Effective Lagrangian for a Strongly-Interacting Light Higgs

Giudice, Grojean, Pomarol, Rattazzi   hep-ph/0703164

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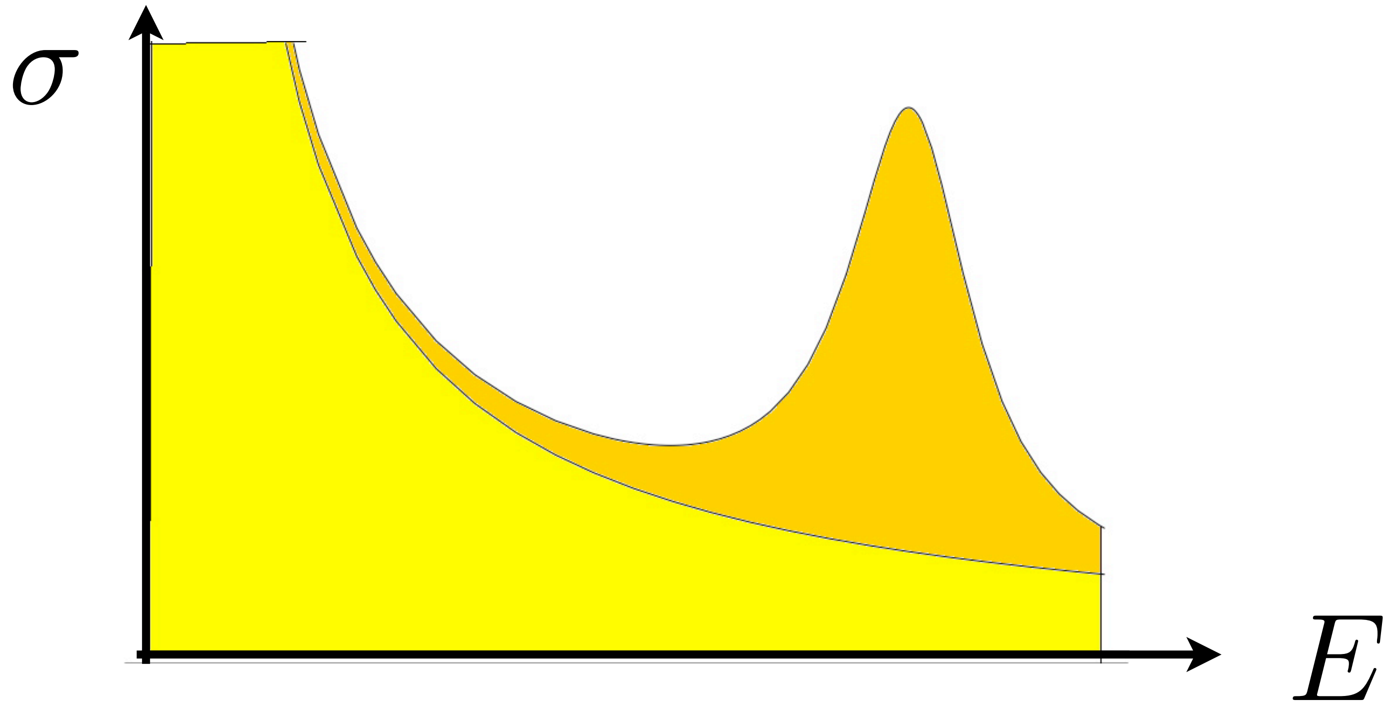
Two modes for New Physics discovery: resonances & tails



Ex. : dim = 6 operators from physics at scale m_ρ and coupling g_ρ

$$\mathcal{L}_{eff} = \frac{g_\rho^2}{m_\rho^2}\mathcal{O}_{d=6}$$

Tails are important in the limit

$m_\rho > E_{beam}$

g_ρ large

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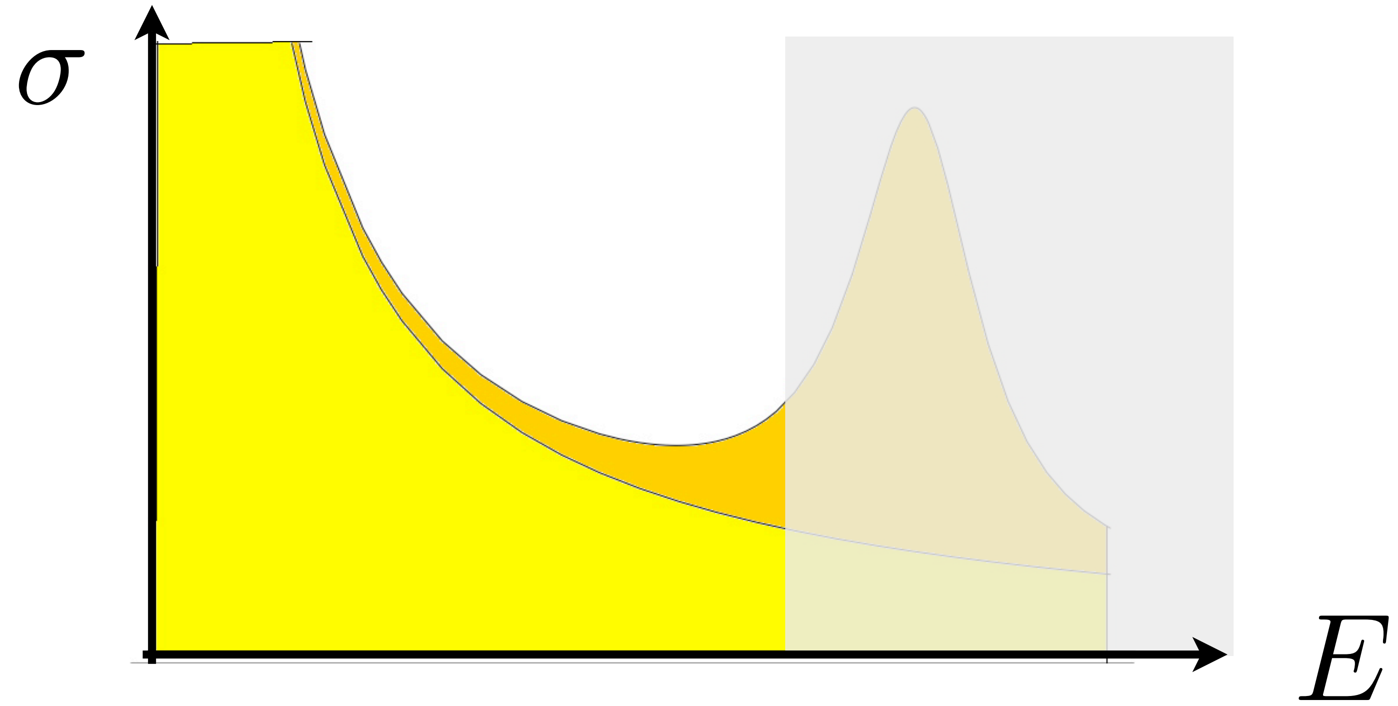

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$g_\rho \sim 4\pi$: compositeness bounds

LEP + Tevatron

$$\mathcal{L}_{4f} = \frac{(4\pi)^2}{\Lambda_c^2} (\bar{e}_L \gamma_\mu e_L)(\bar{e}_L \gamma^\mu e_L) \longrightarrow \Lambda_c > 30\ \text{TeV}$$

quarks $(\bar{q}\gamma_\mu q)^2 \longrightarrow \Lambda_c > 9\ \text{TeV}$

quarks & leptons $(\bar{q}\gamma_\mu q)(e\gamma^\mu e) \longrightarrow \Lambda_c > 20\ \text{TeV}$

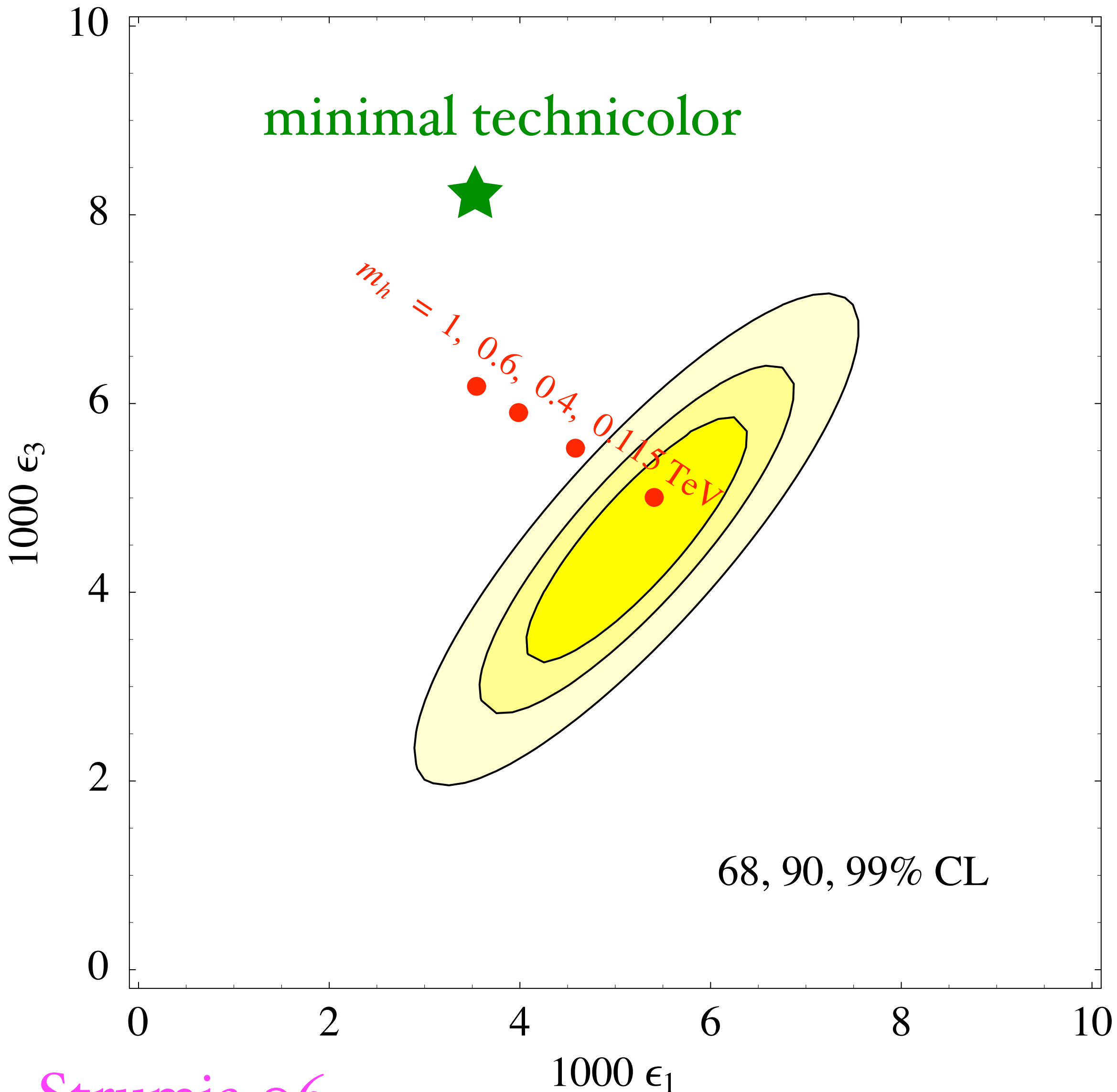
transverse vector bosons: $\longrightarrow \Lambda_c \gtrsim 10\ \text{TeV}$

What about the electroweak breaking sector (eaten Goldstones + ...) ?

hierarchy problem better motivates compositeness in this sector

Technicolor: simplest possibility

but most dramatic in that there is not even a narrow Higgs resonance



Strumia 06

$$\Delta\epsilon_3 \equiv \widehat{S} = \widehat{S}_{UV} + \frac{g^2}{96\pi^2}\ln(m_h/m_Z)$$

$$\widehat{S}_{UV} \sim \frac{g^2}{96\pi^2} N_{TF} N_{TC}$$

Peskin, Takeuchi '89

$$\Delta\epsilon_1 \equiv \widehat{T} = \widehat{T}_{UV} + \frac{3g^2\tan^2\theta_W}{32\pi^2}\ln(m_h/m_Z$$

Minimal TC has no parameter to play with in order to reduce $\widehat{S}$

a light pseudo-Goldstone Higgs helps in possibly two ways

Georgi, Kaplan '84
Dimopoulos, Preskill '82
Banks '84

- it screens IR contribution to $\widehat{S}, \widehat{T}$

- $\widehat{S}_{UV} \simeq \dfrac{g^2 N}{96\pi^2} \times \dfrac{v^2}{f^2}$

$$\begin{cases} \langle H \rangle \equiv v \\ f = \text{pseudo-Goldstone decay const.} \end{cases}$$

$\dfrac{v^2}{f^2}$ depends on extra parameters $\Rightarrow$ can in principle be tuned to be a little bit smaller than 1

Compositeness scale $4\pi f$ could still be as low as a few TeV

Strong sector
$H = \mathcal{G}/\mathcal{H}$

(proto)-Yukawas
$\longleftrightarrow$
gauge coupl.

quarks, leptons
&
gauge bosons

Simplest case:
'80's

- Strong mass scale = m_ρ
- NDA coupling $g_\rho \sim 4\pi$

$$f = \frac{m_\rho}{g_\rho} \sim \frac{m_\rho}{4\pi}$$

'Weakly' coupled version: g_ρ is a free parameter

5D models

$m_\rho \sim m_{KK}$

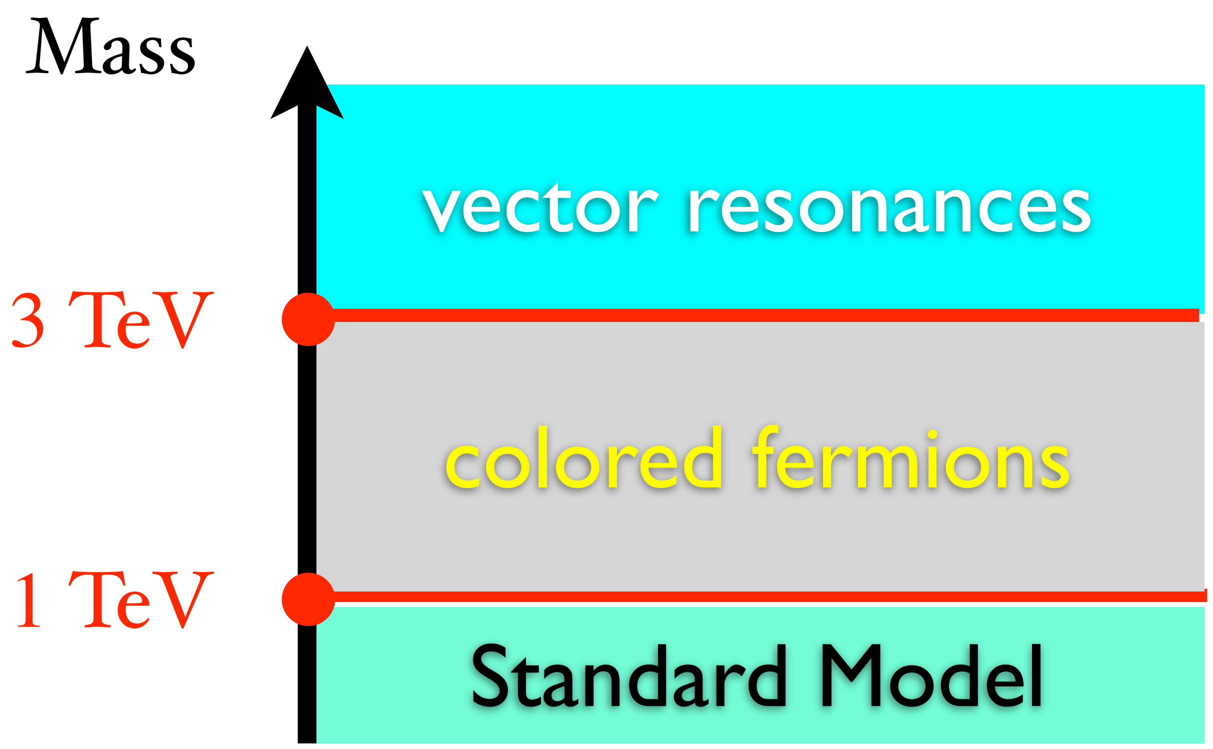
$g_\rho \sim g_{KK}$

Little Higgs

$(m_\rho,\ g_\rho)$

mass and coupling
of 'regulators'

If



Low-energy effective lagrangian for a composite light Higgs
is a useful tool

$$\mathcal{G}/\mathcal{H} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$ + no other fields

$$SO(5)/SO(4) \qquad\qquad SU(3)/SU(2)\times U(1)$$

- Agashe, Contino, Pomarol '04: 5D example
- Chang '03: $SO(9)/SO(5)\times SO(4)$ LH model with 'strongish' extra gauge groups

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Custodial Symmetry

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Derive $(m_\rho,\ g_\rho)$ dependence of dim = 6 effective low-energy lagrangian

$$U = e^{iH/f} \qquad\qquad f = \frac{m_\rho}{g_\rho}$$

$$\mathcal{L}_{strong} = \frac{m_\rho^4}{g_\rho^2}\left[\mathcal{L}^{(0)}(U,\partial/m_\rho) + \frac{g_\rho^2}{(4\pi)^2}\mathcal{L}^{(1)}(U,\partial/m_\rho) + \dots\right] + \mathcal{L}_{break}(U,\Phi_{SM})$$

Basic rules

- each extra H leg costs $\dfrac{g_\rho}{m_\rho}$

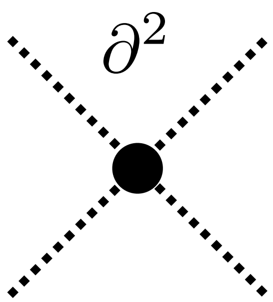
- each extra ∂_μ costs $\dfrac{1}{m_\rho}$

$$\partial_\mu \to \partial_\mu + iA_\mu$$

$$\frac{\partial^2}{m_\rho^2} \to \frac{F_{\mu\nu}}{m_\rho^2}$$

‘Higgs field insertions’

1)



$$\frac{g_\rho^2 \partial^2}{m_\rho^2} = \frac{\partial^2}{f^2}$$

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

$$\left\{ \begin{array}{ll} \frac{1}{f^2} H^\dagger H |D_\mu H|^2 \quad \sim \quad \frac{1}{f^2}\partial^\mu \left(H^\dagger H\right) \partial_\mu \left(H^\dagger H\right) + & \text{non-derivative terms} \\ \text{by field redefinition} & H^\alpha \to H^\alpha + (H^\dagger H) H^\alpha / f^2 \end{array} \right.$$

2) $\lambda_H (H^\dagger H)^2 \to \mathcal{O}_6 = c_6 \dfrac{\lambda_H}{f^2}(H^\dagger H)^3$

3) $y_{ij}\, \bar\psi_i H \psi_j \to \mathcal{O}_y = c_y\, y_{ij}\, \bar\psi_i H \psi_j \dfrac{H^\dagger H}{f^2}$

minimal flavor violation ➡ just one universal operator

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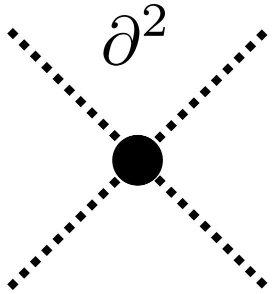
1) 

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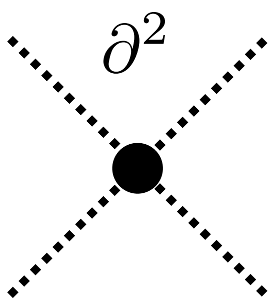

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2 Higgses & 4 covariant derivatives (CP conserving)

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

- generated at tree level by massive vector exchange
- $\widehat{S} = (c_W + c_B)\frac{m_W^2}{m_\rho^2}$ $\qquad$ $m_\rho \gtrsim (c_W + c_B)^{1/2}\ 2.5\,\text{TeV}\quad \text{at}\quad 95\%\ \text{CL}$

$$\frac{v^2}{f^2} \lesssim \frac{1.5}{c_W + c_B}\left(\frac{g_\rho}{4\pi}\right)^2$$

In a maximally strongly coupled theory f could well be quite low

$$\widehat{S} \sim \frac{g^2}{16\pi^2} \times \frac{16\pi^2}{g_\rho^2} \times \frac{v^2}{f^2}$$

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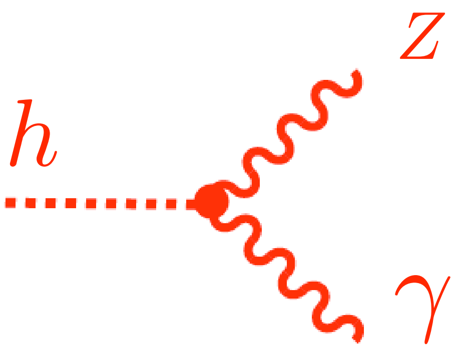
In a maximally strongly coupled theory f could well be quite low

$$\widehat{S} \sim \frac{g^2}{16\pi^2} \times N \times \frac{v^2}{f^2}$$

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



$\propto c_{HW} - c_{HB}$ $\qquad$ $(g-2)_W \propto c_{HW} + c_{HB}$

one does not expect these effects by integrating out heavy modes at tree level in a minimally coupled gauge theory $\Rightarrow$ 1-loop suppression

3) $$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\left(\frac{g}{g_\rho}\right)^p H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

minimal coupling

Goldstone shift symmetry

the gauging of $U(1)_{EM}$ preserves the shift symmetry of neutral Higgs

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

- analogous results apply for Higgs coupling to gluons
- gauging color is consistent with the whole Higgs multiplet being exactly a Goldstone

◆ 'New Couplings'

$$\mathcal{L}_{NC} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y}{f^2} H^\dagger H\,\bar{\psi}_L H \psi_R + \text{h.c.}\right)$$

$$\frac{\delta\mathcal{A}}{\mathcal{A}_{SM}} \sim \frac{v^2}{f^2}$$

◆ 'Form Factors'

$$\mathcal{L}_{FF} = \frac{ic_W}{2m_\rho^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu}H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{ic_B}{2m_\rho^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)\left(\partial^\nu B_{\mu\nu}\right) + \frac{c_\gamma g^2}{16\pi^2 m_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g y_t^2}{16\pi^2 m_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}$$

$$\frac{\delta\mathcal{A}}{\mathcal{A}_{SM}} \sim \frac{E^2}{m_\rho^2}$$

‘Special Form Factors’

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

in principle they test
the strong dynamics

$$\frac{\delta\Gamma(h \to \gamma Z)}{\Gamma(h \to \gamma Z)_{SM}} \sim (c_{HW} - c_{HB})\frac{v^2}{f^2}$$

however this process is hard to measure and the well measured observables are affected as

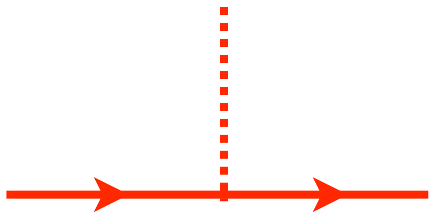
$$\frac{\delta \mathcal{A}}{\mathcal{A}_{SM}} \sim \frac{E^2}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}$$

Effects in Higgs production & decay

all couplings rescaled by

$$c_H \quad \longrightarrow \quad \mathcal{L}_{kin} = \frac{1}{2}\left(1 + c_H \frac{v^2}{f^2}\right) \partial_\mu h \partial^\mu h \qquad \frac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \simeq 1 - c_H \frac{v^2}{2f^2}$$

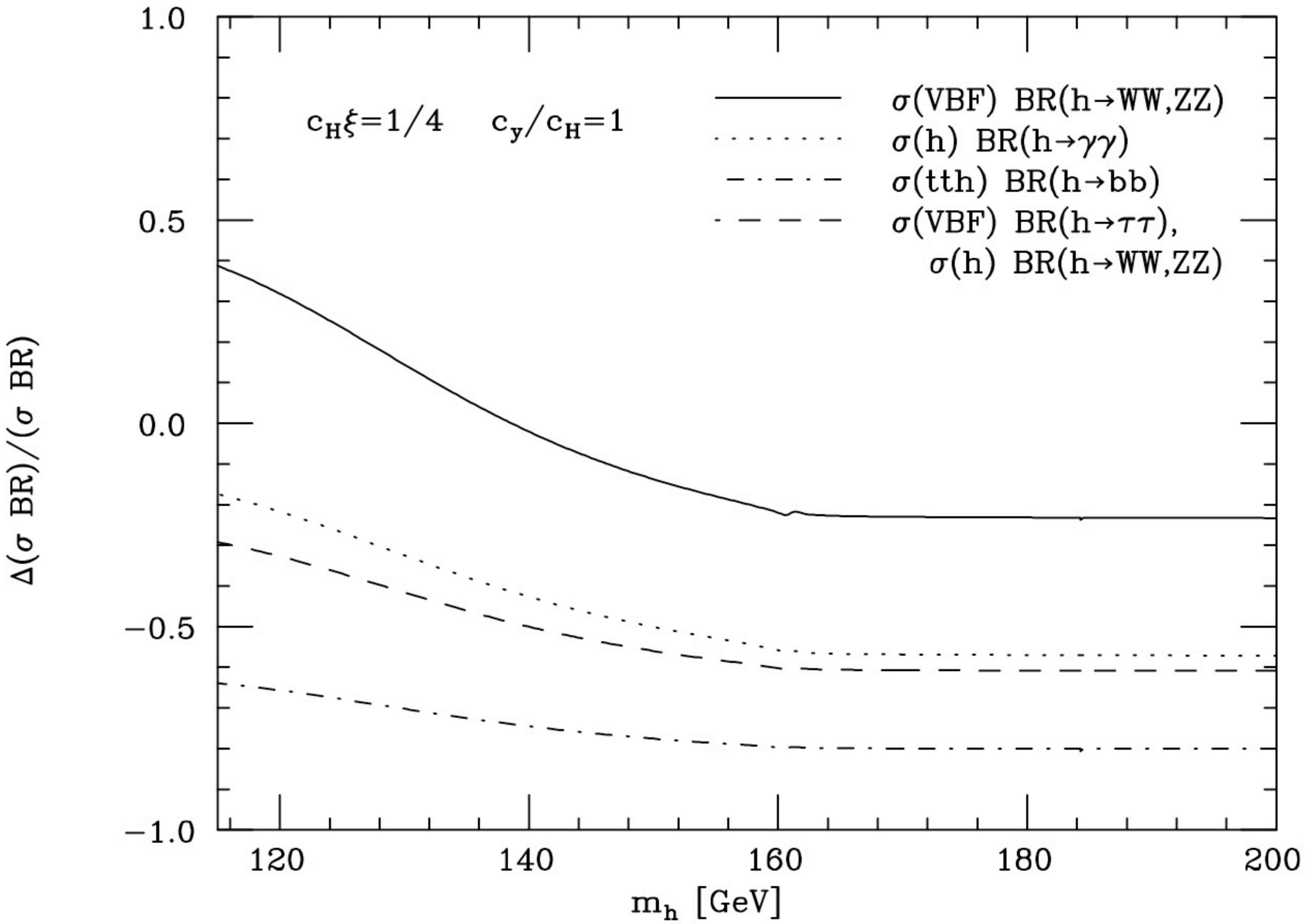
$$c_y \quad \longrightarrow$$



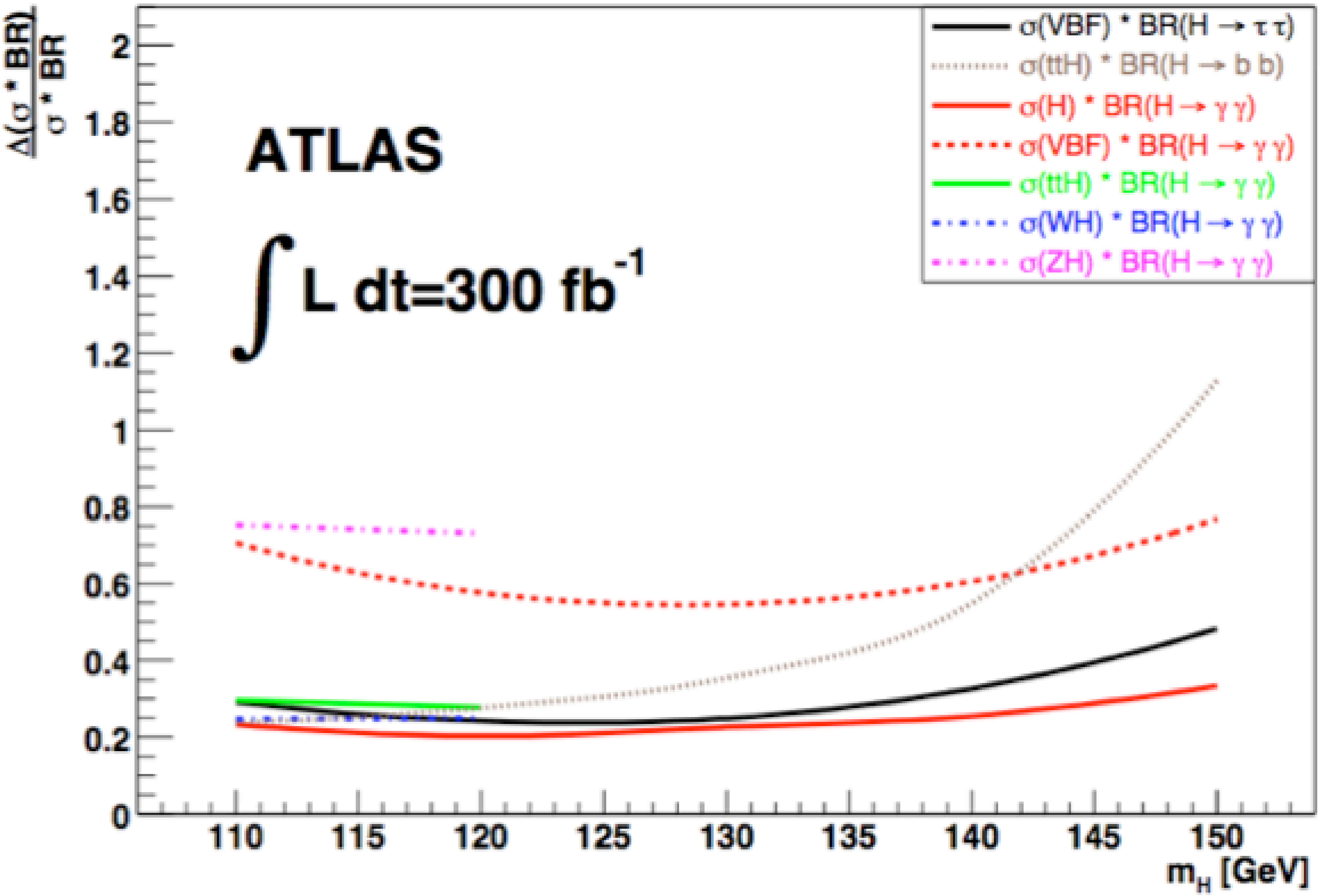
$$\frac{m_\psi}{v}\left(1 - c_y \frac{v^2}{f^2}\right)$$

$$\frac{\Delta\left(\sigma(\mathrm{prod}) \times \mathrm{Br}\right)}{\left(\sigma(\mathrm{prod}) \times \mathrm{Br}\right)_{SM}}$$

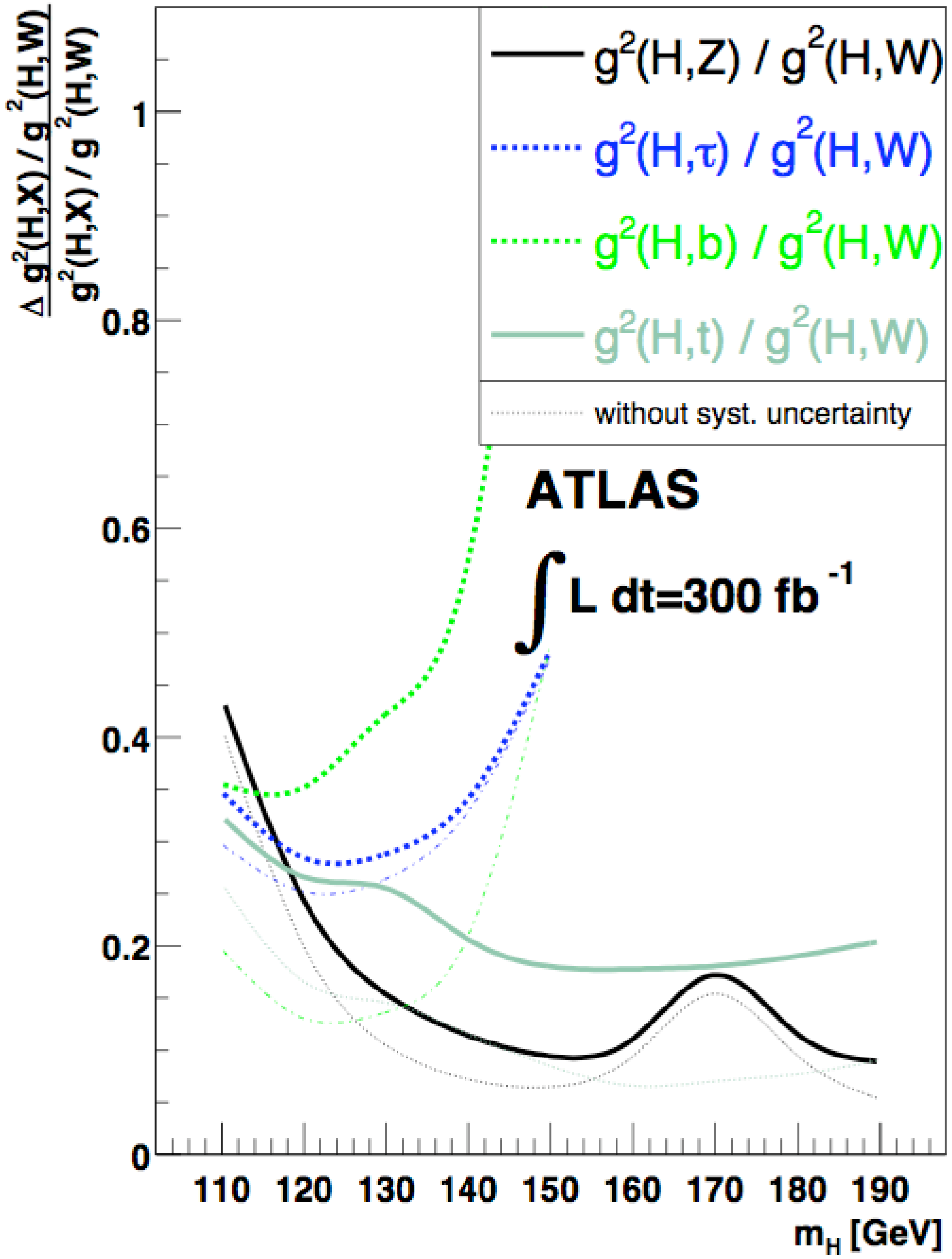
$$= \# c_H \frac{v^2}{f^2} + \# c_y \frac{v^2}{f^2}$$



- at LHC can measure $c_y \frac{v^2}{f^2}, \; c_H \frac{v^2}{f^2}$ up to 20-40 %



Duhrssen 03



- A sizeable deviation from SM in the absence of new light states would be indirect evidence for the composite nature of the Higgs

Coupling	$M_H = 120$ GeV	140 GeV
g_{HWW}	$\pm$ 0.012	$\pm$ 0.020
g_{HZZ}	$\pm$ 0.012	$\pm$ 0.013
g_{Htt}	$\pm$ 0.030	$\pm$ 0.061
g_{Hbb}	$\pm$ 0.022	$\pm$ 0.022
g_{Hcc}	$\pm$ 0.037	$\pm$ 0.102
$g_{H\tau\tau}$	$\pm$ 0.033	$\pm$ 0.048
g_{HWW}/g_{HZZ}	$\pm$ 0.017	$\pm$ 0.024
g_{Htt}/g_{HWW}	$\pm$ 0.029	$\pm$ 0.052
g_{Hbb}/g_{HWW}	$\pm$ 0.012	$\pm$ 0.022
$g_{H\tau\tau}/g_{HWW}$	$\pm$ 0.033	$\pm$ 0.041
g_{Htt}/g_{Hbb}	$\pm$ 0.026	$\pm$ 0.057
g_{Hcc}/g_{Hbb}	$\pm$ 0.041	$\pm$ 0.100
$g_{H\tau\tau}/g_{Hbb}$	$\pm$ 0.027	$\pm$ 0.042

- At ILC one would test $\frac{v^2}{f^2}$ at % level

Barger, Han, Langacker, McElrath, Zerwas 03

J.A. Aguilar Saavedra et al. [ECFA/DESY LC Physics WG]

- Also test deviation from SM in Higgs potential $\frac{c_6 \lambda}{f^2}\left(H^\dagger H\right)^3$

$$c_6 \frac{v^2}{f^2} < 20\%$$

ILC can rule out Higgs compositeness scale $4\pi f$ below 30 TeV

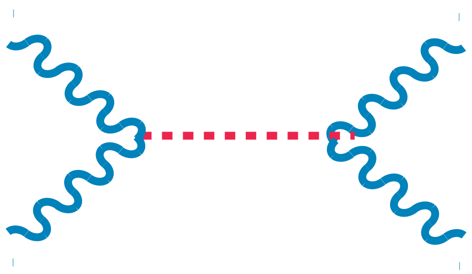
Direct signal of Higgs compositeness

$$\frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)$$

equivalence theorem

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

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



$\propto 1 - c_H \frac{v^2}{f^2}$ fails to unitarize the amplitude

$$\sigma\left(pp \to V_L V_L' X\right)_{c_H} = \left(c_H \frac{v^2}{f^2}\right)^2 \sigma\left(pp \to V_L V_L' X\right)_{\not{H}}$$

leptonic and semileptonic vector decay channels with 300 fb^{-1} $\xrightarrow{\text{sensitivity}}$ $c_H \frac{v^2}{f^2} = 0.5 - 0.7$

Bagger et al., '95
Butterworth et al., '02

$O(4)$ symmetry: Higgs is approximately a 4th (uneaten) Goldstone

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

sum rule

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

$$= O(\mathrm{fb}) \times \left(c_H \frac{v^2}{f^2}\right)^2 \qquad \text{for} \qquad m_{hh} > 1\,\mathrm{TeV}$$

- $hh \to bbbb$ tough QCD background, but worth a try
  - high p_T of b jets
  - signal rather clean from minijets
  - can use forward jet tag
  - can use jet structure

Butterworth, Cox, Forshaw 02

- $hh \to 4W \to \ell^\pm \ell^\pm \nu\nu jets$ more promising

Baur, Plehn, Rainwater 03
Pierce, Thaler, Wang 06

Trilinear vector boson couplings

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

$$g_1^Z = \frac{m_Z^2}{m_\rho^2}\left[c_W + (\frac{g_\rho}{4\pi})^2 c_{HW}\right]$$

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

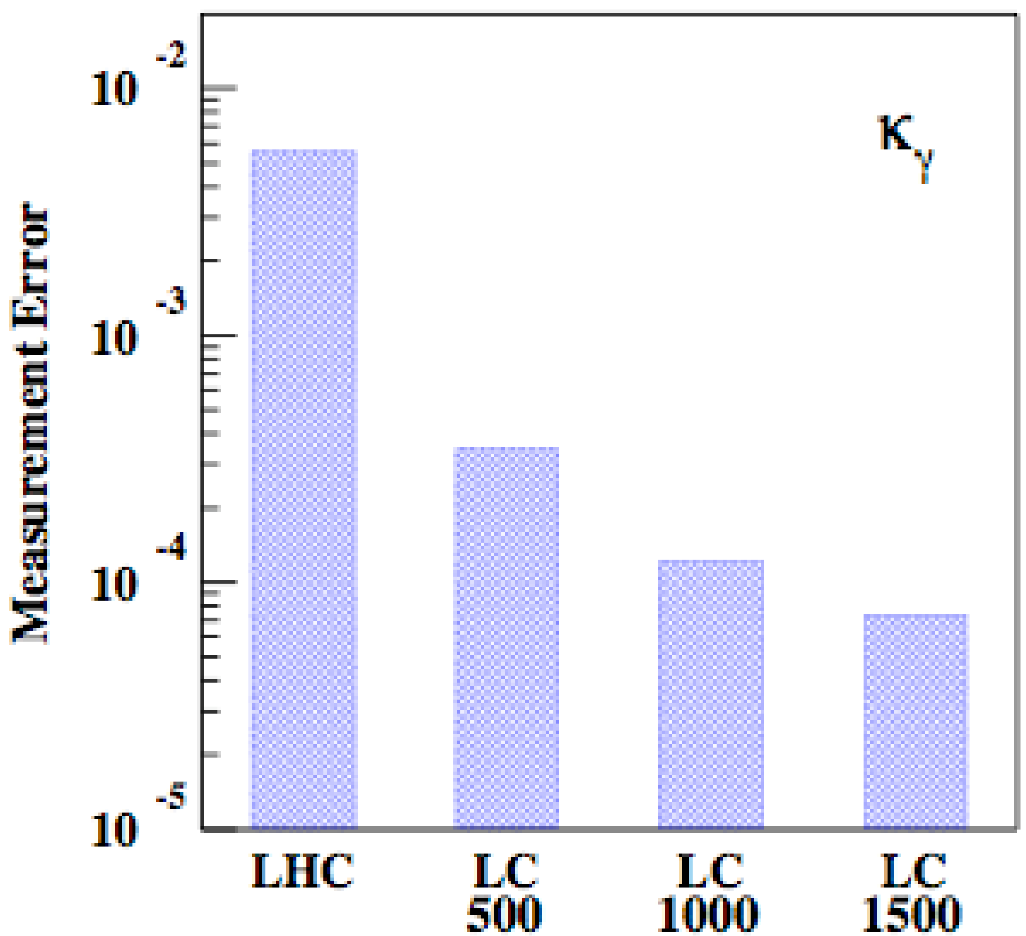
other trilinears $\lambda_{Z,\gamma} \sim \frac{\alpha_W}{4\pi} k_{Z,\gamma}$ $\longrightarrow$ negligible

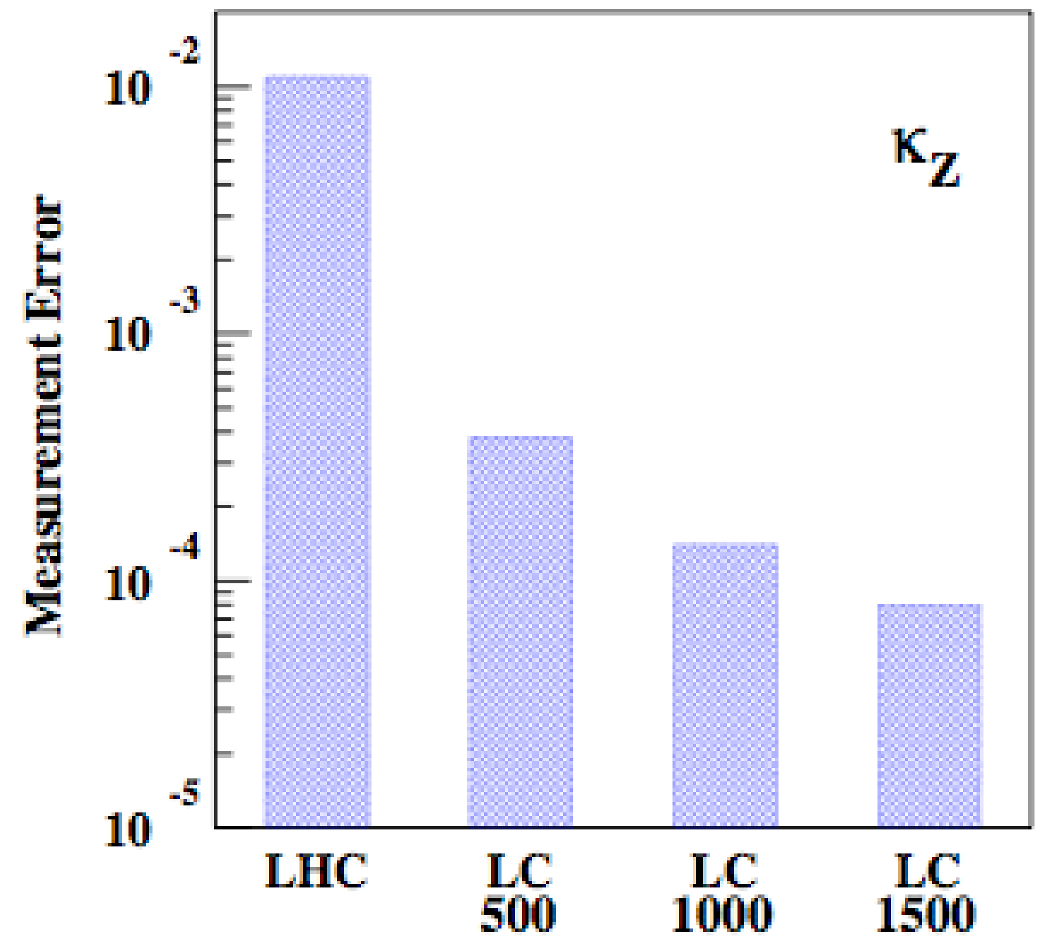
LHC with 100 fb^{-1} can test down to $g_1^Z = 1\%\,,\qquad k_{Z,\gamma} = 5\%$

weaker sensitivity on m_ρ than from direct production of heavy states

or than LEP bound $\widehat{S} < 2 \times 10^{-3}$

Trilinears at ILC



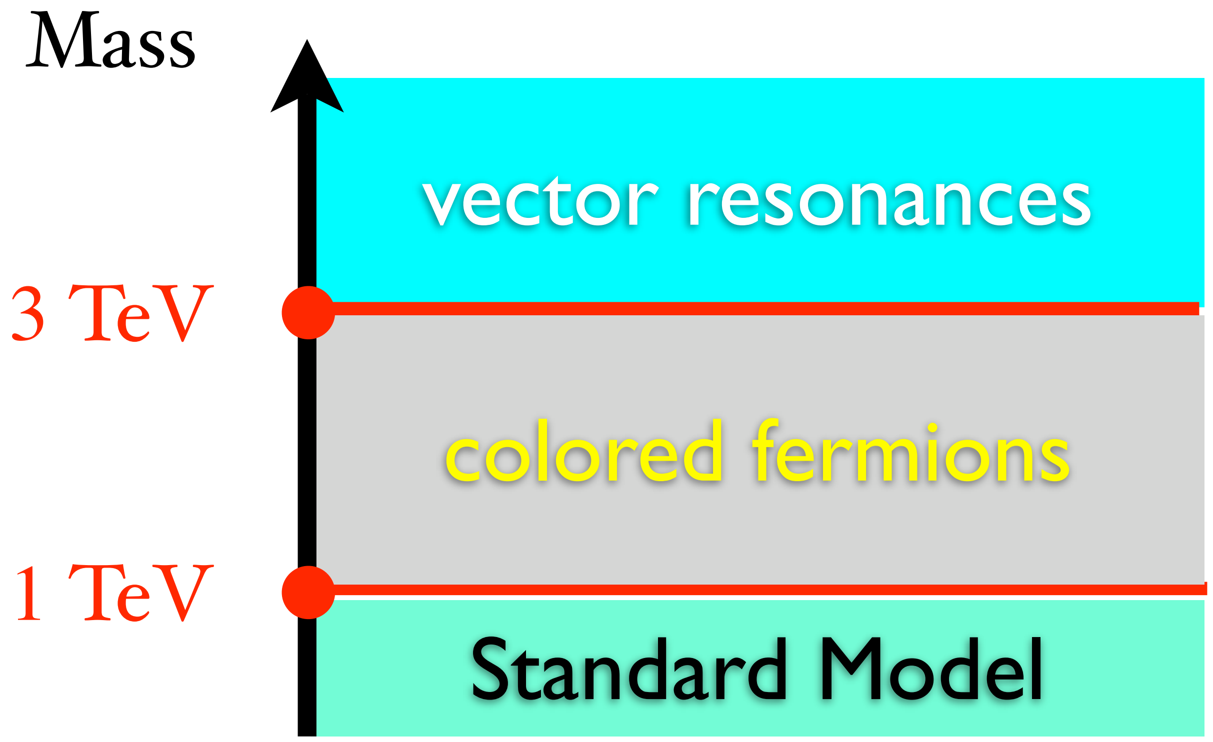


T.Abe et al., [American Linear Collider Working Group]
Snowmass 2001.

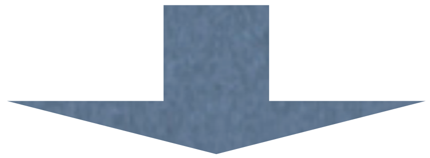
indirect reach $m_\rho = 6 - 8\,\mathrm{TeV}$

in NDA limit $g_\rho = 4\pi$

If



A 'precision' study of Higgs properties would help understanding the origin of the weak scale



Low-energy effective lagrangian description for a composite light Higgs

Custodial & Goldstone Symmetry + Minimal Flavor Violation

3 leading operators

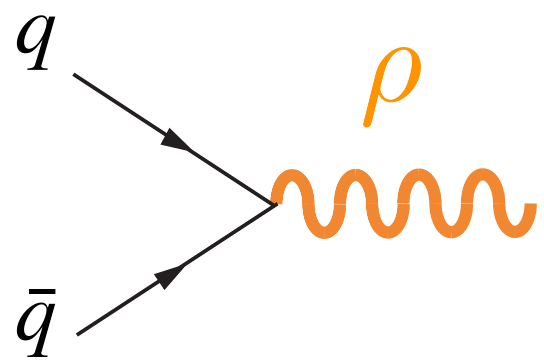
$$\frac{c_H}{2f^2}\left[\partial_\mu\left(H^\dagger H\right)\right]^2 \qquad \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 \qquad \frac{c_y y_{ij}}{f^2} H^\dagger H\,\bar{\psi}_L^i H \psi_R^j$$

Most analyses focus instead on $H^\dagger H\, F_{\mu\nu}F^{\mu\nu}$ Manohar, Wise 06

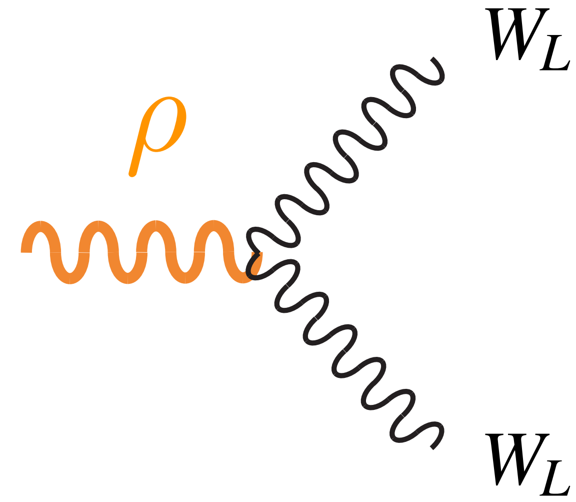
- Single Higgs production with 300 fb^{-1} $\longrightarrow$ $\frac{v^2}{f^2} \lesssim 0.2$
- $W_L W_L$ scattering emerges as a relevant process to study even in the presence of a light Higgs
- $W_L W_L \to hh$
- ILC, with 500 fb^{-1} and $\sqrt{s} = 500\,\mathrm{GeV}$ $\longrightarrow$ $\frac{v^2}{f^2} \lesssim 10^{-2}$

$$4\pi f \gtrsim 30\,\mathrm{TeV}$$

Drell-Yan production of heavy resonances



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



$$= g_\rho$$

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

at fixed $f = \dfrac{m_\rho}{g_\rho}$ resonances are increasingly harder to see as $g_\rho \to 4\pi$

- broad & heavy
- couple weakly to SM fermions