New Physics in the Higgs Sector

Tilman Plehn

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Higgs boson

Two problems for spontaneous gauge symmetry breaking

- problem 1: Goldstone's theorem
  $SU(2)_L \times U(1)_Y \to U(1)_Q$ gives 3 massless scalars
- problem 2: massive gauge theories
  massive gauge bosons have 3 polarizations, and $3 \neq 2$

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Higgs-related papers [also Brout & Englert; Guralnik, Hagen, Kibble]

– 1964: combining two problems to one predictive solution

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if

about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \quad (2a)$$

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A detailed discussion of these questions will be presented elsewhere.

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

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[1] P. W. Higgs, to be published.
[2] J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev.

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PHYSICAL REVIEW VOLUME 145, NUMBER 4 27 MAY 1966

Spontaneous Symmetry Breakdown without Massless Bosons*

PETER W. HIGGS†
Department of Physics, University of North Carolina, Chapel Hill, North Carolina
(Received 27 December 1965)

We examine a simple relativistic theory of two scalar fields, first discussed by Goldstone, in which as a result of spontaneous breakdown of $U(1)$ symmetry one of the scalar bosons is massless, in conformity with the Goldstone theorem. When the symmetry group of the Lagrangian is extended from global to local $U(1)$ transformations by the introduction of coupling with a vector gauge field, the Goldstone boson becomes the longitudinal state of a massive vector boson whose transverse states are the quanta of the transverse gauge field. A perturbative treatment of the model is developed in which the major features of these phenomena are present in zero order. Transition amplitudes for decay and scattering processes are evaluated in lowest order, and it is shown that they may be obtained more directly from an equivalent Lagrangian in which the original symmetry is no longer manifest. When the system is coupled to other systems in a $U(1)$ invariant Lagrangian, the other systems display an induced symmetry breakdown, associated with a partially conserved current which interacts with itself via the massive vector boson.

I. INTRODUCTION

THE idea that the apparently approximate nature of the internal symmetries of elementary-particle physics is the result of asymmetries in the stable solutions of exactly symmetric dynamical equations, rather than an indication of asymmetry in the dynamical

appear have been used by Coleman and Glashow[3] to account for the observed pattern of deviations from $SU(3)$ symmetry.

The study of field theoretical models which display spontaneous breakdown of symmetry under an internal Lie group was initiated by Nambu,[4] who had noticed[5]

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II. THE MODEL

The Lagrangian density from which we shall work is given by[29]

$$\mathcal{L} = -\tfrac{1}{4} g^{\kappa\mu} g^{\lambda\nu} F_{\kappa\lambda} F_{\mu\nu} - \tfrac{1}{2} g^{\mu\nu} \nabla_\mu \Phi_a \nabla_\nu \Phi_a + \tfrac{1}{4} m_0^2 \Phi_a \Phi_a - \tfrac{1}{8} f^2 (\Phi_a \Phi_a)^2. \quad (1)$$

In Eq. (1) the metric tensor $g^{\mu\nu} = -1$ ($\mu = \nu = 0$), $+1$ ($\mu = \nu \neq 0$) or 0 ($\mu \neq \nu$), Greek indices run from 0 to 3 and Latin indices from 1 to 2. The $U(1)$-covariant derivatives $F_{\mu\nu}$ and $\nabla_\mu \Phi_a$ are given by

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,$$

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derivatives $F_{\mu\nu}$ and $\nabla_\mu \Phi_a$ are given by

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i. Decay of a Scalar Boson into Two Vector Bosons

The process occurs in first order (four of the five cubic vertices contribute), provided that $m_0 > 2m_1$. Let p be the incoming and k_1, k_2 the outgoing momenta. Then

$$M = i\{e[a^{*\mu}(k_1)(-ik_{2\mu})\phi^*(k_2) + a^{*\mu}(k_2)(-ik_{1\mu})\phi^*(k_1)] - e(ip_\mu)[a^{*\mu}(k_1)\phi^*(k_2) + a^{*\mu}(k_2)\phi^*(k_1)] - 2em_1 a_\mu^*(k_1) a^{*\mu}(k_2) - fm_0\phi^*(k_1)\phi^*(k_2)\} .$$

By using Eq. (15), conservation of momentum, and the transversality $(k_\mu b^\mu(k) = 0)$ of the vector wave functions we reduce this to the form

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– lots of collider phenomenology starting in 1976

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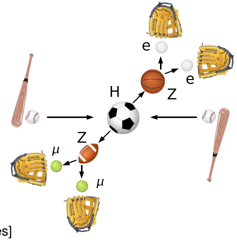
Adding in Glashow–Weinberg–Salam–'t Hooft–Veltman

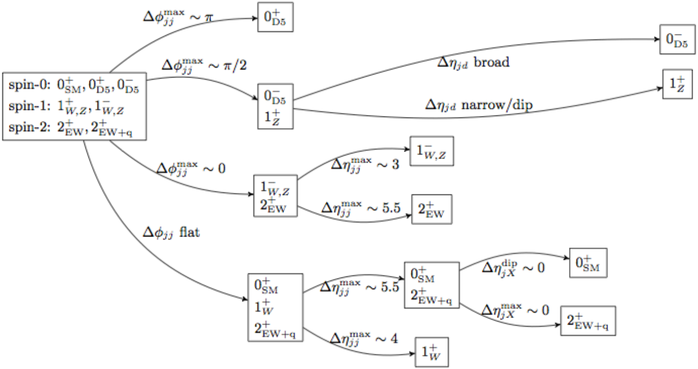
– massive, minimal Standard Model complete
– renormalizability unique for particle physics [and cosmology]
– only fundamental Higgs helps
$\Rightarrow$ Higgs a powerful handle for new physics

Questions for Run 2



1. What is the 'Higgs' Lagrangian?

- psychologically: looked for Higgs, so found a Higgs
- CP-even spin-0 scalar expected, which operators?
  spin-1 vector unlikely
  spin-2 graviton unexpected
- ask flavor colleagues [Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles]



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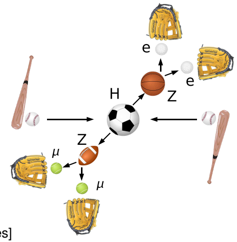

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   - set of ‘couplings’ given Lagrangian
   - modified Higgs sectors
   - Higgs effective theory

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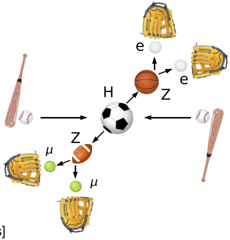

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3. What does all this tell us?

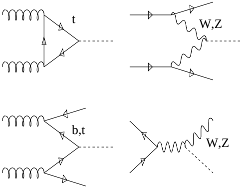
   – strongly interacting models?

   – weakly interacting two-Higgs-doublet models?

   – TeV-scale new physics?

   – vacuum stability, Higgs inflation, etc

Couplings



Standard Model operators

[SFitter: Gonzalez-Fraile, Klute, TP, Rauch, Zerwas]

– assume: narrow CP-even scalar
  Standard Model operators
– couplings from production & decay rates
– test Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible decays} \; ,$$

– electroweak renormalizability through UV completion
– QCD renormalizability not an issue
– frequentist likelihood everywhere
– total rates only

$gg \to H$
$qq \to qqH$
$gg \to t\bar{t}H$
$qq' \to VH$

$\longleftrightarrow$ $g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)$ $\longleftrightarrow$

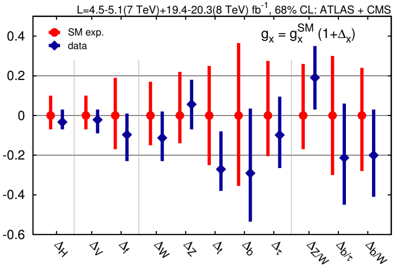
$H \to ZZ$
$H \to WW$
$H \to b\bar{b}$
$H \to \tau^+\tau^-$
$H \to \gamma\gamma$

Couplings now and in the future

Run I legacy [Corbett, Eboli, Goncalves, Gonzalez-Fraile, Lopez-Val, TP, Rauch]

– assume SM-like [secondary solutions possible]

– SFitter: correct theory uncertainties



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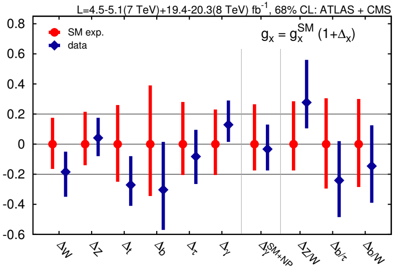

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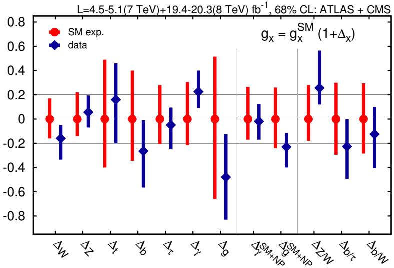

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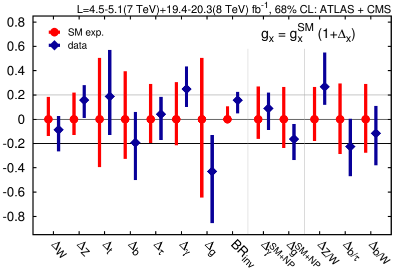
– eight couplings state of the art

⇒ Standard Model within 25%



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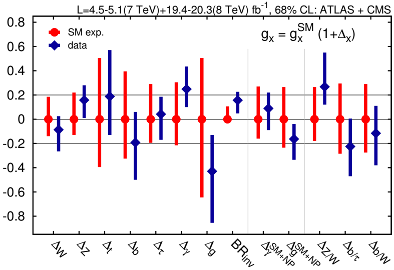
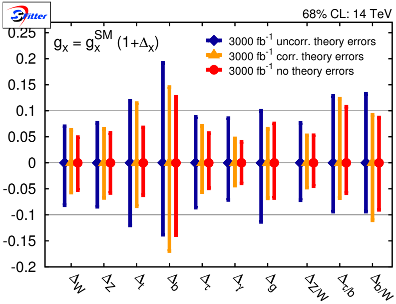


Future [SFitter; Cranmer, Kreiss, Lopez-Val, TP]

- LHC extrapolations unclear
- systematic/theory uncertainties large
- ratios sensible

$\Rightarrow$ who deals with theory uncertainties?



Modified Higgs sector

Non-minimal Higgs sectors [Lopez-Val, TP, Rauch; many, many, many papers]

- what is the Higgs sector's structure?
- assume we see 'a Higgs', extend by singlet or doublet
- coupling modifications of SM-like state
- proper renormalizable models

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Two doublets [no flavor, CP, custodial troubles]

– angle $\beta = \text{atan}(v_2/v_1)$
angle α defining h and H
gauge boson coupling $g_{W,Z} = \sin(\beta - \alpha) g_{W,Z}^{\text{SM}}$

– type-I: all fermions with ϕ_2
type-II: up-type fermions with ϕ_2
lepton-specific: type-I quarks and type-II leptons
flipped: type-II quarks and type-I leptons
interpolated as Yukawa aligned: $y_b \cos(\beta - \gamma_b) = \sqrt{2} m_b / v$

– compressed masses $m_h \sim m_H$ [thanks to Berthold Stech]
single hierarchy $m_h \ll m_{H,A,H^\pm}$ protected by custodial symmetry

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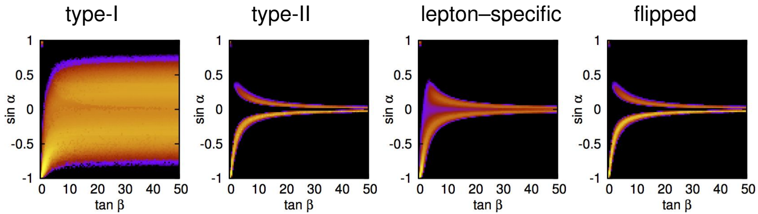
Facing data

– fit including single heavy Higgs mass
– decoupling regime $\sin^2\alpha \sim 1/(1+\tan^2\beta)$
⇒ 2HDMs good fit with decoupling heavy Higgs



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Yukawa-aligned 2HDM

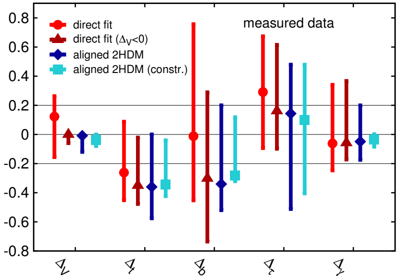
– $\Delta_V \leftrightarrow (\beta - \alpha) \qquad \Delta_{b,t,\tau} \leftrightarrow \{\beta, \gamma_{b,\tau}\} \qquad \Delta_\gamma \leftrightarrow m_{H^\pm}$

– Δ_g not free parameter, top partner?
custodial symmetry built in at tree level $\Delta_V < 0$

– Higgs-gauge quantum corrections
enhanced $\Delta_V < 0$

– fermion quantum corrections
large for $\tan\beta \ll 1$
$\Delta_W \neq \Delta_Z > 0$ possible

$\Rightarrow$ free SM couplings well defined



Extended Higgs sectors

Decoupling in one dimension [Cranmer, Kreiss, Lopez-Val, TP]

– decoupling defined through the massive gauge sector

$$\frac{g_V}{g_V^{\text{SM}}} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \qquad \Leftrightarrow \qquad \Delta_V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3)$$

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$$\Gamma_{\text{inv}} = \xi^2 \Gamma_{\text{SM}} \qquad\qquad \mu_{p,d} = \frac{\Gamma_{\text{SM}}}{\Gamma_{\text{SM}} + \Gamma_{\text{inv}}} = 1 - \xi^2 + \mathcal{O}(\xi^3) < 1$$

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$$1 + \Delta_x = \cos\theta = \sqrt{1 - \xi^2} \qquad\qquad \mu_{p,d} = 1 - \xi^2 + \mathcal{O}(\xi^3) < 1$$

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– composite Higgs

$$\xi = \frac{v}{f} \qquad \frac{\mu_{\text{WBF},d}}{\mu_{\text{GF},d}} = \frac{(1 - \xi^2)^2}{(1 - 2\xi^2)^2} = 1 + 2\xi^2 + \mathcal{O}(\xi^3) > 1$$

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$$1 + \Delta_V = \sin(\beta - \alpha) = \sqrt{1 - \xi^2}$$

– MSSM [plus tan β]

$$\xi^2 =\simeq \frac{m_h^2\,(m_Z^2 - m_h^2)}{m_A^2(m_H^2 - m_h^2)} \sim \frac{m_Z^4\ \sin^2(2\beta)}{m_A^4}$$

Extended Higgs sectors

Decoupling in one dimension [Cranmer, Kreiss, Lopez-Val, TP]

– decoupling defined through the massive gauge sector

$$\frac{g_V}{g_V^{\text{SM}}} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \qquad \Leftrightarrow \qquad \Delta_V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3)$$

– dark singlet

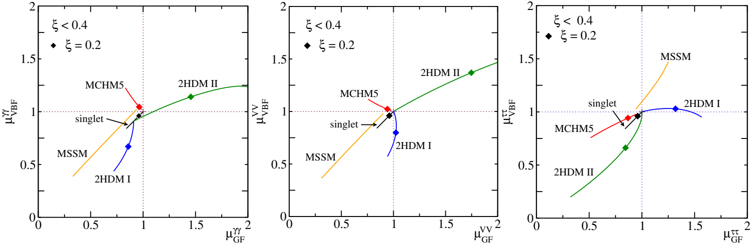
$$\Gamma_{\text{inv}} = \xi^2 \Gamma_{\text{SM}} \qquad \mu_{p,d} = \frac{\Gamma_{\text{SM}}}{\Gamma_{\text{SM}} + \Gamma_{\text{inv}}} = 1 - \xi^2 + \mathcal{O}(\xi^3) < 1$$

– mixing singlet [no anomalous decays]

$$1 + \Delta_x = \cos\theta = \sqrt{1 - \xi^2} \qquad \mu_{p,d} = 1 - \xi^2 + \mathcal{O}(\xi^3) < 1$$

– composite Higgs

$$\xi = \frac{v}{f} \qquad \frac{\mu_{\text{WBF},d}}{\mu_{\text{GF},d}} = \frac{(1-\xi^2)^2}{(1-2\xi^2)^2} = 1 + 2\xi^2 + \mathcal{O}(\xi^3) > 1$$



D6 operators

Higgs sector effective field theory [following Corbett, Eboli, Gonzalez-Fraile, Goncales-Garcia]

– set of Higgs-gauge operators

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– relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_{B} + \frac{f_W}{\Lambda^2} \mathcal{O}_{W} + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2}$$

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– Higgs couplings to SM particles

$$\begin{aligned}
\mathcal{L}^{HVV} &= g_g \; H G^a_{\mu\nu} G^{a\mu\nu} + g_\gamma \; H A_{\mu\nu} A^{\mu\nu} \\
&+ g_Z^{(1)} \; Z_{\mu\nu} Z^\mu \partial^\nu H + g_Z^{(2)} \; H Z_{\mu\nu} Z^{\mu\nu} + g_Z^{(3)} \; H Z_\mu Z^\mu \\
&+ g_W^{(1)} \; \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu H + \text{h.c.} \right) + g_W^{(2)} \; H W^+_{\mu\nu} W^{-\,\mu\nu} + g_W^{(3)} \; H W^+_\mu W^{-\,\mu} + \cdots
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– plus Yukawa structure $f_{\tau,b,t}$

– 9 operators for Run I data

D6 operators

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– observable Higgs couplings

$$g_g = \frac{f_{GG} v}{\Lambda^2} \equiv -\frac{\alpha_s}{8\pi} \frac{f_g v}{\Lambda^2} \qquad g_\gamma = -\frac{g^2 v s_w^2}{2\Lambda^2} \frac{f_{BB} + f_{WW}}{2}$$

$$g_Z^{(1)} = \frac{g^2 v}{2\Lambda^2} \frac{c_w^2 f_W + s_w^2 f_B}{2 c_w^2} \qquad g_W^{(1)} = \frac{g^2 v}{2\Lambda^2} \frac{f_W}{2}$$

$$g_Z^{(2)} = -\frac{g^2 v}{2\Lambda^2} \frac{s_w^4 f_{BB} + c_w^4 f_{WW}}{2 c_w^2} \qquad g_W^{(2)} = -\frac{g^2 v}{2\Lambda^2} f_{WW}$$

$$g_Z^{(3)} = M_Z^2 (\sqrt{2} G_F)^{1/2} \left(1 - \frac{v^2}{2\Lambda^2} f_{\Phi,2} \right) \qquad g_W^{(3)} = M_W^2 (\sqrt{2} G_F)^{1/2} \left(1 - \frac{v^2}{2\Lambda^2} f_{\Phi,2} \right)$$

$$g_f = -\frac{m_f}{v} \left(1 - \frac{v^2}{2\Lambda^2} f_{\Phi,2} \right) + \frac{v^2}{\sqrt{2}\Lambda^2} f_f$$

D6 operators

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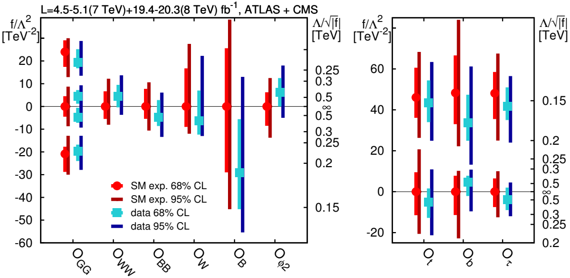
SFitter analysis

– same setup and data as before



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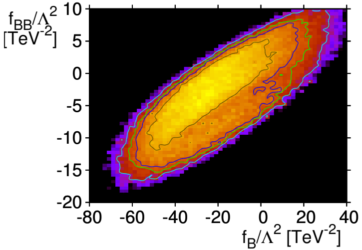
– correlations a problem [diagonalization means $1 + \Delta$]

– improvement on theory side?



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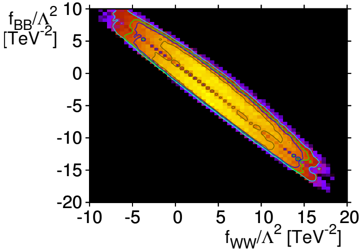

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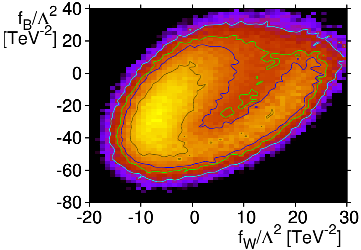

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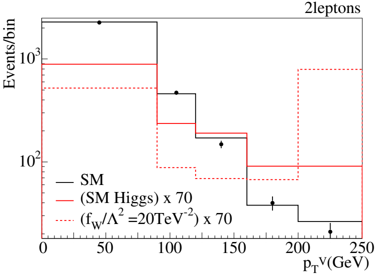
Including distributions

– some operators momentum-dependent

– example: $p_{T,V}$ or $\Delta\Phi_{jj}$



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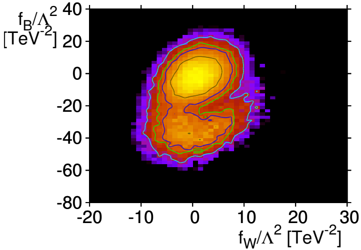

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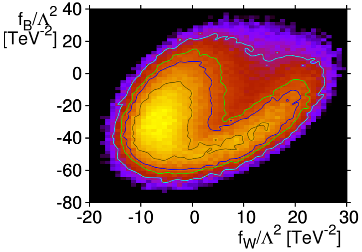

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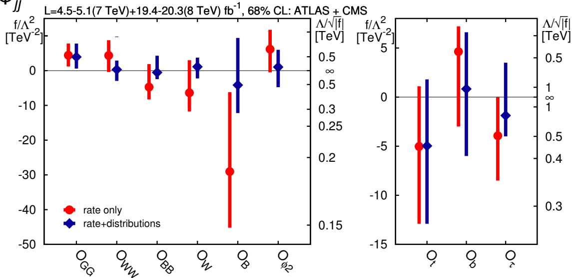
$\Rightarrow$ just a start...



Distributions 1: Boosted Higgs

Top–Higgs–gluon Lagrangian [Ellis, Hinchliffe, Soldate, v d Bij; Baur & Glover]

– *ggH* vertex structure [to keep production rate]

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \left(\Delta_t g_{ggH} + \Delta_g \frac{\alpha_s}{12\pi} \right) \frac{H}{v} G_{\mu\nu} G^{\mu\nu}$$

– high-p_T logarithms from 1,2 jets [Banfi etal; Azatov etal; Grojean etal; Buschmann etal]

$$|\mathcal{M}_{Hj(j)}|^2 \sim \frac{m_t^4}{p_T^4} \log^4 \frac{p_T^2}{m_t^2}$$

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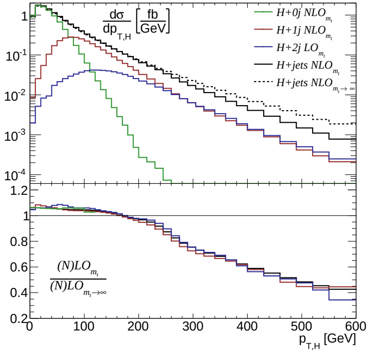
Measuring $\Delta_{t,g}$ from $p_{T,H}$ distributions [Buschmann, Goncalves, Kuttimalai, Schönherr, Krauss, TP]

– simulation: SHERPA-NLO

– sensitive region $p_{T,H} > 250$ GeV
theory errors not small [ask Alessandro, Giancarlo]

– NLO vs top mass orthogonal
jet count vs top mass orthogonal



Distributions 1: Boosted Higgs

Top–Higgs–gluon Lagrangian [Ellis, Hinchliffe, Soldate, v d Bij; Baur & Glover]

– *ggH* vertex structure [to keep production rate]

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \left(\Delta_t g_{ggH} + \Delta_g \frac{\alpha_s}{12\pi} \right) \frac{H}{v} G_{\mu\nu} G^{\mu\nu}$$

– high-p_T logarithms from 1,2 jets [Banfi etal; Azatov etal; Grojean etal; Buschmann etal]

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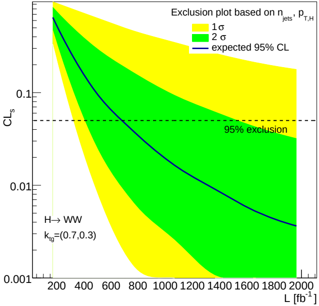
$H \to WW$ analysis
2D likelihood study of $n_{\text{jets}}, p_{T,H}$

$\Rightarrow$ $\Delta_t = -0.3$ to 95% CL with 700 fb^{-1}



Distributions 2: Off-Shell Higgs

Not-model-independent width measurements [Kauer & Passarino; Caola & Melnikov; Ellis & Williams]

– peak cross section vs off-shell interference in $H \to ZZ$

$$\sigma_{\text{peak}} \sim \frac{g_g^2 g_Z^2}{(s-m^2)^2 + m^2\Gamma^2} = \frac{g_g^2 g_Z^2}{m^2\Gamma^2} \qquad \sigma_{\text{off}}(g_g g_Z) \sim \sigma_{cont} - \frac{A_{\text{int}}\, g_g g_Z}{s-m^2} + \frac{A_H\, g_g^2 g_Z^2}{(s-m^2)^2}$$

– top–Higgs–gluon Lagrangian again [$m_{4\ell} \gg m_t > m_H$]

$$\mathcal{M}_{gg\to ZZ} \sim \pm \frac{m_t^2}{m_Z^2} \log^2 \frac{m_{4\ell}^2}{m_t^2}$$

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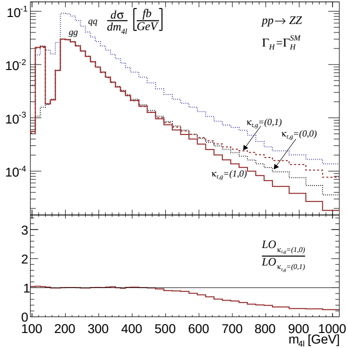

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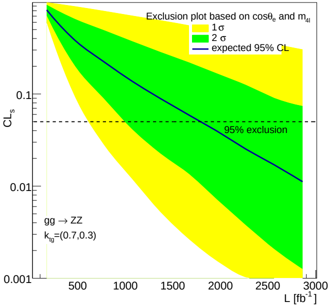
$H \to ee\mu\mu$ analysis
2D likelihood study of $\cos\theta_e, m_{4\ell}$

$\Rightarrow$ $\Delta_t = -0.3$ to 95% CL with 1700 fb^{-1}

$\Rightarrow$ still included in SFitter analysis



Meaning

TeV scale

- fourth chiral generation excluded
- strongly interacting models retreating [Goldstone protection]
- extended Higgs sectors wide open
- no final verdict on the MSSM
- hierarchy problem worse than ever [light fundemental scalar discovered]

$\Rightarrow$ whatever...

Meaning

High scales [Holthausen, Lim, Lindner; Wetterich etal; Buttazo etal; Gies etal]

– Planck-scale extrapolation

$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda\left(3g_2^2 + g_1^2\right) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

– IR fixed point for λ/λ_t^2 fixing m_H^2/m_t^2 [with gravity: Shaposhnikov, Wetterich]

$$m_H = 126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5$$

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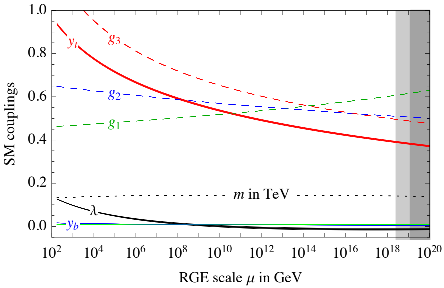
– RG running of Higgs potential

– $\lambda < 0$ at finite energy? [Buttazo etal]



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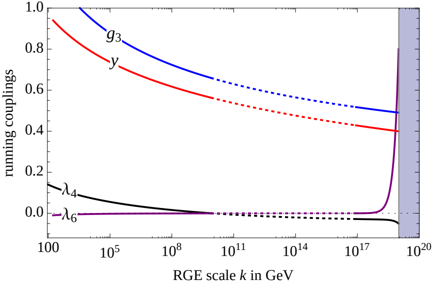

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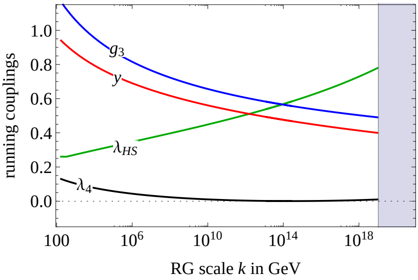

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Exercise: top–Higgs renormalization group

Running of coupling/mass ratios [Wetterich]

Higgs self coupling and top Yukawa with stable zero IR solutions

$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left(12\lambda^2 + 6\lambda y_t^2 - 3y_t^4\right) \qquad \frac{d\,y_t^2}{d\,\log Q^2} = \frac{9}{32\pi^2}\,y_t^4$$

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running ratio $R = \lambda/y_t^2$

$$\frac{dR}{d\log Q^2} = \frac{3\lambda}{32\pi^2 R}\left(8R^2 + R - 2\right) \stackrel{!}{=} 0 \qquad \Leftrightarrow \qquad R_* = \frac{\sqrt{65}-1}{16} \simeq 0.44$$

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numbers in the far infrared, better for $Q \sim v$

$$\frac{\lambda}{y_t^2} = \frac{m_H^2}{2v^2}\,\frac{v^2}{2m_t^2}\bigg|_{\text{IR}} = \frac{m_H^2}{4m_t^2}\bigg|_{\text{IR}} = 0.44 \qquad \Leftrightarrow \qquad \frac{m_H}{m_t}\bigg|_{\text{IR}} = 1.33$$

Questions

Big questions

- is it really the Standard Model Higgs?
- is there new physics in/outside the Higgs sector?
- does fundamental theory still hold to Planck scale?

More specifically

- need to test Higgs models
- weak-scale Lagrangian the appropriate description
- extrapolation to high scales my reason to be here

Interpretations of Higgs measurements

- Higgs couplings most universal for rates
- effective theories well defined, but less universal
- do not trust theorists when they offer ‘big picture’

Lectures on LHC Physics, Springer, arXiv:0910.4182 updated under `www.thphys.uni-heidelberg.de/~plehn/`

Much of this work was funded by the BMBF Theorie-Verbund which is ideal for relevant LHC work

Bundesministerium für Bildung und Forschung

Longitudinal WW scattering

WW scattering at high energies [Tao etal; Dawson]

- historically alternative to light Higgs
- *WW* scattering at high energies [via Goldstones]

$$g_V \; H \; \left(a_L V_{L\mu} V_L^\mu + a_T V_{T\mu} V_T^\mu \right)$$

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Tagging jet observables [Brehmer, Jäckel, TP]

- polarization defined in Higgs frame
- transverse momenta

$$P_T(x, p_T) \sim \frac{1 + (1-x)^2}{x} \; \frac{p_T^3}{((1-x) m_W^2 + p_T^2)^2}$$

$$P_L(x, p_T) \sim \frac{1-x}{x} \; \frac{2(1-x) m_W^2 p_T}{((1-x) m_W^2 + p_T^2)^2}$$

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– azimuthal angle

$$A_\phi = \frac{\sigma(\Delta\phi_{jj} < \frac{\pi}{2}) - \sigma(\Delta\phi_{jj} > \frac{\pi}{2})}{\sigma(\Delta\phi_{jj} < \frac{\pi}{2}) + \sigma(\Delta\phi_{jj} > \frac{\pi}{2})}$$

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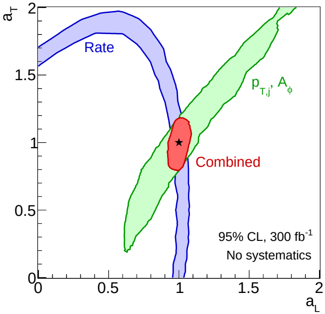
- total rate $\sigma \sim (A_L a_L^2 + A_T a_T^2)$

$\Rightarrow$ simple question, clear answer



Exercise: higher-dimensional operators

Higgs sector including dimension-6 operators

$$\mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} \mathcal{O}_i \quad \text{with} \quad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi)\, \partial^\mu (\phi^\dagger \phi)\;, \quad \mathcal{O}_{\phi,3} = -\frac{1}{3} (\phi^\dagger \phi)^3$$

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first operator, wave function renormalization

$$\mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi)\, \partial^\mu (\phi^\dagger \phi) = \frac{1}{2}\, (\tilde{H} + v)^2\, \partial_\mu \tilde{H}\, \partial^\mu \tilde{H}$$

proper normalization of combined kinetic term [LSZ]

$$\mathcal{L}_{\text{kin}} = \frac{1}{2} \partial_\mu \tilde{H}\, \partial^\mu \tilde{H} \left(1 + \frac{f_{\phi,2} v^2}{\Lambda^2} \right) \stackrel{!}{=} \frac{1}{2} \partial_\mu H\, \partial^\mu H \quad \Leftrightarrow \quad H = \tilde{H} \sqrt{1 + \frac{f_{\phi,2} v^2}{\Lambda^2}}$$

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second operator, minimum condition giving v

$$v^2 = -\frac{\mu^2}{\lambda} - \frac{f_{\phi,3} \mu^4}{4 \lambda^3 \Lambda^2}$$

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both operators contributing to Higgs mass

$$\mathcal{L}_{\text{mass}} = -\frac{\mu^2}{2} \tilde{H}^2 - \frac{3}{2} \lambda v^2 \tilde{H}^2 - \frac{f_{\phi,3}}{\Lambda^2} \frac{15}{24} v^4 \tilde{H}^2 \stackrel{!}{=} -\frac{m_H^2}{2} H^2$$

$$\Leftrightarrow \qquad m_H^2 = 2 \lambda v^2 \left(1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{f_{\phi,3} v^2}{2 \Lambda^2 \lambda} \right)$$

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$$- \frac{m_H^2}{8v^2} \left[\left(1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{4 f_{\phi,3} v^4}{\Lambda^2 m_H^2} \right) H^4 - \frac{4 f_{\phi,2} v^2}{\Lambda^2 m_H^2} H^2 \, \partial_\mu \, H \partial^\mu H \right]$$

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alternatively, strong multi-Higgs interactions

$$H = \left(1 + \frac{f_{\phi,2} v^2}{2\Lambda^2} \right) \tilde{H} + \frac{f_{\phi,2} v}{2\Lambda^2} \tilde{H}^2 + \frac{f_{\phi,2}}{6\Lambda^2} \tilde{H}^3 + \mathcal{O}(\tilde{H}^4)$$

Exercise: higher-dimensional operators

Higgs sector including dimension-6 operators

$$\mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} \mathcal{O}_i \quad \text{with} \quad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \, \partial^\mu (\phi^\dagger \phi) \, , \quad \mathcal{O}_{\phi,3} = -\frac{1}{3} (\phi^\dagger \phi)^3$$

Higgs self couplings momentum dependent

$$\begin{aligned} \mathcal{L}_{\text{self}} = &- \frac{m_H^2}{2v} \left[\left(1 - \frac{f_{\phi,2} v^2}{2\Lambda^2} + \frac{2 f_{\phi,3} v^4}{3\Lambda^2 m_H^2} \right) H^3 - \frac{2 f_{\phi,2} v^2}{\Lambda^2 m_H^2} H \, \partial_\mu H \, \partial^\mu H \right] \\ &- \frac{m_H^2}{8v^2} \left[\left(1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{4 f_{\phi,3} v^4}{\Lambda^2 m_H^2} \right) H^4 - \frac{4 f_{\phi,2} v^2}{\Lambda^2 m_H^2} H^2 \, \partial_\mu \, H \partial^\mu H \right] \end{aligned}$$

alternatively, strong multi-Higgs interactions

$$H = \left(1 + \frac{f_{\phi,2} v^2}{2\Lambda^2} \right) \tilde{H} + \frac{f_{\phi,2} v}{2\Lambda^2} \tilde{H}^2 + \frac{f_{\phi,2}}{6\Lambda^2} \tilde{H}^3 + \mathcal{O}(\tilde{H}^4)$$

$\Rightarrow$ operators and distributions linked to poor UV behavior

Higher-dimensional operators

Light Higgs as a Goldstone boson [Contino, Giudice, Grojean, Pomarol, Rattazzi, Galloway,...]

– strongly interacting models not looking like that [Bardeen, Hill, Lindner]
– light state if protected by Goldstone's theorem [Georgi & Kaplan]
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– adding specific D6 operator set

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$$\begin{aligned}
\mathcal{L}_{\text{SILH}} = & \frac{c_H}{2f^2} \partial^\mu \left(H^\dagger H \right) \partial_\mu \left(H^\dagger H \right) + \frac{c_T}{2f^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) \left(H^\dagger \overleftrightarrow{D}_\mu H \right) \\
& - \frac{c_6 \lambda}{f^2} \left(H^\dagger H \right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.} \right) \\
& + \frac{i c_W g}{2 m_\rho^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) \left(D^\nu W_{\mu\nu} \right)^i + \frac{i c_B g'}{2 m_\rho^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) \left(\partial^\nu B_{\mu\nu} \right) \\
& + \frac{i c_{HW} g}{16\pi^2 f^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i c_{HB} g'}{16\pi^2 f^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{c_\gamma g'^2}{16\pi^2 f^2} \frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2} \frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} .
\end{aligned}$$

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& - \frac{c_6}{(3f)^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) \\
& + \frac{i c_W}{(16f)^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) (D^\nu W_{\mu\nu})^i + \frac{i c_B}{(16f)^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) (\partial^\nu B_{\mu\nu}) \\
& + \frac{i c_{HW}}{(16f)^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i c_{HB}}{(16f^2)} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{c_\gamma}{(256f)^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g}{(256f)^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} .
\end{aligned}$$

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Anomalous Higgs couplings [Hagiwara etal; Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

- assume Higgs is largely Standard Model
- additional higher-dimensional couplings

$$\mathcal{L}_{\text{eff}} = -\frac{\alpha_s v}{8\pi}\frac{f_g}{\Lambda^2}(\phi^\dagger\phi)G_{\mu\nu}G^{\mu\nu} + \frac{f_{WW}}{\Lambda^2}\phi^\dagger W_{\mu\nu}W^{\mu\nu}\phi$$
$$+ \frac{f_W}{\Lambda^2}(D_\mu\phi)^\dagger W^{\mu\nu}(D_\nu\phi) + \frac{f_B}{\Lambda^2}(D_\mu\phi)^\dagger B^{\mu\nu}(D_\nu\phi) + \frac{f_{WWW}}{\Lambda^2}\text{Tr}(W_{\mu\nu}W^{\nu\rho}W_\rho^\mu)$$
$$+ \frac{f_b}{\Lambda^2}(\phi^\dagger\phi)(\overline{Q}_3\phi d_{R,3}) + \frac{f_\tau}{\Lambda^2}(\phi^\dagger\phi)(\overline{L}_3\phi e_{R,3})$$

$\Rightarrow$ before measuring couplings remember what your operators are!