Tadpole Induced EWSB & the pNGB Higgs

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LHC SKI 4/11/16

K.H., John Kearney, Roni Harnik. arXiv:1603.03772

Structure of EWSB

LHC8 { 125 GeV Higgs, $\Delta(\sigma \times \mathrm{BR}) \lesssim 10\%$, No light extended Higgs states } → SM-like EwSB?

Aligned Decoupling Limit

$H_1, H_2, \ldots$ — $\Lambda \sim \mathrm{TeV}$

$$H = c_1 H_1 + c_2 H_2 + \ldots$$

$$V = -\frac{m_h^2}{2}|H|^2 + \lambda |H|^4$$

EWSB

246 GeV: $\langle H \rangle = \frac{v}{\sqrt{2}}$

125 GeV: $v^2 = \frac{m_h^2}{2\lambda}$ ~1/8

'Tadpole' Decoupling Limit

$H_1, H_2, \ldots$ — $\Lambda \sim \mathrm{TeV}$

Auxiliary EWSB

$$\langle \Sigma \rangle = d_1 \langle H_1 \rangle + d_2 \langle H_2 \rangle + \ldots$$

$$H = c_1 H_1 + c_2 H_2 + \ldots$$ misaligned

tadpole

$$V = -\kappa^2 \langle \Sigma \rangle \cdot H + \mathrm{h.c.} + m_h^2 |H|^2$$

'Induced' Higgs EWSB

$$\langle \Sigma \rangle^2 + \langle H \rangle^2 = (v_H^2 + f_\Sigma^2)/2 = v^2/2$$

~235 GeV → v_H, ~70 GeV → f_Σ: $\frac{v_H}{f_\Sigma} = \frac{\kappa^2}{m_h^2}$ ← ~230 GeV

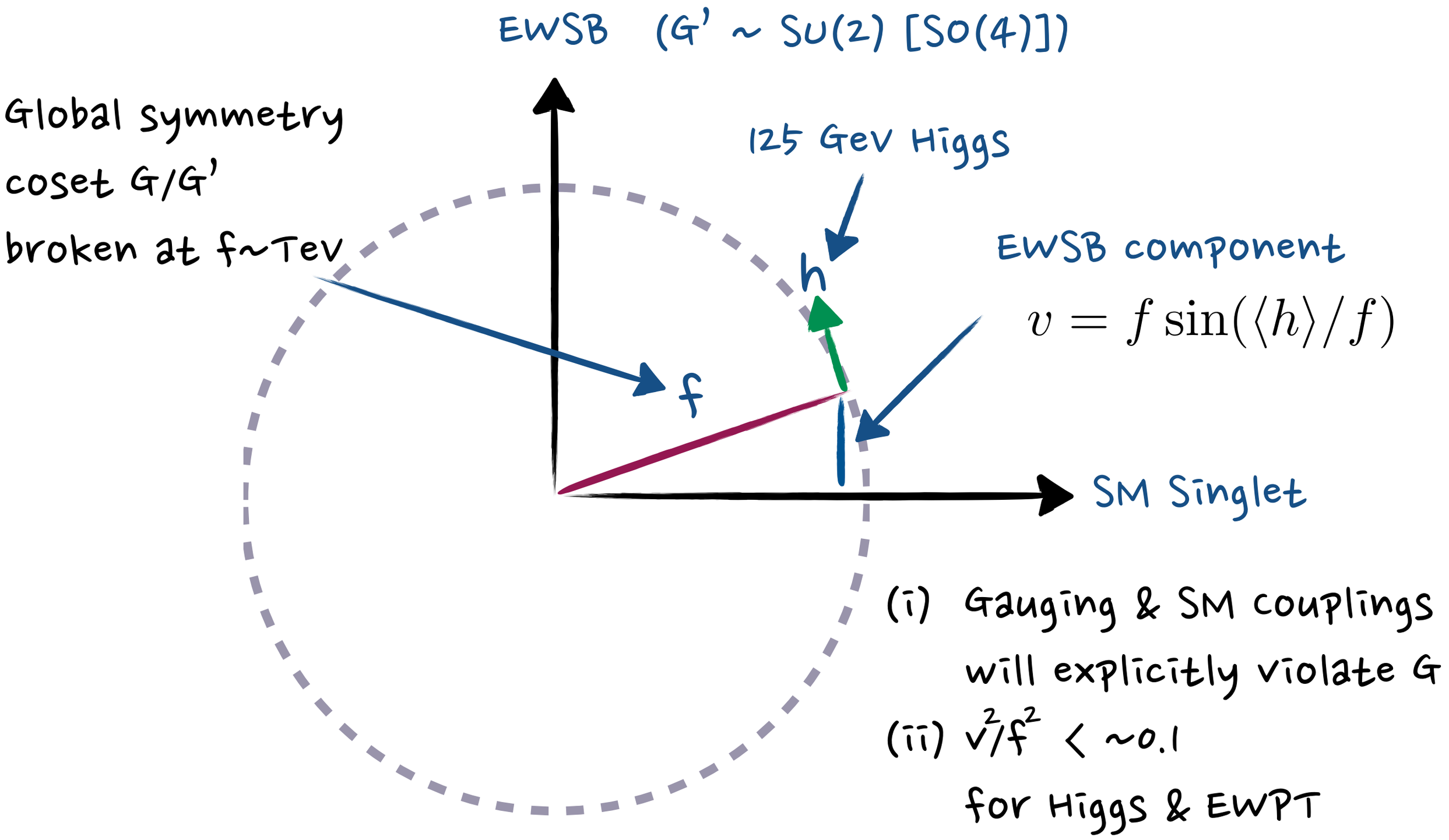
Structure of UV Completions

	SUSY	PNGB Higgs
Higgs Sector SM-like $V = -\frac{m_h^2}{2}\|H\|^2 + \lambda\|H\|^4$	SM	MSSM	MCHM SO(5)/SO(4) Little Higgs Twin Higgs
Tadpole $V = -\kappa^2\langle\Sigma\rangle \cdot H + \text{h.c.} + m_h^2\|H\|^2$	Bosonic Technicolor Kagan, Samuel. '90, '92 Carone, Georgi. '93 hep-ph/9308205	Induced EWSB Luty et. al. 1306.6354, 1411.6023, Kagan et. al.	???

Motivated by mh=125 GeV

pNGB Higgs potential + tadpoles

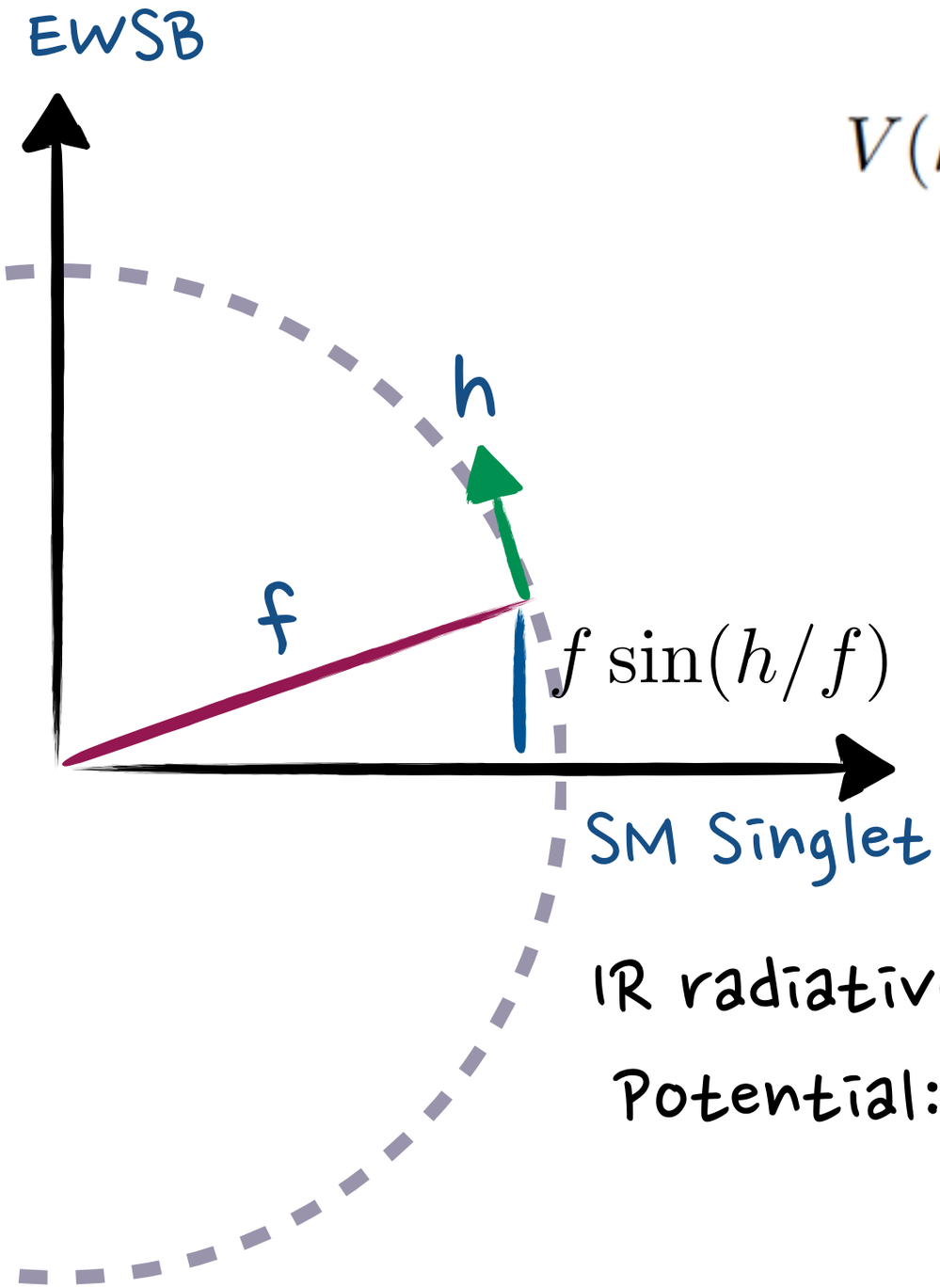
Pseudo-goldstone Higgs (pNGB)



(i) Gauging & SM couplings will explicitly violate G

(ii) $v^2/f^2 < \sim 0.1$ for Higgs & EWPT

pNGB potential



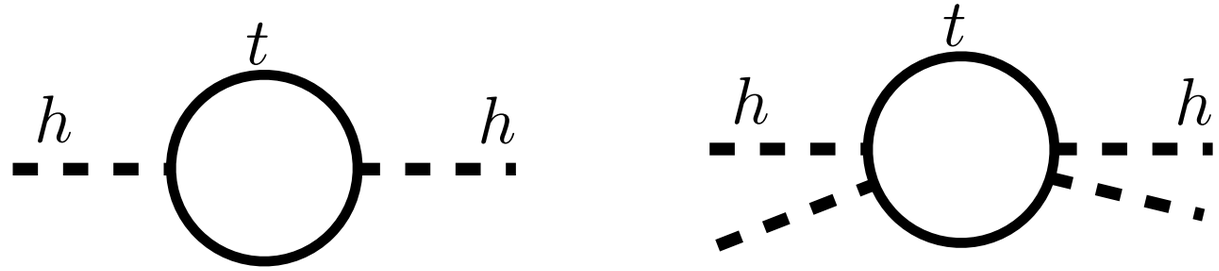
$$V(h) = -\alpha f_H^4 \sin^2\left(\frac{h}{f_H}\right) + \beta f_H^4 \sin^4\left(\frac{h}{f_H}\right)$$

($\alpha \sim m_h^2/(4f_H^2)$, $v/f \ll 1$)

($\beta \sim \lambda/4$, $v/f \ll 1$)

EWSB vacuum	$\dfrac{v}{f} = \dfrac{\alpha}{2\beta}$

IR radiative Potential:

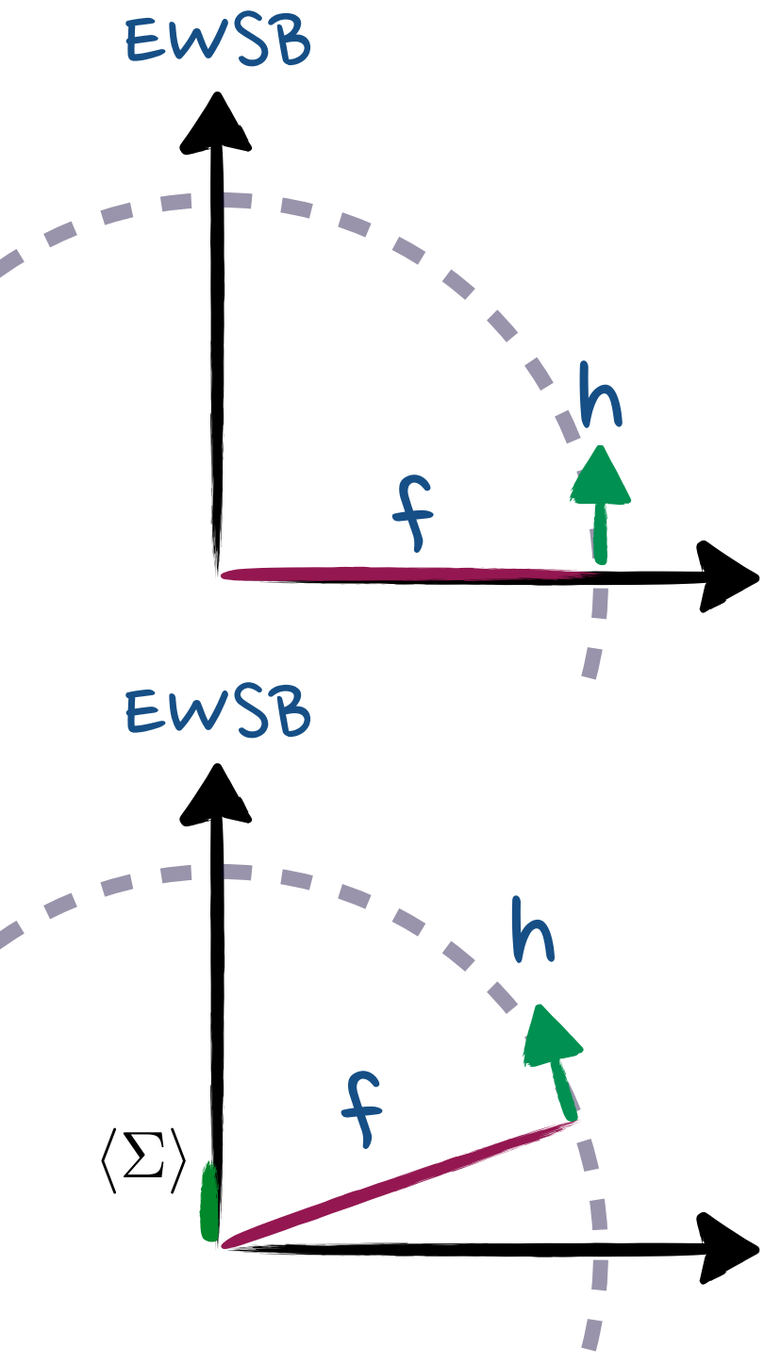


$$\alpha \gtrsim \frac{3y_t^2}{16\pi^2}\frac{m_*^2}{f^2} \;\gg\; \beta \gtrsim \frac{3y_t^2}{32\pi^2}\log\frac{m_*^2}{m_t^2}$$

including thresholds:

$$\alpha \gtrsim \beta \longrightarrow \sim v^2/f^2 \text{ tuning in } \alpha$$

‘Frozen’ Tadpole



$$V(h) = -\alpha f_H^4 \sin^2\left(\frac{h}{f_H}\right) + \beta f_H^4 \sin^4\left(\frac{h}{f_H}\right)$$

radiative $\alpha < 0 \longrightarrow v = 0$

tadpole

$$\Delta V = -\kappa^2 \langle \Sigma \rangle \cdot H = -\gamma f^4 \sin(h/f)$$

$$\frac{v_H}{f_H} = \frac{\gamma}{2\alpha}$$

EWSB vacuum	$\dfrac{v_H}{f_H} = \dfrac{\gamma}{2\alpha}$	$\gamma \ll \alpha$ Natural!

SO(5)/SO(4) 5+1

composite Higgs in (nonlinear) 5

$$\mathcal{H} = (\underbrace{0, 0, 0, f\sin(h/f), f\cos(h/f)}_{SO(4)})$$

composite top partners in 5 = 4 + 1

$$\psi = (\psi_4^i, \psi_1),\ \psi^c = (\psi_4^{ci}, \psi_1^c)$$

Partial compositeness:

composite Yukawa ~ m/f

$$\mathcal{L}_y = m_*(\frac{\mathcal{H}}{f}\cdot\psi)(\frac{\mathcal{H}}{f}\cdot\psi^c) = m_*\psi_4\sin(h/f)\psi_1^c + ...$$

$$\mathcal{L}_{\text{mix}} = y_L f q_L\cdot\psi^c + y_R t_R(\mathcal{H}\cdot\psi)$$

Explicit SO(5) breaking

light states

$$\psi_1^c = \sin\theta_R\hat{t}_R + ...$$
$$\psi_4 = \sin\theta_L\hat{t}_L + ...$$
$$\tan\theta_L \approx y_L f/m_*$$

Top Yukawa

$$y_t = \frac{m_*}{f}(\sin\theta_L\sin\theta_R)$$

($\sin\theta_R \sim 1 \rightarrow y_L = y_t$: composite RH top)

$$\rightarrow\ y_L \gtrsim y_t$$

top partner contributions

$$\Delta\alpha \sim \frac{3y_L^2}{16\pi^2}\frac{m_*^2}{f^2} \qquad \Delta\beta \sim \frac{3y_L^4}{16\pi^2}$$

Tuning of 5+1 Model

top partner contributions

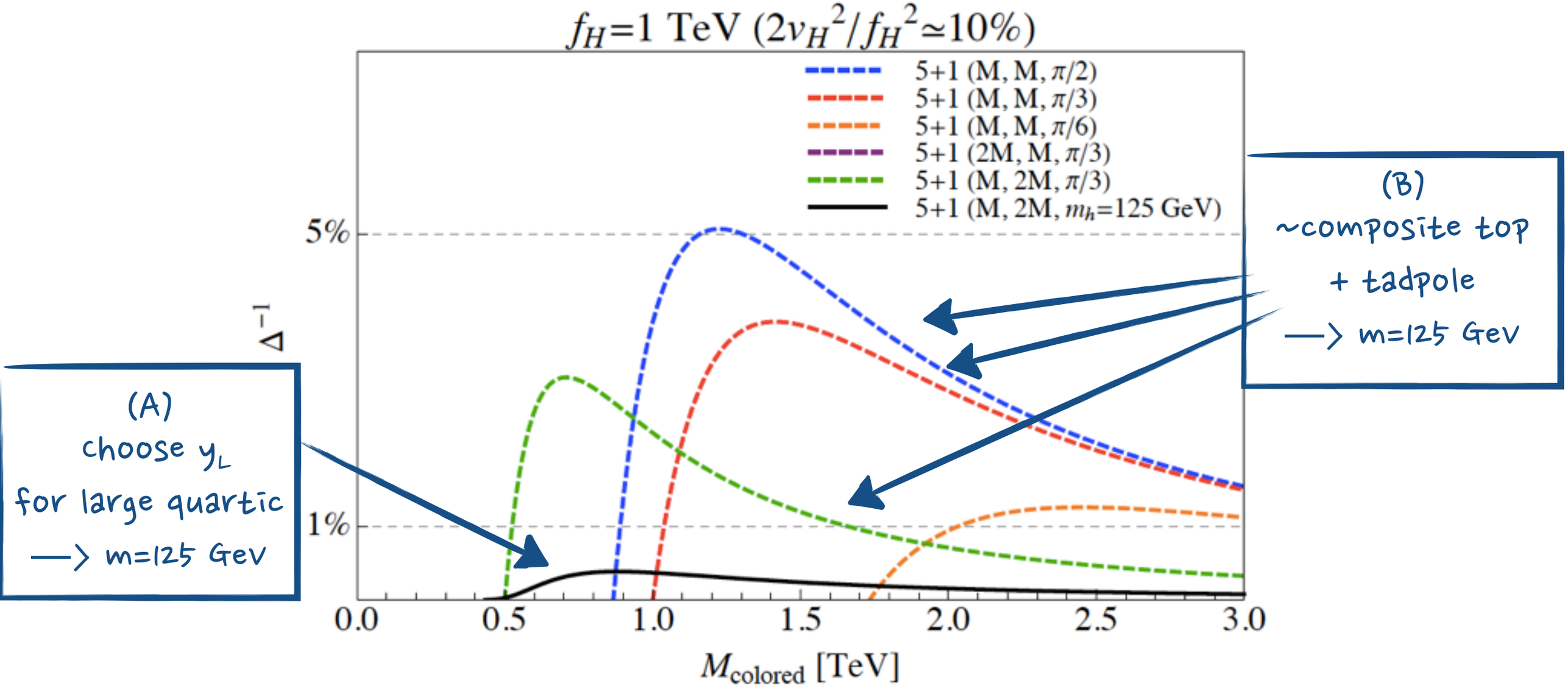
$$\Delta\alpha \sim \frac{3y_L^2}{16\pi^2}\frac{m_*^2}{f^2} \qquad \Delta\beta \sim \frac{3y_L^4}{16\pi^2}$$

Two-Site Model
(1-loop calculable)

tuning measure

$$\Delta = \frac{\partial \ln \alpha}{\partial \ln \alpha_0} = 1 - \frac{\delta\alpha}{\alpha_{\rm obs}}$$

$$\alpha_{\rm obs} = \alpha_0 + \delta\alpha \simeq \frac{(125\ {\rm GeV})^2}{2f_H^2} \simeq \frac{1}{8}\frac{v_H^2}{f_H^2}$$



(A)
choose y_L
for large quartic
—> m=125 Gev

(B)
~composite top
+ tadpole
—> m=125 Gev

Tuning of 5+1 Model

(c)

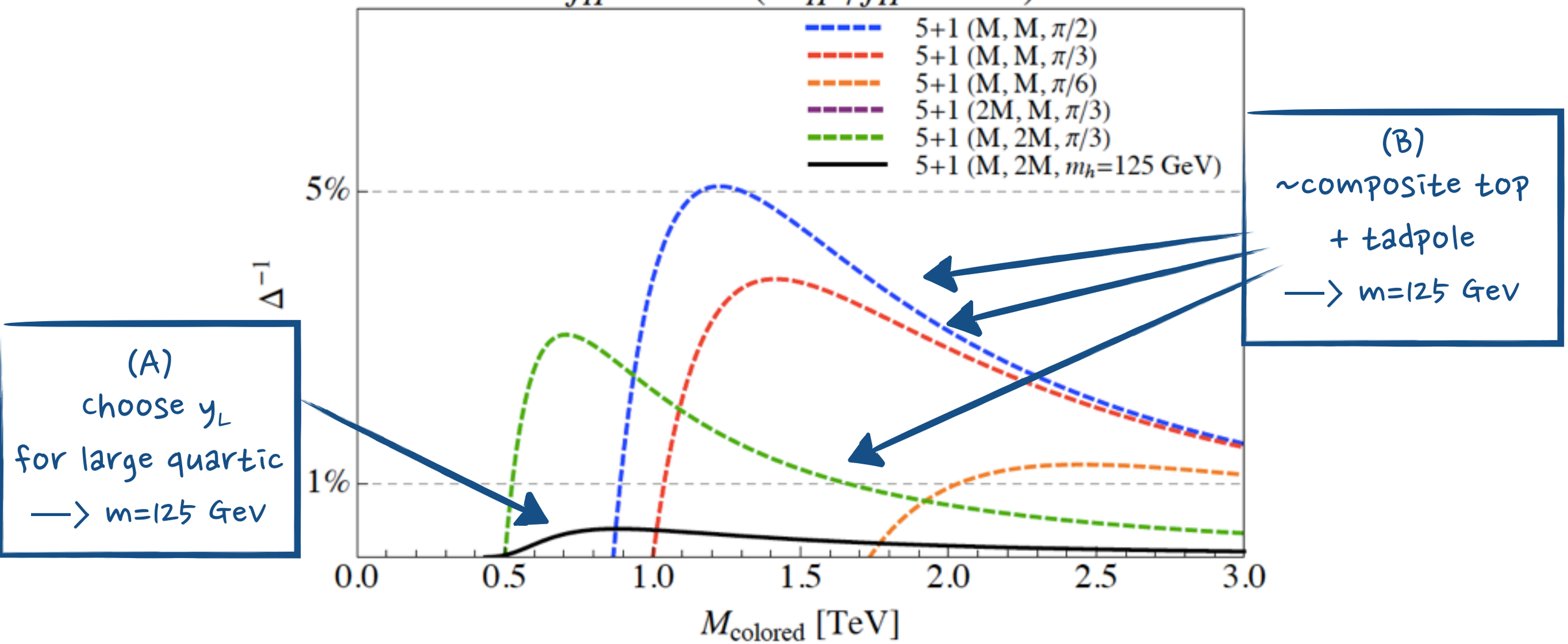
non-minimal radiative contributions

(e.g. from tau)

$\Delta\alpha' \sim \Delta\beta'$ —> m=125 GeV

$\Delta^{-1} \lesssim v^2/f^2 \sim 5\%$

'irreducible tuning'

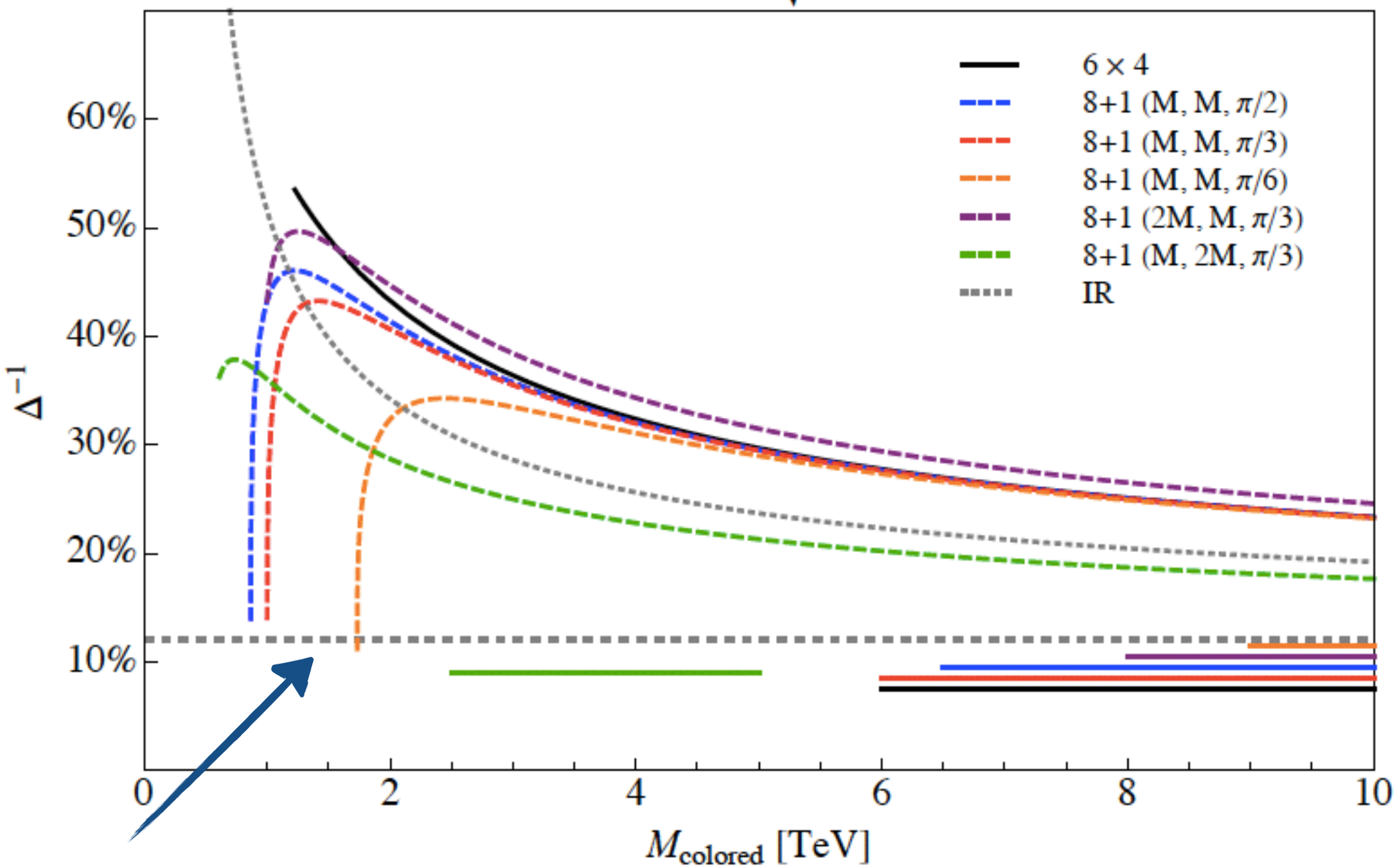


(A)
choose y_L
for large quartic
—> m=125 GeV

(B)
~composite top
+ tadpole
—> m=125 GeV

Tuning of Twin Higgs 8+1

f_H=1 TeV ($m_{t_B} \approx \frac{y_t f_H}{\sqrt{2}} \approx$700 GeV)



$2v^2/f^2 \sim 10\%$

Auxiliary Sector Dynamics & Pheno

Guidance from nature...

spontaneous
h2o 'condensate'

"A Frozen Tadpole"

Linear Sigma Model

unperturbed sector

$$V_\Sigma = -\Lambda_\Sigma^2 |\Sigma|^2 + \delta_\Sigma |\Sigma|^4$$

$$f_\Sigma^2 = \frac{\Lambda_\Sigma^2}{\delta_\Sigma}$$

Higgs as a perturbation:

$$|\Sigma| = \frac{f_\Sigma + \sigma}{\sqrt{2}}$$

fluctuations of aux vev

"tadpole back-reaction"

$$V_\Sigma = \Lambda_\Sigma^2 \sigma^2 - \kappa^2 (f_H s_h)\sigma$$

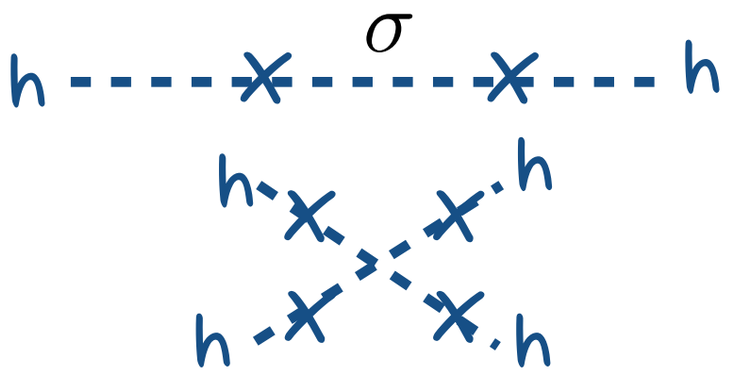
Mixing with light Higgs:

$$\epsilon = \frac{\kappa^2}{2\Lambda_\Sigma^2} \qquad \epsilon \simeq 0.14 \left(\frac{4\pi^2}{\delta_\Sigma}\right)\left(\frac{70\ \text{GeV}}{f_\Sigma}\right)^4$$

extra tuning?

$$V_h \supset -\epsilon^2 \Lambda_\Sigma^2 f_H^2 s_h^2 \simeq -\frac{\kappa^4}{4\Lambda_\Sigma^2 f_H^2} f_H^4 s_h^2$$

$$\left|\frac{(\delta\alpha)_\Sigma}{\alpha}\right| \simeq 0.5 \left(\frac{4\pi^2}{\delta_\Sigma}\right)\left(\frac{70\ \text{GeV}}{f_\Sigma}\right)^4$$



consistency

$$\frac{\langle\sigma\rangle}{f_\Sigma} \simeq \frac{m_h^2 v_H^2}{\delta_\Sigma f_\Sigma^4} \simeq 0.5 \left(\frac{4\pi^2}{\delta_\Sigma}\right)\left(\frac{70\ \text{GeV}}{f_\Sigma}\right)^4$$

Strongly Coupled Auxiliary

Λ_H ~10 TeV

f_H ~TeV

?? $\Lambda_\Sigma \sim 4\pi f_\Sigma$ ~700 GeV

$\mathcal{O}_\Sigma = \Sigma^I + ... \approx \frac{1}{f_\Sigma \Lambda_\Sigma} \psi_\Sigma \bar{\psi}_\Sigma$ Technicolor-like confinement

$\kappa^2 : SO(4)_\Sigma \times SO(4)_H \to SO(4)$

Vector Mesons $\rho^{\pm,0}$

2HDM States $A, H^\pm, H^0$

v ~246 GeV

f_Σ ~70 GeV

Higgs couplings

Higgs Couplings

Tadpole Sector

$$\kappa_f \equiv \frac{g_{hf\bar{f}}}{g_{hf\bar{f}}^{(\mathrm{SM})}} = \frac{1}{\sqrt{1-\frac{f_\Sigma^2}{v^2}}},$$

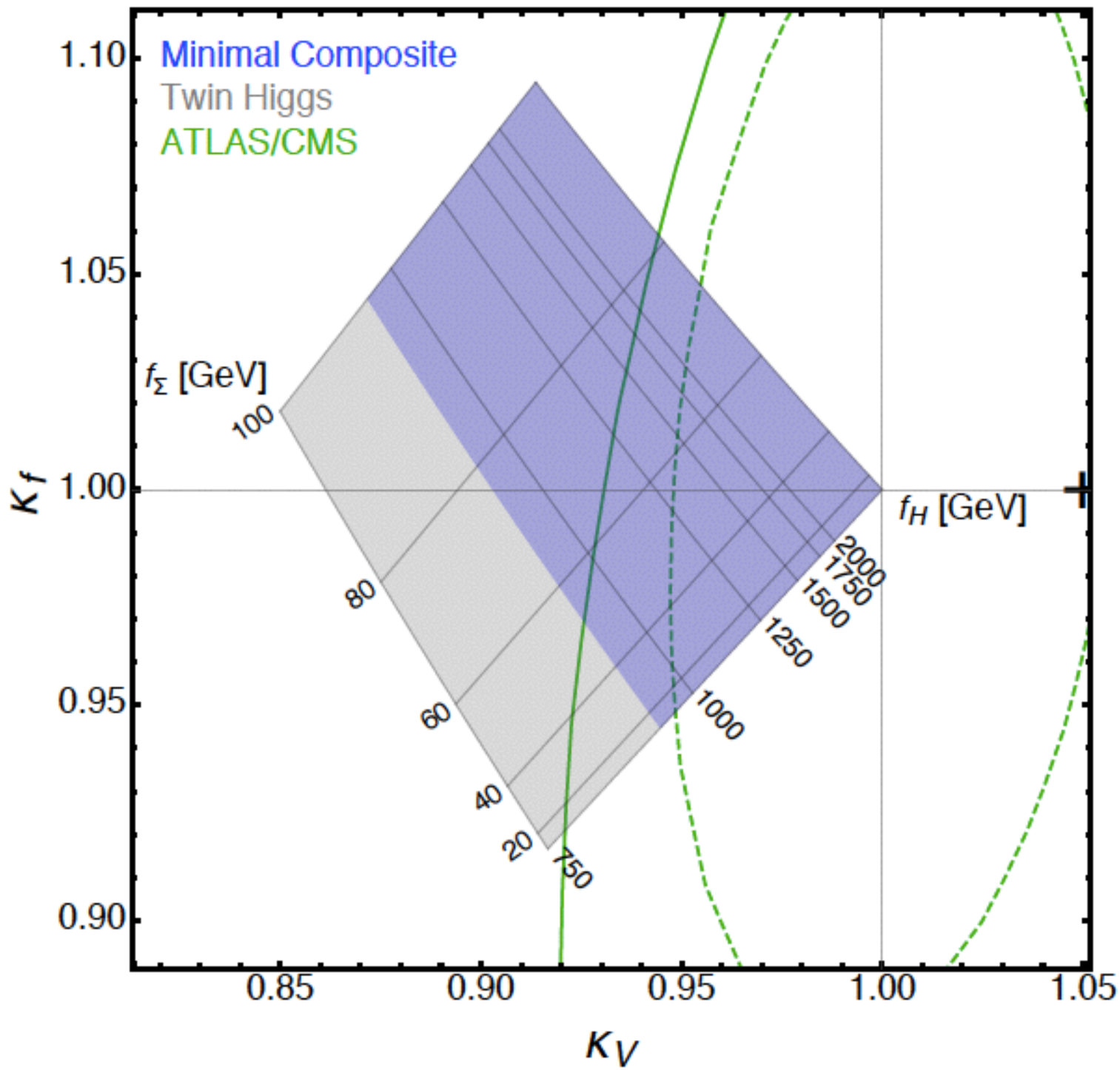
$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{(\mathrm{SM})}} = \sqrt{1-\frac{f_\Sigma^2}{v^2}}.$$

PNGB

$$\kappa_h^{(\mathrm{pNGB})} \simeq \sqrt{1-\frac{v_H^2}{f_H^2}}.$$

Upper bound:

$f_\Sigma < 80$ GeV



Extra States

$m_\rho \sim 4\pi f_\Sigma$ ~700 GeV

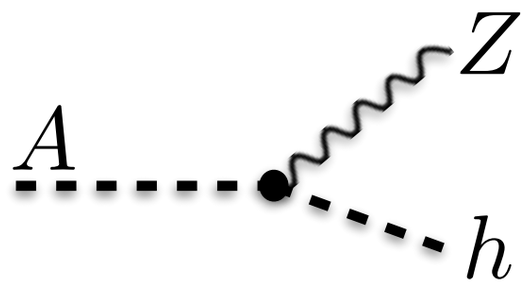
$m_A^2 = m_{H^\pm}^2 \simeq m_h^2 \frac{v^2}{f_\Sigma^2}$

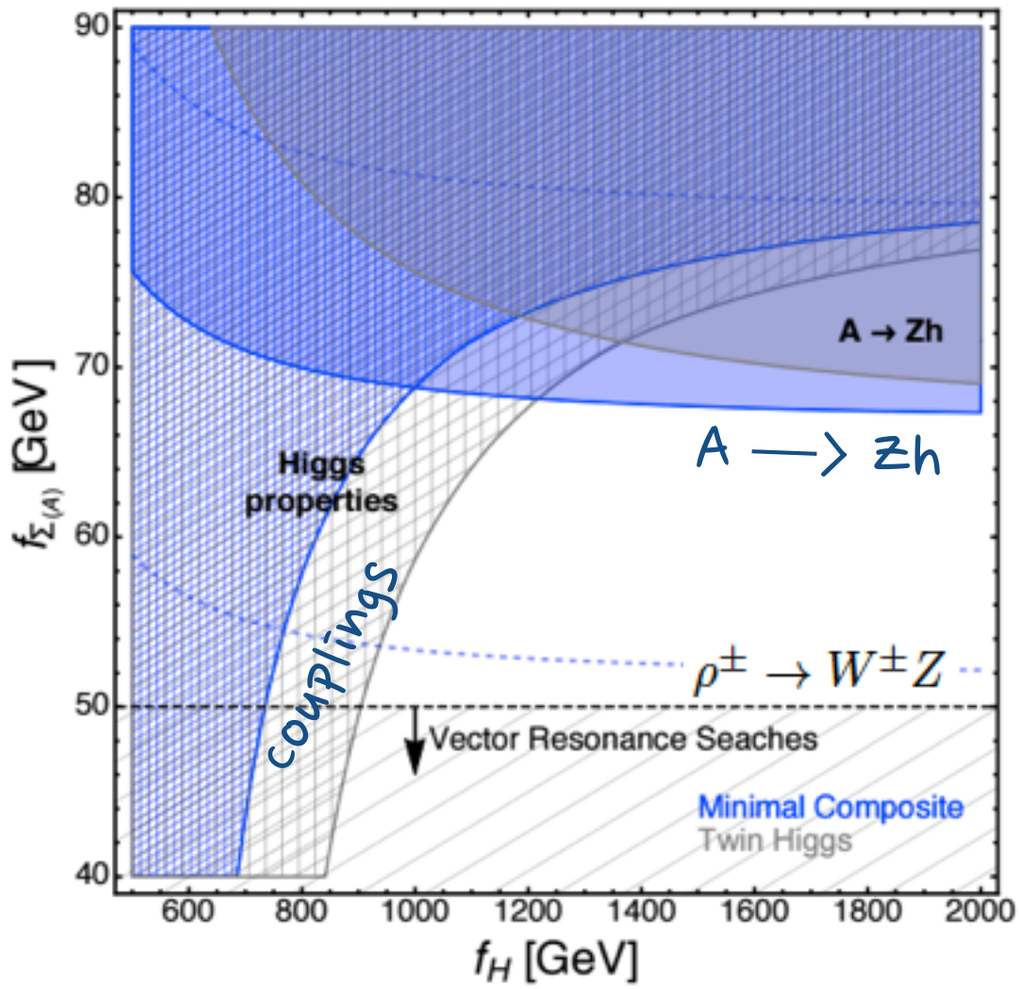
~400-700 GeV

f_Σ ~70 GeV

Upper bound:

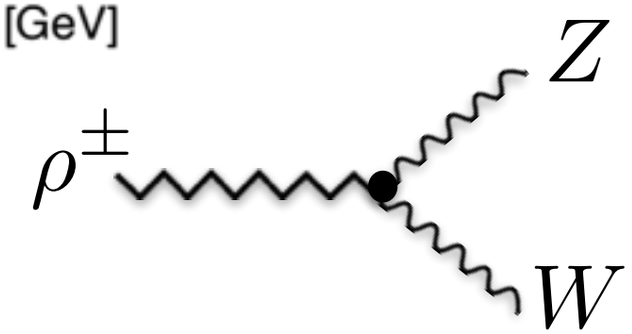
f_Σ <~ 70 GeV





Lower bound:

f_Σ >~ 50 GeV



CONCLUSIONS

- Composite Higgs Models can have analog of SUSY little Hierarchy

- Tadpole induced EWSB can alleviate tuning by factor of 5-10

  — even the 'irreducible' tuning $\sim v^2/f^2$

  — 5+1 ~ 10% tuned, Twin Higgs ~50%

  (other twin benefits: U(1) breaking, Spontaneous Z2)

  - Auxiliary dynamics consistent with strongly coupled sector, no extra tuning

- Higgs couplings + extra states give lower and upper bounds on scales

  (—> if scales related, fH ~ TeV)

Thanks!

back-ups

SUSY Little Hierarchy analogies

tuning

	MSSM	PNGB (MCHM 5+1/twin)
Large IR contribution	stops >> Tev	top partners >> Tev
Extra thresholds from top partners	Large A-Terms	Large t_L compositeness
Non-minimal thresholds	extra vector-like matter	Large tau compositeness [carone et. al. 1410.8555]
Tree-level quartic	D-terms NMSSM / lambda-SUSY	Little Higgs-like
Tadpole	Induced EWSB	...

Linear Sigma Model

unperturbed sector

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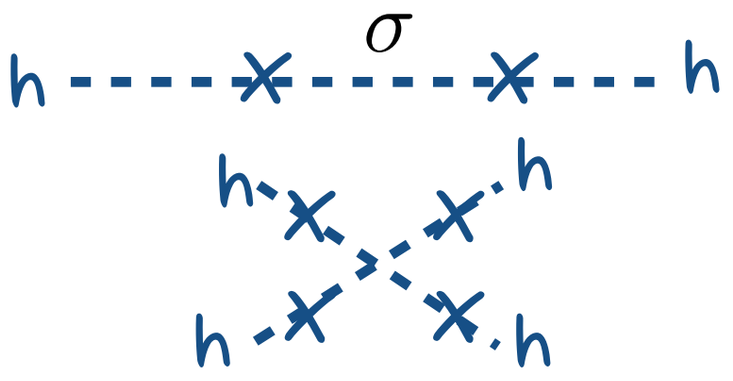

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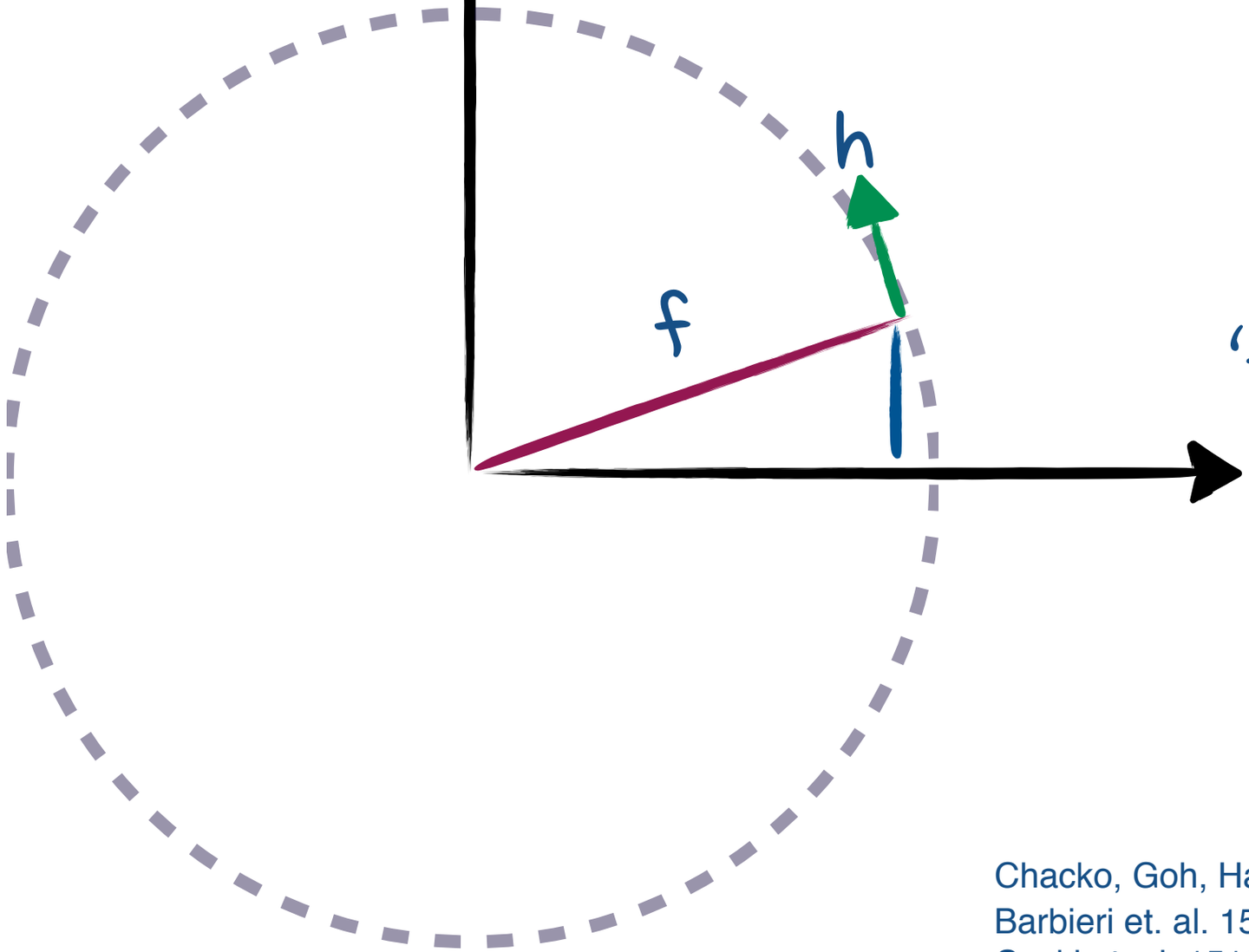
Twin Higgs (pNGB)

EWSB
$SO(4)_A$

$G/G' \sim SO(8)/SO(7)$

$SO(8) \longrightarrow SO(4)_A \times SO(4)_B \times Z_2$

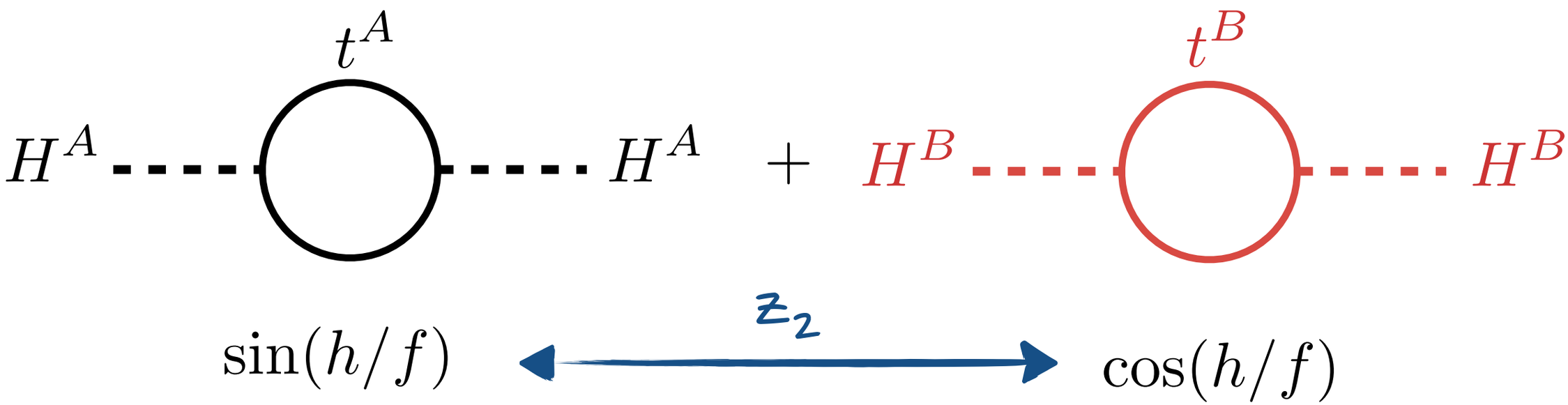


'twin sector'
EWSB B
$SO(4)_B$

$$m_{t_B} \approx \frac{f}{v} m_t$$

Chacko, Goh, Harnik hep-ph/0506256, hep-ph/0512088
Barbieri et. al. 1501.07803, Low et. al. 1501.07890,
Csaki et. al. 1512.03427

Twin Higgs (pNGB)



$$V = \hat{\alpha} f^4 \sin^2(h/f) + \hat{\beta} f^4 \sin^4(h/f)$$
$$+\hat{\alpha} f^4 \cos^2(h/f) + \hat{\beta} f^4 \cos^4(h/f)$$

$$V = -2\hat{\beta} f^4 \sin^2(h/f) + 2\hat{\beta} \sin^4(h/f)$$

$$\alpha = \beta = 2\hat{\beta}$$

$$\delta\alpha \simeq -\frac{3y_t^4}{32\pi^2} \log \frac{M_T^2}{m_{t_B}^2}$$

colored top partners

Twin Cosmology

BBN + CMB: $\Delta N_{eff} \lesssim 0.5$

$$T_{A-B,eq} \sim 0.1 - 1 \text{ GeV}$$

Light B-sector quarks and leptons removed with asymmetric Yukawas, but neutrinos+gluons+photons give ~1.4 DOF

Option 1: Low asymmetric reheat (successful BBN possible)

Option 2: Splitting between QCD phase transition

$$T^B_{\text{QCD}} < T_{A-B,eq} < T^B_{\text{QCD}}$$

Option 3: Entropy production in QCD phase transition

$$N(q^A) \neq N(q^B)$$