Testing the Higgs Sector

Tilman Plehn

Universität Heidelberg

Mainz, July 2015

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 $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

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

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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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– 1966: original Higgs phenomenology

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]

$$\mathcal{L} = -\tfrac14 g^{\kappa\mu} g^{\lambda\nu} F_{\kappa\lambda} F_{\mu\nu} - \tfrac12 g^{\mu\nu} \nabla_\mu \Phi_a \nabla_\nu \Phi_a + \tfrac14 m_0^2 \Phi_a \Phi_a - \tfrac18 f^2 (\Phi_a \Phi_a)^2 . \quad (1)$$

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

$$M = i\{ e[a^{*\mu}(k_1)(-ik_{2\mu})\phi^*(k_2) + a^{*\mu}(k_2)(-ik_{1\mu})\phi^*(k_1)] - e(ip_\mu)[a^{*\mu}(k_1)\phi^*(k_2) + a^{*\mu}(k_2)\phi^*(k_1)] - 2em_1 a_\mu^*(k_1) a^{*\mu}(k_2) - f m_0 \phi^*(k_1)\phi^*(k_2) \} .$$

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

Higgs boson

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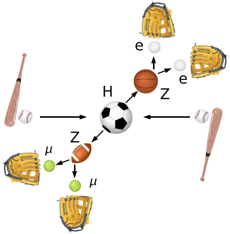
Adding in Glashow–Weinberg–Salam–'t Hooft–Veltman

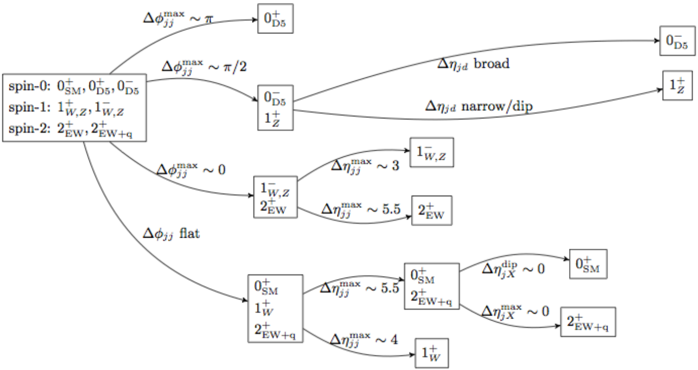
– massive, minimal Standard Model complete
– renormalizability unique for particle physics [and cosmology]
– Higgs sector the perfect way to test structure [remember LEP for gauge structure]
$\Rightarrow$ bias: no strongly interacting Higgs sector!

Questions for Run 2+x



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 Stephie and Uli [Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles]



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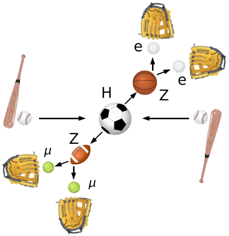

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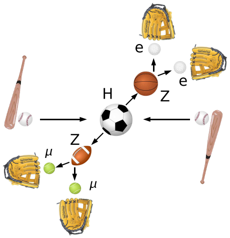
2. What is the Lagrangian?
   - naive-but-useful: set of 'couplings' given Lagrangian
   - bottom-up: Higgs effective theory
   - top-down: modified Higgs sectors

Questions for Run 2+x



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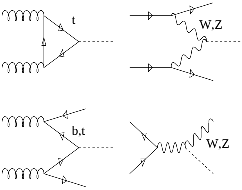
3. What does all this tell us?

- strongly interacting models?
- weakly interacting extensions?
- TeV-scale new physics?
- hierarchy problem, vacuum stability, Higgs inflation, etc

Couplings



Standard Model operators

– assume: narrow CP-even scalar
  Standard Model operators

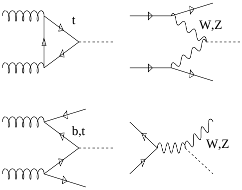
– couplings proportional to masses?

– Lagrangian

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

– 2nd generation Yukawas $\Delta_{\mu,c,s}$? [ask MatthiasN]

Couplings



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– 2nd generation Yukawas $\Delta_{\mu,c,s}$? [ask MatthiasN]

– total rates only [on-shell and off-shell, Keith or Kirill around?]

– electroweak renormalizability through some UV completion

– QCD renormalizability not an issue

$$\begin{array}{|l|}\hline gg \to H \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \\ \hline\end{array} \quad \longleftrightarrow \quad \boxed{g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)} \quad \longleftrightarrow \quad \begin{array}{|l|}\hline H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \\ \hline\end{array}$$

Higgs Portal

Higgs portal to new physics [dark matter, etc]

– all-renormalizable extended potential [with or without VEV]

$$V(\Phi, S) = \mu_1^2 (\Phi^\dagger \Phi) + \lambda_1 |\Phi^\dagger \Phi|^2 + \mu_2^2 |S|^2 + \lambda_2 |S|^4 + \lambda_3 |\Phi^\dagger \Phi| |S|^2$$

– mixing to the observed Higgs mass eigenstate

$$H_1 = \cos\chi \, H_\Phi + \sin\chi \, S$$

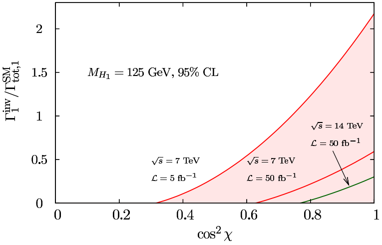
– visible and invisible decays

$$\Gamma_1 = \cos^2\chi \, \Gamma_1^{\text{SM}} + \sin^2\chi \, \Gamma_1^{\text{hid}} \qquad \Rightarrow \qquad \text{BR}_{\text{inv}} = \frac{\sin^2\chi \, \Gamma_1^{\text{hid}}}{\cos^2\chi \, \Gamma_1^{\text{SM}} + \sin^2\chi \, \Gamma_1^{\text{hid}}}$$

– event rate

$$\frac{(\sigma \times \text{BR})_{H_1}}{(\sigma \times \text{BR})_{H_1}^{\text{SM}}} = \frac{\cos^2\chi}{1 + \tan^2\chi \, \dfrac{\Gamma_1^{\text{hid}}}{\Gamma_1^{\text{SM}}}}$$

– collider reach



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Higgs portal to new physics [dark matter, etc]

– all-renormalizable extended potential [with or without VEV]

$$V(\Phi, S) = \mu_1^2 \, (\Phi^\dagger \, \Phi) + \lambda_1 \, |\Phi^\dagger \Phi|^2 + \mu_2^2 \, |S|^2 + \lambda_2 \, |S|^4 + \lambda_3 \, |\Phi^\dagger \, \Phi| \, |S|^2$$

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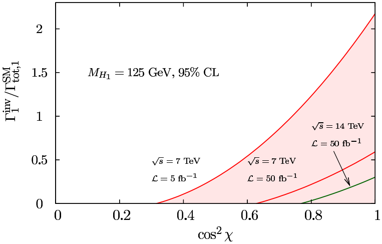
$\Rightarrow$ invisible Higgs the key



Two Higgs doublets

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
- single hierarchy $m_h \ll m_{H,A,H^\pm}$ [custodial symmetry]

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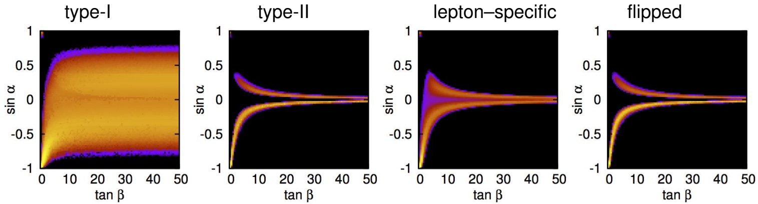
Facing data

– decoupling regime $\sin^2\alpha \sim 1/(1+\tan^2\beta)$

$\Rightarrow$ 2HDMs good fit with decoupling heavy Higgs



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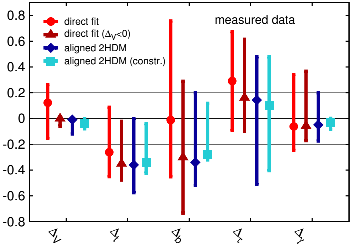
Yukawa-aligned 2HDM

- $\Delta_V \leftrightarrow (\beta - \alpha)$ $\quad \Delta_{b,t,\tau} \leftrightarrow \{\beta, \gamma_{b,\tau}\}$ $\quad \Delta_\gamma \leftrightarrow m_{H^\pm}$
- Δ_g not free parameter, add top partner
- custodial symmetry at tree level $\Delta_V < 0$

$\Rightarrow$ realistic model not yet in reach



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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– dark singlet

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

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– mixing singlet [no anomalous decays]

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

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– additional doublet [type-X fermion sector]

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

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

– additional doublet [type-X fermion sector]

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

– 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

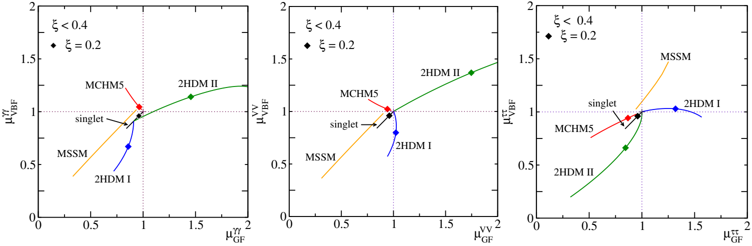
$$\Gamma_{\text{inv}} = \xi^2 \Gamma_{\text{SM}} \qquad\qquad \mu_{p,d} = \frac{\Gamma_{\text{SM}}}{\Gamma_{\text{SM}} + \Gamma_{\text{inv}}} = 1 - \xi^2 + \mathcal{O}(\xi^3) < 1$$

– mixing singlet [no anomalous decays]

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

– composite Higgs

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



Higgs Effective theory

Limits in terms of effective field theory in Higgs sector

– set of Higgs-gauge operators

$$\mathcal{O}_{GG} = \Phi^\dagger \Phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{BB} = \cdots$$

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– relevant part after equation of motion, etc

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

– plus Yukawa structure $f_{\tau,b,t}$

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– plus Yukawa structure $f_{\tau,b,t}$

– Higgs couplings to SM particles

$$\begin{aligned}
\mathcal{L}^{HVV} &= g_g \; H G^a_{\mu\nu} G^{a\mu\nu} + g_\gamma \; H A_{\mu\nu} A^{\mu\nu} \\
&+ g^{(1)}_Z \; Z_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_Z \; H Z_{\mu\nu} Z^{\mu\nu} + g^{(3)}_Z \; H Z_\mu Z^\mu \\
&+ g^{(1)}_W \; \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu H + \text{h.c.} \right) + g^{(2)}_W \; H W^+_{\mu\nu} W^{-\,\mu\nu} + g^{(3)}_W \; H W^+_\mu W^{-\,\mu} + \cdots
\end{aligned}$$

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– observable Higgs couplings

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

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

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

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

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

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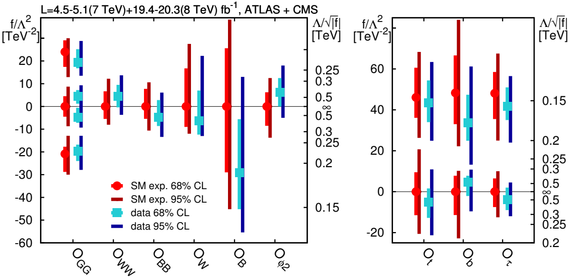
SFitter analysis

– same setup and data as before



Higgs Effective theory

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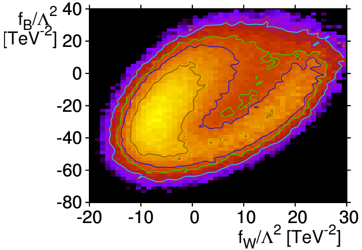
SFitter analysis

– same setup and data as before

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



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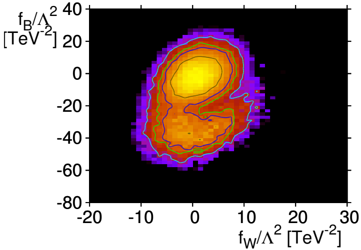
Including distributions

– some operators momentum-dependent

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

$\Rightarrow$ just a start...



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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Higgs self couplings momentum dependent

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

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alternatively, strong multi-Higgs interactions

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

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

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 [Lindner etal, Wetterich etal, Bauer etal]

– Planck-scale extrapolation

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

Meaning

High scales [Lindner etal, Wetterich etal, Bauer etal]

– Planck-scale extrapolation

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

– Landau pole: exploding λ for large Q, small λ_t

– stability issue: sign change in λ for large Q, large λ_t

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

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

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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Running of coupling/mass ratios [Wetterich]

Higgs self coupling and top Yukawa with stable zero IR solutions

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

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

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

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

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

Meaning

High scales [Lindner etal, Wetterich etal, Bauer etal]

– Planck-scale extrapolation

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

– Landau pole: exploding λ for large Q, small λ_t

– stability issue: sign change in λ for large Q, large λ_t

– 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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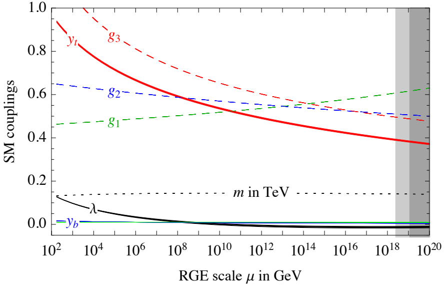
– $\lambda < 0$ at 10^{10} GeV? [Buttazo etal]



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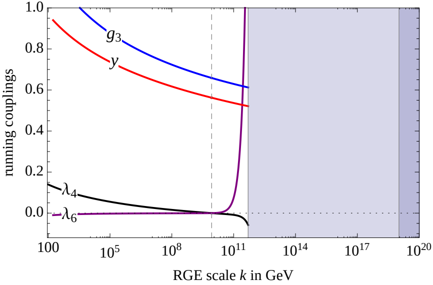

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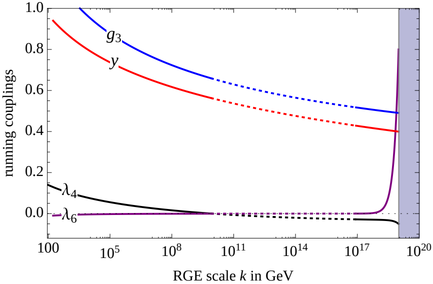

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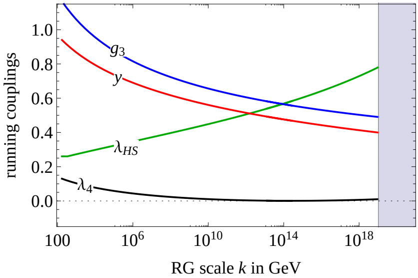
– TeV-scale DM portal?



Questions

Big questions

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

Practical questions

- can we define interesting extended models?
- can we set general limits in effective theories?
- are there links to other interesting sectors?
- how can we increase the precision?
- are there any good ideas out there?

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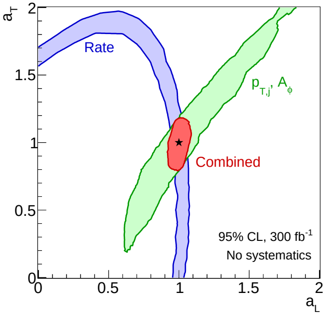
– total rate $\sigma \sim (A_L a_L^2 + A_T a_T^2)$

$\Rightarrow$ simple question, clear answer



Hierarchy problem

Tuning in Lagrangian [Giudice 0801.2562]

– electron Yukawa $m_e/v \ll 1$ a problem?

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Quantum field theory

– stability with respect to quantum corrections

$$G_F \sim \frac{1}{v^2} \sim \frac{1}{m_H^2} \qquad \text{with} \qquad \delta m_H^2 \propto \Lambda^2$$

– scale hierarchy unstable

– effective field theory broken

$\Rightarrow$ symmetries welcome

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SUSY little hierarchy

– quadratic Higgs divergence gone

– logarithmic dependence left

$$\delta m_H^2 \propto v^2 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$