

Top partners: alternative scenarios



Technische Universität München

Strong Dynamics at the Electroweak Scale Montpellier, 7 December 2017



The uses or abuses of symmetries

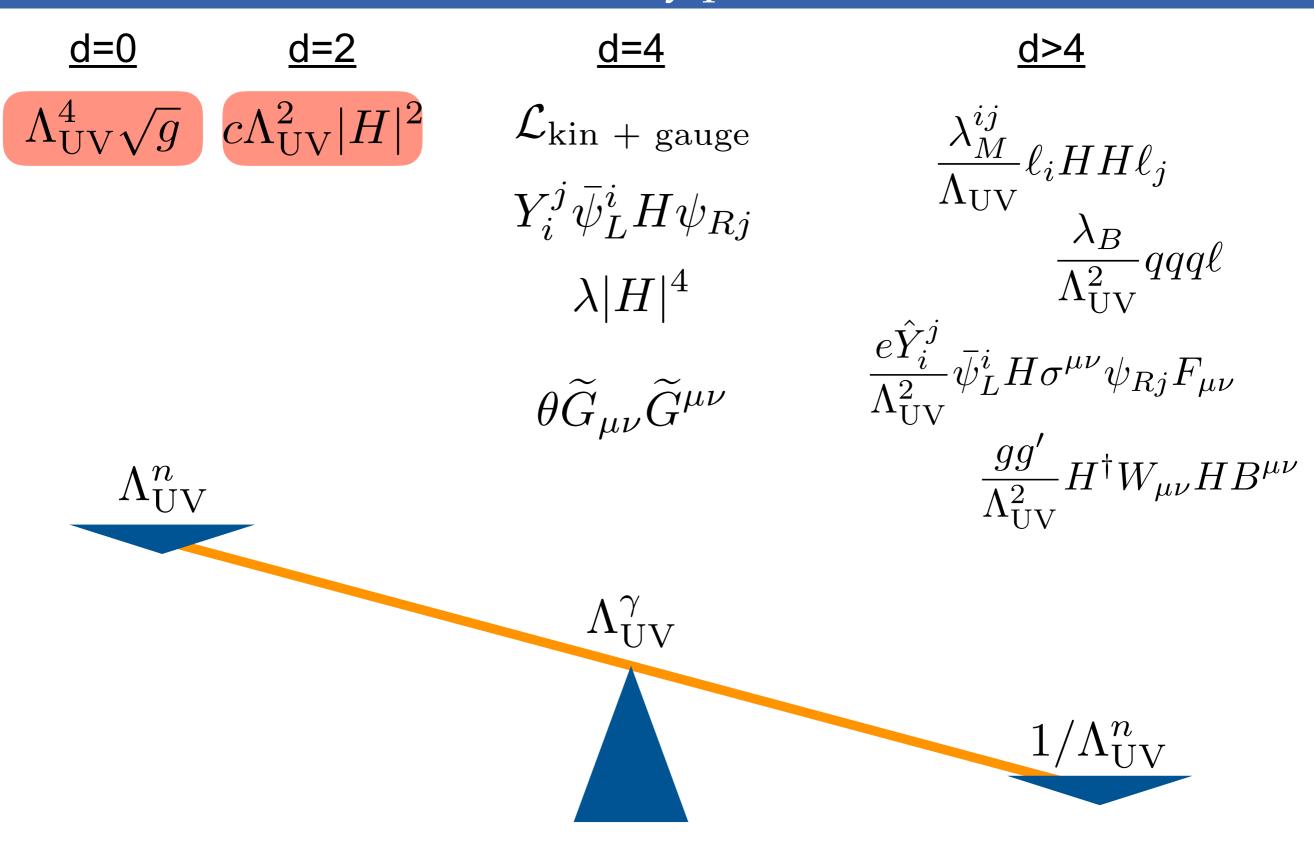


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Strong Dynamics at the Electroweak Scale Montpellier, 7 December 2017 SM & hierarchy problems

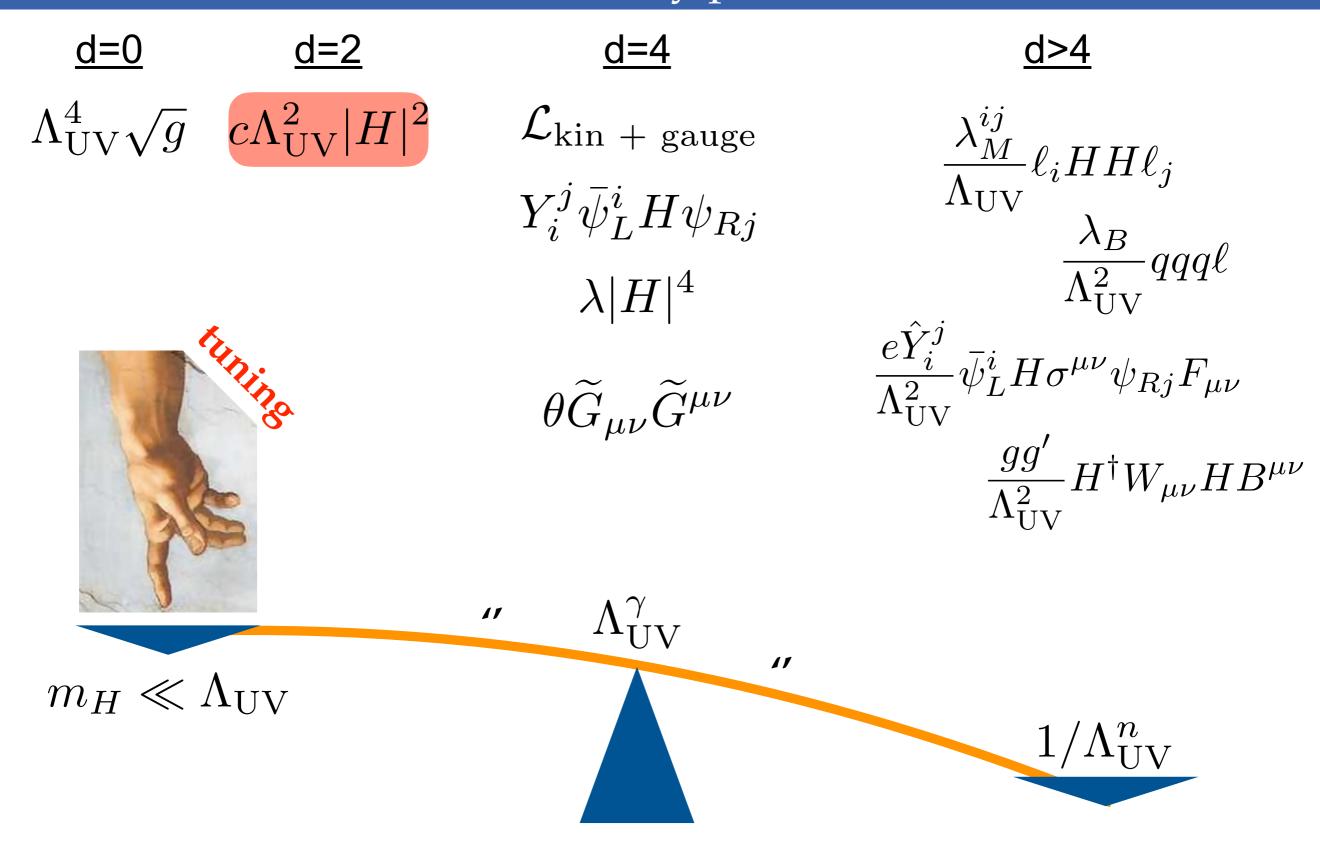
<u>d=0</u>	<u>d=2</u>	<u>d=4</u>	<u>d>4</u>
$\Lambda_{ m UV}^4 \sqrt{g}$	$c\Lambda_{\rm UV}^2 H ^2$	$\mathcal{L}_{\mathrm{kin}+\mathrm{gauge}}$	$\frac{\lambda_M^{ij}}{\Lambda_{\rm UV}}\ell_i H H \ell_j$
		$Y_i^j \bar{\psi}_L^i H \psi_{Rj}$	$rac{\lambda_{ m UV}}{\lambda_B}$
		$\lambda H ^4$	$\frac{\lambda_B}{\Lambda_{\rm UV}^2} q q q \ell$
		$ heta \widetilde{G}_{\mu u} \widetilde{G}^{\mu u}$	$\frac{e\hat{Y}_i^j}{\Lambda_{\rm UV}^2}\bar{\psi}_L^iH\sigma^{\mu\nu}\psi_{Rj}F_{\mu\nu}$
		F	$\frac{gg'}{\Lambda_{\rm UV}^2} H^{\dagger} W_{\mu\nu} H B^{\mu\nu}$

SM & hierarchy problems



Natural expectation gives rise to known hierarchy problems.

SM & hierarchy problems



Gauge principle + (unnatural) separation of scales describes observations.

	symmetry	<u>spurion</u>
B, L numbers	$U(1)_{B,L_e,L_\mu,L_\tau}$	"exact"
Flavor	$SU(3)_{q,u,d,\ell,e}$	$Y \to 0$
	$SU(2)^3_{ m quarks}$	$y_t \neq 0$
СР	$\psi o \psi^*$	$\delta \to 0$
Custodial	$SO(4)_C \cong SU(2)_L \times SU(2)_R$	$y_t, g' \to 0$
Unification	SU(5)	"remnant"
		$ar{f 5}+{f 10}$

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Gauge principle + (unnatural) decoupling has been "corroborated":

neutrino masses?

$$m_{\nu} \approx 0.05 \text{eV} \longleftrightarrow \frac{\lambda_M}{\Lambda_{\text{UV}}} \sim (10^{15} \text{GeV})^{-1}$$

 $\Lambda_{\rm UV} \lesssim 10^7 {
m GeV}$ type I

strong CP problem?

$$\theta \ll 1 \longleftrightarrow \frac{a}{f_a} \widetilde{G}_{\mu\nu} \widetilde{G}^{\mu\nu}$$
$$\Lambda_{\rm UV} \lesssim 4\pi f_a \,, f_a \gtrsim 10^9 {\rm GeV} \qquad \qquad \Lambda_{\rm UV} \lesssim 10 {\rm TeV}$$
KSVZ

dark matter?

$$(-1)^{3B+L+2s} = -1 \longleftrightarrow$$
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symmetries & BSM physics



We are not content with unnatural separation of scales:

 $\Lambda_{\rm UV} \sim {\rm TeV}$

If no separation of scales, SM symmetries (successes) are generically lost. \mathcal{E} No BSM physics discovered yet. symmetries & BSM physics



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We are not content with unnatural separation of scales:

 $\Lambda_{\rm UV} \sim {\rm TeV}$

If no separation of scales, SM symmetries (successes) are generically lost. & No BSM physics discovered yet. BSM must enjoy SM **symmetries** (and **spurions**) at TeV energies.

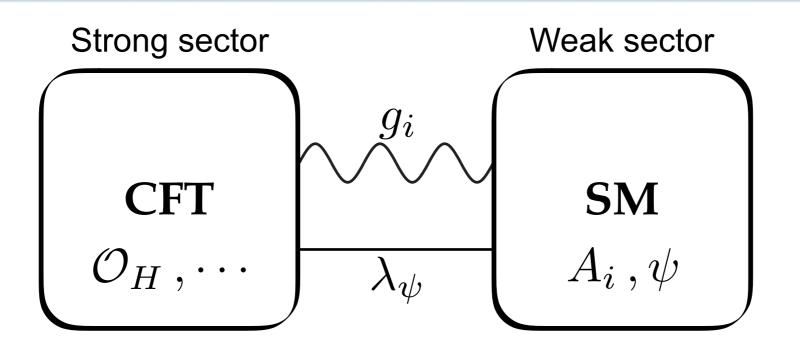
 \mathcal{E}

If **natural**, characteristic scale of *some* phenomena best kept high.

Higgs (of course) and **top** are singled out: $\Lambda^{H}_{\rm UV} \sim \Lambda^{t}_{\rm UV} \sim {\rm TeV}$

modern Composite Higgs models

$$\Lambda'_{\rm UV} \equiv \Lambda_{\not\!\!B} , \Lambda_{\not\!\!L} , \Lambda_{Flqvor} , \Lambda_{S \not\!\!U(5)} ?$$



 $d(\mathcal{O}_{|H|^2}) \gtrsim 4$ no more EW hierarchy problem

 g_* = Higgs coupling $g_* \gtrsim g_i, \lambda_\psi$ f = Higgs scale $m_* \sim g_* f$ = Composites' mass $\Lambda_{\rm UV}^H \equiv m_*$

$$\epsilon_{g_i} \equiv g_i/g_* \quad \epsilon_\psi \equiv \lambda_\psi/g_*$$

$$\begin{split} \begin{array}{l} \textbf{Conformal Technicolor (CTC)} \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\ & & \\$$

$$d_{H} = d(\mathcal{O}_{H})$$

$$\uparrow$$

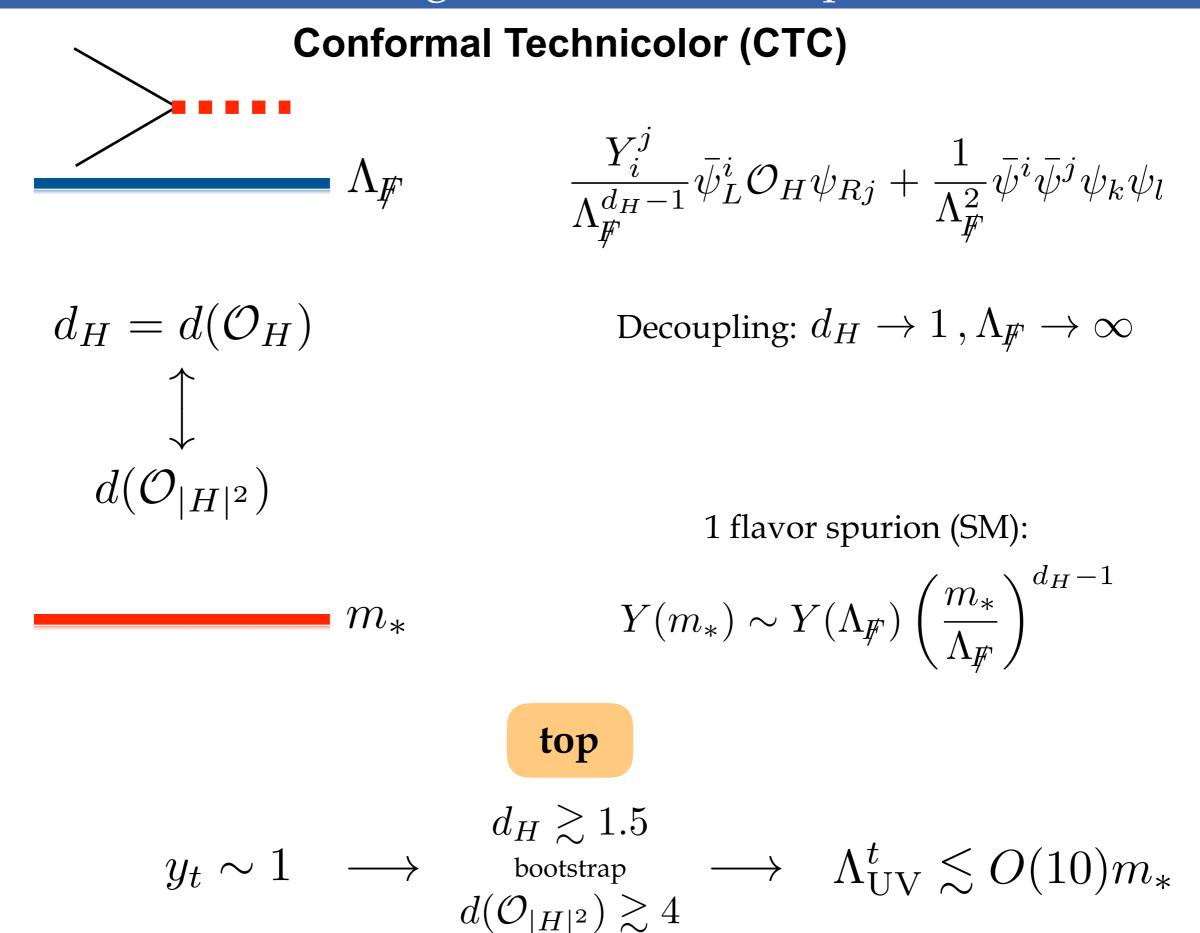
$$d(\mathcal{O}_{|H|^{2}})$$

 m_*

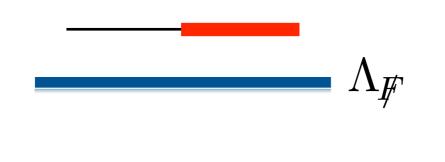
Decoupling:
$$d_H \to 1, \Lambda_{
var} \to \infty$$

1 flavor spurion (SM):

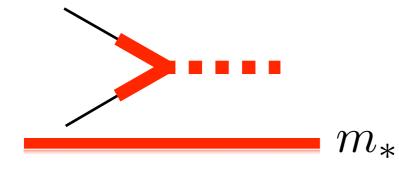
$$Y(m_*) \sim Y(\Lambda_{F}) \left(\frac{m_*}{\Lambda_{F}}\right)^{d_H - 1}$$



Partial Compositeness (PC)



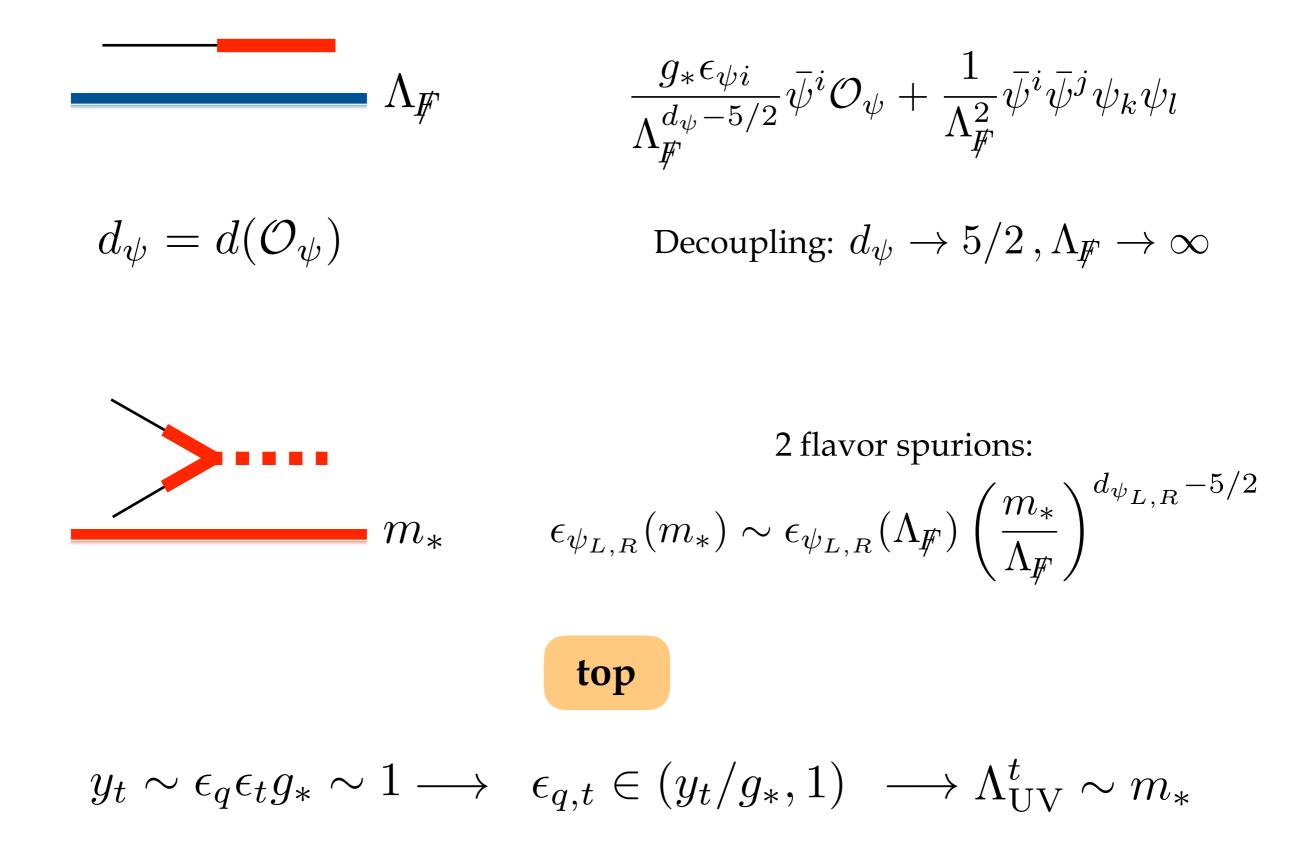
 $d_{\psi} = d(\mathcal{O}_{\psi})$



2 flavor spurions:

$$\epsilon_{\psi_{L,R}}(m_*) \sim \epsilon_{\psi_{L,R}}(\Lambda_{\not\!\!F}) \left(\frac{m_*}{\Lambda_{\not\!\!F}}\right)^{d_{\psi_{L,R}}-5/2}$$

Partial Compositeness (PC)



Energy

B, L numbers

 $m_* = 3$ TeV , $g_* = \pi$

$$U(1)_{B,L_e,L_\mu,L_ au}$$

e.g. neutrino masses

<u>CTC</u>

$$m_{\tau} \sim \frac{g_* v}{\sqrt{2}} \left(\frac{m_*}{\Lambda_{F}}\right)^{d_H - 1} \longrightarrow d_H \approx 2, \Lambda_{F} \approx 10^6 \text{GeV}$$
$$m_{\nu} \sim \frac{(g_* v)^2}{2m_*} \left(\frac{m_*}{\Lambda_{F}}\right)^{2d_H - 1} \approx 10^5 (\Delta m)_{\text{atm}}$$

B, *L* numbers $U(1)_{B,L_e,L_\mu,L_\tau}$

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We must require *L* number at Λ_{F}



B, L numbers

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Note that in PC X number must exist such that: $Y = T_R^3 + X$

 $X = \alpha L = \beta B$

 $SU(3)_{q,u,d,\ell,e} \quad \psi \to \psi^*$ Flavor & CP

$$EDMs, \mu \rightarrow e\gamma, \epsilon_K$$

<u>PC</u>

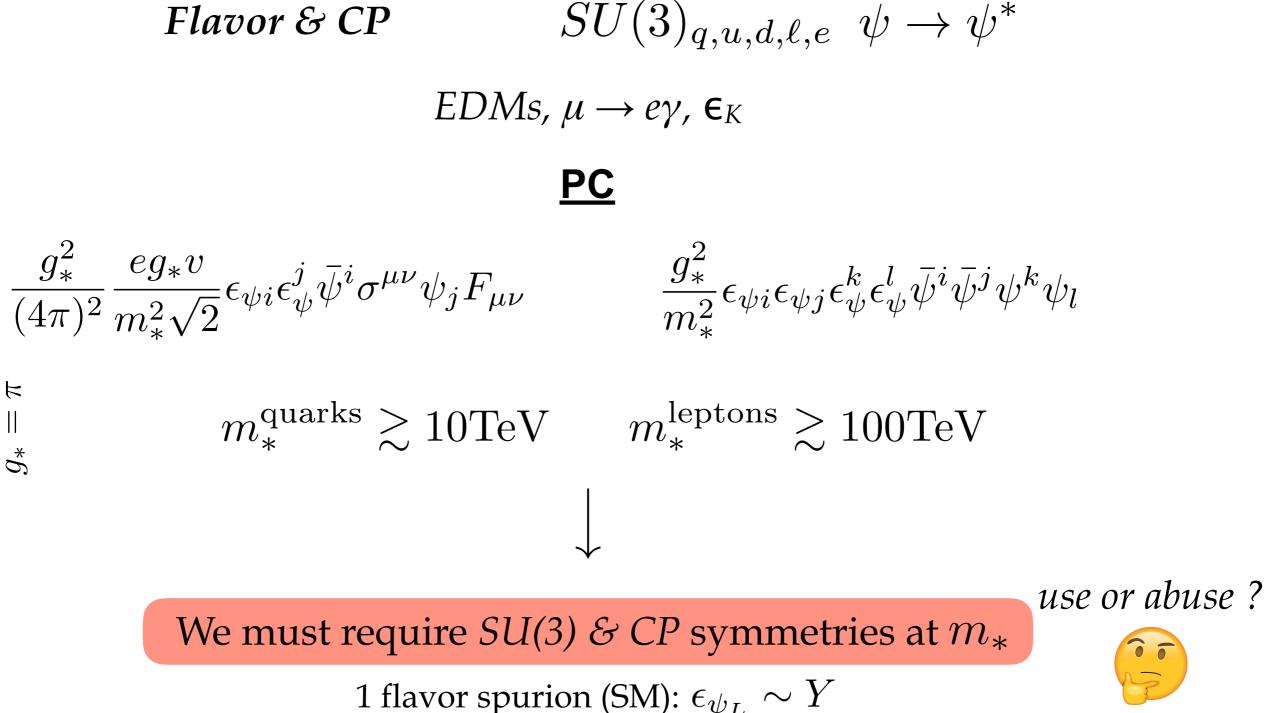
 $\frac{g_*^2}{(4\pi)^2} \frac{eg_*v}{m_+^2\sqrt{2}} \epsilon_{\psi i} \epsilon_{\psi}^j \bar{\psi}^i \sigma^{\mu\nu} \psi_j F_{\mu\nu}$

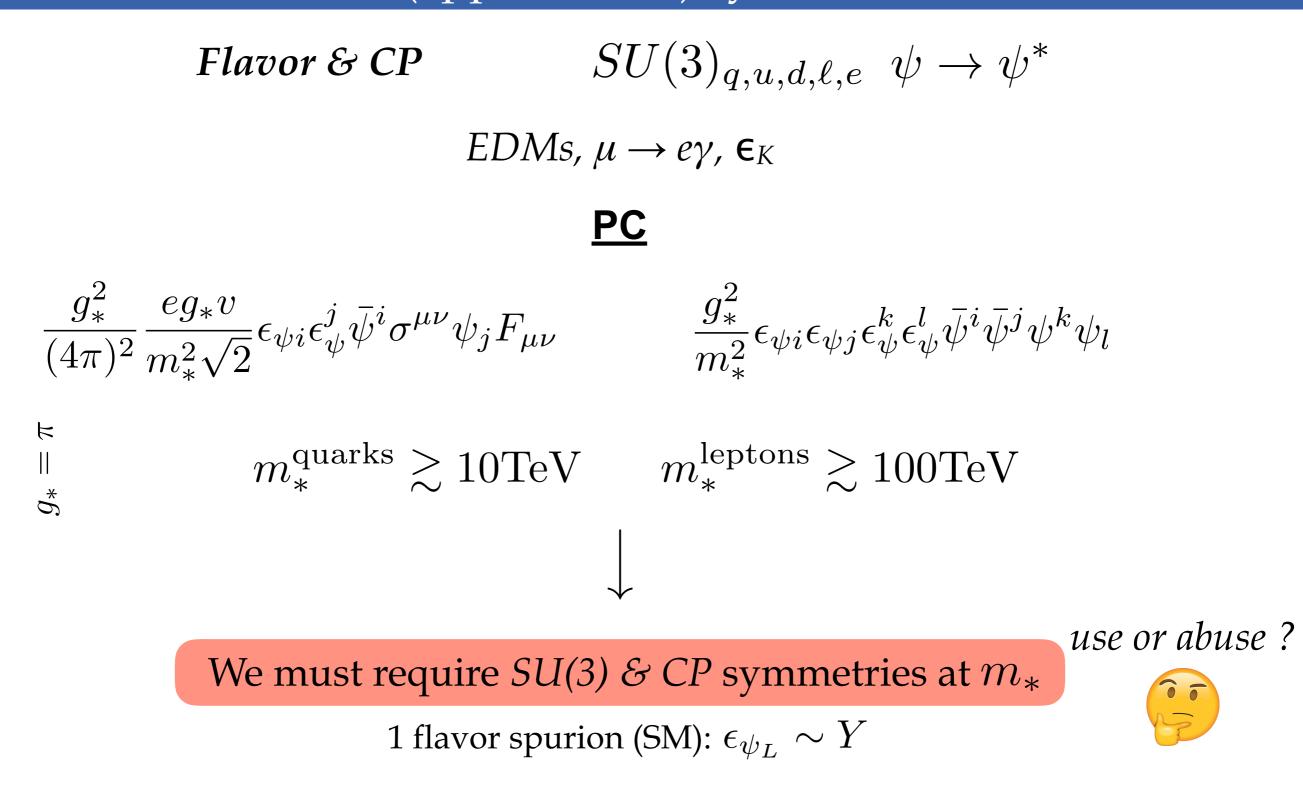
arepsilon

 g_*

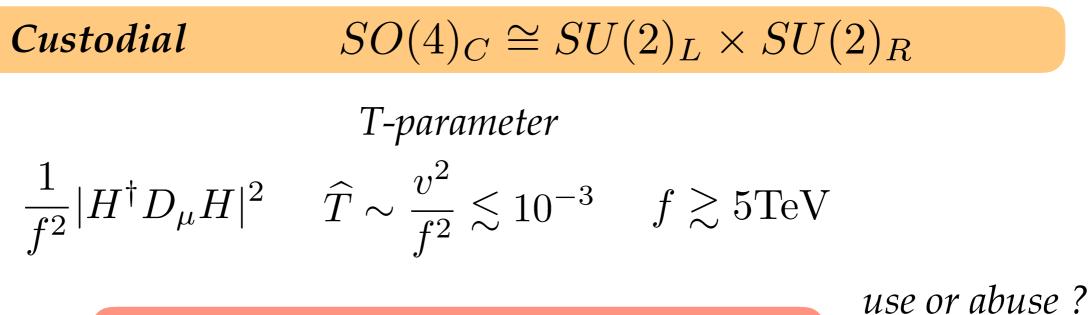
 $\frac{g_*^2}{m_+^2}\epsilon_{\psi i}\epsilon_{\psi j}\epsilon_{\psi}^k\epsilon_{\psi}^l\bar{\psi}^i\bar{\psi}^j\psi^k\psi_l$

 $m_*^{\text{quarks}} \gtrsim 10 \text{TeV} \qquad m_*^{\text{leptons}} \gtrsim 100 \text{TeV}$





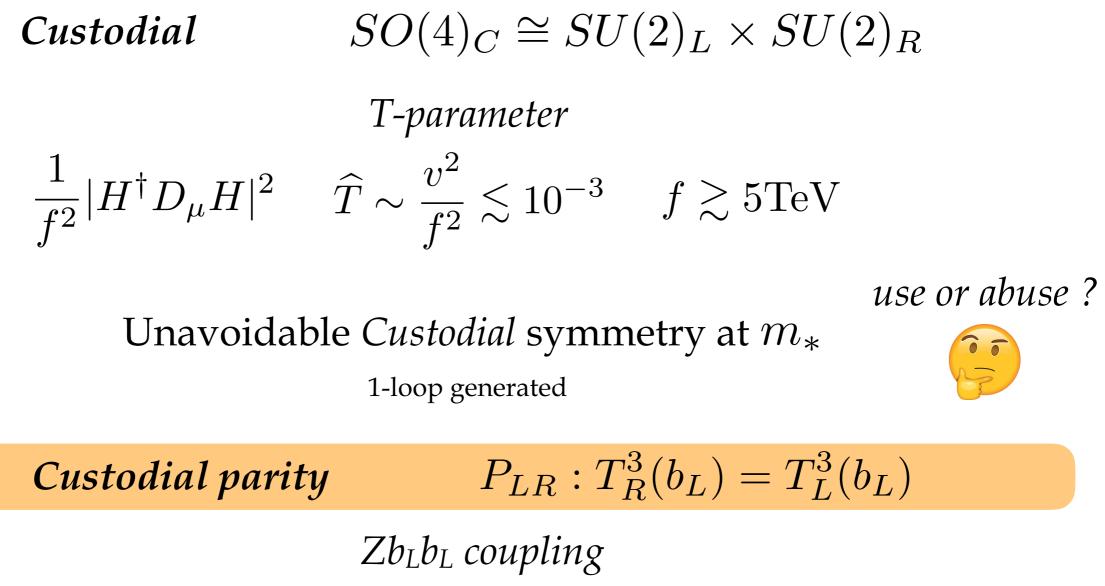
Note dynamics (PC + CTC) can eliminate the need for accidental symmetries at m_*



Unavoidable *Custodial* symmetry at m_*

1-loop generated





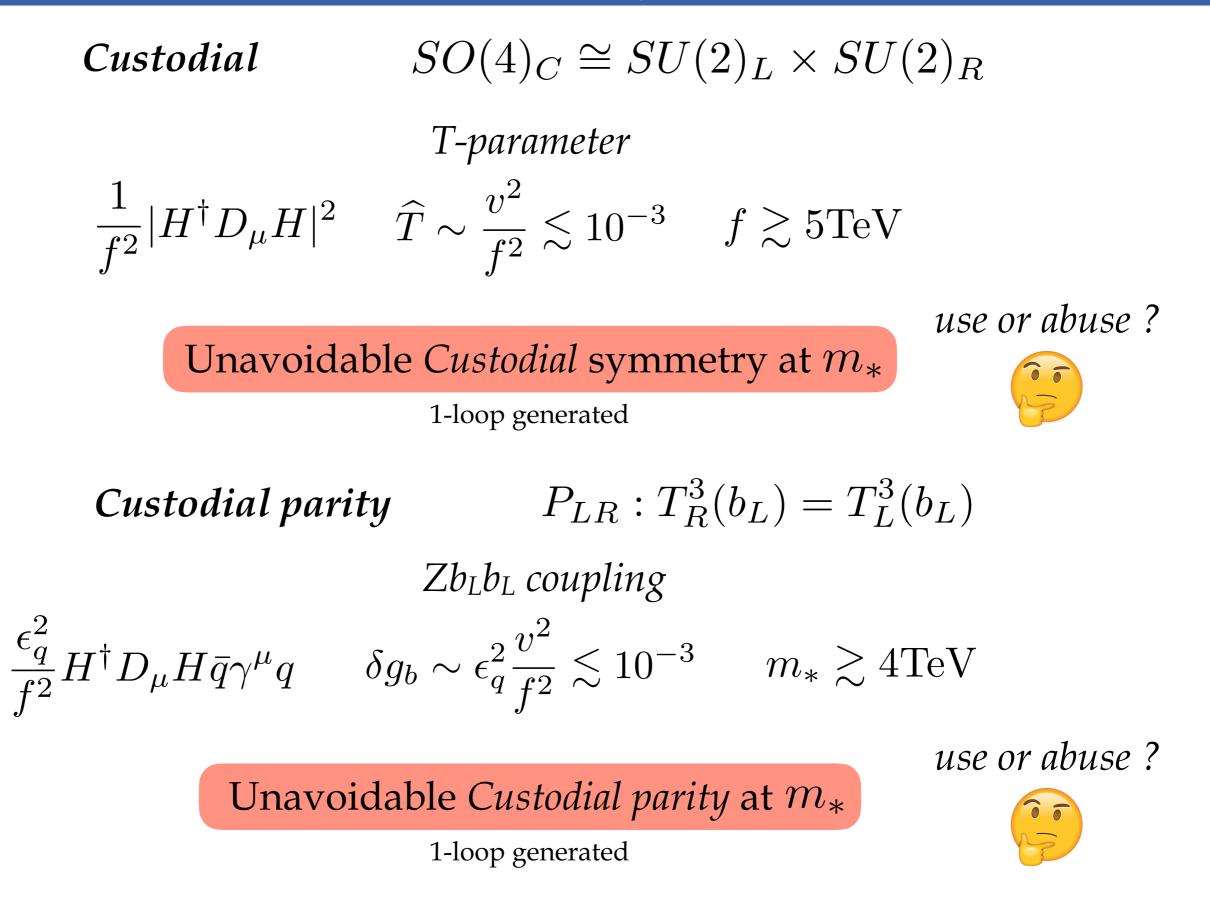
$$\frac{\epsilon_q^2}{f^2} H^{\dagger} D_{\mu} H \bar{q} \gamma^{\mu} q \qquad \delta g_b \sim \epsilon_q^2 \frac{v^2}{f^2} \lesssim 10^{-3} \qquad m_* \gtrsim 4 \text{TeV}$$

Unavoidable *Custodial parity* at m_*

1-loop generated

use or abuse ?





Note most CH models easily incorporate these symmetries; see next.

Some effects cannot be suppressed by symmetries...

S-parameter

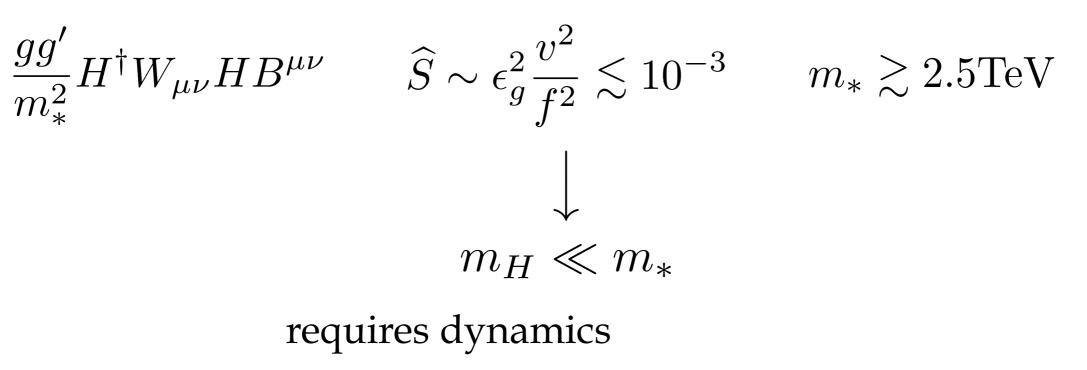
 $\frac{gg'}{m_*^2}H^{\dagger}W_{\mu\nu}HB^{\mu\nu}$

$$\widehat{S} \sim \epsilon_g^2 \frac{v^2}{f^2} \lesssim 10^{-3} \qquad m$$

$$m_* \gtrsim 2.5 \text{TeV}$$

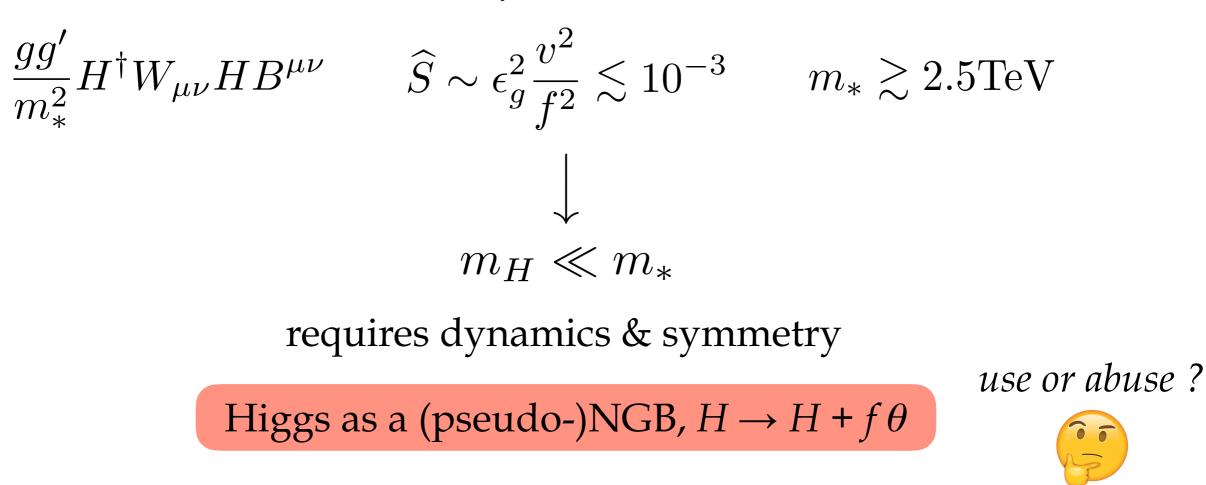
Some effects cannot be suppressed by symmetries...

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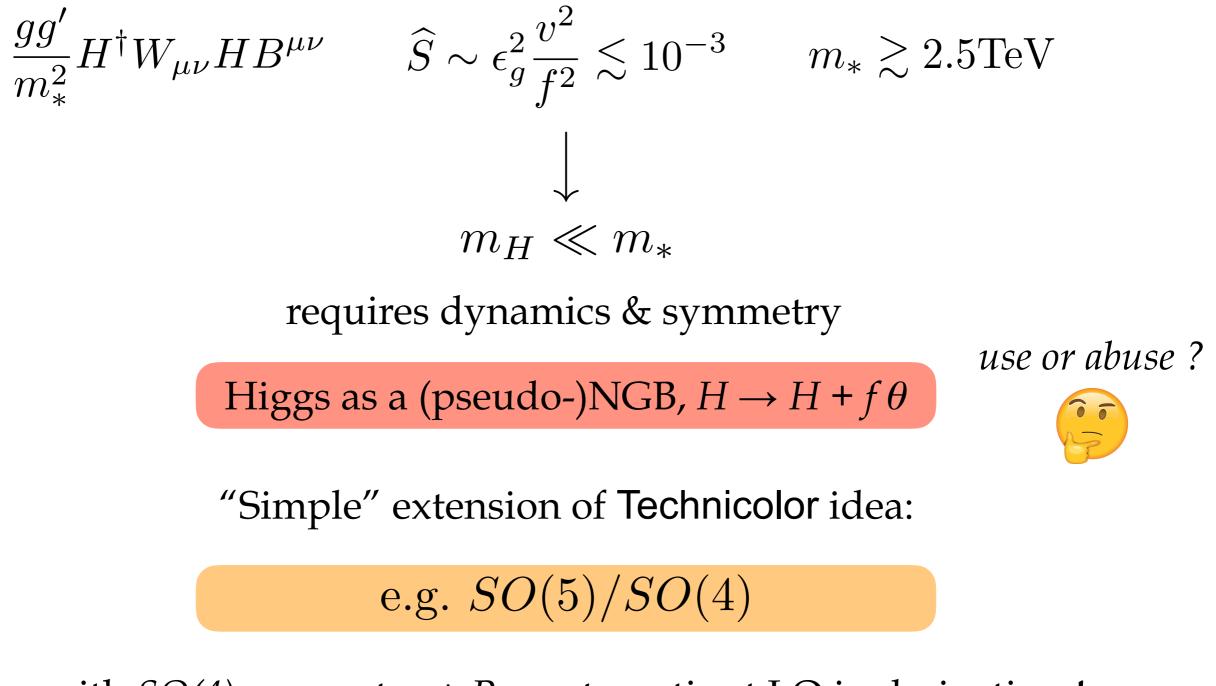
Some effects cannot be suppressed by symmetries...

S-parameter



Some effects cannot be suppressed by symmetries...

S-parameter



with SO(4) symmetry + P_{LR} automatic at LO in derivatives!

Higgs potential & top partners 1 JeV / A versions as welersions servere brites as welersions radiative & Beisemechotehia inantiken glaute in the grange $O(\epsilon^2): V = \operatorname{pre}_{\epsilon_t} \int_{\epsilon_t}^{t_{L,R}} \operatorname{or theo}_{\epsilon_t} \int_{\epsilon_t}^{SO(5)_R} \int_{\epsilon_t}^{SO(4)_R} \int_{\epsilon_t}^{g_s} \int_$ the quartic is three quarto ps salpendy to p self-interactionsekt-ühltheeæffectivelly beveffe is cut off at a iscale big later at head the glogr,

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Higgs potential & top partners
$$\Box$$
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versions as weld; such a several site share of
 $V(H/f) = \epsilon_{SM}^2 \frac{m_*^4}{(4\pi)^2} \ln \left(\frac{|H|^2}{120} \log^2 \frac{h}{2} \frac{|H|^4}{120} \log^2 \frac{h}{2} \frac{h}{2} \log^2 \frac{h}{2} \frac{h}{2} \log^2 \frac{h}{2}$

Higgs potential & top partners
$$\Box K$$

Versions as well subtractions are subtracted as well subtractions are subtracted as well subtractions are subtracted as well subtractions and the subtractions are subtracted as well subtractions and the subtractions are subtracted as well subtractions are subtracted as well subtractions and the subtractions are subtracted as well subtractions and the subtractions are subtracted as well subtractions are subtracted as well subtractions are subtracted as well subtractions and the subtractions are subtracted as well subtracted a

 \mathbf{X}

Top partners control the Higgs potential.

$$V_{\rm exp} \approx -\frac{m_h^2}{2} |H|^2 + \frac{m_h^2}{2v^2} |H|^4 \qquad \begin{array}{l} m_h \approx 125 {\rm GeV} \\ v \approx 246 {\rm GeV} \end{array}$$

reproduced only if **light & weakly coupled top partners**:

$$\Delta_{\mu^2} \sim (0.1)^{-1} \left(\frac{\lambda_{q,t}^2}{3y_t^2}\right) \left(\frac{m_T}{1\text{TeV}}\right)^2 \qquad \Delta_\lambda \sim (1)^{-1} \left(\frac{\lambda_{q,t}^2}{3y_t^2}\right) \left(\frac{g_T}{2}\right)^2$$
$$g_T = m_T/f$$

Top partners control the Higgs potential.

$$V_{\rm exp} \approx -\frac{m_h^2}{2} |H|^2 + \frac{m_h^2}{2v^2} |H|^4 \qquad \begin{array}{l} m_h \approx 125 {
m GeV} \\ v \approx 246 {
m GeV} \end{array}$$

reproduced only if **light & weakly coupled top partners**:

$$\Delta_{\mu^2} \sim (0.1)^{-1} \left(\frac{\lambda_{q,t}^2}{3y_t^2}\right) \left(\frac{m_T}{1\text{TeV}}\right)^2 \qquad \Delta_\lambda \sim (1)^{-1} \left(\frac{\lambda_{q,t}^2}{3y_t^2}\right) \left(\frac{g_T}{2}\right)^2$$
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 $g_T = m_T / f$

and a *mild* tuning.

Higgs couplings

$$\frac{1}{f^2} (\partial_\mu |H|^2)^2 \qquad \delta g_h \sim \frac{v^2}{f^2} \lesssim 0.1 \qquad f \gtrsim 750 \text{GeV}$$

Phenomenology dictated by **quantum numbers**: $SU(3)_C \times [SO(5)/SU(2)_L \times SU(2)_R] \times U(1)_X$

 ${f 5}=({f 1},{f 1})\oplus({f 2},{f 2})$

$$\Psi_1 = (\mathbf{3}, \mathbf{1}, \mathbf{1})_{2/3}$$

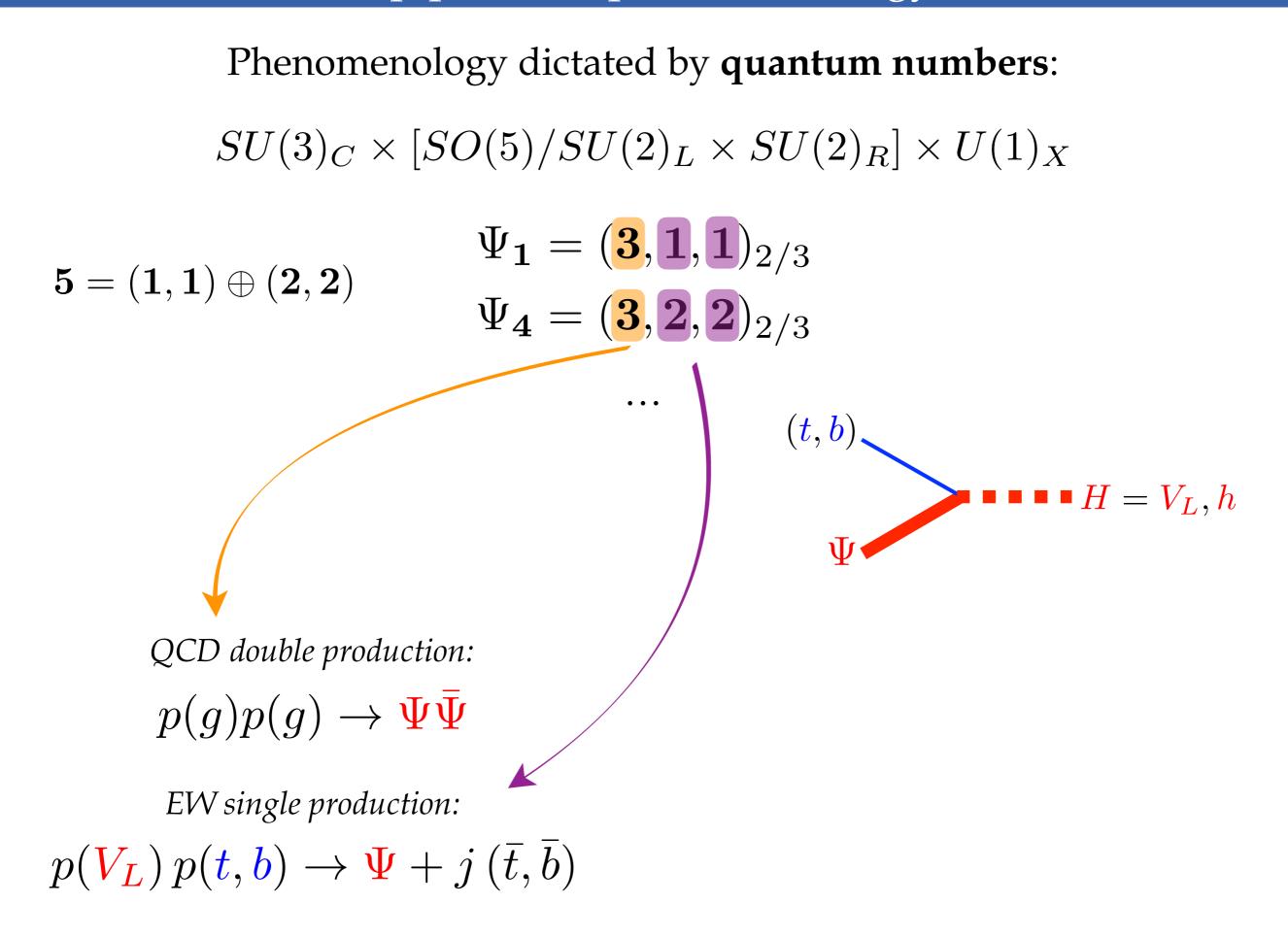
 $\Psi_4 = (\mathbf{3}, \mathbf{2}, \mathbf{2})_{2/3}$

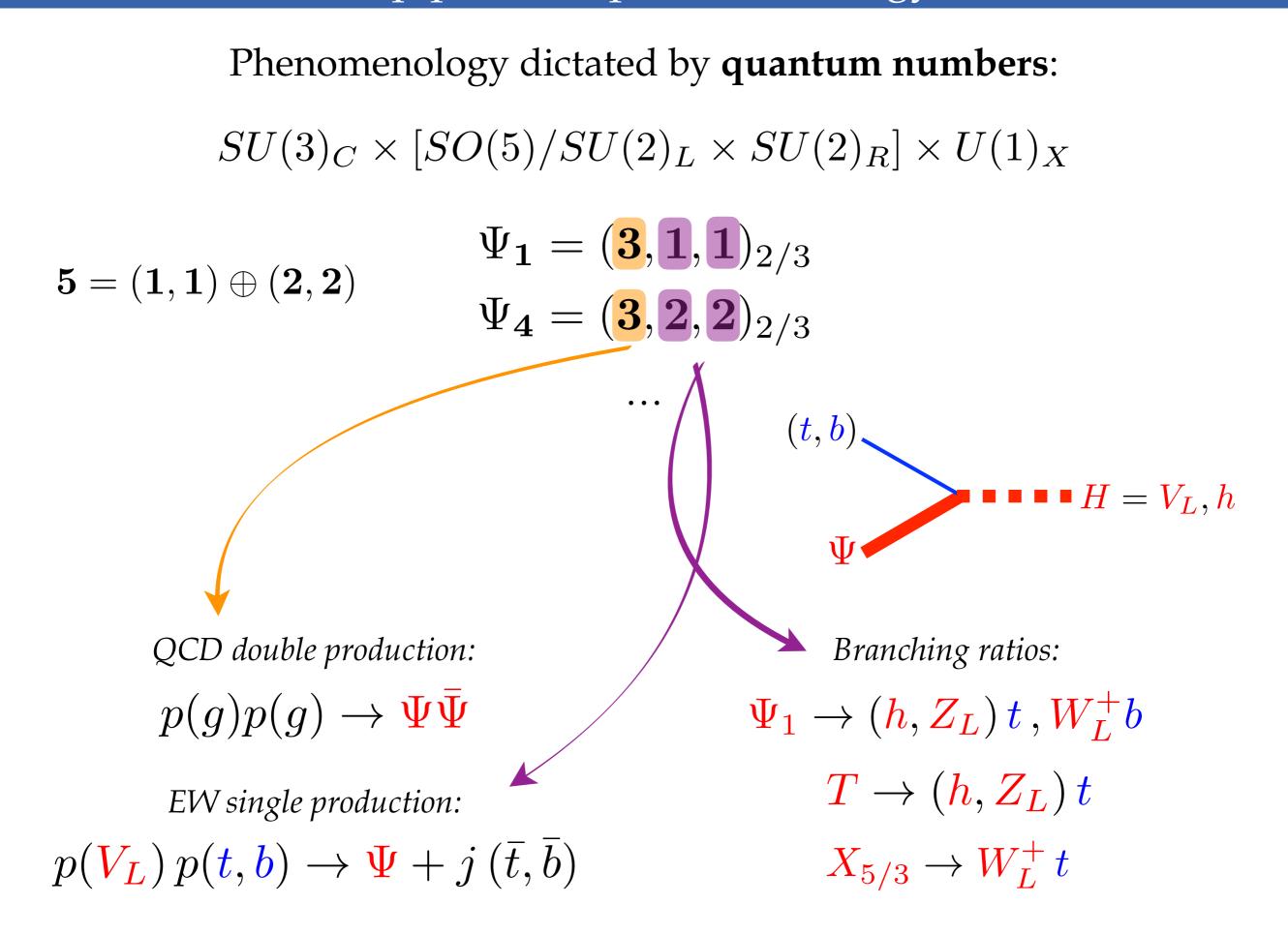
. . .

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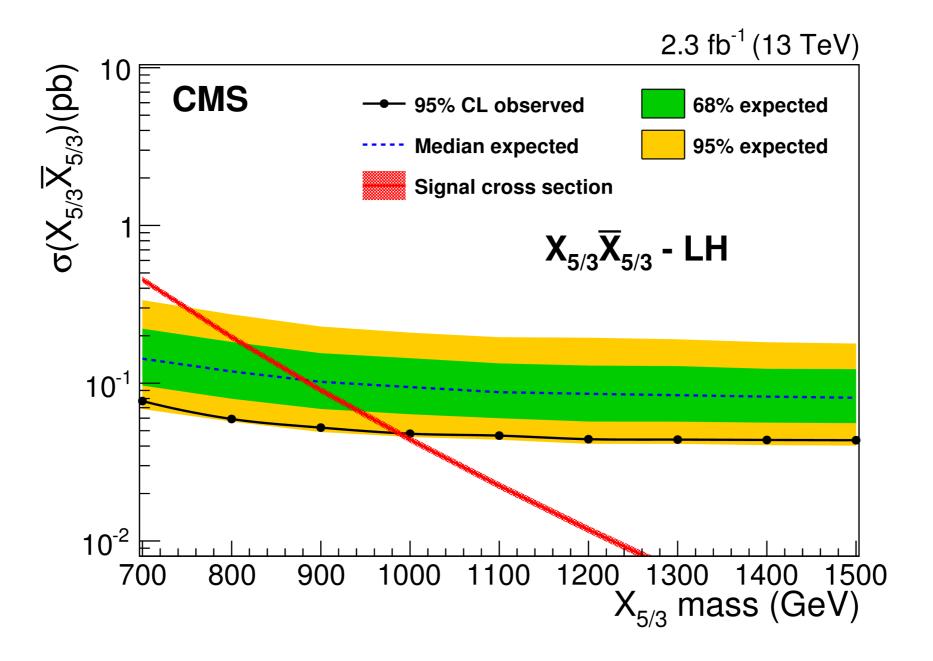
 $5 = (1,1) \oplus (2,2)$ $\Psi_1 = (3,1,1)_{2/3}$ $\Psi_4 = (3,2,2)_{2/3}$...

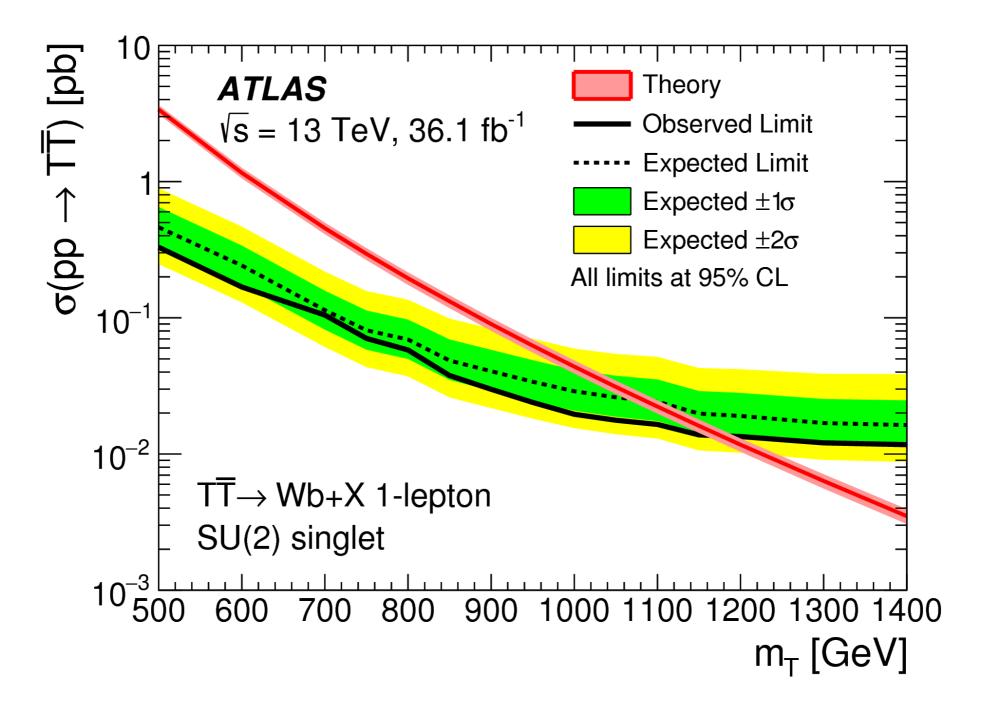
QCD double production: $p(g)p(g) \rightarrow \Psi \bar{\Psi}$



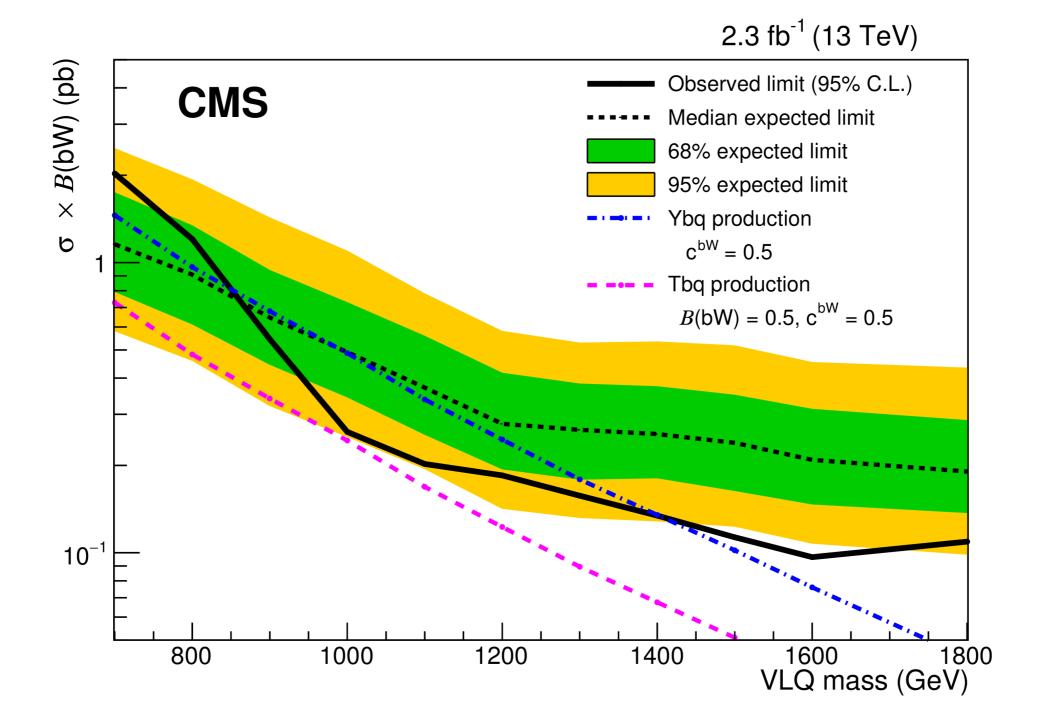


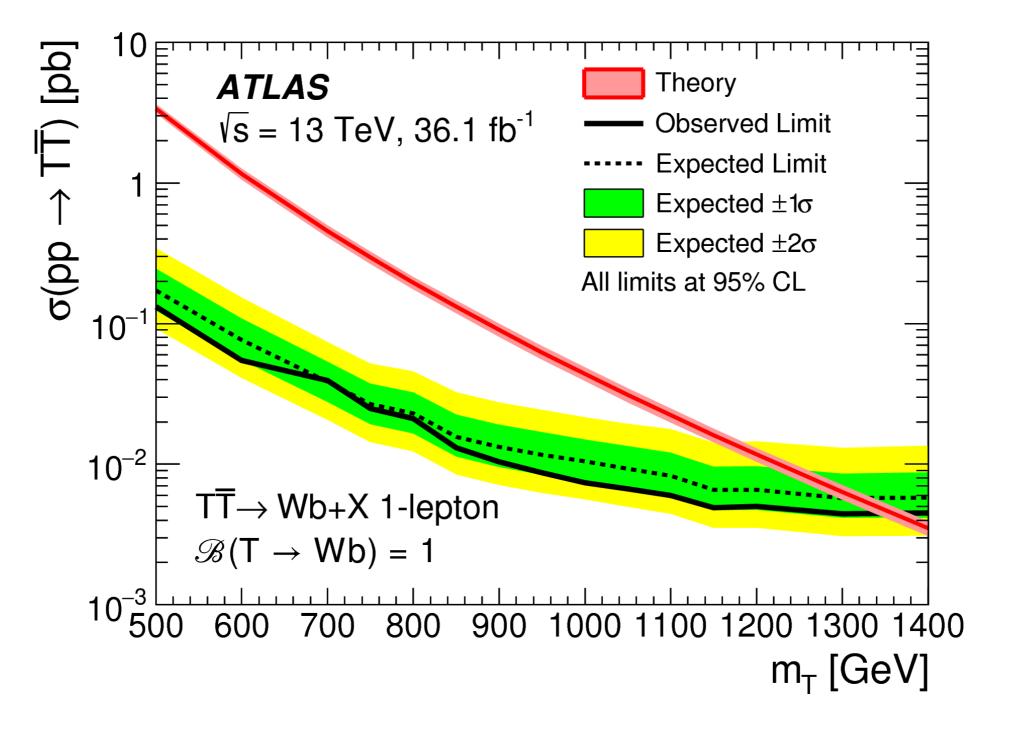
where are the top partners?



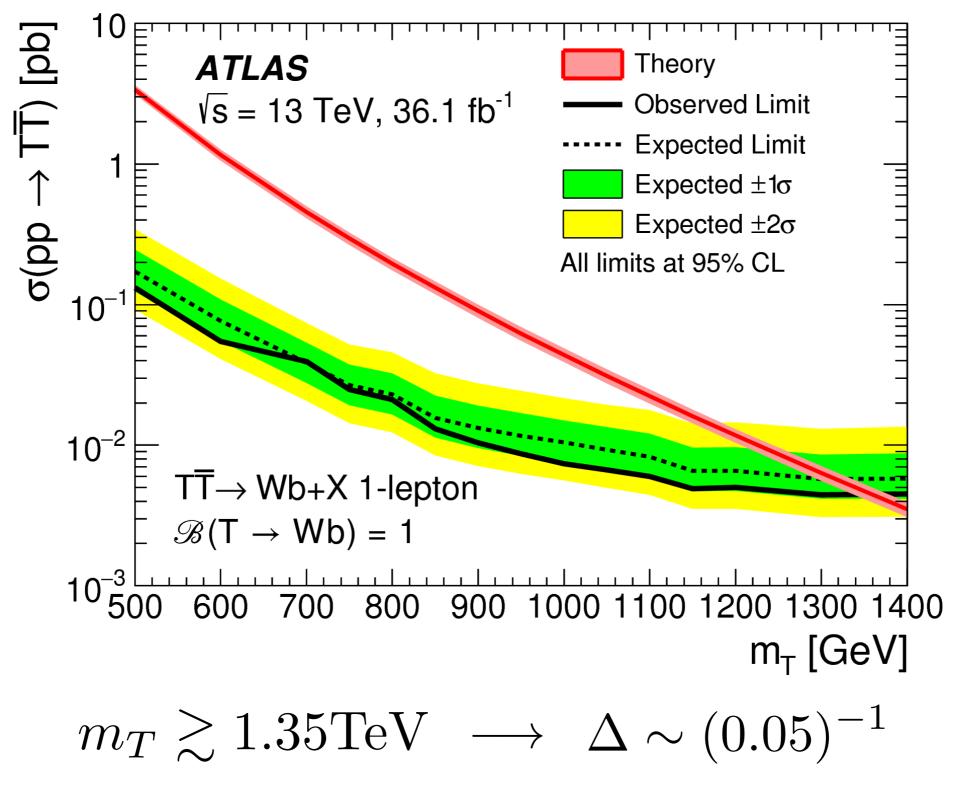


where are the top partners?





LHC 13TeV data



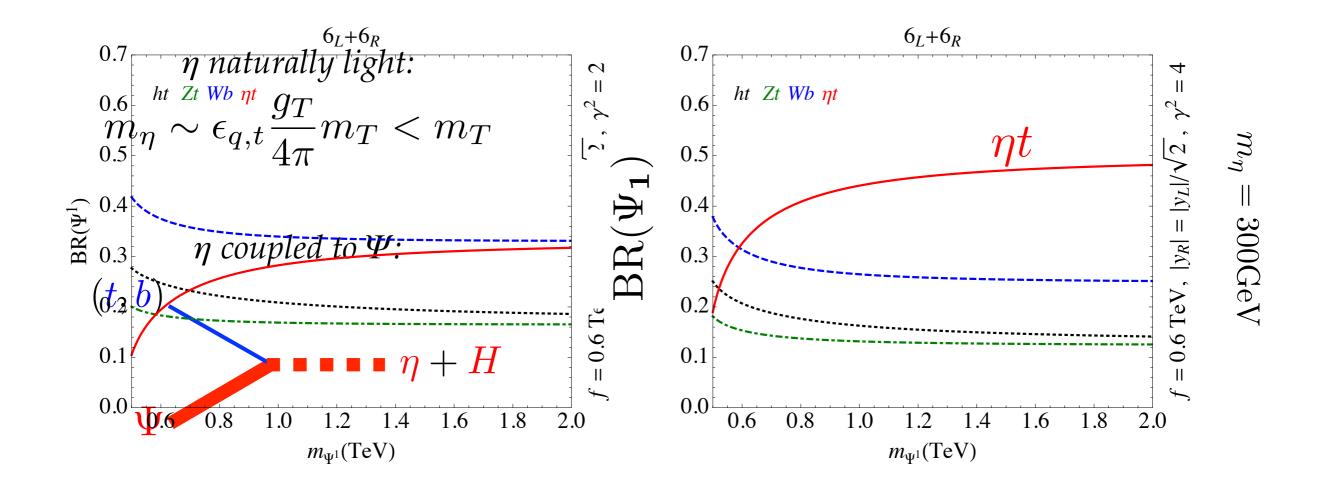
Increased tuning from LHC searches.

What if there are **non-standard** top-partner **decays**.

e.g. SO(6)/SO(5)

One extra singlet NGB beyond the Higgs:

 ${f 5}={m \eta}+H=({f 1},{f 1})\oplus ({f 2},{f 2})_{SU(2)_L imes SU(2)_R}$



What if there are **non-standard** top-partner **decays**.

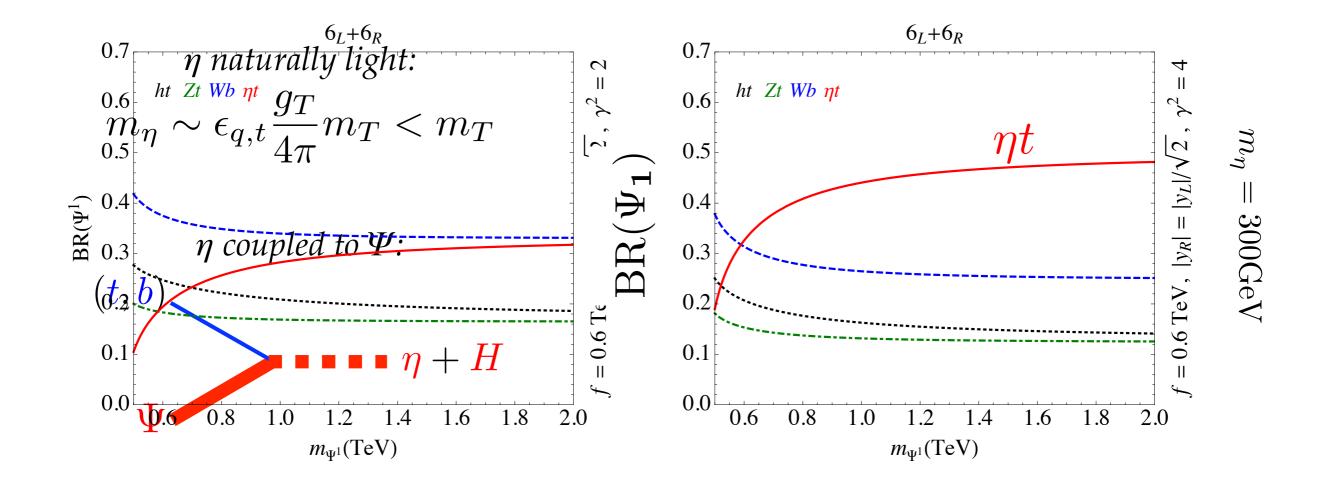
e.g.
$$SO(6)/SO(5)$$

Note this is the minimal CH model with $SO(4)_C$ realizable à la QCD (technifermions).

One extra singlet NGB beyond the Higgs:

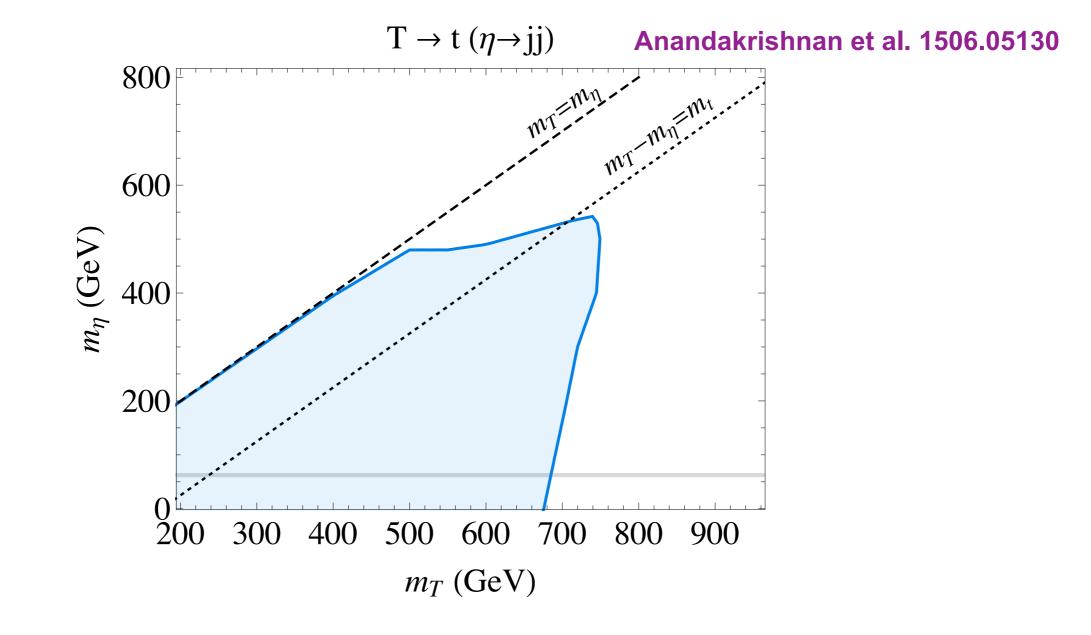
 ${f 5}={m \eta}+H=({f 1},{f 1})\oplus ({f 2},{f 2})_{SU(2)_L imes SU(2)_R}$

use or abuse ?





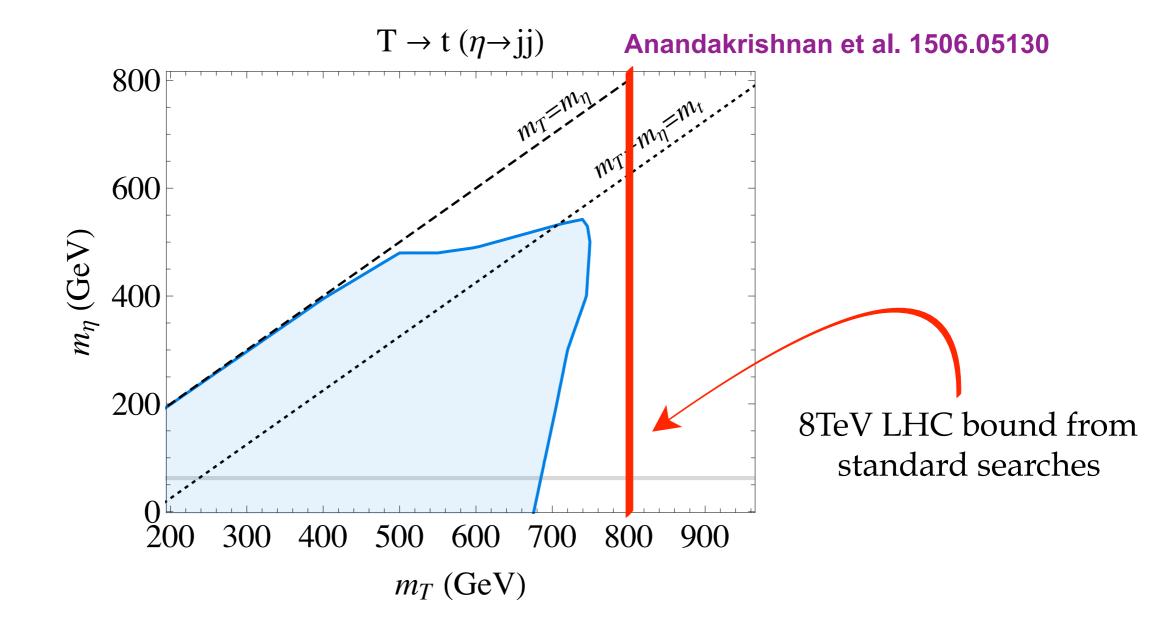
(recast of) LHC 8TeV data



The bounds, thus tuning, are *mildly* weaker.



(recast of) LHC 8TeV data

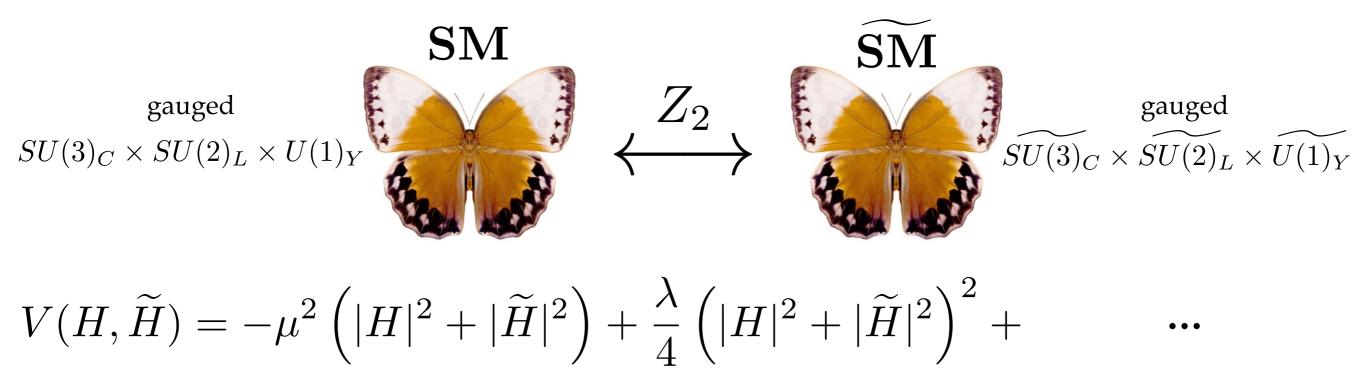


The bounds, thus tuning, are *mildly* weaker.

the last epicycle on BSM (approximate) symmetries

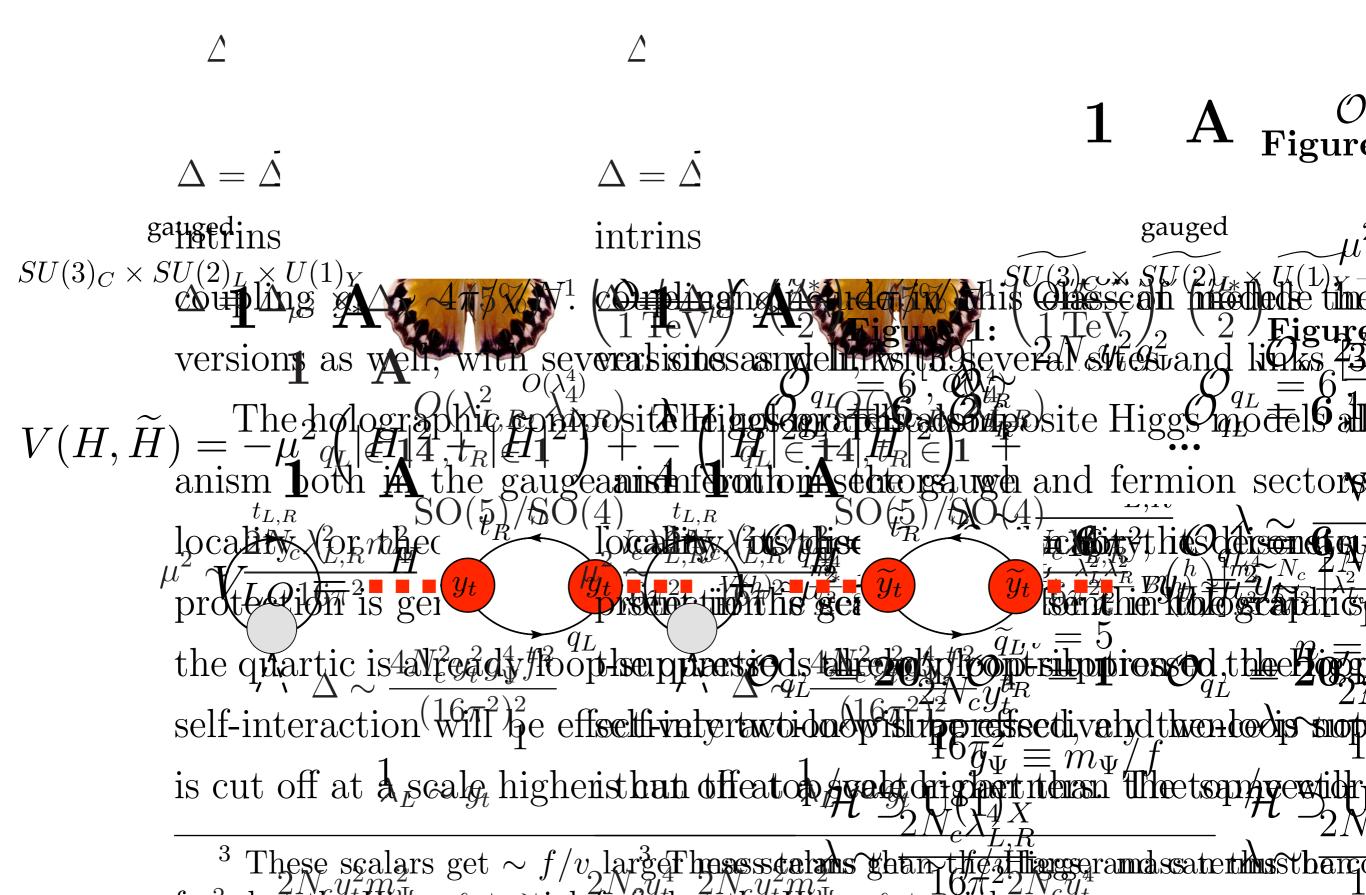
Are *colored* top partners really needed?

Twin Higgs mechanism





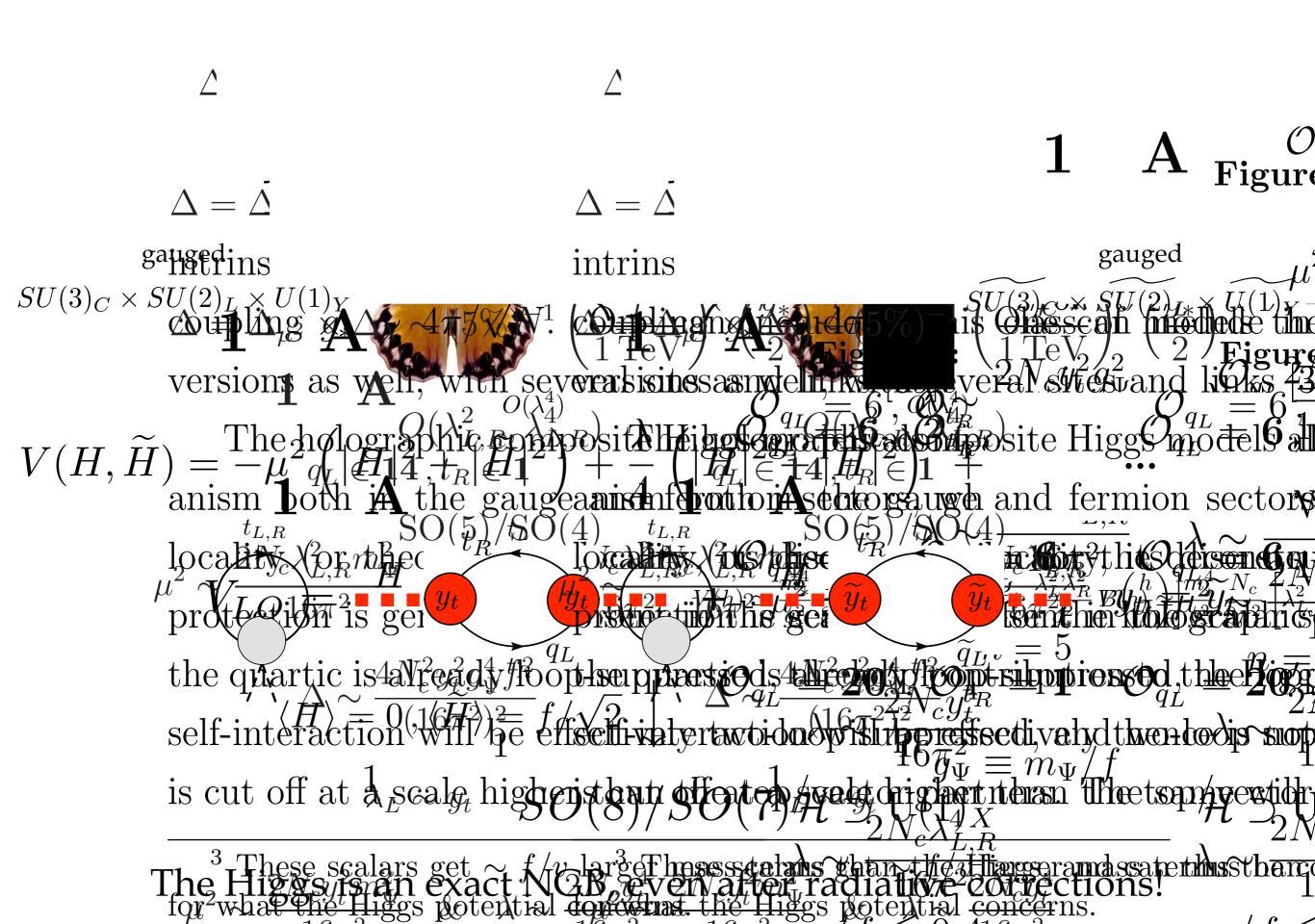




for²what the Higgs potential convenie. the Higgs potential concerns.













$\Delta = \angle$	$\Delta = \bar{\Delta}$		Figure 1
intrins	intrins		$\mu^2 \sim$
coup ling	$\mathcal{A}_{\mathcal{A}} \sim 4\pi \mathcal{B}_{\mathcal{A}} \mathcal{N}^{1} \mathcal{A}_{\mathcal{A}} $	Figure 1: 1 1 Te	sapi (melle their
$V(H, \widetilde{H}) \stackrel{\text{sions}}{=} \mathbf{I}$ The h	as H_{μ} with several since H_{μ} as H_{μ} with several since H_{μ} and H_{μ} a		Hegend liver and the set
anism b o	$a_{I} \in 14, t_{P} \in 1$	$\vec{q}_L \in 14, t_R \in 1$ forthion state of sugehigh \vec{q}_L	$SO(4) \times SO(4)$
$locality_{c}$	$\begin{array}{c} \text{SO(5)} \\ \text{p,} \\ \text{rh} \\ \text{rh} \\ \text{e} \\ \text{solution} \\ solutio$		Ty?the descuse true
	y_t		
the quart	tic is 4all ready no opheupp	$\frac{y_t}{\Delta q_L^2}, l = $	tressed the 1055
self-inter	action ⁽¹⁶ 72 ² ² e ef sect-iv e	by a stip to $p_{T}^{2} = v_{c} y_{t}^{R}$ by a stip to $p_{T}^{2} = v_{c} y_{t}^{R}$ $10 g_{\Psi} \equiv m$ of the trapped of the m	and the doe is support
is cut off	at a scale highers then	officit appropriate the product of the second state of the second	t het spreaticly be $2N$
$\frac{3}{10}$ These for r^2 what t	e scalars get ~ $f/v_1 a^3$ gah $y_1^2 m_2^2$ he ^t Higgs potential conversion $16\pi^2$ $16\pi^2$	esesscatanssettan the Higgs potential concern $16\pi^2 - \frac{1}{2}N_c y_t^4$ s.the Higgs potential concern $16\pi^2 - v/f \leq 0.46\pi^2$	annabscater the state $\frac{1}{16\pi}$ is. $v/f \leq 0$
	1	1 7	7

$\Delta = \angle$	$\Delta = \bar{\Delta}$		Figure 1
intrins	intrins		$\mu^2 \sim$
	$\Delta \sim -4\pi 5\%$ N ¹ .		
The hold	$ \mathbf{x} = \mathbf{y} + \mathbf{y} $	$\frac{1}{2}$	Iggrinatel alle
$t_{L,R}$.	$ \begin{array}{c} \mathbf{\tilde{f}} 14, t_R \in 1 \\ \mathbf{\tilde{f}} $	SO(5)	$\frac{L,L}{L}$ λ $ \frac{L-\lambda}{L}$
$\frac{\text{locality}}{\text{prot}} \frac{20 \text{ R}}{1000}$	s gei y_t y_t y_t y_t iontise	$\widetilde{y}_{t}^{4} \widetilde{y}_{t} \widetilde{y}_{$	2the descustry $2h 2 N_c 2 2 C 212$ C 212 C 2 C 212 C 2 C 212 C 2 C 212 C 2
the quartic i	is4aVreadynoopheuppretseois	$\frac{\partial f}{\partial t} = 0$	ieszedet the 1055
self-interact	$\cos(\frac{16\pi^2}{4})^2$ on $(16\pi^2)^2$ of sect-ively action	$H^{10} \overline{q}_{\Psi}^{2} \equiv m_{\Psi}^{2}$	it the flow is supply
is cut off st	Ascale highers through atta	277 399 higherthern. t	het spreetide be
3 These set $2N$ y_t^2 for y_t^2 what the $16\pi^2$	alars get ~ f/v_1 arguines scalars f/v_2 arguines scalar $V_2 = 100000000000000000000000000000000000$	$\frac{2 R_c R_{L,R}}{\sqrt{4}}$	matscater the state $\frac{21}{c}$, $\frac{21}{c}$, $\frac{1}{c}$, $\frac{1}{6}\pi$. $v/f \lesssim 0$
	1 1	7	7

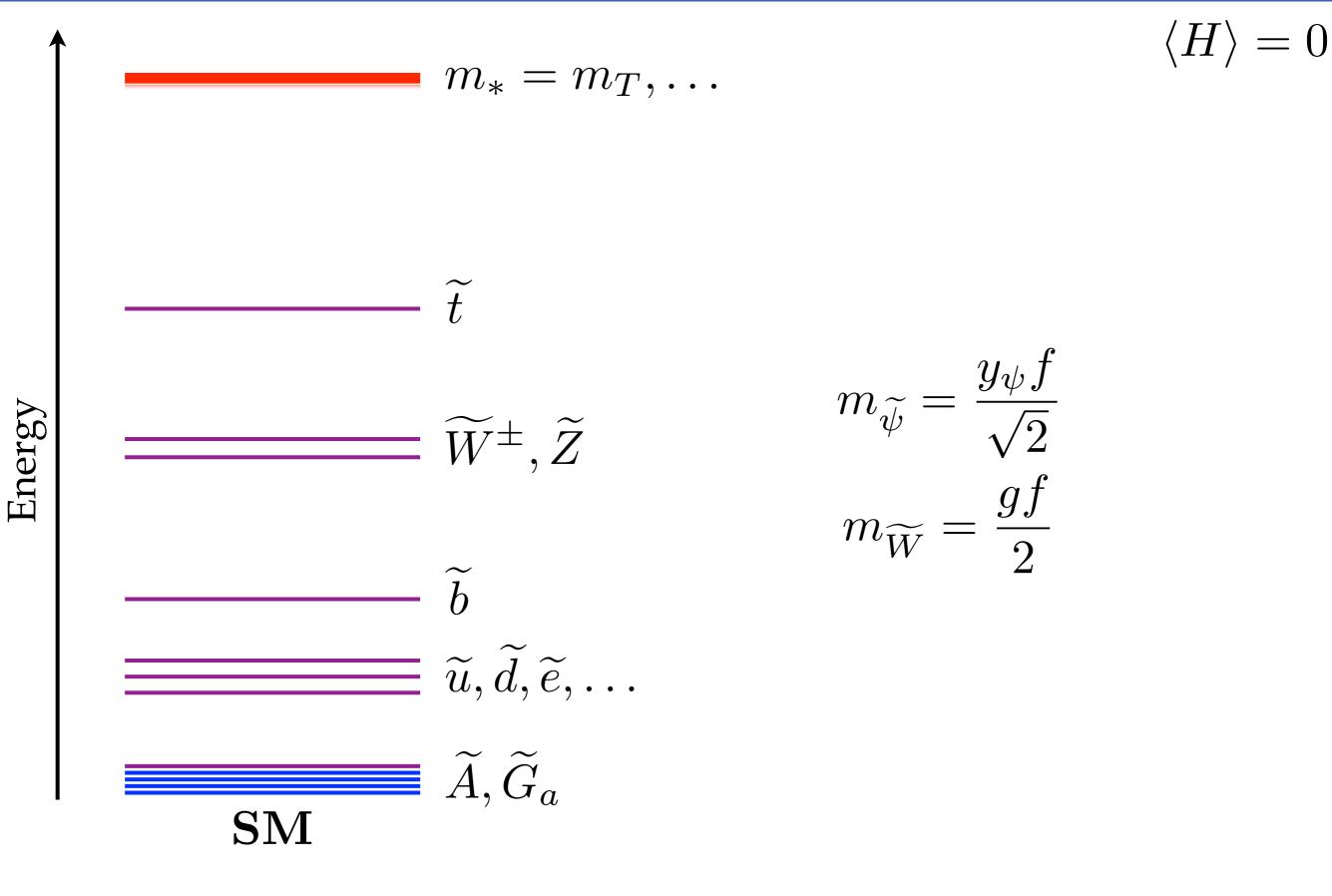
$\Delta = \angle$	$\Delta = \dot{\Delta}$		Figure 1
intrins	intrins		$\mu^2 \sim$
coup ling	$\chi \sim 4\pi 5\%$ N ¹ .	Figure 1: 1 Tev	sabi (meddels theth
$V(H, \widetilde{H}) \stackrel{\text{sions}}{=} \mathbb{T}$	as μ^{2} H^{2} with several sites in μ^{2} $\mu^{$	estand linkst Beveral sit estand linkst Beveral sit Hole and linkst Beveral sit Hole and linkst Beveral sit Hole and linkst Beveral sit	$\frac{2}{2}$ $\frac{2}{2}$ $\frac{1}{2}$ $\frac{1}$
anism 1	$q_L \in 14, t_R \in 1$ oth A the gauge minth f	$q_L \in 14, t_R \in 1$	$SO(4) \times SO(4)$
$locality_c$		\mathcal{N}^{2}	z ² , the descuster we
protoqie			ne klozogran nisper
the quar	tic is 4all ready no opheupper	$\widetilde{y_t}, l = 5$	rieszered the Higgs C
self-inter	action ⁽¹⁶ 77 ² ² e ef sect-ive	ration of 1672 2 cgt	<u>Fi</u> t the locies in the locies
		$\begin{array}{c} \Delta \sim q_L & = 0 \\ P = 0 \\$	
3 These for 2 what t	e scalars get $\sim f/v_2 hrghha y_t m_{\Psi}^2het Higgs potential converses16\pi^2 16\pi^2$	sesschennssgehan the Higgs potential concerns $16\pi^2 N_c y_4^4$, the Higgs potential concerns $16\pi^2 v/f \lesssim 0.46\pi^2$	amabs: $ter the ishan the form r = 16\pi s.$
	1	1 7	7

$\Delta = \angle$	$\Delta = \bar{\Delta}$		- Figure 1
intrins	intrins		$\mu^2 \sim$
coupling s	$\Delta \sim -4\pi 5\%$) \mathbb{N}^1	Figure 1: 1 TeV	$\sqrt{2}$
The holo	$\begin{array}{c} \text{ yell with seven signation of } \\ \text{graphic composited by } \end{array}$		gersiontol saller
$\operatorname{anism}_{t_L B} \overset{q_L \in \mathcal{B}}{\operatorname{both}}$	$q_L \in 1$ A the gauge mind for the second secon	$4, t_R \in 1$ S select or a use high Vise a SO(5) = 0.4	$O(4) \times SO(4)$
$loca \frac{1}{\mu V} \frac{2}{\rho R} r$		Λ^4	The descuest N_c N_c N_c N_c
prote Rich 2		\widetilde{u}	$\frac{1}{10} \frac{1}{10} \frac$
the quartic i	$s_{43}V_{16\pi^2}^2$	$\frac{1}{(16\pi^2)^2} V_c y_t^{R}$	\mathbf{xod}_{q_L} the 26 $\mathbf{xod}_{2N_{c_1}}$
self-interacti		$I = \frac{1}{2} = $	
	kseals higheis three for the		
3 These set for 2 what the y_{t}	alars get ~ f/v_1 arguinesesscher Higgs potential conversion the Higg $16\pi^2$ $16\pi^2$	Asgentan <u>tha Haggar</u> ama	$bscater the state has the sector 16\pi$
19μ what the 1 $16\pi^2$	$16\pi^2$ $16\pi^2$	$v/f \lesssim 0.46\pi^2$	$v/f \lesssim 0$
	1 1	7	7

Figure 1 $\Delta = \Delta$ intrins intrins $\cos \frac{1}{2} \sin \frac{$ $V(H, H) \stackrel{=}{=} \mu^2 \mathcal{A}_{\mu}^{ell}$ with several sizes and lines as veral sizes and lines as \mathcal{A}_{μ}^{ell} Figure The holographic composite the possite to the classic for the c anism both A^{T} , $t_R \in 1$ $\tilde{q}_L \in 14$, $t_R \in 10$ $\tilde{q}_L \in 14$, $t_R \in 10$, $t_R \in 100$ $\tilde{q}_L \in 14$, $t_R \in 100$ $\tilde{q}_L \in 14$, $t_R \in 100$ $\tilde{q}_L \in 100$, $t_R \in 100$, t_R (5) $\begin{pmatrix} 4 \\ 1 \end{pmatrix} \quad t_{L,R} \quad S(t_{L,R})$ locality (prothec Jeanstry?the descustry y_t y_t y_t y_t \tilde{y}_t protection is gen y_t the quartic is 4 all ready no opheup arts of 4 all ready to opheup arts of the 20 and 20 all ready to opheup arts of the 20 and 20 all ready to opheup arts of the 20 and 2self-interaction (1672)² e effectively action of the support state of the support of the suppo is cut off storscale higheis the nothall appropriate big bert nears. I here say ected ³ These scalars get ~ f/v argethese scalars get an the Higgs random the formula for $y_{t}^{2}m_{t}^{2}$ what the Higgs potential converses the Higgs potential concerns. $V(H) = \frac{3f}{64\pi^{2}} \begin{bmatrix} 16\pi^{2} \\ y_{t} \end{bmatrix} + \begin{bmatrix} 16\pi^{2} \\ y_{t} \end{bmatrix} +$

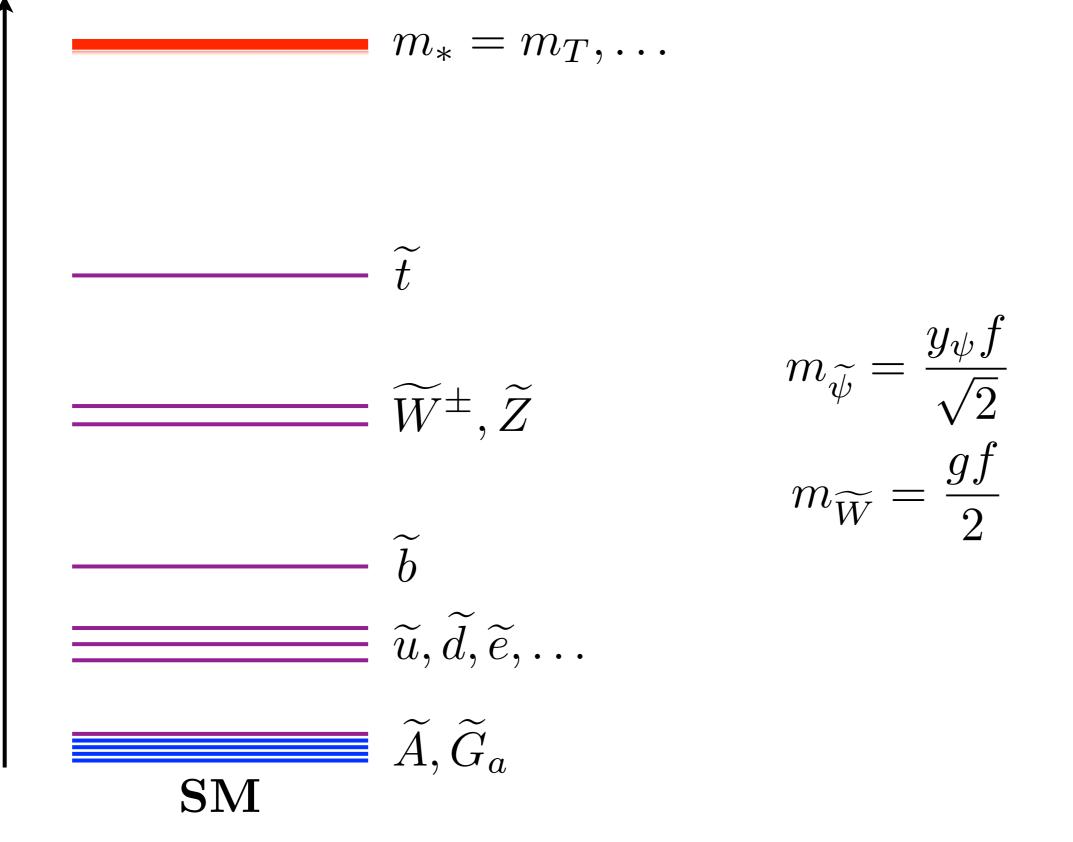
The Higgs potential is not sensitive to (colored) top partner mass. There is no tension (tuning) coming from LHC searches.







 $\langle H \rangle = 0$

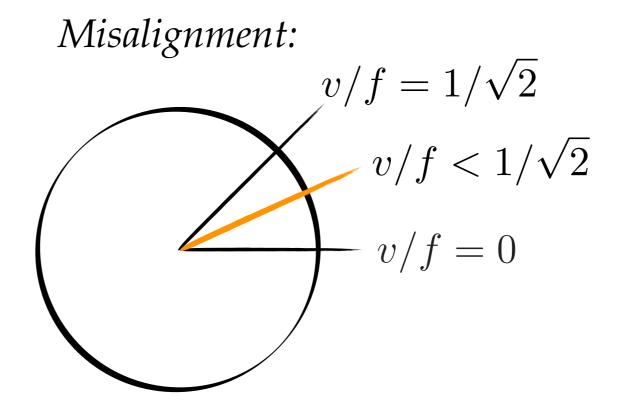


All twin states are SM-neutral.

Energy

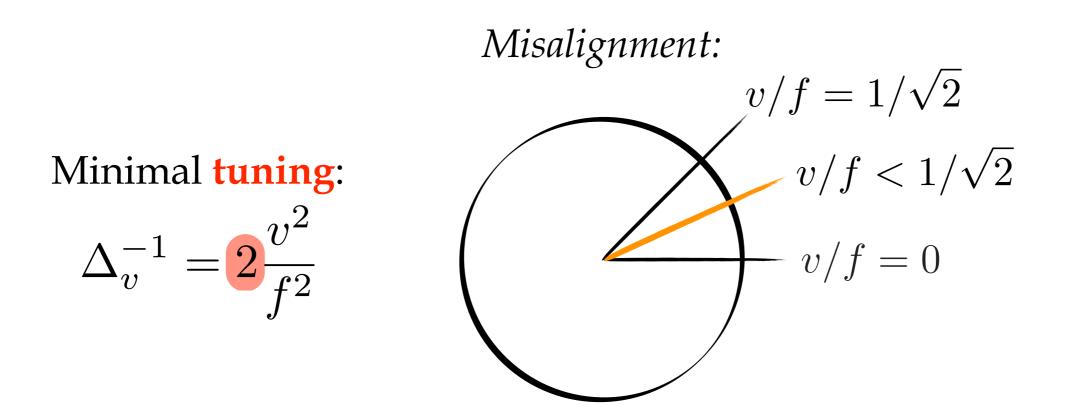
twin Higgs

$$V(H) = \frac{3f^4}{64\pi^2} \left[y_t^4 |H|^2 + \tilde{y}_t^4 (1 - |H|^2)^2 \right] \log \quad y_t = \tilde{y}_t$$



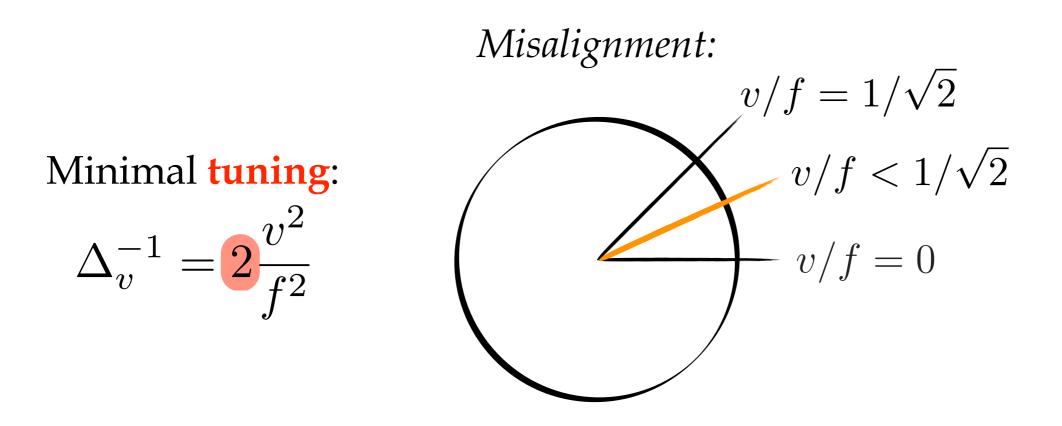
twin Higgs

$$V(H) = \frac{3f^4}{64\pi^2} \left[y_t^4 |H|^2 + \tilde{y}_t^4 (1 - |H|^2)^2 \right] \log \quad y_t = \tilde{y}_t$$



twin Higgs

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Explicit **Z**₂ **breaking** is required to misalign the Higgs VEV, e.g.:

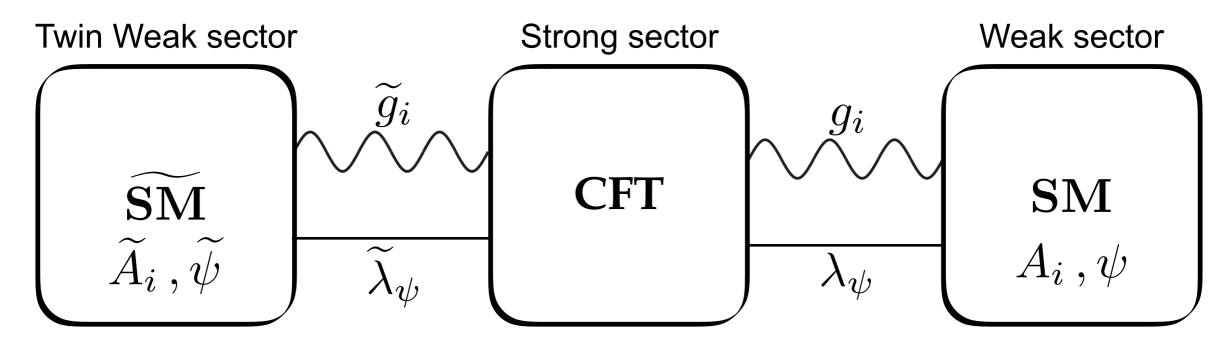
• Twin $U(1)_Y$ is not gauged.

. . .

- Only 3rd generations fermions have twins (*fraternal Higgs*).
- Only the top has a twin (*brother Higgs*); see next.

composite twin Higgs

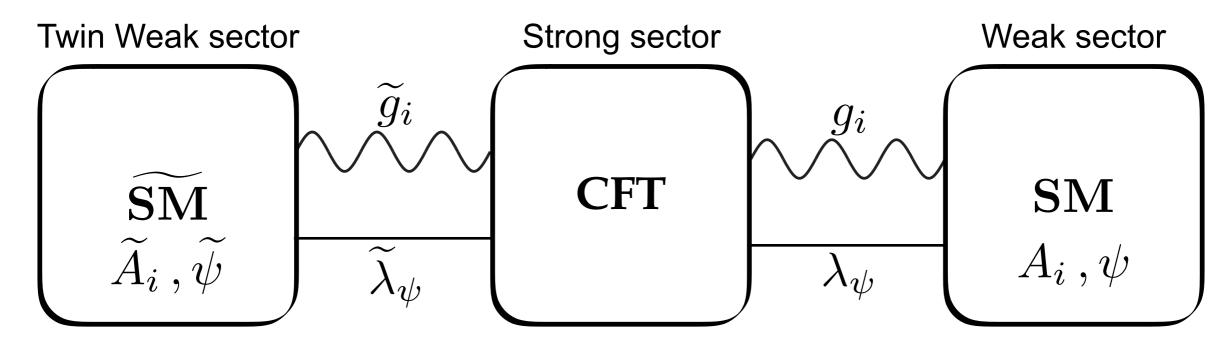
Replace the linear σ -model by strong sector and follow through.



 $[SO(8)/SO(7)] \times SU(3)_C \times \widetilde{SU(3)}_C \times U(1)_X \times \widetilde{U(1)}_X \times Z_2$

composite twin Higgs

Replace the linear σ -model by strong sector and follow through.



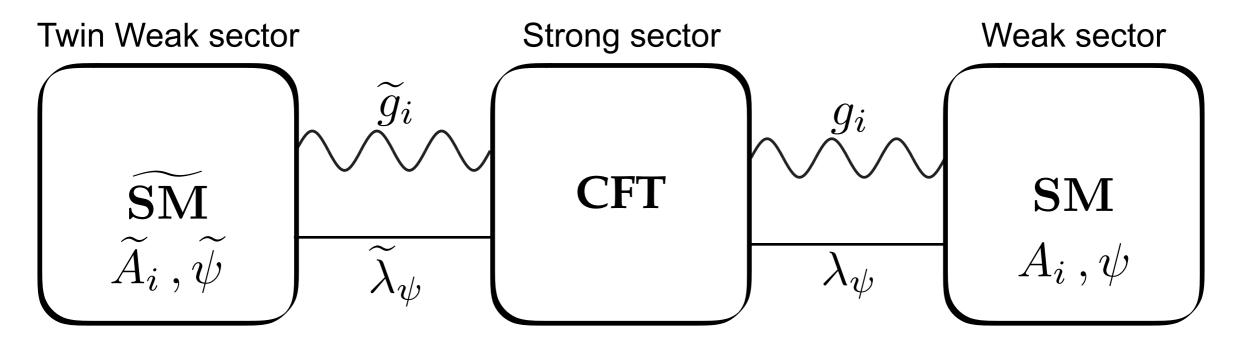
 $[SO(8)/SO(7)] \times SU(3)_C \times \widetilde{SU(3)}_C \times U(1)_X \times \widetilde{U(1)}_X \times Z_2$

<u>PC</u>

$$Z_2: \widetilde{A}_i \leftrightarrow A_i \longleftrightarrow \widetilde{g}_i = g_i$$

composite twin Higgs

Replace the linear σ -model by strong sector and follow through.



 $[SO(8)/SO(7)] \times SU(3)_C \times \widetilde{SU(3)}_C \times U(1)_X \times \widetilde{U(1)}_X \times Z_2$

<u>PC</u>

$$Z_2: \widetilde{A}_i \leftrightarrow A_i \longleftrightarrow \widetilde{g}_i = g_i$$

 $\lambda_q q_L \mathcal{O}_q + \lambda_t t_R \mathcal{O}_t \qquad \mathcal{O}_q = (\mathbf{8}, \mathbf{3}, \mathbf{1})_{2/3, 0} \quad \mathcal{O}_t = (\mathbf{1}, \mathbf{3}, \mathbf{1})_{0, 2/3}$ $\widetilde{\lambda}_q \widetilde{q}_L \widetilde{\mathcal{O}}_q + \widetilde{\lambda}_t \widetilde{t}_R \widetilde{\mathcal{O}}_t \qquad \widetilde{\mathcal{O}}_q = (\mathbf{8}, \mathbf{1}, \mathbf{3})_{0, 2/3} \quad \widetilde{\mathcal{O}}_t = (\mathbf{1}, \mathbf{1}, \mathbf{3})_{0, 2/3}$

$$Z_2: \quad \widetilde{\psi} \leftrightarrow \psi \longleftrightarrow \widetilde{\lambda}_{\psi} = \lambda_{\psi}$$

• The Higgs remains a pseudo-NGB:

$$\begin{array}{ll} Higgs \ couplings\\ \frac{1}{f^2} (\partial_\mu |H|^2)^2 & \delta g_h \sim \frac{v^2}{f^2} \lesssim 0.1 & f\gtrsim 750 {\rm GeV} \end{array}$$

• The strong sector has a mass gap naturally high*: $m_* pprox 5 {
m TeV}$

e.g. S-parameter $\widehat{S} \sim \frac{m_W^2}{m_*^2} \lesssim 10^{-3}$

• No production of heavy resonances at the LHC.

• Higgs portal type of collider phenomenology.

Symmetries have shaped the way we address the limitations of the SM.

One may argue that we have taken this philosophy to the extreme, for a good purpose, the *electroweak hierarchy problem*.

Variants of the standard solutions based on symmetries, such as Composite Higgs models, no longer require light colored top partners.

Searches for these theories are on its way.



Thank you!

current LHC searc

New particle searches a CMS Exotics Searches

			LQ1, β=0.5			
CMS EX	OTICA	95% CL E>	CLUSION LIMITS (TEV) LQ1, β=0.5 LQ1, β=1.0 LQ2, β=0.5			
q* (qq), dijet	1 1 1		LQ2, β=1.0			
q* (qW)			LQ3 (bv), Q=±1/3, β=0.0			
q* (qZ)			LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0			
q* , dijet pair			stop (br			
q* , boosted Z				0 1	2	3
e*, Λ = 2 TeV				1 1		1
μ*, Λ = 2 TeV			b' → tW, (3l, 2l) + b-jet			
	0 1 2	3 4	5 q', b'/t' degenerate, Vtb=1			
Z'SSM (ee, μμ)			b' → tW, I+jets			
Z'SSM (ττ)			B' → bZ (100%			
Z' (tt hadronic) width=1.2%			T' → tZ (100%)			
Z' (dijet) Z' (tt lep+jet) width=1.2%			t' → bW (100%), I+jets			
Z'SSM (II) fbb=0.2			t' → bW (100%), I+			
G (dijet)				0 1	2	3
G (ttbar hadronic)			C.I. A , X analysis, A+ LL/RF			
G (jet+MET) k/M = 0.2			C.I. A , X analysis, A- LL/RF			
G (yy) k/M = 0.1			C.I., µµ, destructve LLIN			
G (Z(II)Z(qq)) k/M = 0.1			C.I., µµ, constructive LLIN C.I., single e (HnCM			
W' (lv)			C.I., single e (HICM) C.I., single u (HICM)			
W' (dijet)			C.I., incl. jet, destructive			
W' (td) W'→ WZ(leptonic)			C.I., incl. jet, constructive			
W - WZ(leptonic) WR' (tb)				0	5	10
WR. MNB=MWB/2			Ms, yy, HLZ, nED = 3	ŭ I	5	1
WKK µ = 10 TeV			Ms, vv, HLZ, nED = 6			
ρTC, πTC > 700 GeV			Ms, II, HLZ, nED = 3			
String Resonances (qg)			Ms, II, HLZ, NED = 6			
s8 Resonance (gg)			MD, monojet, nED = 3			
E6 diquarks (qq)			MD, monojet, nED = 6			
Axigluon/Coloron (qqbar) gluino, 3iet, RPV			MD, mono-v, nED = 3			
giuino, sjet, HPV	1 1 1		mD, mono-y, nED = 6			
aluino. Stopped Gluino	0 1 2	3 4	5 MBH. rotating. MD=3TeV. nED = 2			
stop, HSCP			MBH, non-rot, MD=3TeV, nED = 2 MBH, non-rot, MD=3TeV, nED = 2			
stop, Stopped Gluino			MBH, hon-rot, MD=3TeV, hED = 2 MBH, boil, remn., MD=3TeV, hED = 2			
stau, HSCP, GMSB			MBH, boil. remn., MD=31eV, hED = 2 MBH, stable remn., MD=3TeV, nED = 2			
hyper-K, hyper-p=1.2 TeV			MBH, Stable remn., MD=31eV, hED = 2 MBH, Quantum BH, MD=3TeV, nED = 2			
neutralino, cτ<50cm					1	1
	0 1 2	3 4	5	0 1	2	3
			* similar ragy	Ita a	htoin	- A

*similar results obtained

light & weakly coupled top partners

 $m_T < m_* pprox 2.5 {
m TeV}$ S-parameter bound

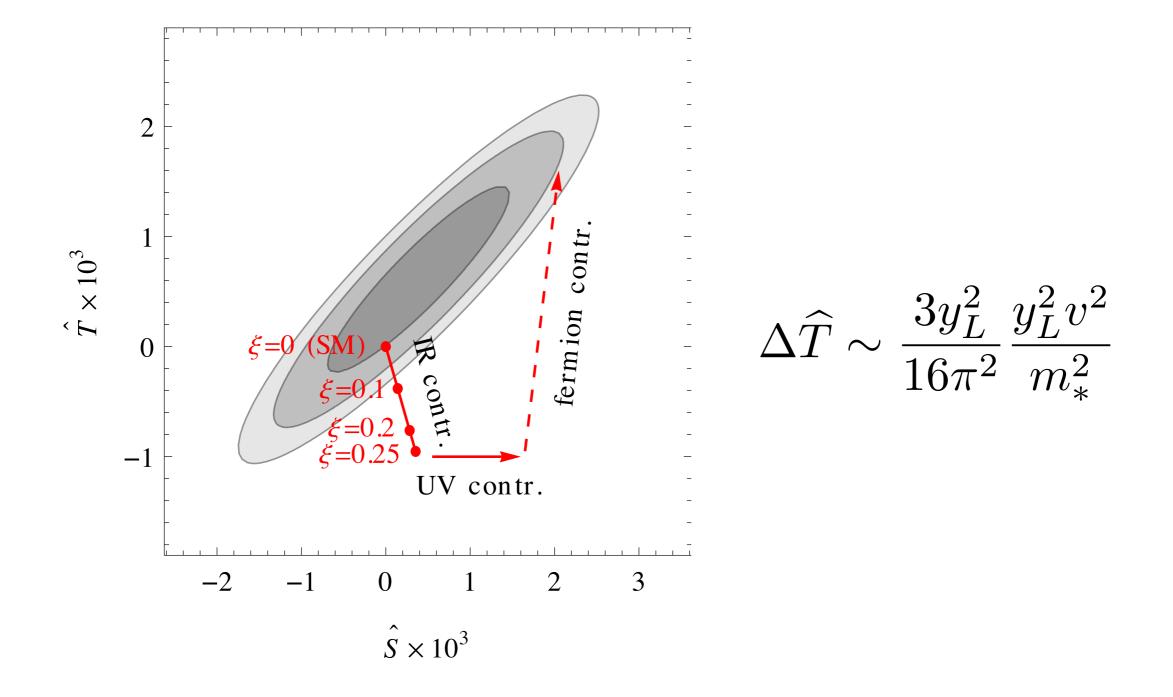
There might be several reasons, e.g.:

• $\epsilon_{q,t} \to 1 \iff d(\mathcal{O}_{q,t}) \to 3/2 = \text{free field dimension}$

• Accidental Ψ chiral symmetry.

• Large *N* counting.

EWPT & top partners



the last epicycle on BSM (approximate) symmetries

Another way to understand twin Higgs:

brother Higgs