The Strongly-Interacting Light Higgs

based on a work in collaboration with

G. Giudice, A. Pomarol and R. Rattazzi

hep-ph/0703164 = JHEP06(2007)045

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Main Question for the LHC

What is the mechanism of EW symmetry breaking?

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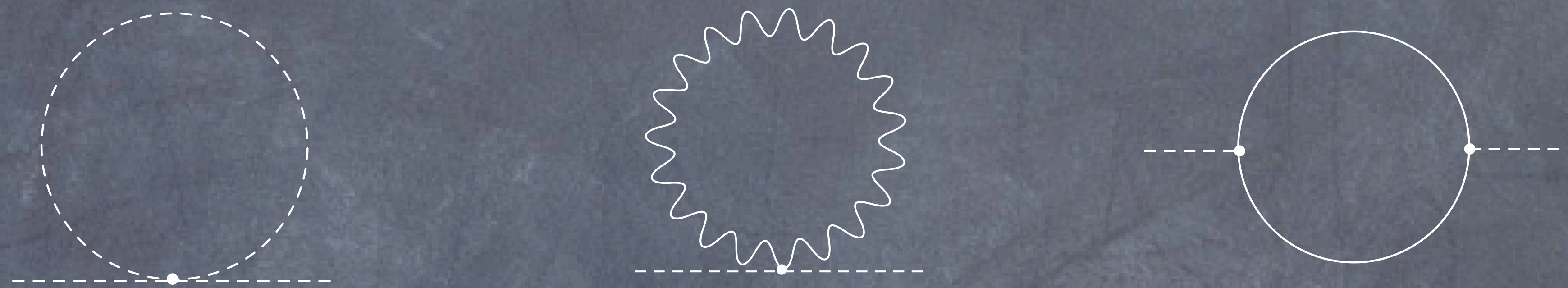
what we usually mean by that question is really

what is canceling these infamous diagrams?



$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\frac{k^2}{(k^2-m^2)^2} \propto \Lambda^2$$

supersymmetry, gauge-Higgs, Little Higgs

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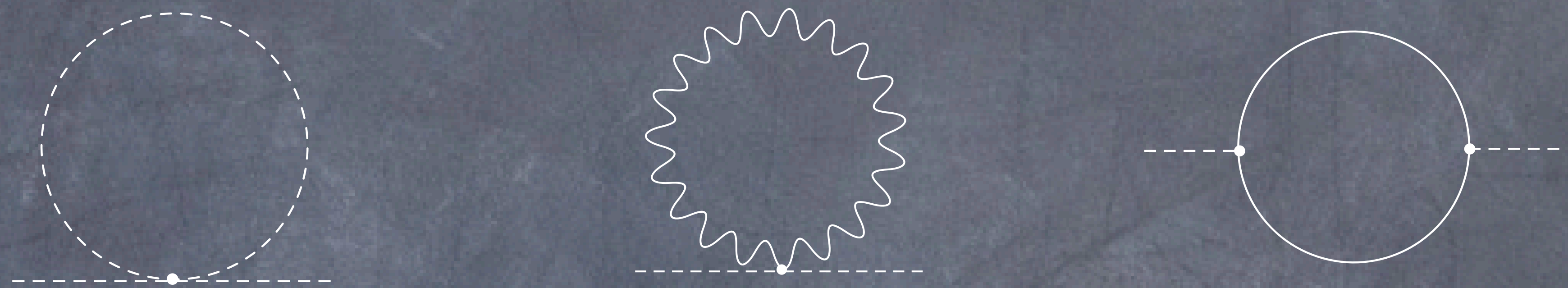

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supersymmetry, gauge-Higgs, Little Higgs

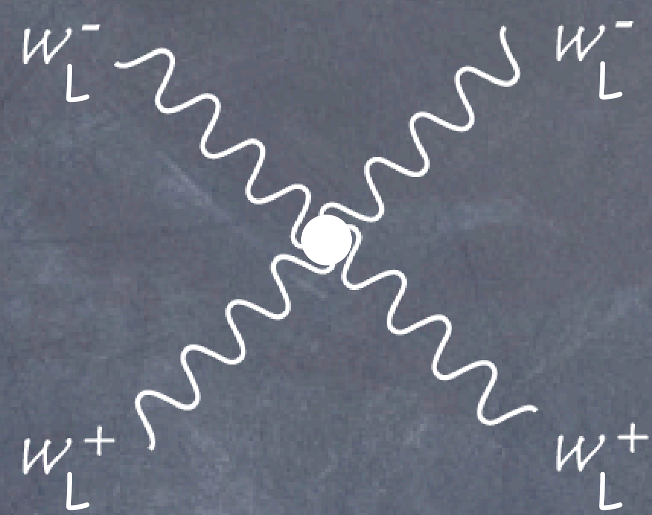
But this is assuming that we already know the answer to

Main Question for the LHC

What is unitarizing the WW scattering amplitudes?

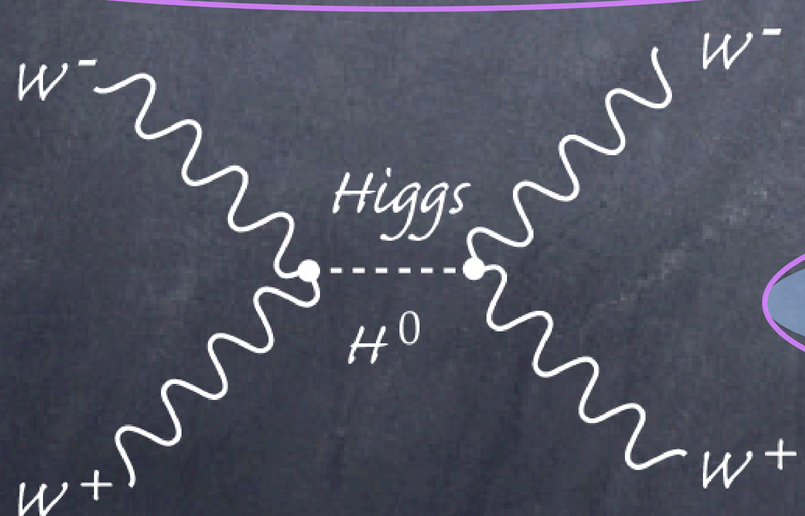
W_L & Z_L part of EWSB sector ➡ W scattering is a probe of Higgs sector interactions

$$\epsilon_l = \left(\frac{|\vec{k}|}{M}, \frac{E}{M} \frac{\vec{k}}{|\vec{k}|} \right)$$



$$\mathcal{A} = g^2 \left(\frac{E}{M_W} \right)^2$$

Weakly coupled models

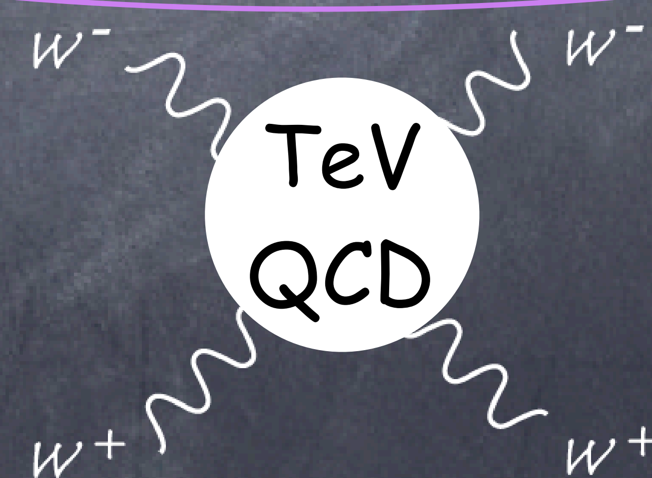


prototype: Susy

susy partners ~ 100 GeV

other ways?

Strongly coupled models



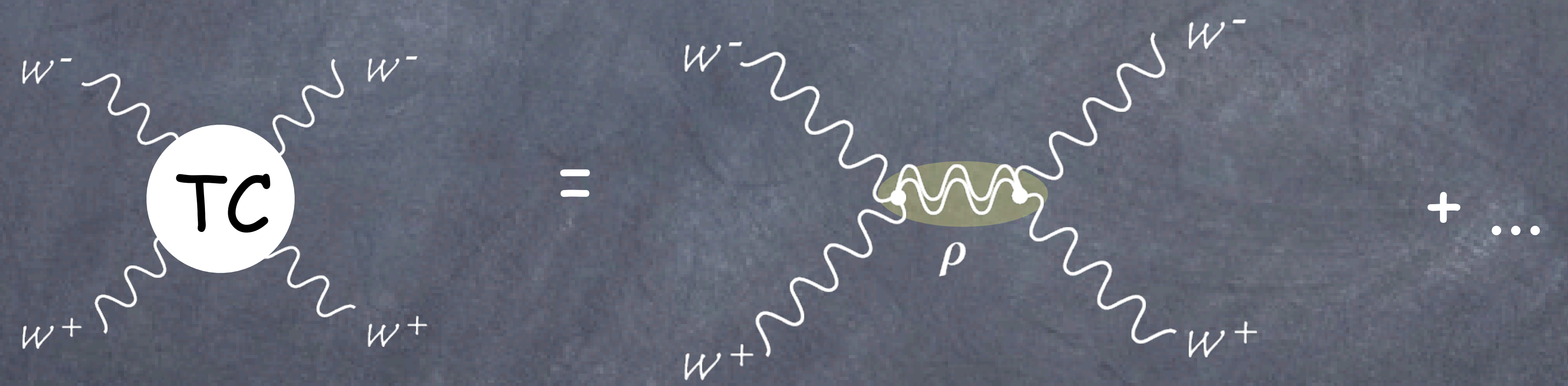
prototype: Technicolor

rho meson ~ 1 TeV

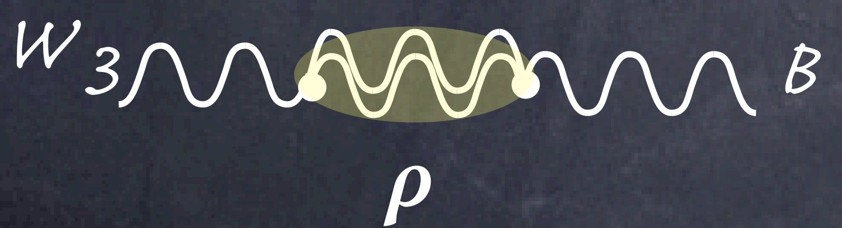
Expected from Technicolor

- No new particles expected at LEP/Tevatron ✓
- Deviations (e.g. oblique corrections) from SM predictions ✗

The resonance that unitarizes the WW scattering amplitudes



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



S parameter of order 1.
Not seen at LEP

Expected from Susy

SUSY has good assets: gauge unification, radiative EWSB, DM candidates...

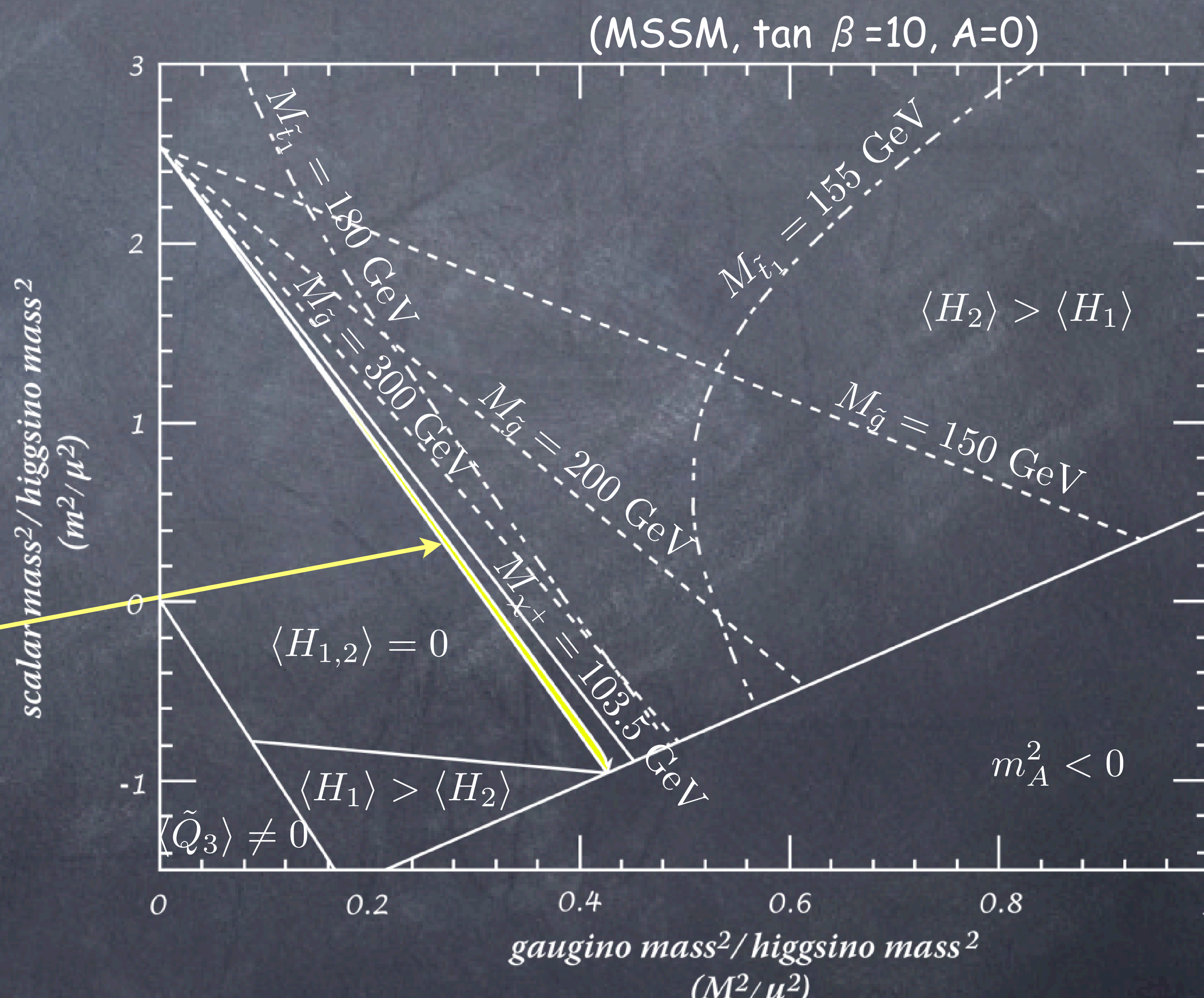
- No oblique corrections: R-parity ➡ one-loop effects only ✓
- New particles around 100 GeV expected at LEP/Tevatron ✗

$$V(H) \sim -m_{\rm susy}^2 H^2 + g_W^2 H^4 \quad ➡ \quad m_Z \sim g_W v \sim m_{\rm susy}$$

no susy partners seen at LEP
no light Higgs

large regions of parameter space ruled out

allowed region ~ 1%



Giudice, Rattazzi '06

motivation to look for other models... NMSSM or more adventurous ones

Back to "Technicolor" from Xdims

AdS/CFT correspondence

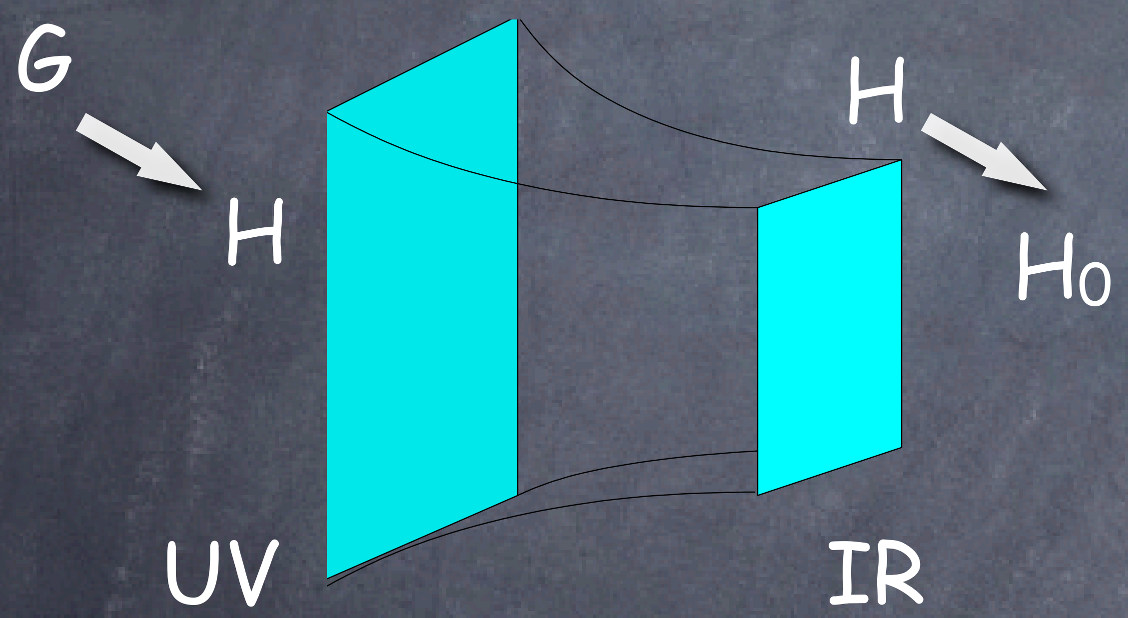
Warped gravity with fermions and gauge field in the bulk and Higgs on the brane

Strongly coupled theory with slowly-running couplings in 4D

$A_5 \to A_5 + \partial_5 \epsilon$

$h \to h + a$

pseudo-Goldstone of a strong force



5D	4D
motion along 5th dim	RG flow
UV brane	UV cutoff
IR brane	break. of conformal inv.
bulk local sym.	global sym.

Advantages

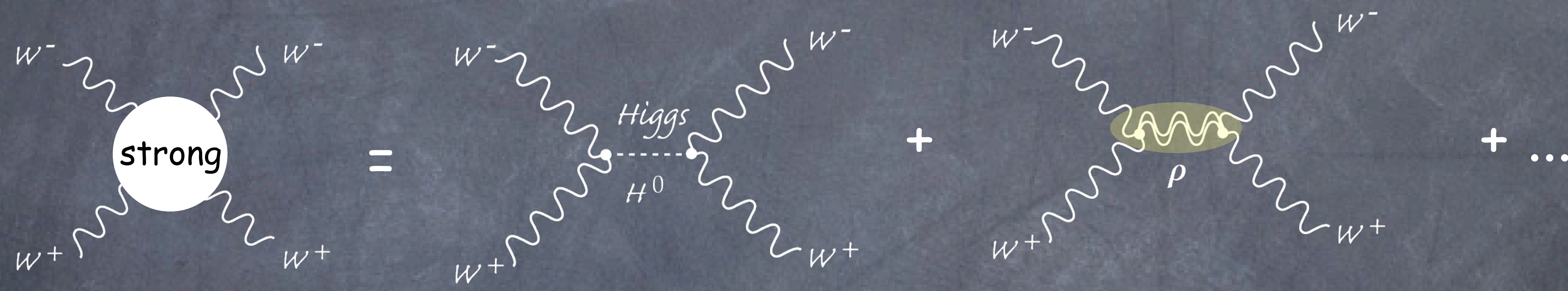
- weakly coupled description ➔ calculable models
- new approach to fermion embedding and flavor problem

Unitarity with Composite Higgs

Technicolor: W_L and Z_L are part of the strong sector

Higgs = composite object (part of the strong sector too)
its couplings deviate from a point-like scalar

Georgi, Kaplan '84



light Higgs
partial unitarization

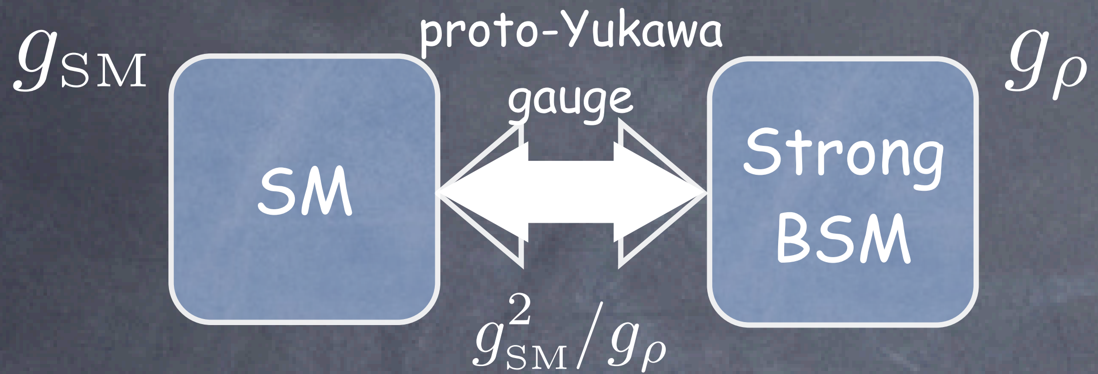
heavy rho

unitarization halfway between weak and strong unitarizations!

- ≠ susy: no naturalness pb ➡ no need for new particles to cancel Λ^2 divergences
- ≠ technicolor: heavier rho ➡ smaller oblique corrections; one tunable parameter: v/f. $\hat{S}_{\rm UV} \sim \frac{g^2 N}{96\pi^2}\frac{v^2}{f^2}$

How to obtain a light composite Higgs?

Higgs=Pseudo-Goldstone boson of the strong sector



$m_{Higgs}=0$ when $g_{SM}=0$

global symmetry $\longrightarrow$ G/H $\longleftarrow$ residual global symmetry

example: SO(5)/SO(4), 4PGB=Doublet of $SU(2)_L$=Higgs

UV completion

$4\pi f$ — 10 TeV

$m_\rho = g_\rho f$ — usual resonances of the strong sector

$v \le f$ — 246 GeV

Higgs = light resonance of the strong sector

$G \supset SU(2)_L \times U(1)_Y$

$H \supset U(1)_{em}$

➡ W_L & Z_L

strong sector broadly characterized by 2 parameters

m_ρ = mass of the resonances

g_ρ = coupling of the strong sector or decay cst of strong sector $f = \dfrac{m_\rho}{g_\rho}$

Some examples

- Georgi-Kaplan: no separation of scales $g_\rho = 4\pi, f = v$
- Holographic Higgs: $m_\rho = m_{KK}, g_\rho = g_{KK}$
- Little Higgs: m_ρ, g_ρ masses and couplings of heavy top', W', Z'

might require some tuning to get, f>v (model dependent question)

Giudice, Grojean, Pomarol, Rattazzi '07

Barbieri, Bellazzini, Rychkov, Varagnolo '07

... more details later

How can we test the composite nature of the Higgs?

if a light Higgs is seen at LHC, is there a way to figure out whether it is part of a strong sector?

- Model-dependent: production of resonances at m_ρ
- Model-independent: study of Higgs properties & W scattering

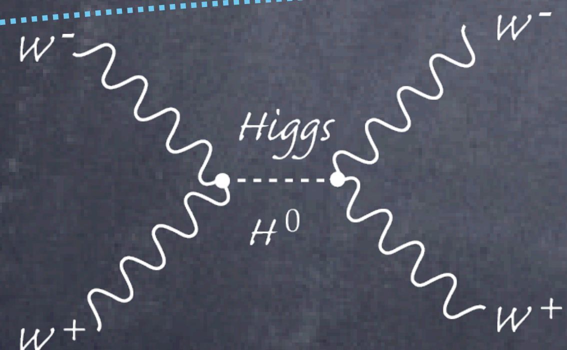
What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2} \partial^\mu \left(|H|^2\right) \partial_\mu \left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \quad \Longrightarrow \quad \mathcal{L} = \frac{1}{2}\left(1 + c_H \frac{v^2}{f^2}\right) (\partial^\mu h)^2 + \ldots$$

Modified Higgs propagator ~ Higgs couplings rescaled by $\dfrac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \sim 1 - c_H \dfrac{v^2}{2f^2}$



$$= -\left(1 - c_H \frac{v^2}{f^2}\right) g^2 \frac{E^2}{M_W^2}$$

no exact cancellation of the growing amplitudes

unitarization restored by heavy resonances

Falkowski, Pokorski, Roberts '07

Strong W scattering below m_ρ ?

SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

2 rules to construct the effective Lagrangian

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

- **Genuine strong operators** (sensitive to the scale f)

- **Form factor operators** (sensitive to the scale m_ρ)

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- **Genuine strong operators** (sensitive to the scale f)

$$\boxed{\frac{c_H}{2f^2}\left(\partial_\mu\left(|H|^2\right)\right)^2} \quad \boxed{\frac{c_T}{2f^2}\underbrace{\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2}_{\text{custodial breaking}}} \quad \boxed{\frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.}} \quad \boxed{\frac{c_6\lambda}{f^2}|H|^6}$$

- **Form factor operators** (sensitive to the scale m_ρ)

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custodial breaking

Form factor operators (sensitive to the scale m_ρ)

$$\frac{i c_W}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i \qquad \frac{i c_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$

$$\frac{i c_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \qquad \frac{i c_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} \qquad \frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

Goldstone sym.

Coset Structure

$$U = e^{i\begin{pmatrix} & H/f \\ H^\dagger/f & \end{pmatrix}} U_0$$

$$f^2\,\mathrm{tr}\left(\partial_\mu U^\dagger \partial^\mu U\right) = |\partial_\mu H|^2 + \frac{\sharp}{f^2}\left(\partial|H|^2\right)^2 + \frac{\sharp}{f^2}|H|^2\,|\partial H|^2 + \frac{\sharp}{f^2}\left|H^\dagger \partial H\right|^2$$

↑

can be removed by field redefinition

$$H \to H + \sharp|H|^2 H/f^2$$

c_H and c_T are fully fixed by the σ-model structure

(up to the overall normalization of f)

(independent of the physics at the scale m_ρ)

SO(5)/SO(4): c_H=1/2, c_T=0

SU(3)/SU(2)xU(1): c_H=c_T=1/36

$$\lambda|H|^4 \to \frac{\sharp}{f^2}\lambda|H|^6 \qquad y\bar{f}_L H f_R \to \frac{\sharp}{f^2} y|H|^2 \bar{f}_L H f_R$$

c_6 and c_y receive contributions both from the σ-model structure and from the resonance at m_ρ

EWPT constraints

$$\hat{T} = c_T \frac{v^2}{f^2} \Longrightarrow |c_T \frac{v^2}{f^2}| < 2 \times 10^{-3}$$

removed by custodial symmetry

$$\hat{S} = (c_W + c_B)\frac{m_W^2}{m_\rho^2} \Longrightarrow \boxed{m_\rho \geq (c_W + c_B)^{1/2}\ 2.5\ \mathrm{TeV}}$$

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There are also some 1-loop IR effects

Barbieri, Bellazzini, Rychkov, Varagnolo '07

$$\hat{S}, \hat{T} = a \log m_h + b$$

modified Higgs couplings to matter

$$\Downarrow$$

$$\hat{S}, \hat{T} = a\left((1 - c_H\xi)\log m_h + c_H\xi \log\Lambda\right) + b$$

$\xi = v^2/f^2$

effective
Higgs mass

$$m_h^{eff} = m_h \left(\frac{\Lambda}{m_h}\right)^{c_H\xi} > m_h$$

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LEPII, for m_h~115 GeV: $\boxed{c_H\xi < 1/3 \sim 1/2}$

IR effects can be cancelled by heavy fermions (model dependent)

Other Operators

operators involving gauge fields only

$$-\frac{c_{2W}\,g^2}{2g_\rho^2 m_\rho^2}(D^\mu W_{\mu\nu})^i(D_\rho W^{\rho\nu})^i-\frac{c_{2B}\,g'^2}{2g_\rho^2 m_\rho^2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu})-\frac{c_{2g}\,g_3^2}{2g_\rho^2 m_\rho^2}(D^\mu G_{\mu\nu})^a(D_\rho G^{\rho\nu})^a$$
$$+\frac{c_{3W}\,g^3}{16\pi^2 m_\rho^2}\epsilon_{ijk}W_\mu^{i\,\nu}W_{\nu\rho}^{j}W^{k\,\rho\mu}+\frac{c_{3g}\,g_3^3}{16\pi^2 m_\rho^2}f_{abc}G_\mu^{a\,\nu}G_{\nu\rho}^{b}G^{c\,\rho\mu}$$

contribute to the oblique corrections

$$W=c_{2W}\frac{g^2 m_W^2}{g_\rho^2 m_\rho^2}\qquad Y=c_{2B}\frac{g'^2 m_W^2}{g_\rho^2 m_\rho^2}$$

weaker constraints than S...

counting of operators agrees with Buchmuller, Wyler '86

Flavor Constraints

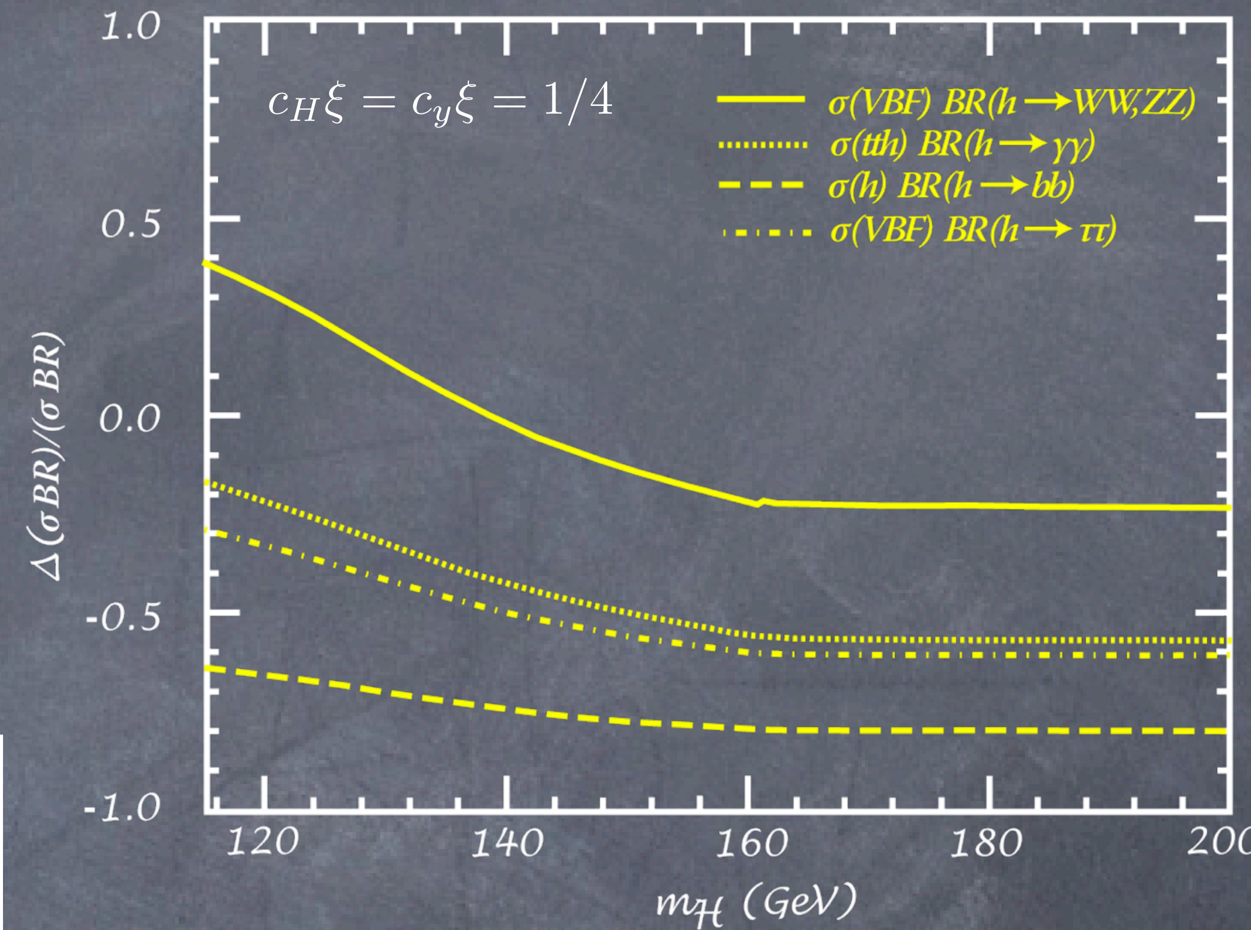
c_y is flavor universal

Minimal flavor violation built in

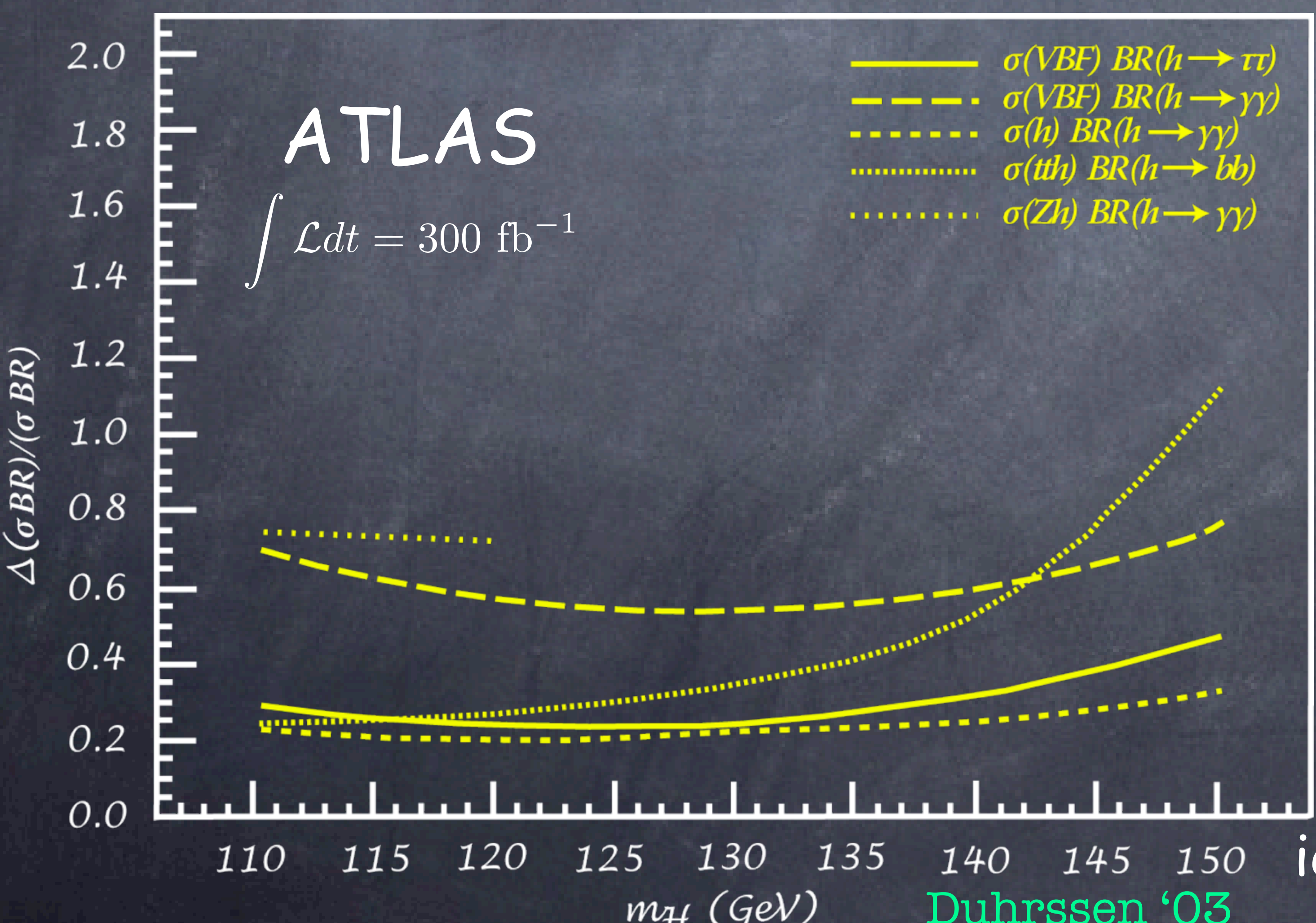
Higgs anomalous couplings

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

$$\Gamma\left(h \to gg\right)_{\mathrm{SILH}} = \Gamma\left(h \to gg\right)_{\mathrm{SM}}\left[1-\left(2c_y + c_H\right)v^2/f^2\right]$$



observable @ LHC?



Duhrssen '03

LHC can measure

$$c_H \frac{v^2}{f^2},\ c_y \frac{v^2}{f^2}$$

up to 20-40%

(composite scale 5-7 TeV)

(ILC could go to few %

ie test composite Higgs up to $4\pi f \sim 30$ TeV)

Higgs anomalous couplings

$$\Gamma\left(h \to f\bar{f}\right)_{\rm SILH} = \Gamma\left(h \to f\bar{f}\right)_{\rm SM}\left[1-\xi\left(2c_y + c_H\right)\right]$$
$$\Gamma\left(h \to W^+W^-\right)_{\rm SILH} = \Gamma\left(h \to W^+W^{(*)-}\right)_{\rm SM}\left[1-\xi c_H\right]$$
$$\Gamma\left(h \to ZZ\right)_{\rm SILH} = \Gamma\left(h \to ZZ^{(*)}\right)_{\rm SM}\left[1-\xi c_H\right]$$
$$\Gamma\left(h \to gg\right)_{\rm SILH} = \Gamma\left(h \to gg\right)_{\rm SM}\left[1-\xi\ \left(2c_y + c_H\right)\right]$$
$$\Gamma\left(h \to \gamma\gamma\right)_{\rm SILH} = \Gamma\left(h \to \gamma\gamma\right)_{\rm SM}\left[1-\xi\ {\rm Re}\left(\frac{2c_y+c_H}{1+J_\gamma/I_\gamma}+\frac{c_H}{1+I_\gamma/J_\gamma}\right)\right]$$
$$\Gamma\left(h \to \gamma Z\right)_{\rm SILH} = \Gamma\left(h \to \gamma Z\right)_{\rm SM}\left[1-\xi\ {\rm Re}\left(\frac{2c_y+c_H}{1+J_Z/I_Z}+\frac{c_H}{1+I_Z/J_Z}+\frac{c_{HB}-c_{HW}}{\sin 2\theta_W\left(I_Z+J_Z\right)}\right)\right]$$

$$\Downarrow$$

$$\Delta\left(\Gamma\left(h \to ZZ\right)/\Gamma\left(h \to W^+W^-\right)\right) = 0$$
$$\Delta\left(\Gamma\left(h \to f\bar{f}\right)/\Gamma\left(h \to W^+W^-\right)\right) = -2\xi c_y$$
$$\Delta\left(\Gamma\left(h \to \gamma\gamma\right)/\Gamma\left(h \to W^+W^-\right)\right) = -2\xi c_y/(1+J_\gamma/I_\gamma)$$

many systematics uncertainties drop out

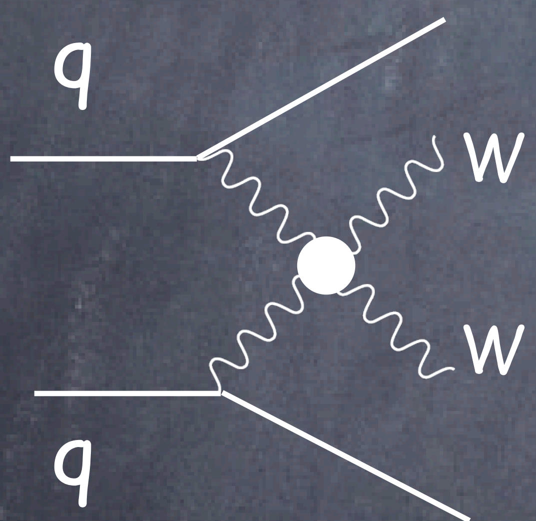
Strong W scattering

Even with a light Higgs, growing amplitudes (at least up to m_ρ)

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

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

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



$$\sigma\left(pp \to V_L V_L' X\right)_{c_H} = \left(c_H \xi\right)^2 \sigma\left(pp \to V_L V_L' X\right)_{\cancel{H}}$$

leptonic and semileptonic
vector decay channels
with 300 fb^{-1}

$\Longrightarrow$

LHC is sensitive to

$$c_H \frac{v^2}{f^2}$$

bigger than
0.5 ~ 0.7

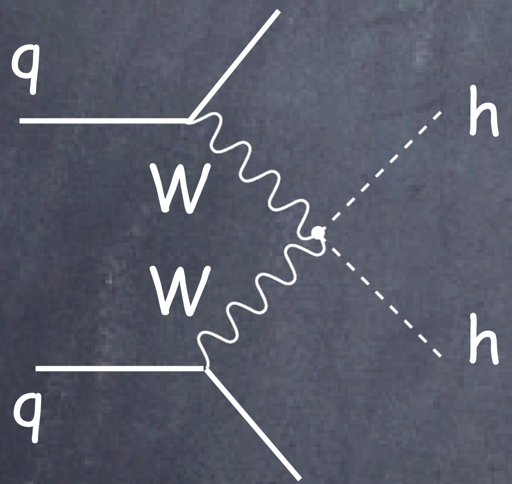
Bagger et al '95
Butterworth et al. '02

Strong Higgs production

O(4) symmetry between W_L, Z_L and the physical Higgs

strong boson scattering ⇔ strong Higgs production

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



signal:
- hh → bbbb
- hh → 4W → $\ell^\pm \ell^\pm \nu\nu$jets

Sum rule (with cuts $|\Delta\eta| < \delta$ and $s < M^2$)

$$2\sigma_{\delta,M}\left(pp \to hhX\right)_{c_H} = \sigma_{\delta,M}\left(pp \to W_L^+ W_L^- X\right)_{c_H} + \frac{1}{6}\left(9 - \tanh^2\frac{\delta}{2}\right)\sigma_{\delta,M}\left(pp \to Z_L^0 Z_L^0 X\right)_{c_H}$$

Gauge boson self-couplings

$$\mathcal{L}_V = -ig\cos\theta_W g_1^Z Z^\mu \left(W^{+\nu}W^-_{\mu\nu} - W^{-\nu}W^+_{\mu\nu}\right) - ig\left(\cos\theta_W \kappa_Z Z^{\mu\nu} + \sin\theta_W \kappa_\gamma A^{\mu\nu}\right) W^+_\mu W^-_\nu$$

TGC are sensitive to the form factor operators

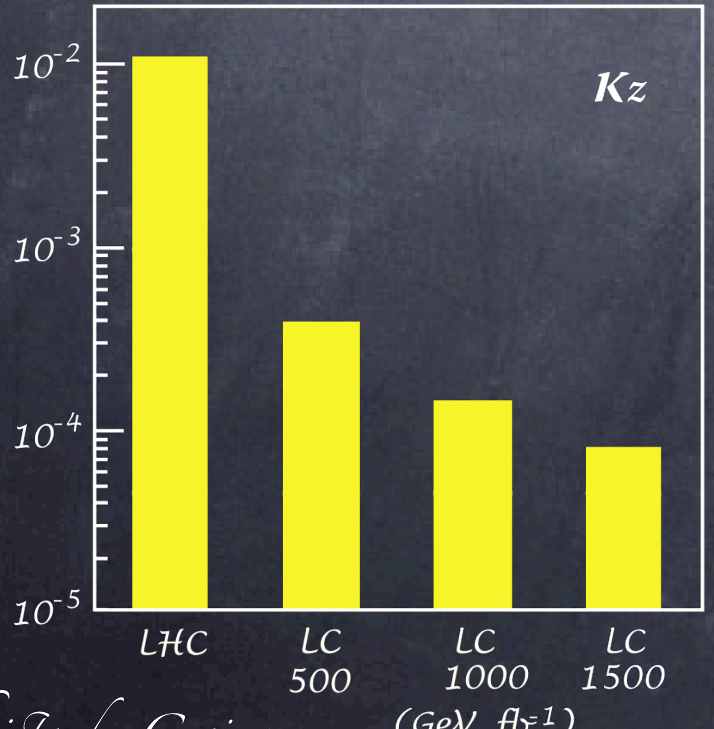
$$g_1^Z = \frac{m_Z^2}{m_\rho^2} c_W \qquad \kappa_\gamma = \frac{m_W^2}{m_\rho^2}\left(\frac{g_\rho}{4\pi}\right)^2 (c_{HW} + c_{HB}) \qquad \kappa_Z = g_1^Z - \tan^2\theta_W \kappa_\gamma$$

@ LHC 100fb^{-1} $\quad g_1^Z \sim 1\% \qquad \kappa_\gamma \sim \kappa_Z \sim 5\%$

sensitive to resonance up to m_ρ~800 GeV

not competitive with the measure of S at LEPII

@ ILC

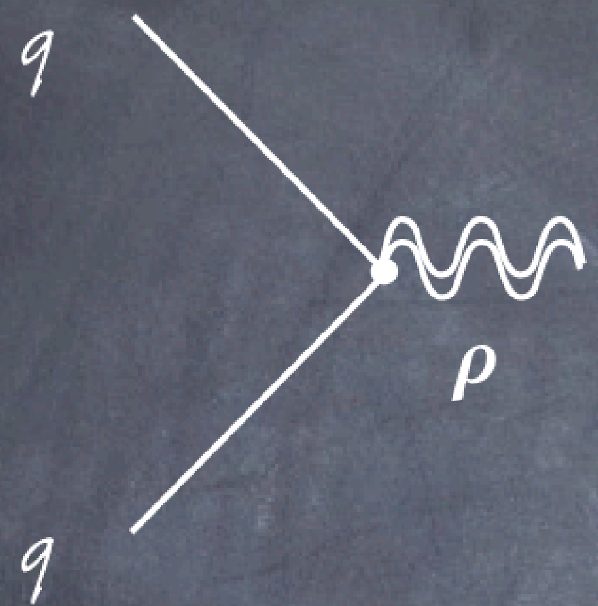


T. Abe et al, Snowmass '01

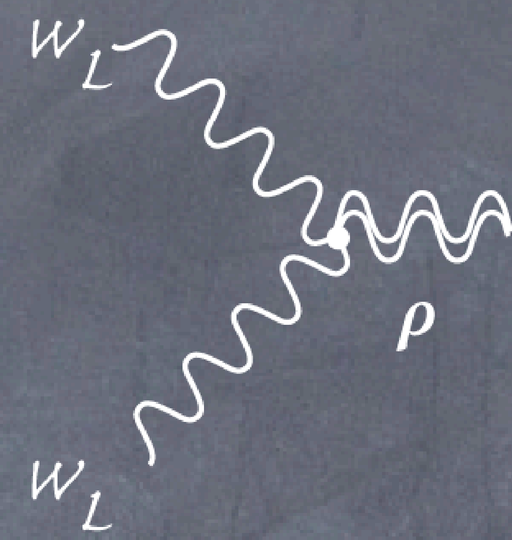
sensitive to resonance up to m_ρ~8TeV

Direct vs. indirect signals

direct production of (TeV) resonances



$$= \frac{g_{SM}^2}{g_\rho}$$



$$= g_\rho$$

$$\sigma\left(pp \to \rho_H^\pm + X\right) = \left(\frac{4\pi}{g_\rho}\right)^2 \left(\frac{3\ \mathrm{TeV}}{m_\rho}\right)^6\ 0.5\ \mathrm{fb}$$

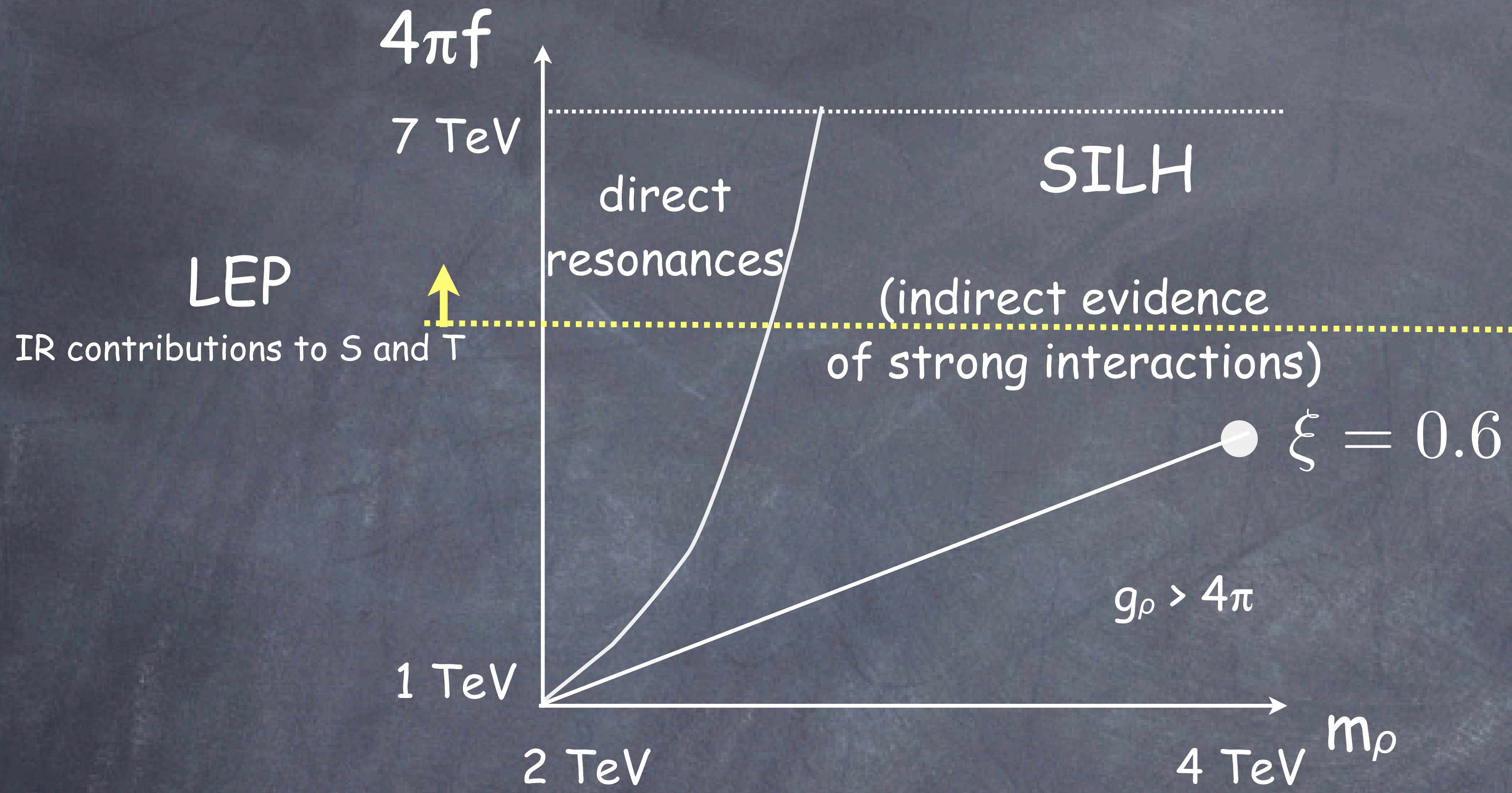
for larger g_ρ, the resonances are increasingly harder to see as

1/ they are broader and heavier

2/ they couple more and more weakly to fermions

LHC could reach a resonance around 4 TeV

Usefulness of SILH effective theory



halfway between model-dependent and blind operator analysis

- dominant effects are associated from strong self-Higgs interactions
- operator analysis: $h \to \gamma\ \gamma$ dominated by c_H and not $|H|^2 B_{\mu\nu}^2$ loop-suppressed

cannot apply the analysis Manohar, Wise '06

(Composite) Top Sector

could the right-handed top belong to the strong sector too?

$$\frac{c_t y_t}{f^2}|H|^2\bar{q}_L\tilde{H}t_R + \frac{ic_R}{f^2}H^\dagger D_\mu H\bar{t}_R\gamma^\mu t_R + \frac{c_{4t}}{f^2}(\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)$$

(composite left-handed top/bottom gives rise to
a too large mass difference of neutral B mesons)

Modified top-quark couplings to h and Z

$$g_{htt} = \frac{gm_t}{2m_W}\left[1-\xi\left(c_t+c_y+\frac{c_H}{2}\right)\right]$$

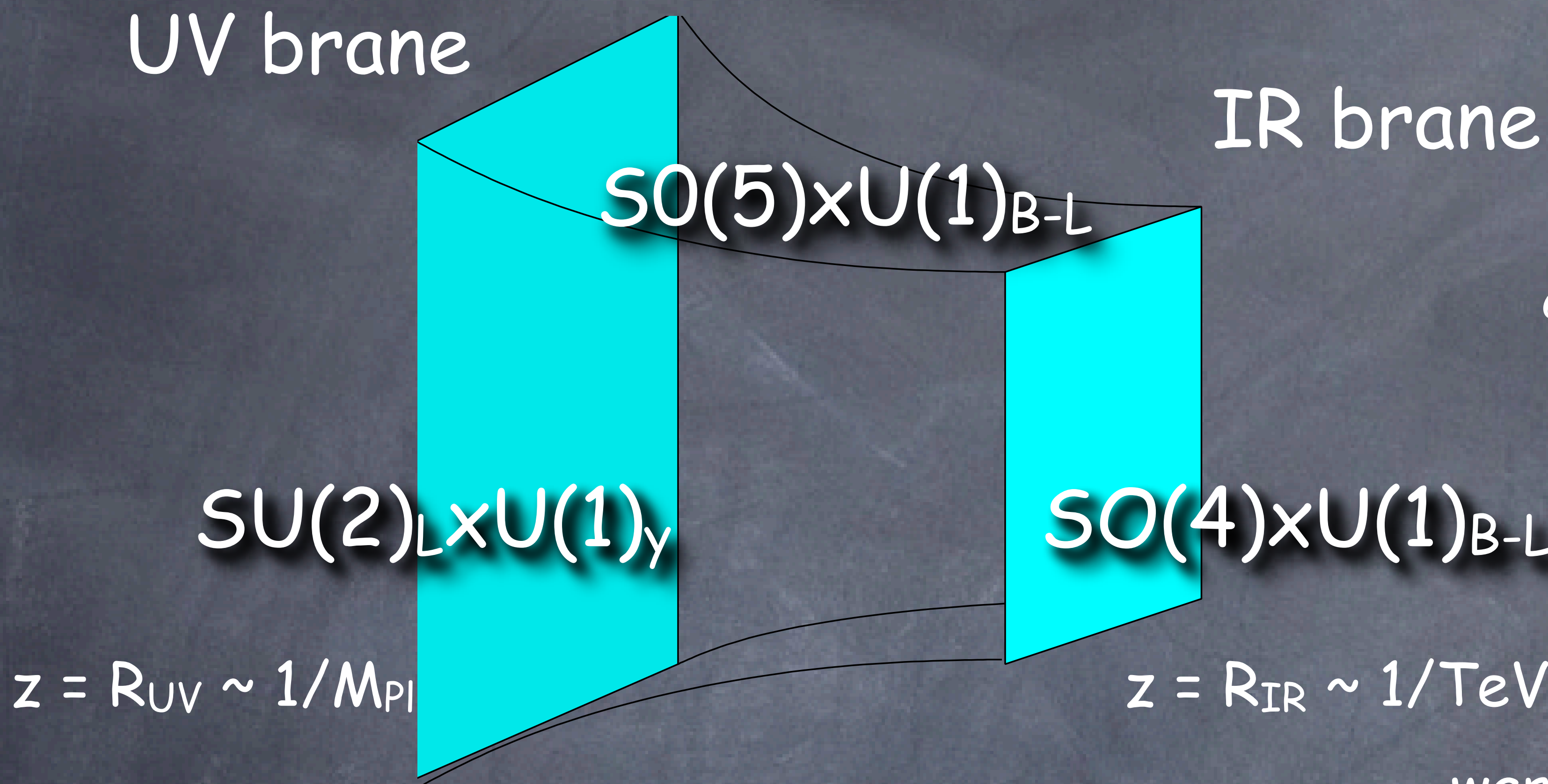
$$g_{Zt_Rt_R} = -\frac{2g\sin^2\theta_W}{3\cos\theta_W}\left(1-\frac{3}{8\sin^2\theta_W}c_R\xi\right)$$

htt can be measured through $gg\to\bar{t}th$ and $h\to\gamma\gamma$

ILC accuracy with √s=800 GeV and L=1000fb^{-1}: 5%

Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04



$$ds^2 = \left(\frac{R}{z}\right)^2 \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$

$$\Omega = \frac{R_{IR}}{R_{UV}} \approx 10^{16}\ \mathrm{GeV}$$

warped dual to composite Higgs model

$$m_W = \frac{gf}{2} \sin\frac{h}{f}$$

$$g_{hWW} = g m_W \left(1 - \frac{\xi}{2}\right) \Rightarrow c_H = 1$$

$$g_{hff} = \frac{g m_f}{2 m_W} \left(1 - \frac{3\xi}{2}\right) \Rightarrow c_y = 1$$

$$g_{hhh} = \frac{3 g m_h^2}{2 m_W} \left(1 - \frac{3\xi}{2}\right) \Rightarrow c_6 = 0$$

SILH

SO(5)/SO(4)

Littlest Higgs

Global symmetry SU(5)/SO(5)

Gauge symmetry $SU(2)_L \times SU(2)_R \times U(1)/SU(2)_W \times U(1)_Y$

(14-3) PGB: 3_1, $2_{1/2}$, 1_0

mass not protected when $g_R \gg g_L$

SILH degrees of freedom

$SU(5)/SO(5) \xrightarrow{g_R \gg g_L} SU(3)/SU(2)$

$$c_H = 1/4 \qquad c_T = -1/16$$

coset structure below the LH partner masses

If $g_R \sim g_L$, $c_T = 0$ and $c_H = 5/16$

but coset structure lost and large corrections of order gL/gR

Little Higgs with Custodial Symmetry

Global symmetry SO(9)/SO(5)xSO(4)

Gauge symmetry $SU(2)_L \times SU(2)_R \times SU(2) \times U(1) / SU(2)_W \times U(1)_Y$

(20-6) PGB: $3_1, 3_0, 2_{1/2}, 1_0$

mass not protected when $g_R \sim g_L \gg g$

SILH degrees of freedom

$$SO(9)/SO(5)\times SO(4) \xrightarrow{g_R \sim g_L \gg g} SO(5)/SO(4)$$

$$c_H = 1/2 \qquad c_T = 0$$

coset structure below the LH partner masses

Conclusions

EW interactions need a UV moderator
to unitarize WW scattering amplitude

Oblique corrections are a test of new physics

W scattering and Higgs anomalous couplings should be able to tell us if the EWSB sector is strongly or weakly coupled.

LHC and ILC are complementary in the exploration
of the TeV scale population