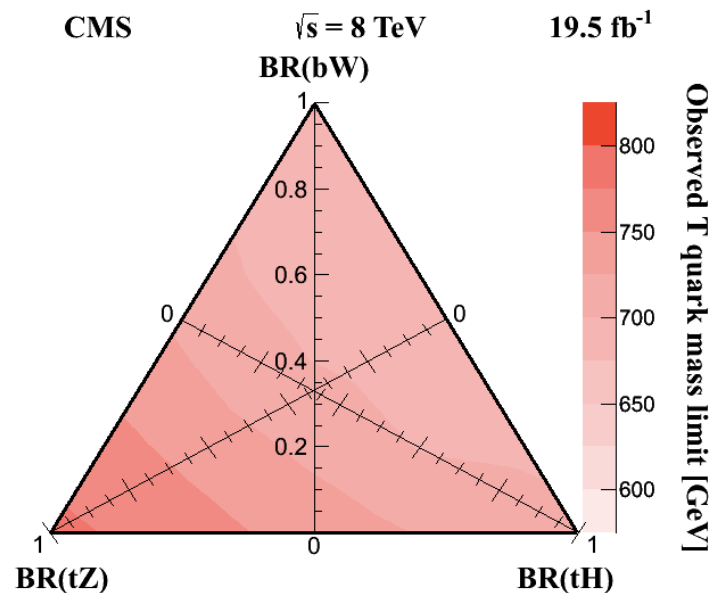
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BMSSM Higgs

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$$\tilde{t} \text{ loops: } \Delta\lambda \sim \frac{3y_t^4}{16\pi^2} \ln \frac{m_{\tilde{t}}}{m_t}$$

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$$\text{tuning} \sim 10\% \times \left(\frac{m_{\tilde{t}}}{500 \text{ GeV}} \right)^2$$

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Take as hint for BMSSM physics.

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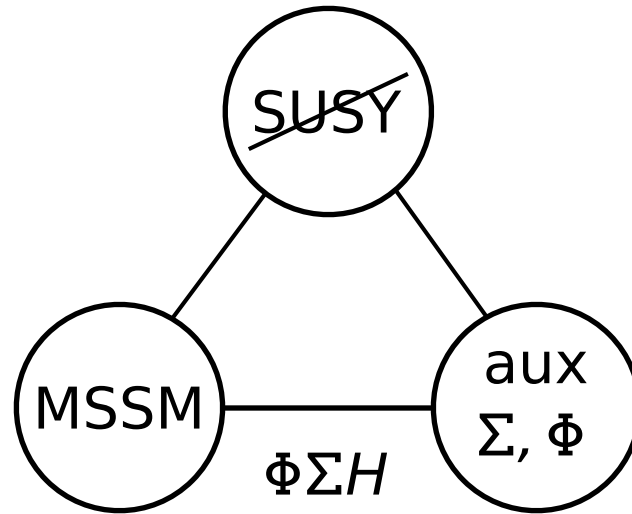
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Another possibility:

- Higgs tadpole from “auxiliary” Higgs sector

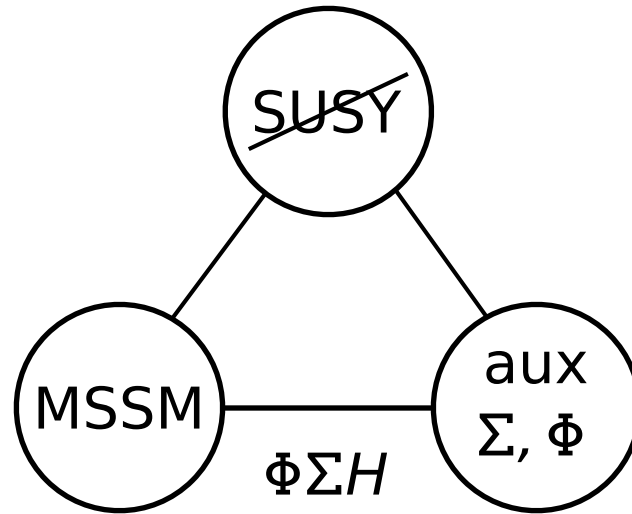
SUSY + Technicolor

Azatov, Galloway, ML, 2012



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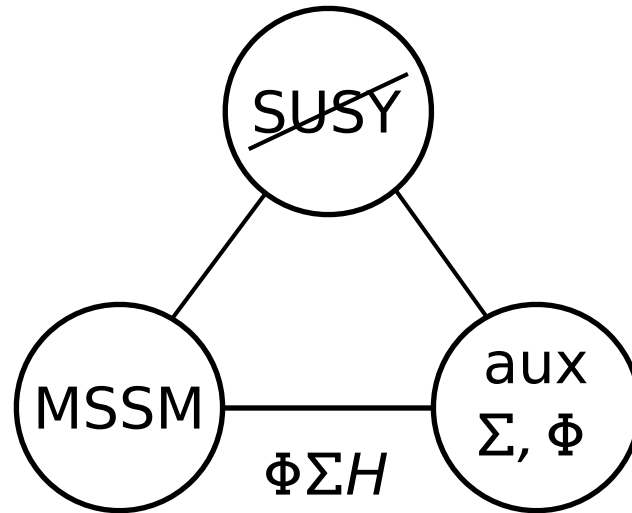
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$$V_{\text{eff}} \simeq m_H^2 H^\dagger H + \kappa H^\dagger e^{i\pi/f} \begin{pmatrix} 0 \\ f \end{pmatrix} + \text{h.c.}$$

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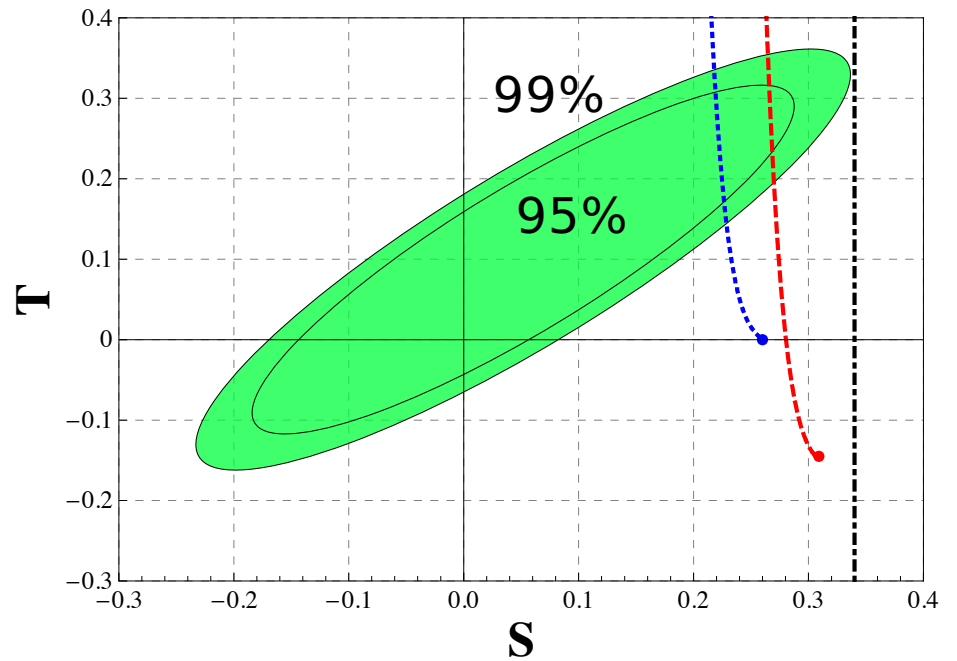
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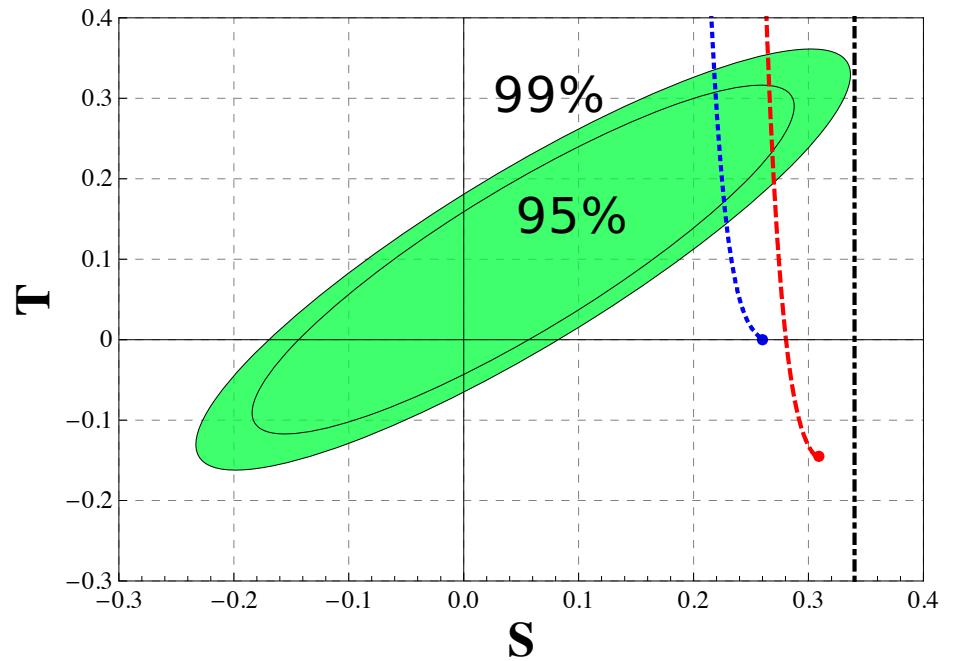


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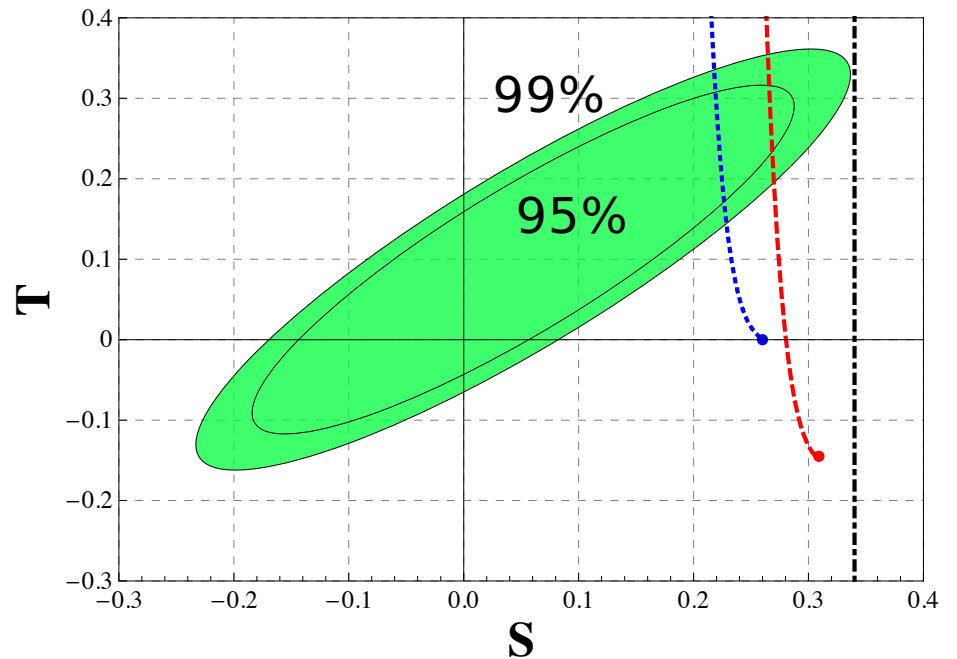


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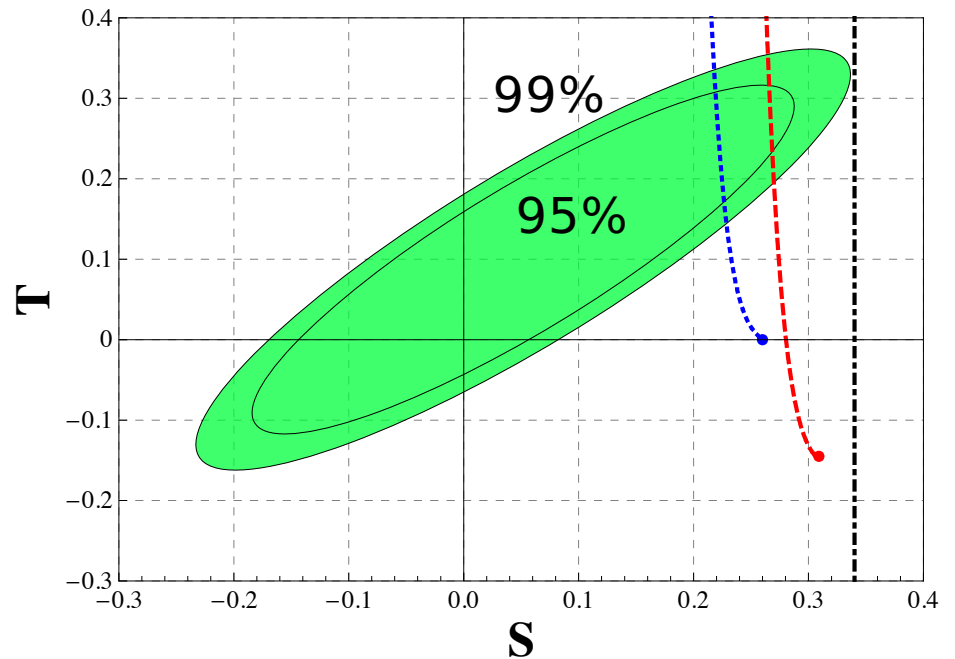
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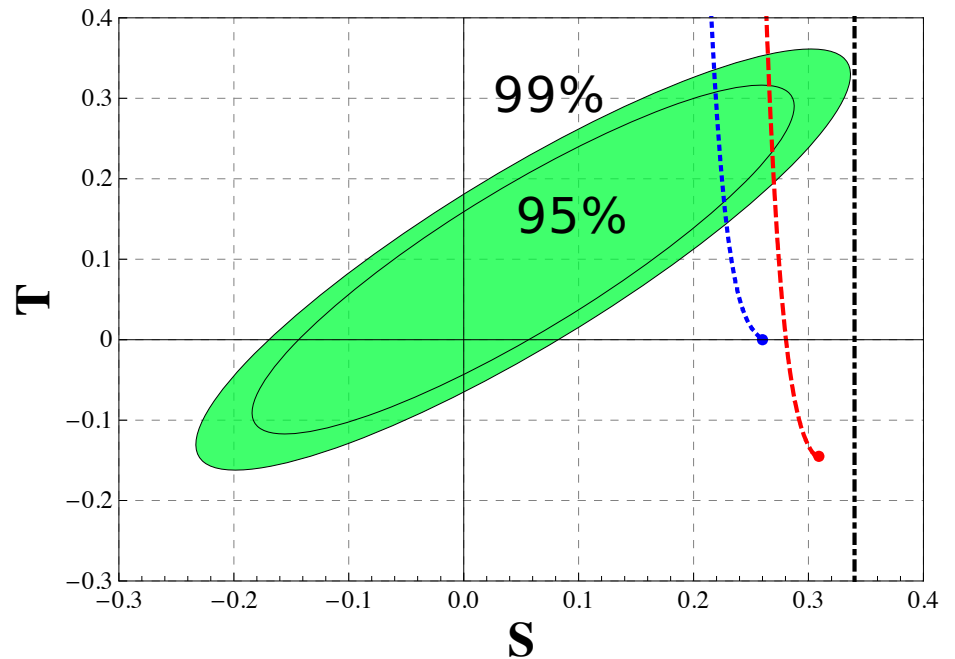


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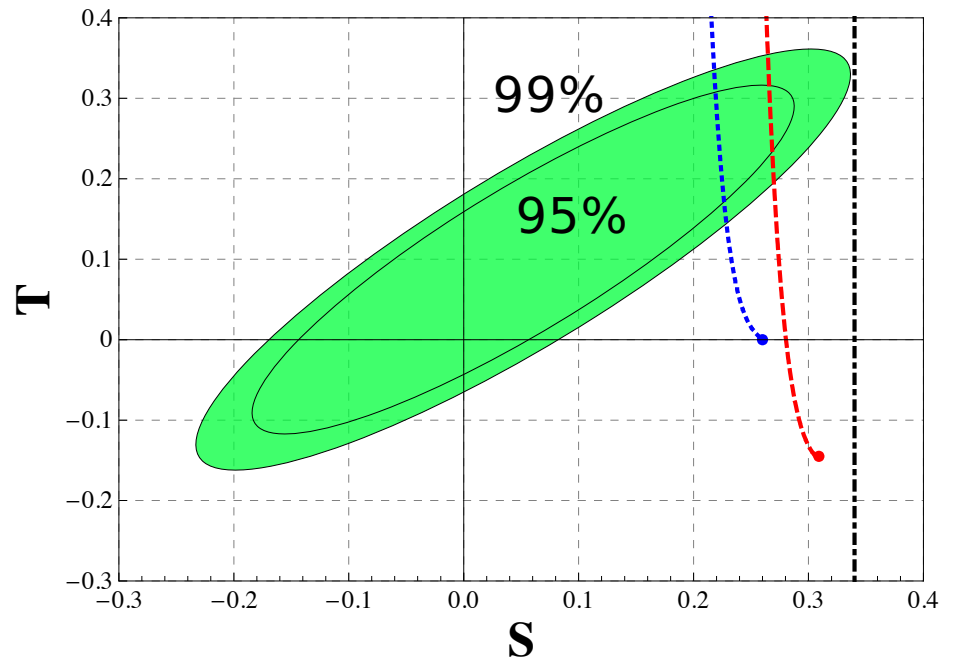
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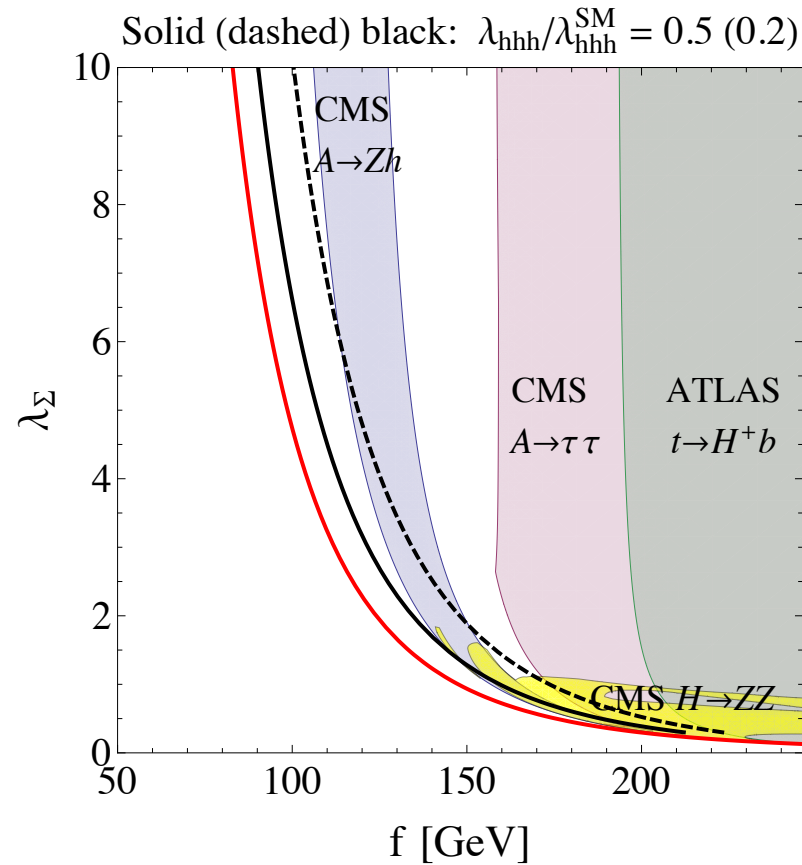
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Galloway, ML, Tsai, Zhao, 2014

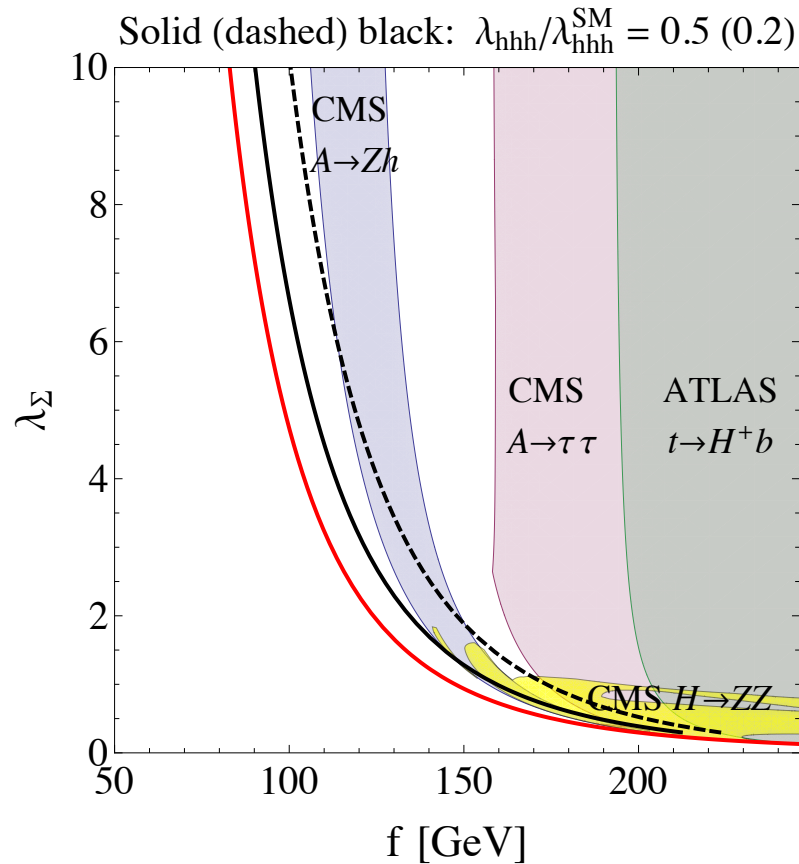
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General message: SUSY naturalness motivates BMSSM Higgs

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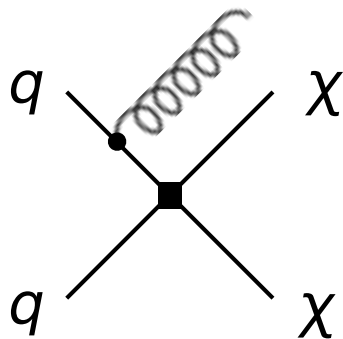
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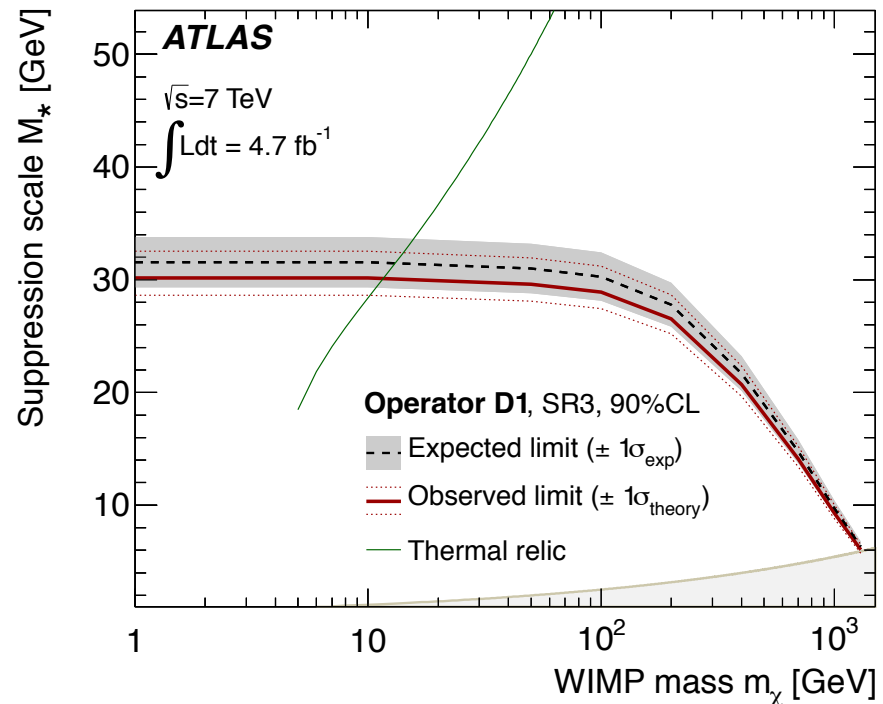
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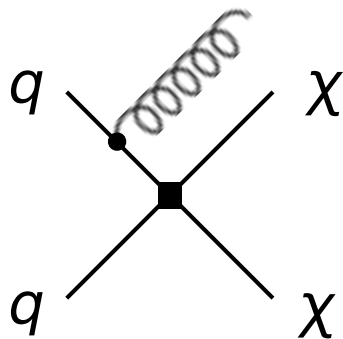
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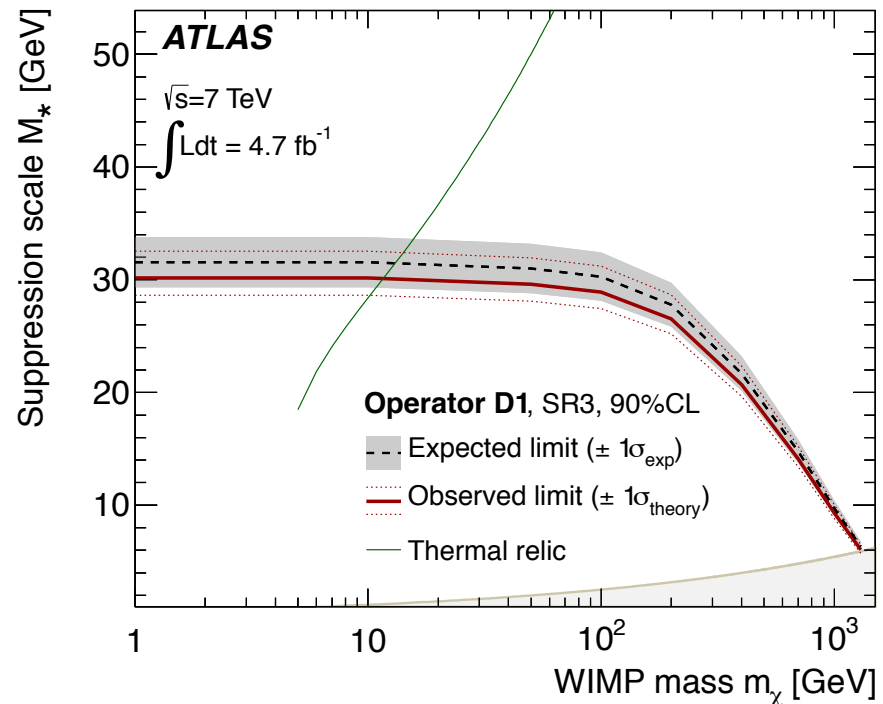
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Generalized to mono- X searches ...

Effective WIMPs

Chang, Hutchinson, Edezath, ML 2013

An, Wang, Zhang, 2013

Bai, Berger, 2013

Relic abundance motivates *renormalizable* couplings to SM.

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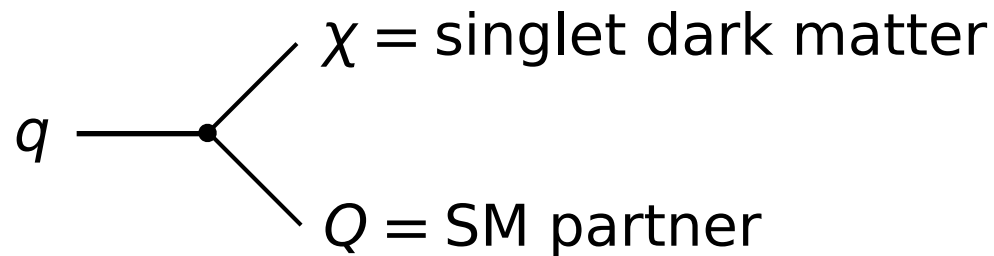
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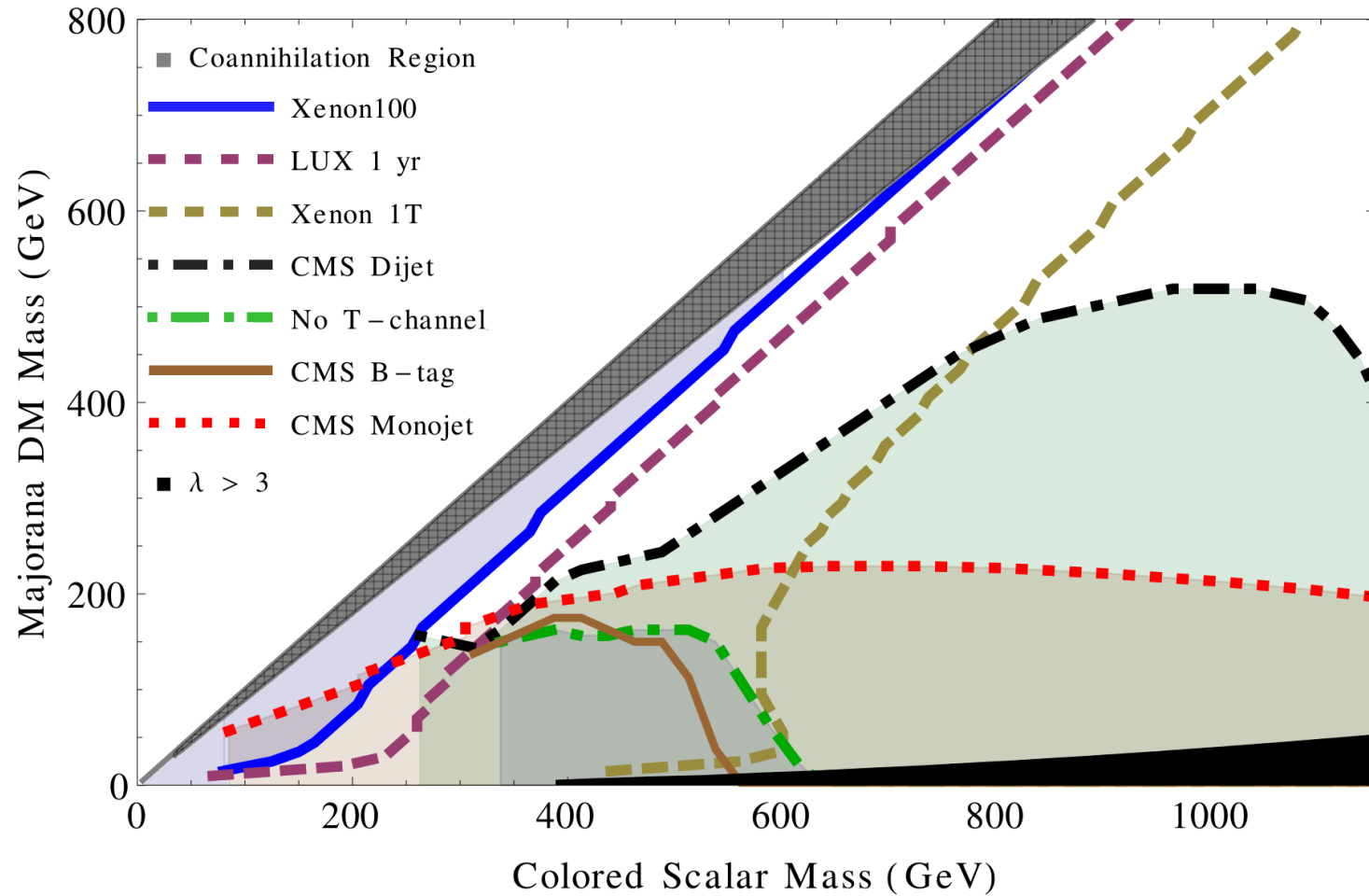
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Simplest models:



Effective WIMPs

Majorana fermion dark matter



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