# Phenomenology of Induced Electroweak Symmetry Breaking

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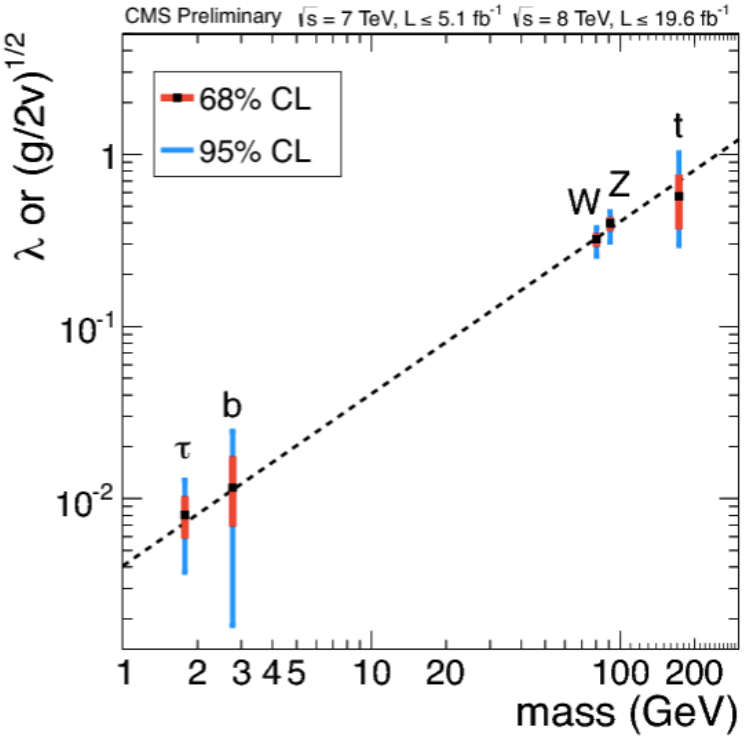
Work w/ Azatov, Craig, Galloway PRD86
Galloway, Luty, Salvioni, Tsai arXiv:1411.6023

# Talk Outline

- Induced Electroweak Symmetry Breaking
- Examples: MSSM + Technicolor (or extra doublets)
- Higgs Mass and Naturalness Implications
- Higgs, Pseudos, Techni-states Phenomenology

# Higgs as we know it




The Higgs discovery and ongoing precision studies are currently pointing to a Standard Model Higgs

# Viable options remain…

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**Standard EWSB**

# Viable options remain…

**Standard EWSB**


**Tilted Hat**

# Viable options remain…

**Standard EWSB**


**Tilted Hat**

**Tilted Bowl**

# Induced EWSB scenarios

**Use an additional source of EWSB to tilt the potential**

Could come from another Higgs doublet with a larger quartic coupling (Galloway et.al. PRD 89)

Could come from a technicolor sector (Azatov et.al. PRL 108)

In paper, we considered both, but for this talk, I focus on the latter possibility

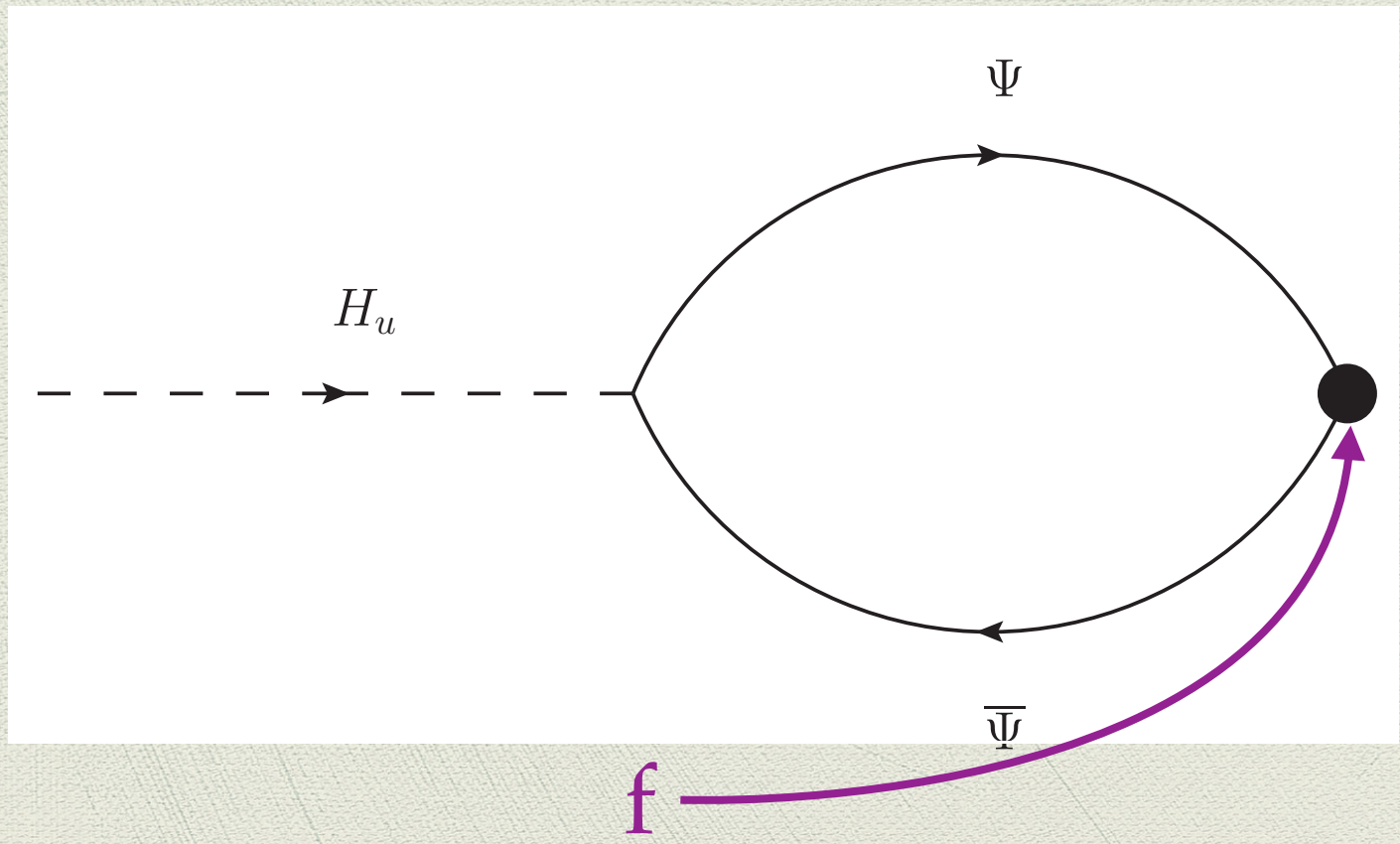
# SUSY + Technicolor

- Supersymmetry plus technicolor is an interesting combination
- If technicolor initiates EWSB at a scale $f \ll v$, can induce EWSB in elementary Higgs sector, $v_u, v_d \gg f$

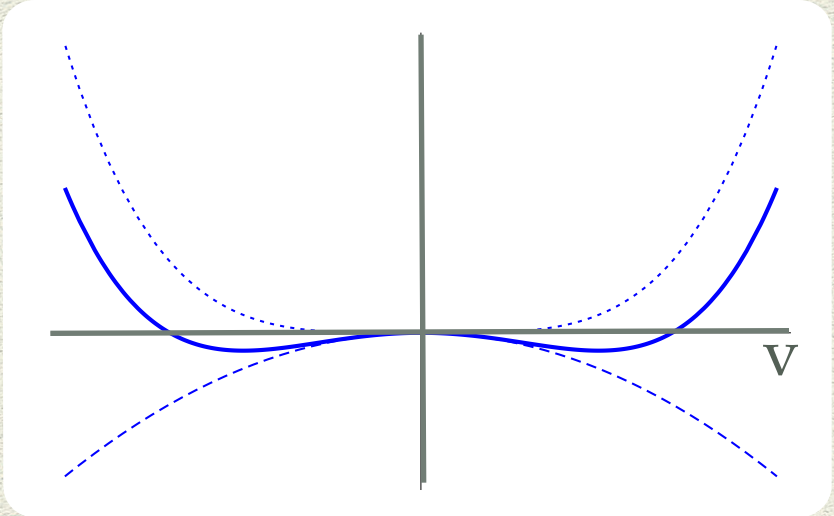
Combination considered in early 80's by Dimopoulos, Raby Dine, Fischler, Srednicki

# Tadpole Couplings

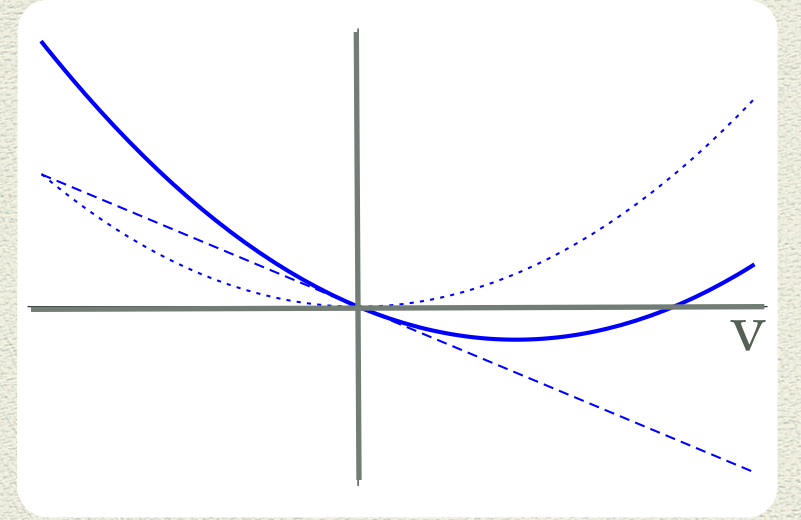
$$V \supset 4\pi f^3 \, Tr\left[\Sigma(\lambda_d H_d \; \lambda_u H_u)\right] + c.c.$$



## Standard EWSB via Mexican Hat



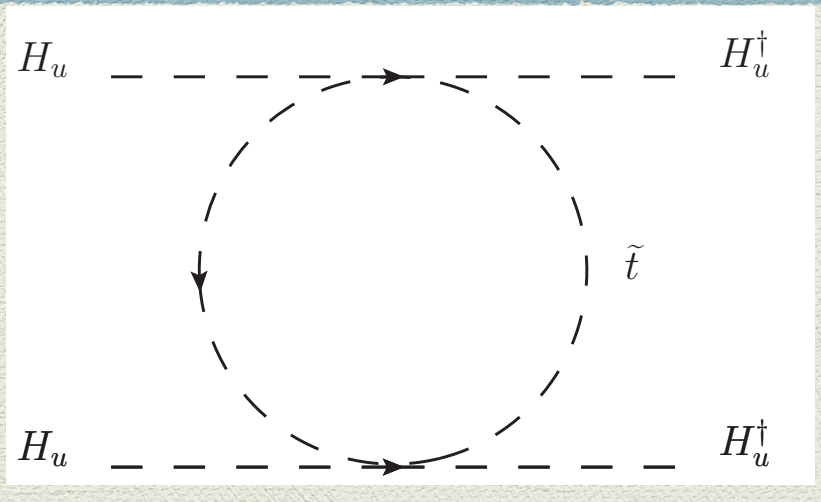

## Tilted EWSB induced by linear tadpole

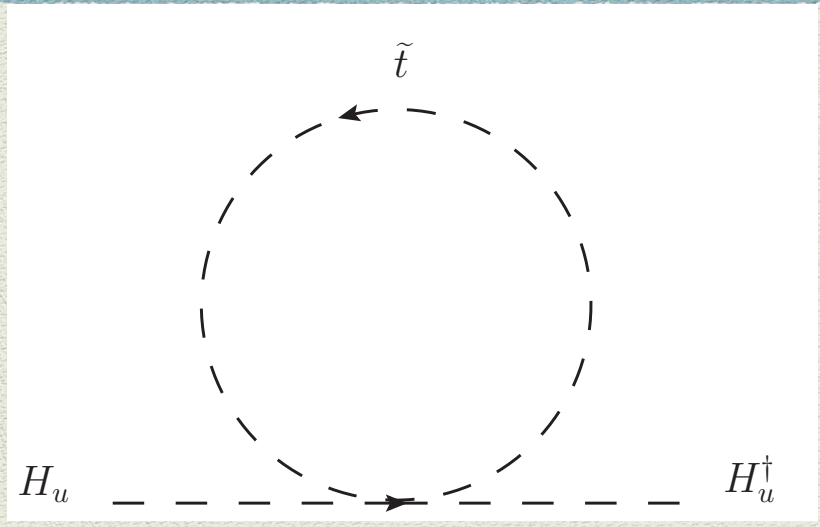



| Mechanism | Standard | Tadpole |
|---|---|---|
| Unstable/Stable Terms | Mass Term/Quartic | Linear Term/ Mass |
| Higgs Mass | 2 | M |

# Why should we combine SUSY and technicolor?

# SUSY (Un)Naturalness




$$\delta m_h^2 \propto y_t^4 \ln \frac{m_{\tilde{t}}}{m_t}$$

$$m_{H_u}^2 \propto y_t^2 m_{\tilde{t}}^2$$

MSSM unnaturalness due to Higgs mass being log related to SUSY mass scale

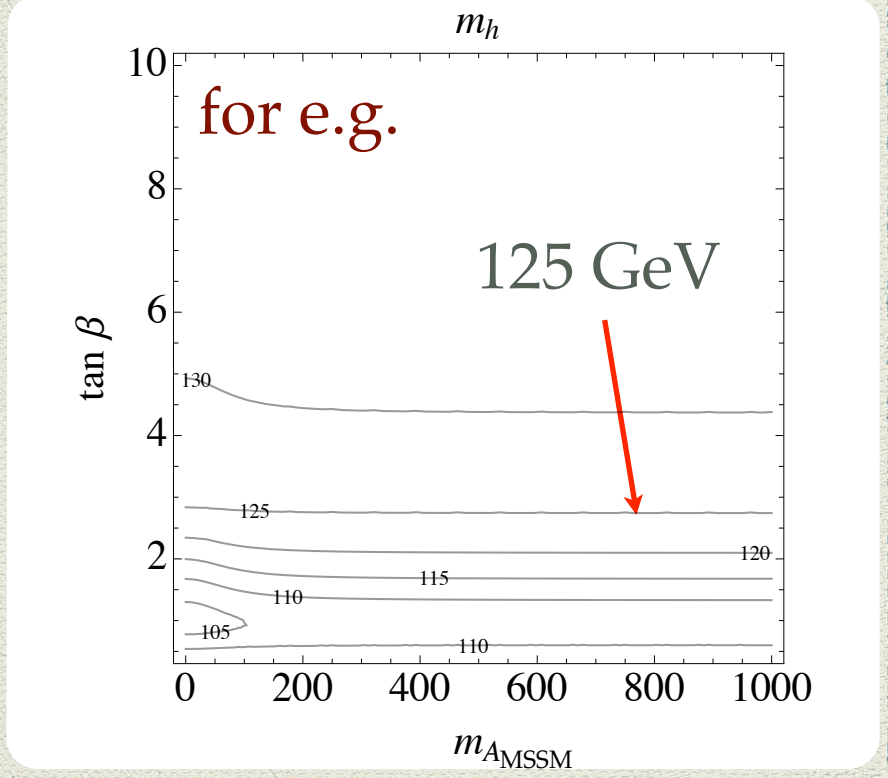
In MSSM + TC Higgs mass gains *linear* dependence on SUSY scale due to properties of induced EWSB

# Higgs Phenomenology

$$\delta m_h^2 = \frac{4\sqrt{2}\pi f^3(\lambda_d \cos\beta + \lambda_u \sin\beta)}{\sqrt{v_u^2 + v_d^2}}$$

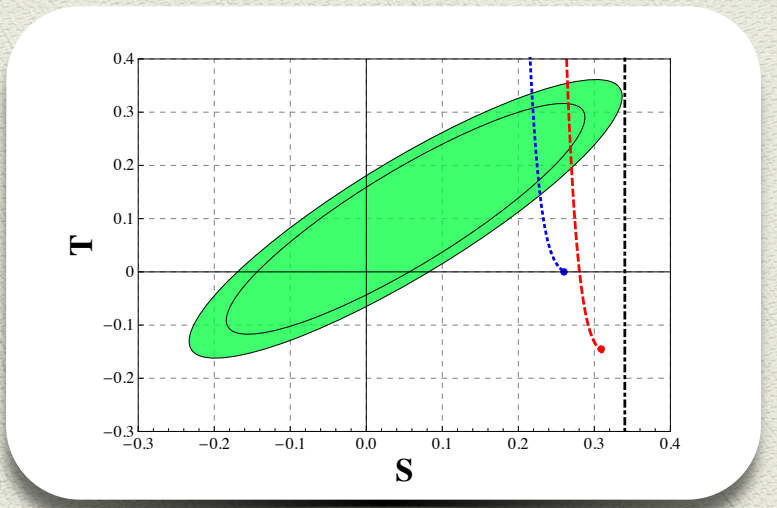
Can substantially increase Higgs mass

With $\lambda \sim O(.1)$ and $f \sim 80$ GeV can get $m_h = 125$ GeV *without* radiative corrections (Gherghetta, Pomarol '11)



# Technicolor Issues

- Flavor not a problem, just write Yukawas in elementary Higgs sector (Simmons, Samuel, ...)
- Precision electroweak is still an issue, but can still stay in (S, T) ellipse (Galloway et al.)



# Higgs and Technicolor

- As pointed out by Carone '12, bosonic technicolor (Higgs + TC) has smaller quartic, bigger top Yukawa, so instability at high Higgs vev is worsened
- With supersymmetry, potential does not go negative and instability is avoided

# Higgs Modifications

w/ Azatov, Craig, Galloway PRD86

# Higgs Couplings

New couplings allow modifications beyond MSSM type-II 2HDM

# (Non)Decoupling

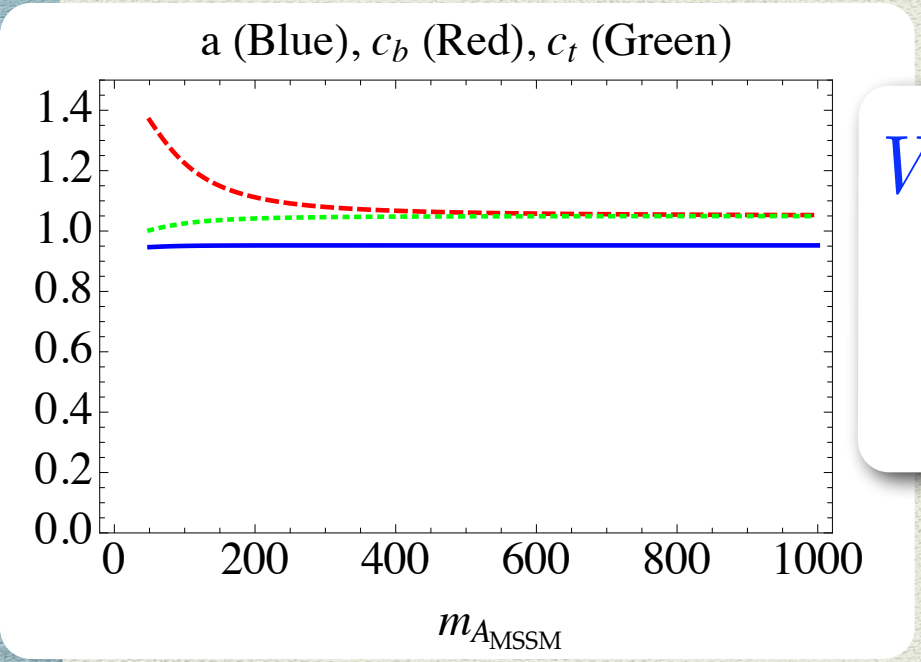
$$\frac{\sin 2\alpha}{\sin 2\beta} = -\frac{m_H^2 + m_h^2 - \dfrac{8\pi\sqrt{2}f^3(\lambda_u \cos\beta + \lambda_d \sin\beta)}{\sin 2\beta\sqrt{v_u^2+v_d^2}}}{m_H^2 - m_h^2}$$

Decoupling limit of MSSM, when $m_H \to \infty$
sets $\alpha$-$\beta$=$\pi/2$, where $h^0$ has SM couplings

New term allows decoupling limit for gauge bosons,
but decouples slower for fermion couplings
which can be enhanced **or** suppressed

# Higgs phenomenology
# Two benchmarks

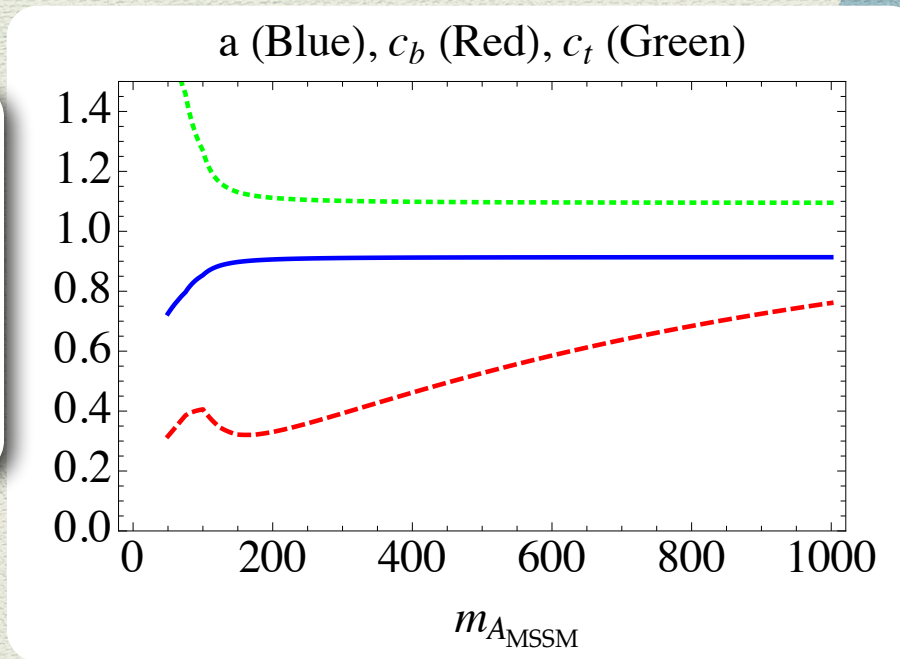
Lighter Higgs fixed to 125 GeV, $m_A$ allowed to vary




$WW/ZZ$

$b\bar{b}/\tau\bar{\tau}$

$t\bar{t}$




Moderate tan β

Largish tan β

Notice delayed decoupling limit for bottom quark coupling in right benchmark

# Collider Phenomenology

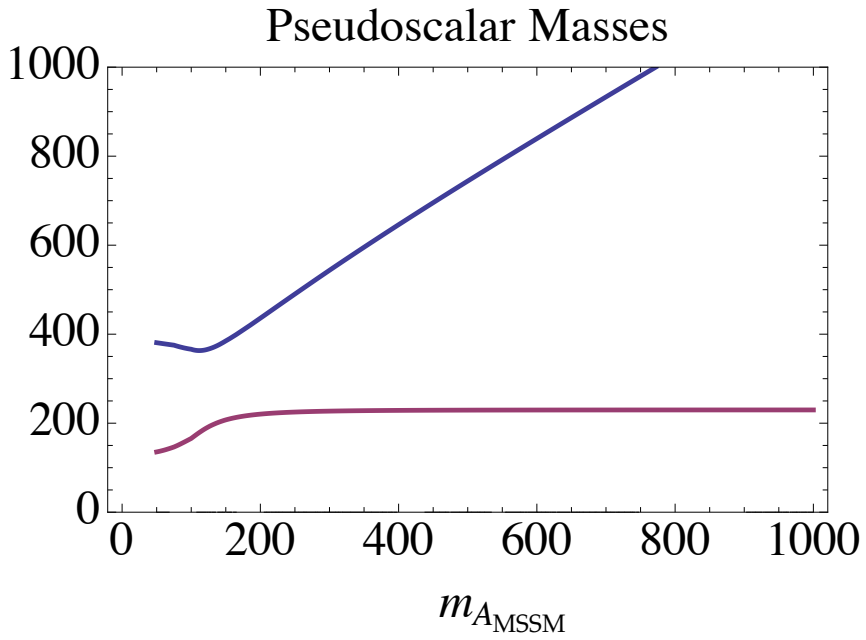
w/ Galloway, Luty, Salvioni, Tsai arXiv:1411.6023

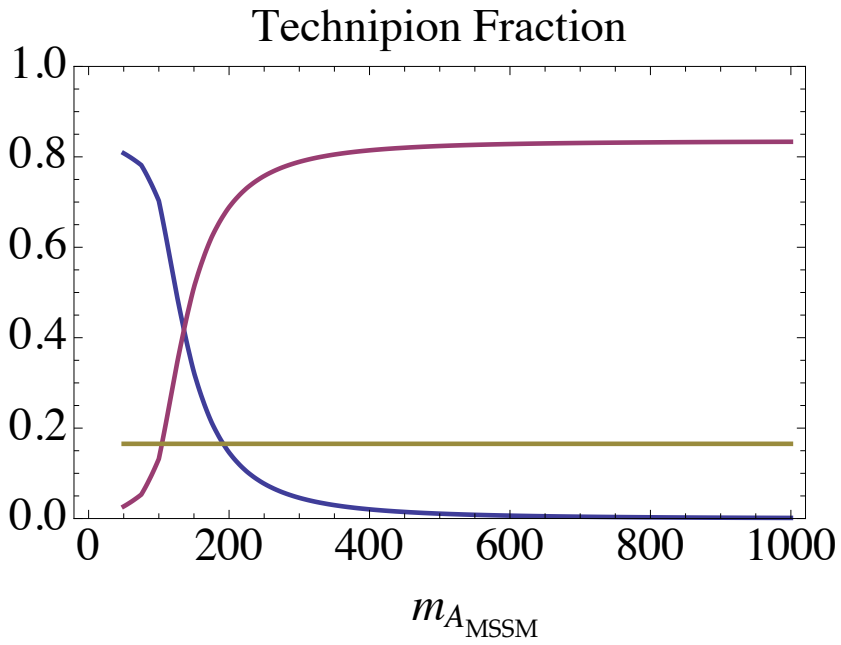
# Pseudoscalars

Of new particles, pseudoscalar pheno is particularly interesting

Due to multiple EWSB, there are would-be-Goldstones from MSSM Higgs as well as technicolor sector

# Pseudoscalars




Normal decoupling limit, decouples MSSM pseudoscalar

Techni-pseudo mixes O(1) and does not decouple

# Decoupling benchmarks

- Considered benchmarks where standard MSSM decoupling limit has been taken ($mA_{MSSM} \rightarrow \infty$)
- Even in this limit, the phenomenology remains interesting

# Coupling

MSSM decoupling limit is reducing its 2HDM to a 1HDM

True goldstone is spread between elementary Higgs and technipions

$$G = \frac{v_h A_h + f A_{TC}}{\sqrt{v_h^2 + f^2}}$$

$$A = \frac{f A_h - v A_{TC}}{\sqrt{v_h^2 + f^2}}$$

So this state has f/v suppressed couplings to the SM

# Mass

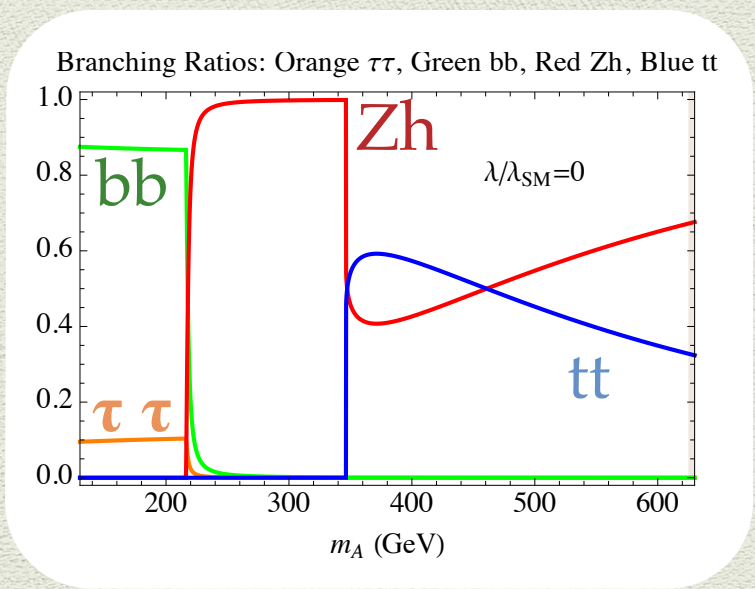
Without interactions with the MSSM, technipions would be true goldstones with no mass

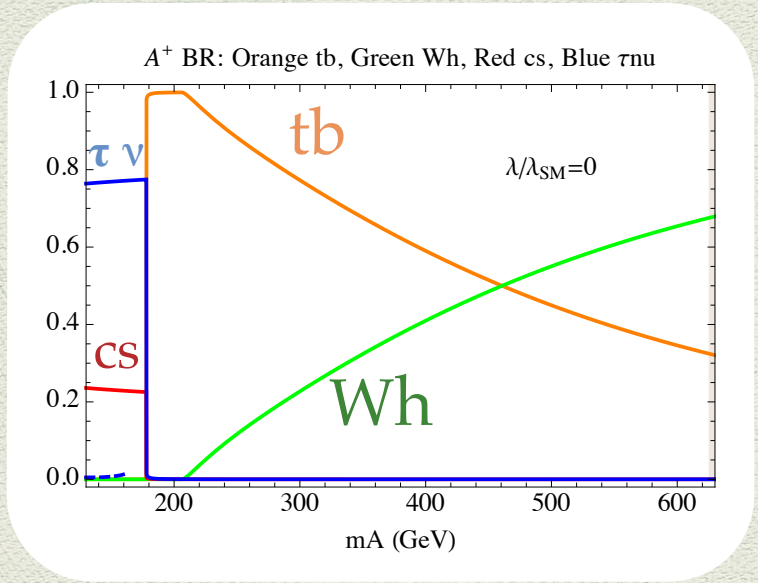
Only cross interaction is the tadpole term

$$m_A = \frac{v}{f}\delta m_h < \frac{v}{f} 126 \text{ GeV}$$

Thus, mass of pseudoscalars are tied to increase in Higgs mass and has an upper bound

# Branching Ratios in Decoupling Limit



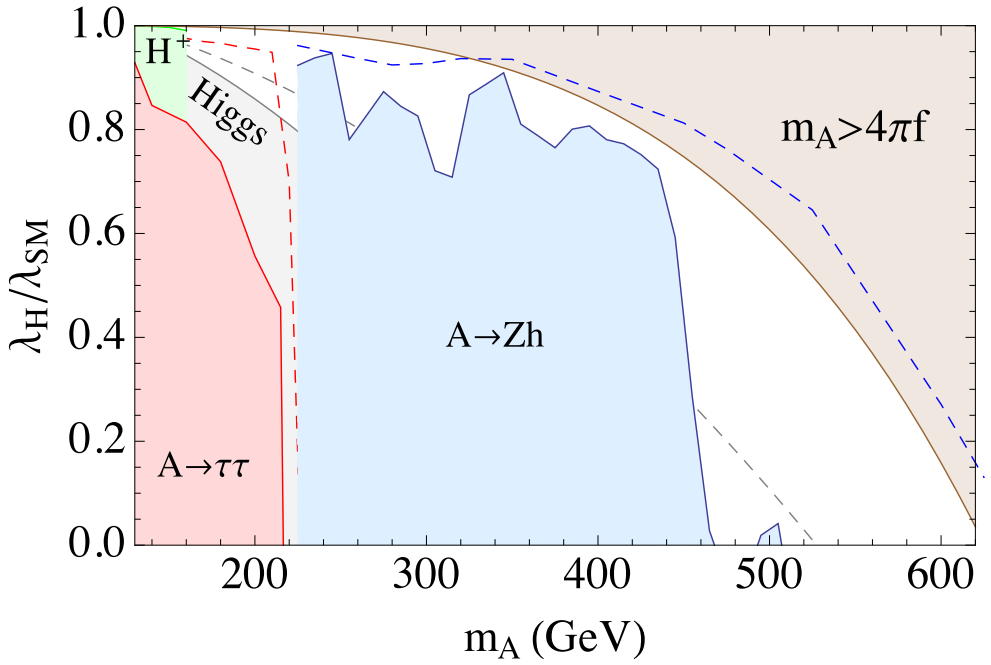

**Neutral pseudoscalar BRs**

**Charged pseudoscalar BRs**

Only weakly sensitive to elementary quartic coupling

Has a tan β= 1 fermion structure

# Pseudoscalar Phenomenology




mA < 160 GeV:
ATLAS: $t \rightarrow H^+ b$

mA < 220 GeV:
CMS: $A \rightarrow \boldsymbol{\tau\,\tau}$

250 GeV <mA < 350 GeV
CMS: A → Zh, Z leptons, h to b jets

**We project LHC14 w/ 300 $fb^{-1}$ can cover the rest w/ tau and Zh search (dashed lines)**

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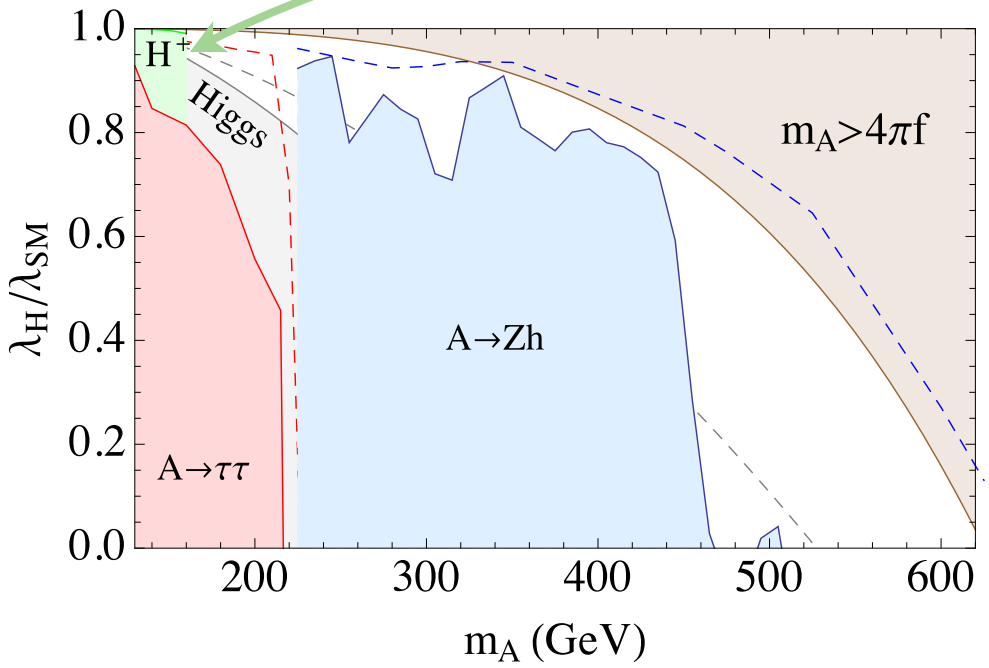


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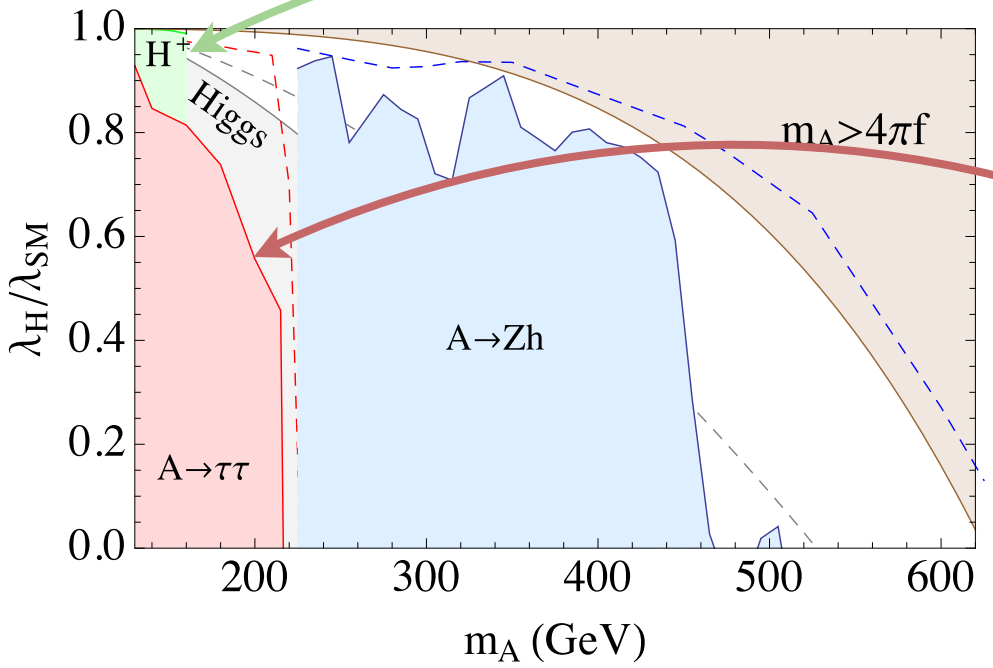


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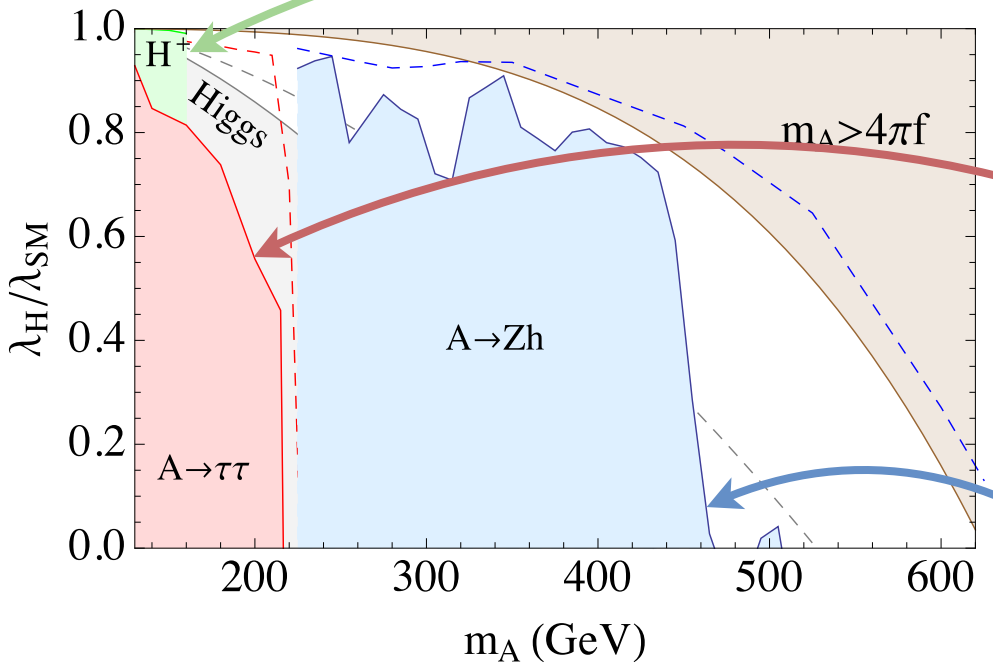


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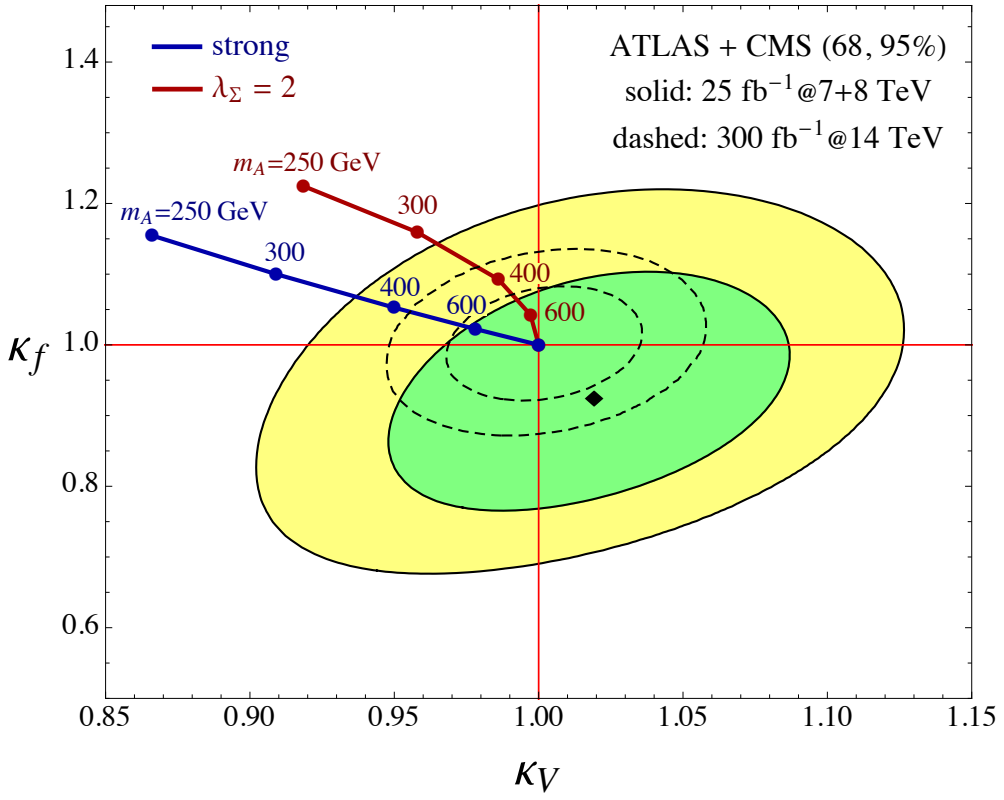
# Higgs coupling constraint

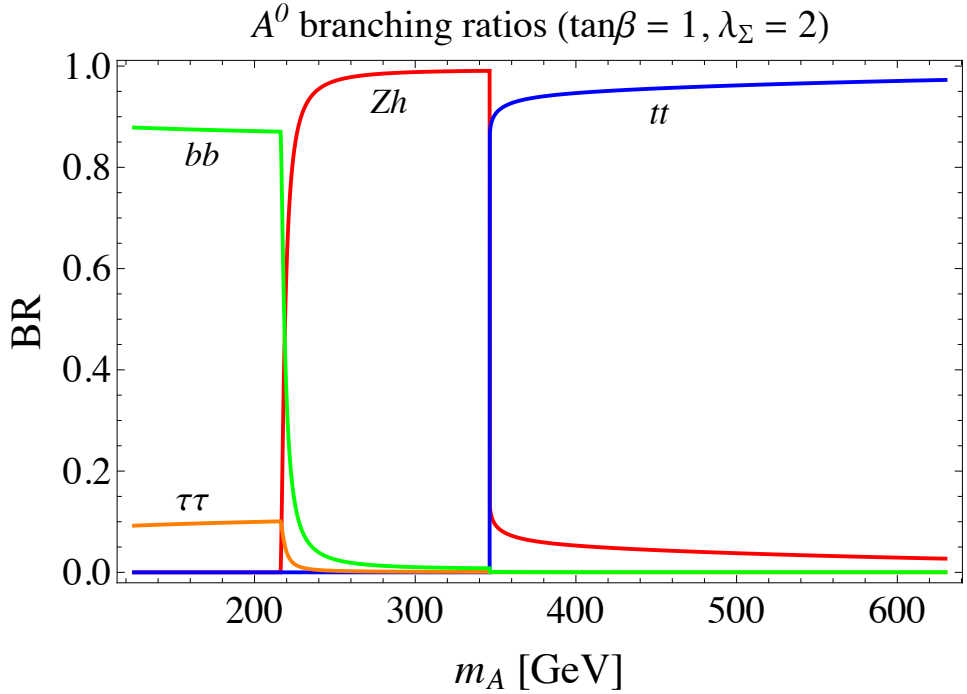
$$\kappa_V = 1/\kappa_f = \sqrt{1 - f^2/v^2}$$

Current limits are strong because they are on the wrong "side"

With Snowmass projection around SM value, limit only improves slightly



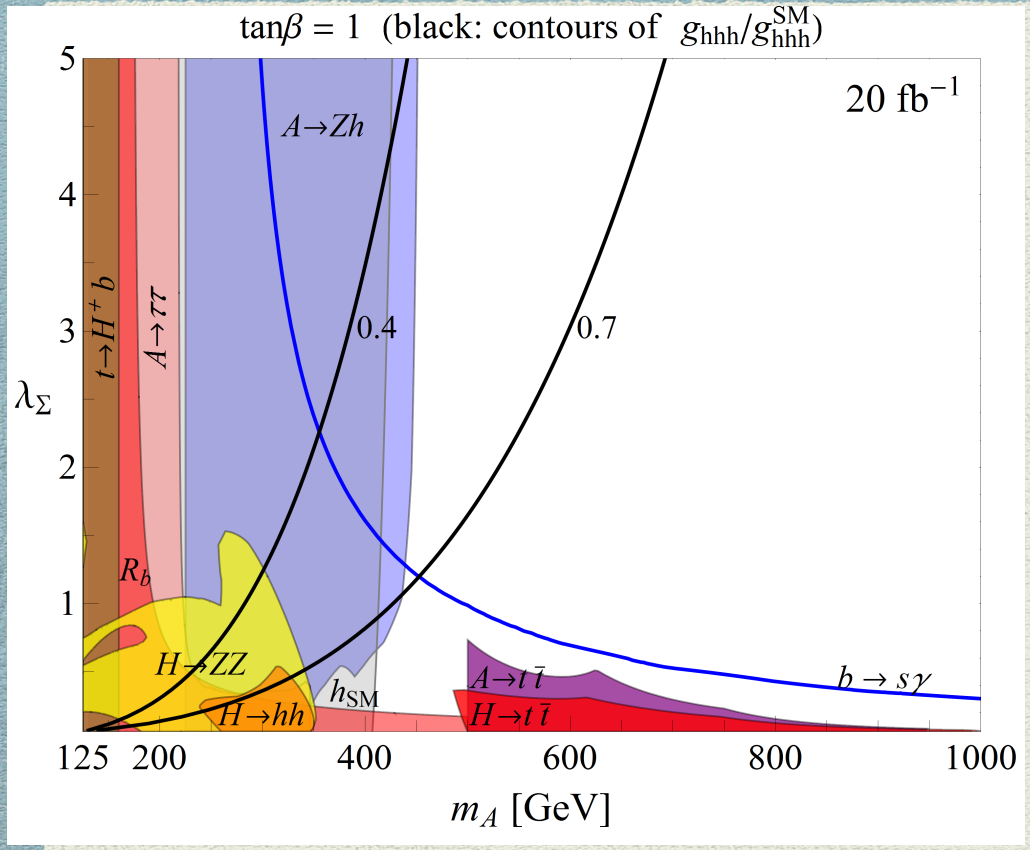
# Induced EWSB w/ extra Higgs

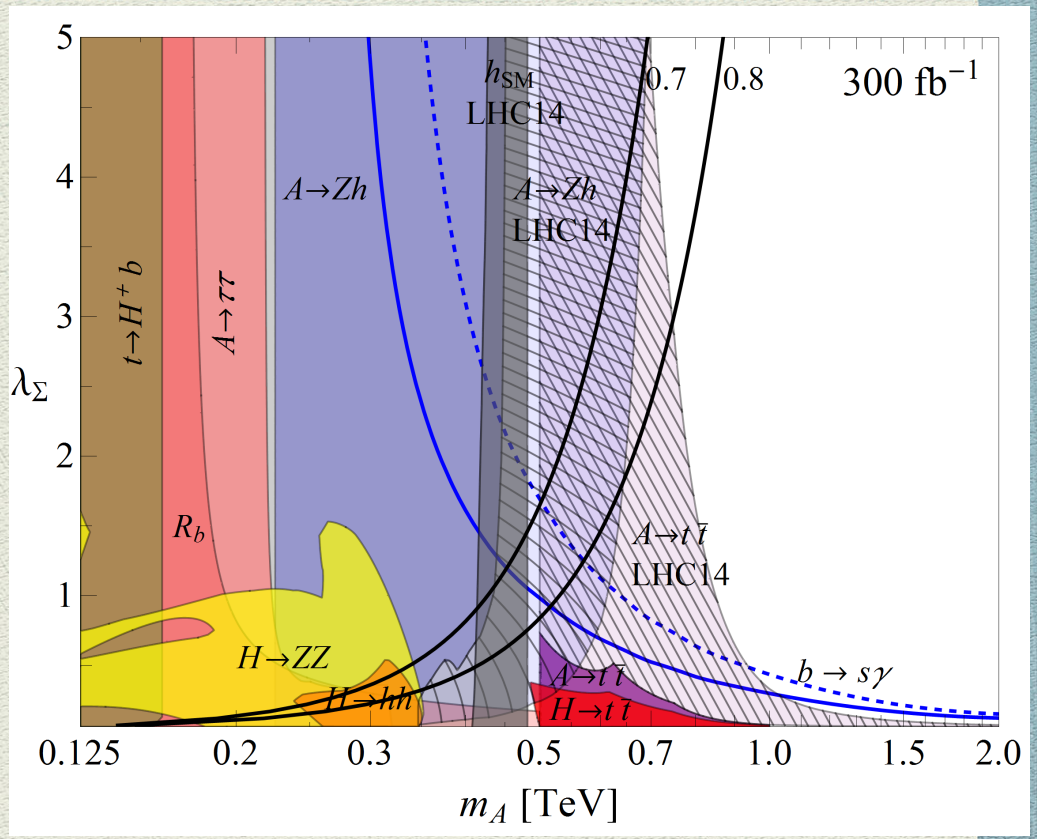



A much larger tt BR for Higgs case (TC: tt was ~50%)

Due to a cancellation in Zh coupling btw. both Higgs doublets

# Induced EWSB from doublet




**Run 2 top resonance search crucial at low $m_A$ to cover this parameter space**

# Some Model Dependent Pheno

# Techni-pheno (also Carone, Erlich, Tan)

Techni-states are an efficient way to produce techni-pseudos (albeit more UV model dependent)

We model techni-rho production ala Falkowski, et.al.

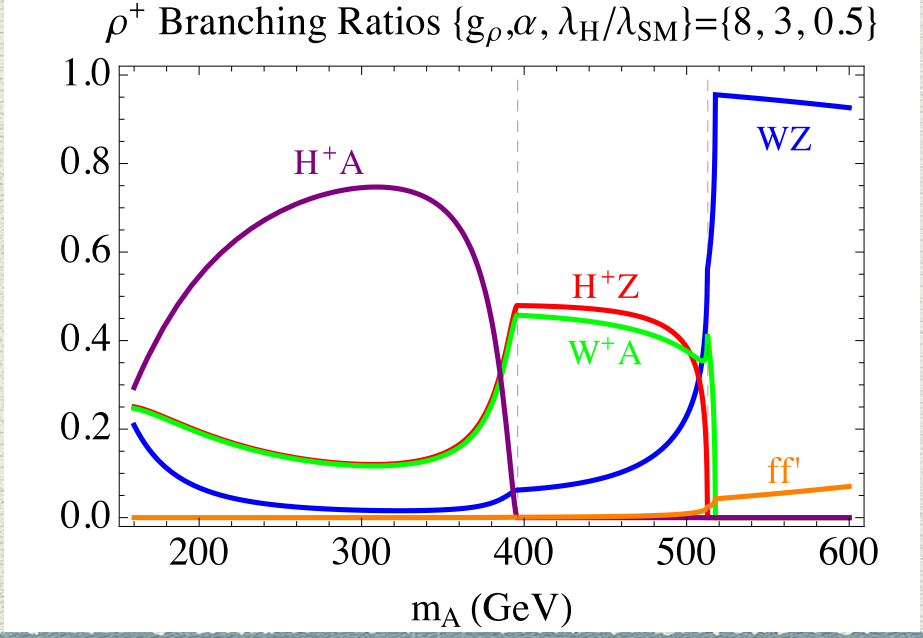
Interestingly, techni-rho couplings to SM are through mixing with W, Z, which does not explicitly depend on f

# Technirhos

**Many possible decay channels due to low mass states**

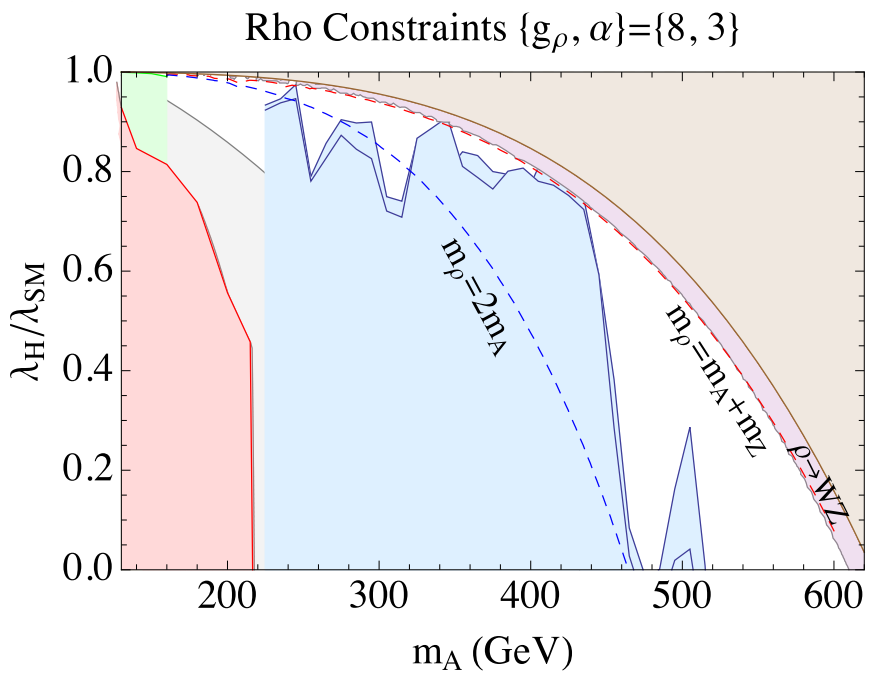
$$pp \to \rho^+ \to W^+Z, H^+A^0, H^+Z, W^+A^0$$

Once kinematically open, technirhos decay into pseudos




Naturally leads to longer cascades, not directly being searched for

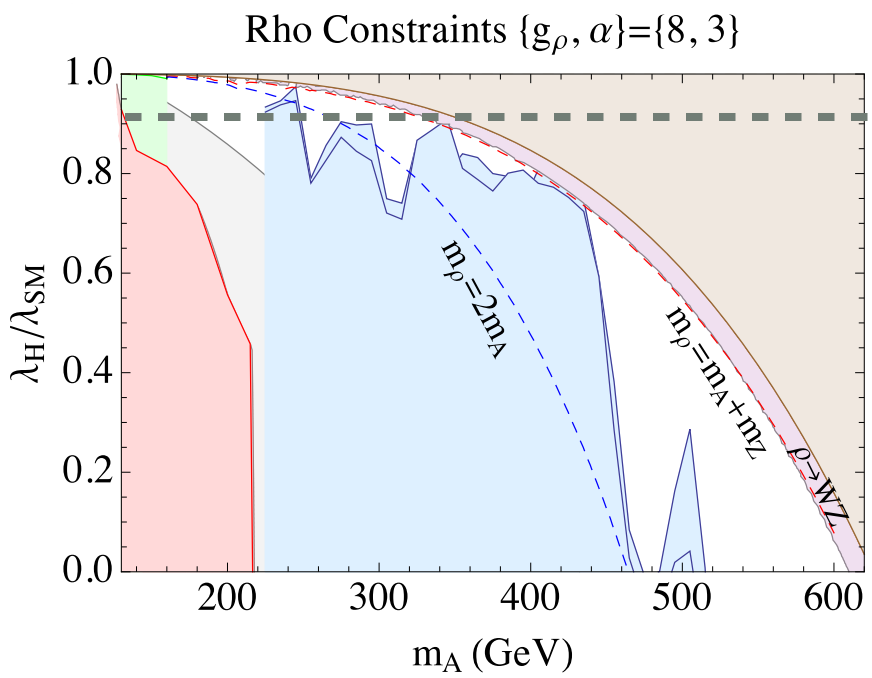
# Benchmarks

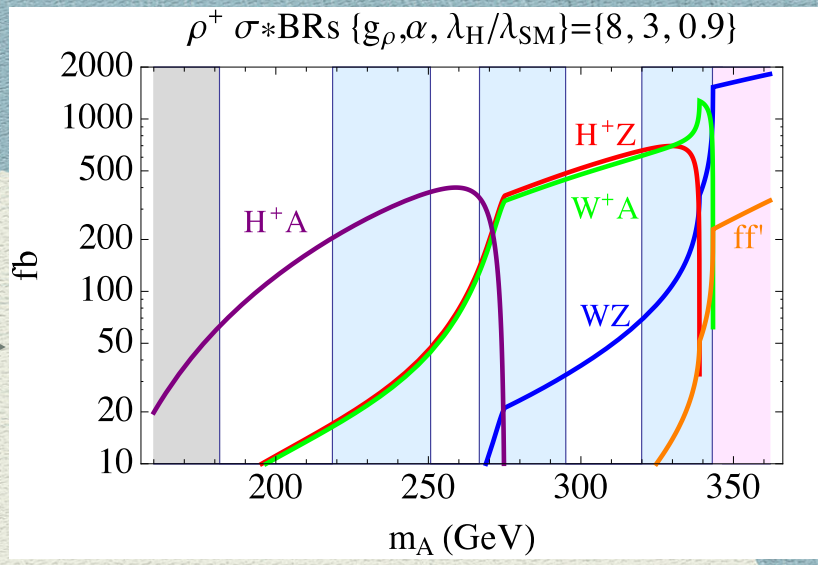



Traditional WZ search is strong until rho can decay into pseudos

For low mass A: $\rho^+ \to H^+ A^0 \to (t\bar{b}, W^+h)(Zh, b\bar{b})$

# Benchmarks

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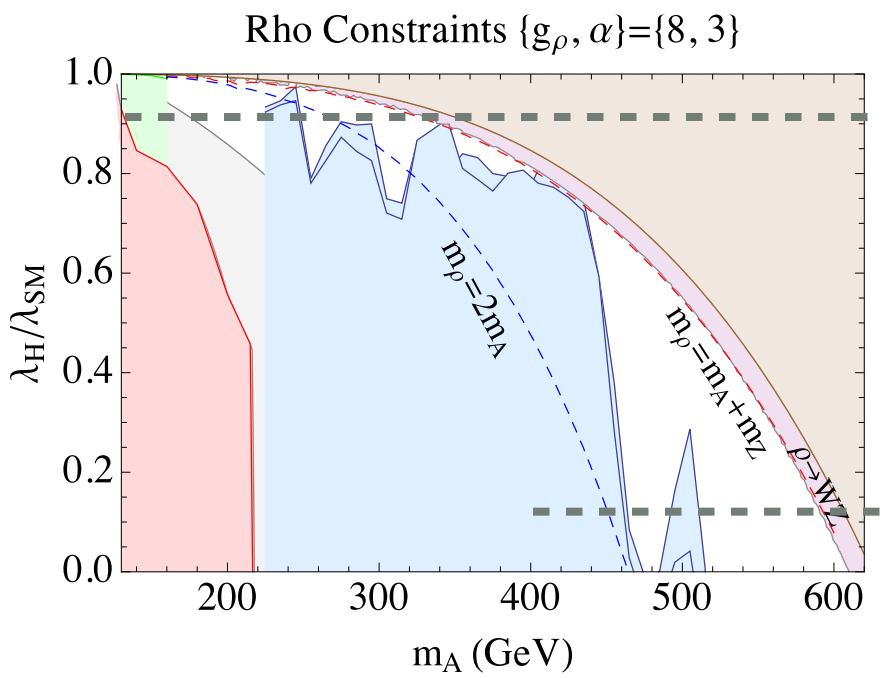


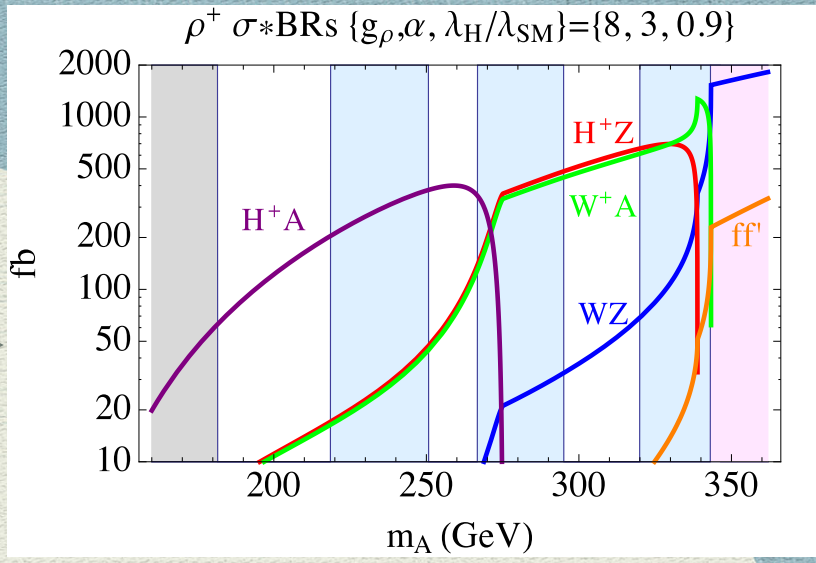


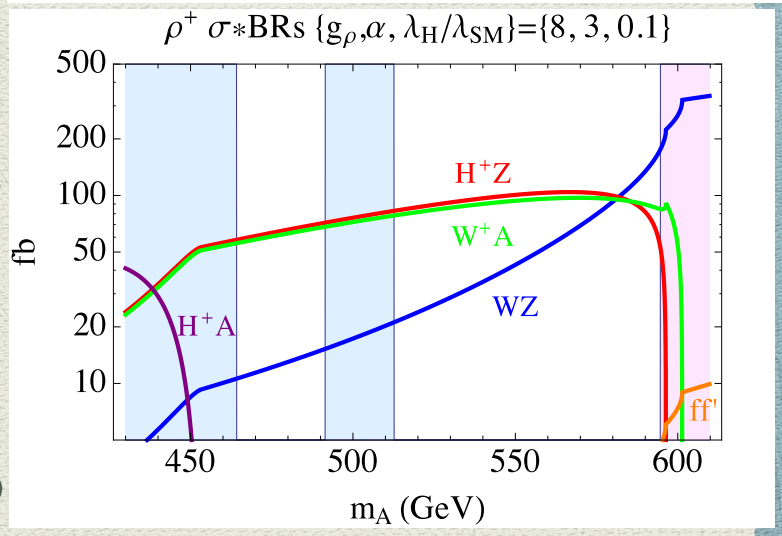


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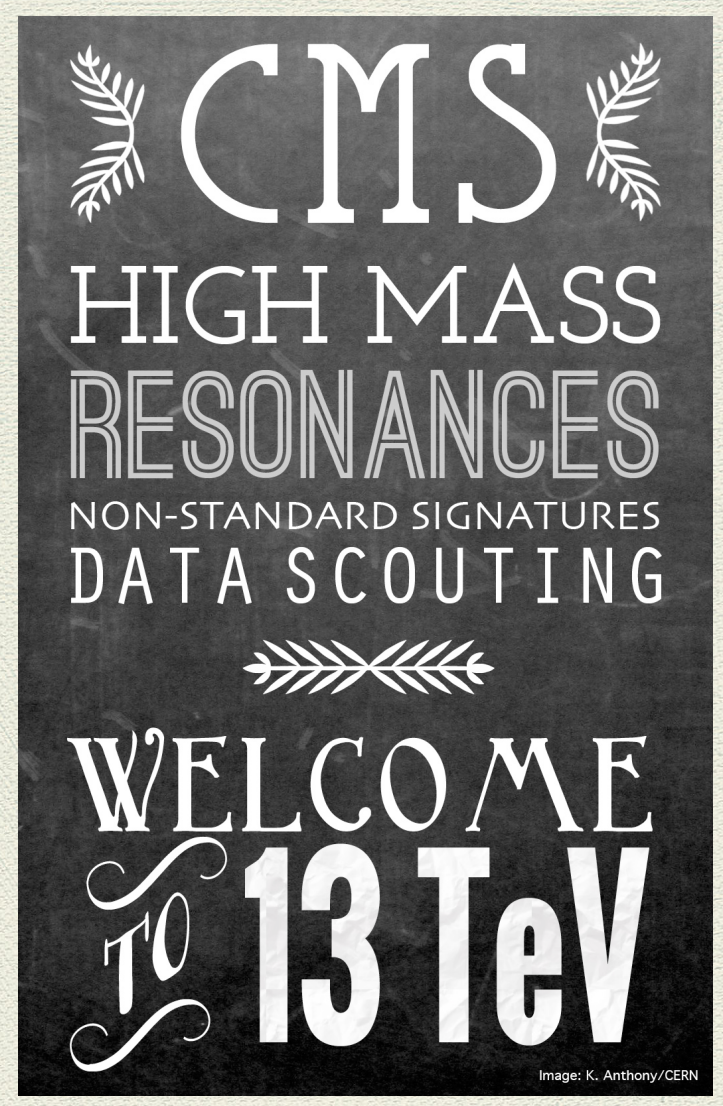
# Conclusion

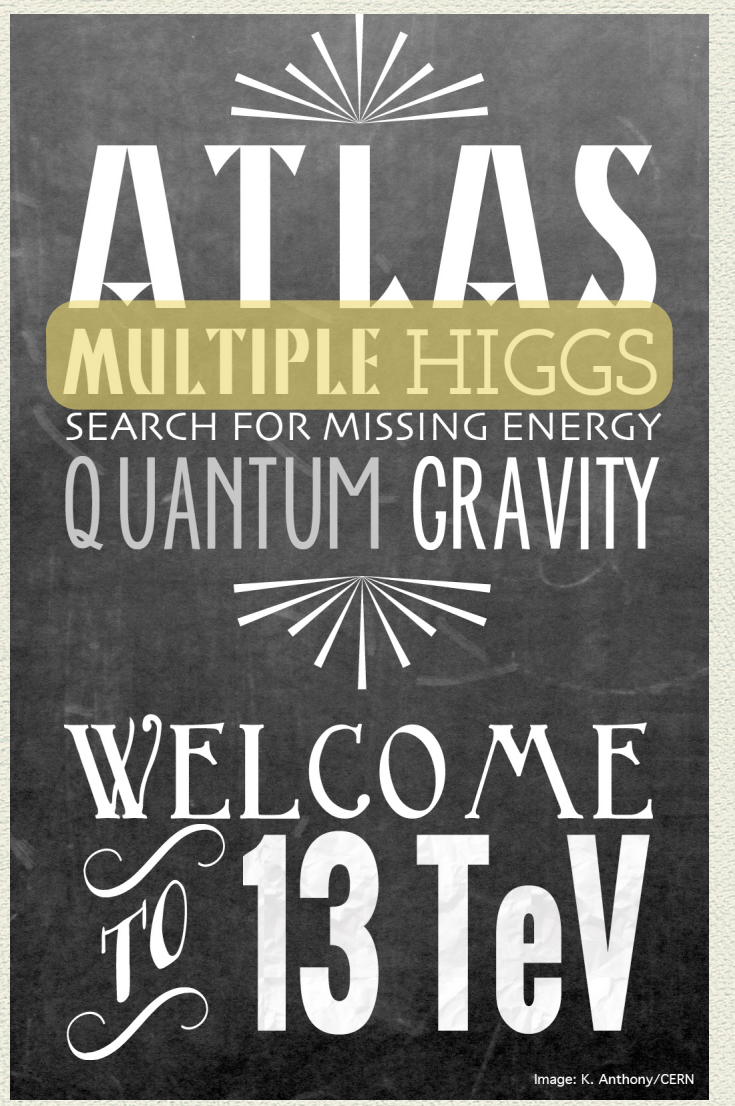
- Modifications of Higgs properties are still allowed
- Higgs potential can be changed w/ induced EWSB
- SUSY+Technicolor hybrid model can help to address SUSY naturalness and TC flavor problem

# Conclusion (cont.)

- In MSSM decoupling, pseudo scalars and other techni-hadrons are still accessible
- Phenomenology has a rich structure which can be searched in Run2


Looking forward to
Run 2!





Looking forward to Run 2!

# Thanks!!!!

# Additional Slides

# Tilted Mexican Hat vs Bowl