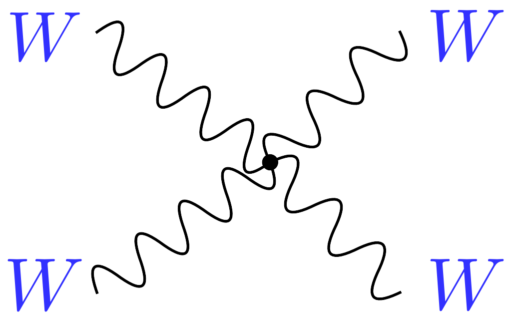
The Strongly-Interacting Light Higgs

Alex Pomarol (Univ. Autonoma Barcelona)

in collaboration with:

Giudice, Grojean, Rattazzi

The SM, as we know it today, is not a complete theory:

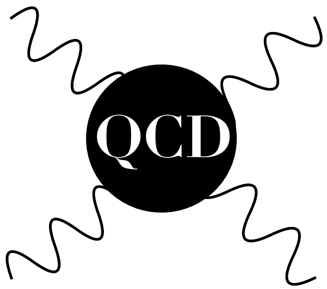


$$\propto \frac{E^4}{m_W^4}$$

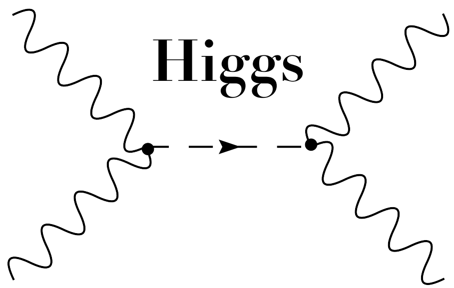
First priority at the LHC:

What unitarize it ?

As in $\pi\pi \to \pi\pi$, a strong sector



Technicolor: repetition of QCD at $m_\rho \sim 1\ TeV$



Supersymmetry needed for naturalness (hierarchy problem)

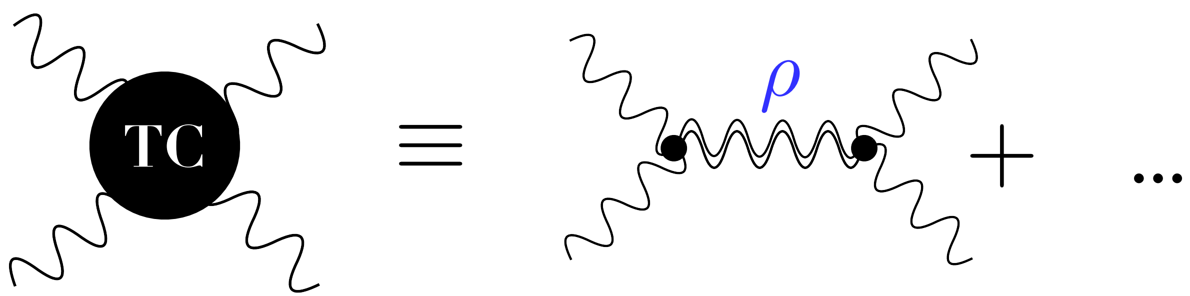
Expected physics before LHC

I. Technicolor:

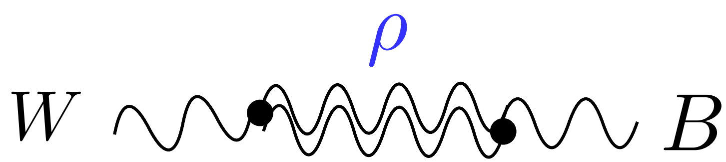
- **No new particles were expected at LEP or Tevatron**
- **Expected deviations from the SM predictions:**

The particle that unitarize the WW amplitudes
(in the "hadron" description)

$m_\rho \sim 1\ TeV$



generates a tree-level effect on the self-energy of
the SM gauge bosons



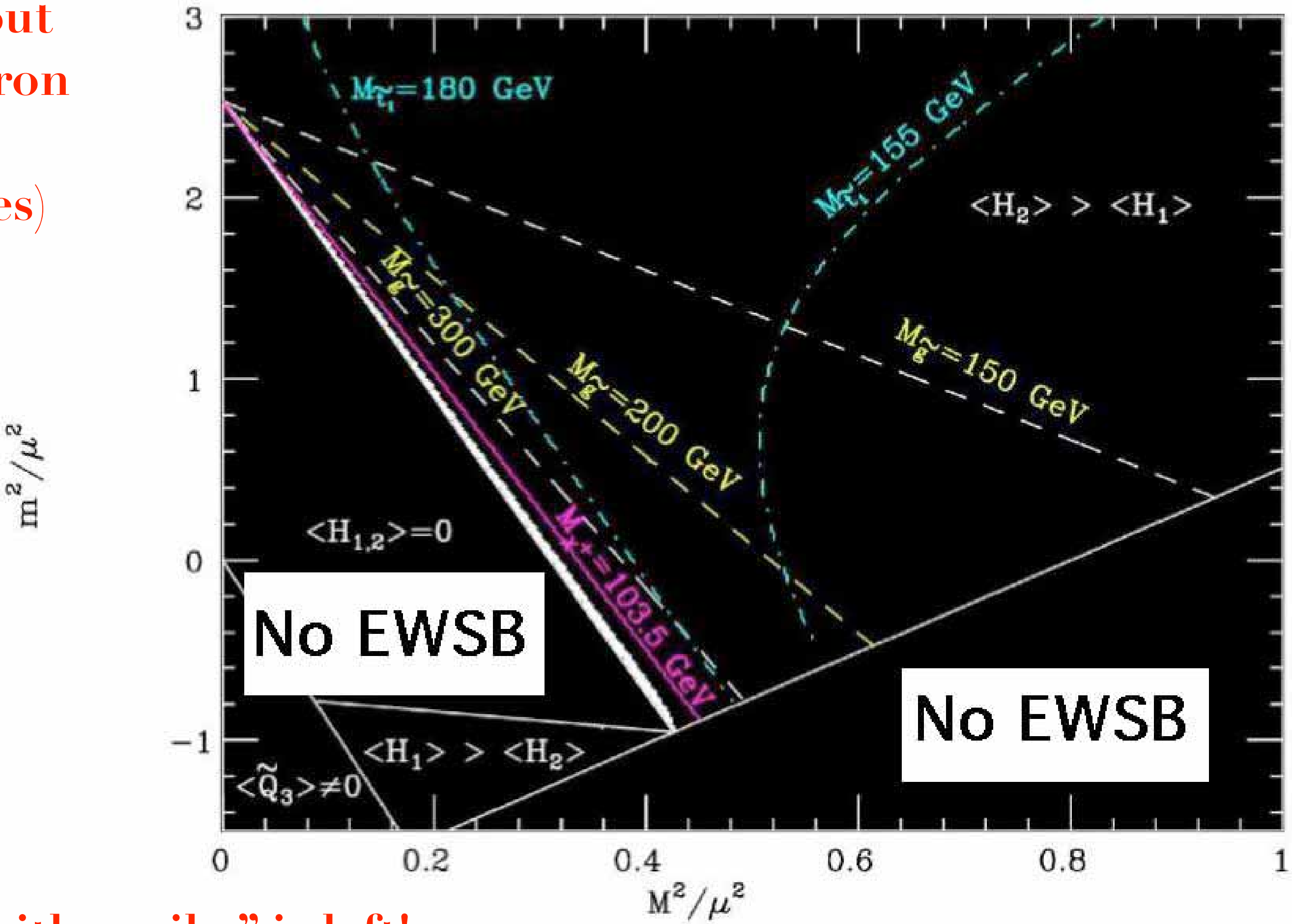
Effects not seen at LEP!

II. Supersymmetry:

- No deviations from SM predictions
  (effects at the loop level)
- New particles were expected at LEP/Tevatron

But Not seen!

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



Only the thin “withe spike” is left!

Giudice, Rattazzi

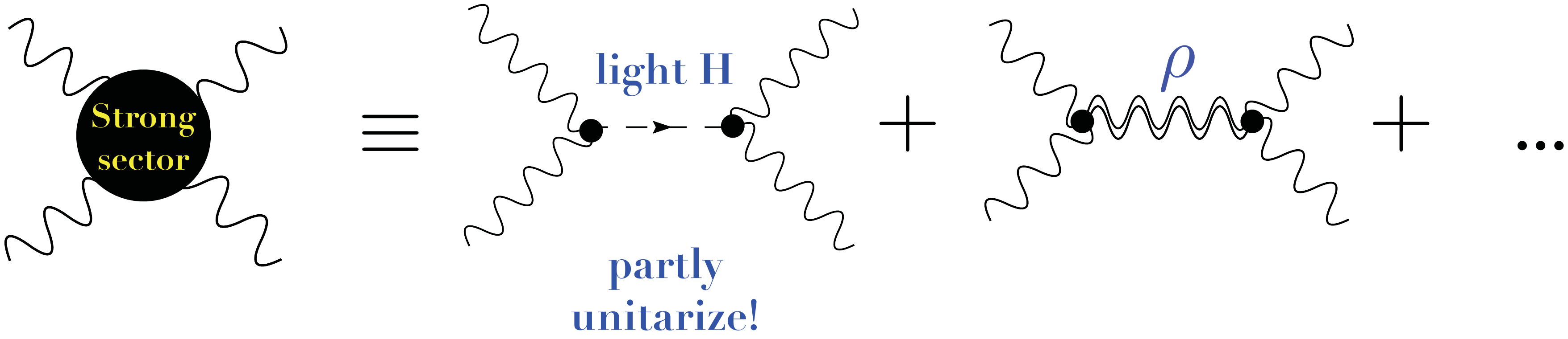
A 3rd way is possible: explored in the recent years

There is a Higgs but it is not elementary: it is composite particle

Georgi,Kaplan 80s

no naturalness problem

WW unitarity:



H is “almost” a Higgs (its couplings deviate from a point-like scalar)

What we gain?

heavy states ρ are needed to unitarize WW at an energy slightly higher that 1 TeV so they can have bigger masses and give smaller effects on the self-energies of the SM gauge bosons

1st important question:

Why the Higgs mass will be smaller than m_ρ ?

Higgs can appear as a Pseudo-Goldstone boson from a "strong" sector

global symmetry breaking: G $\longrightarrow$ H

example: $SO(5) \longrightarrow SO(4)$

4 Goldstones $=$ a doublet of $SU(2)$ $=$ Higgs

Higgs Mass protected by the global G-symmetry

Explicit examples:

- Little Higgs — Arkani-Hamed, Cohen, Katz, Nelson
- Holographic Higgs: Extra dimensions — Agashe, Contino, AP

Predictive models!

details given by request

My interest here:
general properties of the low-energy effective theory arising from these class of models

→ the equivalent of the chiral lagrangian in QCD

Generically:

$$\mathcal{L}_{\rm SM}(f, A_\mu) \quad + \quad \mathcal{L}_{\rm BSM}(H, \rho, \ldots) \quad + \quad \mathcal{L}_{int}$$

symmetries: SM Group

G ⟶ H
e.g. SO(5) ⟶ SO(4)

G-breaking terms

parameters: $g_{\rm SM}$

g_ρ

$\dfrac{g_{\rm SM}}{g_\rho}$

$$g_\rho \gg g_{\rm SM}$$

↓ responsible for V(H/f) and Yukawas

Physics of two scales: $\begin{cases} f & = \text{decay constant} \\ m_\rho & = \text{“hadron” mass} \end{cases}$

$$\langle H \rangle \equiv v \sim f$$

general relation: $m_\rho = g_\rho f$

$$\hookrightarrow \quad m_\rho \gg v \quad \hookleftarrow$$

Heavy states ~ 2-4 TeV

Physics below m_ρ

Effective theory after integrating out the heavy states:

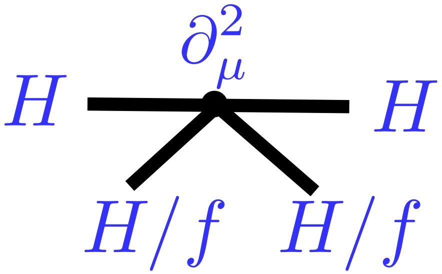
$$\mathcal{L}_{\mathrm{SM+H}} \quad + \quad \text{higher dimensional operators}$$

→ **what are they?**

Parametric counting for the higher-dim operator's coefficients:

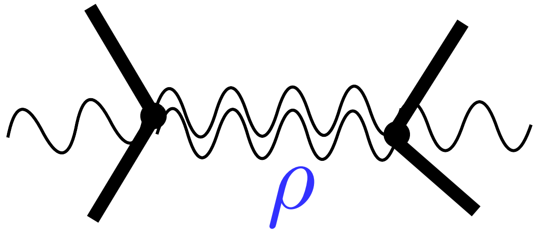
TREE-LEVEL:

leading:



e.g. $$\frac{1}{f^2}(\partial_\mu H^2)^2$$

subleading:



e.g. $$\frac{1}{m_\rho^2}(H^\dagger D^\mu H)(\partial^\nu B_{\mu\nu})$$

ONE-LOOP:

e.g. those suppressed by the Golstone symmetry $$\frac{g'^2}{16\pi^2}\frac{g^2}{m_\rho^2}H^\dagger H G_{\mu\nu}G^{\mu\nu}$$

DIMENSION-6 OPERATORS

leading:

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

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

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

The rest, not tested yet!

subleading:

$$\frac{ic_W g}{2m_\rho^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu}H\right)\left(D^\nu W_{\mu\nu}\right)^i+\frac{ic_B g'}{2m_\rho^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)\left(\partial^\nu B_{\mu\nu}\right)$$

Tested by EWPT at LEP!

one-loop:

$$\frac{ic_{HW}g}{16\pi^2f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu}+\frac{ic_{HB}g'}{16\pi^2f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$

$$\frac{c_\gamma g'^2}{16\pi^2f^2}\frac{g^2}{g_\rho^2}H^\dagger HB_{\mu\nu}B^{\mu\nu}+\frac{c_g g_S^2}{16\pi^2f^2}\frac{y_t^2}{g_\rho^2}H^\dagger HG^a_{\mu\nu}G^{a\mu\nu}.$$

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: $m_\rho > 2\ TeV \longrightarrow f > 200\ GeV \left(\frac{4\pi}{g_\rho}\right)$

Implications: definite modifications of Higgs couplings

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

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

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

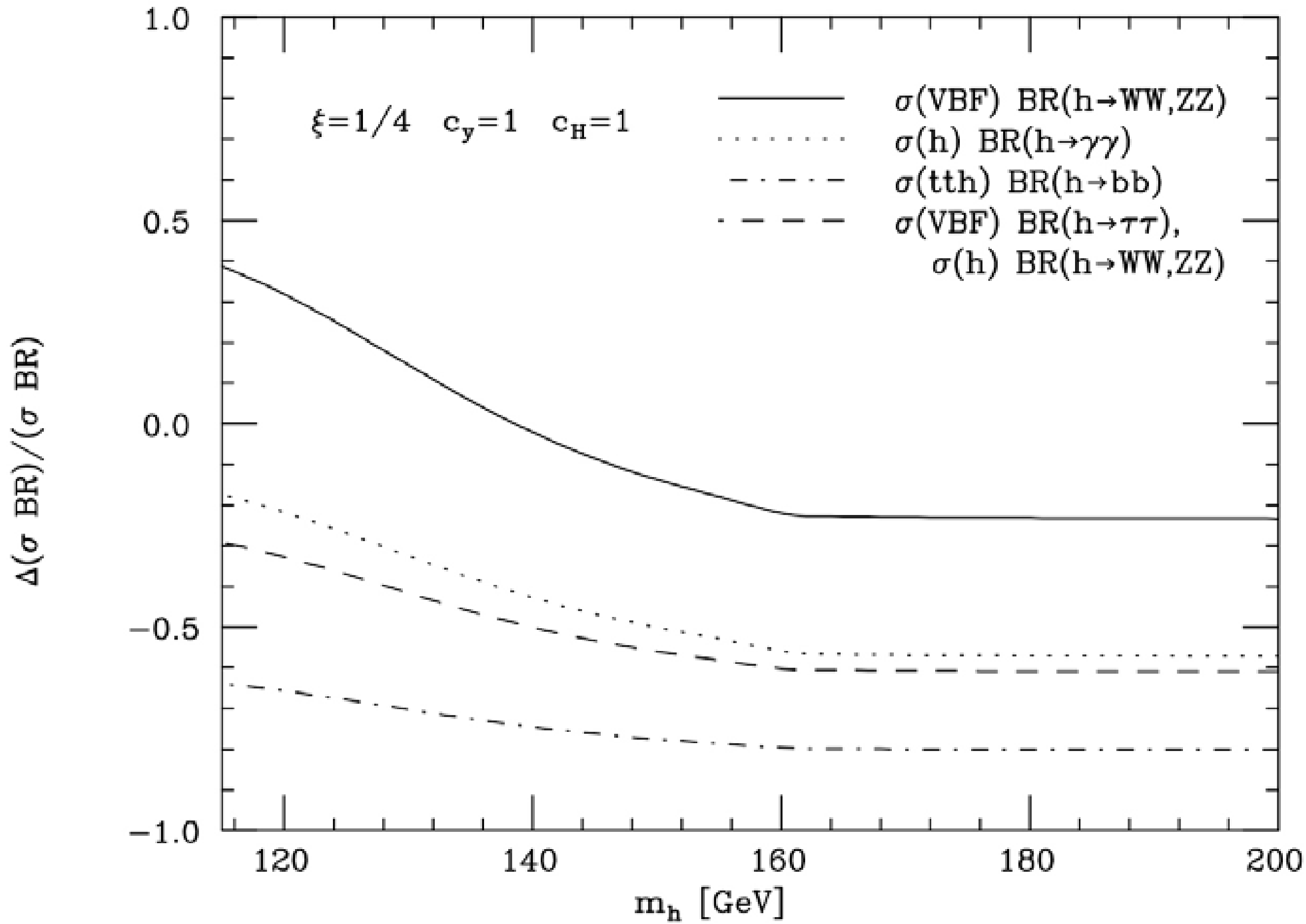
$$\Gamma\left(h \to ZZ\right)_{\rm SILH} = \Gamma\left(h \to ZZ^{(*)}\right)_{\rm SM}\left[1 - \xi\left(c_H - \frac{g^2}{g_\rho^2}\hat{c}_Z\right)\right]$$

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

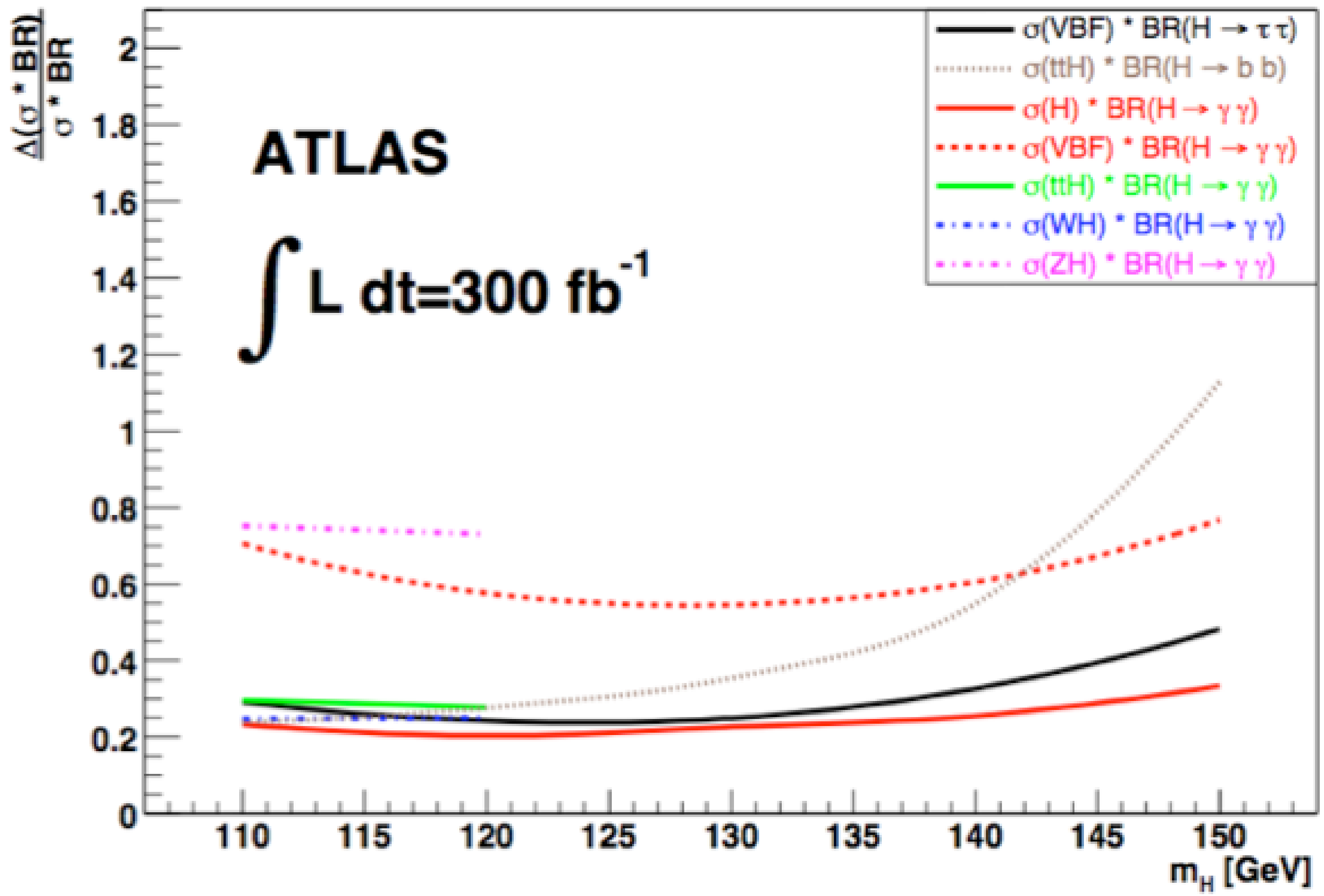
$$\Gamma\left(h \to \gamma\gamma\right)_{\rm SILH} = \Gamma\left(h \to \gamma\gamma\right)_{\rm SM}\left[1 - \xi\ {\rm Re}\left(\frac{2c_y + c_H}{1 + J_\gamma/I_\gamma} + \frac{c_H - \frac{g^2}{g_\rho^2}\hat{c}_W}{1 + I_\gamma/J_\gamma} + \frac{\frac{4g^2}{g_\rho^2}c_\gamma}{I_\gamma + J_\gamma}\right)\right]$$

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

Deviations from the SM:



Visible at LHC?

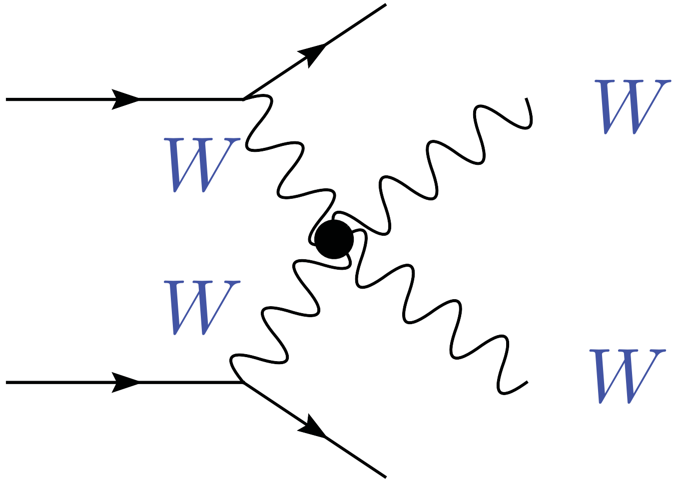


Duhrssen 03

...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

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

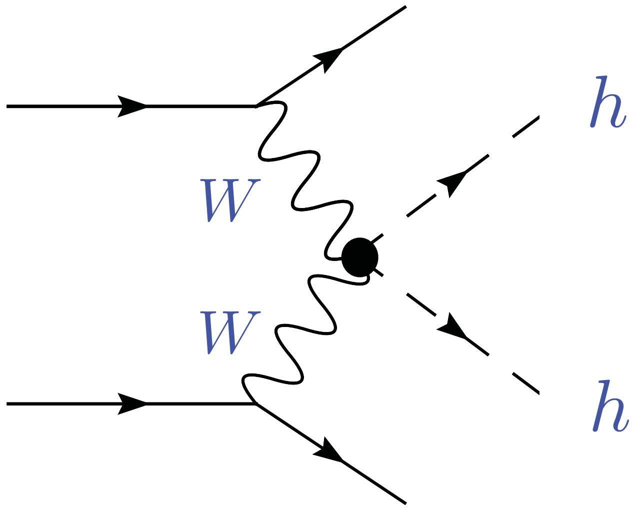
$$\mathcal{A}\left(W^\pm Z_L^0 \to W^\pm Z_L^0\right) = \frac{c_H t}{f^2}, \quad \mathcal{A}\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{c_H (s+t)}{f^2},$$

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

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!

Indirect vs Direct measurements

Indirect: Deviations from SM Higgs

Direct: Detection of heavy particles

Since $m_\rho = g_\rho f$, the larger g_ρ, the more difficult to detect the heavy particles

Maximal coupling: $g_\rho = 4\pi$ $\begin{cases} m_\rho \sim 5\ TeV \\ (v/f)^2 \sim 0.2 \end{cases}$

- $m_\rho \sim 5\ TeV$: Heavy particles out of reach at LHC
- $(v/f)^2 \sim 0.2$: Possible to see at least at ILC

Complementarity between Indirect and Direct searches

Conclusions

If at LHC...

No Higgs

Conclusions

If at LHC...

No Higgs ⟶ **look for strong WW-scattering**

Conclusions

If at LHC...

No Higgs → look for strong WW-scattering

Ligh Higgs

Conclusions

If at LHC...

No Higgs ⟶ **look for strong WW-scattering**

Ligh Higgs ⟶ **look for supersymmetry**

Conclusions

If at LHC...

No Higgs $\longrightarrow$ look for strong WW-scattering

Ligh Higgs $\longrightarrow$ look for supersymmetry

.. but also, it is possible:

Ligh Higgs $\longrightarrow$ not look for supersymmetry, but for strong WW-scattering

Higgs can be composite (strongly-interacting).

I presented the most general effective theory arising from this scenario

$\longrightarrow$ useful to know where to expect deviations from a SM Higgs

- Precise effects on Higgs decays, strong WW $\longrightarrow$ hh
- Complementary to heavy states searches: $\rho \equiv$ W′,t′,...