COMPOSITE (PNGB) HIGGS AND PARTIALLY COMPOSITE (REST OF) SM (WITH A BROAD BRUSH)

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Disclaimer

- mostly review (except neutrino mass seesaw at end!): for details, see other talks in this program and/or reviews by Contino, 2010 (pre-Higgs discovery); Panico, Wulzer, 2015
- references not complete (for more, see above reviews)
- Only PNGB Higgs here: for ``comparison" of it with other ideas, see Markus Luty's talk at BSM lattice workshop at Livermore, 2015

Summary

Composite (PNGB) Higgs + (all) SM fermions and gauge bosons partially composite

- addresses Planck-weak hierarchy problem
- flavor hierarchy built-in
- fits data without (severe) tuning
- predicts signals at LHC

- from generalization (and scaling-up) of hadrons/QCD

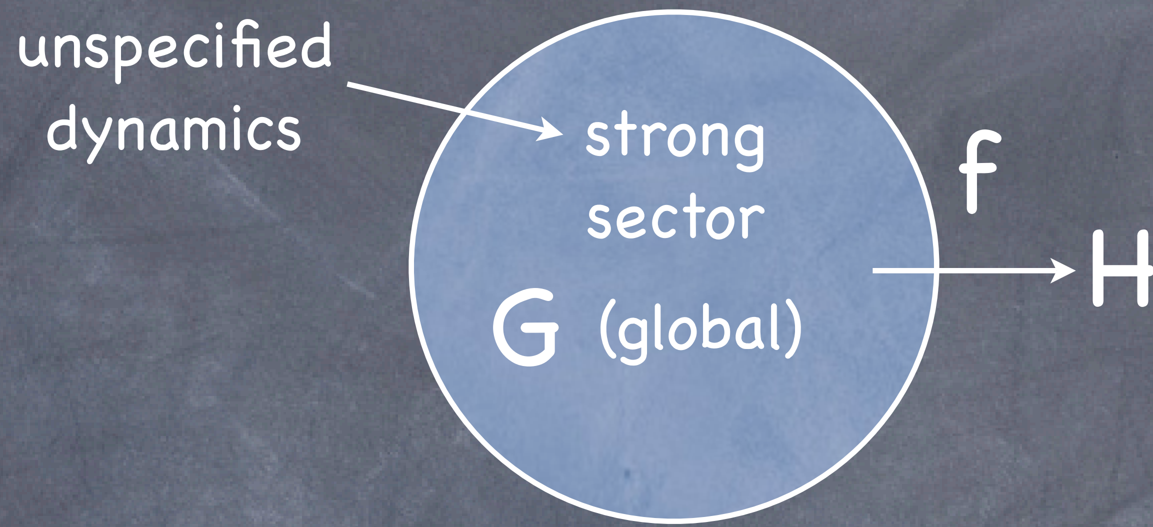
Plan

- start simple (a la QCD), build-up naturally to complete framework
- assume only basic EWSB (W/Z and top massive) "to begin with"
- ...only later, EW precision data first and then Higgs

Vacuum (mis)alignment in strongly-coupledtheories

Dynamical (spontaneous) global

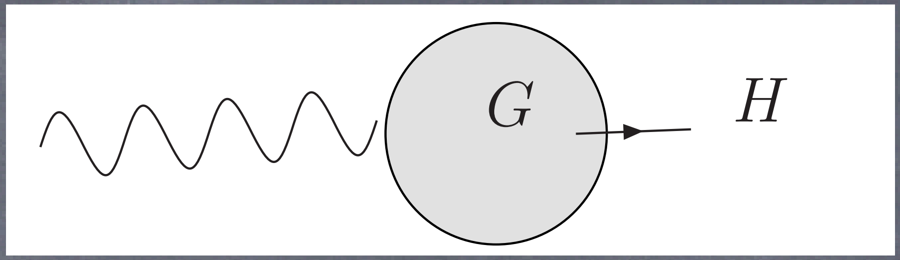
symmetry breaking $\Rightarrow$ NGBs



- dimensional transmutation for $f \ll M_{\rm Pl}$
- NGBs (h) parametrize vacuum degeneracy (orientation of H inside G): $\theta \sim h/f$ (not fixed)
- E.g., (pure) QCD with massless up and down quarks ($f \sim$ 200 MeV) : $SU(2)_L \times SU(2)_R \to SU(2)_V$
  h are (massless) π

...but in general, strong dynamics need not be QCD-like!

Weakly gauging subgroup of global symmetry (light) PNGBs



- External, weak gauging of subgroup of G
- E.g., QED coupled to QCD: $U(1)_{\mathrm{EM}} \subset SU(2)_L \times SU(2)_R$
- Direction of (weak) gauging relative to (strong) breaking?
- Dynamical answer: gauging explicitly breaks G, generates potential V(h) for NGBs (making them pseudo): vacuum fixed by minimizing V (naturally) light, weakly-coupled PNGBs

Fate of (weakly-coupled) gauge boson

- E.g.: in QCD-QED, vectorial still unbroken (photon massless; $m_{\pi^\pm}^2 > 0$ from photon loop)
- Vector-like gauge theories (L and R fermions transforming identically) break axial global symmetries (Vafa-Witten...)
- no such ``theorem" for general strong dynamics!!

Onto breaking (or not) EW symmetry (f ~TeV)

- For QCD-like theories, two cases for embedding of EW inside G

$\mathrm{EW} \subset G_{\mathrm{vectorial}}$

v = 0

due to

$V(h) \propto +\sin^2(h/f)$

(like photon)
(not desired here!)

$\mathrm{EW} \subset G_{\mathrm{axial}}$

(as in scaled-up 2-flavor QCD)

$\Rightarrow$ v = f

light PNGB if non-minimal G (more flavors), but cannot call it "Higgs" (not part of "doublet"): no EW symmetry below f $\Rightarrow$ couplings to W/Z not SM-like (in general, deviate from SM by $\sim v^2/f^2$)

Intermediate Summary (I)

Two extremes for v

Vacuum misalignment with only EW gauging

$\Downarrow$

- v = f: light PNGB, but not SM-like....or,
- v = 0 (to be discarded?!)

...but, tale (of two extremes) is incomplete (even before EW precision or Higgs data)!

- another, mandatory source of explicit breaking: SM fermion masses (especially top quark)!
- contributes to PNGB potential, can it give $0 \leq v \leq f$? Yes!

Detour on fermion masses

Two possibilities

Extended technicolor (ETC)-like: SM fermion bilinear coupling to strong dynamics vs.

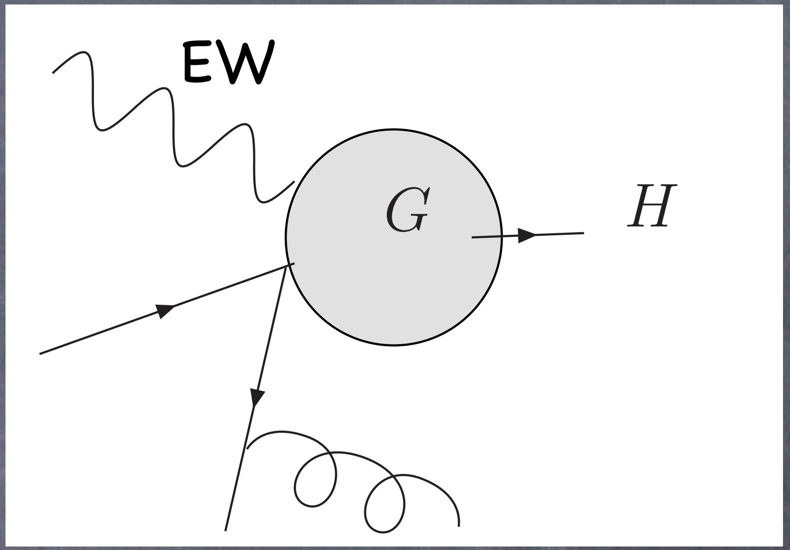
Partial compositeness (PC): linear coupling ⇒
SM fermion is admixture of external and composite fermion

ETC-like: not "unified" vs. PC is...

``technifermion"

- ETC: $\psi^2_{\rm SM}\langle T^2\rangle$; naively irrelevant, but walking (conformal) dynamics (large anomalous dimension, γ for T^2) can save it

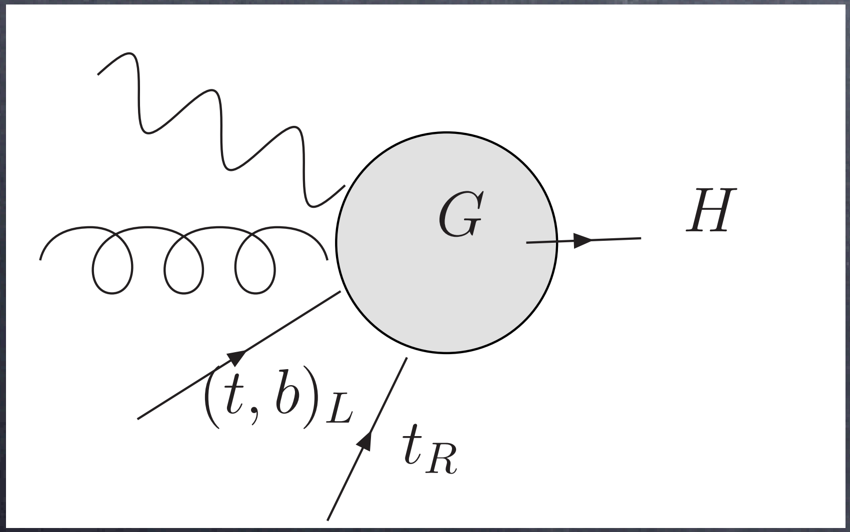
(Eichten, Lane...)



$only$ $\mathrm{EW} \subset G$ ⇨

no spin-1/2 composites for SM quarks to mix with (cf. W/Z)

- PC: SM fermions obtain mass by mixing with composites (like W/Z); *also* $SU(3)_c \subset G$ (like EW)



(D.B. Kaplan, 1991; Contino, Pomarol, 2004 for AdS/CFT version)

PC in QCD (coupled to QED)?!

$$e^- \, (\, u \; u \; d \,) \text{ allowed by gauge symmetries} \Rightarrow e^+ - p \text{ mixing!}$$

external fermion

(composite) operator

- Negligible in IR, but not so with large γ for fermionic operator (walking/conformal dynamics needed for ETC-like as well!)

Ingredients

Fermionic operators:

- singlet of strong dynamics (generic, e.g., in QCD!)
- large γ (many e.g. of walking/conformal known)
- charged under SM gauge group, e.g., $U(1)_{\mathrm{EM}}$ in QCD: for PC, all SM fermions (quarks and leptons) couple linearly ⇨ $\textit{entire}\ \mathrm{SM} \subset G$
- e.g., $\psi_{\mathrm{SM}} T^3$: each T being **3** of $SU(3)_{\mathrm{TC}}$; ***only*** **1** T **is 3 of** $SU(3)_{\mathrm{color}}$**...or** $SU(2)_{\mathrm{TC}}$**, with "**T^3**" being 2.2.3 (numerous possibilities)**

Anatomy of SM fermion mass

- Two different [$SU(2)_L$ doublet (D) and singlet (S)] linear couplings:

$$\lambda_D \psi^D_{\rm SM} T^3 + \lambda_S \psi^S_{\rm SM} T'^{\,3}$$

(Strictly speaking, SM is admixture!)

- RGE from UV cut-off (where generated) to TeV: v interpolated by $T^3 T'^{\,3}$ $\Rightarrow$ $m_{\rm SM} \propto \lambda_D \lambda_S v$

[Equivalently, $\psi_{\rm SM}$ mix with (Dirac) composites, which feel EWSB]

...so far, PC as (unified) alternative to ETC-like: next, flavor is better with PC...

Flavor performance: general considerations

e.g., new gauge bosons

- ETC-like or PC couplings generated at Λ_F ...but also (in general):

$$\frac{1}{\Lambda_F^2}\psi_{\rm SM}^4 \quad \text{(flavor/CP-violating)}$$

- Bound on above from ϵ_K: $\Lambda_F \gtrsim 10^5$ TeV

(getting right SM fermion mass)

- Large γ for $\mathcal{O}$ (either T^2 in ETC-like or T^3 in PC)

(small scaling dimension for $\mathcal{O}$)

$\mathcal{O}^2$ (scalar, SM gauge singlet) *relevant* $\rightarrow$ get back hierarchy problem?!

...yes for ETC-like, but not for PC!

(Minimal) ETC-like: tension between generating (right) fermion mass and suppressing flavor violation

- Start with $\frac{1}{\Lambda_F^2}\psi_{\rm SM}^2 T^2$, but try $[T^2] = 3+\gamma$

$$m_{\rm SM} \sim v \left(\frac{m_\rho}{\Lambda_F} \right)^{2+\gamma}$$

SM singlet

- Bounds on γ: want $[(\bar{T}T)^2] \geq 4$ (otherwise, new mass scale generated)...but in large-N, it is $(6+2\,\gamma)$ $\Rightarrow$

$$\gamma \geq -1 \Rightarrow m_{\rm SM} \stackrel{<}{\sim} v \left(\frac{m_\rho}{\Lambda_F} \right)$$ (still from irrelevant coupling!)

- For $\Lambda_F \stackrel{>}{\sim} 10^5$ TeV (from ϵ_K), need $m_\rho \stackrel{>}{\sim} 10^3$ TeV (severe tuning of v) even for $m_{b,c}$!

PC: flavor scale/violation can be decoupled!

- With $\frac{1}{\Lambda_F^2}\psi_{\rm SM}T^3$, more "room" for γ to do its job: e.g., for marginal coupling, we need $[T^3] = 9/2 + \gamma = 5/2$ $\Longrightarrow$
  $\gamma = -2$ (same as for ETC-like for *that* coupling to be marginal)
- ...but in ETC-like $(\bar{T}T)^2$ would then be relevant (like Higgs mass term: causes hierarchy problem, hence not allowed!)
- ....whereas in PC, $[\bar{T}^3 T^3] \sim 5 (> 4)$ is safe!
- In PC, with only one T^3, only $\bar{T}^3 \not\partial\, T^3$ is allowed (by chiral symmetry) $\Longrightarrow$ $[T^3] \geq 3/2$ (free fermion limit!) for avoiding hierarchy problem: linear coupling can even be relevant! (not a worry, since reaches new fixed point)
- $\Lambda_F \gg 10^5$ TeV allowed in PC (assuming large γ till then), suppressing flavor violation, while keeping SM fermions masses

Summary of ETC-like vs. PC

- In ETC-like (bilinear coupling) theory: $two\ \psi_{\rm SM}$ "soak-up" dimension 3 ⇒ $[\bar{T}T]$ has to be (very) small (=1) for marginal coupling ⇒
  hierarchy problem for $(\bar{T}T)^\dagger \bar{T}T$ ...vs...
  in PC, 1 $\psi_{\rm SM}$'s share is only 3/2 ⇒ $[T^3]$ can be larger (= 5/2), again for marginal coupling

- And, $(\bar{T}T)^\dagger \bar{T}T$ is always allowed (scalars not protected by chiral symmetry) vs. $\bar{T^3}T^3$ is not Lorentz-invariant for fermionic operator!

Obtaining fermion mass hierarchy naturally with PC

- different T^3, but same order γ's for three generations ⇒ hierarchical couplings $\frac{\lambda}{\Lambda_F^2}\psi_{\rm SM} T^3$ in IR:

$$\lambda(\mathrm{IR}) \sim \lambda(\mathrm{UV}) \left(\frac{\mathrm{m}_\rho}{\Lambda_\mathrm{F}}\right)^\gamma$$

- ...even if no so in UV!

- With $m_{\rm SM} \propto \lambda_D \lambda_S v$, we get flavor hierarchy (vs. in ETC-like theories, put in by hand in UV coupling)

UV-completions for PC (large anomalous dimension for fermionic operators)

- Lattice simulations underway

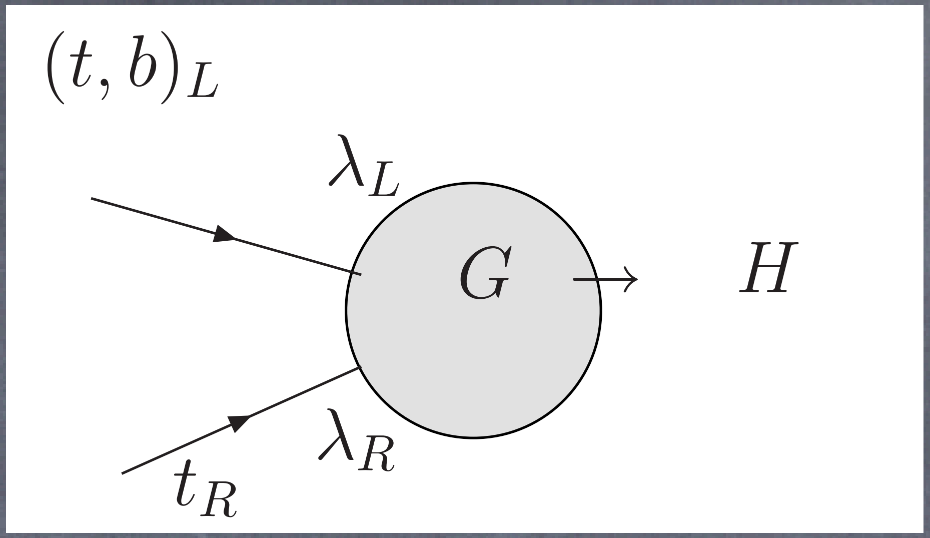
For marginal coupling, need $\gamma = -2$ for T^3, but $\gamma = -1$ for $T_{\text{adjoint}}\sigma^{\mu\nu}G_{\mu\nu}$! (Wulzer)

- warped extra dimension: partial [KK to warped-down 5D cut-off $\sim O(10)$ higher; string theory (Kachru, Simic, Trivedi, 2009) beyond that?!]

...end detour on fermion masses

- Pick PC...and follow one’s nose...

Two contributions from top quark



- top quark contribution to V(h) dominates
- Separate (linear) couplings of t_R and $(t,b)_L$ (possibly to different representations of G)
- contributions with different functional forms, e.g., in $SO(5)/SO(4)$, with (both) top-operators being 4 :

$$\beta \sin^2(h/f) + \alpha \cos(h/f)$$

(KA, Contino, Pomarol, 2004)

Range of v generic

- minimizing V(h) gives (depending on parameters, e.g., couplings/masses entering coefficients $\beta,\ \alpha$):

$$0 \leq v \leq f$$

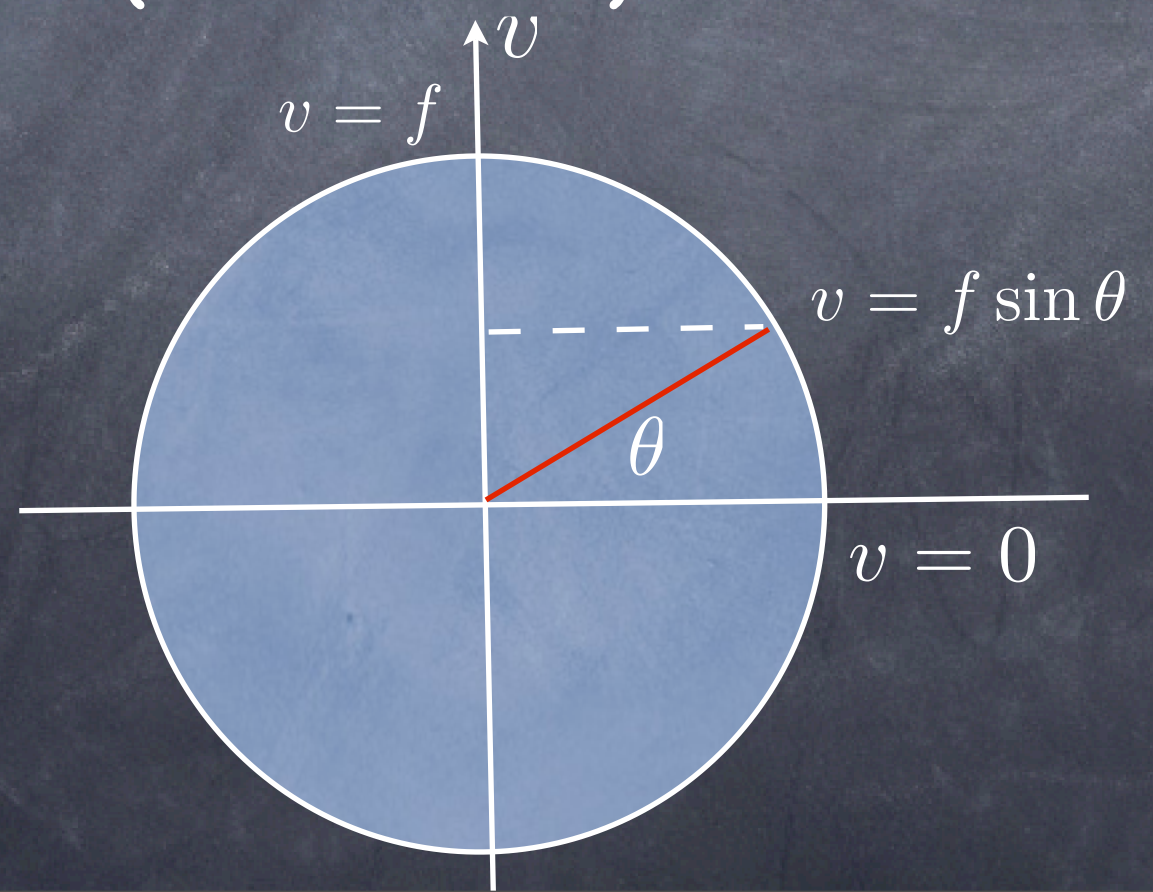
- ...vs. in ETC-like, (bilinear) coupling of top (only), dominates gauge: not much "room"

$$\Rightarrow \quad v/f \text{ fixed } (v = f \text{ or } v = f/2 \text{ etc.})$$

- Back to PC, naturally, still $v \lesssim f$ (e.g., $v \sim f/2$)

v << f (fine-tuning): SM-like Higgs ``emerges"!

- For $(v \ll) E \ll f$, we have (unbroken) EW symmetry ⇒ (light) scalar must be doublet (its VEV breaks EW): viewed as ``2-stage" breaking (at $\sim f$, $G \to H$, but EW intact) (Georgi, Kaplan...1984)
- ...but SM-like PNGB composite Higgs is continuously connected to v = f (technicolor) limit



Intermediate Summary (II)

Vacuum alignment with PC

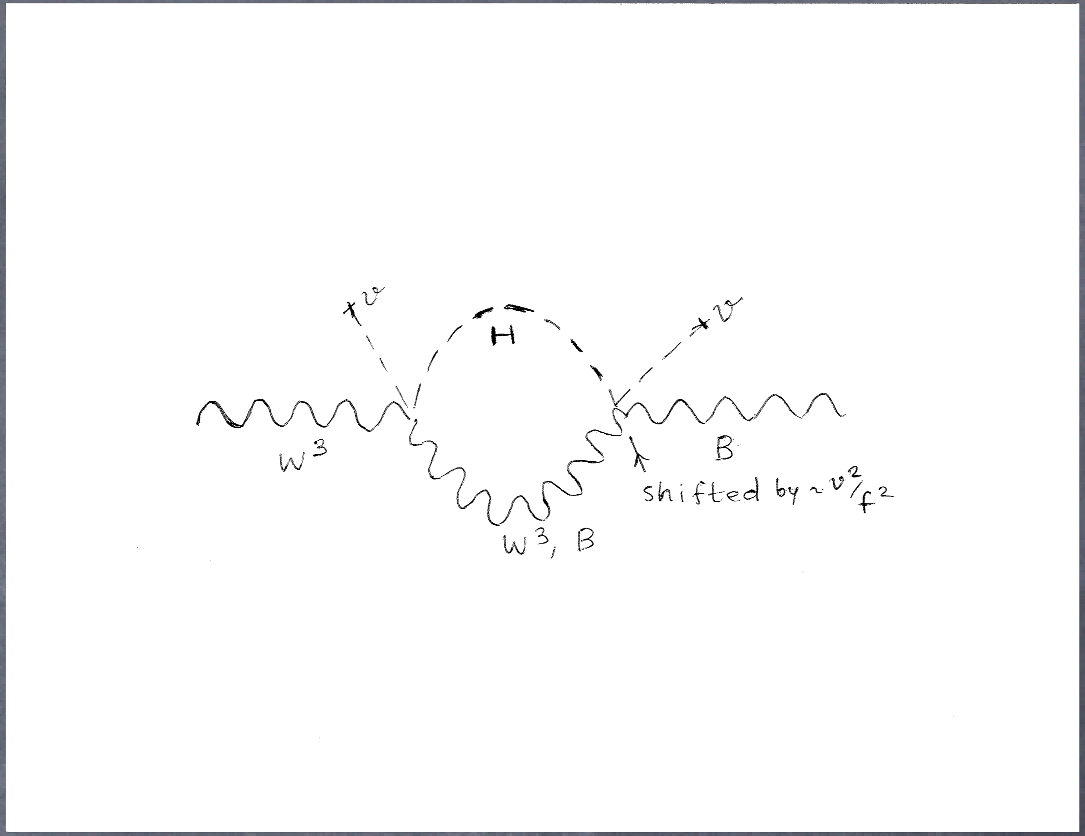
- heavy top dominates: $0 \leq v \leq f$
- features SM-like PNGB composite Higgs ($v \ll f$)
- ...only W/Z, top massive (before mid-1990's) used so far
- ...onto EW precision data (mid-1990's)

(Custodial isospin required from W/Z masses already)

S parameter [$S = (16\pi)\Pi_{3Y}$] : 2 contributions

convention

- IR: Higgs couplings to W/Z shift by $\sim v^2/f^2$

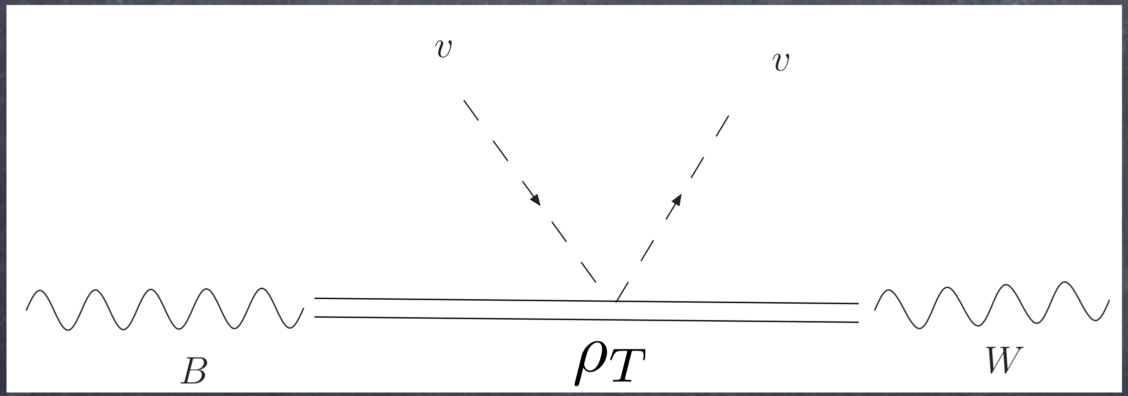


(Barbieri, Bellazzini, Rychkov, Varagnolo)

$$S \sim \frac{1}{\pi}\frac{v^2}{f^2}\log\left(\frac{m_\rho}{m_h}\right)$$

- UV: techni-rho exchange:

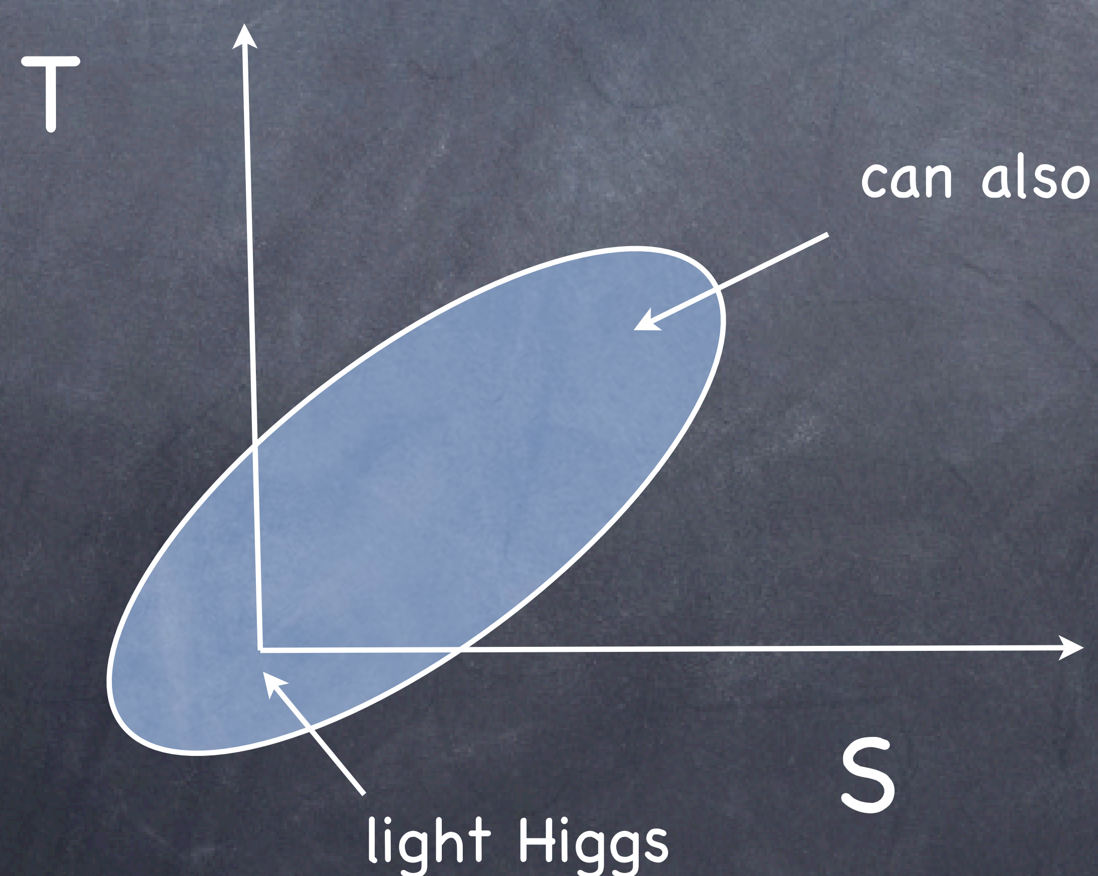
$$S \sim 16\pi\frac{v^2}{m_\rho^2} \sim \frac{N}{\pi}\frac{v^2}{f^2}\ (\text{with } m_\rho \sim \frac{4\pi}{\sqrt{N}}f)$$



S parameter data: $v/f \sim 1/\text{a few}$ favored

- Depending on T parameter, $S \lesssim O(0.1)$

- Difficult to ``rule out" v = f, but smaller v is safer!



Intermediate Summary (III)

SM-like composite Higgs ``selected" pre-LHC!

- EW precision data prefers $v/f \lesssim 1/\text{a few}$

$$\Downarrow$$

- PNGB is SM-like Higgs

Higgs discovery (2012)

- Does not (by itself) rule out $v \sim f$ (technicolor limit)

(due to presence of light, PNGBs even in this limit!)

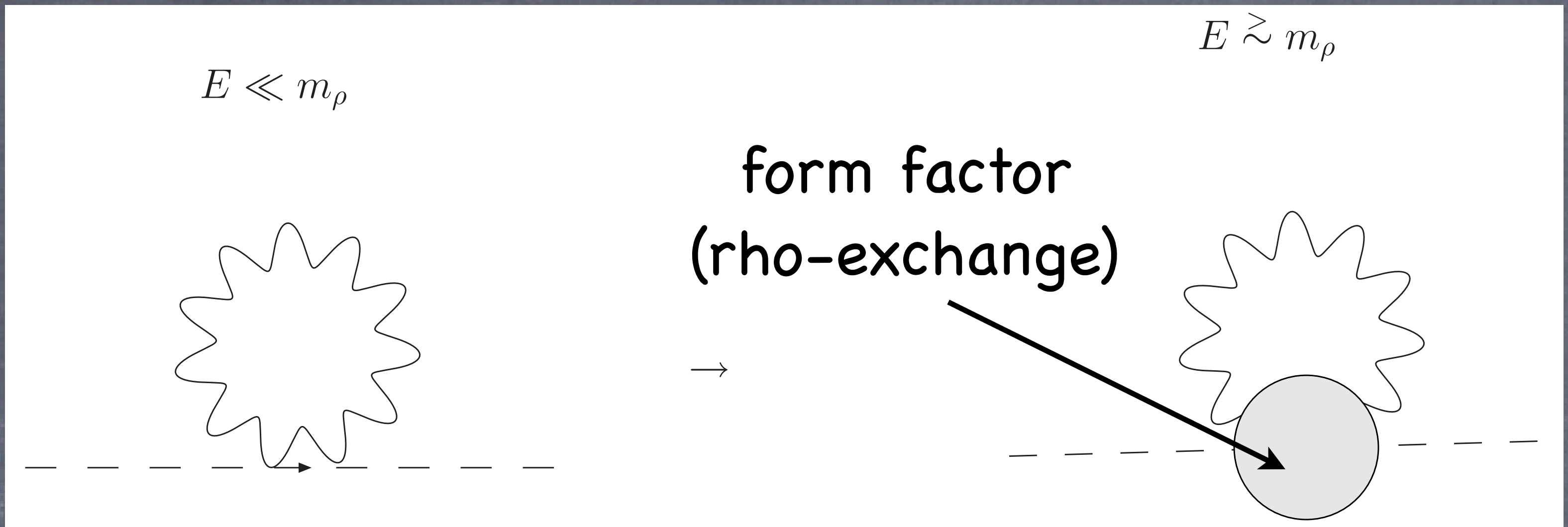
Higgs couplings agree with SM (2013)

- Technicolor limit $(v \sim f)$ *not* viable
  [since expect $O(1)$ shifts in PNGB couplings to W/Z]

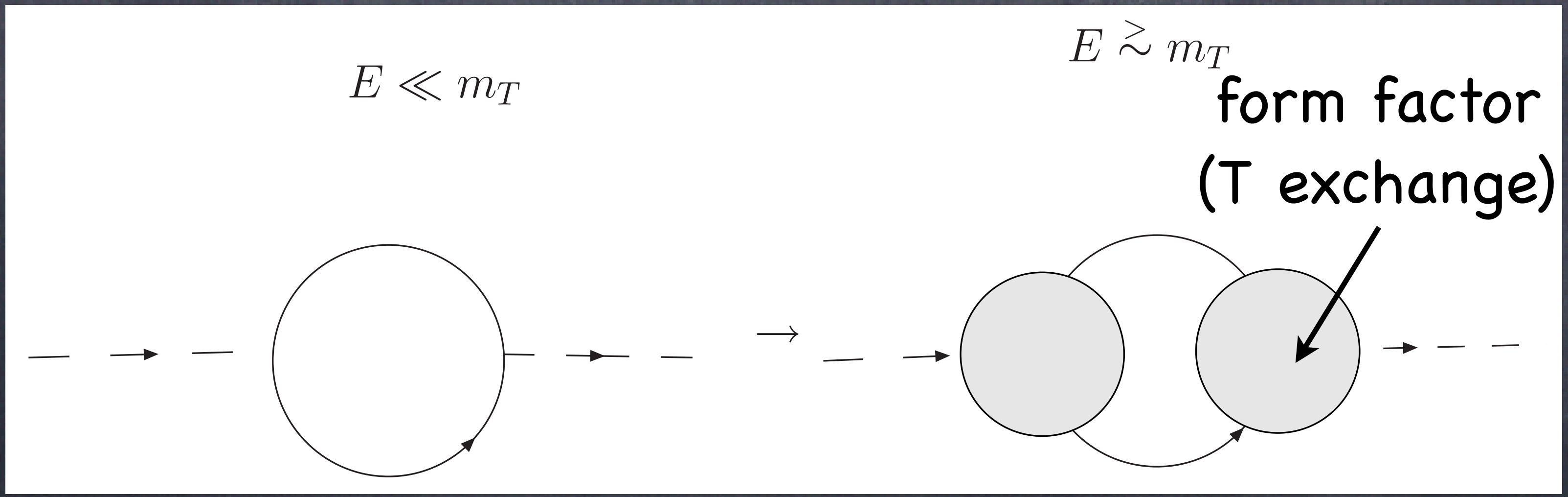
- Getting it light is necessary, but might not be sufficient!

Higgs and top-partner mass; tuning

Top-partner ``built-in" (analog with rho-meson in QCD)!



- Top quark mixing with composites is dominant source of V(h) ⇒ divergence in Higgs mass from top loop cancelled by that composite, T (aka ``top-partner")



Higgs potential from top-partners:

- Neglect gauge loops; top-partner (mass m_T) effect:

$$V(h) = \frac{N_c y_t^2}{8\pi^2} m_T^2 \left(a\, h^2 + b \frac{h^4}{f^2} \right)$$

(Panico, Redi, Tesi, Wulzer...)

like

$$m_{\pi^+}^2 - m_{\pi^-}^2 \sim \frac{e^2}{16\pi^2} m_\rho^2$$

due to

$\sin^2$ or cos etc. of (h/f)

- a, b depend on model, but naturally $\sim O(1)$

$\Rightarrow$ naturally: $v \sim f$

Fine-tune mass term (a) to get $v \ll f$

choose top-partner mass to get Higgs mass

(no tuning of b here!)

- (Model-independent) tuning needed is $\sim v^2/f^2$

(independent of Higgs mass: even pre-LHC, based on EW precision data)

- Top-partner mass given by observed Higgs quartic:

$$0.15 = \frac{bN_c}{8\pi^2}\left(\frac{m_T}{f}\right)^2$$

$$\Rightarrow m_T = \frac{2f}{\sqrt{b}} \qquad (\gtrsim f\text{: reasonable for composite!})$$

(Colored) Top-partner (direct) bound vs. EWPT: now (top-partner is weaker)

- Compare bound on f from top-partner vs. EWPT/Higgs data:

  For $b = 1$ and $f \gtrsim 600$ GeV (EW and Higgs data), we get $m_T \gtrsim 1.2$ TeV ⇒

did not expect to find it in Run 1 of lHC!

(LHC run 1 bound on top-partner is about 800 GeV)

Top-partner (direct) bound vs. EWPT: after HL-LHC (Matsedonskyi, Panico, Wulzer...)

- Pair-production bound 2 TeV (single might be higher)

  ⇒ $f \gtrsim 1\ \mathrm{TeV}$ (stronger than EW/Higgs data)

[EWPT will not change: as of now bit stronger than Higgs couplings; latter will improve, but (roughly) only reach as far as EWPT]

- Tweakings (from b = 1):

  $b = 1/2 \Rightarrow m_T \gtrsim 1.7\ \mathrm{TeV}$ for $f \gtrsim 600\ \mathrm{GeV}$ (from EW/Higgs data): still a *bit* weaker than direct HL-LHC bound!

  $b = 2 \Rightarrow m_T \gtrsim 900\ \mathrm{GeV}$ for $f \gtrsim 600\ \mathrm{GeV}$ (from EW/Higgs data): still above run 1 reach, but *easily* superseeded by Run 2!

Other possibilities (more structure)

- little Higgs (Arkani-Hamed, Cohen, Georgi, 2002...): quartic (only) is larger: $v \ll f$ naturally
- twin Higgs (Chacko, Goh, Harnik, 2005...): top-partners are not colored: avoid that bound on f (but not EWPT/Higgs data)

Neutrino mass: seesaw, but ``inverse"!

(KA, Hong, Vecchi, in preparation)

PC for (Dirac) neutrino mass

- Like for charged fermions, N (SM singlet) couples to $\mathcal{O}_N$ (and lepton doublet, L to $\mathcal{O}_L$)

$$\Downarrow$$

$$m_\nu^{\text{Dirac}} \propto \lambda_N \lambda_L v$$

(Super-)Large Majorana mass for (external) singlet $\Rightarrow$ (super-) small Majorana mass terms for TeV-mass singlet

- Unlike charged fermions, $M_N N^2$ allowed $\Rightarrow$

$integrate$ out N (as usual)...but here, generates $\mathcal{O}_N^2 / M_N$ (no SM neutrino mass yet)!

$\Downarrow$

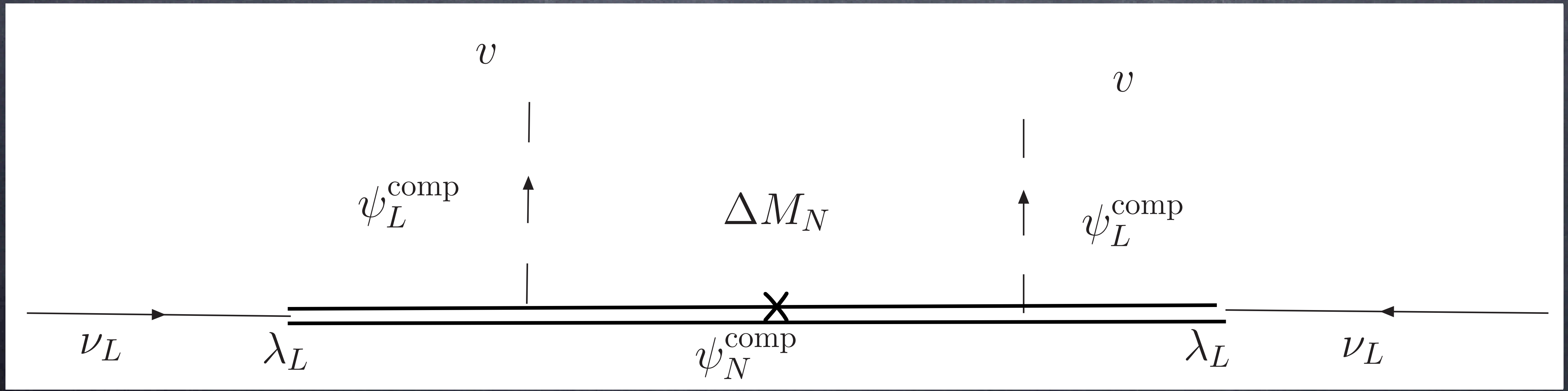
- A seesaw for Majorana mass term ΔM_N for ($\sim$TeV Dirac mass) composite singlets (assume $\lambda_N \sim$ marginal coupling):

$$\Delta M_N \sim \frac{\text{TeV}^2}{M_N}$$

Exchange of TeV-mass composites ⟹ (super-)small Majorana mass for SM neutrino

- ~TeV composite singlets have unsuppressed Yukawa couplings, but are pseudo-Dirac

$$m_\nu \sim (\lambda_L v)^2 \frac{\Delta M_N}{\mathrm{TeV}^{\;2}}$$
$$\sim \frac{(\lambda_L v)^2}{M_N}$$



Nature of seesaw for SM neutrino mass

- formula mimics high-scale (type I) seesaw (Huber, Shafi, 2003... in warped extra dimension)
- ...but structure/underlying dynamics is subtle (~TeV-mass states crucial): like ``inverse" (Mohapatra, Valle, 1986), that too naturally so!
- leptogenesis: from ~TeV-mass singlets, not (super-)heavy N!
- LHC/100 TeV can (more directly than in high-scale seesaw) probe mechanism of generation of neutrino mass!

Conclusions

- Adapting QCD/hadrons to EW breaking can ``deliver'' composite SM-like PNGB Higgs

- Top-quark is key player: heavy + partially composite

  ⇒ can drive v/f around ``circle''

  $[0 \text{ to small (fits EW/Higgs data) to } 1 = \text{technicolor}]$

  ⇒ Top-partner (composite) naturally in the game

- Top-partner's search will probe compositeness scale beyond EW/Higgs data

- ``Partially composite'' seesaw for neutrino mass is accessible!

BACK-UP

Parity of PNGB composite Higgs: to be odd or even

- In general, parity of NGB from (purely) strong dynamics viewpoint might not be relevant for its couplings to SM (external) fields: latter need not respect parity (i.e., it's "accidental")

- QCD-like theories with EW $\subset G_{\text{vectorial}} \Rightarrow$ NGB is odd

Also, $v = 0$ with only gauging, but top coupling $\Rightarrow v \neq 0$ (small), (spontaneously) *breaking* parity!

More on flavor-violation in PC

- from exchange of ($\sim$ TeV-mass desired!) composites, with direct, flavor violating couplings to SM fermions
- ...albeit small: Yukawa strength (just like to another composite, i.e., Higgs!)

$f \gtrsim O(10)$ TeV (from $\mu \to e\gamma$...),
assuming anarchy of *composite* Yukawa couplings
(still much *weaker* than generic bound of 10^5 TeV)

- some flavor symmetry protection needed

Grand unified G (I) → ``prediction" of $\sin^2\theta_W$

- Another bonus of (partially) composite top quark: running of SM gauge couplings modified above TeV...
- ...such that they unify (with precision similar to SUSY) close to (usual) GUT scale!

Grand unified G (II) → Dark Matter from proton stability!

- SM singlet GUT-partner of top quark with 1/3 baryon-number (exotic RH neutrino!) can be stable...
- ...and WIMP!