SCGT15 — Summary Talk

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SCGT15

I am honored to give the summary talk at this historic conference. Of course, it is impossible to summarize everything in all of the interesting talks that we have heard in the last four days. But I will try to highlight a couple of major themes.

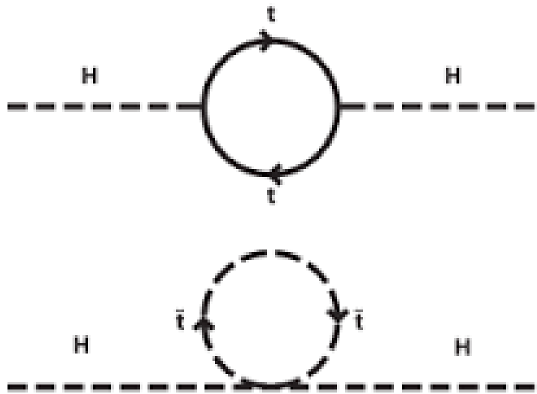
SCGT15

I should say from the beginning that there was a lot of beautiful work presented at the conference that I could not summarize even if I had lots of time, because I don’t understand it.

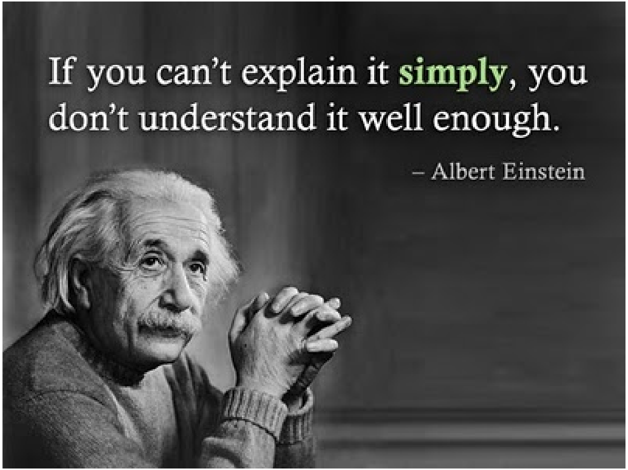
$$V = \frac{e^{-2(g+2(p+x))}}{128}\left[16\left(a^4 + 2\left(\left(e^g - e^{6p+2x}\right)^2 - 1\right)a^2 + e^{4g} - 4e^{g+6p+2x}\left(1 + e^{2g}\right) + 1\right) + e^{12p+2x+\phi}\left(2e^{2g}(a-b)^2 + e^{4g} + \left(a^2 - 2ba + 1\right)^2\right)N_c^2\right],$$

$$G_{ab} = \mathrm{diag}\left(\frac{1}{2}, 6, 1, \frac{1}{4}, \frac{e^{-2g}}{2}, \frac{e^{-2x+\phi}N_c^2}{32}\right)$$

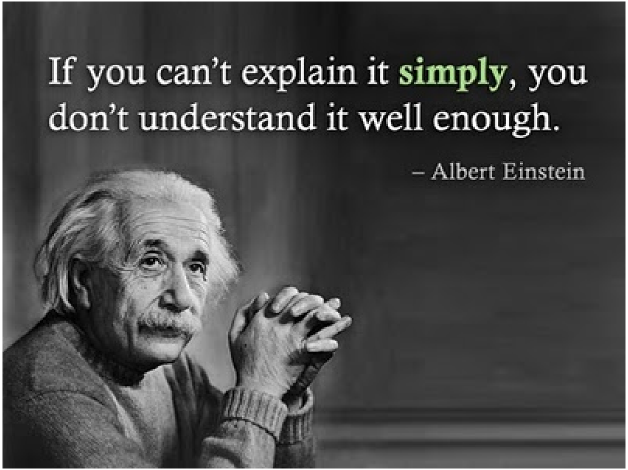
My favorite comment related to my ignorance came from Daniel Elander "If I had had a choice, I would not have made it this complicated." I have felt that way frequently in the last four days.



There are some things that I won't discuss because I don't understand why I should care. For example, I won't mention quadratic divergences. I don't care about them because continuum quantum field theory doesn't care about them either. I will come back to this later when I talk about Francesco's fascinating contribution.



What I will do is to try to fit what I have heard into my own simple-minded language of perturbative effective field theory PEFT, and to explain when this is not possible, and why.



In PEFT one tries to hide from the hard problems of strong dynamics by choosing different degrees of freedom that are appropriate at different scales.

χPT

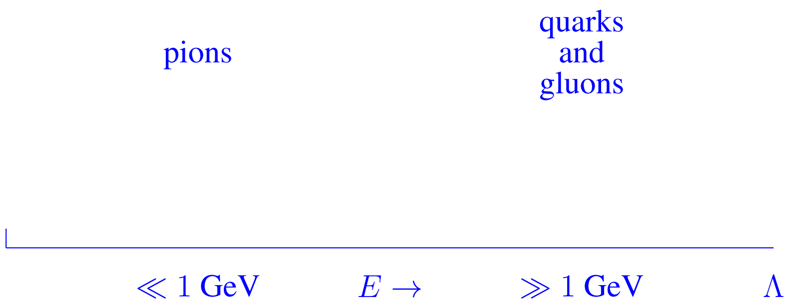
pions

quarks
and
gluons

$\ll 1$ GeV $E \rightarrow$ $\gg 1$ GeV Λ

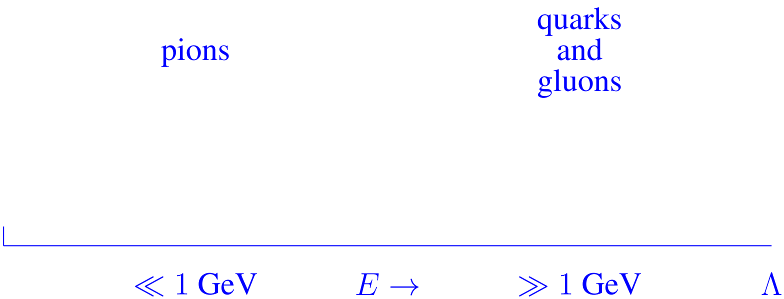
The classic example is chiral perturbation theory, which allows us to parameterize the physics of pions at low energies in terms of a manageable number of parameters.

χPT



The QCD gauge theory of quarks and gluons is, we think, an accurate description of their interactions up to some scale very large compared to 1 GeV (Liz & Sekhar's colorons?).

χ**PT**



The QCD gauge theory of quarks and gluons is, we think, an accurate description of their interactions up to some scale very large compared to 1 GeV (Liz & Sekhar's colorons?). And below 1 GeV it is not wrong — **but it is useless.** Fortunately, we can make progress by focusing on the right degrees of freedom.

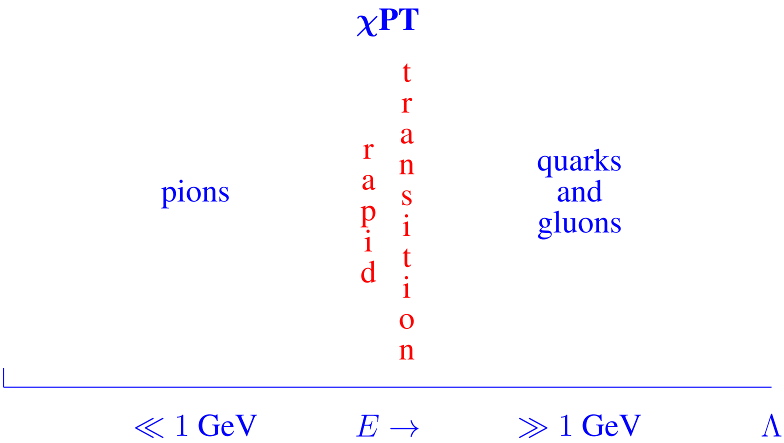
χPT

pions

quarks
and
gluons

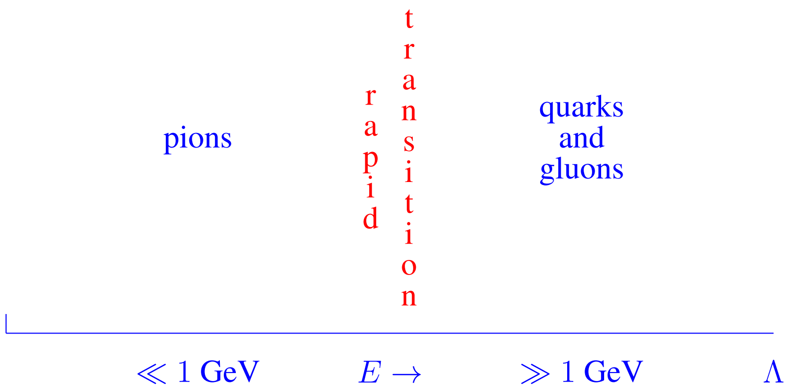
$\ll 1$ GeV $\quad E \rightarrow \quad \gg 1$ GeV $\quad \Lambda$

The pseudo-Goldstone Bosons are parametrically light, and we can describe their low energy interactions accurately.

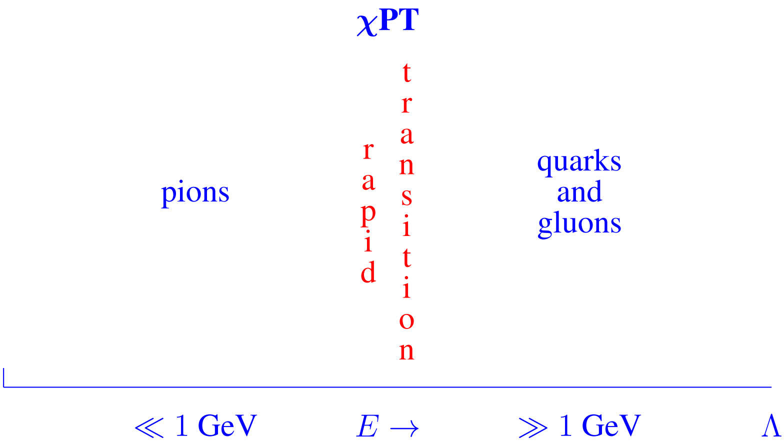


χPT works because the transition between the high-energy and low-energy descriptions of QCD is rather abrupt. This is another way of saying that the number of parameters in the χPT is manageable. The effective scale of the higher dimension operators in χPT is relatively large.

χPT



χPT is my model for understanding complicated physics. When I am trying to understand something, I try to fit it into this paradigm, and if I can't I get confused, and try to understand why I can't.



With that introduction, let me review the complex of ideas that is the major subject of the conference. I hope to give a thought-provoking but also a short talk so that we have time to discuss!

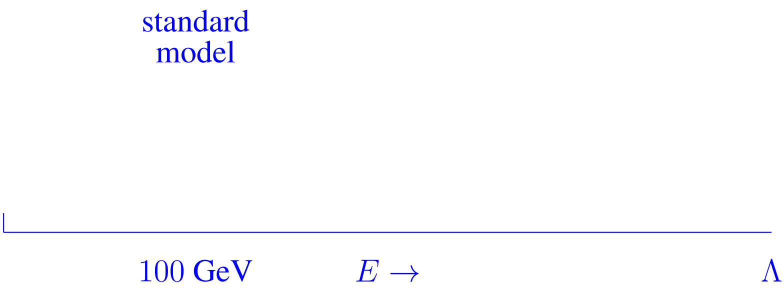
Plain Old Higgs

standard
model

100 GeV $E \rightarrow$ Λ

In the effective theory that we call the standard model, we assume that we know the physics up to some very high scale, Λ. Everything is perturbative at low energies. We know the source of EWSB so we know exactly what the Goldstone bosons and the Higgs are. Of course we know that this works beautifully.

Plain Old Higgs



Furthermore, the only sources of scale violation in this theory are the scale anomaly from quantum renormalization effects (small at the 100 GeV scale) and the doublet mass parameter that is very small compared to whatever the high scale is. So there is a fairly precise sense in which the violation of scale invariance is small and the Plain Old Higgs is also a pseudo-Dilaton.

Plain Old Technicolor

standard model w/o Higgs

new strong QCD-like TC

perturbative ETC from unknown physics

100 GeV | Λ_{TC} | Λ_{ETC} | Λ

In a classic technicolor theory, there is a new QCD-like strong interaction with U and D techniquarks analgous to the u and d quarks of QCD, but with the chiral symmetry breaking scale scaled up to about 1 TeV. This is a beautiful dynamical way of giving mass to the W and Z.

Plain Old Technicolor

standard model w/o Higgs	new strong QCD-like TC	perturbative ETC from unknown physics	
100 GeV	Λ_{TC}	Λ_{ETC}	Λ

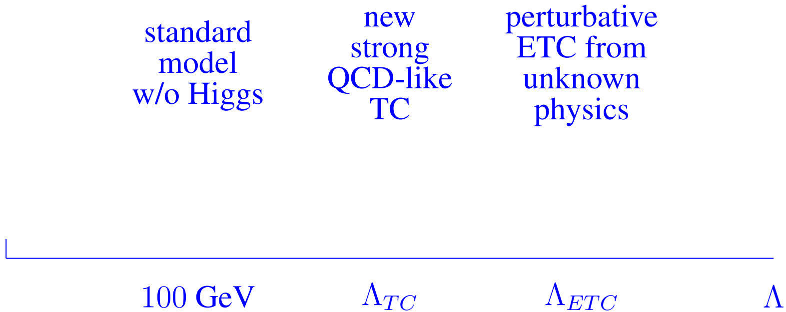
In Plain Old Technicolor, there is no Higgs and there is no pseudo-Dilaton. Let me be more precise about what I mean.

Plain Old Technicolor

standard model w/o Higgs	new strong QCD-like TC	perturbative ETC from unknown physics	
100 GeV	Λ_{TC}	Λ_{ETC}	Λ

What I mean by a Higgs (and I will defend this definition to my last breath) is an object that is part of an electroweak $SU(2) \times U(1)$ doublet with the longitudinal components of the W and Z, and therefore plays the dominant role of canceling the bad high-energy behavior of WW scattering.

Plain Old Technicolor



In Plain Old Technicolor, the longitudinal components of the W and Z are the technipions. They are well-described at the W, Z scale by an effective chiral theory, and, analogous to pions in χPT, the bad high-energy behavior in their scattering is controlled by the contribution of techni-resonances like the techni-rho.

Plain Old Technicolor

standard model w/o Higgs

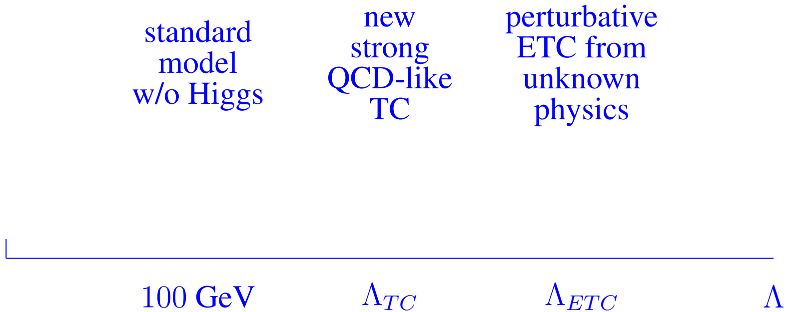
new strong QCD-like TC

perturbative ETC from unknown physics

100 GeV Λ_{TC} Λ_{ETC} Λ

Plain Old Technicolor also does not have a pseudo-Dilaton. Except for the Goldstone bosons, the resonances have masses (and/or widths) of the order of the technicolor scale. At this this scale, where the technicolor interaction is strong and scale invariance is very badly broken. There is no reason for a techni-Dilaton to be lighter than anthing else, and no sense in talking about such an object.

Plain Old Technicolor



Plain Old Technicolor also doesn't give the right structure of the W, Z masses at the level of the radiative corrections. We know this because it is QCD like and we can just scale up parameters from χPT. We also know a lot about these things from detailed studies on the lattice.

Plain Old Technicolor

standard model w/o Higgs — new strong QCD-like TC — perturbative ETC from unknown physics

100 GeV — Λ_{TC} — Λ_{ETC} — Λ

But nobody should be too upset about that, because the ETC sector is the really ugly part of Plain Old Technicolor.

Plain Old Technicolor

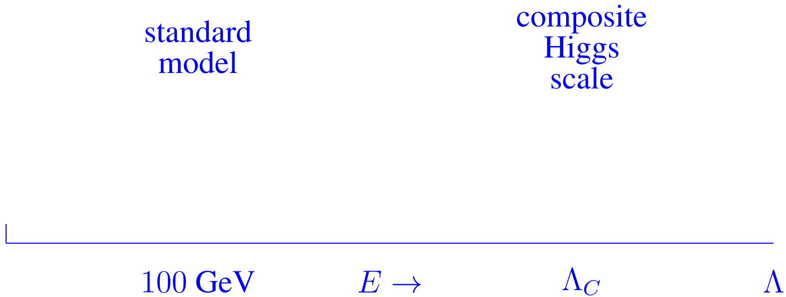
standard model w/o Higgs	new strong QCD-like TC	perturbative ETC from unknown physics	
100 GeV	Λ_{TC}	Λ_{ETC}	Λ

Robert Shrock reminded us of a very old but very beautiful complex of ideas — Extended technicolor - self-breaking of chiral gauge theories — but it is never enough. My personal belief is that nobody has ever constructed to completely realistic model without explicit scalars.

KOBAYASHI-MASKAWA INSTITUTE FOR THE ORIGIN OF PARTICLES AND THE UNIVERSE

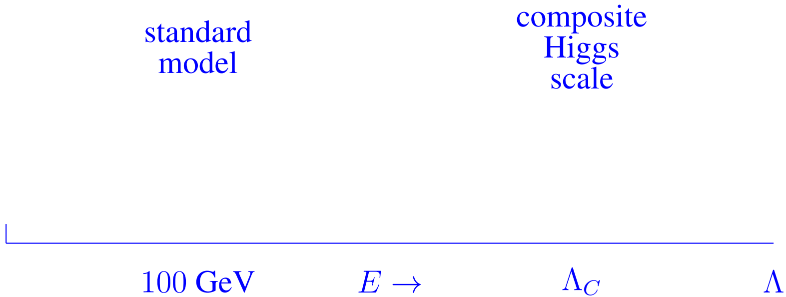
I find it a little ironic that at KMI, an insitute built on flavor, there was so little mention of the physics of standard model flavors. This is a huge problem for any theory without scalars. I was hoping to have some time to think about this question at the conference — But Koichi worked us all too hard.

Composite Higgs



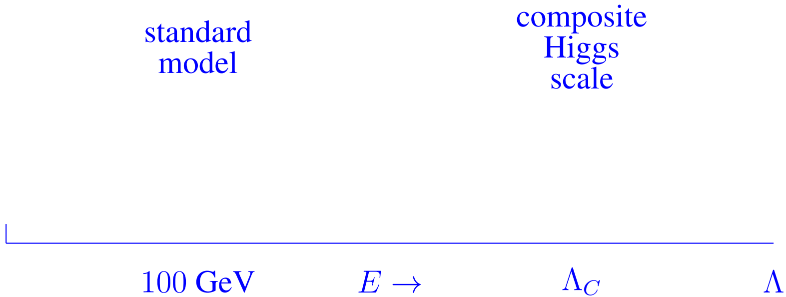
The composite Higgs idea originally developed out of χPT. You can build a Higgs doublet out of PGBs produced by some strong interaction that gets strong at Λ_C above a TeV.

Composite Higgs



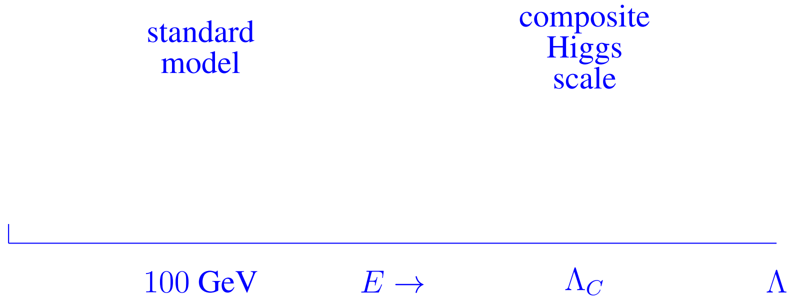
To generate a Higgs potential you have to break the global symmetries and finely tune the parameters to keep the mass of the Higgs doublet well below Λ_C (which you typically have to do to satisfy electroweak constraints)..

Composite Higgs



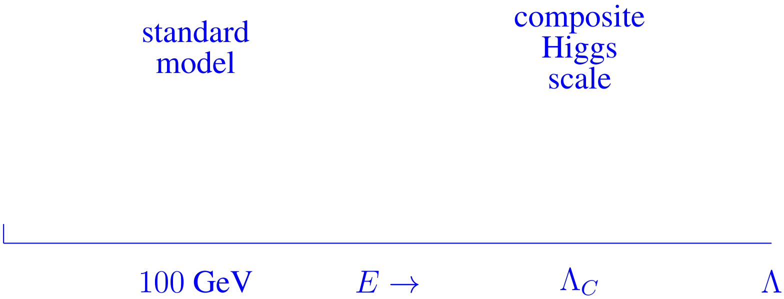
There are clever ideas like “little higgs” to make the required tuning less severe.

Composite Higgs



In principle, a composite Higgs need not be a PGB. But either you or your theory at Λ_C has to somehow make a scalar doublet that is much lighter than Λ_C. Otherwise, there is no reason for such a model to give anything like the standard model.

Composite Higgs



And if you do succeed in making your composite Higgs light, then it is just a Higgs! So like the Plain Old Higgs, a composite Higgs is both a Higgs and a techni-Dilaton.

Walking/nearly conformal/... Technicolor

standard model + scalar?	new nearly conformal TC	perturbative ETC from unknown physics	
100 GeV	Λ_{TC}	Λ_{ETC}	Λ

You have all been very patient with my summary of the last 40 years of particle theory, and finally, I am getting to the main subject of many (if not most) of the talks at this conference. What happens as our technicolor theory approaches walking/conformality? Now I want to claim that in this case, this picture is very misleading.

Walking/nearly Conformal/... Technicolor

standard
model
+ scalar?

perturbative(??)
ETC from
unknown
physics

nearly conformal TC

100 GeV Λ_{TC} $\leftrightarrow$ Λ_{ETC} Λ

walking/conformality

From here on, I will be speculating. But I hope that these speculations will be thought provoking, and will help us make sense of some of the amazing amount of work that has gone into studying theories of this kind, as exemplified by many of the beautiful talks we have heard at this conference.

Walking/nearly Conformal/... Technicolor

standard
model
+ scalar?

perturbative(??)
ETC from
unknown
physics

nearly conformal TC

100 GeV Λ_{TC} $\leftrightarrow$ Λ_{ETC} Λ

walking/conformality

It may also be that these speculations are so obvious to everyone else, that they are not worth discussing. But I found them useful for my own thinking, so I am going to subject all of you to them.

Walking/nearly Conformal/... Technicolor

standard
model
+ scalar?

perturbative(??)
ETC from
unknown
physics

nearly conformal TC

100 GeV Λ_{TC} $\leftrightarrow$ Λ_{ETC} Λ

walking/conformality

Walking/Conformal TC is in many ways just the opposite of Plain Old Technicolor and QCD. Rather than having a sharp transition from a high-energy theory to a low-energy theory, WCTC spreads the transition out over the entire region between the ETC scale and the electroweak scale.

Walking/nearly Conformal/... Technicolor

standard model + scalar?

perturbative(??) ETC from unknown physics

nearly conformal TC

100 GeV $\Lambda_{TC} \leftrightarrow \Lambda_{ETC}$ Λ

walking/conformality

Given what we said about the importance of a sharp transition from the high scale to the low scale for the success of χPT, this should make you worry a lot about the applicability of a conventional low energy EFT at the weak scale in the WCTC scenario.

Walking/nearly Conformal/... Technicolor

standard
model
+ scalar?

perturbative(??)
ETC from
unknown
physics

nearly conformal TC

100 GeV $\qquad \Lambda_{TC} \quad \leftrightarrow \quad \Lambda_{ETC} \qquad \Lambda$

walking/conformality

There is another way of arriving at the same conclusion. We have heard a lot about light dilatons in WCTC theories. It is not clear to me whether a light dilaton is an inescapable consequence of this picture. Scale invariance is tricky and this might be model dependent.

Walking/nearly Conformal/... Technicolor

standard
model
+ scalar?

perturbative(??)
ETC from
unknown
physics

nearly conformal TC

100 GeV $\Lambda_{TC} \leftrightarrow \Lambda_{ETC}$ Λ

walking/conformality

But what is clear is that there must be some small dynamical scales in WCTC. Otherwise, the dynamics could not be spread even appoximately uniformly between Λ_{TC} and Λ_{ETC}. For this you need small energy splittings.

Walking/nearly Conformal/... Technicolor

standard
model
+ scalar?

perturbative(??)
ETC from
unknown
physics

nearly conformal TC

100 GeV Λ_{TC} $\leftrightarrow$ Λ_{ETC} Λ

walking/conformality

Approximate walking/conformal invariance is a very strong constraint. There may not be small masses, but there must be small mass scales.

Walking/nearly Conformal/... Technicolor

standard
model
+ scalar?

perturbative(??)
ETC from
unknown
physics

nearly conformal TC

100 GeV $\qquad \Lambda_{TC} \leftrightarrow \Lambda_{ETC} \qquad \Lambda$

walking/conformality

The dilaton mass, or whatever the small dynamical scale is in your favorite WCTC theory is not at all like the Higgs mass. The Higgs self-coupling can give us a light Higgs independent of the scale of symmetry breaking.

Walking/nearly Conformal/... Technicolor

standard
model
+ scalar?

perturbative(??)
ETC from
unknown
physics

nearly conformal TC

100 GeV Λ_{TC} $\leftrightarrow$ Λ_{ETC} Λ

walking/conformality

The small scale of WCTC is built into the theory in a much more dynamical way and I believe that it will surely appear in the denominator of any effective field theory description of the physics of WCTC.

Walking/nearly Conformal/... Technicolor

standard
model
+ scalar?

perturbative(??)
ETC from
unknown
physics

nearly conformal TC

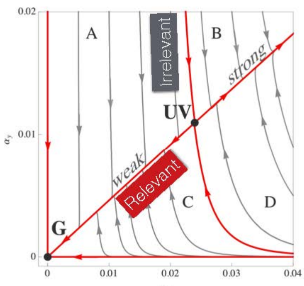
100 GeV Λ_{TC} $\leftrightarrow$ Λ_{ETC} Λ

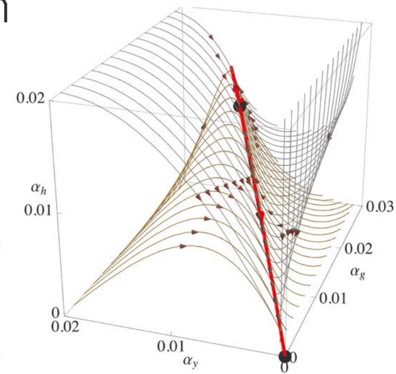
walking/conformality

Thus my tentative conclusion is that one reason I have found all this so confusing is that it is impossible (or at least not useful) to fit WCTC into a perturbative EFT at low energies. A different description is required.

Phase Diagram

$$\vartheta_1 = -0.608\,\epsilon^2 + \mathcal{O}(\epsilon^3)$$
$$\vartheta_2 = \quad 2.737\,\epsilon + \mathcal{O}(\epsilon^2)$$
$$\vartheta_3 = \quad 4.039\,\epsilon + \mathcal{O}(\epsilon^2)$$
$$\vartheta_4 = \quad 2.941\,\epsilon + \mathcal{O}(\epsilon^2)\,.$$



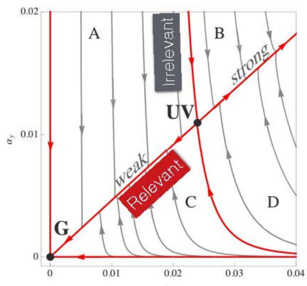


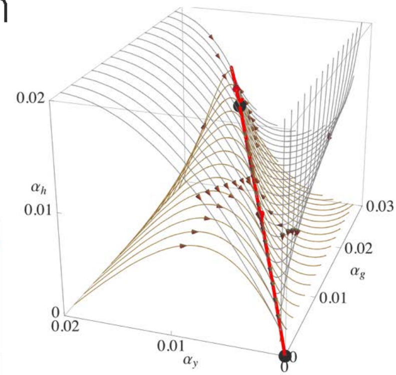
$$\vartheta_1 < 0 < \vartheta_2 < \vartheta_4 < \vartheta_3$$

The same, I think will be true of the interesting theories that Francesco described for us. The big question here is what to say about scalar masses. As I mentioned above, I agree with Francesco that the naive treatment of quadratic divergences in the RG is not appropriate.

Phase Diagram

$$\begin{aligned}\vartheta_1 &= -0.608\,\epsilon^2 + \mathcal{O}(\epsilon^3)\\ \vartheta_2 &= \quad 2.737\,\epsilon + \mathcal{O}(\epsilon^2)\\ \vartheta_3 &= \quad 4.039\,\epsilon + \mathcal{O}(\epsilon^2)\\ \vartheta_4 &= \quad 2.941\,\epsilon + \mathcal{O}(\epsilon^2)\,.\end{aligned}$$





$$\vartheta_1 < 0 < \vartheta_2 < \vartheta_4 < \vartheta_3$$

But the issue was never about quadratic divergences. The question is whether these new theories help us with the issues of fine tuning at the large scale. This would be great, but it is not obvious.

Walking/nearly Conformal/... Technicolor

standard
model
+ scalar?

perturbative(??)
ETC from
unknown
physics

nearly conformal TC

100 GeV Λ_{TC} $\leftrightarrow$ Λ_{ETC} Λ

walking/conformality

Returning to WCTC, my conclusion is that I don't know what the appropriate description of the low energy physics in such theories is. Maybe this is what holography is trying to get for us, if I could only understand and believe it. But I hope that knowing the nature of the problem will help, even if I don't know the solution.

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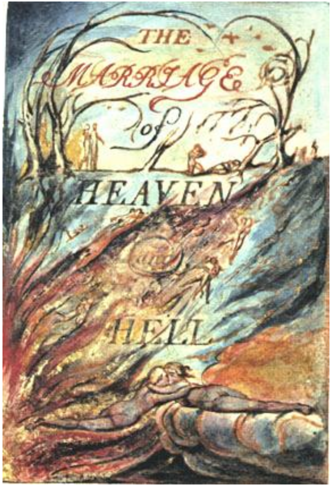
Let me close by thanking the organizers, particularly Koichi Yamawaki, for this amazing conference. I say thanks in spite of the fact that I have never been so tired at the end of a conference before. Koichi has worked us very hard.

SCGT15

But one thing you know about Koichi is that no matter how hard he works you, he is working even harder himself. I am sure that this will continue even after as he moves on to a new phase of his career.



A couple of hundred years ago, the English poet and print maker William Blake wrote a wonderful poem called “The Marriage of Heaven and Hell” and there is a line in that poem that I would like to recall as we thank Koichi not just for this conference, but for many many years of physics.

Energy is Eternal Delight!