Theory Questions to the Higgs Sector

Tilman Plehn

Universität Heidelberg

CPAN, Santiago de Compostela, 11/2013

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

[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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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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– 1976 etc: collider phenomenology

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^- p \to Hn$ or $\gamma p \to Hp$ near threshold. If its mass is $\lesssim$300 MeV, the Higgs boson may be present in the decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one of the new particles: $3.7 \to 3.1 + H$ with a branching ratio $O(10^{-4})$. If its mass is $\lesssim$4 GeV, the Higgs

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334 *J. Ellis et al. / Higgs boson*

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Higgs
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Higgs boson

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$\Rightarrow$ Higgs discovery a triumph of quantum field theory

Higgs boson

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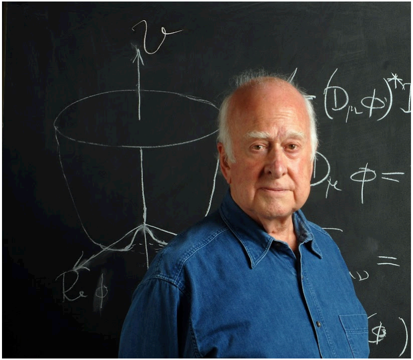
In terms of mexican hat potential

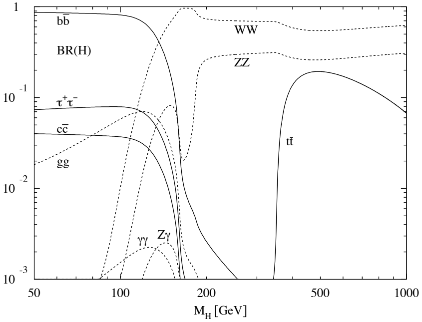


Higgs discovery

Higgs decays easy [Hdecay]

– weak-scale scalar coupling proportional to mass
– off-shell decays below threshold
– decay to $\gamma\gamma$ via W and top loop [destructive interference]

$\Rightarrow$ $m_H = 126$ GeV perfect choice



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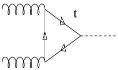
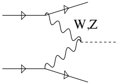
Higgs production hard [7-8 TeV, 5-15/fb]





– quantum effects needed

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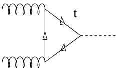

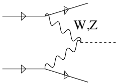

– quantum effects needed

– easy channels for 2011-2012

$pp \to H \to ZZ \to 4\ell$
$pp \to H \to \gamma\gamma$
$pp \to H \to WW \to (\ell^- \bar{\nu})(\ell^+ \nu)$

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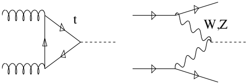

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$pp \to H \to ZZ \to 4\ell$
$pp \to H \to \gamma\gamma$
$pp \to H \to WW \to (\ell^- \bar{\nu})(\ell^+ \nu)$

$\Rightarrow$ fun slowly starting

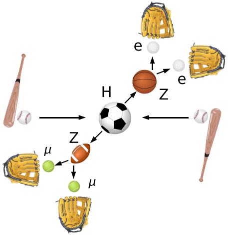
$pp \to H \to \tau\tau$ plus jets
$pp \to ZH \to (\ell^+ \ell^-)(b\bar{b})$ boosted
$pp \to t\bar{t}H$ waiting for a good idea...

Questions

1. What is the ‘Higgs’ Lagrangian?

   – psychologically: looked for Higgs, so found a Higgs

   – CP-even spin-0 scalar expected, but which operators?
   spin-1 vector unlikely
   spin-2 graviton unexpected



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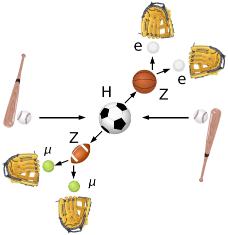

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– ‘coupling’ after fixing operator basis
– Standard Model Higgs vs anomalous couplings

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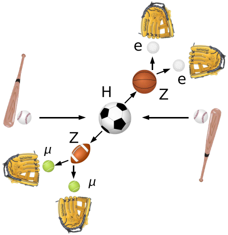

2. What are the coupling values?

– ‘coupling’ after fixing operator basis

– Standard Model Higgs vs anomalous couplings

3. What does all this tell us?

– weakly interacting two-Higgs-doublet models?

– TeV-scale new physics?

– renormalization group based Hail-Mary passes?

Angular Correlations

Measurements of operator structures [learning from the flavor people]

– Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles for $H \to ZZ$

[Melnikov etal; Lykken etal; v d Bij etal; Choi etal; Maltoni etal]

$$\cos\theta_e = \hat{p}_{e^-} \cdot \hat{p}_{Z_\mu}\Big|_{Z_e} \qquad \cos\theta_\mu = \hat{p}_{\mu^-} \cdot \hat{p}_{Z_e}\Big|_{Z_\mu} \qquad \cos\theta^* = \hat{p}_{Z_e} \cdot \hat{p}_{\text{beam}}\Big|_X$$

$$\cos\phi_e = (\hat{p}_{\text{beam}} \times \hat{p}_{Z_\mu}) \cdot (\hat{p}_{Z_\mu} \times \hat{p}_{e^-})\Big|_{Z_e}$$

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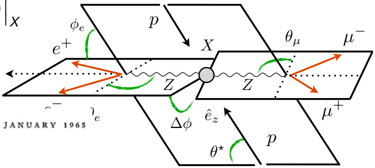

PHYSICAL REVIEW VOLUME 137, NUMBER 2B 25 JANUARY 1965

Angular Correlations in K_{e4} Decays and Determination of Low-Energy π-π Phase Shifts*

NICOLA CABIBBO† AND ALEXANDER MAKSYMOWICZ
Lawrence Radiation Laboratory, University of California, Berkeley, California

(Received 1 September 1964)

The study of correlations in K_{e4} decays can give unique information on low-energy π-π scattering. To this end we introduce a particularly simple set of correlations. We show that the measurement of these correlations at any fixed π-π c.m. energy allows one to make a model-independent determination of the difference δ_0-δ_1 between the S- and P-wave π-π phase shifts at that energy. Information about the average value of δ_0-δ_1 can be obtained from a measurement of the same correlations averaged over the energy spectrum. Measurement of the average correlations is particularly suited to the testing of any model of low-energy π-π scattering. We discuss in particular two such models: (a) the Chew-Mandelstam effective-range description of S-wave scattering and (b) the Brown-Faier σ-resonance model for the S wave. If the Chew-Mandelstam description is adequate, the suggested measurements should yield a value for the S-wave scattering length in the $I=0$ state. If the σ-resonance model is correct, these measurements should yield a value for the mass of the resonance.

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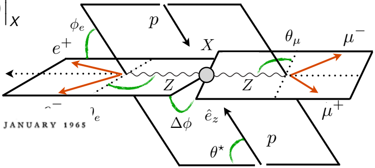

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* This work was done under the auspices of the U. S. Atomic Energy Commission.

† On leave from the Frascati National Laboratory, Frascati, Italy; present address: CERN, Geneva, Switzerland.

[1] L. B. Okun' and E. P. Shabalin, Zh. Eksperim. i Teor. Fiz. **37**, 1775 (1959) [English transl.: Soviet Phys.—JETP **10**, 1252 (1960)].
[2] K. Chadan and S. Oneda, Phys. Rev. Letters **3**, 292 (1959).
[3] V. S. Mathur, Nuovo Cimento **14**, 1322 (1959).
[4] E. P. Shabalin, Zh. Eksperim. i Teor. Fiz. **39**, 345 (1960) [English transl.: Soviet Phys.—JETP **12**, 245 (1961)].
[5] R. W. Birge, R. P. Ely, G. Gidal, G. E. Kalmus, A. Kernan, W. M. Powell, U. Camerini, W. F. Fry, J. Gaidos, R. H. March, and S. Natali, Phys. Rev. Letters **11**, 35 (1963). Members of this group have kindly communicated to us that the total of 11 events reported in this paper has now increased to at least 80.
[6] G. Ciocchetti, Nuovo Cimento **25**, 385 (1962).
[7] L. M. Brown and H. Faier, Phys. Rev. Letters **12**, 514 (1964).
[8] B. A. Arbuzov, Nguyen Van Hieu, and R. N. Faustov, Zh. Eksperim. i Teor. Fiz. **44**, 329 (1963) [English transl.: Soviet Phys.—JETP **17**, 225 (1963)].

dominated by the postulated σ resonance. Measurement of average correlations could then be used to determine the mass of this resonance.

II. KINEMATICS AND CORRELATIONS

Our approach to the kinematics of the reaction $K^+ \to \pi^+\pi^- e^+\nu$ is the same as that used in analyzing resonances. We visualize this reaction as a two-body decay into a dipion of mass $M_{\pi\pi}$ and a dilepton of mass $M_{e\nu}$. We then consider the subsequent decay of each of these two "resonances" in its own center-of-mass system.

[9] The usefulness of angular correlations in the determination of $\delta_0-\delta_1$ was first recognized by E. P. Shabalin, Zh. Eksperim. i Teor. Fiz. 44, 765 (1963) [English transl.: Soviet Phys.—JETP **17**, 517 (1963)]. See also erratum, Zh. Eksperim. i Teor. Fiz. **45**, 2085 (1963).

Angular Correlations

Measurements of operator structures [learning from the flavor people]

– Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles for $H \to ZZ$

[Melnikov etal; Lykken etal; v d Bij etal; Choi etal; Maltoni etal]

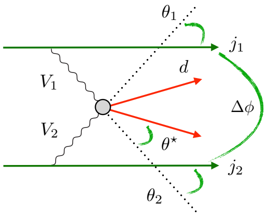
– Breit frame or hadron collider (η, ϕ) in WBF [Breit: boost into space-like]

[Rainwater, TP, Zeppenfeld; Hagiwara, Li, Mawatari; Englert, Mawatari, Netto, TP]

$$\cos\theta_1 = \hat{p}_{j_1} \cdot \hat{p}_{V_2}\Big|_{V_1\,\text{Breit}} \qquad \cos\theta_2 = \hat{p}_{j_2} \cdot \hat{p}_{V_1}\Big|_{V_2\,\text{Breit}} \qquad \cos\theta^* = \hat{p}_{V_1} \cdot \hat{p}_d\Big|_X$$

$$\cos\phi_1 = (\hat{p}_{V_2} \times \hat{p}_d) \cdot (\hat{p}_{V_2} \times \hat{p}_{j_1})\Big|_{V_1\,\text{Breit}}$$

$$\cos\Delta\phi = (\hat{p}_{q_1} \times \hat{p}_{j_1}) \cdot (\hat{p}_{q_2} \times \hat{p}_{j_2})\Big|_X \; .$$



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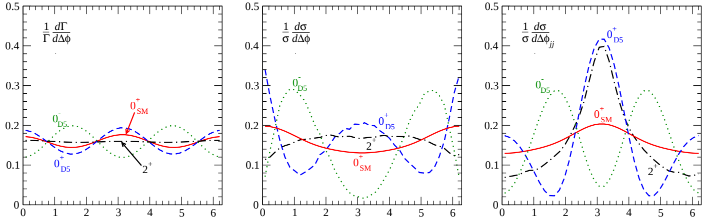
$\Rightarrow$ different channels, same physics



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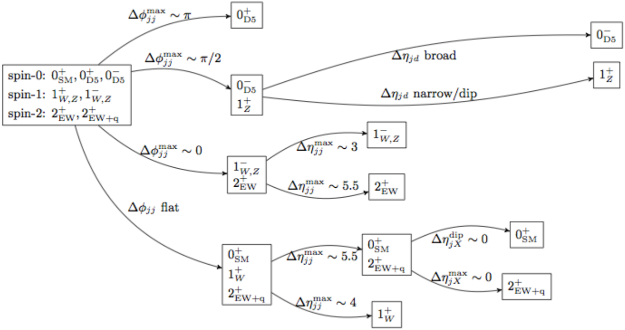

Scalar Lagrangians

Fundamental or strongly interacting? [Contino, Giudice, Grojean, Pomarol, Rattazzi,...]

– strongly interacting models not looking like what we see

– light state if protected by Goldstone's theorem [Georgi & Kaplan, now RS]

– D6 Lagrangian [$v \ll f < 4\pi f \sim m_\rho$]
  linear representation with ϕ doublet
  link to non-linear representation hard work [BCEGGGMR, 1311.1823]

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– light state if protected by Goldstone's theorem [Georgi & Kaplan, now RS]

– D6 Lagrangian [$v \ll f < 4\pi f \sim m_\rho$]

linear representation with ϕ doublet
link to non-linear representation hard work [BCEGGGMR, 1311.1823]

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

Scalar Lagrangians

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Full set of anomalous Higgs couplings [Hagiwara etal; Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

– assume Higgs is largely Standard Model [linear representation]

– D6 Lagrangian with unbroken SM symmetries

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

– linked to e-w precision data and triple gauge couplings

$\Rightarrow$ Higgs Lagrangian wide open field

Couplings

Couplings vs masses? [SFitter: Klute, Lafaye, TP, Rauch, Zerwas, Dührssen]

– Standard Model operators

– couplings from production & decay rates

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

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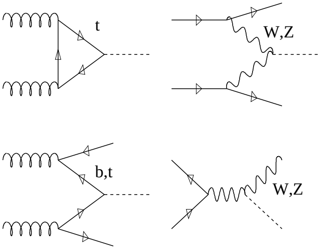

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Now and in the future

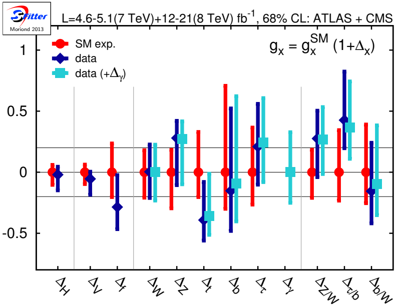
– focus SM-like [secondary solutions possible]

– six couplings and ratios from data

g_b from width

g_g vs g_t not yet possible

[similar: Ellis etal, Djouadi etal, Strumia etal, Grojean etal]



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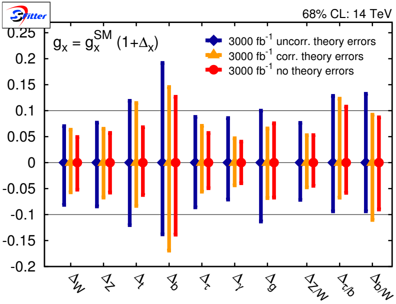
– theory soon the limiting factor



2HDM as weakly interacting completion

Extended Higgs sectors: 2HDM [SFitter + Lopez-Val; many, many, papers mostly from Spain]

– $\beta = \text{atan}\, v_2/v_1$
  α defining h^0 and H^0
  coupling shift $\quad g_{W,Z} = \sin(\beta - \alpha) g_{W,Z}^{\text{SM}}$

– type-I: 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
  Yukawa aligned $\quad y_b \cos(\beta - \gamma_b) = \sqrt{2} m_b / v$

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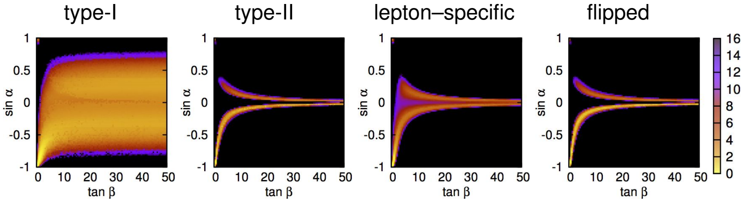
  Yukawa aligned $y_b \cos(\beta - \gamma_b) = \sqrt{2} m_b / v$
– fit including heavy Higgs mass
– decoupling regime $\sin^2 \alpha \sim 1/(1 + \tan^2 \beta)$

⇒ good fit, but decoupling heavy Higgs



2HDM as a consistent UV completion

How to think of coupling measurements

– $\Delta_x \neq 0$ violating renormalizability, unitarity [only QCD really matters...]

– EFT approach:

(1) define consistent 2HDM, decouple heavy states
(2) fit 2HDM model parameters, plot SM couplings
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Yukawa-aligned 2HDM

– $\Delta_V \leftrightarrow (\beta - \alpha)$ $\Delta_{b,t,\tau} \leftrightarrow \{\beta, \gamma_{b,\tau}\}$ $\Delta_\gamma \leftrightarrow m_{H^\pm}$ $\Delta_g \overset{?}{\leftrightarrow} m_{\tilde{T}'}$

– custodial symmetry and $\Delta_V < 0$

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

– fermion quantum corrections
$\Delta_W \neq \Delta_Z > 0$ possible

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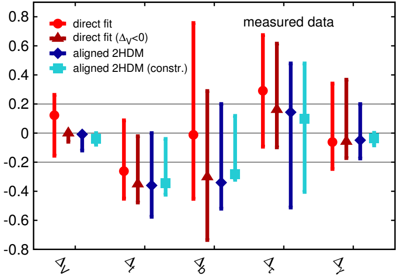
$\Rightarrow$ SM couplings measurement fine



Meaning

TeV scale

– extended Higgs sectors wide open

– no final verdict on the MSSM [talk Cristian Bosch Serrano]

– strongly interacting models modified [talk Juan Sanz-Cillero]

– fourth chiral generation excluded

– hierarchy problem worse than ever [light fundemental scalar discovered]

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High scales

– scale extrapolation [Holthausen, Lim, Lindner; Buttazo etal]

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

– vacuum stability right at edge
– $\lambda = 0$ at finite energy?
– IR fixed point for λ/λ_t^2 fixing m_H^2/m_t^2 [with gravity: Shaposhnikov, Wetterich]

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

$\Rightarrow$ do not know

MadMax

Understanding modern analyses

– hardly any counting experiments left
– number of useful observables ever increasing
– relevant information still (mostly) in hard process

$\Rightarrow$ poor man's MEM analysis at parton level?

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Differential significance distribution [TP, Schichtel, Wiegand]

– Neyman–Pearson lemma
log-likelihood ratio the best discriminator
– maximum significance through PS integral [Cranmer & TP]

$$q(r) = -\sigma_{\text{tot},s}\,\mathcal{L} + \log\left(1 + \frac{d\sigma_s(r)}{d\sigma_b(r)}\right) .$$

– evaluated in parallel to cross sections [in Madgraph]

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Link to Higgs couplings: ZH, $H \to b\bar{b}$ [talk Garoe Gonzales Parra, similar for $t\bar{t}H$]

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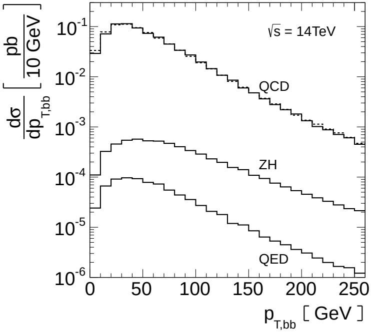
– $p_{T,bb}$ distributions
– subjet analyses one solution



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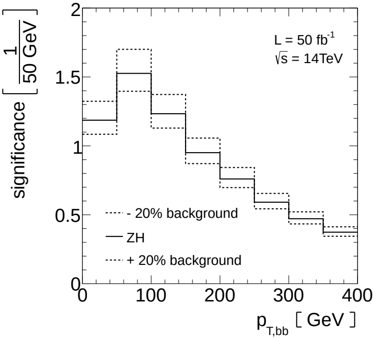
$\Rightarrow$ anyone got a question for our answer?



Exercise: top–Higgs renormalization group

Running of coupling/mass ratios

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 $R = \lambda/y_t^2$

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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 there new physics in the Higgs sector?
- is there new physics outside the Higgs sector?

Small questions

- what are good alternative ‘Higgs’ test hypotheses?
- how can we improve the couplings fit precision?
- how can we measure the bottom Yukawa?
- how can we measure the top Yukawa?
- how can we measure the Higgs self coupling?
- how do we avoid dominant theory uncertainties
- can QCD really be fun?

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

Exercise: what operators can do

Higgs sector including dimension-6 operators

$$\mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} \mathcal{O}_i \quad \text{with} \quad \mathcal{O}_1 = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \, \partial^\mu (\phi^\dagger \phi) \,, \quad \mathcal{O}_2 = -\frac{1}{3} (\phi^\dagger \phi)^3$$

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first operator, wave function renormalization

$$\mathcal{O}_1 = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \, \partial^\mu (\phi^\dagger \phi) = \frac{1}{2} \, (\tilde{H} + v)^2 \, \partial_\mu \tilde{H} \, \partial^\mu \tilde{H}$$

proper normalization of combined kinetic term [LSZ]

$$\mathcal{L}_{\text{kin}} = \frac{1}{2} \partial_\mu \tilde{H} \partial^\mu \tilde{H} \left(1 + \frac{f_1 v^2}{\Lambda^2} \right) \stackrel{!}{=} \frac{1}{2} \partial_\mu H \, \partial^\mu H \quad \Leftrightarrow \quad H = \tilde{H} \sqrt{1 + \frac{f_1 v^2}{\Lambda^2}}$$

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second operator, minimum condition to fix v

$$\frac{v^2}{2} = \begin{cases} -\dfrac{\mu^2}{2\lambda} - \dfrac{f_2 \mu^4}{8\lambda^3 \Lambda^2} + \mathcal{O}(\Lambda^{-4}) = -\dfrac{\mu^2}{2\lambda} \left(1 + \dfrac{f_2 \mu^2}{4\lambda^2 \Lambda^2} \right) \\ -\dfrac{2\lambda\Lambda^2}{f_2^2} + \mathcal{O}(\Lambda^0) \end{cases}$$

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physical Higgs mass

$$\mathcal{L}_{\text{mass}} = -\frac{\mu^2}{2} \tilde{H}^2 - \frac{3}{2} \lambda v^2 \tilde{H}^2 - \frac{f_2}{\Lambda^2} \frac{15}{24} v^4 \tilde{H}^2 \stackrel{!}{=} -\frac{m_H^2}{2} H^2$$

$$\Leftrightarrow \qquad m_H^2 = 2 \lambda v^2 \left(1 - \frac{f_1 v^2}{\Lambda^2} + \frac{f_2 v^2}{2 \Lambda^2 \lambda} \right)$$

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Higgs self couplings momentum dependent

$$\begin{aligned} \mathcal{L}_{\text{self}} = &- \frac{m_H^2}{2v} \left[\left(1 - \frac{f_1 v^2}{2\Lambda^2} + \frac{2 f_2 v^4}{3\Lambda^2 m_H^2} \right) H^3 - \frac{2 f_1 v^2}{\Lambda^2 m_H^2} H\, \partial_\mu H\, \partial^\mu H \right] \\ &- \frac{m_H^2}{8v^2} \left[\left(1 - \frac{f_1 v^2}{\Lambda^2} + \frac{4 f_2 v^4}{\Lambda^2 m_H^2} \right) H^4 - \frac{4 f_1 v^2}{\Lambda^2 m_H^2} H^2\, \partial_\mu\, H \partial^\mu H \right] \,. \end{aligned}$$

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$$\mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} \mathcal{O}_i \quad \text{with} \quad \mathcal{O}_1 = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \, \partial^\mu (\phi^\dagger \phi) \, , \quad \mathcal{O}_2 = -\frac{1}{3} (\phi^\dagger \phi)^3$$

Higgs self couplings momentum dependent

$$\begin{aligned} \mathcal{L}_\text{self} = &- \frac{m_H^2}{2v} \left[\left(1 - \frac{f_1 v^2}{2\Lambda^2} + \frac{2 f_2 v^4}{3\Lambda^2 m_H^2} \right) H^3 - \frac{2 f_1 v^2}{\Lambda^2 m_H^2} H \, \partial_\mu H \, \partial^\mu H \right] \\ &- \frac{m_H^2}{8v^2} \left[\left(1 - \frac{f_1 v^2}{\Lambda^2} + \frac{4 f_2 v^4}{\Lambda^2 m_H^2} \right) H^4 - \frac{4 f_1 v^2}{\Lambda^2 m_H^2} H^2 \, \partial_\mu H \partial^\mu H \right] \, . \end{aligned}$$

field renormalization, strong multi-Higgs interactions

$$H = \left(1 + \frac{f_1 v^2}{2\Lambda^2} \right) \tilde{H} + \frac{f_1 v}{2\Lambda^2} \tilde{H}^2 + \frac{f_1}{6\Lambda^2} \tilde{H}^3 + \mathcal{O}(\tilde{H}^4)$$