Overview of Composite Higgs at Future Colliders

Ian Low (羅亦安)
Argonne/Northwestern

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Jockey Club IAS, HKUST
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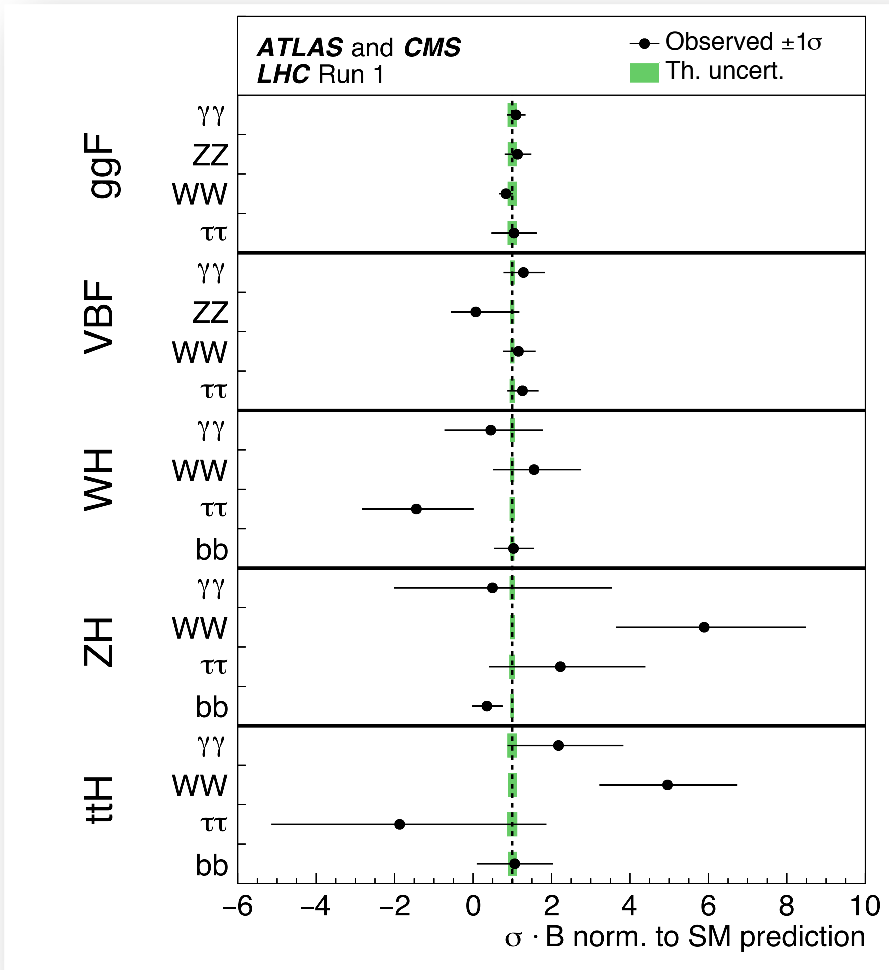
The Higgs has been discovered…



ATLAS+CMS Run 1 legacy combination: 1606.02266

An incredible joint effort by theorists and experimentalists together!

Although we’ve come a long way since 1964, there’re still many questions we have no answer to.

Some time ago I was reminded by my (then) 7-year-old of one such question:

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Some time ago I was reminded by my (then) 7-year-old of one such question:

What is it made of?

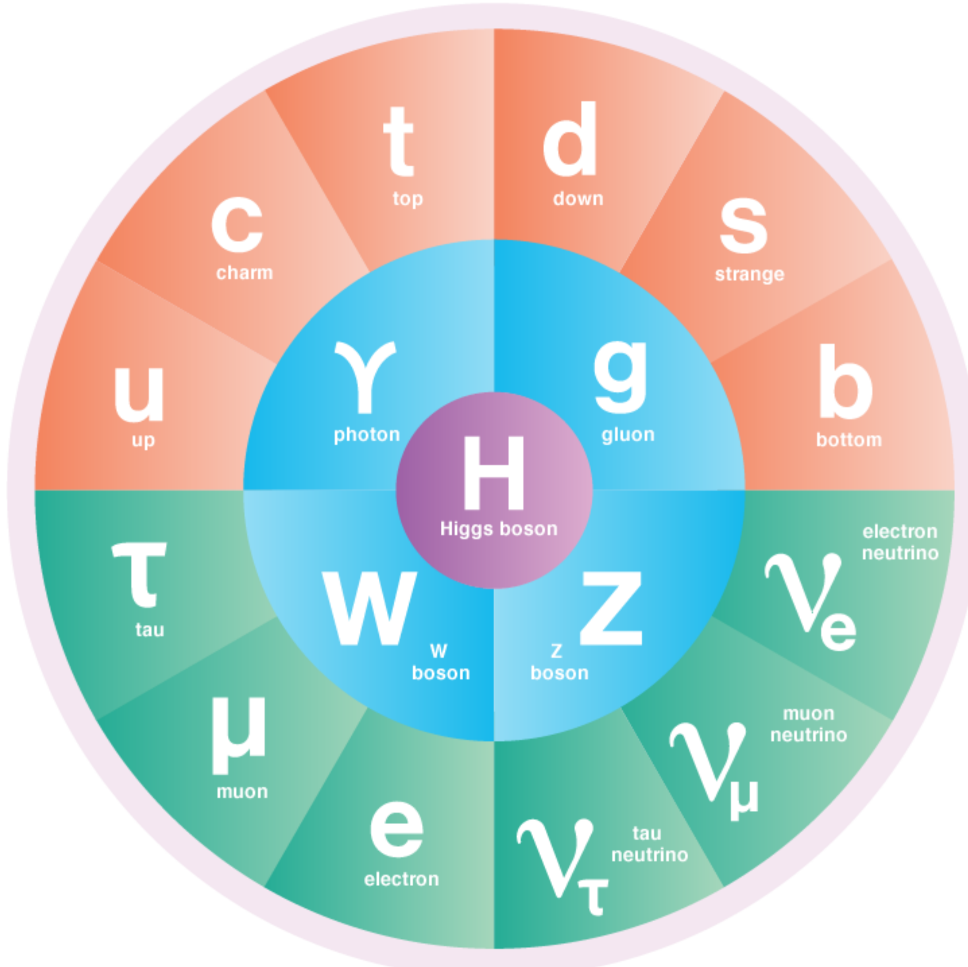
A physics Ph.D. could ask the same question in a slightly (but not much!) more sophisticated way:

Is it made of even smaller degrees of freedom, like the proton is made of quarks?

Or is it part of the fundamental structure of our Universe, like the electron?

It is worth recalling two simple observations regarding the Higgs:

1) It is the ONLY scalar particle in the Standard Model.



It is worth recalling two simple observations regarding the Higgs:

2) All other scalar particles we observe in Nature so far are "composite scalar"!

See also the table of suggested $q\bar{q}$ quark-model assignments in the Quark Model section.
• Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$
• π^0	$1^-(0^{-+})$
• η	$0^+(0^{-+})$
• $f_0(500)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$
• $\omega(782)$	$0^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$
• $\phi(1020)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$
• $b_1(1235)$	$1^+(1^{+-})$
• $a_1(1260)$	$1^-(1^{++})$
• $f_2(1270)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$
• $\eta(1295)$	$0^+(0^{-+})$
• $\pi(1300)$	$1^-(0^{-+})$
• $a_2(1320)$	$1^-(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$
• $\pi_1(1400)$	$1^-(1^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$
• $f_1(1420)$	$0^+(1^{++})$
• $\omega(1420)$	$0^-(1^{--})$
$f_2(1430)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$
• $f_0(1500)$	$0^+(0^{++})$
$f_1(1510)$	$0^+(1^{++})$
• $f'_2(1525)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$
$h_1(1595)$	$0^-(1^{+-})$
• $\pi_1(1600)$	$1^-(1^{-+})$
$a_1(1640)$	$1^-(1^{++})$
$f_2(1640)$	$0^+(2^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$
• $\omega(1650)$	$0^-(1^{--})$
• $\omega_3(1670)$	$0^-(3^{--})$
• $\pi_2(1670)$	$1^-(2^{-+})$
• $\phi(1680)$	$0^-(1^{--})$
• $\rho_3(1690)$	$1^+(3^{--})$
• $\rho(1700)$	$1^+(1^{--})$
$a_2(1700)$	$1^-(2^{++})$
• $f_0(1710)$	$0^+(0^{++})$
$\eta(1760)$	$0^+(0^{-+})$
• $\pi(1800)$	$1^-(0^{-+})$
$f_2(1810)$	$0^+(2^{++})$
$X(1835)$	$?^?(0^{-+})$
$X(1840)$	$?^?(?^{??})$
$a_1(1420)$	$1^-(1^{++})$
• $\phi_3(1850)$	$0^-(3^{--})$
$\eta_2(1870)$	$0^+(2^{-+})$
• $\pi_2(1880)$	$1^-(2^{-+})$
$\rho(1900)$	$1^+(1^{--})$
$f_2(1910)$	$0^+(2^{++})$
$a_0(1950)$	$1^-(0^{++})$
• $f_2(1950)$	$0^+(2^{++})$
$\rho_3(1990)$	$1^+(3^{--})$
• $f_2(2010)$	$0^+(2^{++})$
$f_0(2020)$	$0^+(0^{++})$
• $a_4(2040)$	$1^-(4^{++})$
• $f_4(2050)$	$0^+(4^{++})$
$\pi_2(2100)$	$1^-(2^{-+})$
$f_0(2100)$	$0^+(0^{++})$
$f_2(2150)$	$0^+(2^{++})$
$\rho(2150)$	$1^+(1^{--})$
• $\phi(2170)$	$0^-(1^{--})$
$f_0(2200)$	$0^+(0^{++})$
$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$\eta(2225)$	$0^+(0^{-+})$
$\rho_3(2250)$	$1^+(3^{--})$
• $f_2(2300)$	$0^+(2^{++})$
$f_4(2300)$	$0^+(4^{++})$
$f_0(2330)$	$0^+(0^{++})$
• $f_2(2340)$	$0^+(2^{++})$
$\rho_5(2350)$	$1^+(5^{--})$
$a_6(2450)$	$1^-(6^{++})$
$f_6(2510)$	$0^+(6^{++})$

OTHER LIGHT

Further States

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
$K^*_0(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
$K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

	$I(J^P)$
• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D^*_0(2400)^0$	$1/2(0^+)$
$D^*_0(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D^*_2(2460)^0$	$1/2(2^+)$
• $D^*_2(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(?^?)$
$D^*_J(2600)$	$1/2(?^?)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2740)^0$	$1/2(?^?)$
$D(2750)$	$1/2(3^-)$
$D(3000)^0$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)

	$I(J^P)$
• $D^\pm_s$	$0(0^-)$
• $D^{*\pm}_s$	$0(?^?)$
• $D^*_{s0}(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)$	$0(2^+)$
• $D^*_{s1}(2700)^\pm$	$0(1^-)$
$D^*_{s1}(2860)^\pm$	$0(1^-)$
$D^*_{s1}(2860)^\pm$	$0(3^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
• $B_1(5721)^+$	$1/2(1^+)$
• $B_1(5721)^0$	$1/2(1^+)$
$B^*_J(5732)$	$?(?^?)$
• $B^*_2(5747)^+$	$1/2(2^+)$
• $B^*_2(5747)^0$	$1/2(2^+)$
$B_J(5840)^+$	$1/2(?^?)$
$B_J(5840)^0$	$1/2(?^?)$
• $B_J(5970)^+$	$1/2(?^?)$
• $B_J(5970)^0$	$1/2(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B^0_s	$0(0^-)$
• B^*_s	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B^*_{s2}(5840)^0$	$0(2^+)$
$B^*_{sJ}(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

• B^+_c	$0(0^-)$
$B_c(2S)^\pm$	$0(0^-)$

$c\bar{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $\psi(3823)$	$?^?(2^{--})$
• $X(3872)$	$0^+(1^{++})$
• $X(3900)$	$1^+(1^{+-})$
• $X(3915)$	$0^+(0/2^{++})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $X(4020)$	$1(?^?)$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4055)^\pm$	$?(?^?)$
• $X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4200)^\pm$	$?(1^+)$
$X(4230)$	$?^?(1^{--})$
$X(4240)^\pm$	$?^?(0^-)$
$X(4250)^\pm$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
• $X(4430)^\pm$	$?(1^+)$
• $X(4660)$	$?^?(1^{--})$

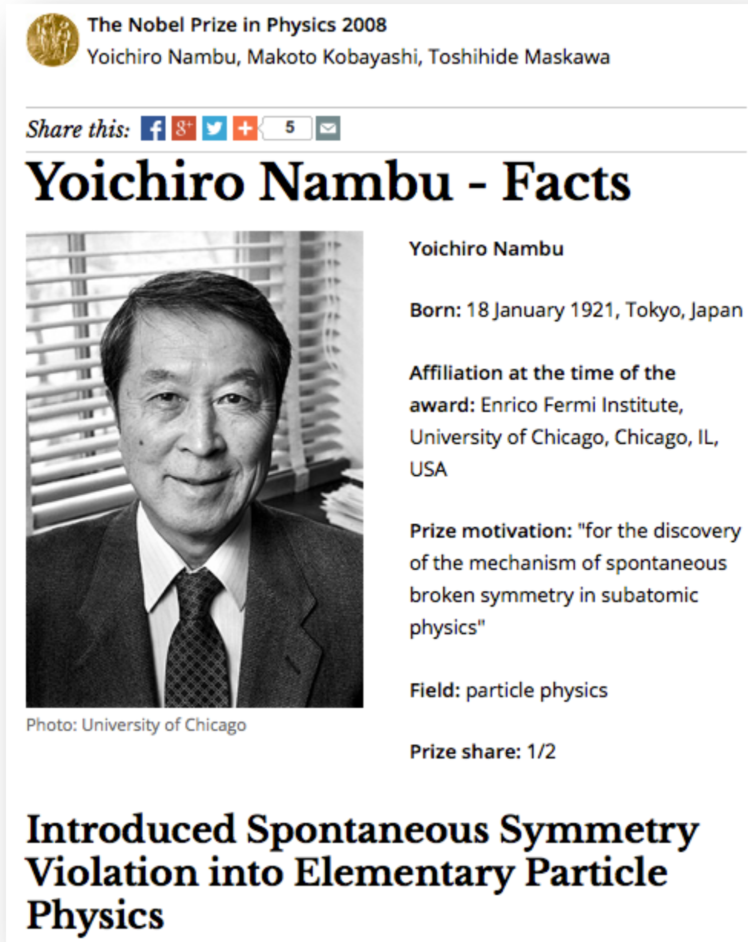
$b\bar{b}$

• $\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$?^?(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$?^?(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_{b1}(3P)$	$0^+(1^{++})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $X(10610)^\pm$	$1^+(1^+)$
• $X(10610)^0$	$1^+(1^+)$
$X(10650)^\pm$	$?^+(1^+)$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

Particle Data Group

In particle physics, the most famous example of a composite scalar is the pion in low-energy QCD and the theory of spontaneously broken symmetry.

Just like the Higgs boson, this is another Prize-winning work:



The Nobel Prize in Physics 2008
Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa

Share this: 5

Yoichiro Nambu - Facts

Photo: University of Chicago

Yoichiro Nambu

Born: 18 January 1921, Tokyo, Japan

Affiliation at the time of the award: Enrico Fermi Institute, University of Chicago, Chicago, IL, USA

Prize motivation: "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

Field: particle physics

Prize share: 1/2

Introduced Spontaneous Symmetry Violation into Elementary Particle Physics

Today we understand the pion as the pseudo-Nambu-Goldstone boson (pNGB) arising from the spontaneously broken chiral symmetry:

$$\mathbf{SU(3)_L \times SU(3)_R \rightarrow SU(3)_V}$$

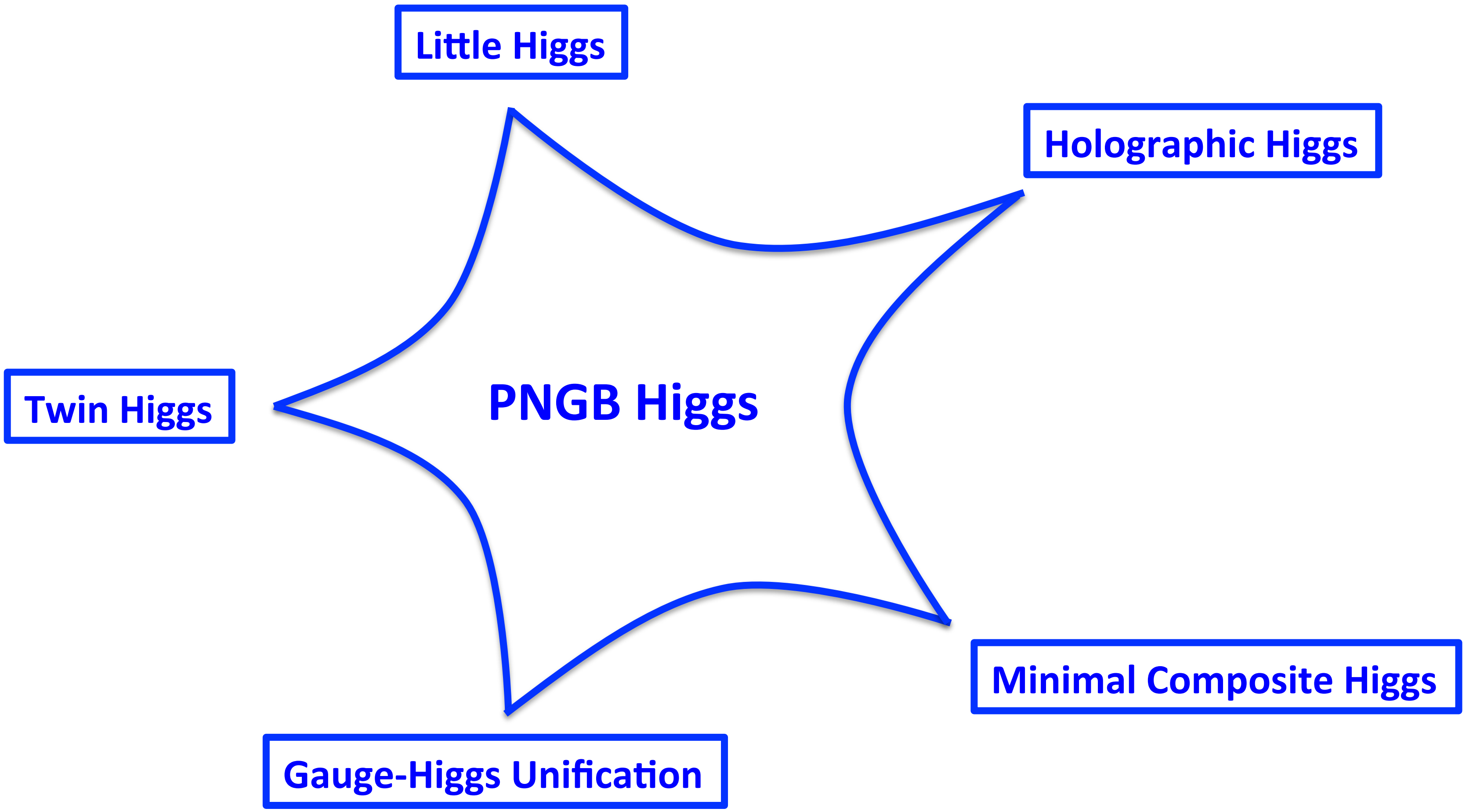
It is natural to wonder, could the Higgs boson be a composite scalar à la pion in low-energy QCD?

The Higgs boson would be a pNGB of some global symmetry G that is spontaneously broken to a subgroup H at an energy scale higher than 1 TeV:

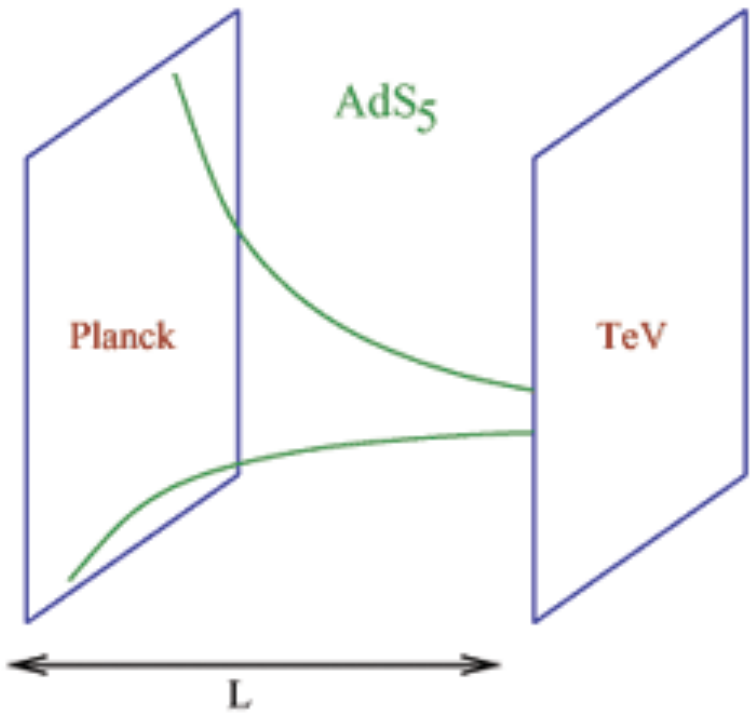
$$\mathbf{G \rightarrow H}$$

Nowadays this class of theories goes under the name of "Composite Higgs Boson."

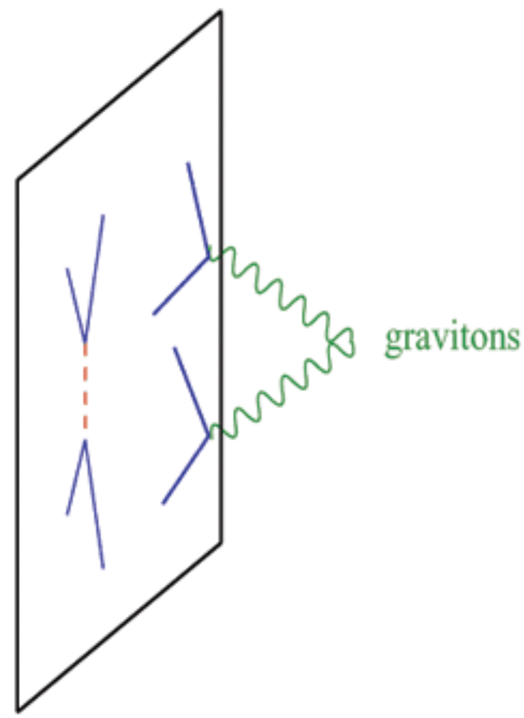
Over the last decade the Composite Higgs model has become an all-encompassing paradigm, with many different realizations:



Many of you heard of the buzz word “extra dimensions” in the past:



Warped extra-dimension



Flat extra-dimension

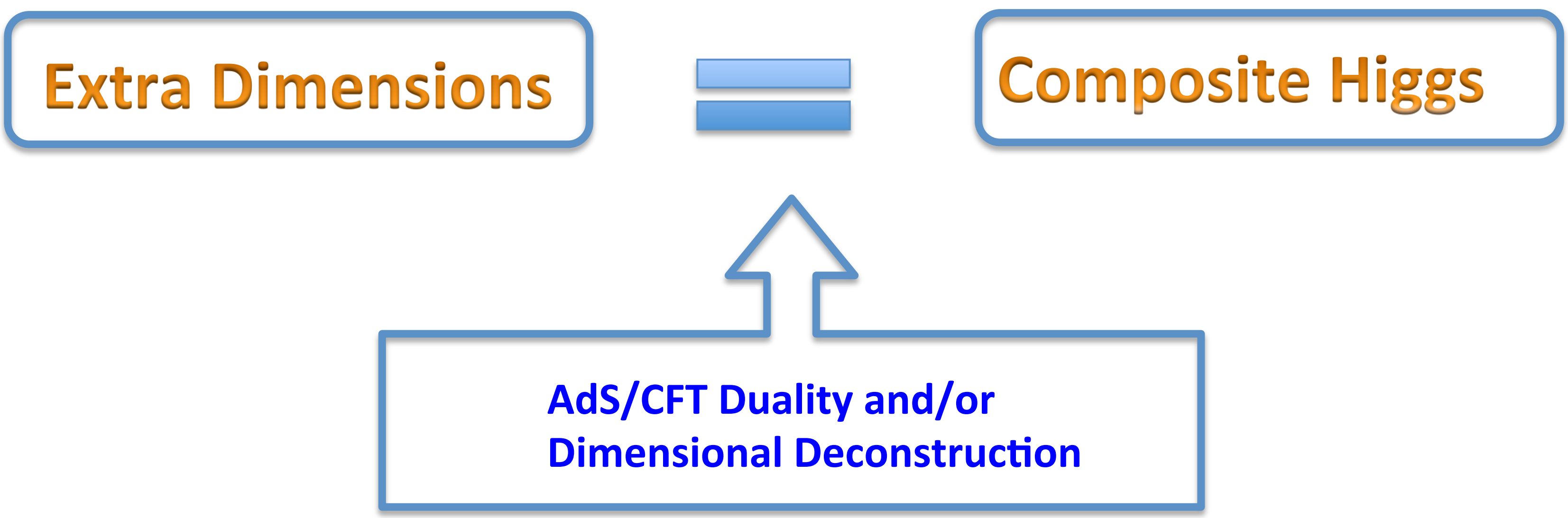
Photo credit: G. Burdman

But nowadays people seem to have stopped talking about extra dimensions...

The two paradigms model builders talk about are:

Supersymmetry ⟷ **Composite Higgs**

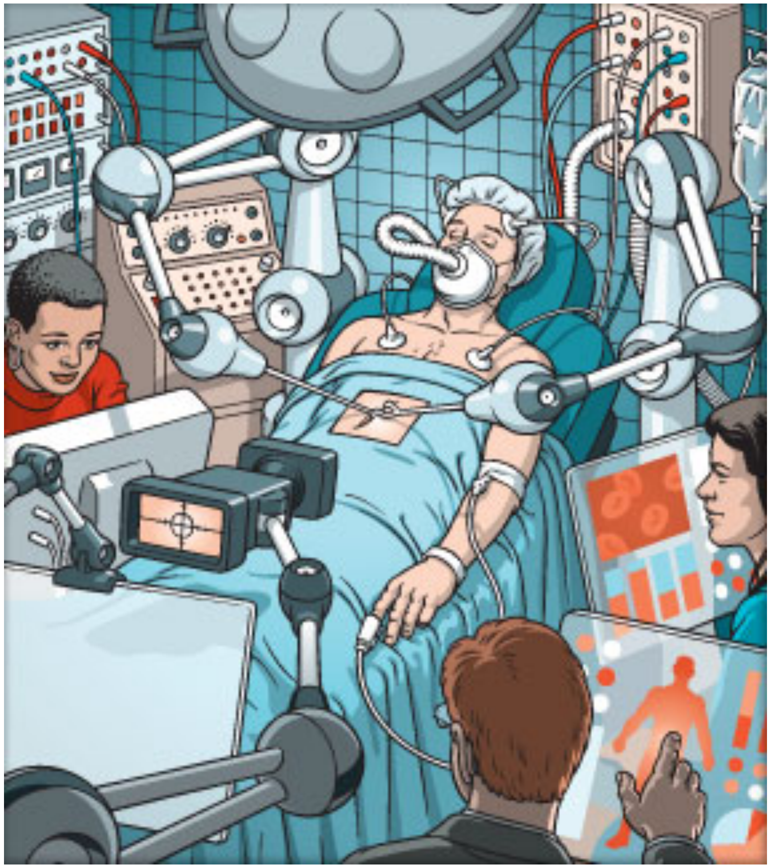
But extra dimensions didn't go away; they in fact are related to composite Higgs models in modern thinking:



Supersymmetry v.s. Composite Higgs:

Supersymmetry v.s. Composite Higgs:

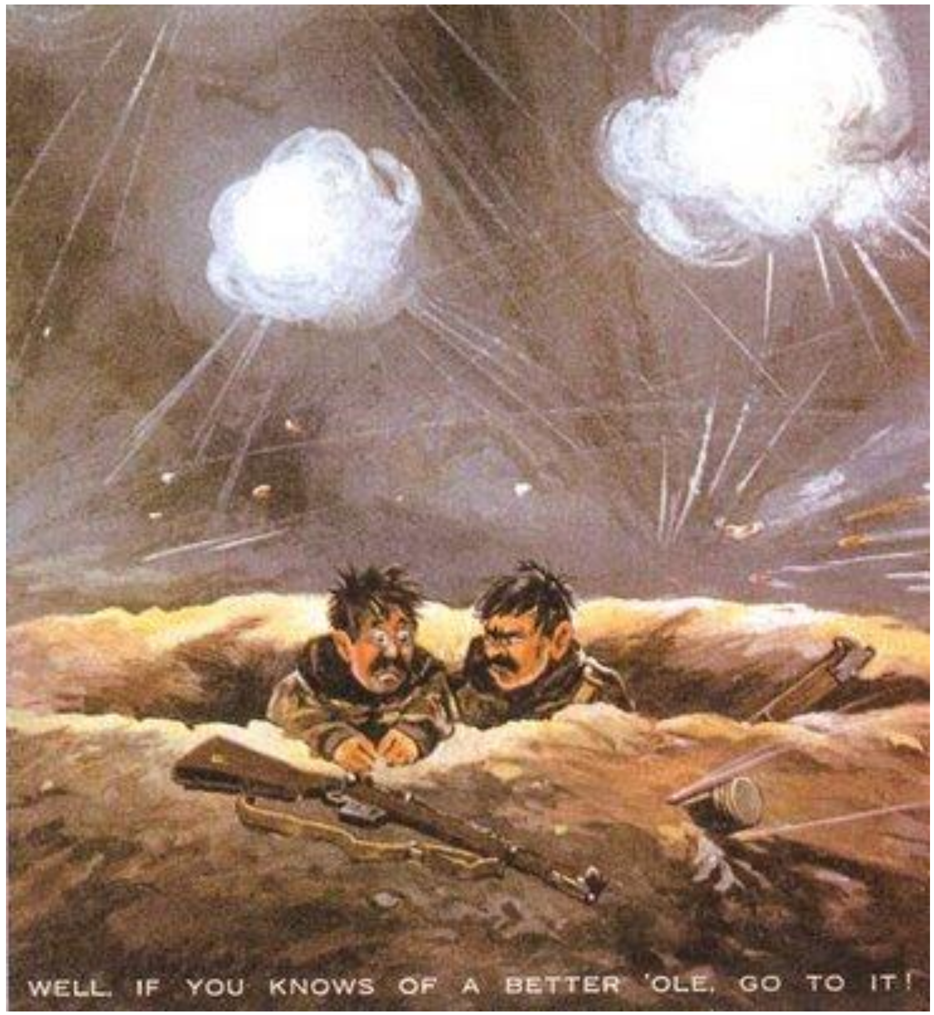
Neither of them is doing great --



Supersymmetry v.s. Composite Higgs:

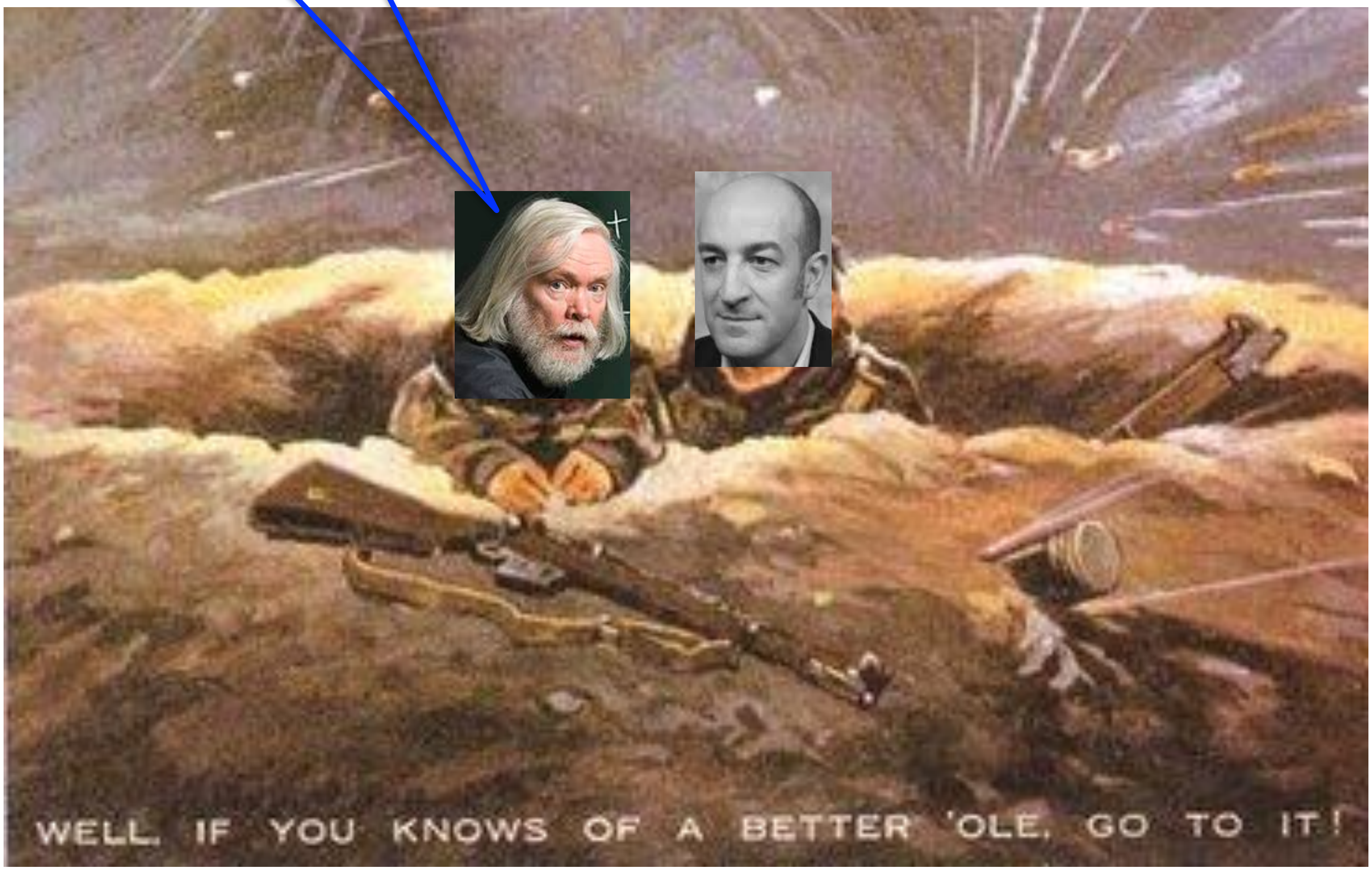
John Ellis' defense of Supersymmetry:

"If you know of a better hole, go to it!"



Supersymmetry v.s. Composite Higgs:

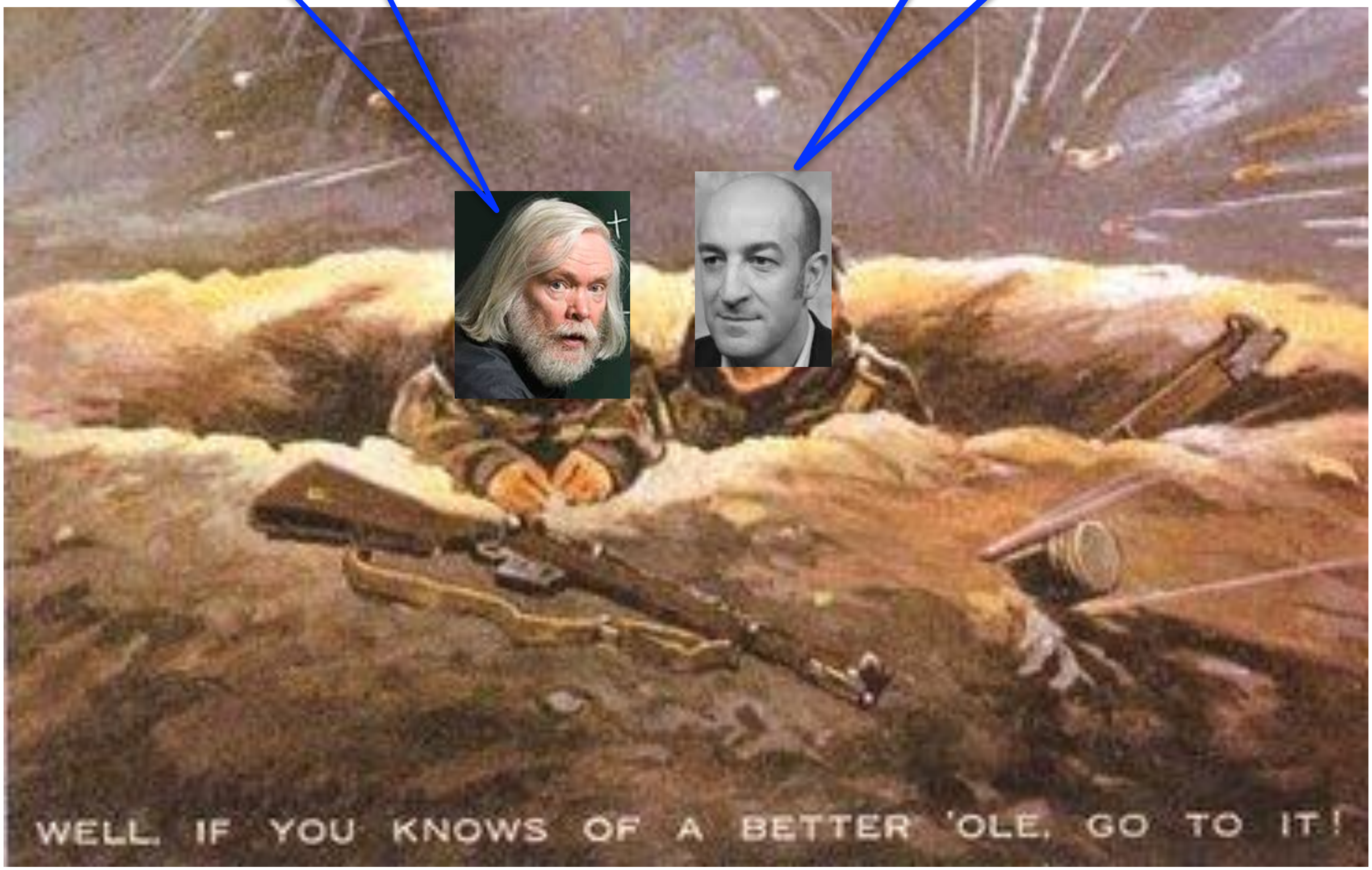
If you know of a better
hole, go to it!



Supersymmetry v.s. Composite Higgs:

If you know of a better hole, go to it!

I am outta here!



In QCD the effective theory describing pion interactions is the chiral Lagrangian:

$$\Pi = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix} \qquad U = e^{i\Pi/f_\pi}$$

$$\mathcal{L}_{\chi PT} = \frac{f_\pi^2}{2}\mathrm{Tr}\left(\partial_\mu U^\dagger \partial_\mu U\right) + c_0 f_\pi^2 \mathrm{Tr}\left(\mathcal{M}_q U^\dagger + U\mathcal{M}_q\right)$$

This effective lagrangian is based on the spontaneously broken chiral symmetry in QCD:

$$SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$$

Theorists have come up with many different possibilities for the broken symmetry G and the unbroken symmetry H:

$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{SU(2)\times SU(2)}\,(\mathbf{r}_{SU(2)\times U(1)})$	Ref.
SO(5)	SO(4)	✓	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$	[11]
SU(3) × U(1)	SU(2) × U(1)		5	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$	[10, 35]
SU(4)	Sp(4)	✓	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[29, 47, 64]
SU(4)	$[\mathrm{SU}(2)]^2 \times \mathrm{U}(1)$	✓*	8	$(\mathbf{2},\mathbf{2})_{\pm 2} = 2\cdot(\mathbf{2},\mathbf{2})$	[65]
SO(7)	SO(6)	✓	6	$\mathbf{6} = 2\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	–
SO(7)	G_2	✓*	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	[66]
SO(7)	SO(5) × U(1)	✓*	10	$\mathbf{10}_0 = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	–
SO(7)	$[\mathrm{SU}(2)]^3$	✓*	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\cdot(\mathbf{2},\mathbf{2})$	–
Sp(6)	Sp(4) × SU(2)	✓	8	$(\mathbf{4},\mathbf{2}) = 2\cdot(\mathbf{2},\mathbf{2})$	[65]
SU(5)	SU(4) × U(1)	✓*	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2\cdot(\mathbf{2},\mathbf{2})$	[67]
SU(5)	SO(5)	✓*	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$	[9, 47, 49]
SO(8)	SO(7)	✓	7	$\mathbf{7} = 3\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	–
SO(9)	SO(8)	✓	8	$\mathbf{8} = 2\cdot(\mathbf{2},\mathbf{2})$	[67]
SO(9)	SO(5) × SO(4)	✓*	20	$(\mathbf{5},\mathbf{4}) = (\mathbf{2},\mathbf{2}) + (\mathbf{1}+\mathbf{3},\mathbf{1}+\mathbf{3})$	[34]
$[\mathrm{SU}(3)]^2$	SU(3)		8	$\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$	[8]
$[\mathrm{SO}(5)]^2$	SO(5)	✓*	10	$\mathbf{10} = (\mathbf{1},\mathbf{3}) + (\mathbf{3},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[32]
SU(4) × U(1)	SU(3) × U(1)		7	$\mathbf{3}_{-1/3} + \bar{\mathbf{3}}_{+1/3} + \mathbf{1}_0 = 3\cdot\mathbf{1}_0 + \mathbf{2}_{\pm 1/2}$	[35, 41]
SU(6)	Sp(6)	✓*	14	$\mathbf{14} = 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{3}) + 3\cdot(\mathbf{1},\mathbf{1})$	[30, 47]
$[\mathrm{SO}(6)]^2$	SO(6)	✓*	15	$\mathbf{15} = (\mathbf{1},\mathbf{1}) + 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3})$	[36]

Table 1: Symmetry breaking patterns $\mathcal{G} \to \mathcal{H}$ for Lie groups. The third column denotes whether the breaking pattern incorporates custodial symmetry. The fourth column gives the dimension N_G of the coset, while the fifth contains the representations of the GB's under $\mathcal{H}$ and $\mathrm{SO}(4) \cong \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ (or simply $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ if there is no custodial symmetry). In case of more than two SU(2)'s in $\mathcal{H}$ and several different possible decompositions we quote the one with largest number of bi-doublets.

Bellazzni, Csaki and Serre:1401.2457

So how are we going to test all these “Composite Higgs” models?

It turns out there are two salient features of composite Higgs that are quite generic:

- Interactions of a composite Higgs have a certain pattern.

- Exist new fermions that are partners of the Standard Model top quarks.

It turns out there are two salient features of composite Higgs that are quite generic:

- Interactions of a composite Higgs have a certain pattern.
  The pattern is different from supersymmetry.
  Precision measurement is the key here! → **A Higgs factory!**

- Exist new fermions that are partners of the Standard Model top quarks.
  In supersymmetry partners of the top quark are scalars!!
  Need **energy reach** to be able to
  1) produce the top partners
  2) measure their spin quantum number and couplings to the Higgs
  → **A new hadron collider!**

At this point it is worth emphasizing the Standard Model Higgs boson is a very special one!

In the Standard Model:

Couplings to massive gauge bosons →

$$\left(\frac{2m_W^2}{v}\, h\, W_\mu^+ W^{-\,\mu} + \frac{m_Z^2}{v}\, h\, Z_\mu Z^\mu\right)$$

Couplings to massless gauge bosons →

$$+c_g \frac{\alpha_s}{12\pi v} h\, G_{\mu\nu}^a G^{a\,\mu\nu} + c_\gamma \frac{\alpha}{8\pi v} h\, F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{8\pi v s_w}\, h\, F_{\mu\nu} Z^{\mu\nu}$$

$$c_g^{(SM)}(125\ \text{GeV}) = 1\ , \qquad c_\gamma^{(SM)}(125\ \text{GeV}) = -6.48\ , \qquad c_{Z\gamma}^{(SM)}(125\ \text{GeV}) = 5.48\ .$$

Couplings to fermions → $\sum_f \frac{m_f}{v} h \bar{f} f$

Self-couplings → $\frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{v} h^3 + \frac{2m_h^2}{v^2} h^4$

Once the mass is known, every single coupling is then determined!!

At the LHC we have only measured a subset of these couplings with uncertainties of 10 – 20 % or larger:

In the Standard Model:

Couplings to massive gauge bosons →

$$\left(\frac{2m_W^2}{v} h\, W_\mu^+ W^{-\,\mu} + \frac{m_Z^2}{v} h\, Z_\mu Z^\mu\right)$$

Couplings to massless gauge bosons →

$$+c_g \frac{\alpha_s}{12\pi v} h\, G^a_{\mu\nu} G^{a\,\mu\nu} + c_\gamma \frac{\alpha}{8\pi v} h\, F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{8\pi v s_w} h\, F_{\mu\nu} Z^{\mu\nu}$$

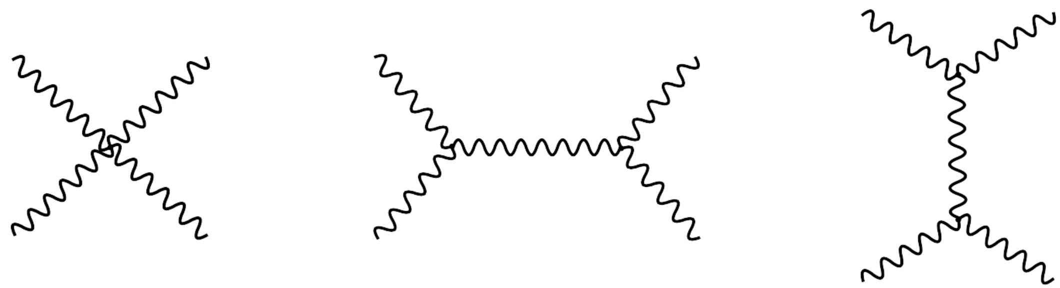
$$c_g^{(SM)}(125 \text{ GeV}) = 1 \,, \qquad c_\gamma^{(SM)}(125 \text{ GeV}) = -6.48 \,, \qquad c_{Z\gamma}^{(SM)}(125 \text{ GeV}) = 5.48 \,.$$

Couplings to fermions → $\sum_f \frac{m_f}{v} h \bar{f} f$ ✔ for *bb*, *tt*, and *ττ* only!

Self-couplings → $\frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{v} h^3 + \frac{2m_h^2}{v^2} h^4$

These couplings allow the SM Higgs to do one very special thing in the SM:

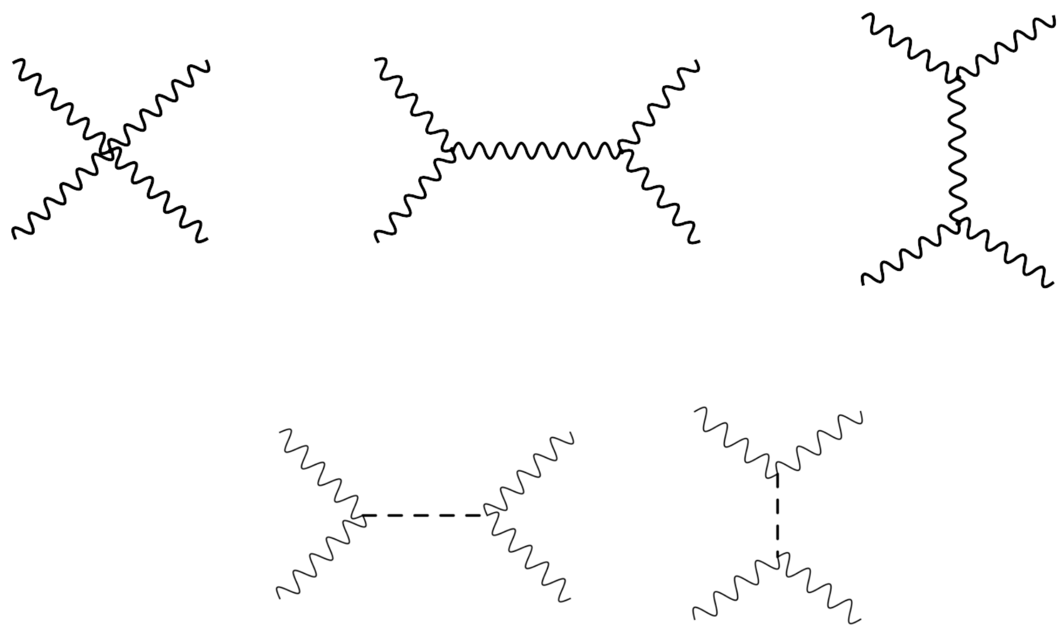
It is well-known that, in the SM without the Higgs, WW scattering amplitude violates unitarity:



$$\mathcal{A}(W_L^+ W_L^- \to W_L^+ W_L^-) \simeq \frac{g^2}{4m_W^2}\,(s+t)\ .$$

Before the Higgs discovery, this was the strongest evidence/argument for the existence of “something” which unitarizes WW scattering.

Including the Higgs diagrams allows the growth to be cancelled completely, provided the hWW couplings have precisely the forms in the SM:



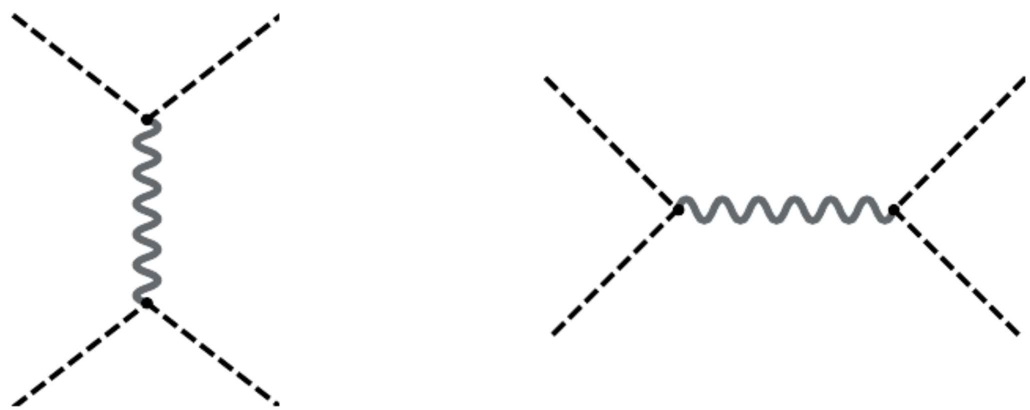
This is an extremely simple and economical solution, except…

Except that this is not how Nature *usually* deals with a situation like this.

(Recall we have NOT observed a fundamental scalar previously!)

Except that this is not how Nature *usually* deals with a situation like this.
(Recall we have NOT observed a fundamental scalar previously!)

For example, pi-pi scattering is unitarized NOT by a fundamental scalar, but by a series of heavier resonances, the spin-1 rho meson for instance:



Each resonance only partially unitarizes the pi-pi scattering.

This raises the interesting possibility:

Can the Higgs boson we observed is only the first one of a series of resonances that partially unitarize WW scattering?

In this case the Higgs coupling to WW boson is reduced from the SM expectation!!

This raises the interesting possibility:

Can the Higgs boson we observed is only the first one of a series of resonances that partially unitarize WW scattering?

In this case the Higgs coupling to WW boson is reduced from the SM expectation!!

Objection:

Where are the other "resonances" that will fully unitarize the WW scattering?

The 125 GeV Higgs can be "naturally" lighter than other resonances if it is a (pseudo) Nambu-Goldstone boson, just like pions are significantly lighter than the spin-1 rho meson in low-energy QCD.

To answer the question of whether the 125 GeV Higgs **fully** unitarizes WW scattering, we need to measure hWW coupling very precisely!

Current LHC measurements have

$$\delta_{hWW} \sim \frac{v^2}{f^2} \sim 10\% \quad \Rightarrow \quad f \sim 500 \text{ GeV}$$

If the precision is improved,

$$\text{HL}-\text{LHC}: \ \delta_{hWW} \sim 1\% \quad \Rightarrow \quad f \sim 1.7 \text{ TeV}$$

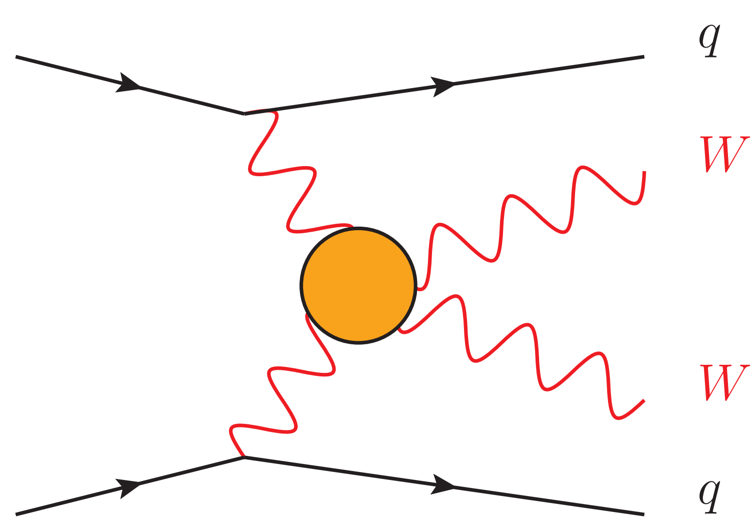
$$\text{CEPC}: \ \delta_{hWW} \sim 0.1\% \quad \Rightarrow \quad f \sim 5.5 \text{ TeV}$$

But of course we would like to be able to directly probe WW scatterings at a collider.

Then a PNGB Higgs predicts the following interesting relations:

$$\mathcal{A}(W_L W_L \to Z_L Z_L) = -\mathcal{A}(W_L W_L \to hh)$$

$$\mathcal{A}(V_L V_L \to hhh) = 0$$



These predictions are generic and do not depend on what G and H are!!

Contino et. al.: 1309.7038
Low: 1412.2146

A nice study on WW scattering at a linear lepton collider:

$$\mathcal{A} = a^2 \left(\mathcal{A}_{SM} + \mathcal{A}_1\, \delta_b + \mathcal{A}_2\, \delta_{d_3}\right) \qquad \delta_b \equiv 1 - \frac{b}{a^2}, \qquad \delta_{d_3} \equiv 1 - \frac{d_3}{a}$$

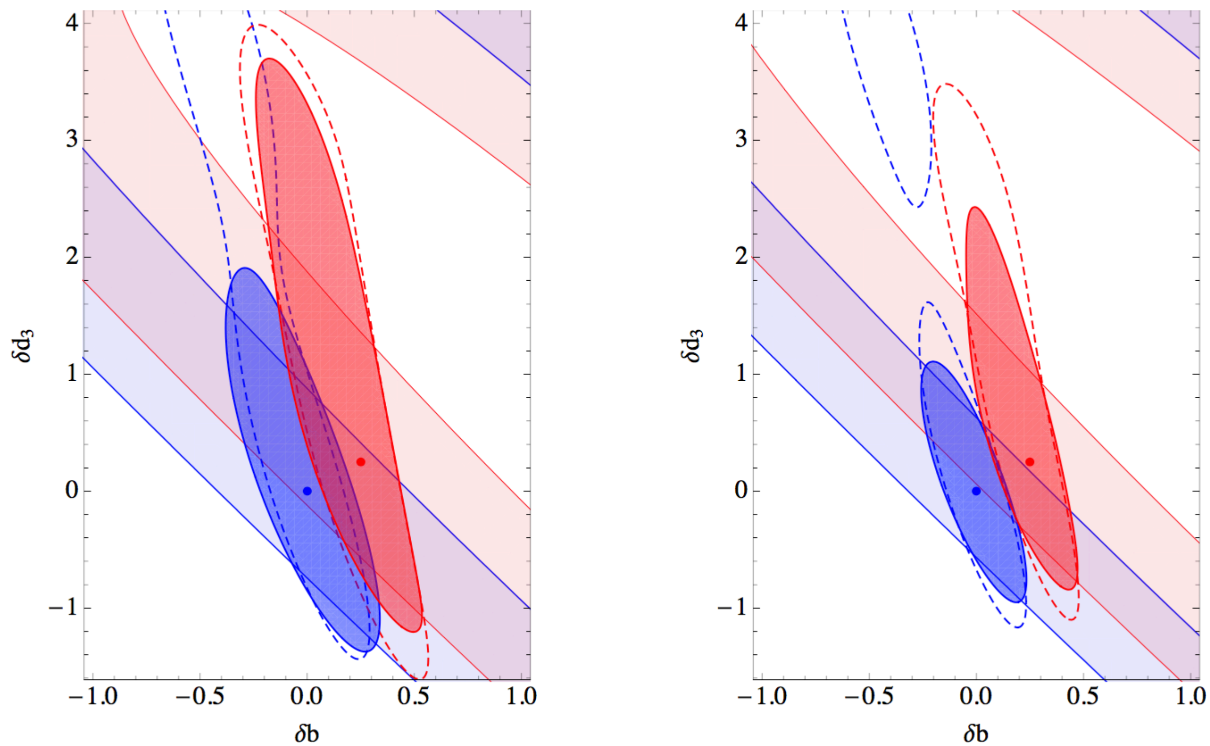


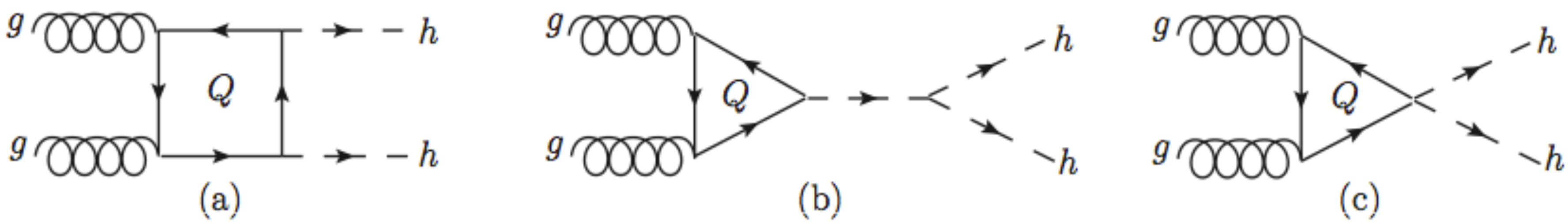
Figure 10: Regions of 68% probability in the plane (δ_b, δ_{d_3}) obtained from the analysis of double Higgs-strahlung at various collider energies. Blue (red) shapes and contours are relative to the case of injected values $\bar{\delta}_b = 0$, $\bar{\delta}_{d_3} = 0$ ($\bar{\delta}_b = 0.25$, $\bar{\delta}_{d_3} = 0.25$). Lighter shaded bands: 500 GeV; Dashed contours: 1 TeV; Darker shaded regions: 500 GeV + 1 TeV. The plots have been obtained by assuming an integrated luminosity $L = 1\,\text{ab}^{-1}$ and setting $a^2(BR(b\bar{b})/BR(b\bar{b})_{SM}) = 0.81$ (left plot) and $a^2(BR(b\bar{b})/BR(b\bar{b})_{SM}) = 1$ (right plot).

Contino, Grojean, Pappadopulo, Rattazzi, Thamm: 1309.7038

Another important channel for composite Higgs models is gg->hh:

- Within SM the interest stems from directly measuring the Higgs self-coupling.

SM **SM** **Composite Higgs**



$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left[\left| \left(c_{tri} \frac{3m_h^2}{\hat{s} - m_h^2} + c_{nl} \right) F_\triangle + c_{box} F_\square \right|^2 + |c_{box} G_\square|^2 \right]$$

$$c_{box}^{(\mathrm{SM})} = 1 \,, \qquad c_{tri}^{(\mathrm{SM})} = 1 \,, \qquad c_{nl}^{(\mathrm{SM})} = 0$$

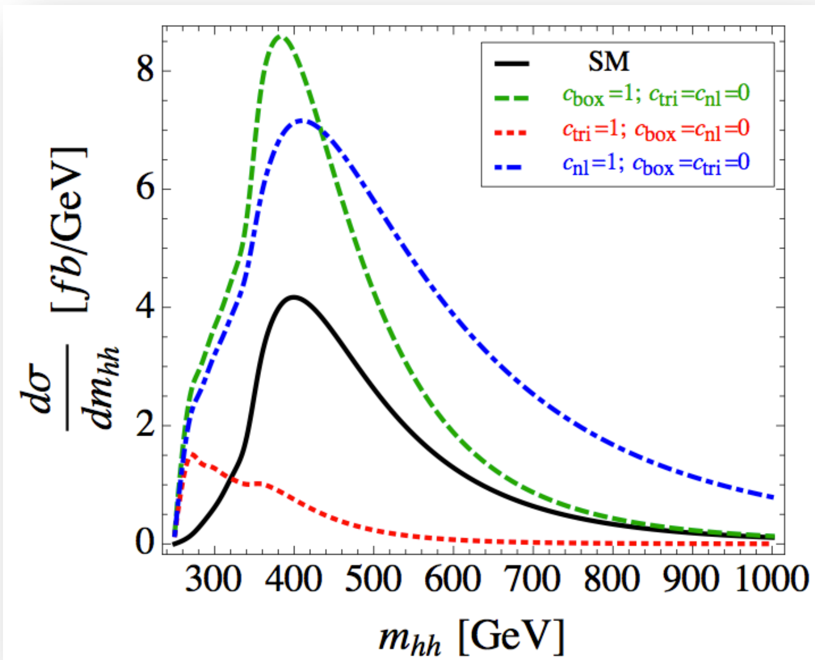
Higgs self-couplings

If one looks at the total rate only, there's going to be degeneracy in extracting the self-coupling:

$$\sigma(gg \to hh) = \sigma^{SM}(gg \to hh)[1.849\ c_{box}^2 + 0.201\ c_{tri}^2 + 2.684\ c_{nl}^2 - 1.050\ c_{box}c_{tri} - 3.974\ c_{box}c_{nl} + 1.215\ c_{tri}c_{nl}].$$

We can look at distributions to break the degeneracy.

The challenge -- a small c_{nl} could easily overshadow effects from the Higgs self-coupling:



C.-R. Chen and IL:1405.1040

An example of the comparison between HL-LHC and FCC-hh:

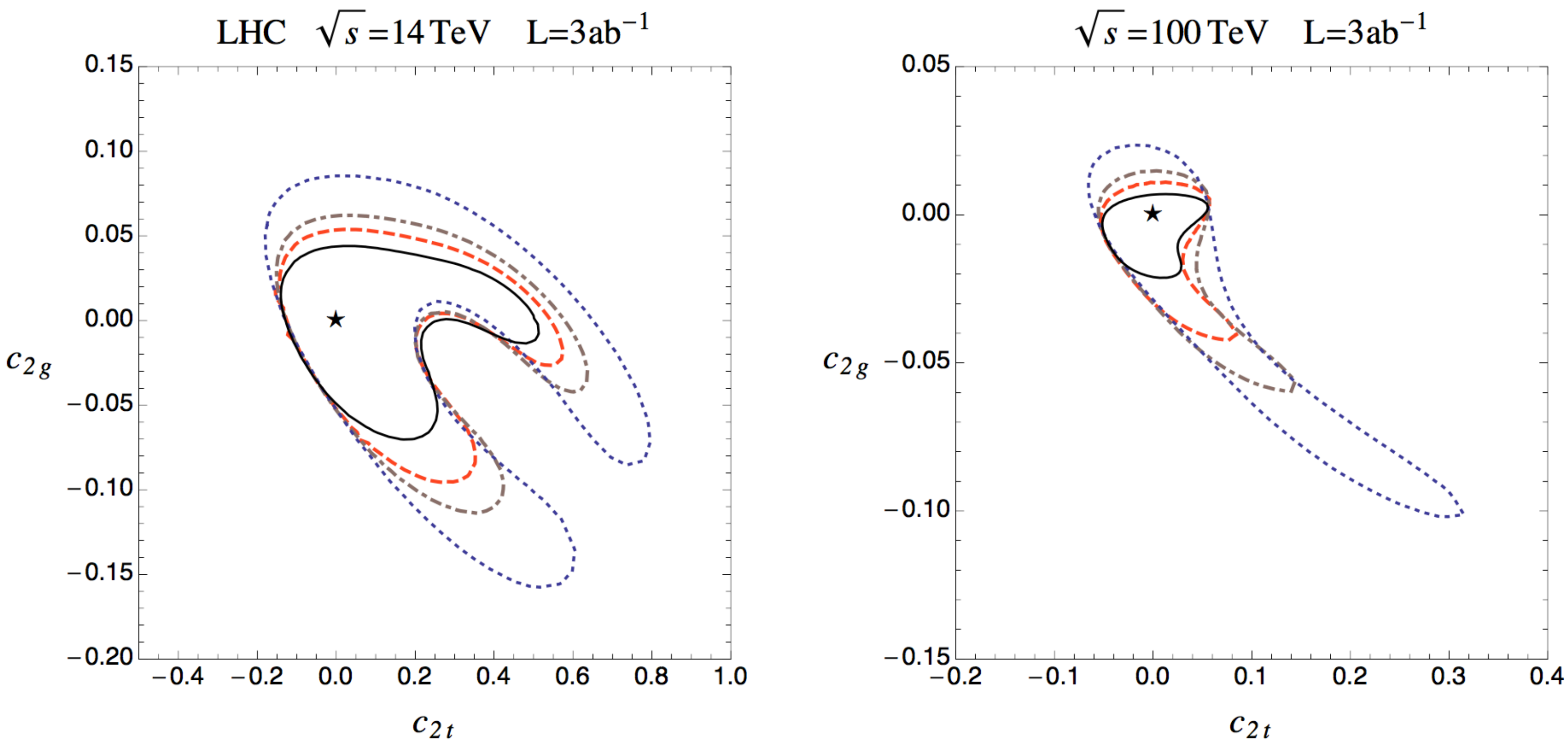


FIG. 16: 68% probability contours in the plane (c_{2t}, c_{2g}) for the HL-LHC (left plot) and the FCC_{100} (right plot). The different curves have been obtained by removing the following m_{hh} categories of Tables V and VII from the fit: 6 (dashed red line); 6 and 5 (dot-dashed brown line); 6, 5 and 4 (dot blue line). The continuous black contour is obtained by including all the categories in the fit.

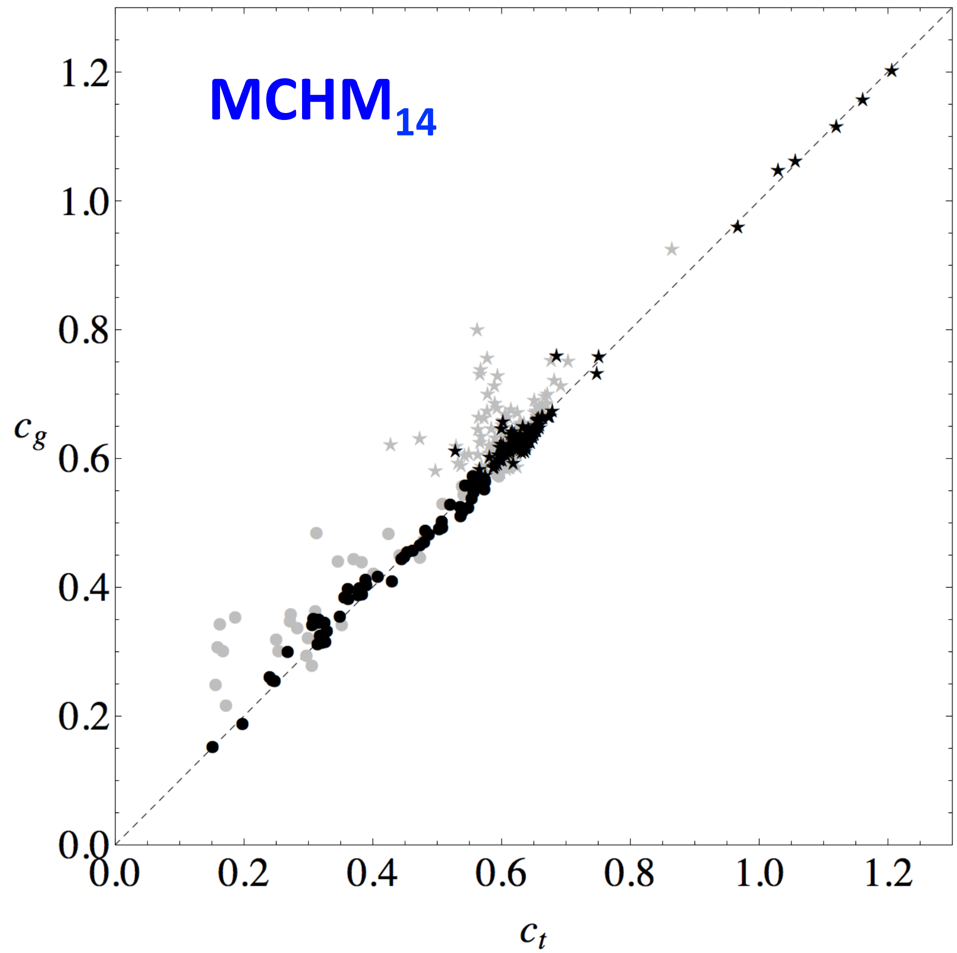
Aztov, Contino, Panico, Son: 1502.00539

For couplings of the 125 GeV Higgs, there are several interesting patterns for composite Higgs models. One example is

Montull, Riva, Salvioni, Torre: 1308.0559

$$c_t \equiv \frac{g_{ttH}}{(g_{ttH})_{\rm SM}}$$

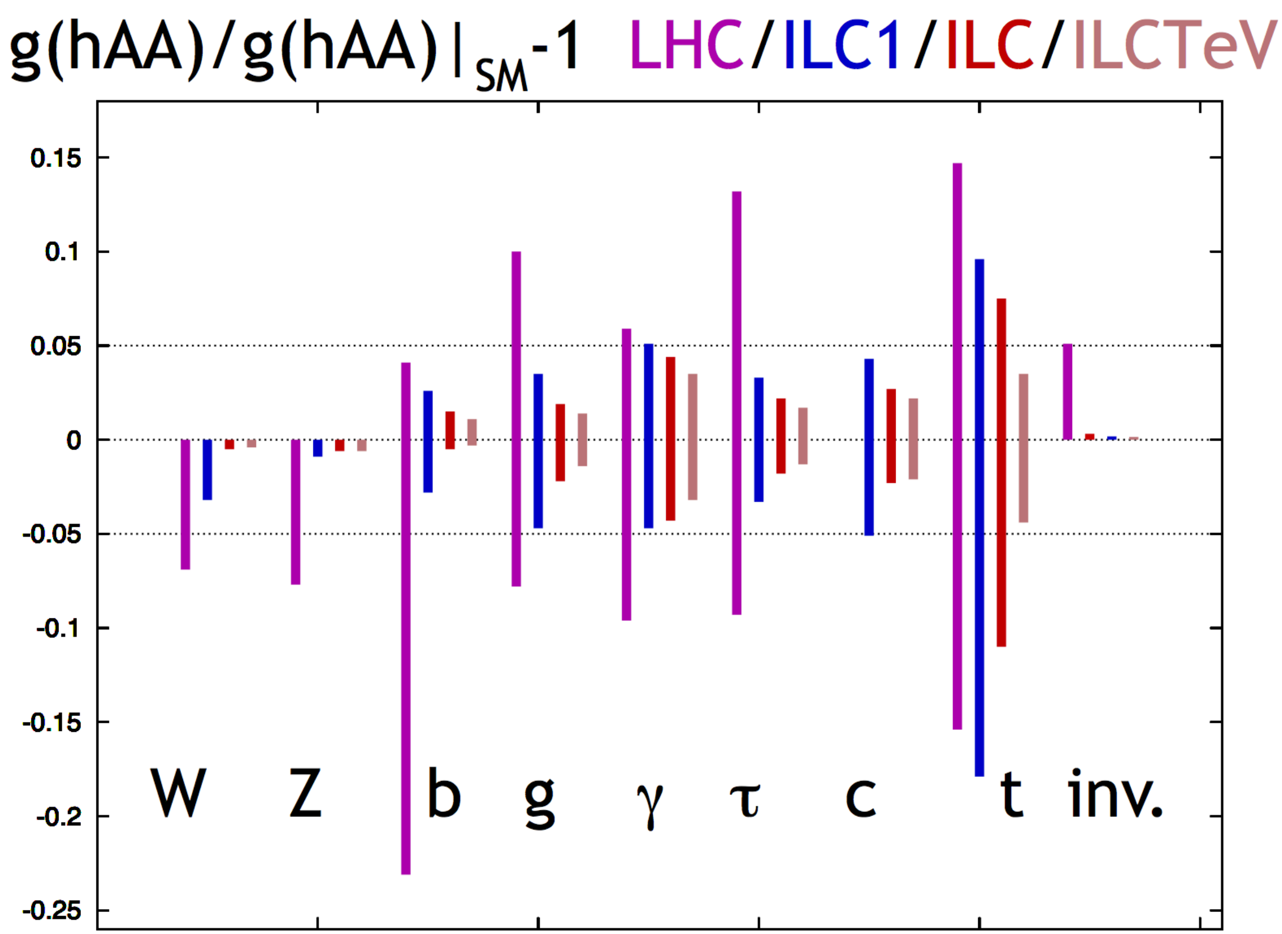
$$c_g \equiv \frac{g_{ggH}}{(g_{ggH})_{\rm SM}}$$



The relation $c_t \sim c_g$ seems to be generic among Composite Higgs models.

(D. Liu, IL, C. Wagner: to appear)

At ILC this relation can be tested very well:



ILC TDR

So far I have motivated the PNGB Higgs using pions in QCD.

But the story of composite Higgs cannot be as simple as pions, where the pion mass is roughly,

$$m_\pi^2 \sim \frac{1}{16\pi^2}\Lambda_{QCD}^2$$

Applying the same formula to composite Higgs models, m_h ~ 125 GeV, one would conclude that the cut-off of the low-energy effective theory is at

$$\Lambda_{cutoff} \ \sim \ 1 \quad \mathrm{TeV}$$

Such a low cut-off creates tension with precision electroweak measurements and direct searches.

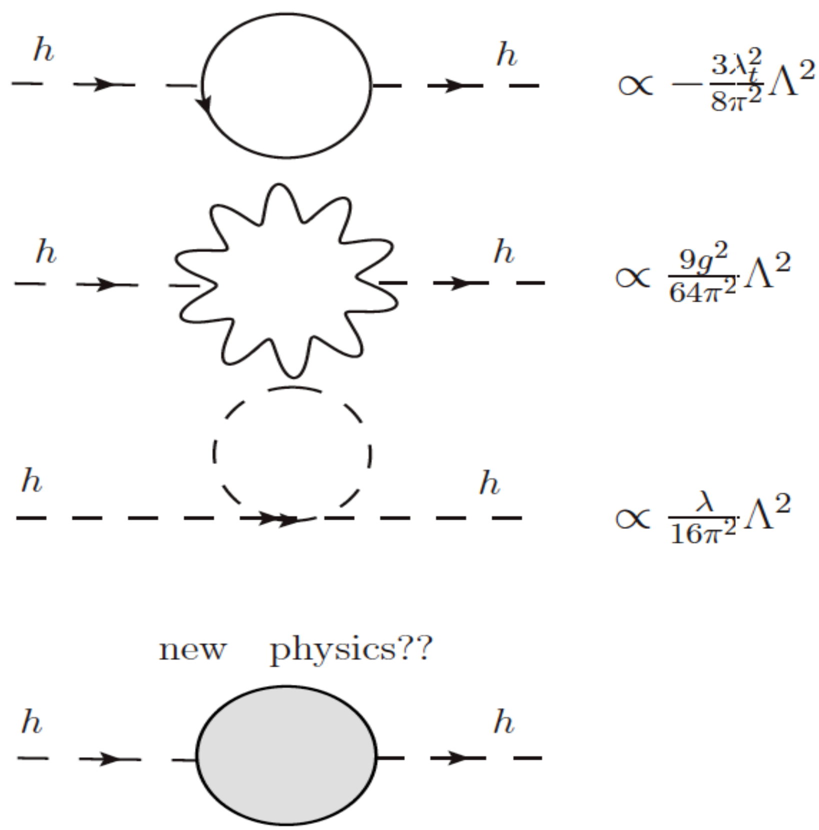
So some other model-building tricks are needed to have a larger separation between m_h and the cut-off scale Λ. Typically one can engineer so that

$$\Lambda_{cutoff} \sim 10 \quad \mathrm{TeV}$$

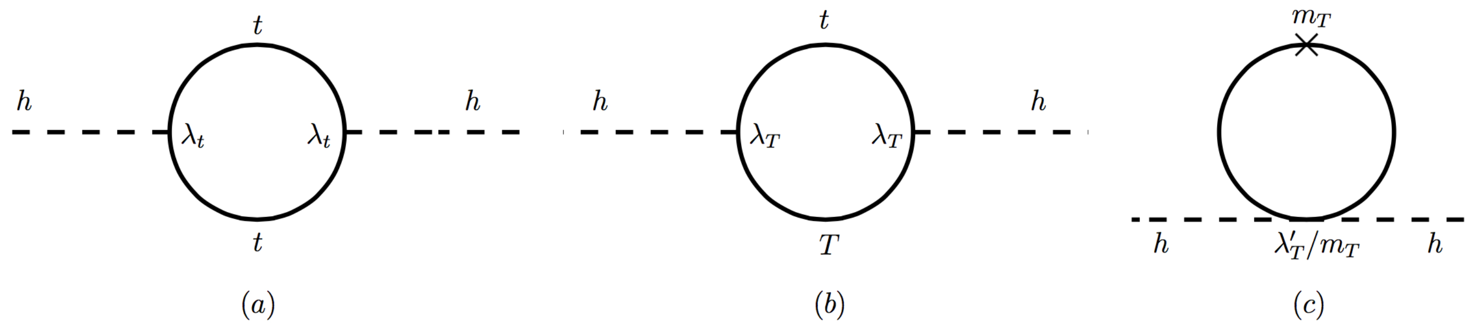
Among these tricks, a universal feature is the introduction of fermionic "top partners" T, whose purpose is to cancel the quadratic sensitivity coming from the SM top quark in the Higgs mass.

In the SM there are three dangerous contributions to the quadratic UV-sensitivity in the Higgs mass at the one-loop level.

"Naturalness principle" expects these to be cancelled by "something" at the TeV scale:

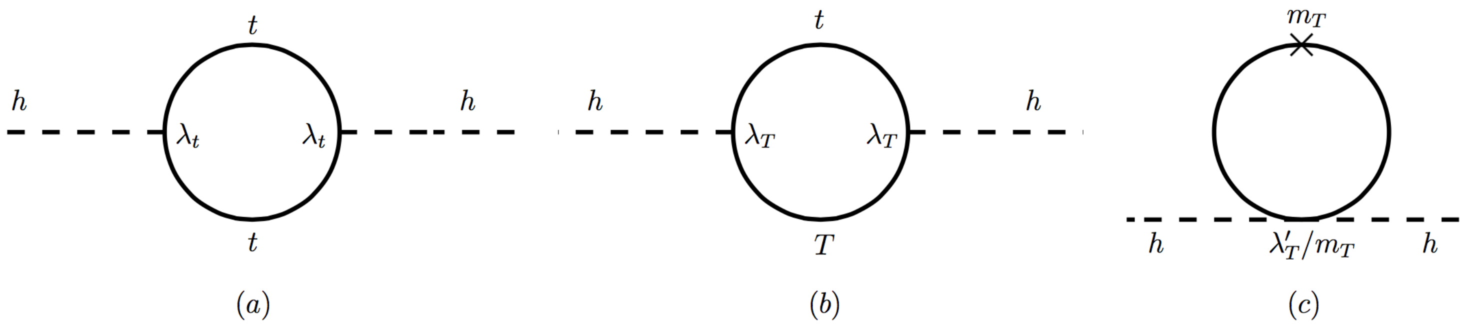


Cancellation of quadratic divergences in the top sector by introducing a fermionic top partner T:



The Naturalness condition: $\lambda'_T = \lambda_t^2 + \lambda_T^2$

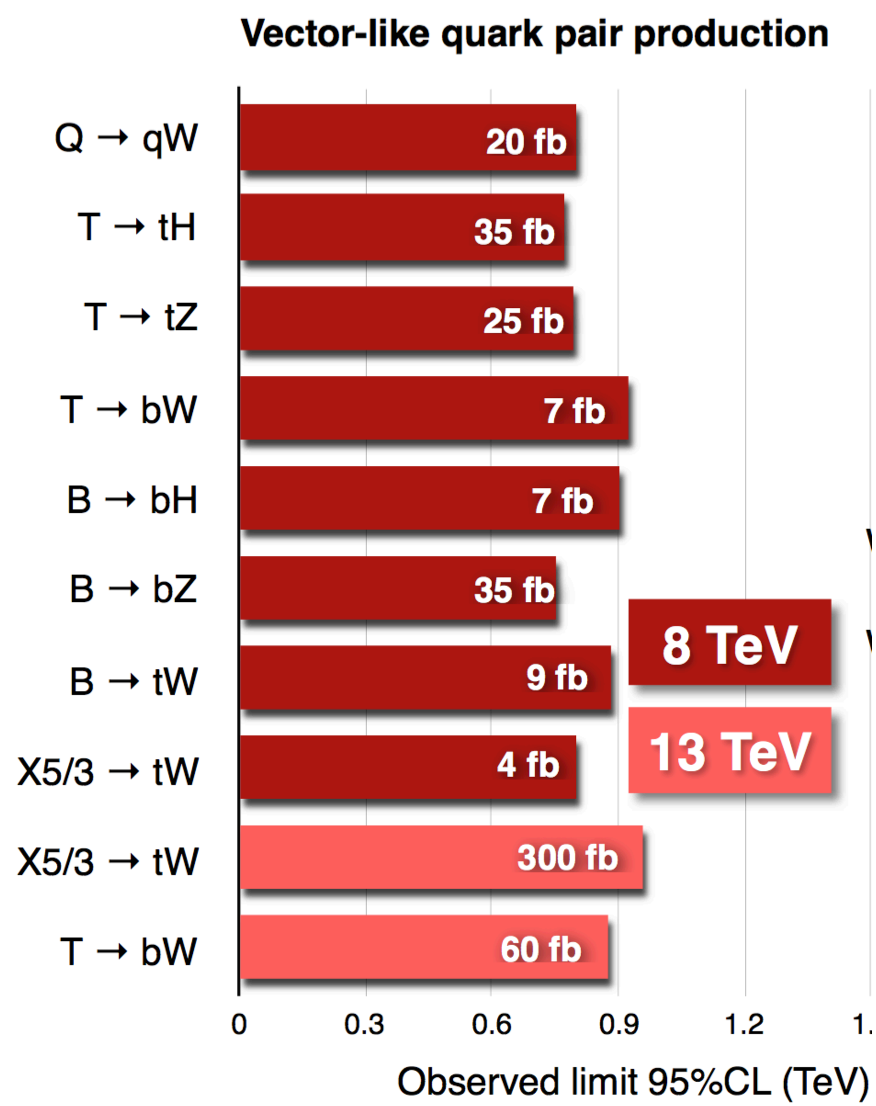
Cancellation of quadratic divergences in the top sector by introducing a fermionic top partner T:



The Naturalness condition: $\lambda'_T = \lambda_t^2 + \lambda_T^2$

- λ_T could vanish if there is a "parity" in the top sector.
  (H.-C.Cheng, IL, L.-T. Wang: hep-ph/0510225.)
- The top partner doesn't have to carry QCD color.
  (Chacko, Goh, Harnik: hep-ph/0506256.)
- The Naturalness condition need to be guaranteed by some symmetry
  → This is the (broken) symmetry group G for the PNGB Higgs.

Colored top partners have been searched for extensively at the LHC:



CMS B2G Summary

Projections at 100 TeV:

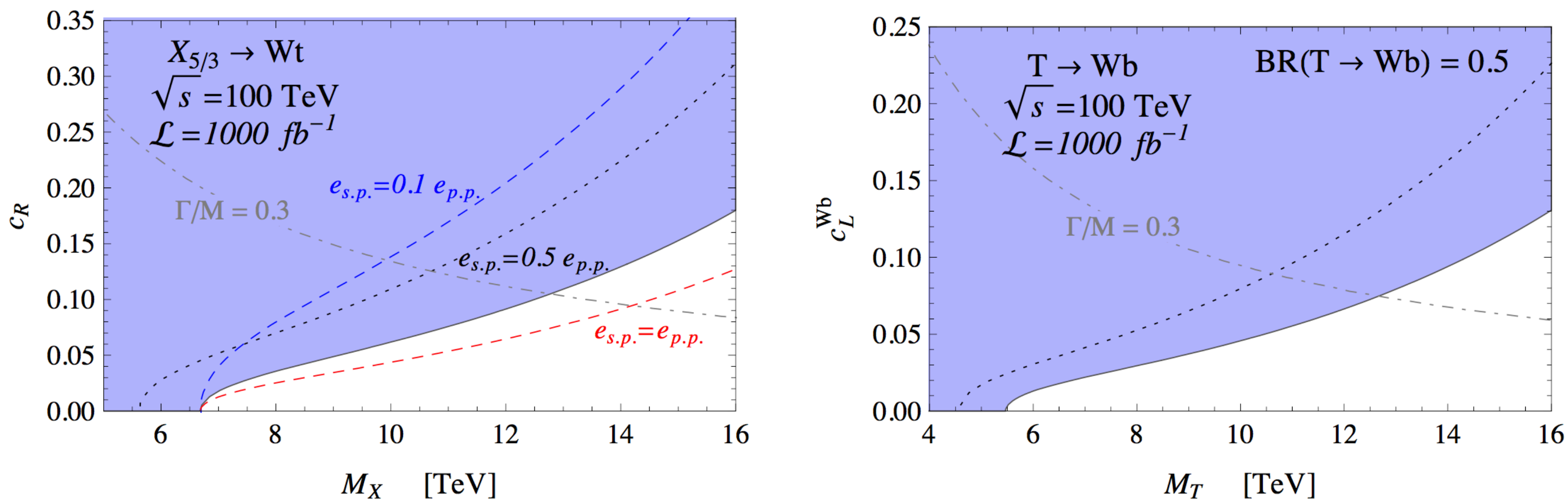
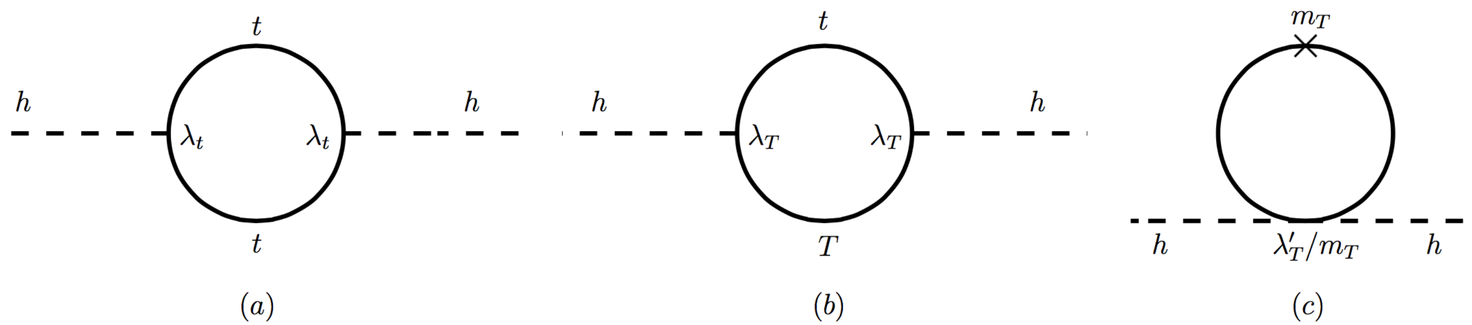


Figure 12: Estimated exclusion bounds on the mass of a charge-5/3 state decaying exclusively to Wt (left panel) and of a charge-2/3 state decaying into Wb with 50% branching ratio. To obtain the excluded regions we assumed $\sqrt{s} = 100$ TeV collider energy and $L = 1000$ fb^{-1} integrated luminosity. For the $X_{5/3}$ exclusions (left panel) the solid and dashed curves are obtained by assuming $S_{exc} = 10$ for different values of the single production efficiency $e_{s.p.} = 0.1\, e_{p.p.}$ (blue curve), $e_{s.p.} = 0.5\, e_{p.p.}$ (black curve) and $e_{s.p.} = e_{p.p.}$ (red curve). The dotted black line corresponds to $S_{exc} = 30$ and $e_{s.p.} = 0.5\, e_{p.p.}$. For the charge-2/3 resonance exclusion (right panel) we assumed the same efficiency for single and pair production ($e_{p.p.} = e_{s.p.} = 0.012$) and $S_{exc} = 25$ (solid curve) and $S_{exc} = 75$ (dashed curve). In both plots the dash-dotted gray line shows the contour with $\Gamma/M = 0.3$.

Matsedonskyi, Panico, Wulzer: 1409.0100

However, I wish to emphasize that discovering the “top partner” is only HALF of the job…

To be sure of the underlying mechanism of “Naturalness”, we need to test the Naturalness relation:



$$\lambda'_T = \lambda_t^2 + \lambda_T^2$$

Naively we need to measure three processes to directly measure three couplings:

$$pp \to ttH \ , \quad pp \to tTH \ , \quad pp \to TTHH$$

At leading order in v^2/M_T^2 and after rotating to mass eigenstates, the Naturalness relation is encoded in only two processes:

$$pp \to ttH \ , \qquad pp \to TTH$$

Even at 100 TeV, the production cross-section is not so large:

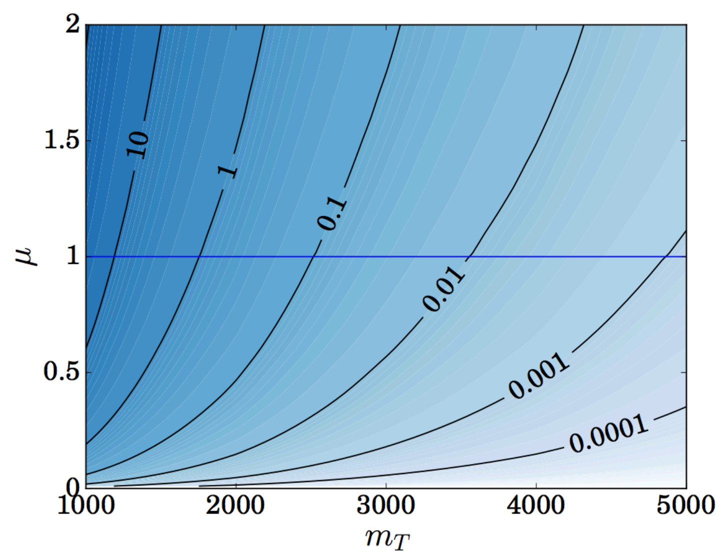
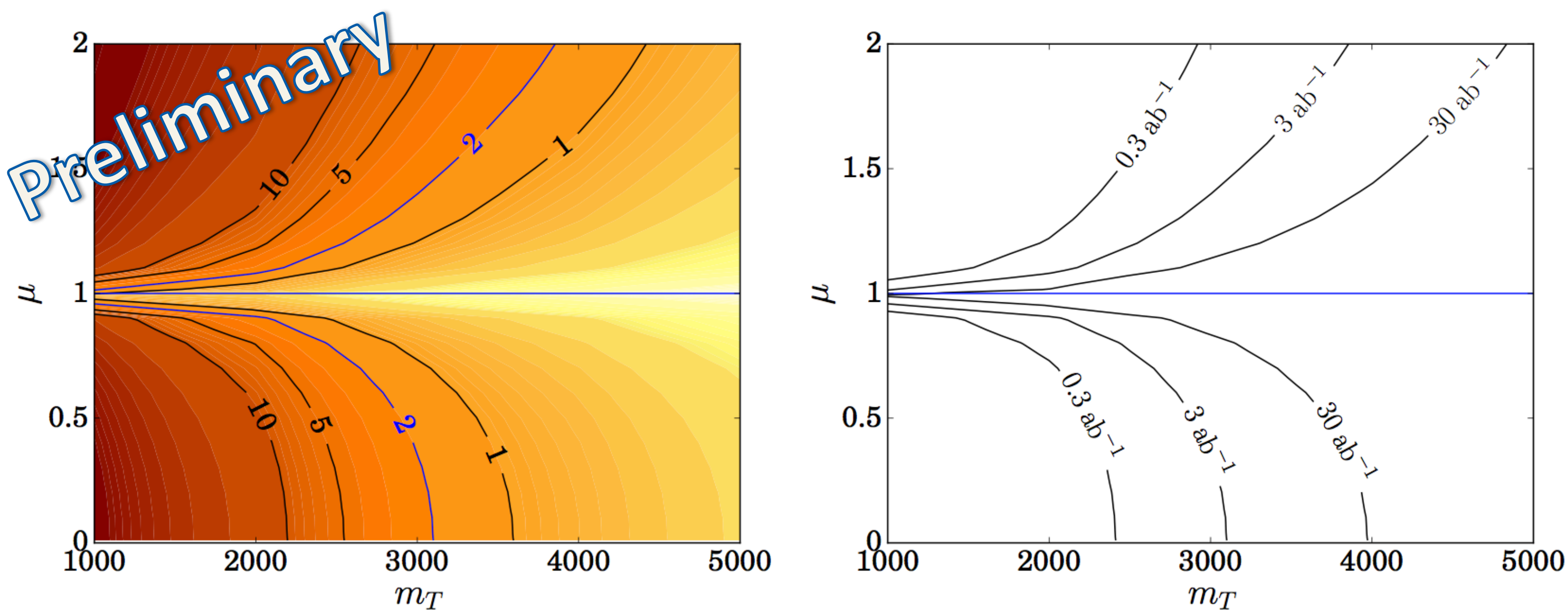


Figure 1: Cross section of the signal process $\overline{T}Th$ at 100 TeV in fb as a function of the top partner mass m_T and the naturalness parameter μ. The horizontal line at $\mu = 1$ indicates natural models.

C.-R. Chen, J. Hajer, T. Liu, IL and H. Zhang: to appear

Given the small rates, we need luminosity even at 100 TeV!



(a) Luminosity of $3\,\mathrm{ab}^{-1}$.

(b) Significance of 2.

Figure 5: Exclusion limit for unnatural theories defined by $Z(b+s|b+s|_{\mathrm{nat}})$ as a function of the top partner mass. Based on $\overline{T}Th$ production at 100 TeV. For a luminosity of $3\,\mathrm{ab}^{-1}$ in Figure (a) and for 0.3, 3, $30\,\mathrm{ab}^{-1}$ and a fixed significance of $Z=2$ in Figure (b).

Question: Is 100 TeV enough?

Slide from Gao Jie on Monday

SPPC Parameter Choice and Optimize

CEPC and SppC CDR Circumference will be 100km

Feng SU

Table 1: SPPC Parameter List.

	SPPC(Pre-CDR)	SPPC-59.2Km	SPPC-100Km	SPPC-100Km	SPPC-80Km
Main parameters and geometrical aspects					
Beam energy[E_0]/TeV	35.6	35.0	50.0	65.0	50.0
Circumference[C_0]/km	54.7	59.2	100.0	100.0	80.0
Dipole field[B]/T	20	19.70	15.52	19.83	19.74
Dipole curvature radius[ρ]/m	5928	5921.5	10924.4	10924.4	8441.6
Bunch filling factor[f_2]	0.8	0.8	0.8	0.8	0.8
Arc filling factor[f_1]	0.79	0.78	0.78	0.78	0.78
Total dipole length [L_{Dipole}]/m	37246	37206	68640	68640	53040
Arc length[L_{ARC}]/m	47146	47700	88000	88000	68000
Straight section length[L_{ss}]/m	7554	11500	12000	12000	12000
Physics performance and beam parameters					
Peak luminosity per IP[L]/ $cm^{-2}s^{-1}$	1.1×10^{35}	1.20×10^{35}	1.52×10^{35}	1.02×10^{36}	1.52×10^{35}

For such an important question on Naturalness, is it possible to have a definitive answer at the next pp collider?

Summary (the conclusion is yet to be written…)

- The Higgs is a brand new type of particles that we had not observed previously!
- Whenever we observed a new type of matter/state, it's our job to study the heck out of it.

  The first fermion was discovered by J. J. Thompson in 1897.

  To this date we are still doing "precision measurements" on the electron!

- There is a rich program in pursuing questions raised by the discovery of the Higgs boson.

  We need both the precision and the energy reach!