Higgs Physics for the LHC

Tilman Plehn

Universität Heidelberg

Brookhaven, 9/2013

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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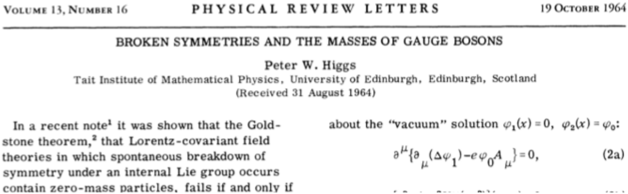

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

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]

d- l rs ly if

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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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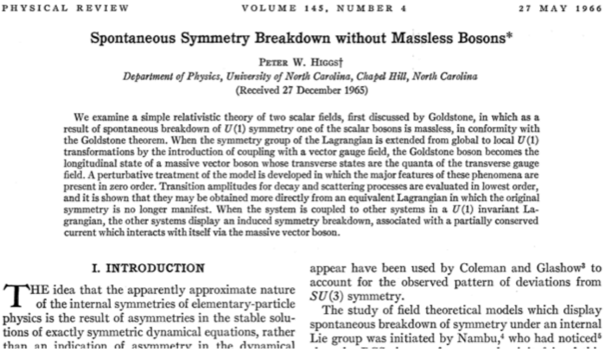

PHYSICAL REVIEW VOLUME 145, NUMBER 4 27 MAY 1966

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]

Higgs boson

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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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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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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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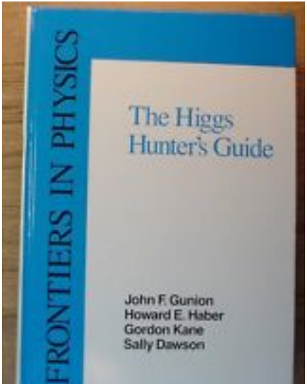

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$\Rightarrow$ Higgs boson predicted from mathematical field theory

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In terms of Higgs potential

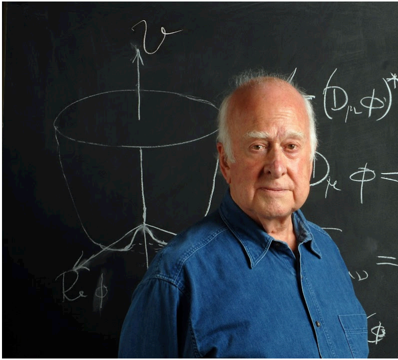
$$V = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

minimum at $\phi = \dfrac{v}{\sqrt{2}}$

$$\frac{\partial V}{\partial |\phi|^2} = \mu^2 + 2\lambda |\phi|^2 \;\Rightarrow\; \frac{v^2}{2} = \frac{-\mu^2}{2\lambda}$$

excitation $\phi = \dfrac{v + H}{\sqrt{2}}$

$$m_H^2 = \left.\frac{\partial^2 V}{\partial H^2}\right|_{\text{minimum}} = 2\lambda v^2$$



Higgs signatures

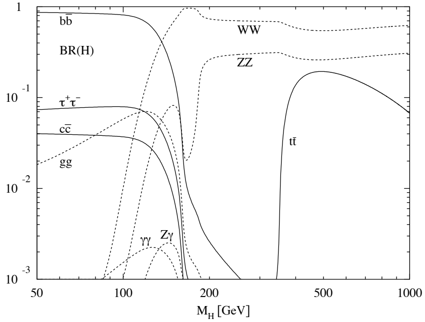
Higgs decays easy [Hdecay]

– 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



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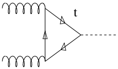
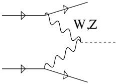
Higgs production hard [7-8 TeV, 5-15/fb]

– quantum effects needed

gluon fusion production loop induced [$\sigma \sim$ 15000 fb]
weak boson fusion production with jets [$\sigma \sim$ 1200 fb]





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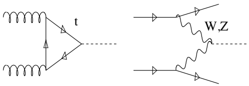

– easy channels for 2011-2012

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

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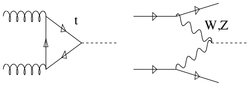

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$\Rightarrow$ fun still waiting

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

Higgs discovery

4th of July fireworks [no theory input needed beyond basic Pythia/Herwig]

– ‘silver channel’ $H \to \gamma\gamma$
  local significance 4.5σ (ATLAS), 4.1σ (CMS)
– ‘golden channel’ $H \to ZZ \to 4\ell$
  local significance 3.4σ (ATLAS), 3.2σ (CMS)
– WW and $\tau\tau$, bb adding little (CMS)
– combined 5.0σ (ATLAS), 4.9σ (CMS) [LEE 4.3σ]

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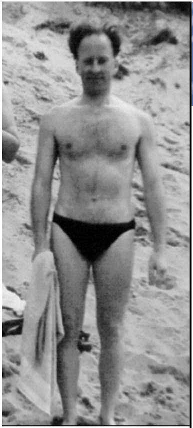
$\Rightarrow$ Rolf Heuer: ‘We have him’



A sure sighting of a higgs... Peter Higgs on the shores of the Firth of Fourth by Prof J D Jackson, July 1960

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CERN-PH-EP/2012-220
2012/08/01

CMS-HIG-12-028

31 Jul 2012

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

The CMS Collaboration*

CERN-PH-EP-2012-218
Submitted to: Physics Letters B

31 Jul 2012

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

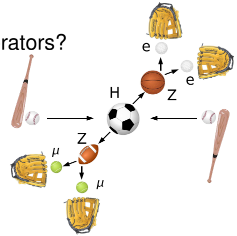
The ATLAS Collaboration

Questions

1. What is the 'Higgs' Lagrangian?

   – psychologically: looked for Higgs, so found a Higgs

   – CP-even spin-0 scalar expected, what about D6 operators?
   spin-1 vector unlikely
   spin-2 graviton unexpected



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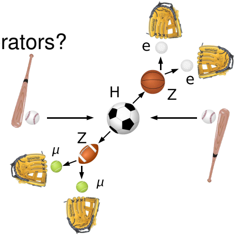

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   - 'coupling' after fixing operator basis
   - Standard Model Higgs vs anomalous couplings

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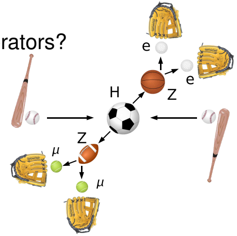

2. What are the coupling values?

– 'coupling' after fixing operator basis

– Standard Model Higgs vs anomalous couplings

3. What does all this tell us?

– two-Higgs-doublet models?

– models predicting weak-scale new physics?

– renormalization group based Hail-Mary passes?

Example: Higgs potential

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

proper normalization of combined kinetic term [LSZ]

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

second operator, minimum condition to fix v

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

physical Higgs mass

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

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

Example: Higgs potential

Higgs sector including dimension-6 operators

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

Higgs self couplings momentum dependent

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

Example: Higgs potential

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$$- \frac{m_H^2}{8v^2} \left[\left(1 - \frac{f_1 v^2}{\Lambda^2} + \frac{4 f_2 v^4}{\Lambda^2 m_H^2} \right) H^4 - \frac{4 f_1 v^2}{\Lambda^2 m_H^2} H^2\, \partial_\mu\, H \partial^\mu H \right] \; .$$

field renormalization, strong multi-Higgs interactions

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

Higher-dimensional operators

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

– strongly interacting models predicting heavy broad resonance(s)

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

– interesting if $v \ll f < 4\pi f \sim m_\rho$ [little Higgs $v \sim g^2 f/(2\pi)$]

– adding specific D6 operator set

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$$
\begin{aligned}
\mathcal{L}_{\rm SILH} = & \frac{c_H}{2f^2} \partial^\mu \left(H^\dagger H \right) \partial_\mu \left(H^\dagger H \right) + \frac{c_T}{2f^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) \left(H^\dagger \overleftrightarrow{D}_\mu H \right) \\
& - \frac{c_6 \lambda}{f^2} \left(H^\dagger H \right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.} \right) \\
& + \frac{i c_W g}{2 m_\rho^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) (D^\nu W_{\mu\nu})^i + \frac{i c_B g'}{2 m_\rho^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) (\partial^\nu B_{\mu\nu}) \\
& + \frac{i c_{HW} g}{16\pi^2 f^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i c_{HB} g'}{16\pi^2 f^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{c_\gamma g'^2}{16\pi^2 f^2} \frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2} \frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} .
\end{aligned}
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&- \frac{c_6}{(3f)^2} \left(H^\dagger H \right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.} \right) \\
&+ \frac{i c_W}{(16 f)^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) (D^\nu W_{\mu\nu})^i + \frac{i c_B}{(16 f)^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) (\partial^\nu B_{\mu\nu}) \\
&+ \frac{i c_{HW}}{(16 f)^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i c_{HB}}{(16 f^2)} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
&+ \frac{c_\gamma}{(256 f)^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g}{(256 f)^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} .
\end{aligned}$$

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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

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

– plus e-w precision data and triple gauge couplings

⇒ remember what your operators are!

Angular Correlations

Measurements of operator structures

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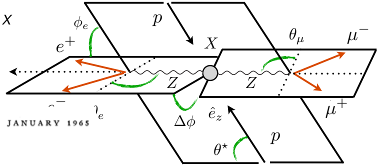
[Melnikov etal; Lykken etal; v d Bij etal; Choi etal]

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

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

$$\cos\Delta\phi = (\hat{p}_{e^-} \times \hat{p}_{e^+}) \cdot (\hat{p}_{\mu^-} \times \hat{p}_{\mu^+})\Big|_{X}$$



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.

Angular Correlations

Measurements of operator structures

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

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

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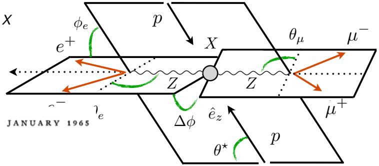

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* This work was done under the auspices of the U. S. Atomic Energy Commission.
† On leave from the Frascati National Laboratory, Frascati, Italy; present address: CERN, Geneva, Switzerland.

[1] L. B. Okun' and E. P. Shabalin, Zh. Eksperim. i Teor. Fiz. **37**, 1775 (1959) [English transl.: Soviet Phys.—JETP **10**, 1252 (1960)].
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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).

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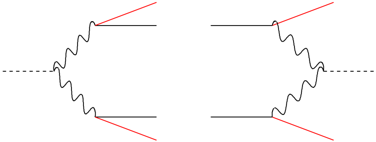
[Melnikov etal; Lykken etal; v d Bij etal; Choi etal]

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

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



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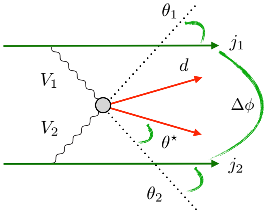

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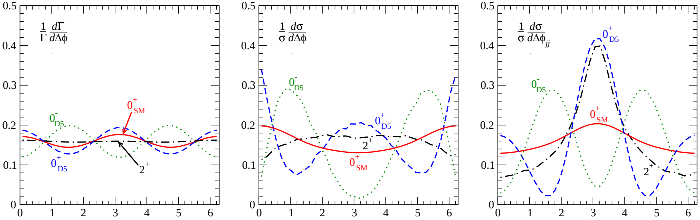
– possible scalar couplings

$$\mathcal{L} \supset (\phi^\dagger \phi) W^\mu W_\mu \qquad \frac{1}{\Lambda^2} (\phi^\dagger \phi) W^{\mu\nu} W_{\mu\nu} \qquad \frac{1}{\Lambda^2} (\phi^\dagger \phi) \epsilon_{\mu\nu\rho\sigma} W^{\mu\nu} W^{\rho\sigma}$$

$\Rightarrow$ different channels, same physics



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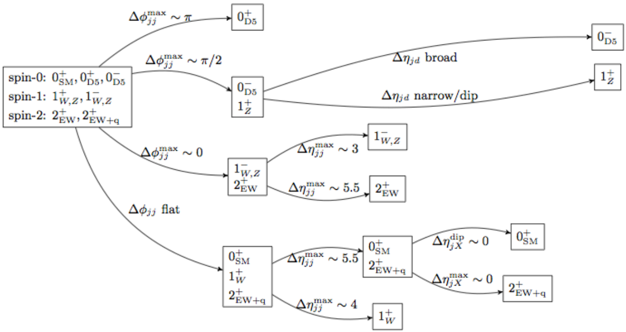
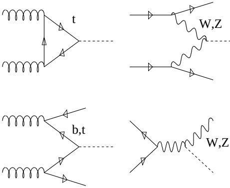


Couplings



Standard Model operators [SFitter: Klute, Lafaye, TP, Rauch, Zerwas]

- assume: narrow CP-even scalar
  Standard Model operators
  couplings proportional to masses?
- couplings from production & decay rates

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

$\longleftrightarrow$

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

$\longleftrightarrow$

$$H \to ZZ$$
$$H \to WW$$
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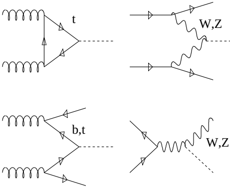
$$H \to \tau^+\tau^-$$
$$H \to \gamma\gamma$$

Couplings



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Total width

– non-trivial scaling

$$N = \sigma \, BR \propto \frac{g_p^2}{\sqrt{\Gamma_{\text{tot}}}} \; \frac{g_d^2}{\sqrt{\Gamma_{\text{tot}}}} \sim \frac{g^4}{g^2 \dfrac{\sum \Gamma_i(g^2)}{g^2} + \Gamma_{\text{unobs}}} \stackrel{g^2 \to 0}{\longrightarrow} = 0$$

gives constraint from $\sum \Gamma_i(g^2) < \Gamma_{\text{tot}} \to \Gamma_H|_{\text{min}}$

– $WW \to WW$ unitarity: $g_{WWH} \lesssim g_{WWH}^{\text{SM}} \to \Gamma_H|_{\text{max}}$

– SFitter assumption $\Gamma_{\text{tot}} = \sum_{\text{obs}} \Gamma_j$ [plus generation universality]

Error analysis

Sources of uncertainty

- statistical error: Poisson
  systematic error: Gaussian, if measured
  theory error: not Gaussian
- simple argument
  LHC rate 10% off: no problem
  LHC rate 30% off: no problem
  LHC rate 300% off: Standard Model wrong
- theory likelihood flat centrally and zero far away
- profile likelihood construction: RFit [CKMFitter]

$$-2 \log \mathcal{L} = \chi^2 = \vec{\chi}_d^T \; C^{-1} \; \vec{\chi}_d$$

$$\chi_{d,i} = \begin{cases} 0 & |d_i - \bar{d}_i| < \sigma_i^{\text{(theo)}} \\ \dfrac{|d_i - \bar{d}_i| - \sigma_i^{\text{(theo)}}}{\sigma_i^{\text{(exp)}}} & |d_i - \bar{d}_i| > \sigma_i^{\text{(theo)}} \end{cases}$$

Couplings now and in the future

Now [Aspen/Moriond 2013; Lopez-Val, TP, Rauch]

– 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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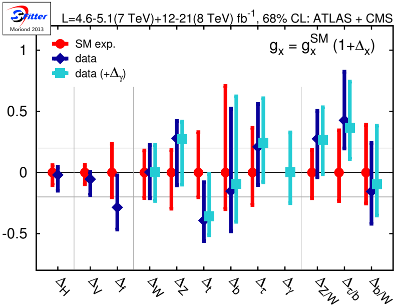

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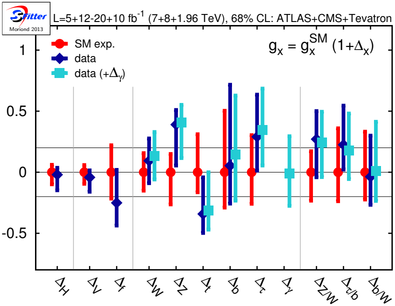

Couplings now and in the future

Now [Aspen/Moriond 2013; Lopez-Val, TP, Rauch]

- 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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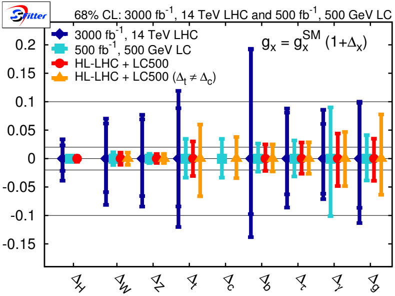
Future

- LHC extrapolations unclear
- theory extrapolations tricky
- ILC case obvious
- interplay in loop-induced couplings



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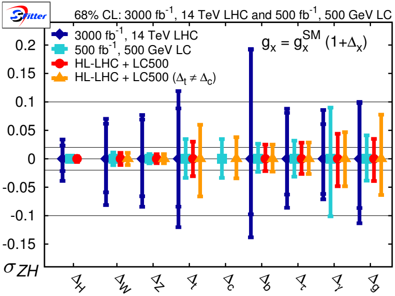
– fundamental e^+e^- advantages:

unobserved decays avoided
width measured from rates including σ_{ZH}
$H \to c\bar{c}$ accessible
invisible decays hugely improved
QCD theory error bars avoided



2HDM as a weakly interacting new physics

Extended Higgs models [Lopez-Val, TP, Rauch; Chen & Dawson, many, many papers]

– assume the Higgs really is a Higgs

– allow for coupling modifications

– consider portals/singlet extensions boring [Englert TP, Rauch, Zerwas, Zerwas]

⇒ how would 2HDMs look?

$$\begin{aligned} V(\Phi_1,\Phi_2) = m_{11}^2\,\Phi_1^\dagger\Phi_1 + m_{22}^2\,\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\,\Phi_1^\dagger\Phi_2 + \text{h.c.}\right] \\ + \frac{\lambda_1}{2}\,(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}\,(\Phi_2^\dagger\Phi_2)^2 + \lambda_3\,(\Phi_1^\dagger\Phi_1)\,(\Phi_2^\dagger\Phi_2) + \lambda_4\,|\Phi_1^\dagger\,\Phi_2|^2 \\ + \left[\frac{\lambda_5}{2}\,(\Phi_1^\dagger\Phi_2)^2 + \lambda_6\,(\Phi_1^\dagger\Phi_1)\,(\Phi_1^\dagger\Phi_2) + \lambda_7\,(\Phi_2^\dagger\Phi_2)\,(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right] \end{aligned}$$

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Physical parameters

– angle $\beta = \text{atan}(v_2/v_1)$
  angle α defining h^0 and H^0
  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
  Yukawa aligned: $y_b \cos(\beta - \gamma_b) = \sqrt{2} m_b / v$
– compressed masses $m_{h^0} \sim m_{H^0}$ [thanks to Berthold Stech]
  single hierarchy $m_{h^0} \ll m_{H^0, A^0, H^\pm}$ protected by custodial symmetry
  PQ-violating terms m_{12} and $\lambda_{6,7}$

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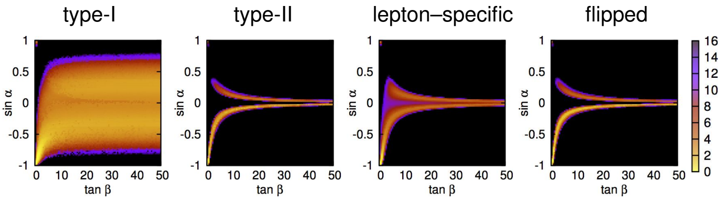
Facing data

– fit including single heavy Higgs mass
– decoupling regime $\sin^2\alpha \sim 1/(1+\tan^2\beta)$
– little impact of additional theoretical and experimental constraints
⇒ 2HDMs generally good fit, but decoupling heavy Higgs



2HDM as a consistent UV completion

How to think of SFitter coupling results

- $\Delta_x \neq 0$ violating renormalization, unitarity,...
- experimentally irrelevant, only QCD matters
  theoretically (supposedly) of great interest
- EFT approach:
  (1) define consistent 2HDM, decouple heavy states
  (2) fit 2HDM model parameters, plot range of SM couplings
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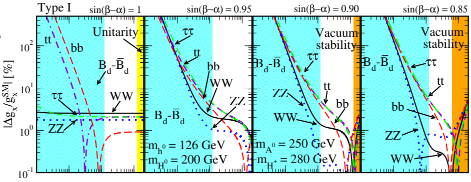
Yukawa-aligned 2HDM

- $\Delta_V \leftrightarrow (\beta - \alpha) \qquad \Delta_{b,t,\tau} \leftrightarrow \{\beta, \gamma_{b,\tau}\} \qquad \Delta_\gamma \leftrightarrow m_{H^\pm}$
- 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 $\tan\beta \ll 1$



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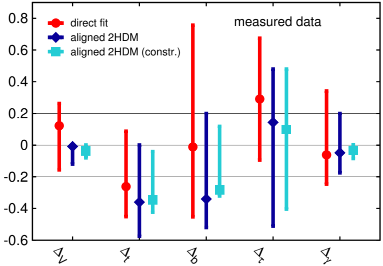
Consistent coupling fits

- 2HDM pretty good at tree level
- $\Delta_W \neq \Delta_Z > 0$ through loops

$\Rightarrow$ free SM couplings fine?



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]

$\Rightarrow$ do not know

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High scales

- Planck-scale extrapolation [Holthausen, Lim, Lindner; Buttazzo 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]

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

- IR fixed points phenomenological nightmare

$\Rightarrow$ do not know

Example: 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 $R = \lambda/y_t^2$

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

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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 space for new physics outside the Higgs sector?
- when will we finally kiss stronly interacting models good bye?

Small questions

- what are good alternative 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 theory dominating uncertainties
- which backgrounds do we need to know better?
- ...

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

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Bundesministerium für Bildung und Forschung