A Theorist's Take on the Higgs Discovery

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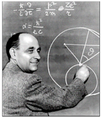
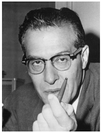
Weak interaction

Massive exchange bosons

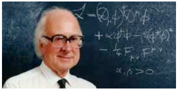
– Fermi 1934: weak interactions [$n \to p e^- \bar{\nu}_e$]
  point-like ($2 \to 2$) amplitude $\mathcal{A} \propto G_F E^2$
  unitarity violation [$E < 600$ GeV]
  pre-80s effective theory



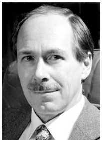
– Yukawa 1935: massive particles
  Fermi's theory for $E \ll M$
  modified amplitude $\mathcal{A} \propto g^2 E^2/(E^2 - M^2)$
  unitarity violation in $WW \to WW$ [$E < 1.2$ TeV]
  pre-LHC effective theory



– Schwinger, Tomonaga 1942: QED
  consistent and applicable quantum field theory
  massless role model of Standard Model



– Higgs 1964: spontaneous symmetry breaking
  unitary through Higgs particle
  particle masses allowed
  fundamental weak-scale scalar



– 't Hooft & Veltman 1971: renormalizability
  no $1/M$ couplings allowed
  theory valid to high energy
  Standard Model with Higgs fundamental

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 $3 \neq 2$

Higgs boson

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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 the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these par-

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

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}=0, \qquad (2a)$$

$$\{\partial^2-4\varphi_0^2V''(\varphi_0^2)\}(\Delta\varphi_2)=0, \qquad (2b)$$

$$\partial_\nu F^{\mu\nu}=e\varphi_0\{\partial^\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}. \qquad (2c)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c)

Weak interaction
Higgs boson
Lagrangian
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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.

Higgs boson

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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]

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

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

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

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- 1964: combining two problems to one predictive solution
- 1966: original Higgs phenomenology
- 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

Higgs boson

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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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$\Rightarrow$ Higgs boson predicted from mathematical field theory

Higgs boson

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In terms of Higgs potential

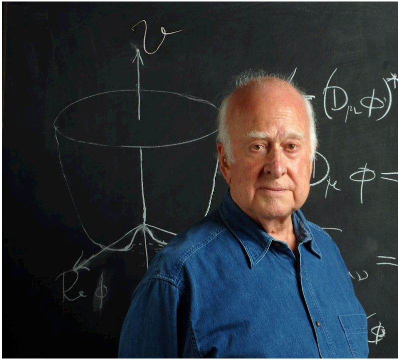
$$V = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

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

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

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

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



The heroes according to Inspire

Lessons for the field

– obviously, Higgs etal are outstanding physicists
– would we hire these brilliant people nowadays?
– is Nobel-worthy research visible by numbers?
– do non-Nobel-laureates look worse?

	papers	citations	top500	top250	top100
Peter Higgs	7	6979	PRL 13 (1964): 2382 PL 12 (1964): 2536 PR 145 (1966): 1867	0	1
Robert Brout	54	3393	PRL 13 (1964): 2161	0	3
Francois Englert	74	4563	PRL 13 (1964): 2161	1	6
Gerald Guralnik	66	3424	PRL 13 (1964): 1722	1	1
Carl Hagen	94	3761	PRL 13 (1964): 1722	0	6
Tom Kibble	72	8655	PRL 13 (1964): 1722 PR 155 (1967): 940 five more: 569-1582	0	6
Andrzej Buras	182	22458	4	10	53
Lance Dixon	109	16868	6	13	38
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$\Rightarrow$ non-Nobel-laureates are excellent company

Exercise: strongly or weakly interacting

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

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

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

field renormalization, strong multi-Higgs interactions

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

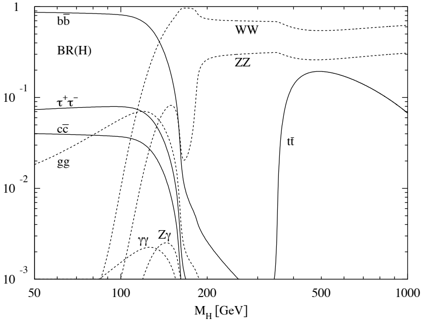
Higgs signatures

Higgs decays easy

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

$\Rightarrow$ $m_H = 126$ GeV perfect

[destructive interference]



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

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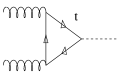
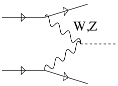
gluon fusion production loop induced [$\sigma \sim$ 15000 fb]
weak boson fusion production with jets [$\sigma \sim$ 1200 fb]





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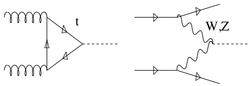

- easy channels for 2011-2012

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

Weak interaction
Higgs boson
Lagrangian
Discovery
Lagrangian
Couplings
Meaning

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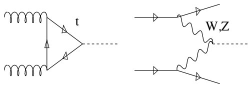

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$\Rightarrow$ fun still waiting

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

Weak interaction
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Higgs discovery

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

- '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)
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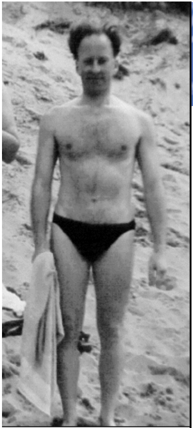
$\Rightarrow$ Rolf Heuer: ‘We have him’



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

Higgs discovery

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CMS-HIG-12-028

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

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

The CMS Collaboration*

31 Jul 2012

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

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

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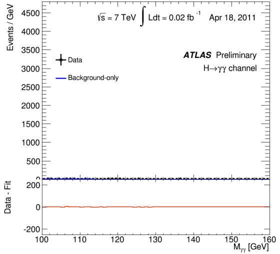
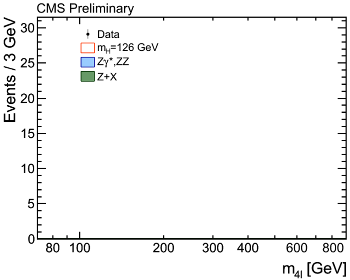
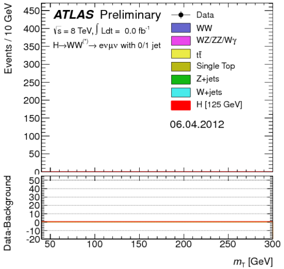
Update







Higgs-like boson turned into

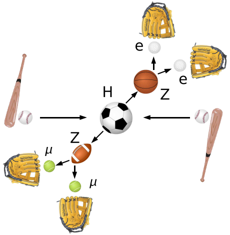
Standard-Model-like Higgs into a Higgs boson

Questions

1. What is the 'Higgs' Lagrangian?

   – psychologically: looked for Higgs, so found a Higgs

   – CP-even spin-0 scalar expected
   spin-1 vector unlikely
   spin-2 graviton unexpected



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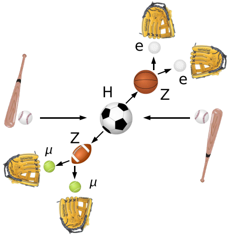

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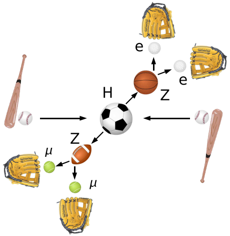

2. What are the coupling values?

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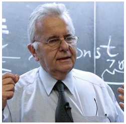
3. What does all this tell us?

- models predicting weak-scale new physics?
- renormalization group based Hail-Mary passes?

Lagrangian



Angular correlations like the flavor people

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

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

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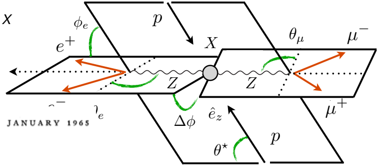


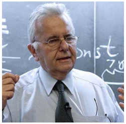
PHYSICAL REVIEW VOLUME 137, NUMBER 2B 25 JANUARY 1965

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.

Lagrangian



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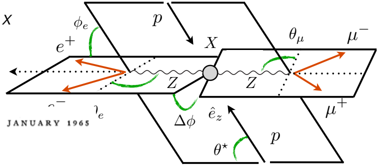

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* This work was done under the auspices of the U. S. Atomic Energy Commission.

† 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)].

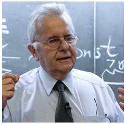
dominated by the postulated σ resonance. Measurement of average correlations could then be used to determine the mass of this resonance.

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).

Lagrangian



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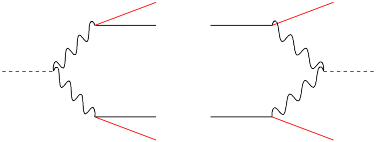

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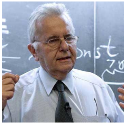

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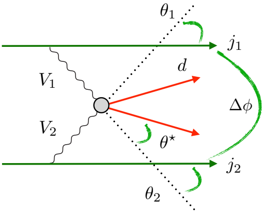

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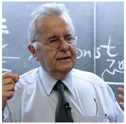

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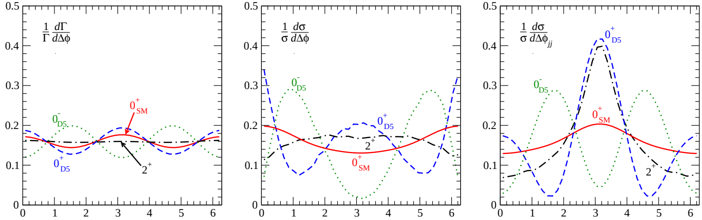
$$\mathcal{L} \supset (\phi^\dagger \phi) W^\mu W_\mu \qquad \frac{1}{\Lambda^2} (\phi^\dagger \phi) W^{\mu\nu} W_{\mu\nu} \qquad \frac{1}{\Lambda^2} (\phi^\dagger \phi) \epsilon_{\mu\nu\rho\sigma} W^{\mu\nu} W^{\rho\sigma}$$

$\Rightarrow$ different channels, same physics



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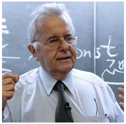

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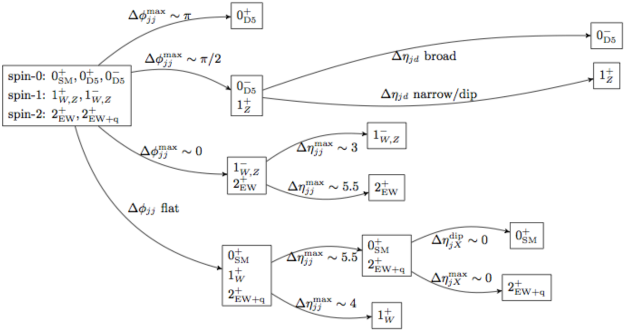

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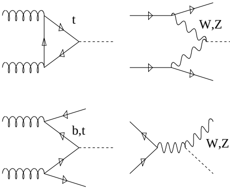
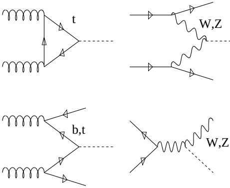


Standard Model operators [SFitter]

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

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

Couplings



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Production		Coupling		Decay
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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]

Couplings now and in the future

Now [Aspen/Moriond 2013]

– focus SM-like [secondary solutions possible]

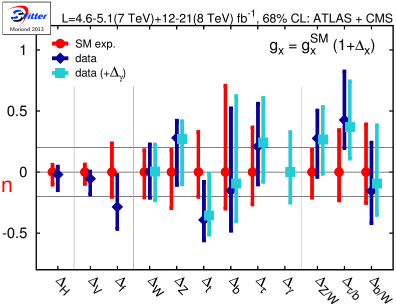
– six couplings and ratios from data

g_b from width

g_g vs g_t not yet possible

– poor man's analyses: $\Delta_H, \Delta_V, \Delta_f$

– almost too exactly the 1964 prediction



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- theory extrapolations tricky
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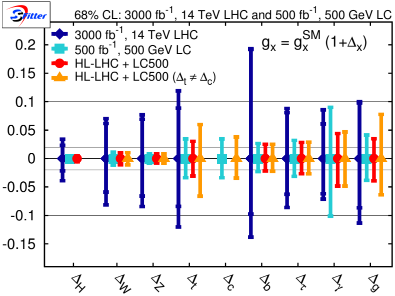
- interplay in loop-induced couplings



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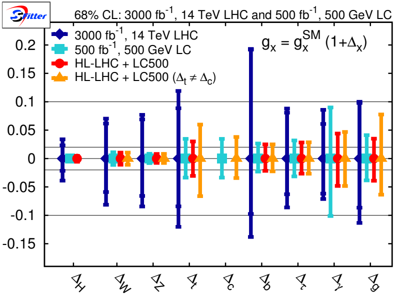
- interplay in loop-induced couplings
- fundamental e^+e^- advantages:
  unobserved decays avoided
  width measured from rate σ_{ZH}
  $H \to c\bar{c}$ accessible
  invisible decays hugely improved
  QCD theory error bars avoided



Weak interaction
Higgs boson
Lagrangian
Discovery
Lagrangian
Couplings
Meaning

Meaning

TeV-scale scenarios

- 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

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

– vacuum stability right at edge

– IR fixed point for λ/λ_t^2 fixing m_H^2/m_t^2

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

$\Rightarrow$ do not know

Exercise: top–Higgs renormalization group

Running of coupling/mass ratios

Higgs self coupling and top Yukawa with stable zero IR solutions

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

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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 $Q \sim v$

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

Exciting times...

...for LHC physicists

- Higgs discovery after almost 50 years [waiting since Fermi]
- detailed studies just starting
- all open physics territory

- many Higgs analysis challenges ahead
- technical expertize the key
- QCD always helpful

$\Rightarrow$ young and bright ideas in high demand

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