

# Naturalness and the EWPT

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# NATURALNESS and the ELECTROWEAK PHASE TRANSITION

# DISCLAIMER

- Information flow

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*Audience → speaker*

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- Information flow

**Audience → speaker**

- Intended to

**Michael, Andrey, Maxim**

# PHASE TRANSITION

$$V(\phi, T) = V_0(\phi) + V_T$$

# PHASE TRANSITION

$$V(\phi, T) = V(\phi) + V_T$$

$$V_T = (-)^F T \int \frac{d^3 k}{(2\pi)^3} \times$$

$$\log \left[ 1 - (-)^F e^{-\omega_k(\phi)/T} \right]$$

# PHASE TRANSITION

$$\omega_k^2(\phi) \simeq k^2 + m^2(\phi) + c T^2$$

# PHASE TRANSITION

In SM:

transition **not**  
strongly 1st order

# PHASE TRANSITION

What about

BSM

?

# A NATURALENESS

## PRIMER

# WILSONIAN EST

$$\mathcal{L}_\lambda = \sum c_i(\lambda) \frac{\phi_i}{\lambda^{\delta_i}}$$

$\delta_i > 0$  irrelevant

$\delta_i < 0$  relevant

$\delta_i > 0$  irrelevant

$\delta_i < 0$  relevant

$c_i$  grows at long distance !

when  $c_i$  gets large  
profound changes  
to  
spectrum and symmetry

# RELEVANT OPS

## In the Standard Model

# RELEVANT OPS

In the Standard Model

1

CC

$H^+ H^-$  Higgs mass

$$H^\dagger H$$

$$c(M_h) = 1$$

$$\mathcal{H}^\dagger \mathcal{H}$$

$$c(M_h) = 1$$

tree level

$$c(\Lambda) = \frac{M_h^2}{\Lambda^2}$$

$$H^\dagger H$$

$$c(M_h) = 1$$

tree level

$$c(\Lambda) = \frac{M_h^2}{\Lambda^2}$$

Odds

$H^\dagger H$

one loop

$$c(\Lambda) = \frac{M_h^2}{\Lambda^2} \left( 1 - \frac{3y_t^2}{16\pi^2} \right) + \frac{3y_t^2}{16\pi^2}$$

$\sim 6\%$   
↑

$H^\dagger H$

one loop

$$c(\lambda) = \frac{M_h^2}{\lambda^2} \left(1 - \frac{3y_t^2}{16\pi^2}\right) + \frac{3y_t^2}{16\pi^2}$$

Even Odder

$\sim 6\%$   
↑

$$c(\lambda) = \frac{M_h^2}{\lambda^2} \left( 1 - \frac{3y_x^2}{16\pi^2} \right) + \frac{3y_x^2}{16\pi^2}$$

"UV"



"IR"



$$c(\Lambda) = \frac{M_h^2}{\Lambda^2} \left( 1 - \frac{3y_x^2}{16\pi^2} \right) + \frac{3y_x^2}{16\pi^2}$$



"UV"



"IR"

TWO PROBLEMS!

# SHADES OF NATURALNESS

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Parametric Naturalness

At some scale the  $\{c\}$   
are all of  $O(1)$

# Complete Parametric Naturalness

At some scale the  $\{c\}$   
are all given by fundamental  
mathematical constants

# Technical Parametric Naturalness

coefficients of operators that carry global charges may be small

# Loop Parametric Naturalness

Loops using  $\{c\}$   
are no bigger than  
the  $\{c\}$  themselves

# EXAMPLE

SM with  $\Lambda \sim 1 \text{ TeV}$   
put  $c(\Lambda) \sim 10^{-2}$

LPN but not TPN

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SM with  $\Lambda \sim 1 \text{ TeV}$   
put  $c(\Lambda) \sim 10^{-2}$

LPN but not TPN  
 $\Lambda > \text{TeV}$  not even LPN!

# NATURALNESS REQUIRES NEW PHYSICS BY

$\Lambda \sim \text{TeV}$

# WHY THESE ?

LPN eliminates the  
IR problem

TPN eliminates (maybe)  
the UV problem

by enforcing symmetries  
it's easier to **uv**  
complete

A LONG TIME AGO  
the focus was on the  
**UV**

# A LONG TIME AGO

the focus was on the

UV

when  $\Lambda \sim \text{TeV}$

the IR is the right size

# TODAY

the focus has shifted

# TODAY

the focus has shifted  
the IR part is being  
challenged by the  
LHC

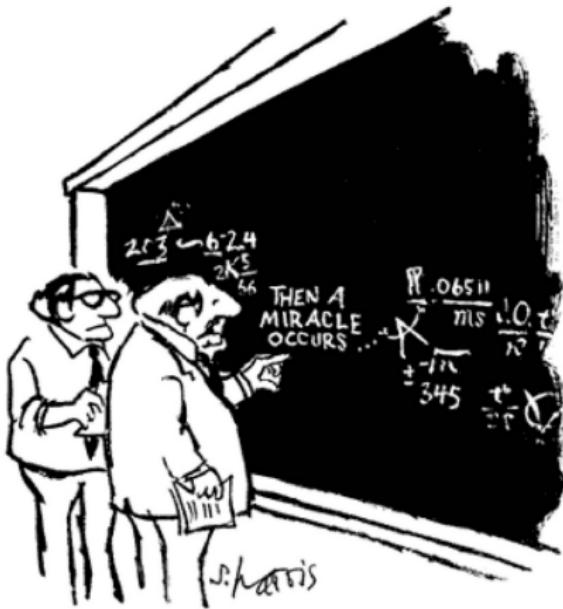
Solving the ~~TR~~  
part is a necessity

∴ Postpone the ~~UV~~  
part to a higher  
scale

# MODEL BUILDER

*how to talk  
about natural  
models*

# MODEL BUILDER



how to talk  
about natural  
models

"I think you should be more explicit here in step two."

# Higgs as a Pseudo Nambu Goldstone BOSON

# COMPOSITE HIGGS

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strong interactions with  
composites  
light particles  $\Lambda_c$

# COMPOSITE HIGGS

strong interactions with

composites

light particles

$$\Lambda_c \quad f$$

Naively

$$\Lambda_c \sim 4\pi f$$

# COMPOSITE HIGGS

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choose  $\Lambda_c$  high enough  
(FCNC)

# COMPOSITE HIGGS

choose  $\Lambda_c$  high enough  
(FCNC)

typical SM corrections

$$\left(\frac{v}{f}\right)^2$$

# COMPOSITE HIGGS

LPN

# COMPOSITE HIGGS

LPN

*complex  
strong dynamics*

# COMPOSITE HIGGS

## Problems:

# COMPOSITE HIGGS

Problems:

1. Not TPN

# COMPOSITE HIGGS

Problems:

1. Not TPN  
don't care

# COMPOSITE HIGGS

Problems:

1. Not TPN  
don't care

2.  $\sigma \rightarrow f$

# COMPOSITE HIGGS

Problems:

1. Not TPN  
don't care

2.  $V \rightarrow f$

fine tuning

# LITTLE HIGGS

# LITTLE HIGGS

PNEB with pattern of  
symmetries to ensure

TPN\*

# LITTLE HIGGS

PNEB with pattern of  
symmetries to ensure

$$\left(\frac{v}{f}\right)^2 \text{ naturally } \ll 1$$

$\text{TPN}^*$

# LITTLE HIGGS

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current models remove  
quadratic sensitivity but  
leave logarithmic sensitivity

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current models remove  
quadratic sensitivity but  
leave logarithmic sensitivity

$$\frac{3\lambda_t^2}{16\pi^2} m_T^2 \ln(16\pi^2) \text{ tuning of } 5\%$$

# TWIN HIGGS

# TWIN HIGGS or NEUTRAL NATURALNESS



partners that cancel  
top quark loop  
need not be colored

NN

partners that cancel  
top quark loop  
need not be colored

LPN\*

NN

but like Composite Higgs

$V \rightarrow f$   
so

some fine tuning

# NATURAL PHILOSOPHY

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Composite Higgs &  
Twin/Orbifold Higgs

# NATURAL PHILOSOPHY

Composite Higgs &  
Twin/Orbifold Higgs

Lower the scale of new  
physics by making it  
harder to see

CH & TH

$$\left(\frac{v}{f}\right)^2$$

CH & TH

$$\left(\frac{v}{f}\right)^2$$



BSM

CORRECTIONS

# CH & TH

$$\left(\frac{v}{f}\right)^2$$



BSM  
CORRECTIONS      FINE  
TUNING

# LITTLE HIGGS

# LITTLE HIGGS

Keep the new physics  
above TeV

# LITTLE HIGGS

Keep the new physics  
above TeV

must remove log  
sensitivity

# LH fully natural\*