The Twin Higgs

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with
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hep-ph/0506256, 0512088

Outline

- Motivation – LHC, New Physic and the little hierarchy problem
- Illustration – a toy model
- A Realistic Model
- Some Phenomenology
- Discussion

LHC & Naturalness

- An argument I've heard somewhere:

LHC's 1st year will be exciting!

This is because naturalness tells us something must cancel the quadratic divergence from the top sector.

⇓

This new physics should be at a TeV, and is related to the top by some symmetry.

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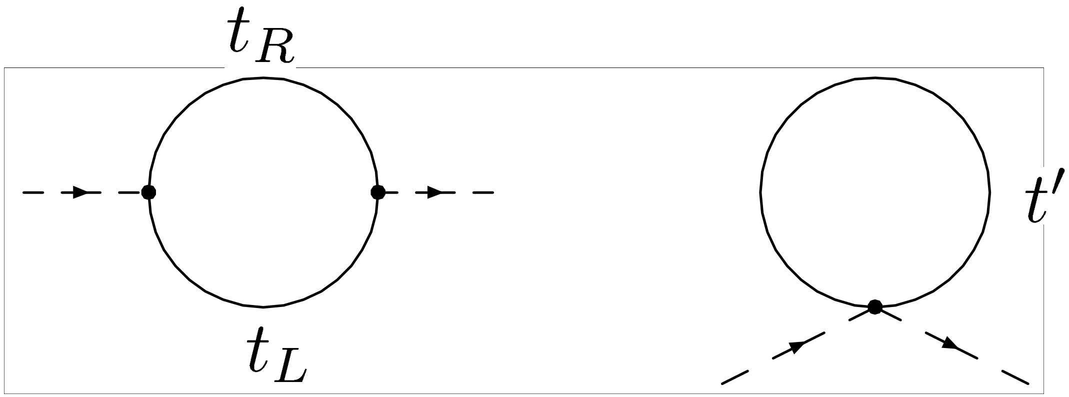
Not necessarily…

Invisible New Physics



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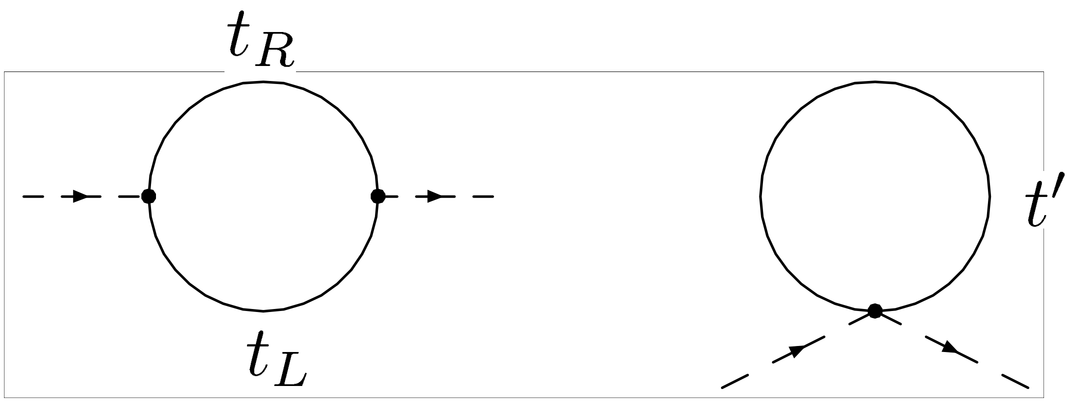


- In the Twin Higgs –
  All of the new physics added to the SM at the TeV may be invisible.

The Little Hierarchy Problem

A Mexican Hat

- Examine a complex scalar with a potential

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

$$\Downarrow$$

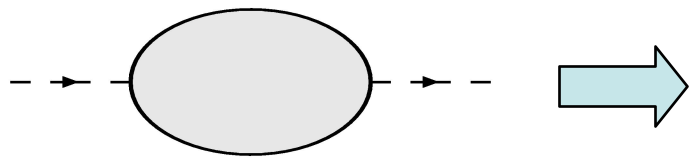
$$\langle\phi\rangle^2 = \frac{\mu^2}{2\lambda} \equiv v^2$$

- The physics Higgs field has a mass

$$m_h^2 = 2\mu^2 = 4\lambda v^2$$

Fine Tuning

- The Higgs potential is sensitive to the UV



$$\mu^2 = \mu_0^2 + c\Lambda^2$$

$$\text{F.T.} \sim \text{Sensitivity to UV} \sim \frac{\Lambda^2}{v^2}\frac{\partial v^2}{\partial \Lambda^2}, \ldots$$

In our case

$$\text{F.T.} \sim \frac{c}{2\lambda}\frac{\Lambda^2}{v^2} = 2c\frac{\Lambda^2}{m_h^2}$$

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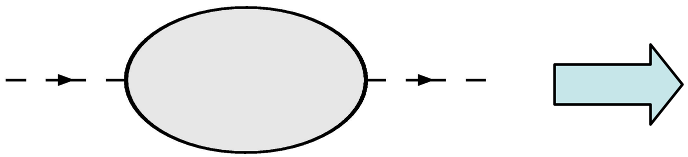

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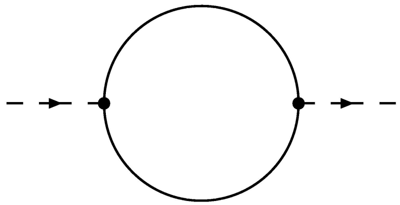
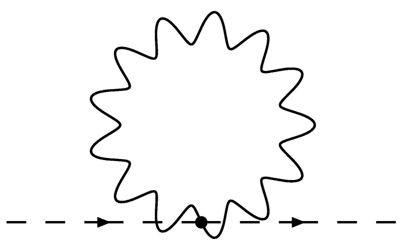
- An anthropological statement about our field:

Fine tuning is considered Bad

SM Divergences



$$= \frac{3y_t^2}{8\pi^2}\Lambda^2$$



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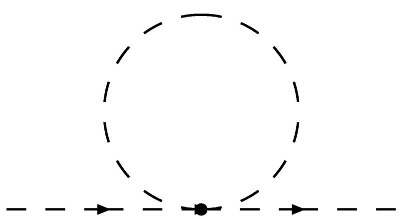

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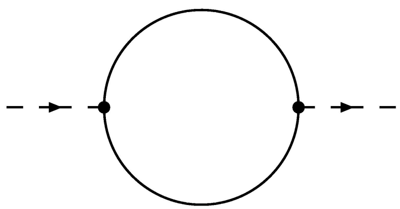

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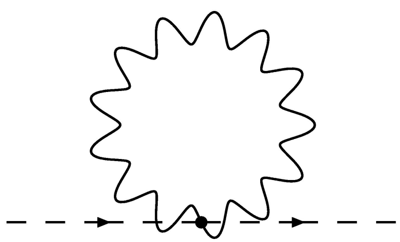

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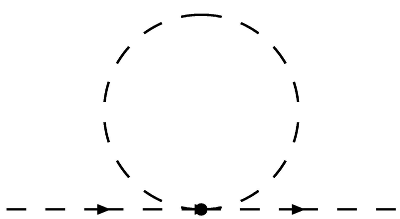

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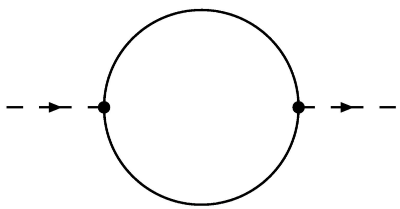

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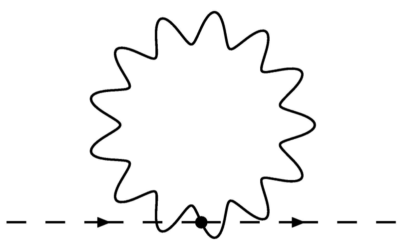

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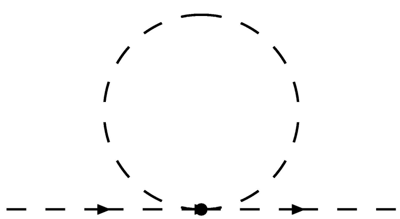
Low cutoff or Heavy Higgs



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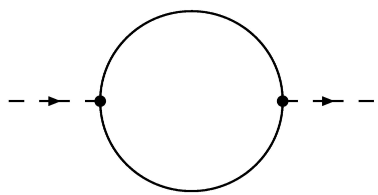
Low cutoff

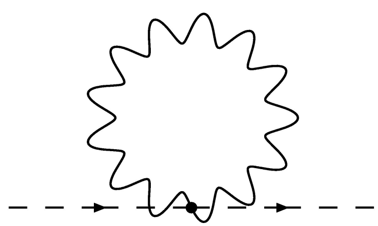
Fine Tuning in SM

- For $\Lambda = 5$ TeV and $m_h = 120 - 200 \text{ GeV}$:



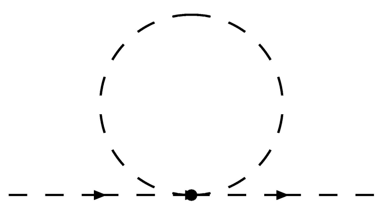
$$\text{F.T.} = \frac{3y_t^2}{4\pi^2}\frac{\Lambda^2}{m_h^2}$$

~ 0.75% - 2%



$$\text{F.T.} = \frac{9g^2}{32\pi^2}\frac{\Lambda^2}{m_h^2}$$

~ 5% - 13%



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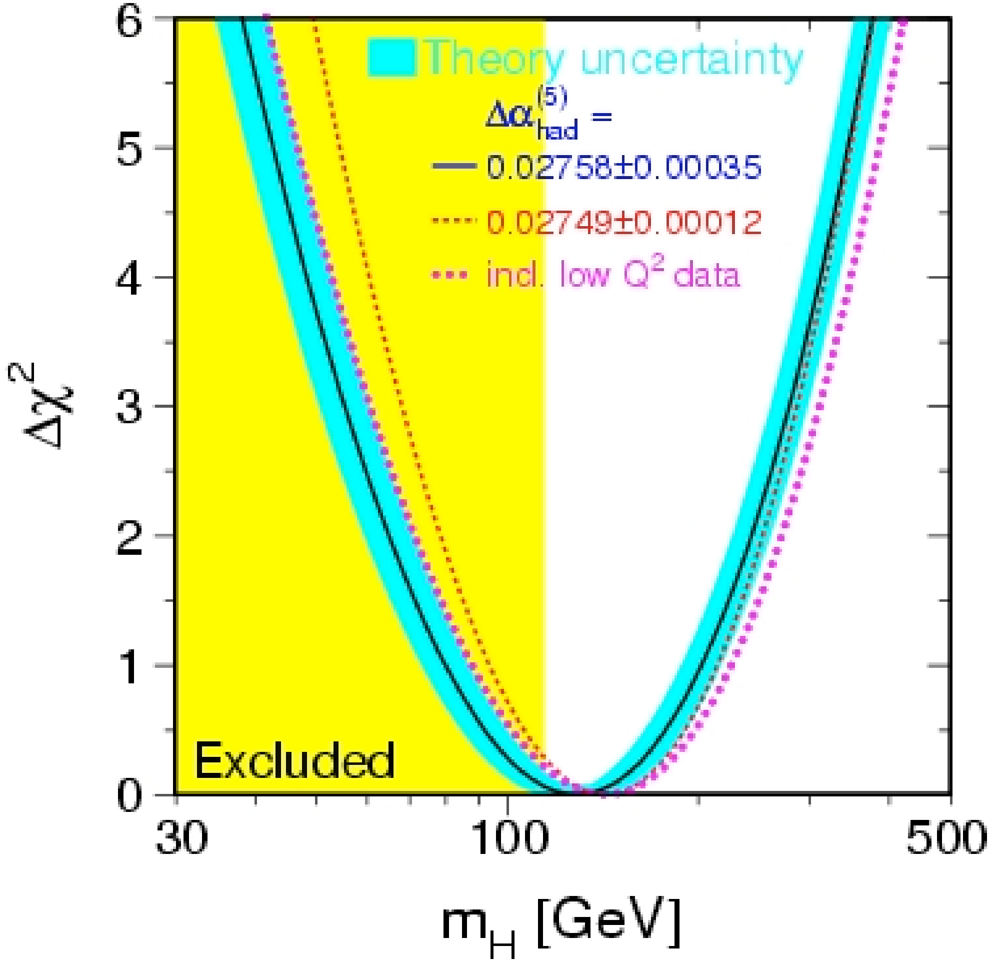
~ 6%

Precision EW I



EW data highly favors a light SM Higgs

Precision EW II

Barbieri, Strumia
hep-ph/0007265

Dimensions six operators	$m_h = 115$ GeV	
	$c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB} = (H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.7	10
$\mathcal{O}_H = \|H^\dagger D_\mu H\|^2$	4.6	5.6
$\mathcal{O}_{LL} = \frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	7.9	6.1
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$\Lambda \geq 5$ TeV

The EW scale should be stabilized compared to a cutoff of at least 5 TeV

LEP Paradox

- The Little Hierarchy problem is the parametric tension between

Data and Naturalness

Light Higgs
High Cutoff

Heavy Higgs
low Cutoff

- In the SM this is a tuning of order 1%.

However, If its take seriously, it may be a hint for what new physics is at a TeV.

Singlet NP

Dimensions six operators			$m_h = 115$ GeV $c_i = -1$	$c_i = +1$
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$$\Lambda \geq 5 \text{ TeV}$$

This motivates a scenario where all TeV new physics is a singlet under the SM.

Higgs as a PNGB

- If the Higgs is a Goldstone, its mass is insensitive to the cutoff due to symmetry.

  May reduce fine tuning.

- May serve as an explanation for a light Higgs and a low EW scale (compared to 5 TeV)

- Old idea: Kaplan-Georgi

  Revived with Little Higgs.

We propose an alternative realization.

A Toy Model

Global SU(4)

- Take a scalar field H, a fundamental under a global SU(4) .
- Write a potential:

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

$$\Downarrow$$

$$|\langle H\rangle|^2 = \frac{m^2}{2\lambda} \equiv f^2$$

$SU(4) \rightarrow SU(3)$ $\Rightarrow$ 7 Goldstones

Gauge $SU(2)_A \times SU(2)_B$

- Now we gauge an $SU(2)_A \times SU(2)_B$ subgroup

  eventually – $\downarrow$ SM, $\downarrow$ "Twin" SM

- The field H transfoms as

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

Radiative Corrections

- Quadratic terms are generated:

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- Impose a **"Twin"** Z_2 : A ↔ B ⇨ $g_A = g_B$

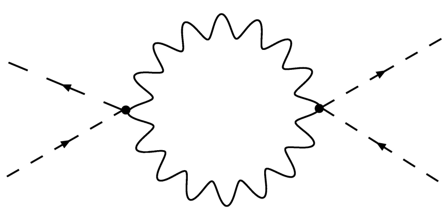
⇨ $$\Delta V = \frac{9g^2\Lambda^2}{64\pi^2}(H_A^\dagger H_A + H_B^\dagger H_B)$$

SU(4) invariant ! Does not give a Goldstone mass !

The Twin Mechanism

- Due to a **discrete** symmetry the quadratic terms in the potential respect a **continuous global** symmetry that is otherwise broken.

- Higher order terms are not SU(4) invariant.



$$\Longrightarrow \quad \Delta V = \kappa(|H_A|^4 + |H_B|^4)$$

with $$\kappa \sim \frac{g^4}{16\pi^2} \log \frac{\Lambda^2}{f^2}$$

See Barbieri et al.
For the κ~ 1 option.
hep-ph/0509242

Symmetric Vacuum

- The potential to minimize is

$$V = -m^2|H|^2 + \lambda|H|^4 + \kappa(|H_A|^4 + |H_B|^4)$$

$$\Longrightarrow \quad |\langle H_A\rangle|^2 = |\langle H_B\rangle|^2 = \frac{f^2}{2} \sim \frac{m^2}{4\lambda}$$

The pseudo-Goldstone mass is

$$m_h \sim \sqrt{\kappa} f \sim \frac{g^2 f}{4\pi}$$

$\Longrightarrow$ f ~ 1 TeV for m_h ~ (EW scale)

Asymmetric Vacuum

- However, when $f_A^2 = \frac{f^2}{2} = (174\mathrm{GeV})^2$ and by NDA Λ is at most 4πf, the cutoff is below 5 TeV.

Nonetheless, Barbieri et al. analyze this case.

Asymmetric Vacuum

- However, when $f_A^2 = \frac{f^2}{2} = (174\text{GeV})^2$ and by NDA Λ is at most $4\pi f$, the cutoff is below 5 TeV.

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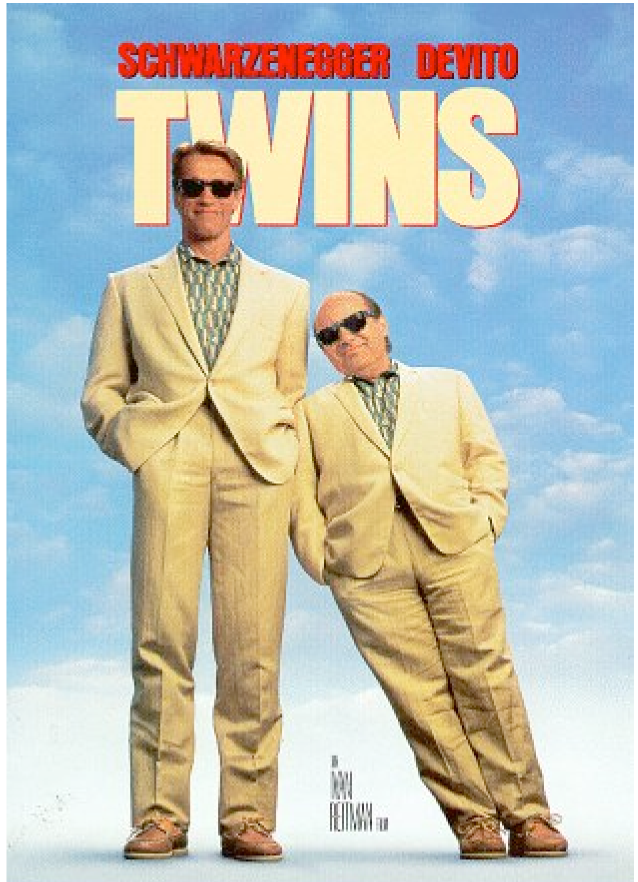
- But if $f_A < f_B$ we can get $f_A << \Lambda$

Asymmetric twins:



Soft Z_2 Breaking

- Add $$V_{\rm soft}(H) = \mu^2 H_A^\dagger H_A$$

a soft breaking of Z_2

$\Rightarrow$ does not introduce quadratic divergences.

μ is the only Z_2 breaking parameter.

$\Downarrow$

$\mu \ll \Lambda$ is technically natural.

μ will be of order EW scale

Fine Tuning

- Minimizing the full potential

$$f_A^2 = \frac{f^2}{2} - \frac{\mu^2}{4\kappa} \quad \text{with} \quad f^2 \sim \frac{m^2}{2\lambda}$$

- An estimate of the fine tuning-

$$\text{F.T.} = \frac{f^2}{v^2}\frac{\partial v^2}{\partial f^2} = \frac{f^2}{2v^2}$$

F.T. ~ 25% – 10%
for
f ~ 500 – 800 GeV.

The Higgs mass dependence is removed.
Eases tension b/w naturalness and data.

A Model

What Do We Need?

- Embed the top sector.
- Construct an EFT that realizes the symmetry.
- Set the cutoff (above 5 TeV).
- Verify that correct EWSB is achievable, and that the Higgs mass is within the bounds.
- Phenomenology, cosmology, etc.

$SM_A \times SM_B$

- We can utilize the Twin mechanism for all of the SM interactions:

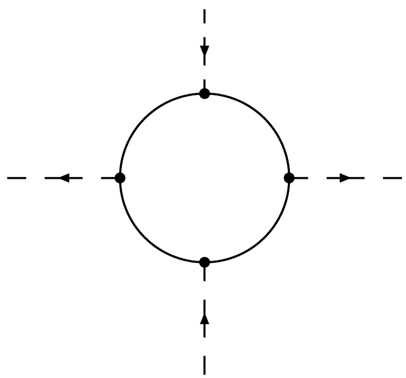
  Take two SM's $SM_A \times SM_B \times Z_2$

- All of the radiative corrections to the Higgs mass, including those from the top, will respect the Z_2 and SU(4).

Top

- The top sector then looks like

$$\mathcal{L} = y_t H_A q_L^A t_R^A + y_t H_B q_L^B t_R^B + \text{h.c}$$



$$\kappa \sim \frac{y_t^4}{16\pi^2} \log \frac{\Lambda^2}{f^2}$$

(with the right sign)

EWSB is triggered by the top (as usual).

Extended Top Sector

- We can remove the cutoff sensitivity from the top sector by breaking SU(4) softly –

under $$\begin{cases} SU(6) \supset SU(3)_A \times SU(3)_B \\ SU(4) \supset SU(2)_A \times SU(2)_B \end{cases}$$

introduce $$H = (1,4) \quad Q = (6,4) \quad T = (6,1)$$

and write $$\mathcal{L} \supset yHQT + \text{h.c.}$$

Finally, we give a mass to the exotic tops, breaking SU(4) softly.

Effective Theory

- The most general way to stabilize the weak scale with the twin mechanism is to realize the symmetries in a non-linear sigma model.
- The d.o.f. in this model may be parameterized by

$$H = e^{iT^a \frac{h^a}{f}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

This is an effective theory of goldstones.

The cutoff Λ is **at most** $4\pi f$ by NDA.

Many UV Completions ?

- The linear model is just an example of a UV completion to the non linear one –

  Lower the cutoff of the linear model to $\Lambda \sim m$

  → we are left with an EFT with just the goldstones.

  The NDA bound is saturated when the linear model is strongly coupled, $\lambda \sim (4\pi)^2$.

- We may well imagine other possible UV completions-

  Strong dynamics, SUSY, Turtles,….

Numbers

- In hep-ph/0506256 we analyzed the parameter space of the non-linear model for strong coupling.

Λ (TeV)	f (GeV)	M (TeV)	M_B (TeV)	μ (GeV)	m_h (GeV)	Tuning
10	800	6	1	239	122	0.134
6	500	5.5	1	145	121	0.378
10	800	—	0	355	166	0.112
6	500	—	0	203	153	0.307

An aside: Left-Right

- The same mechanism may be embedded in an $SU(2)_L \times SU(2)_R$ model with

$$H = \begin{pmatrix} H_L \\ H_R \end{pmatrix}$$

- This model is much more visible-
  - Only one color group
  - Heavy tops
  - Heavy $SU(2)_R$ and $B-L$ gauge bosons

Phenomenology

Twin Photon

- We have introduced a whole twin SM.

  γ_B –a twin photon!

  potentially dangerous:
  - Kinetic mixing can induce mili-charges for twin fermions.

- However,

  Kinetic mixing is not induced upto 3 loops!

  (Fine print: If we choose not to extend the top sector)

Twin Photon II

But-

- If we do extend the top sector, kinetic mixing is induced at one loop.

→ in this case we give γ_B a mass

Cosmology

- The twin sector can have a wide variety of stable particles, e.g. twin neutrons

DM candidates

- SM and twin sectors are in thermal eq. down to

$T_d \sim 1-10$ GeV

We must rid of the relativistic twin d.o.f. before BBN.

Cosmology II

- We can change the relative temperature of the two sectors after T_d:
  1) Raise all twin fermion masses above T_d – annihilations of SM fermions increase T_{SM}.
  (Barbieri et al)
  2) Hope for more SM entropy production in the QCD phase transitions.
- Both of these require breaking the Z_2 for the small yukawas. (technically natural)

LHC Phenomenology

- A standard model Higgs.

LHC Phenomenology

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- But perhaps there is some hope-
- LHC can see invisible decays of the higgs down to a BR of ~15%.
- WW scattering becoming strong?....
- (in progress)

ILC

- The ILC can distinguish this model from the SM:

1) Small modifications, $O(v/f)$, to SM values of

ZZh, ZZhh, tth , hhh, …

2) Higgs decays to twin fermions with BR~ (v^2/f^2).

- All of these modifications are governed by one parameter, v/f. (in the full Z_2 limit).
- Non-trivial correlations b/w observables can be a smoking gun for this model (in progress).

Discussion

Summary

- The twin Higgs –
  A new realization of the Higgs as a PNGB.

- The mechanism –
  Due to a discrete symmetry, the quadratic divergences to the Higgs mass respect a global symmetry `accidentally'.

- Natural EWSB may be achieved, stabilizing the weak scale up to 5-10 TeV.

Twin vs. Little

- What's the difference b/w twin and Little Higgs ?
- EW precision has often forced LH to break the symmetry at a higher scale, typically $f \sim 1\text{–}2$ TeV (unless T-parity is added).
- A higher f comes with additional fine tuning. (recall, in our case $\text{F.T.} \sim f^2/2v^2$).
- In the Twin Higgs f can be smaller because **all new physics is not charged under the SM**.

LHC & Naturalness

- Naturalness does not imply that new physics is easily accessible at LHC.

  We won't have to give up naturalness if LHC does not see NP immediately.

  Instead, we'd have to work hard to distinguish a natural model from an anthropic SM.

Extra slides

Left-Right

- The same mechanism may be embedded in an $SU(2)_L \times SU(2)_R$ model with

$$H = \begin{pmatrix} H_L \\ H_R \end{pmatrix}$$

- This model is much more visible-
  - Only one color group
  - Heavy tops
  - Heavy $SU(2)_R$ and $B-L$ gauge bosons

LHC Phenomenology

- A standard model Higgs.

- Some hope: …
- LHC can see invisible decays of the higgs down to a BR of 15%.
- WW scatering becoming strong?....
- (in progress)

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The Cutoff

- Where is the cutoff ?

m^2 is cutoff sensitive.

Come up with a mechanism to stabilize m^2.	Consider the effective theory below m^2.

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m^2 is cutoff sensitive.

Come up with a mechanism to stabilize m^2.	Consider the effective theory below m^2.

$$\Lambda \sim m$$

- We integrate out the radial mode and are left with an effective theory of goldstones.

Low Cutoff

- Recall: - In this toy model f is set buy m.
  - m is cutoff sensitive.

Naturalness requires that Λ is not much above f.

- If $f_A^2 = \frac{f^2}{2} = 174\mathrm{GeV}$,

→ cutoff is too low for precision EW

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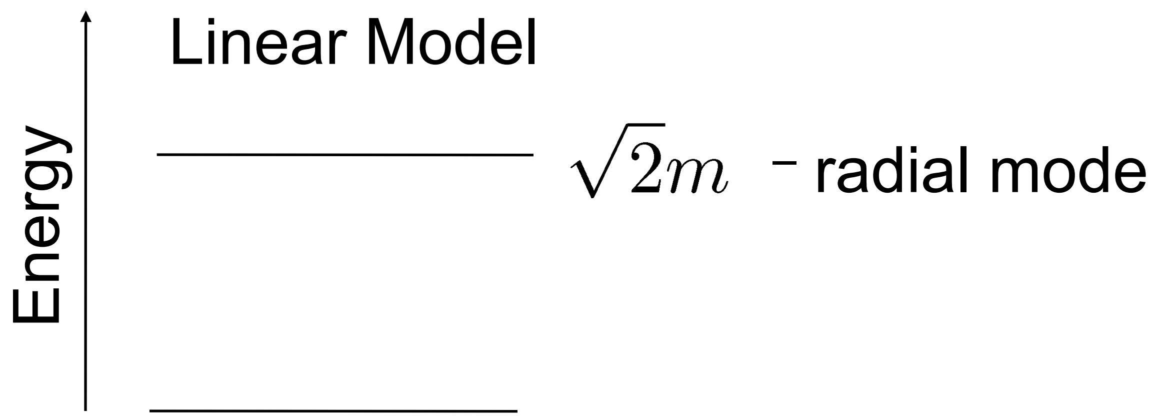
  → cutoff is too low for precision EW

- But if $f_A < f_B$ we can get $f_A << \Lambda$


Linear Model
Energy
$\sqrt{2}m$ - radial mode

Discussion

- The discusion will include a few slides about:
  - Comparison with little higgs. We can afford a low f.
  - The fact that we are refuting the lore that there needs to be new physics charged under the SM. And the lore that naturalness implies the LHC will see new colored states.
  - A summary of the mechanism and how it works.
  - Should I go into outlook and work that is in progress ? (probably not, what do you think?)