STRONGLY-COUPLED (BSM) HIGGS

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Summary of (broad) framework

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

- addresses Planck-weak hierarchy problem
- flavor hierarchy built-in (also neutrino seesaw)
- fits data without (severe) tuning
- predicts signals at LHC: shift in Higgs couplings; new particles (top-partner; composite gluon/W/Z)
- from generalization (and scaling-up) of hadrons/QCD

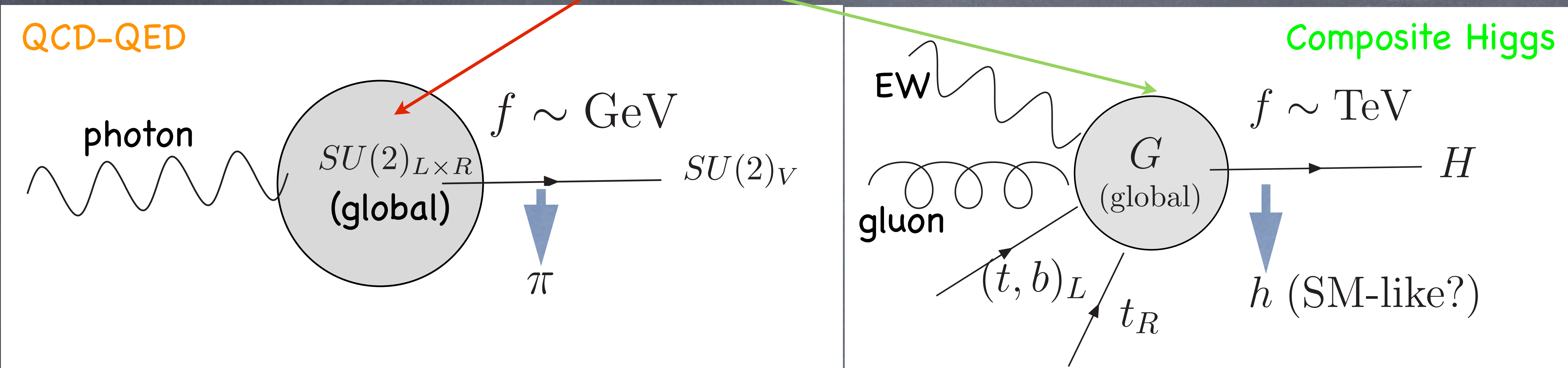
Plan for introduction

- Higgs like π, K → lighter than $\gtrsim$ TeV composites; same ``universality class" as technicolor
- SM fermions partially composite (``like" photon-rho mixing) → flavor nice + top-partner ``delivered"
- Tests: interplay of Higgs couplings (indirect: EW precision tests + direct) vs. top-partner search → did not expect to see top-partner at run 1 of LHC
- (partially) composite seesaw for neutrino mass → (most) natural model + signals at TeV

(SM-LIKE)PNGB HIGGS FROM VACUUM (MIS)ALIGMENT

Analogy with QCD-QED

(old/new) strong dynamics



- External couplings (see later for those of fermions/gluon) break global symmetry explicitly ⇨ generate potential for Nambu-Goldstone boson (NGB): h is pseudo...(PNGB)

- Vacuum (mis)alignment [between directions of external gauging and symmetry (un)broken by strong dynamics]:

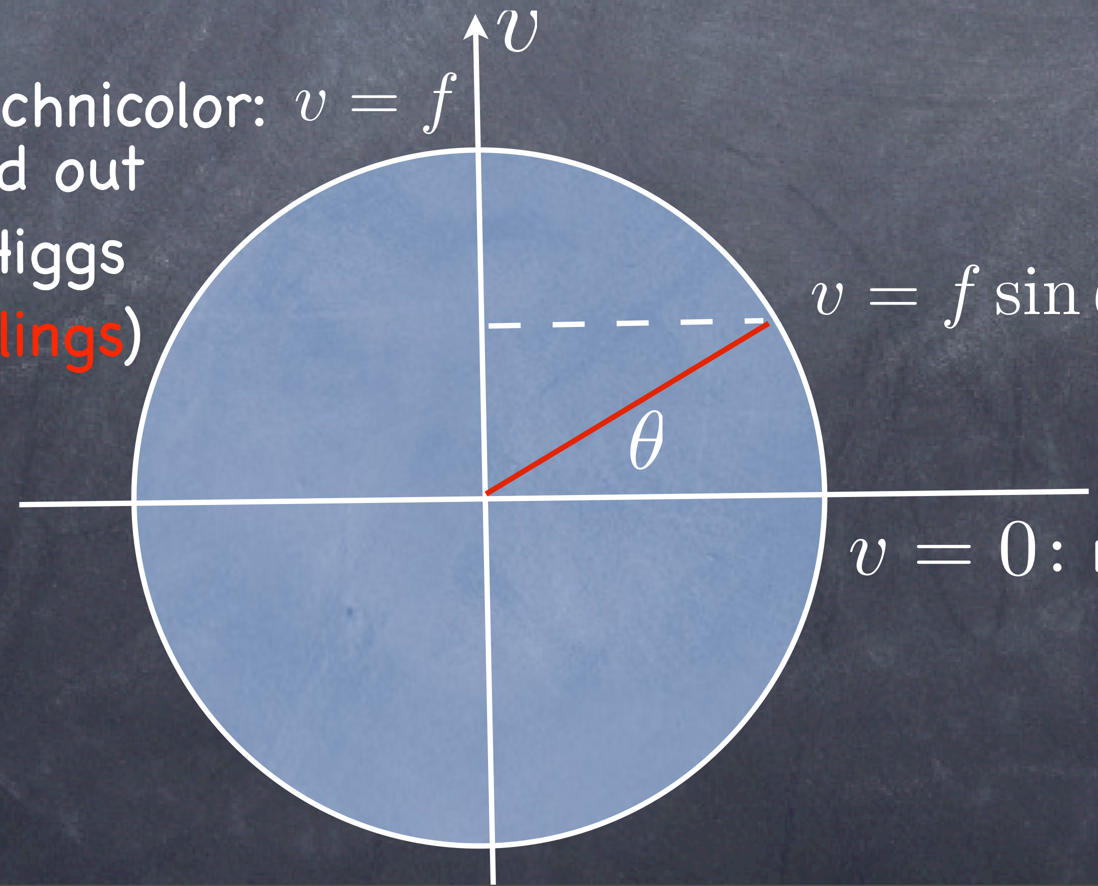
$$0 \leq v \leq f$$

gauged component (VEV of h) → v

overall/global breaking → f

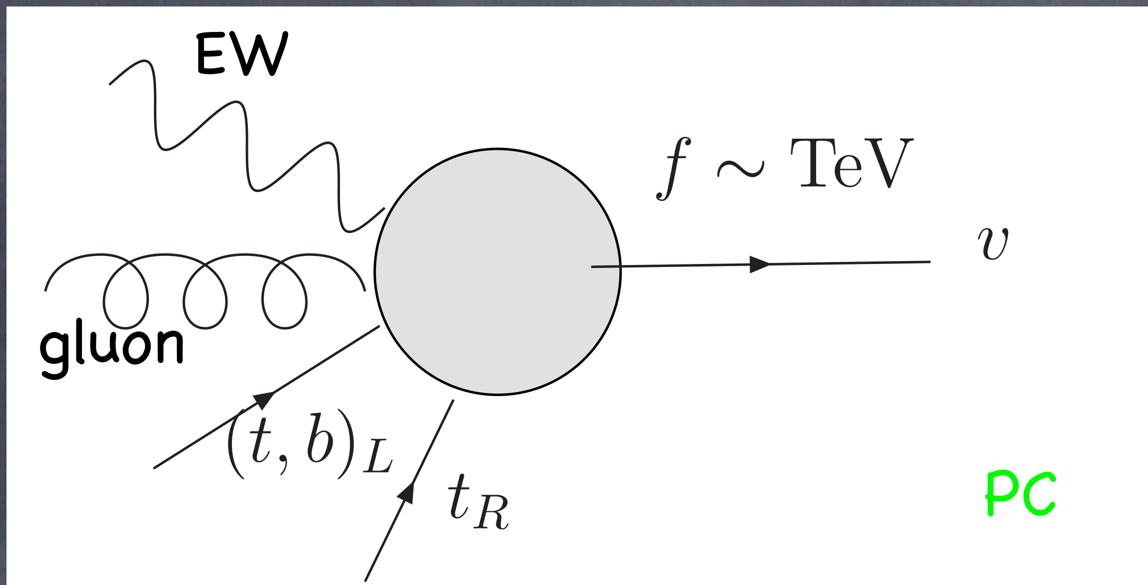
v<<f (fine-tuning): SM-like Higgs ``emerges" (I)!

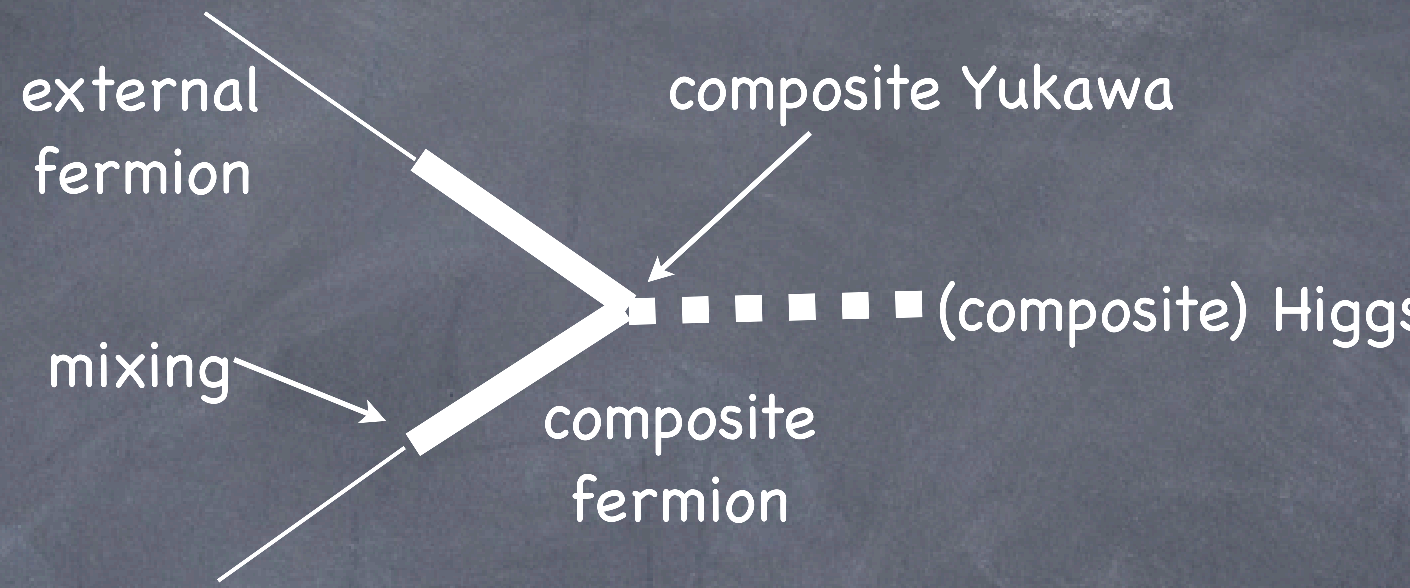
- For $(v \ll) E \ll f$, we have (unbroken) EW symmetry $\Rightarrow$ (light) PNGB must be doublet (couplings of SM Higgs, up to corrections $\sim v^2/f^2$; its VEV breaks EW): viewed as ``2-stage" breaking (at $\sim f$, $G \to H$, but EW intact) (Georgi, Kaplan...1984)
- ...but SM-like PNGB composite Higgs is continuously connected to v = f (technicolor) limit (PNGB, not SM-like)



Partial compositeness (PC) of SM fermions

Basic idea (Higgs PNGB or not): flavor theory





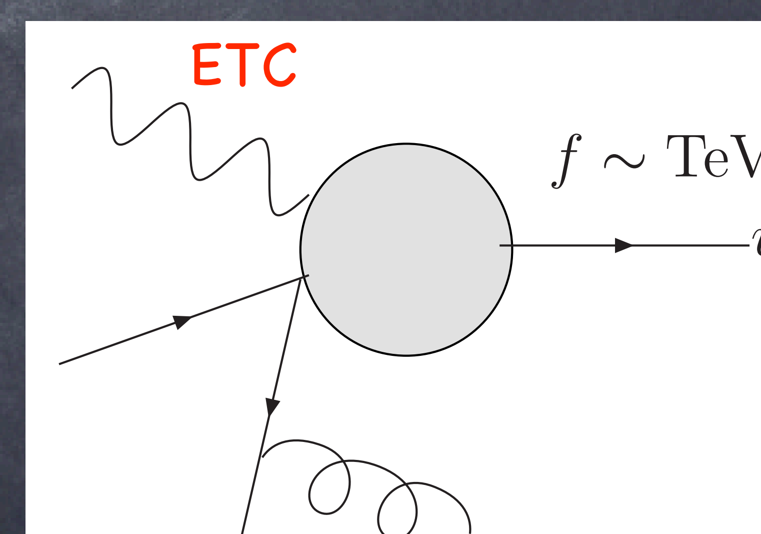
- coupling of external fermion to strong sector (EWSB) is linear ($\psi\, \mathcal{O}_{\text{strong}}$) ⇒ SM fermion is admixture of external and composite (generalization of $\gamma - \rho$ in QCD-QED: $A_\mu J^\mu_{\text{strong}}$) + gluon coupling like EW

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

(Eichten, Lane, 1980...)

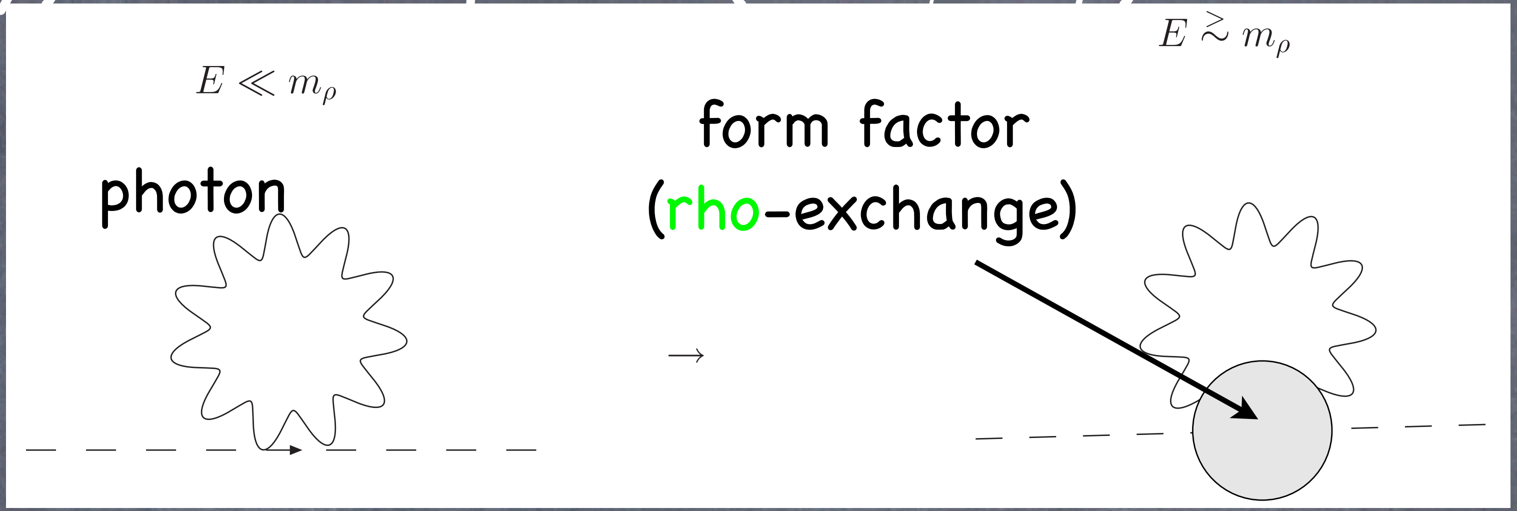
- generate (observed) fermion masses, no (severe) flavor violation

- cf. bilinear coupling (ETC): flavor problem + not "unified"

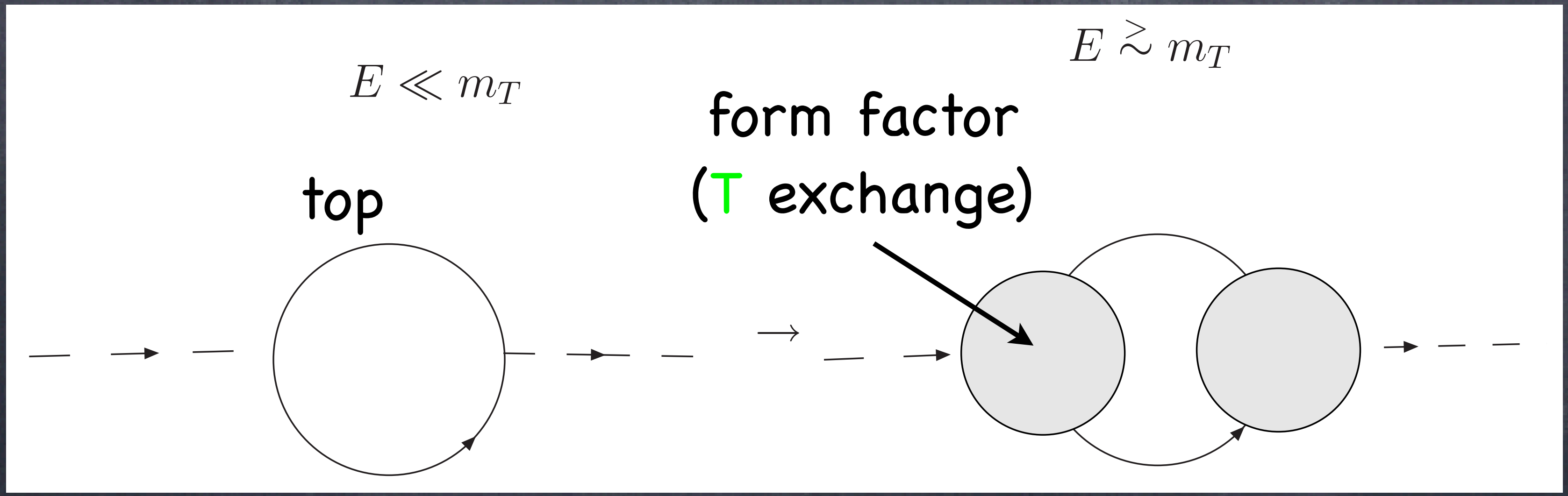


Even better fit for PNGB: Top-partner ``built-in" (analogy with rho-meson in QCD)!

- PC (explicitly) breaks global (like $\gamma - \rho$): focus on top quark



- ``Cause leads to cure": 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")



``Spin-off" of PC top quark: PNGB acquires SM-like Higgs character (II)

- 2 independent (linear) couplings to strong sector
  [t_R and $(t,b)_L$] ⇨
  richer structure in V(h) [e.g., $\sin^2(h/f)$ and $\cos(h/f)$]

  ⇩ minimize...

- v/f scanned $(0 \text{ to } 1)$ in the model parameter space (difficult with ETC or only gauging as explicit breaking: v = 0 or f)

(KA, Contino, Pomarol, 2004)

- possible to fine-tune to get $(0 \neq)\ v/f \ll 1$

Signals: A tale of Higgs couplings vs. top-partner

Higgs coupling: direct vs. indirect

- Tension: shift in Higgs couplings and fine-tuning: $\sim v^2/f^2$
- EW precision tests (S parameter: also UV/technirho)

$$\Rightarrow v^2/f^2 \lesssim O(10\%) \ (f \gtrsim 600 \text{ GeV})$$

- Direct Higgs couplings (Gross talk):
  run 1 $\Rightarrow v^2/f^2 \lesssim O(20\%)$ (a bit weaker)
  HL-LHC $\Rightarrow v^2/f^2 \lesssim O(5\%) \ (f \gtrsim 800 \text{ GeV})$
  (a bit stronger than EW precision tests: won't improve)

New particles: top-partner

- (general) mass $\propto f \Rightarrow$ tuning if not seen
- most closely associated with Higgs potential is top-partner:

$m_T \sim 2f$ (based on physical Higgs mass/quartic)

(Panico, Redi, Tesi, Wulzer, 2012; De Simone, Matsedonskyi, Rattazzi, Wulzer, 2012...)

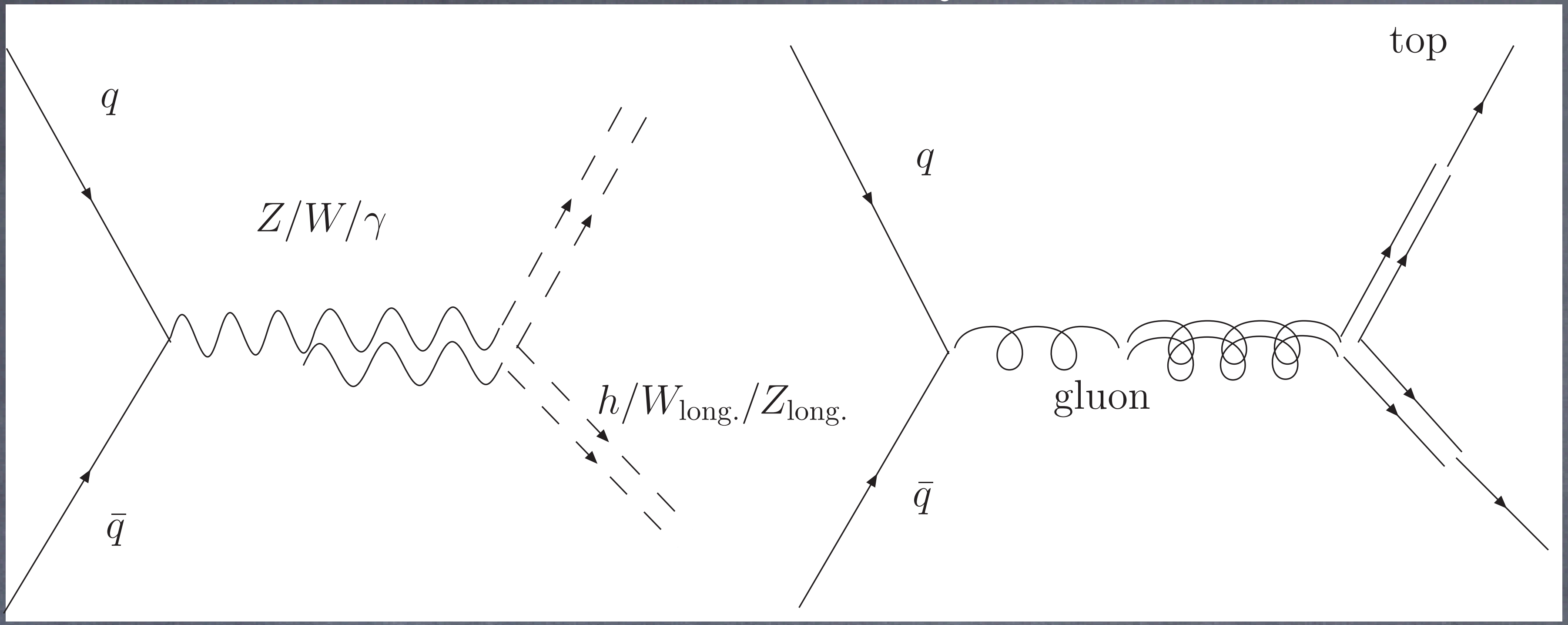
- EW precision tests ($f \gtrsim 600$ GeV)

$$m_T \gtrsim 1.2 \text{ TeV}$$

- not surprising that didn't see it so far (naturalness not (further) stressed by LHC run 1)!
- HL-LHC: $m_T \gtrsim 2$ TeV $\Rightarrow f \gtrsim 1$ TeV [bit stronger than (direct) Higgs couplings]

(Backovic, Flacke, Lee, Perez, 2014; Matsedonskyi, Panico, Wulzer, 2015...)

Other new particles



- composite/heavy gluon ("due to" PC), in addition to W/Z/γ (present in ETC also): Snowmass whitepaper, 2013...

- decay dominantly into (composite) top/Higgs (longitudinal W/Z), that too (highly) boosted!

What if HL-LHC does not find top-partner?!

- Colorless top-partner/neutral naturalness: direct searches less constraining (twin Higgs: Chacko, Harnik, Goh, 2005...; more general: Craig, Knapen, Longhi, 2014...)
- carries mirror color (to match factor of 3 of SM top loop!)
- decays of Higgs into mirror glueballs, which - via mixing with Higgs - decay into displaced b-jets (Craig, Katz, Strassler, Sundrum, 2015; Curtin, Verhaaren, 2015): Murray, Gori talks

(Partially) Composite Seesaw for Neutrino Mass

A tale of ``messenger" between two scales

(Huber, Shafi, 2003...in warped extra dimension; KA, Hong, Vecchi, 2015)

- Lepton-number broken only by external sector [e.g., by Majorana mass term for (external SM singlet)] in UV (at $M_{\rm Pl} \sim 10^{18}$ GeV): strong sector preserves it

- EWSB (Higgs born) only at TeV

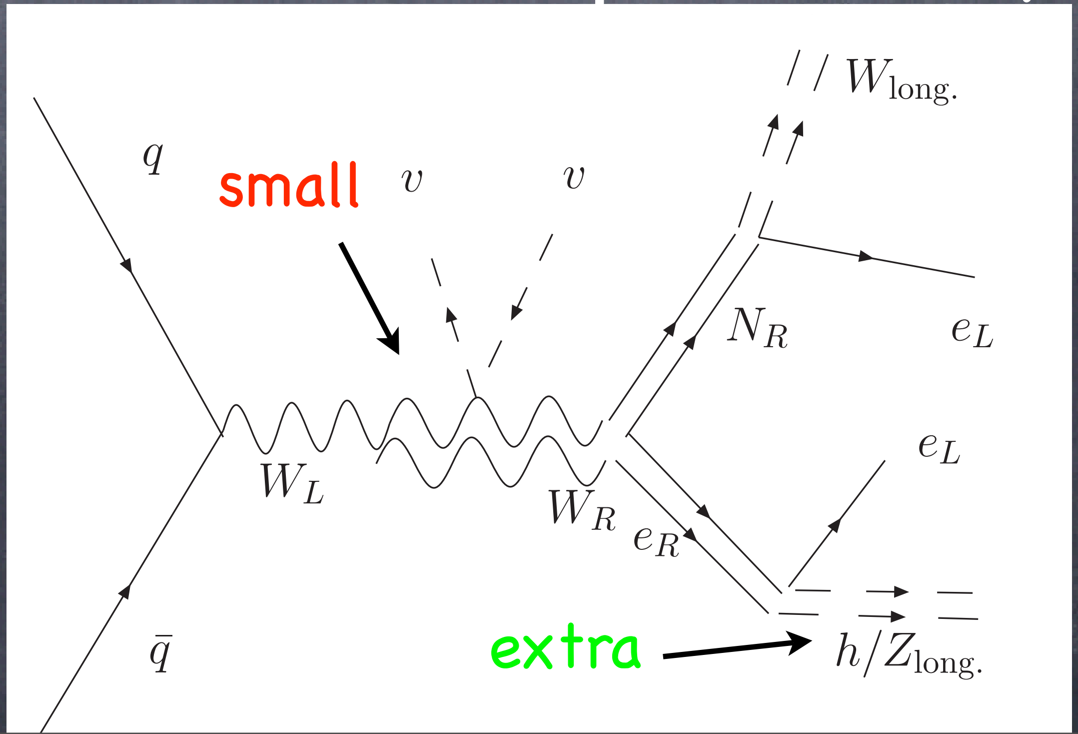
- Composite singlets (mixing with external/Majorana singlet, hence pseudo Dirac/with very small Majorana mass terms): link 2 breakings (both required for generating Majorana SM neutrino mass!)

(Further) Exploiting communication

- RGE ($M_{\rm Pl}$ to TeV!) + anomalous scaling dimensions (if strong dynamics is quasi-conformal) significantly modulate lepton-number violation at TeV ⇒ "effective" seesaw scale naturally smaller ($\sim 10^{12}$ GeV!) (cf. in usual case, invent new mechanism)

- probe origin of neutrino mass at TeV: RH/singlet neutrinos signal different than usual due to compositeness, e.g., 2 TeV W_R still allowed

(KA, Du, Hong, Vecchi)



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 to small (fits EW/Higgs data) to 1 = technicolor]

  ⇒ Top-partner (composite) naturally in the game

- Top-partner's search will probe compositeness scale (a bit) beyond EW/Higgs data

  Exotic Higgs decays for colorless top partners

- ``(Partially) composite'' seesaw for neutrino mass is natural + accessible!

BACK-UP

Disclaimer

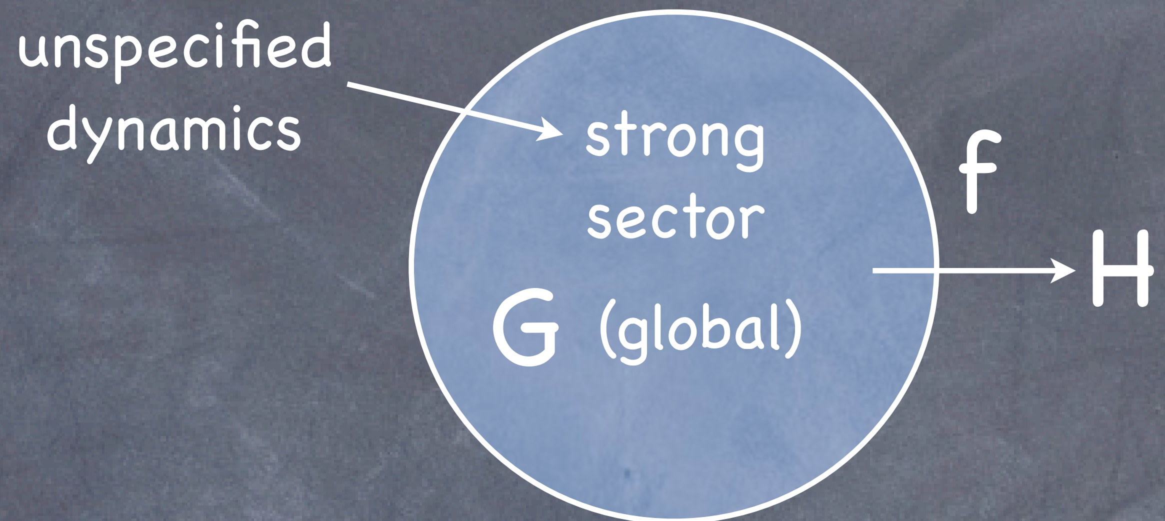
- mostly review (except neutrino mass seesaw at end!): for details, see reviews by Contino, 2010 (pre-Higgs discovery); Panico, Wulzer, 2015
- references not complete (for more, see above reviews)
- Only PNGB Higgs here: for ``comparison" of it with other ideas, see Markus Luty's talk at BSM lattice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

Plan for (composite) Higgs ``emergence"

- 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

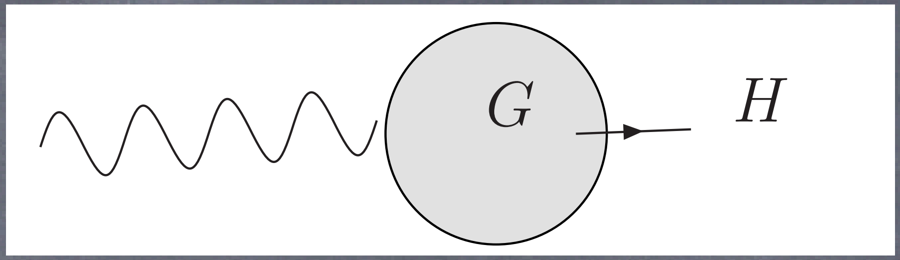
Dynamical (spontaneous) global symmetry breaking ⇒ NGBs



- 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; $m^2_{\pi^\pm} > 0$ 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

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

(as in scaled-up 2-flavor QCD)

⇒ v = f

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

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

v = 0

due to

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

(like photon)

(not desired here!)

Intermediate Summary (1)

Two extremes for v

Vacuum misalignment with only EW gauging

↓

- 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

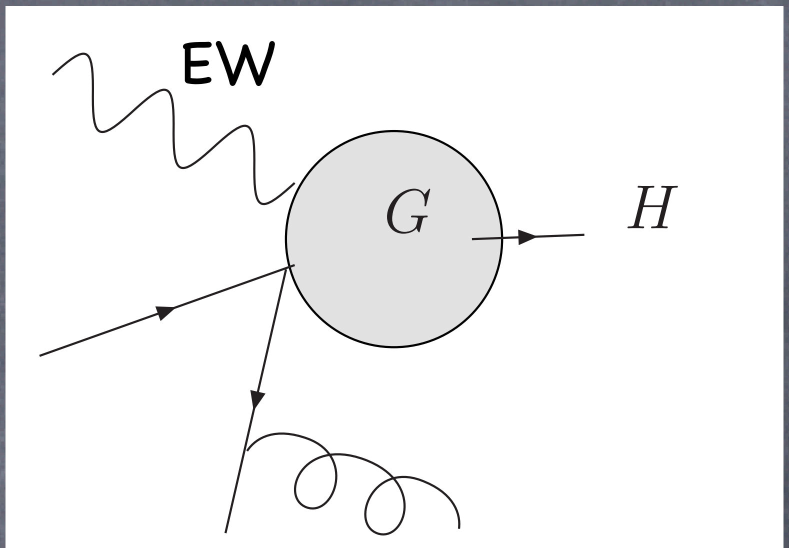
- Extended technicolor (ETC)-like: SM fermion bilinear coupling to strong dynamics vs.
- Partial compositeness (PC): linear coupling → SM fermion is admixture of external and composite fermion (like photon-rho)

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

``technifermion"

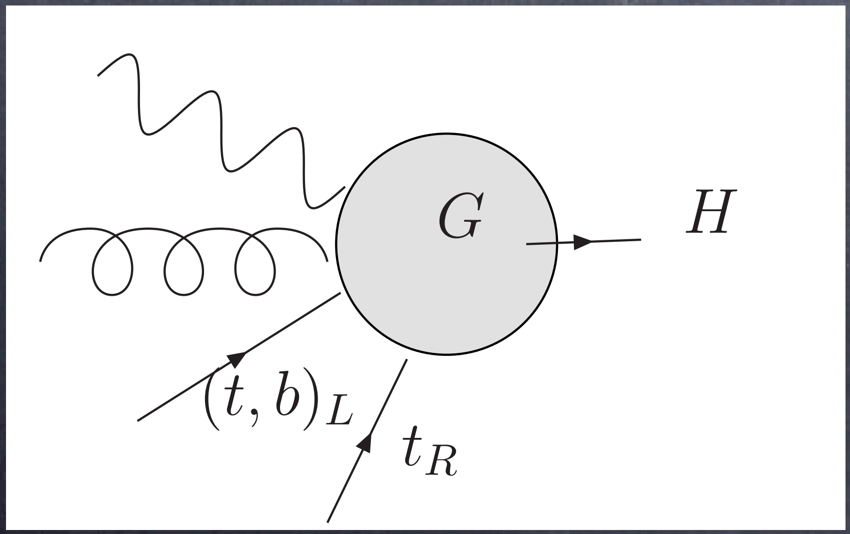
- ETC: $\psi^2_{\rm SM} \langle T^2 \rangle$; naively irrelevant, but walking (conformal) dynamics (large anomalous dimension, γ for T^2) can save it

(Eichten, Lane...)



only $\mathrm{EW} \subset G$ → no spin-1/2 composites for SM quarks to mix with (cf. W/Z here or photon in QED-QCD)

- 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)?!

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

external fermion (e^-)

(composite) operator ($u\,u\,d$)

- 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., $U(1)_{\rm EM}$ in QCD: for PC, all SM fermions (quarks and leptons) couple linearly ⇒ $entire \ {\rm SM} \subset G$
- e.g., $\psi_{\rm SM} T^3$: each T being **3** of $SU(3)_{\rm TC}$; ***only* 1** T **is 3 of** $SU(3)_{\rm color}$**...or** $SU(2)_{\rm TC}$**, 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:

$$\lambda_D \psi^D_{\rm SM} T^3 + \lambda_S \psi^S_{\rm SM} T^{\prime\, 3}$$

(Strictly speaking, SM is admixture!)

- RGE from UV cut-off (where generated) to TeV: v interpolated by $T^3 T^{\prime\, 3}$ ⇒ $m_{\rm SM} \propto \lambda_D \lambda_S v$

[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 $\mathcal{O}$ $\text{(either } T^2 \text{ in ETC-like or } T^3 \text{ in PC)}$

(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 $(6 + 2\,\gamma)$ ⇒

$$\gamma \geq -1 \Rightarrow m_{\rm SM} \stackrel{<}{\sim} v \left(\frac{m_\rho}{\Lambda_F}\right)$$ (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 $[T^3] = 9/2 + \gamma = 5/2$ →
  $\gamma = -2$ (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) → $[T^3] \geq 3/2$ (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

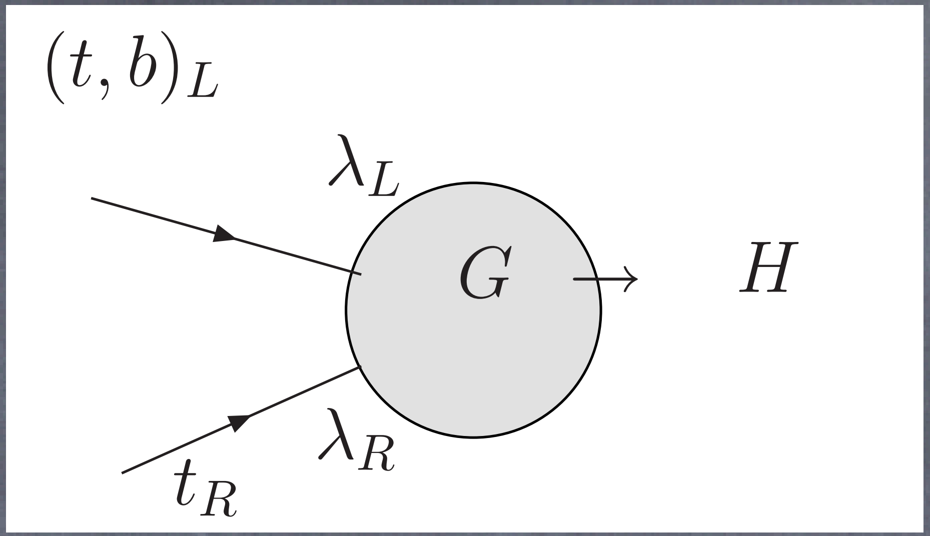
For marginal coupling, need $\gamma = -2$ for T^3, but $\gamma = -1$ for $T_{\text{adjoint}} \sigma^{\mu\nu} G_{\mu\nu}$! (Wulzer)

- 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 β, α):

$$0 \leq v \leq f$$

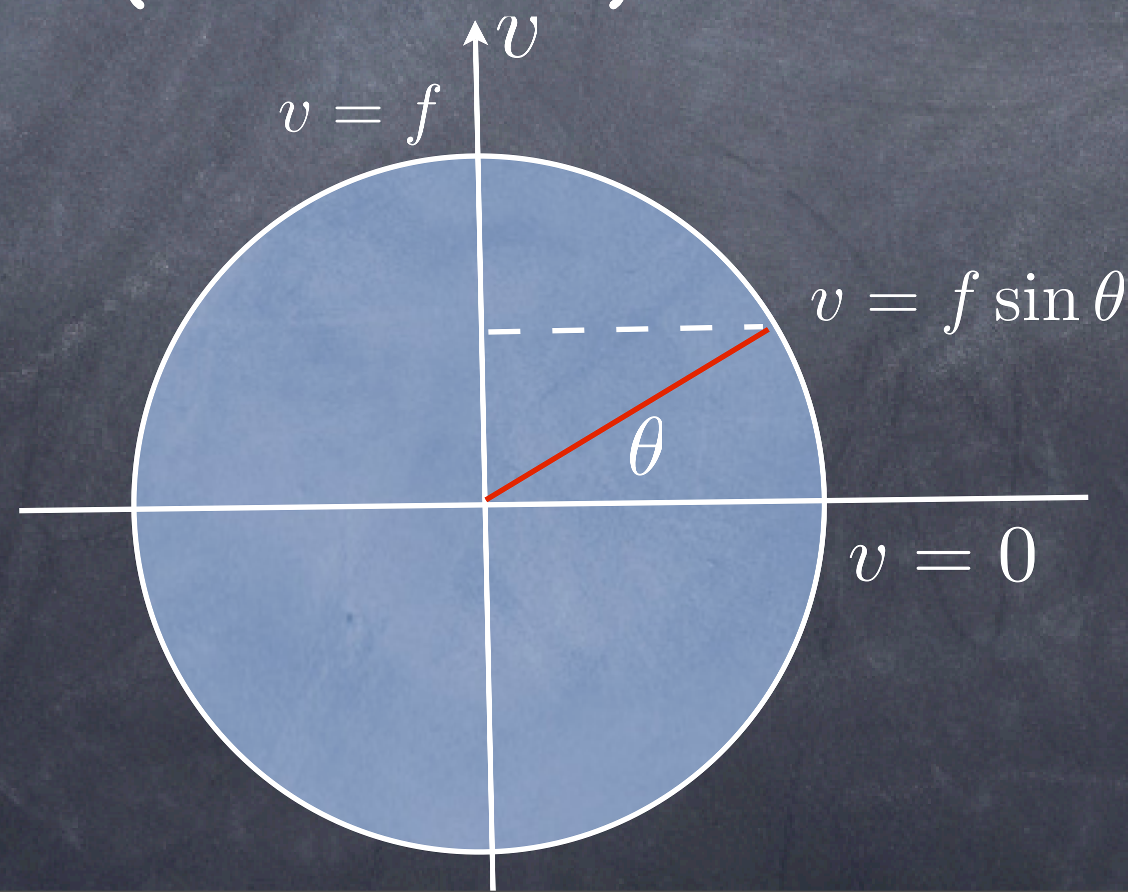
- ...vs. in ETC-like, (bilinear) coupling of top (only), dominates gauge: not much "room"

⇒ v/f fixed ($v = f$ or $v = f/2$ 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

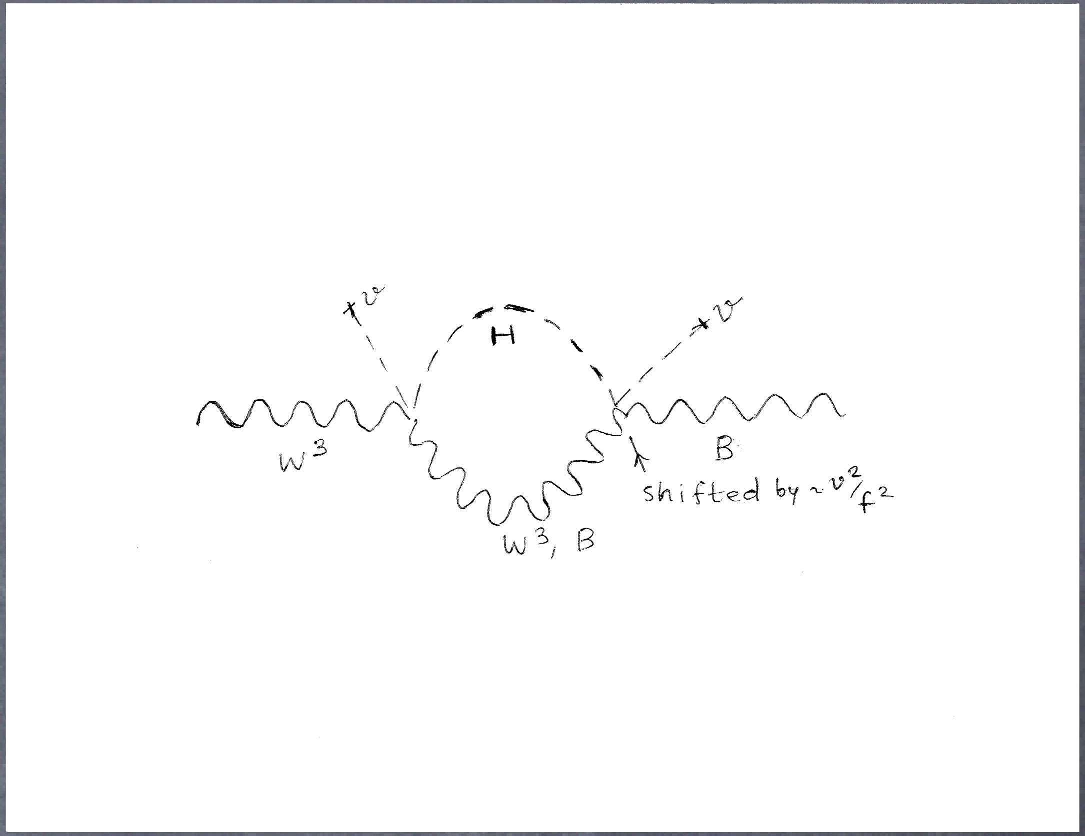
- heavy top dominates: $0 \leq v \leq f$
- features SM-like PNGB composite Higgs ($v \ll f$)
- ...only W/Z, top massive (before mid-1990's) used so far
- ...onto EW precision data (mid-1990's)

(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 $\sim v^2/f^2$ ⟹

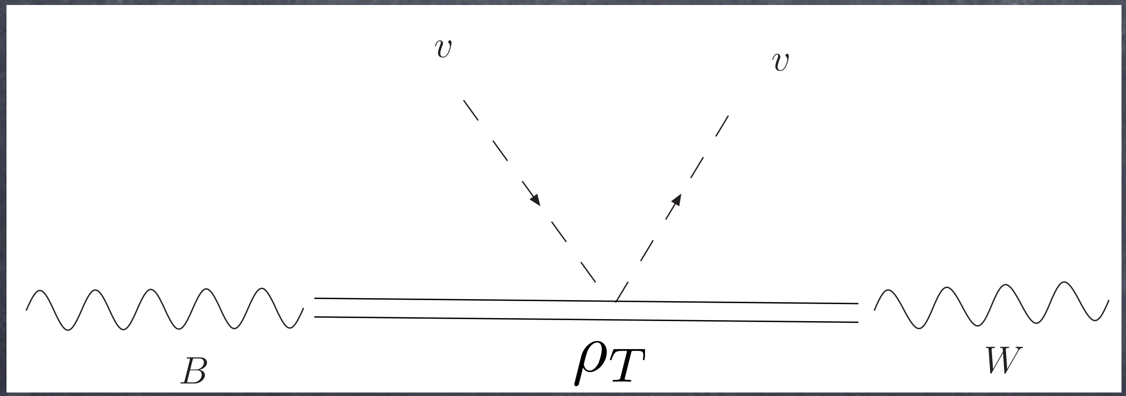


(Barbieri, Bellazzini, Rychkov, Varagnolo)

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

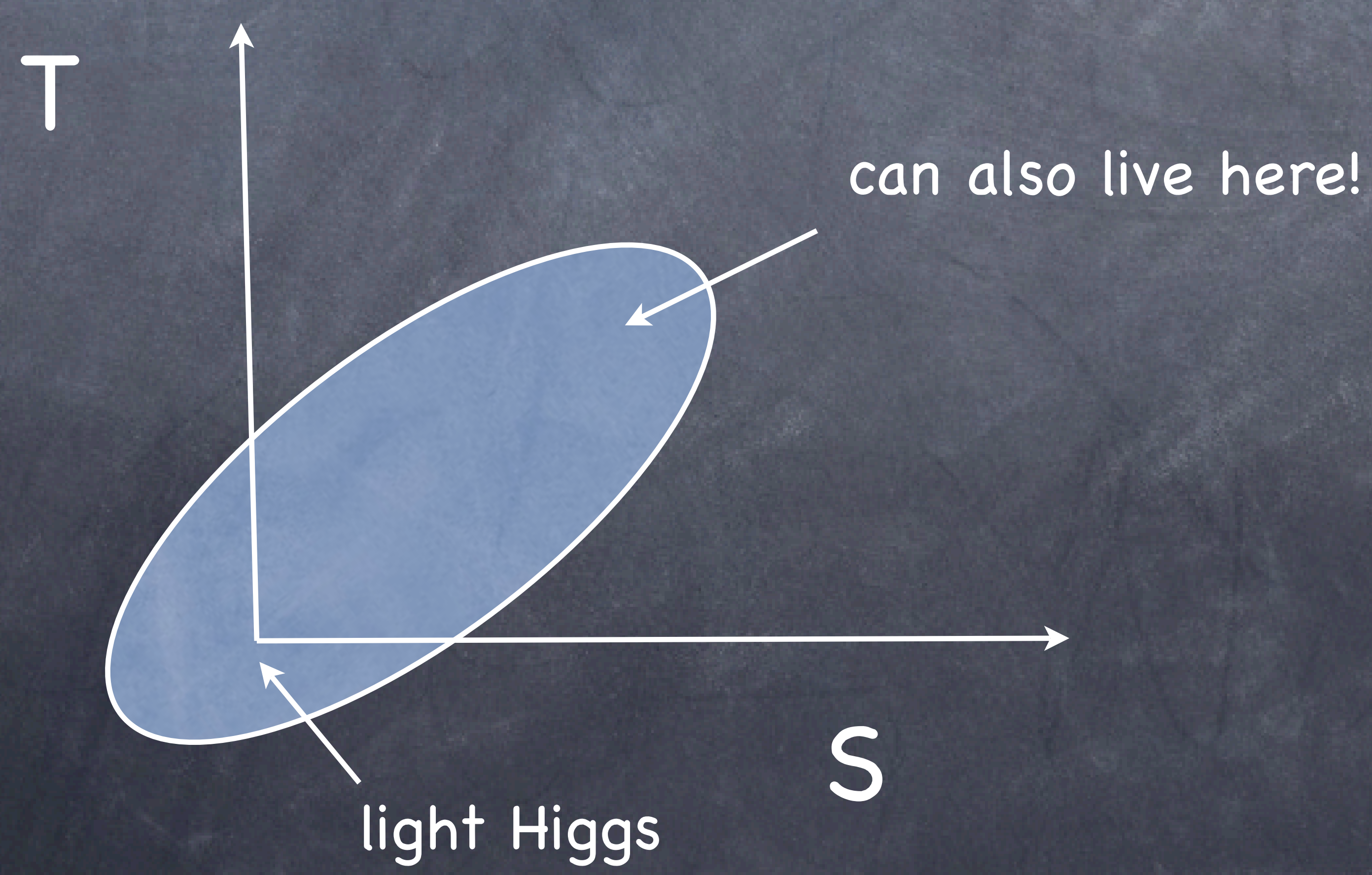
- UV: techni-rho exchange:

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



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 $v/f \lesssim 1/\text{a few}$

↓

- 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!)

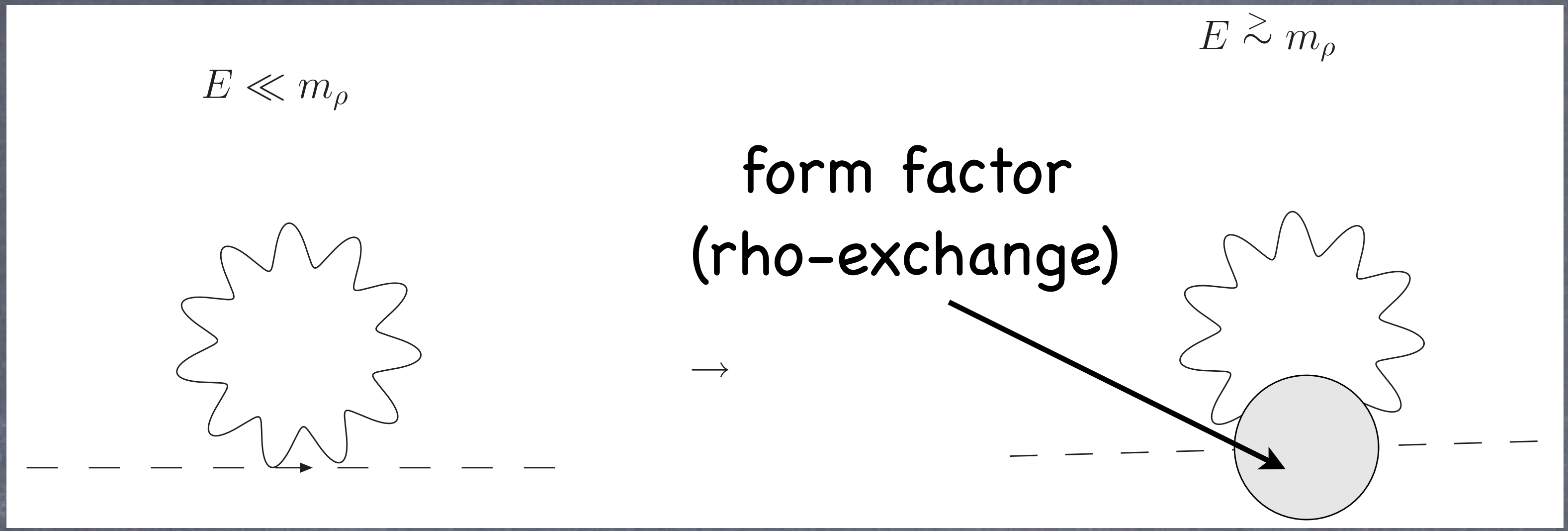
Higgs couplings agree with SM (2013)

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

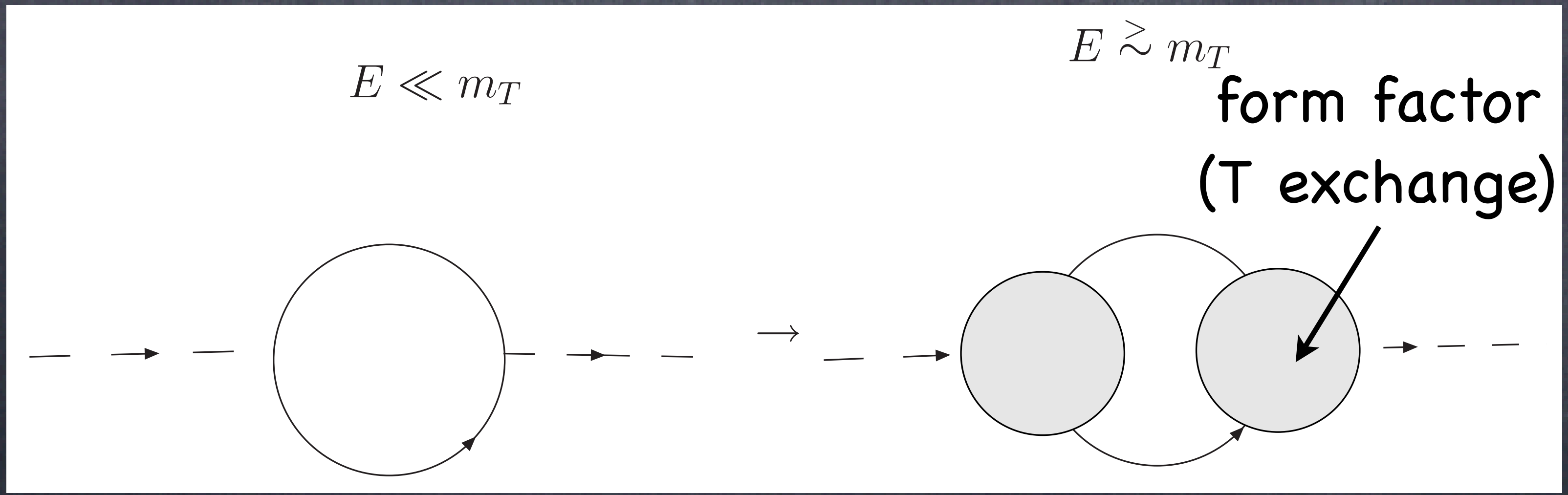
- Getting it light is necessary, but might not be sufficient!

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 $\sim O(1)$

⇒ 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)

  ⇒ $f \gtrsim 1\ \text{TeV}$ (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):

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

  $b = 2 \Rightarrow m_T \gtrsim 900\ \text{GeV}$ for $f \gtrsim 600\ \text{GeV}$ (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 $\mathcal{O}_L$)

⇓

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

(Super-)Large Majorana mass for (external) singlet → (super-) small Majorana mass terms for TeV-mass singlet

- Unlike charged fermions, $M_N N^2$ allowed →

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

↓

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

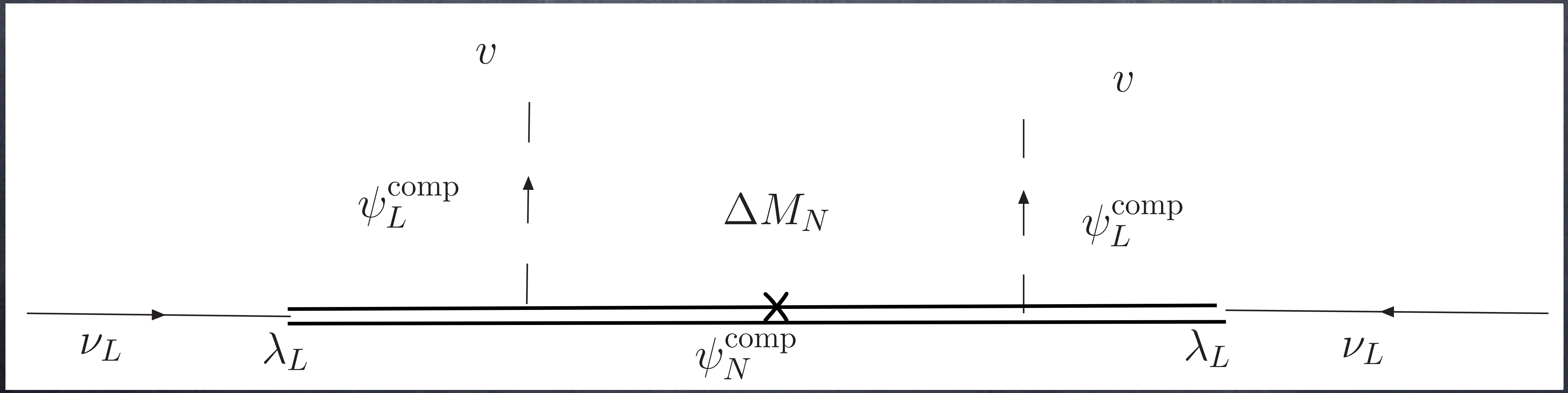
$$\Delta M_N \sim \frac{\mathrm{TeV}^2}{M_N}$$

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

- $\sim$TeV composite singlets have unsuppressed Yukawa couplings, but are pseudo-Dirac

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

$$\sim \frac{(\lambda_L v)^2}{M_N}$$



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!
- small deviation from coupling, λ_N, being marginal: ([$\mathcal{O}_N$]$= 2.5 + \gamma_N$) ⇨

Majorana mass term for composite singlet, $\Delta M_N \sim \frac{\text{TeV}^2}{M_N} \left(\frac{\text{TeV}}{M_N} \right)^{2\gamma_N}$ ⇨

- effective see saw scale can be much smaller than ``input":

$$M_N^{\text{eff}} \sim M_N \left(\frac{\text{TeV}}{M_N} \right)^{-2\gamma_N} \ll M_N \text{ for } \gamma_N < 0$$

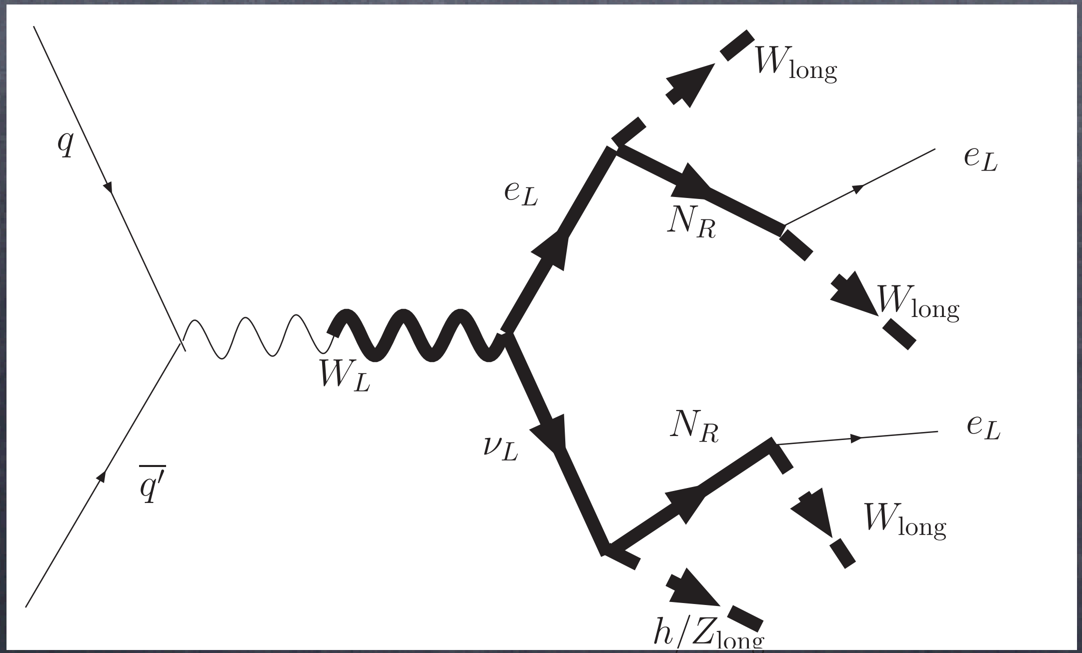
$$(\text{e.g.}, \sim 10^{12} \text{ GeV, even if } M_N \sim M_{\text{Pl}} \sim 10^{18} \text{ GeV})$$

Accessible seesaw

- leptogenesis: from $\sim$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!

Differences from elementary TeV-scale (inverse) seesaw in LHC signals

- W_R coupling suppressed, decay involves extra Higgs/Z
- (Composite) Z' [extra $U(1)$ in $SU(2)_{L\times R}$ models] comparable in mass (cf. a bit heavier in elementary case)
- signal from composite lepton doublet:



(MORE!) BACK-UP

Simpler/general top-partner mass

- 1-loop divergence from SM top cancelled by top-partner (T), with fine-tuning (δ):

$$m_h^2 = \frac{N_c y_t^2}{4\pi^2} m_T^2 \times \delta \quad \Rightarrow$$

$$\begin{aligned} m_T &= \frac{2\pi}{\sqrt{N_c} y_t \sqrt{\delta}} m_h \\ &\approx \frac{450 \text{ GeV}}{\sqrt{\delta}} \text{ for } m_h \approx 125 \text{ GeV};\ y_t \approx 1;\ N_c = 3 \end{aligned}$$

- No tuning ($\delta = 1$) $\Rightarrow$ $m_T \sim 450 \text{ GeV}$
- Composite Higgs (tuning $\sim \frac{v^2}{f^2}$) $\Rightarrow$ $m_T \sim 2 \text{ (or } 3) f$

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!