Recent topics on
Electroweak Symmetry Breaking

(Alternatives to the MSSM)

Alex Pomarol (Univ. Autonoma Barcelona)

In most people's mind:

- Are there really serious alternatives to the MSSM?
- The MSSM is the perfect candidate for physics beyond the SM

It has become the orthodoxy

Relies on the existence of
a fundamental Higgs + symmetry to keep it stable

My role here: Devil's Advocate

Defend the Alternatives:

1) No Higgs (such as Technicolor = a copy of QCD at the TeV)

2) Composite Higgs (Pseudo-Goldstone Higgs = similar to Kaons in QCD)

The MSSM gained its present status after LEP I ,

where it left behind its main competitors (e.g. technicolor)

SUSY 98: TC was stabbed twice (from Electroweak precision tests)

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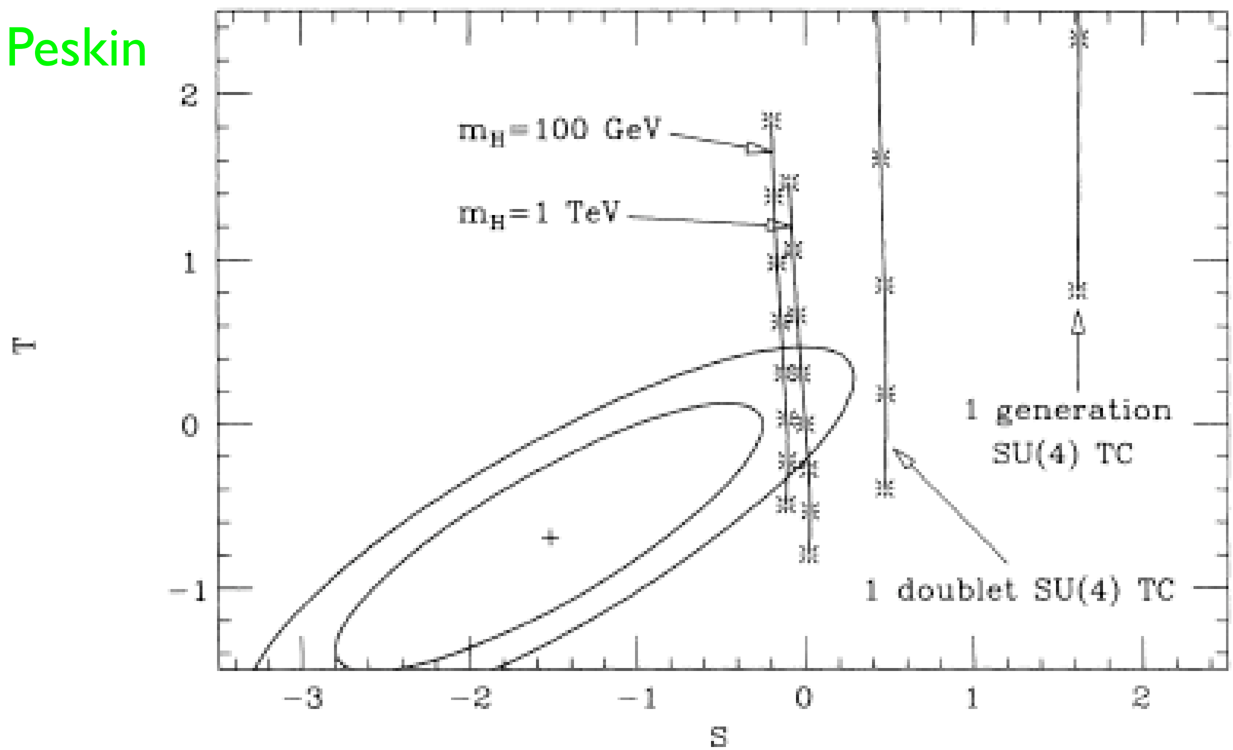
Peskin



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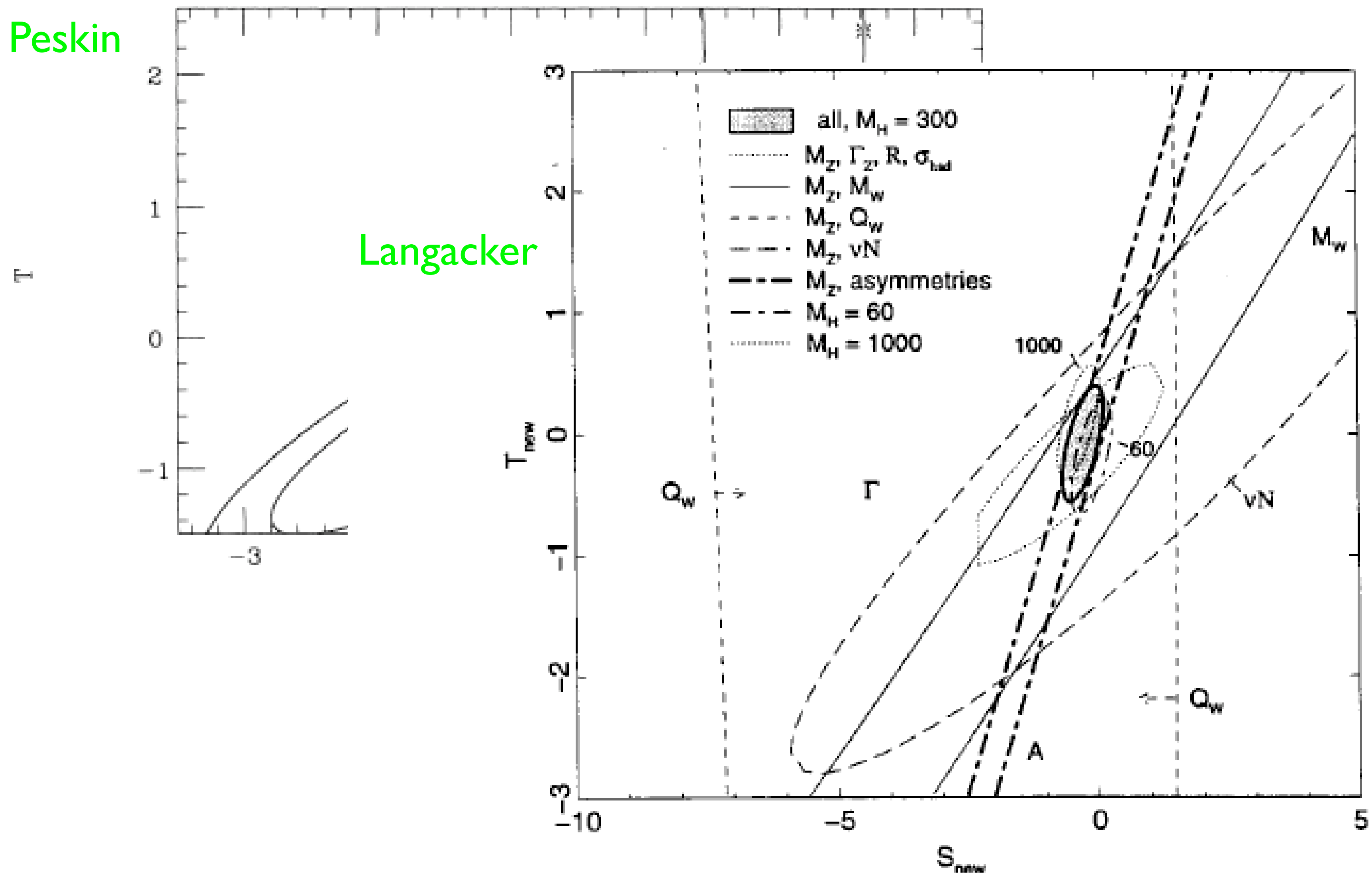

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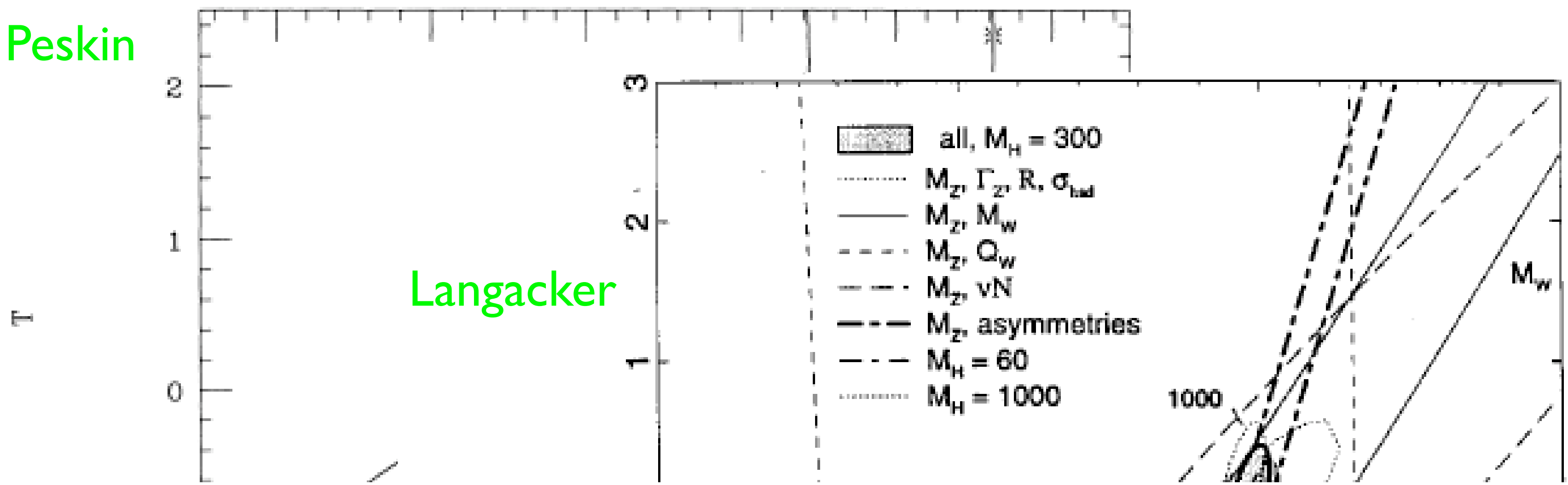

Veneziano summary talk:

To conclude, the score on precision tests puts the SSM first, with the SM itself (with a light Higgs and some additional intermediate scale) a close second. Technicolour theories appear to lag far behind and... there is not much else in the race. I would conclude that, if

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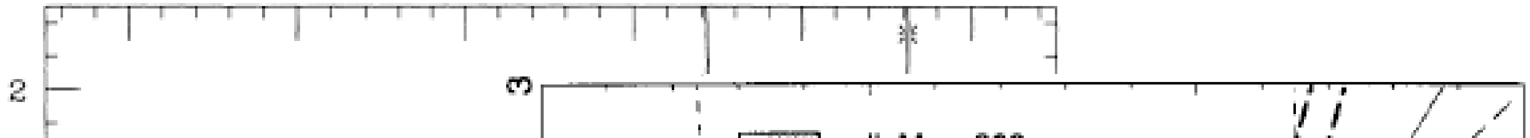

Venezi

To c ... elf (with

a light Hi ... theories

appear to ... e that, if

But after LEP I , it came LEP II and Tevatron...

In the MSSM the Higgs or the sparticles were expected to be seen! **(nothing expected from the alternatives)**

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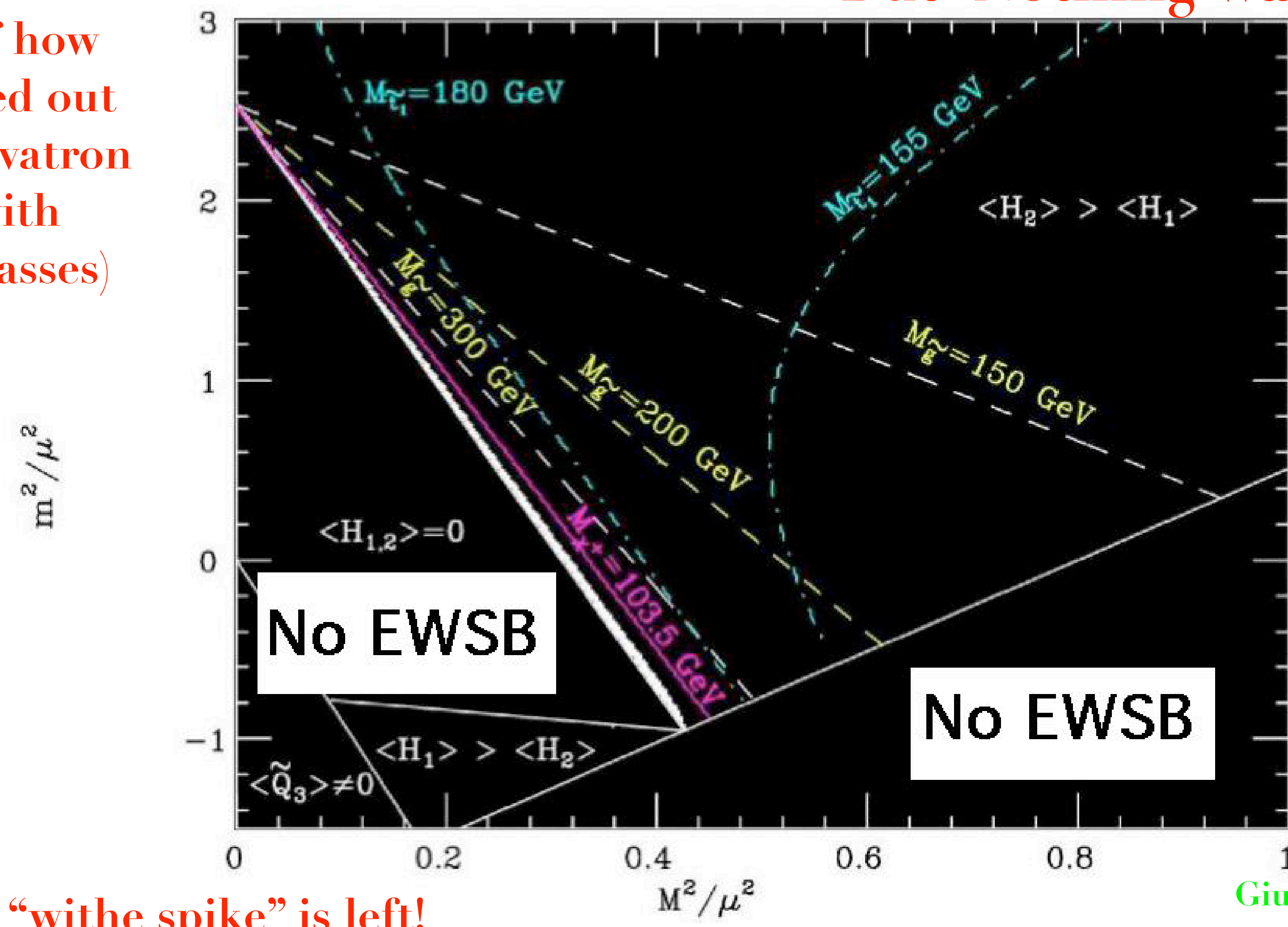
But Nothing was seen!

But after LEP I , it came LEP II and Tevatron...

In the MSSM the Higgs or the sparticles were expected to be seen! (nothing expected from the alternatives)

But Nothing was seen!

Example of how much is ruled out after LEP/Tevatron (MSSM with universal masses)



Only the thin "withe spike" is left!

Giudice, Rattazzi

It is however clear that susy has the bonus of being a predictable theory... not the case for TC $\approx$ QCD

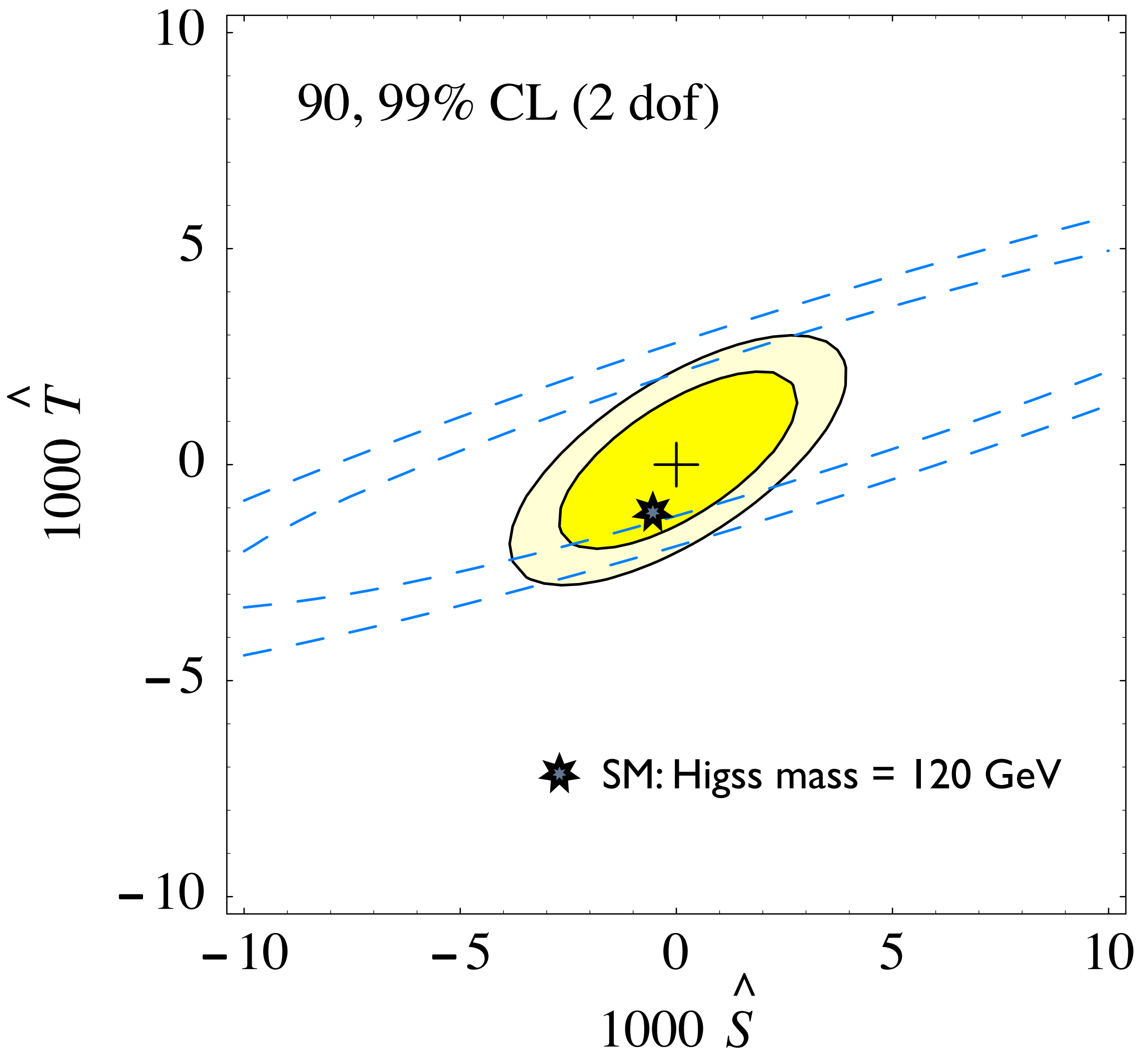
Recent progress: explicit weakly-coupled examples

- Extra dimensional Higgsless models — Csaki,Grojena,Pilo,Terning
- Little Higgs — Arkani-Hamed, Cohen, Katz, Nelson
- Holographic Higgs: Extra dimensional Composite Higgs models — Agashe, Contino, AP

Predictive models!

Still their main obstacle is the S-T ellipse

To any alternative model, one must ask "Where it is in the ellipse?"



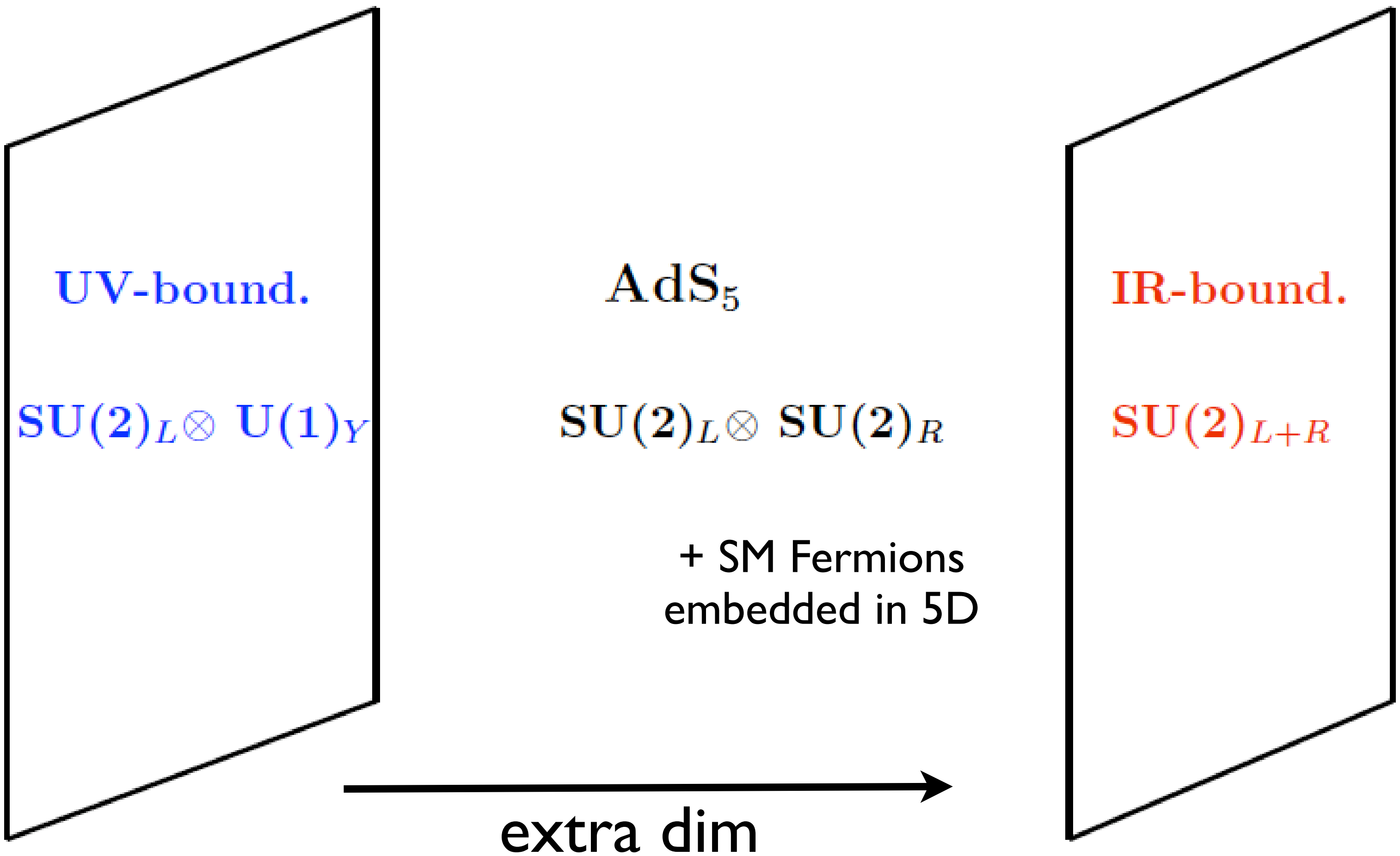
(Zbb can be sometimes also relevant)

$$\hat{S} = g^2\, \Pi'_{W_3 B}(0)$$

$$\hat{T} = \frac{g^2}{M_W^2}\, [\Pi_{W_3}(0) - \Pi_{W^+}(0)]$$

Barbieri, AP, Rattazzi, Strumia

Minimal 5D Higgsless theory



Csaki,Grojena,Pilo,Terning

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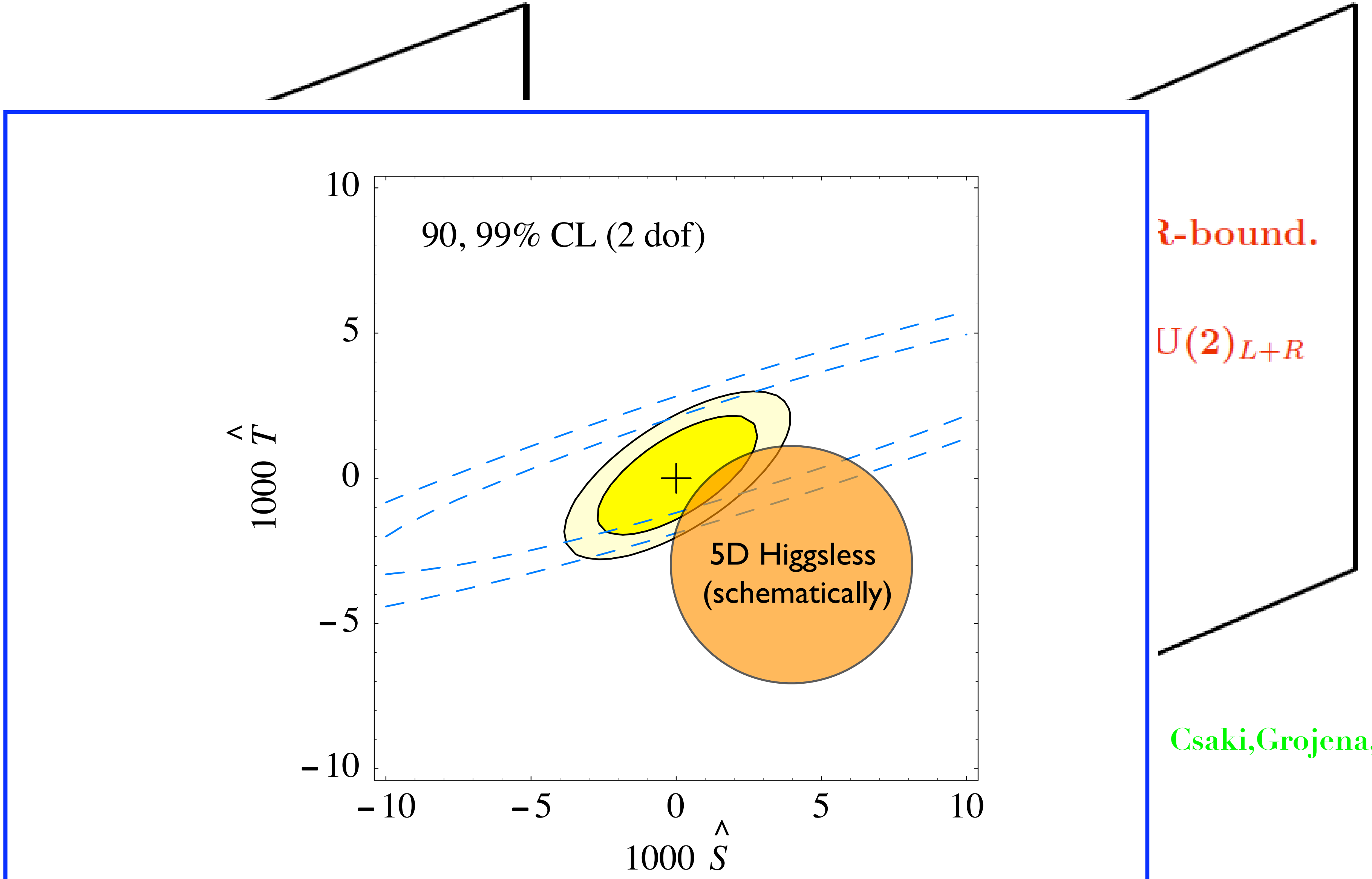


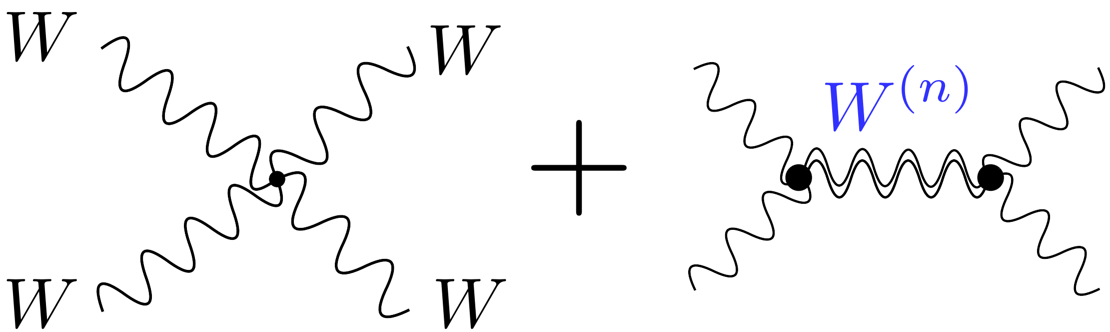
Ɽ-bound.

$U(2)_{L+R}$

Csaki,Grojena,Pilo,Terning

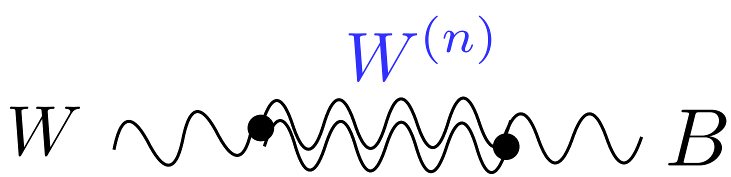
Reason for generic large effects on S:

In 5D WW-scattering unitarized by KK-resonances:



$\longrightarrow \quad m_{W^{(1)}} < 1\ TeV$

This KK-states modify the gauge boson propagators:

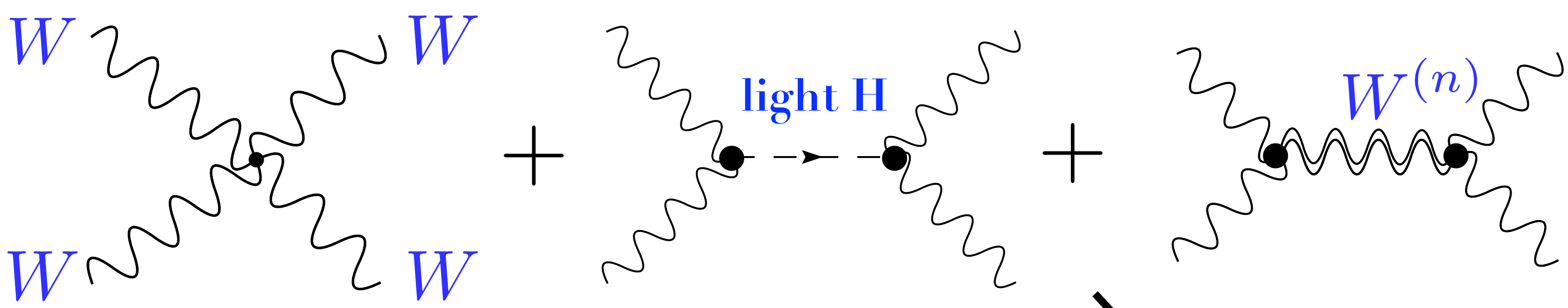


Similar situation to Technicolor theories!

$W^{(n)}$ = **techni-rho**

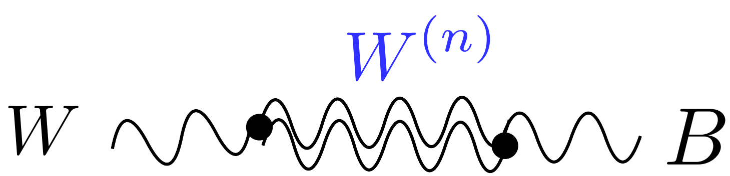
Better situation for the second alternative: composite PGB Higgs:

WW-scattering unitarized by a Higgs + KK-resonances:

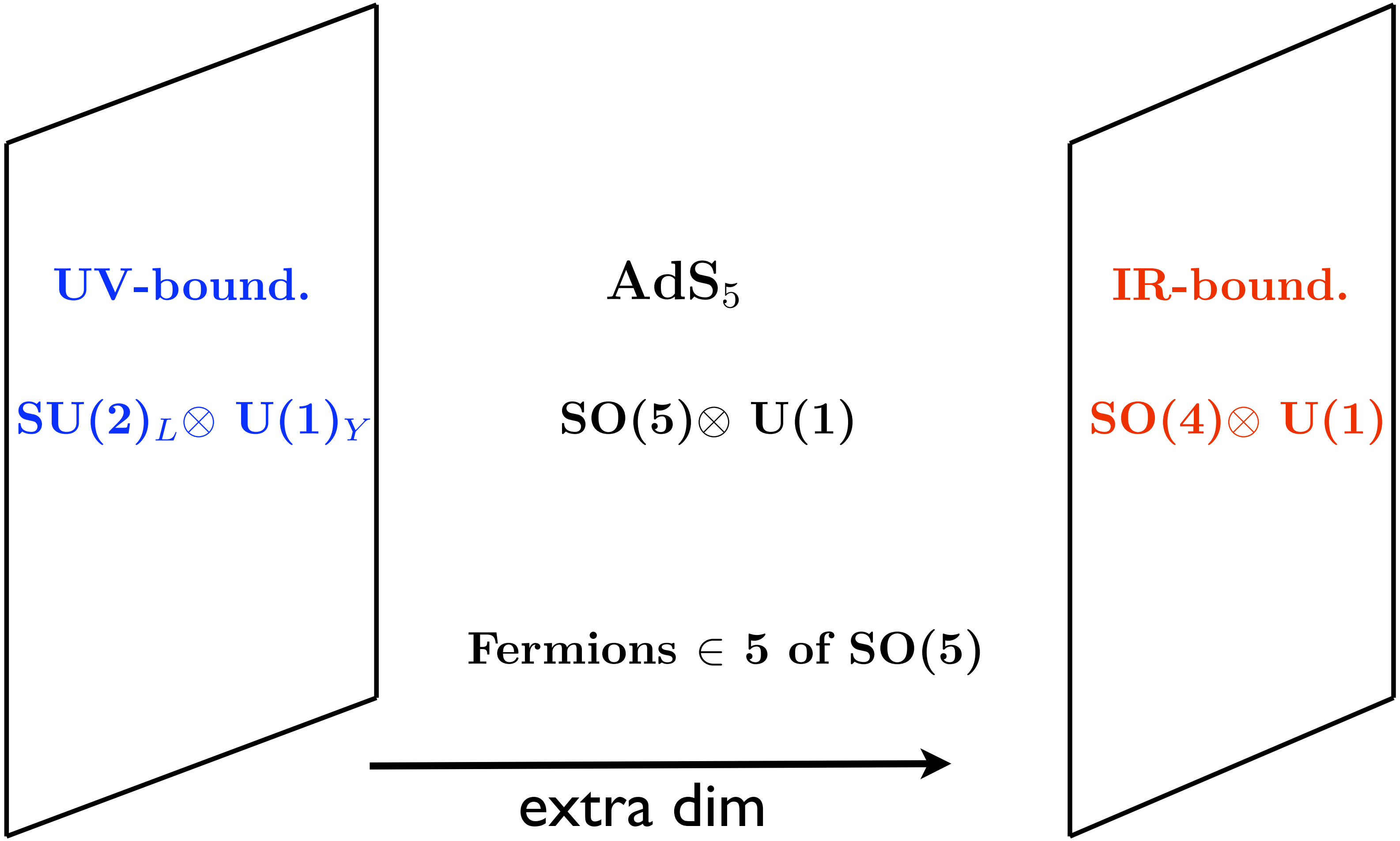


$$m_{W^{(1)}} < 3\ TeV$$

To avoid LEP constrains: → $m_{W^{(1)}} > 2.4\ TeV$



Minimal model of a 5D composite Higgs



Agashe,Contino,A.P.

Why this symmetry breaking pattern?

We are in 5D: $\mathbf{A_M} = (\mathbf{A}_\mu, \mathbf{A_5})$

Massless boson spectrum:

- $\mathbf{A}_\mu$ **of** $\mathbf{SU(2)}_L \otimes \mathbf{U(1)}_Y$ = **SM Gauge bosons**
- $\mathbf{A_5}$ **of SO(5)/SO(4) = 2 of** $\mathbf{SU(2)}_L$ = **SM Higgs**

$\hookrightarrow$ **Higgs-gauge unification**

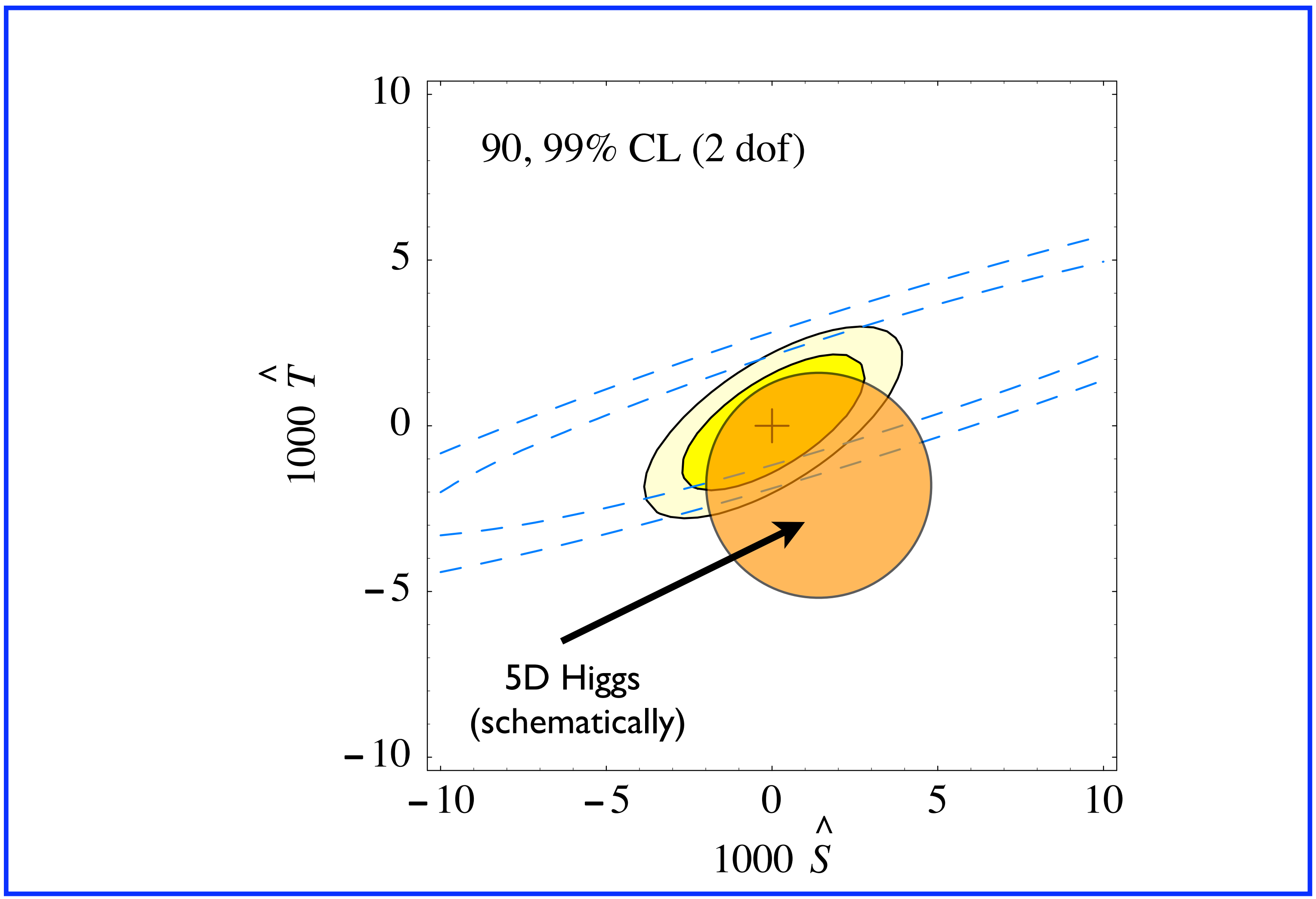
Hosotani mechanism

Higgs mass protected by 5D gauge invariance!

$$A_5 \to A_5 + \partial_5 \theta$$

→ shifts as a PGB

Minimal model of a 5D composite Higgs



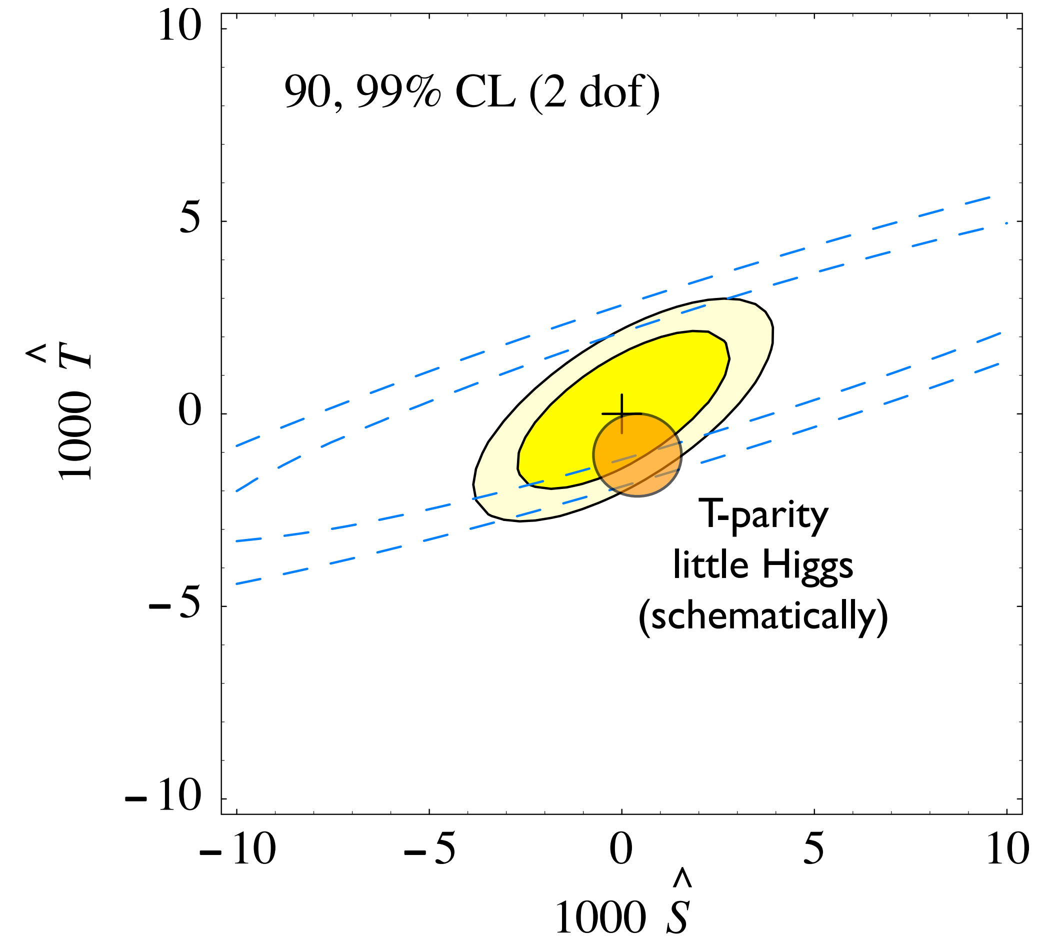
R-bound.

)(4)⊗ U(1)

Agashe,Contino,A.P.

Little Higgs with T-parity

(as in susy virtual effects at one-loop)



Keeping the analogy of Veneziano,
the race now looks more like this...

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As in susy, I consider worthy to look for these alternatives at the LHC

What to expect at the LHC and, maybe, ILC?

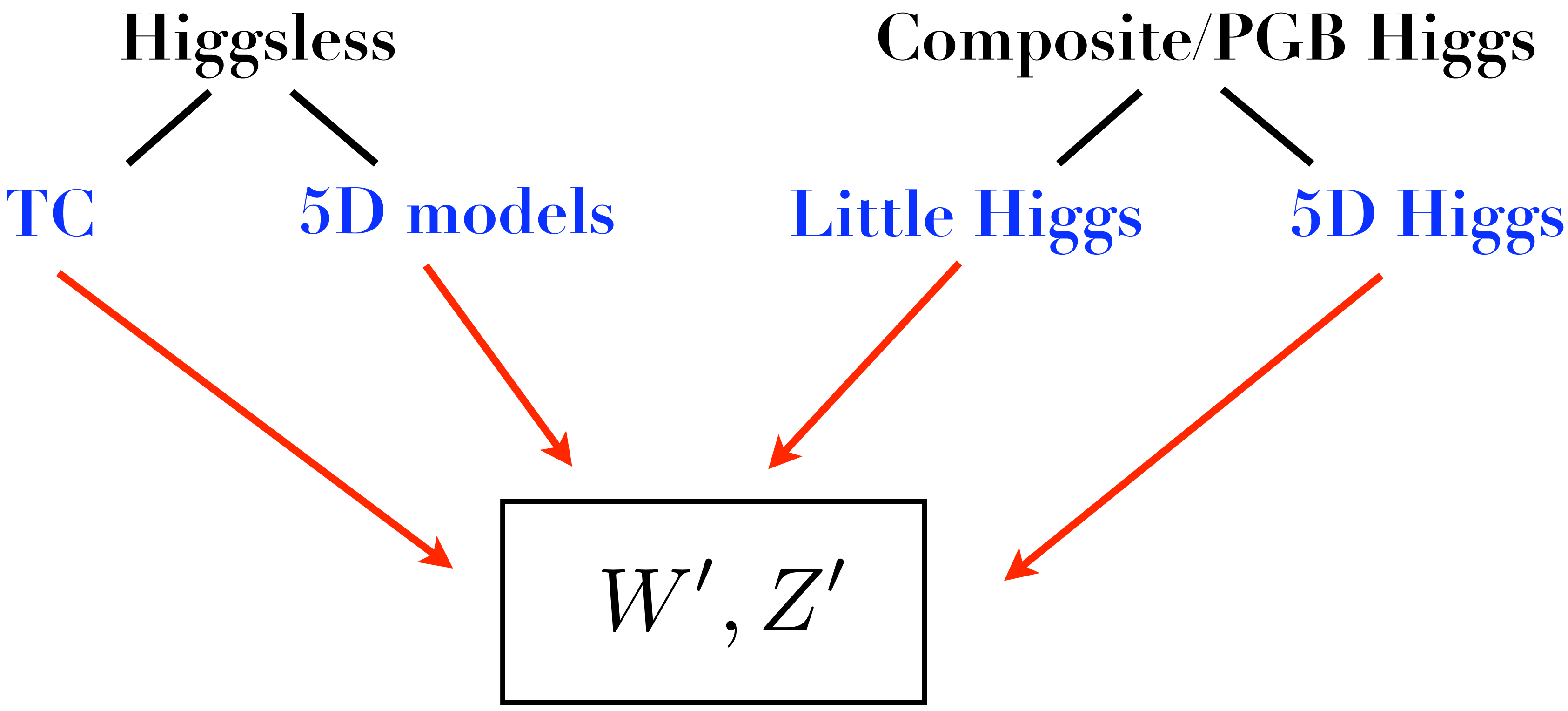
1) Extra resonances around TeV with SM quantum numbers: W', Z', t', b', ...

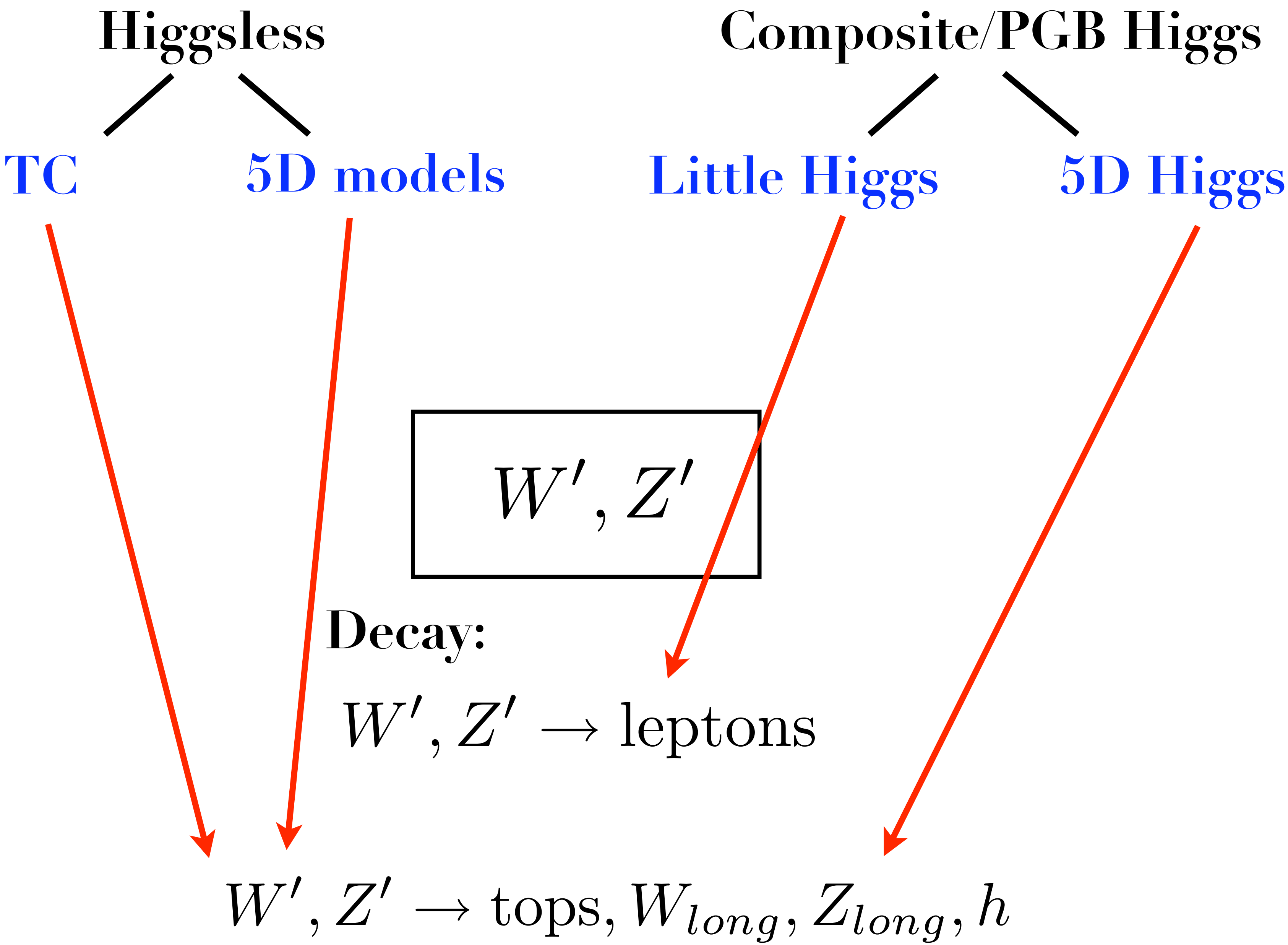
2) Non-elementary Higgs: Its couplings will differ from the SM Higgs

1) Direct searches:

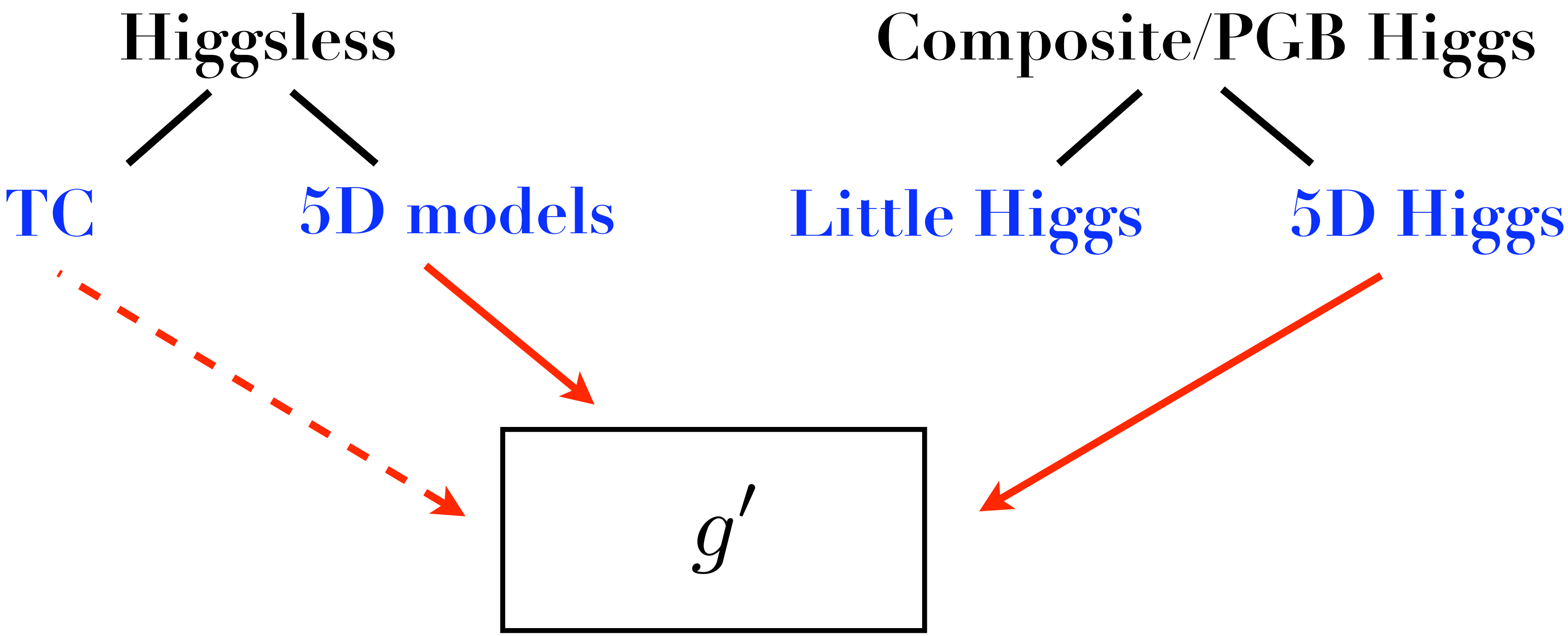
New resonances

- Higgsless
  - TC
  - 5D models
- Composite/PGB Higgs
  - Little Higgs
  - 5D Higgs

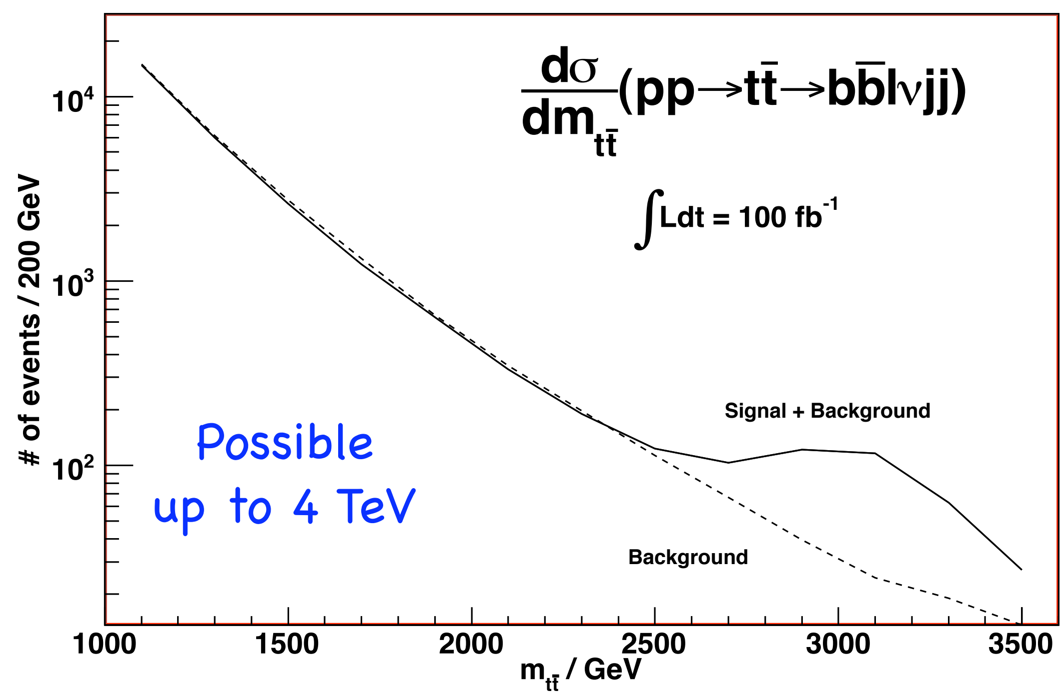

Higgsless
Composite/PGB Higgs
TC
5D models
Little Higgs
5D Higgs
W', Z'



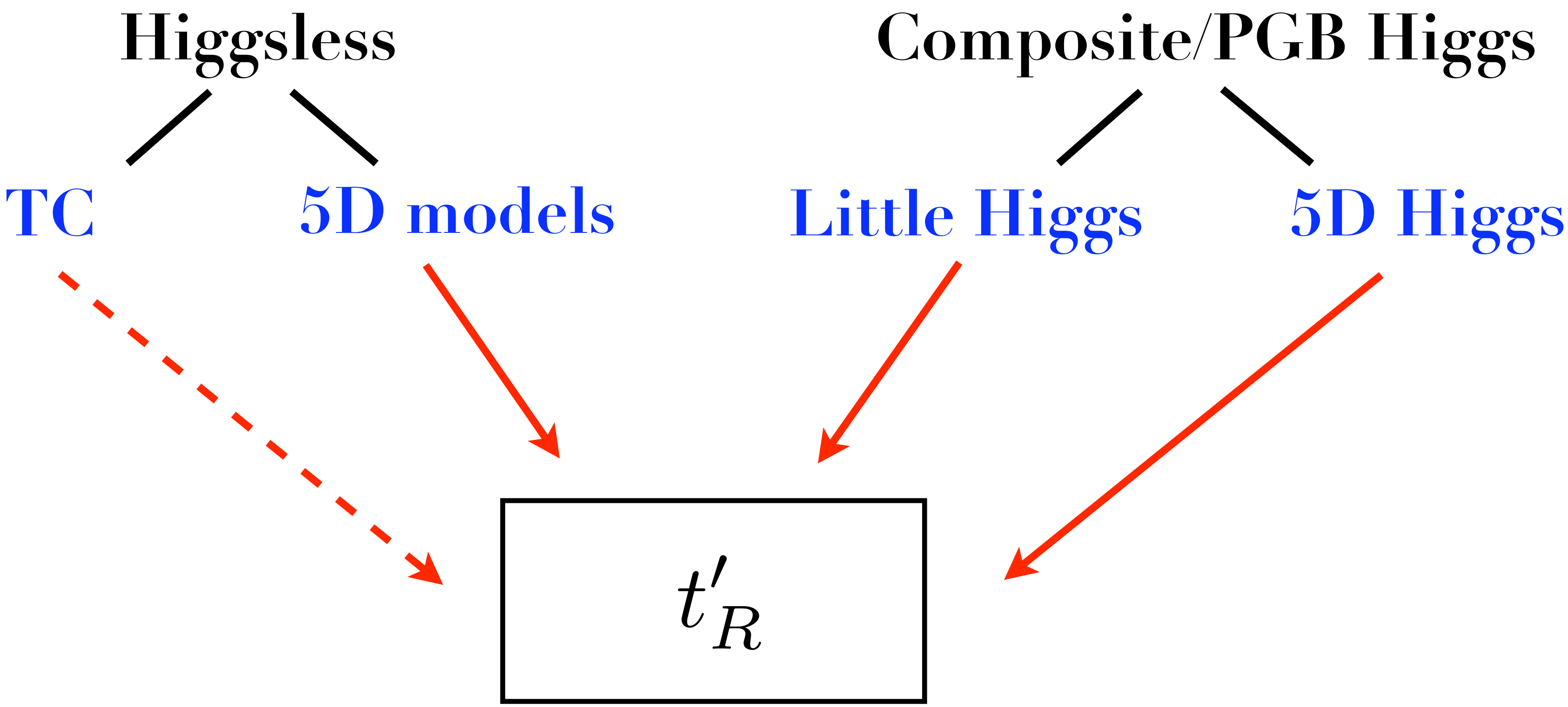
Possible to see up to 2-3 TeV



Decay: $g' \to t\bar{t}$



Agashe et al



Decay: $t'_R \rightarrow W_{long} b$

feasible to see up to 1-2 TeV

2) Indirect searches:

Modifications of the Higgs properties

(...in the case it is there)

Giudice,Grojean,A.P.,Rattazzi

Model independent approach:

Find the effective theory after integrating out the heavy states:

$$\mathcal{L}_{\rm SM+H} \quad + \quad \text{higher dimensional operators}$$

(the equivalent of the pion chiral lagrangian in QCD)

Giudice,Grojean,A.P.,Rattazzi

Model independent approach:

Find the effective theory after integrating out the heavy states:

$$\mathcal{L}_{\rm SM+H} \quad + \quad \text{higher dimensional operators}$$

what are they?

DIMENSION-6 OPERATORS

Suppressed by f **(the analog of** f_π **in QCD):**

$$\frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)+\frac{c_T}{2f^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)\left(H^\dagger\overleftrightarrow{D}_\mu H\right)$$

$$-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3+\left(\frac{c_y y_f}{f^2}H^\dagger H\bar{f}_L H f_R+\text{h.c.}\right)$$

$c_H\,, c_T\,, c_6\,, c_y$ **: model-dependent coefficients**

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tested at LEP: T-parameter
$c_T=0$ if the BSM sector is custodial invariant

The rest, not tested yet!

c_H, c_T, c_6, c_y : **model-dependent coefficients**

Measuring the compositeness of the Higgs:

$$\xi \equiv \frac{v^2}{f^2}$$

Definite modifications of Higgs decay widths:

$$\Gamma\left(h \to f\bar{f}\right)_{\rm SILH} = \Gamma\left(h \to f\bar{f}\right)_{\rm SM}\left[1 - \xi\left(2c_y + c_H\right)\right]$$

$$\Gamma\left(h \to W^+W^-\right)_{\rm SILH} = \Gamma\left(h \to W^+W^{(*)-}\right)_{\rm SM}\left[1 - \xi\left(c_H - \frac{g^2}{g_\rho^2}\hat{c}_W\right)\right]$$

$$\Gamma\left(h \to ZZ\right)_{\rm SILH} = \Gamma\left(h \to ZZ^{(*)}\right)_{\rm SM}\left[1 - \xi\left(c_H - \frac{g^2}{g_\rho^2}\hat{c}_Z\right)\right]$$

$$\Gamma\left(h \to gg\right)_{\rm SILH} = \Gamma\left(h \to gg\right)_{\rm SM}\left[1 - \xi\,{\rm Re}\left(2c_y + c_H + \frac{4y_t^2 c_g}{g_\rho^2 I_g}\right)\right]$$

$$\Gamma\left(h \to \gamma\gamma\right)_{\rm SILH} = \Gamma\left(h \to \gamma\gamma\right)_{\rm SM}\left[1 - \xi\,{\rm Re}\left(\frac{2c_y + c_H}{1 + J_\gamma/I_\gamma} + \frac{c_H - \frac{g^2}{g_\rho^2}\hat{c}_W}{1 + I_\gamma/J_\gamma} + \frac{\frac{4g^2}{g_\rho^2}c_\gamma}{I_\gamma + J_\gamma}\right)\right]$$

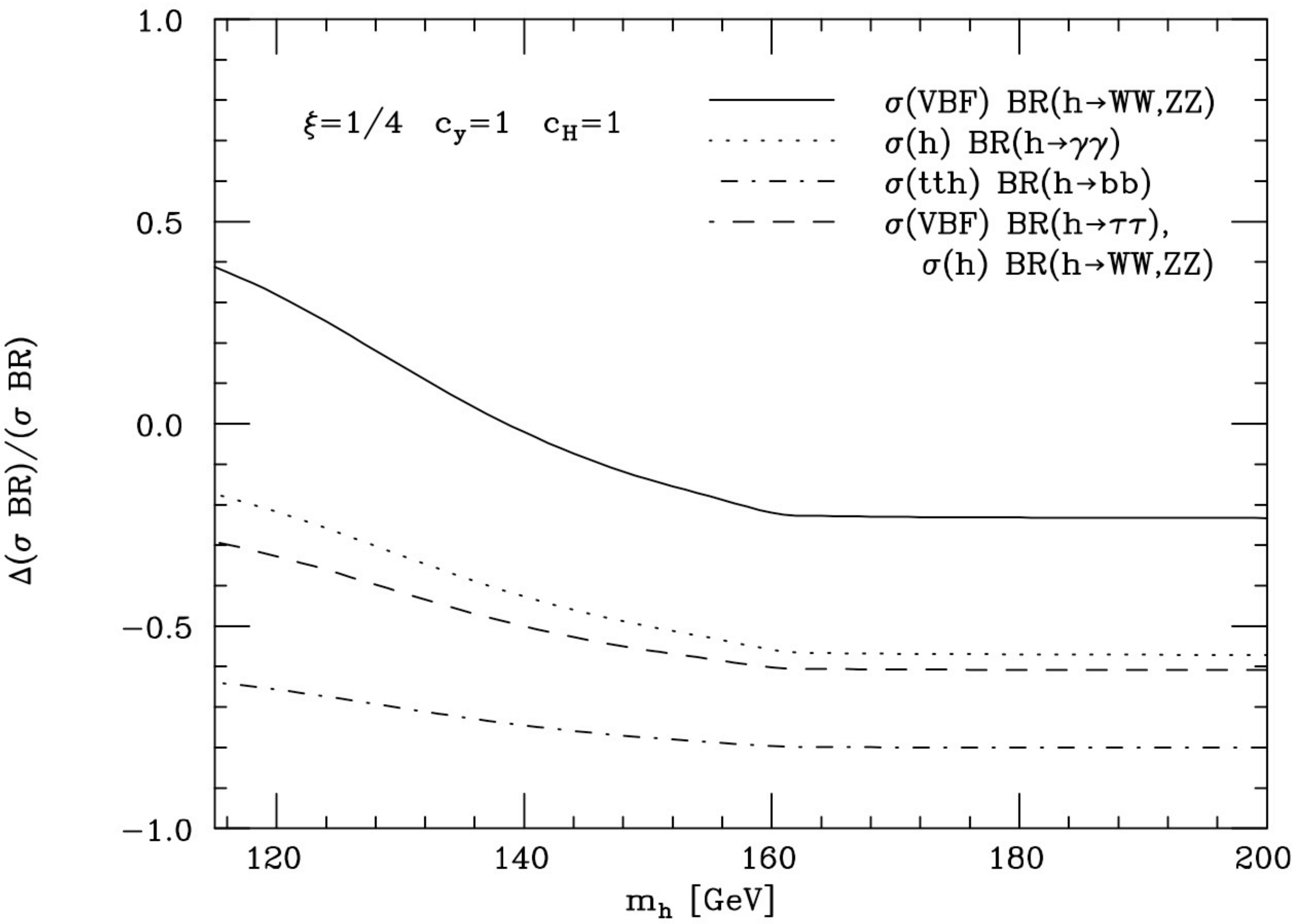
$$\Gamma\left(h \to \gamma Z\right)_{\rm SILH} = \Gamma\left(h \to \gamma Z\right)_{\rm SM}\left[1 - \xi\,{\rm Re}\left(\frac{2c_y + c_H}{1 + J_Z/I_Z} + \frac{c_H - \frac{g^2}{g_\rho^2}\hat{c}_W}{1 + I_Z/J_Z} + \frac{4c_{\gamma Z}}{I_Z + J_Z}\right)\right]$$

Contribution to the coefficients of the dim-6 operators from explicit models:

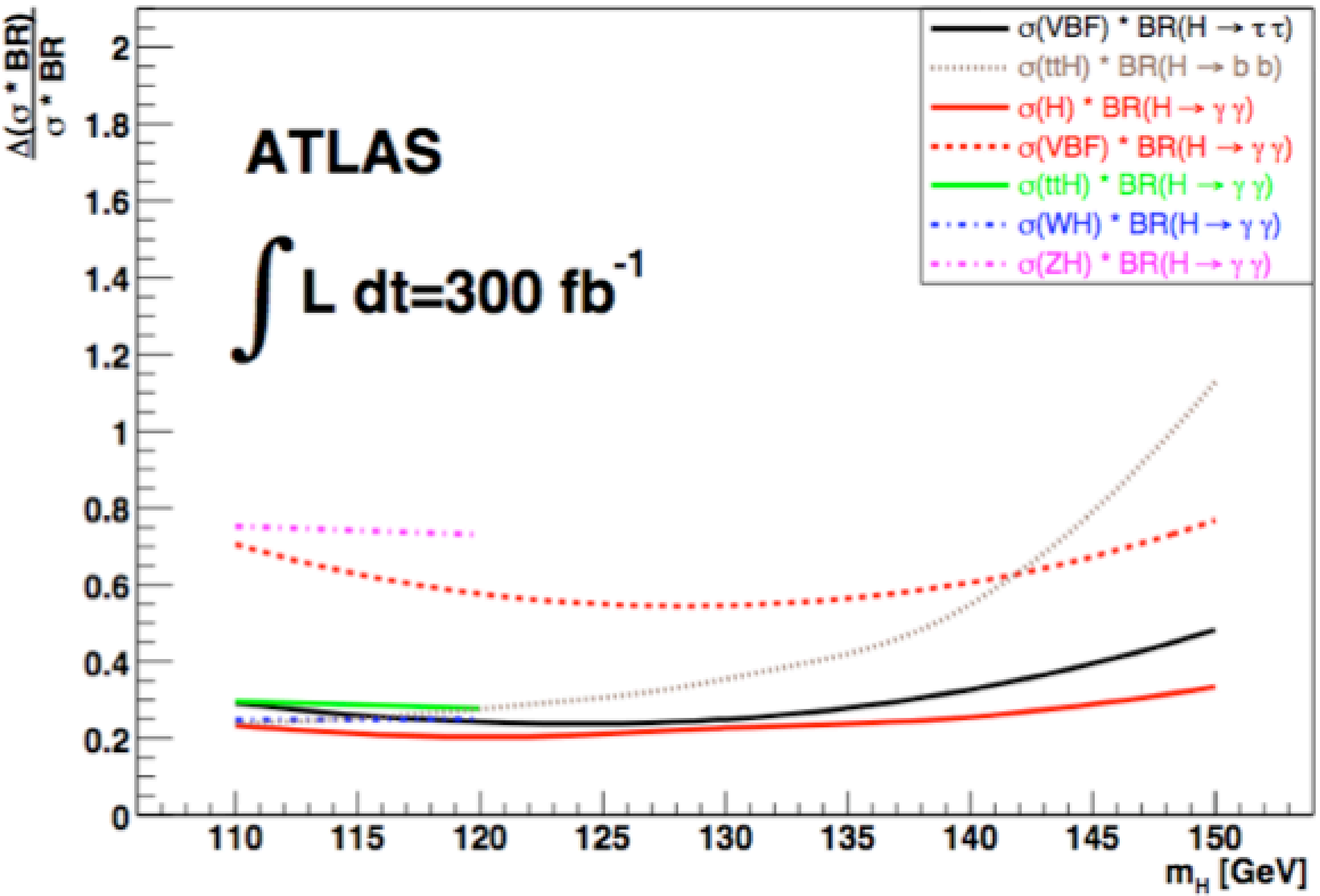
	Holographic Higgs Extra dim	Littlest Higgs
c_T	0	-1/16
c_H	1	1/4
c_y	1	
c_6	0	

From EWPT at LEP: $m_\rho > 2\ TeV \longrightarrow f > 200\ GeV$

Deviations from the SM:



Visible at LHC?

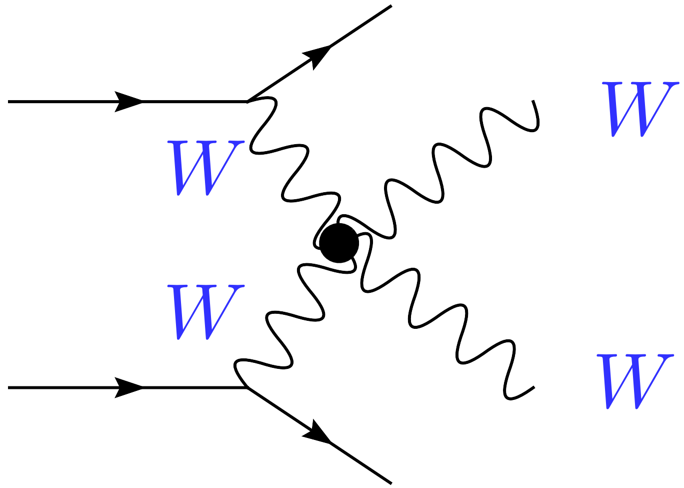


Duhrssen 03

...certainly if they are of order 20-40%

ILC would be a perfect machine to test these scenarios: effects could be measured up to a few %

Best test of composite Higgs: WW-scattering



even that the Higgs is light,
it grows with s

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to W_L^+ W_L^-\right) = \mathcal{A}\left(W_L^+ W_L^- \to Z_L^0 Z_L^0\right) = -\mathcal{A}\left(W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm\right) = \frac{c_H s}{f^2},$$

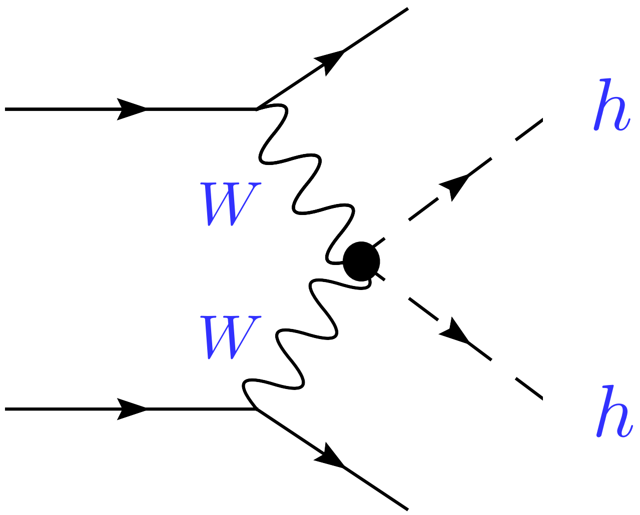
$$\mathcal{A}\left(W^\pm Z_L^0 \to W^\pm Z_L^0\right) = \frac{c_H t}{f^2}, \quad \mathcal{A}\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{c_H (s+t)}{f^2},$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to Z_L^0 Z_L^0\right) = 0.$$

Difficult to see. From Higgsless studies
possible to see if $\frac{c_H v^2}{f^2} \sim 0.5 - 0.7$

Bagger et al

2 Higgs-production also grows with s:



$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \frac{c_H s}{f^2}.$$

Challenging!

Conclusions

- "There is life" beyond the MSSM
- Alternatives based on either (i) No Higgs, or (ii) Composite/PGB Higgs
- WW-amplitudes unitarized by (i) extra states (e.g. KK-states) and, in case (ii) by a non-elementary "Higgs"

→ Worthy to be explored at the LHC

Signals:

- W',Z'-type resonances: Quite generic
- Gluonic resonances: Cleanest signature
- Fermionic resonances: Lightest states "partners" of the top → although also exotic states, e.g. Q=5/3
- Top+Higgs couplings different from the SM, and strong WW-scattering at high E