

A Theorist's Take on Higgs Physics

Tilman Plehn

Universität Heidelberg

Nordic Physics Days, 6/2013

Weak interaction

Weak interaction

Higgs boson

Discovery

Lagrangian

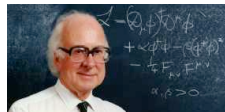
Couplings

Meaning

FW moments

Massive exchange bosons

- Fermi 1934: weak interactions $[n \rightarrow pe^- \bar{\nu}_e]$
point-like ($2 \rightarrow 2$) amplitude $\mathcal{A} \propto G_F E^2$
unitarity violation $[E < 600 \text{ GeV}]$
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 $WW \rightarrow WW$ $[E < 1.2 \text{ TeV}]$
pre-LHC effective theory
- 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

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Two problems for spontaneous gauge symmetry breaking

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



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

- 1964: combining two problems to one predictive solution

VOLUME 13, NUMBER 16

PHYSICAL REVIEW LETTERS

19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

In a recent note¹ 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 $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

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

Higgs boson

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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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¹P. W. Higgs, to be published.

²J. 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 Glashow³ 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 noticed⁵

Higgs boson

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II. THE MODEL

The Lagrangian density from which we shall work is given by²⁹

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

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

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

We consider a simple relativistic theory of two scalar fields, first discussed by Goldstone, in which as a symmetry one of the scalar bosons is massless, in conformity with the group of the Lagrangian is extended from global to local $U(1)$ coupling with a vector gauge field, the Goldstone boson becomes the one whose transverse states are the quanta of the transverse gauge field is developed in which the major features of these phenomena are discussed for decay and scattering processes are evaluated in lowest order, more directly from an equivalent Lagrangian in which the original system is coupled to other systems in a $U(1)$ invariant Lagrangian symmetry breakdown, associated with a partially conserved massive vector boson.

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

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

$$M = i\{e[a^{*\mu}(k_1)(-ik_{2\mu})\phi^*(k_2) + a^{*\mu}(k_2)(-ik_{1\mu})\phi^*(k_1)] - e(ip_{\mu})[a^{*\mu}(k_1)\phi^*(k_2) + a^{*\mu}(k_2)\phi^*(k_1)] - 2em_1a_{\mu}^*(k_1)a^{*\mu}(k_2) - fm_0\phi^*(k_1)\phi^*(k_2)\}.$$

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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- 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 $\pi^- p \rightarrow Hn$ or $\gamma p \rightarrow Hp$ 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: $3.7 \rightarrow 3.1 + H$ with a branching ratio $O(10^{-4})$. If its mass is ≤ 4 GeV, the Higgs

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

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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 predicted from mathematical field theory**

Higgs boson

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In terms of Higgs potential

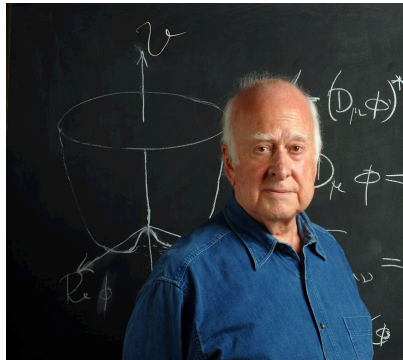
$$V = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

$$\text{minimum at } \phi = \frac{v}{\sqrt{2}}$$

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

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

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

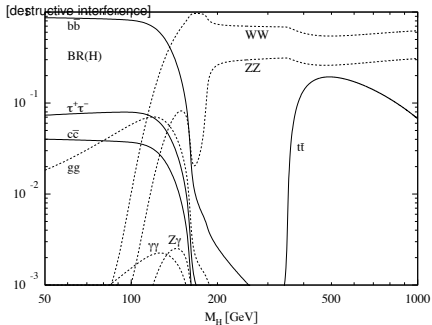


Higgs signatures

Higgs decays easy

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

⇒ $m_H = 125 \text{ GeV}$ perfect



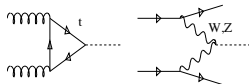
Higgs signatures

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- weak-scale scalar coupling proportional to mass
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 - decay to $\gamma\gamma$ via W and top loop [destructive interference]
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Higgs production hard [7-8 TeV, 5-15/fb]

- quantum effects needed
- gluon fusion production loop induced [$\sigma \sim 15000 \text{ fb}$]
- weak boson fusion production with jets [$\sigma \sim 1200 \text{ fb}$]



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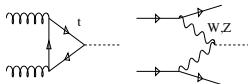
FW moments

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- easy channels for 2011-2012
- $pp \rightarrow H \rightarrow ZZ \rightarrow 4l$ fully reconstructed
 $pp \rightarrow H \rightarrow \gamma\gamma$ fully reconstructed
 $pp \rightarrow H \rightarrow WW \rightarrow (\ell^- \bar{\nu})(\ell^+ \nu)$ large BR

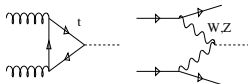
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⇒ fun still waiting

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

Higgs discovery

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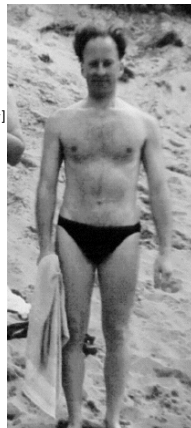
4th of July fireworks [no theory input needed beyond basic Pythia]

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

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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 Forth
by Prof J D Jackson, July 1960



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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

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**

The ATLAS Collaboration

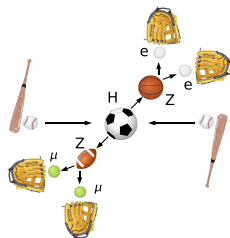
31 Jul 2012

| 31 Jul 2012

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



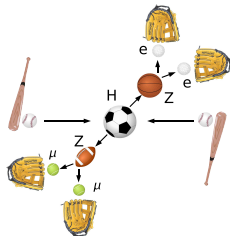
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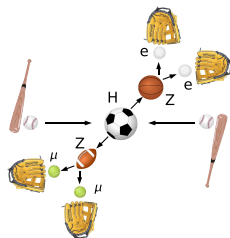
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3. What does all this tell us?

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

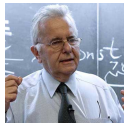


Lagrangian

Angular correlations

- Cabibbo–Maksymowicz–Dell’Aquila–Nelson angles for $H \rightarrow ZZ$

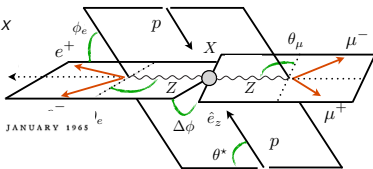
[Melnikov etal; Lykken etal; v d Bij etal; Choi etal; Englert, Spannowsky, Takeuchi]



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

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

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



PHYSICAL REVIEW

VOLUME 137, NUMBER 2B

25 JANUARY 1965

Angular Correlations in K_{s4} Decays and Determination of Low-Energy $\pi\text{-}\pi$ 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_{s4} decays can give unique information on low-energy $\pi\text{-}\pi$ scattering. To this end we introduce a particularly simple set of correlations. We show that the measurement of these correlations at any fixed $\pi\text{-}\pi$ c.m. energy allows one to make a model-independent determination of the difference $\delta_S - \delta_P$ between the S - and P -wave $\pi\text{-}\pi$ phase shifts at that energy. Information about the average value of $\delta_S - \delta_P$ 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 $\pi\text{-}\pi$ scattering. We discuss in particular two such models: (a) the Chew-Mandelstam effective-range description of S -wave scattering and (b) the Brown-Fairer 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

Angular correlations

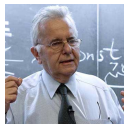
- Cabibbo–Maksymowicz–Dell’Aquila–Nelson angles for $H \rightarrow ZZ$

[Melnikov etal; Lykken etal; v d Bij etal; Choi etal; Englert, Spannowsky, Takeuchi]

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

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

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



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The study of correlations in K_{e4} decays can give unique information at any fixed $\pi-\pi$ c.m. energy allows one to make a measurement of the S - and P -wave $\pi-\pi$ phase shifts at that energy. Such a measurement can be obtained from a measurement of the same α . Measurement of the average correlations is particularly suitable for scattering. We discuss in particular two such models: (a) the description is adequate, the suggested measurements should be made in the $I=0$ state. If the σ -resonance model is correct, these are the resonance.

* 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.

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

* K. Chadan and S. Oneda, Phys. Rev. Letters **3**, 292 (1959).

† V. S. Mathur, Nuovo Cimento **14**, 1322 (1959).

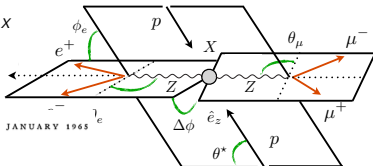
‡ E. P. Shabalin, Zh. Eksperim. i Teor. Fiz. **39**, 345 (1960) [English transl.: Soviet Phys.—JETP **12**, 245 (1961)].

* R. W. Birge, R. P. Ely, G. Gidal, G. E. Kalinus, A. Kernan, W. M. Powell, U. Cameron, W. F. Fry, J. Gaidos, R. H. March, and S. Nostali, Phys. Rev. Letters **11**, 85 (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.

† G. Ciocchetti, Nuovo Cimento **25**, 385 (1962).

‡ L. M. Brown and H. Faiss, Phys. Rev. Letters **12**, 514 (1964).

* 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)].



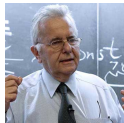
dominated by the postulated σ resonance. Measurement of average correlations could then be used to determine the mass of this resonance.

II. KINEMATICS AND CORRELATIONS

Our approach to the kinematics of the reaction $K^+ \rightarrow \pi^+ \pi^- e^+ e^-$ 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_{ee} . We then consider the subsequent decay of each of these two "resonances" in its own center-of-mass system.

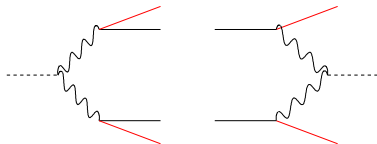
* The usefulness of angular correlations in the determination of $\pi-\pi$ phase shifts was first recognized by E. P. Shabalin, Zh. Eksperim. i Teor. Fiz. **44**, 765 (1963) [English transl.: Soviet Phys.—JETP **17**, 517 (1963)]. See also erratum, Zh. Eksperim. i Teor. Fiz. **45**, 2085 (1963).

Lagrangian

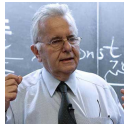


Angular correlations

- Cabibbo–Maksymowicz–Dell’Aquila–Nelson angles for $H \rightarrow ZZ$
[Melnikov etal; Lykken etal; v d Bij etal; Choi etal; Englert, Spannowsky, Takeuchi]
- Breit frame or hadron collider (η, ϕ) in WBF [Breit: boost into space-like]
[Rainwater, TP, Zeppenfeld; Hagiwara, Li, Mawatari; Englert, Mawatari, Netto, TP]



Lagrangian



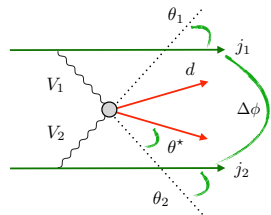
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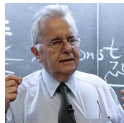
$$\cos \theta_1 = \hat{p}_{j_1} \cdot \hat{p}_{V_2} \Big|_{V_1 \text{ Breit}} \quad \cos \theta_2 = \hat{p}_{j_2} \cdot \hat{p}_{V_1} \Big|_{V_2 \text{ Breit}} \quad \cos \theta^* = \hat{p}_{V_1} \cdot \hat{p}_d \Big|_X$$

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

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



Lagrangian

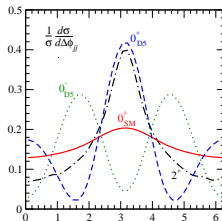
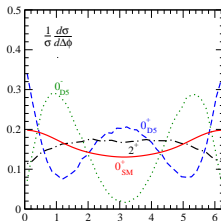
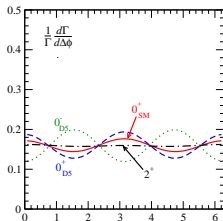


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[Rainwater, TP, Zeppenfeld; Hagiwara, Li, Mawatari; Englert, Mawatari, Netto, TP]
- possible scalar couplings

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

⇒ different channels, same physics



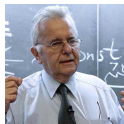
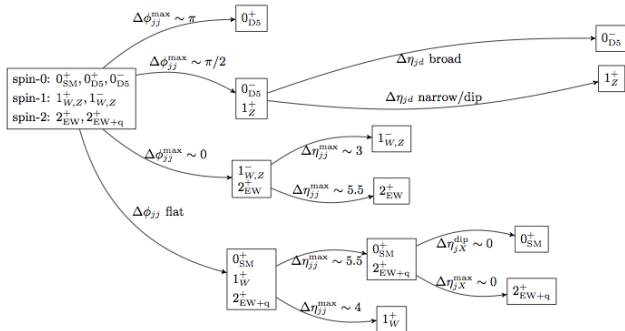
Lagrangian

Angular correlations

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Couplings

Standard-Model-inspired model

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

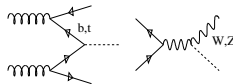
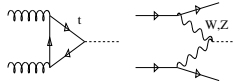
$$\begin{array}{l} gg \rightarrow H \\ qq \rightarrow qqH \\ gg \rightarrow ttH \\ qq' \rightarrow VH \end{array}$$

 \longleftrightarrow

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

 \longleftrightarrow

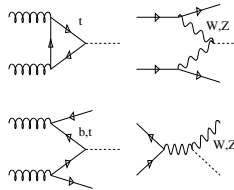
$$\begin{array}{l} H \rightarrow ZZ \\ H \rightarrow WW \\ H \rightarrow b\bar{b} \\ H \rightarrow \tau^+\tau^- \\ H \rightarrow \gamma\gamma \end{array}$$



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$$\begin{aligned} gg &\rightarrow H \\ qq &\rightarrow qqH \\ gg &\rightarrow t\bar{t}H \\ qq' &\rightarrow VH \end{aligned}$$

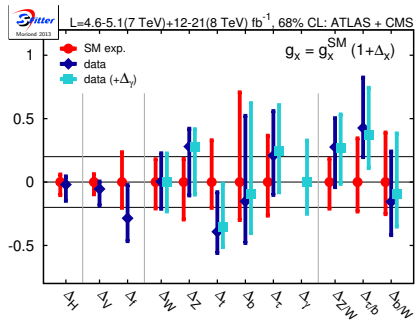
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 \longleftrightarrow

$$\begin{aligned} H &\rightarrow ZZ \\ H &\rightarrow WW \\ H &\rightarrow b\bar{b} \\ H &\rightarrow \tau^+\tau^- \\ H &\rightarrow \gamma\gamma \end{aligned}$$

\Rightarrow almost too exactly the prediction of 1964?



Meaning

Weak interaction

Higgs boson

Discovery

Lagrangian

Couplings

Meaning

FW moments

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 fundamental scalar discovered]
- ⇒ **do not know**



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⇒ **do not know**



High scales

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

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

- vacuum stability right at edge
- IR fixed point for λ/λ_t^2 fixing m_H^2/m_t^2 [with gravity: Shaposhnikov, Wetterich]

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

⇒ **do not know**



Fox-Wolfram moments

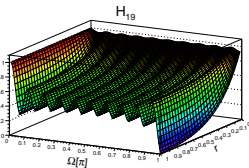
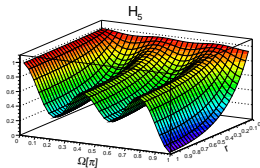
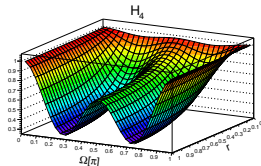
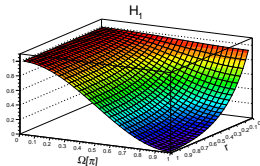
Weighted series in spherical harmonics [Field, Kanev, Tayebnejad; Bernaciak, Buschmann, Butter, TP]

- originally alternative to event shapes

$$H_\ell^T = \frac{4\pi}{2\ell + 1} \sum_{m=-\ell}^{\ell} \left| \sum_{i=1}^N Y_\ell^m(\Omega_i) \frac{p_{T,i}}{p_{T,\text{tot}}} \right|^2 = \sum_{i,j=1}^N \frac{p_{T,i} p_{T,j}}{p_{T,\text{tot}}^2} P_\ell(\cos \Omega_{ij})$$



- tunable for forward jets



	$H_\ell < 0.3$	$0.3 < H_\ell < 0.7$	$0.7 < H_\ell < 1$
even ℓ	forbidden	democratic	ordered, collinear, back-to-back
odd ℓ	back-to-back	democratic	collinear, ordered

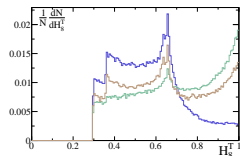
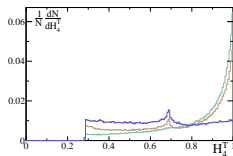
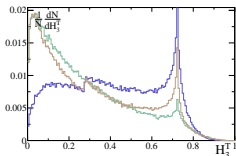
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- tunable for forward jets
- applied to tagging jets in WBF [$m_{jj} > 600 \text{ GeV}$]



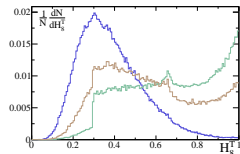
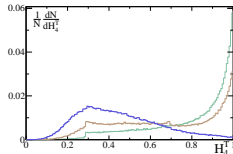
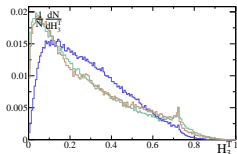
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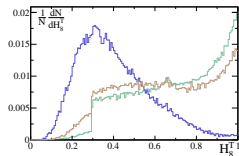
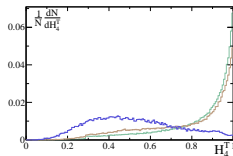
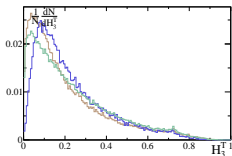
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- applied to tagging jets in WBF [$m_{jj} > 600$ GeV]
- applied to all jets in WBF
- applied to all jets after WBF cuts



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- tunable for forward jets
 - applied to tagging jets in WBF [$m_{jj} > 600$ GeV]
 - applied to all jets in WBF
 - applied to all jets after WBF cuts
- ⇒ **might be useful, bachelor project!**

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 expertise the key
- QCD always helpful

⇒ young and bright ideas in high demand

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

Higgs Physics

Tilman Plehn

Weak interaction

Higgs boson

Discovery

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