Random Thoughts about Higgs Measurements

Tilman Plehn

Universität Heidelberg

Sussex, June 2014

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

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

– 1964: combining two problems to one predictive solution

Volume 13, Number 16 PHYSICAL REVIEW LETTERS 19 October 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if

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

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

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-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)

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]

[1]P. W. Higgs, to be published.
[2]J. Goldstone, Nuovo Cimento 19, 154 (1961);
J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev.

d-
l
rs
ly if

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

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

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

– 1964: combining two problems to one predictive solution

– 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

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

- 1964: combining two problems to one predictive solution
- 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)

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

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

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

...te nature
...-particle
...ble solu-
...s, rather
...ynamical

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

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

– 1964: combining two problems to one predictive solution
– 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

We examine a simple relativ

II. THE MODEL

The Lagrangian density from which we shall w is given by[29]

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

In Eq. (1) the metric tensor $g^{\mu\nu} = -1$ ($\mu = \nu$ $+1$ ($\mu = \nu \neq 0$) or 0 ($\mu \neq \nu$), Greek indices run fro to 3 and Latin indices from 1 to 2. The $U(1)$-covar 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 functions we reduce this to the form

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

- 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

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

– 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

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
is such as
mass of
f its mass
p → Hn or
nt in the
decays of kaons with a branching ratio O(10⁻⁷), or in the decays of one of the new par-
ticles: 3.7 → 3.1 + H with a branching ratio O(10⁻⁴). If its mass is ≤4 GeV, the Higgs

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

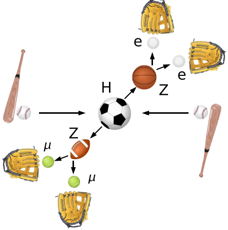
– 1964: combining two problems to one predictive solution

– 1966: original Higgs phenomenology

– 1976 etc: collider phenomenology

$\Rightarrow$ Higgs boson based on field theory

Questions

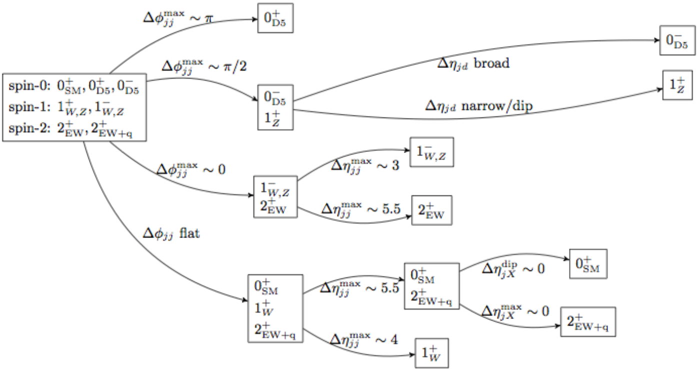


1. What is the ‘Higgs’ Lagrangian?

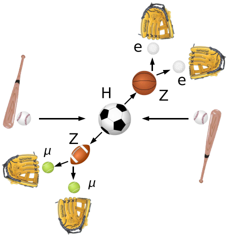
– psychologically: looked for Higgs, so found a Higgs

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

– ask flavor colleagues [Cabibbo–Maksymowicz–Dell’Aquila–Nelson angles]



Questions



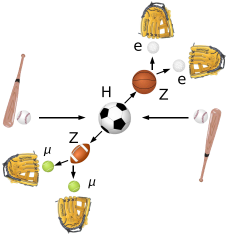
1. What is the 'Higgs' Lagrangian?

- psychologically: looked for Higgs, so found a Higgs
- CP-even spin-0 scalar expected, which operators?
  spin-1 vector unlikely
  spin-2 graviton unexpected
- ask flavor colleagues [Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles]

2. What are the coupling values?

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

Questions

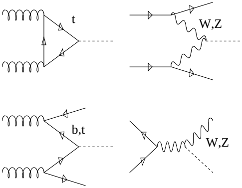


1. What is the 'Higgs' Lagrangian?
   - psychologically: looked for Higgs, so found a Higgs
   - CP-even spin-0 scalar expected, which operators?
     spin-1 vector unlikely
     spin-2 graviton unexpected
   - ask flavor colleagues [Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles]

2. What are the coupling values?
   - 'coupling' after fixing operator basis
   - Standard Model Higgs vs anomalous couplings

3. What does all this tell us?
   - strongly interacting models?
   - weakly interacting two-Higgs-doublet models?
   - TeV-scale new physics?

Couplings



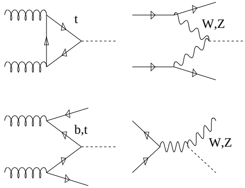
Standard Model operators [SFitter: Klute, Lafaye, TP, Rauch, Zerwas]

– assume: narrow CP-even scalar
  Standard Model operators
  couplings proportional to masses?

– couplings from production & decay rates

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

Couplings



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

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

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: $g_{WWH} \lesssim g_{WWH}^{\text{SM}} \to \Gamma_H|_{\text{max}}$ [HiggsSignals]

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

Couplings now and in the future

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

– focus SM-like [secondary solutions possible]

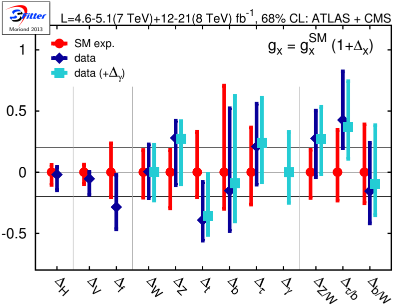
– SFitter: correct theory uncertainties

– g_g vs g_t not yet possible

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

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

$\Rightarrow$ six couplings and ratios from data



Couplings now and in the future

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

– focus SM-like [secondary solutions possible]

– SFitter: correct theory uncertainties

– g_g vs g_t not yet possible

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

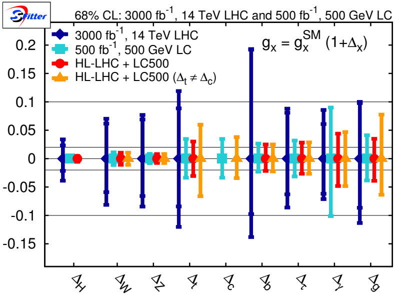
– poor man's analyses: $\Delta_H, \Delta_V, \Delta_f$

$\Rightarrow$ six couplings and ratios from data

Future

– LHC extrapolations unclear

– interplay in loop-induced couplings



Couplings now and in the future

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

– focus SM-like [secondary solutions possible]

– SFitter: correct theory uncertainties

– g_g vs g_t not yet possible

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

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

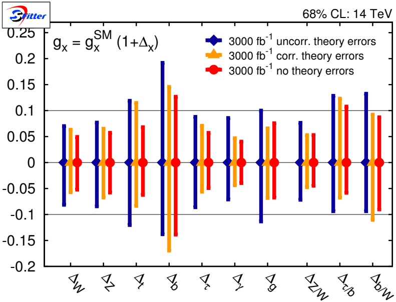
⇒ six couplings and ratios from data

Future

– LHC extrapolations unclear

– interplay in loop-induced couplings

– theory correlations protecting ratios?



Couplings now and in the future

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

– focus SM-like [secondary solutions possible]

– SFitter: correct theory uncertainties

– g_g vs g_t not yet possible

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

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

$\Rightarrow$ six couplings and ratios from data

Future

– LHC extrapolations unclear

– interplay in loop-induced couplings

– theory correlations protecting ratios?

– obvious ILC case:

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

Resolving the ggH vertex

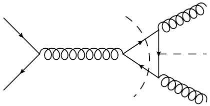
Non–pointlike-ness of *ggH* vertex [Ellis, Hinchliffe, Soldate, v d Bij; Baur & Glover]

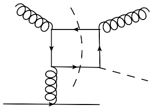
– loop–induced coupling $[\tau = 4m_t^2/m_H^2]$

$$\mathcal{L}_{ggH} \supset -i\frac{H}{v} \; G^{\mu\nu} G_{\mu\nu} \; \frac{\alpha_s}{8\pi} \; \tau \left[1 + (1-\tau) f(\tau)\right]$$

$$f(\tau) \stackrel{\text{on-shell}}{=} \left(\arcsin \sqrt{\frac{1}{\tau}} \right)^2 \stackrel{\tau \to \infty}{=} \frac{1}{\tau} + \frac{1}{3\tau^2}$$

– start with absorptive imaginary parts of loop integrals [like thresholds]





Resolving the ggH vertex

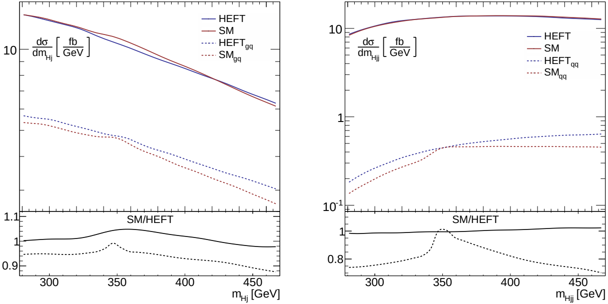
Non–pointlike-ness of *ggH* vertex [Ellis, Hinchliffe, Soldate, v d Bij; Baur & Glover]

– loop–induced coupling $[\tau = 4m_t^2/m_H^2]$

$$\mathcal{L}_{ggH} \supset -i\frac{H}{v}\; G^{\mu\nu} G_{\mu\nu}\; \frac{\alpha_s}{8\pi}\; \tau\left[1+(1-\tau)f(\tau)\right]$$

$$f(\tau) \overset{\text{on-shell}}{=} \left(\arcsin\sqrt{\frac{1}{\tau}}\right)^2 \overset{\tau\to\infty}{=} \frac{1}{\tau}+\frac{1}{3\tau^2}$$

– start with absorptive imaginary parts of loop integrals [like thresholds]



Resolving the ggH vertex

Non–pointlike-ness of *ggH* vertex [Ellis, Hinchliffe, Soldate, v d Bij; Baur & Glover]

– loop–induced coupling [$\tau = 4m_t^2/m_H^2$]

$$\mathcal{L}_{ggH} \supset -i\frac{H}{v} \; G^{\mu\nu} G_{\mu\nu} \; \frac{\alpha_s}{8\pi} \; \tau \left[1 + (1-\tau) f(\tau)\right]$$

$$f(\tau) \stackrel{\text{on-shell}}{=} \left(\arcsin \sqrt{\frac{1}{\tau}} \right)^2 \stackrel{\tau\to\infty}{=} \frac{1}{\tau} + \frac{1}{3\tau^2}$$

– start with absorptive imaginary parts of loop integrals [like thresholds]

– high-p_T logarithmic structure instead [Banfi etal; Azatov etal; Grojean etal]

$$|\mathcal{M}_{Hj}|^2 \propto m_t^4 \; \log^4 \frac{p_T^2}{m_t^2}$$

Resolving the ggH vertex

Non–pointlike-ness of *ggH* vertex [Ellis, Hinchliffe, Soldate, v d Bij; Baur & Glover]

– loop–induced coupling $[\tau = 4m_t^2/m_H^2]$

$$\mathcal{L}_{ggH} \supset -i\frac{H}{v} \; G^{\mu\nu} G_{\mu\nu} \; \frac{\alpha_s}{8\pi} \; \tau \left[1 + (1-\tau) f(\tau)\right]$$

$$f(\tau) \stackrel{\text{on-shell}}{=} \left(\arcsin \sqrt{\frac{1}{\tau}} \right)^2 \stackrel{\tau\to\infty}{=} \frac{1}{\tau} + \frac{1}{3\tau^2}$$

– start with absorptive imaginary parts of loop integrals [like thresholds]

– high-p_T logarithmic structure instead [Banfi etal; Azatov etal; Grojean etal]

Higher multiplicity, more logs? [Buschmann, Englert, Golcalves, TP, Spannowsky]

– check m_{jj}, p_z in *Hjj* production, nothing...

– instead same as *Hj* process

$$|\mathcal{M}_{Hjj}|^2 \propto \frac{m_t^4}{Q^4} \; \log^4 \frac{Q^2}{m_t^2} \sim \frac{m_t^4}{p_T^4} \; \log^4 \frac{p_T^2}{m_t^2}$$

Resolving the ggH vertex

Non–pointlike-ness of *ggH* vertex [Ellis, Hinchliffe, Soldate, v d Bij; Baur & Glover]

– loop–induced coupling $[\tau = 4m_t^2/m_H^2]$

$$\mathcal{L}_{ggH} \supset -i\frac{H}{v}\, G^{\mu\nu}G_{\mu\nu}\, \frac{\alpha_s}{8\pi}\, \tau\, [1 + (1-\tau) f(\tau)]$$

$$f(\tau) \stackrel{\text{on-shell}}{=} \left(\arcsin \sqrt{\frac{1}{\tau}} \right)^2 \stackrel{\tau\to\infty}{=} \frac{1}{\tau} + \frac{1}{3\tau^2}$$

– start with absorptive imaginary parts of loop integrals [like thresholds]

– high-p_T logarithmic structure instead [Banfi etal; Azatov etal; Grojean etal]

Higher multiplicity, more logs? [Buschmann, Englert, Golcalves, TP, Spannowsky]

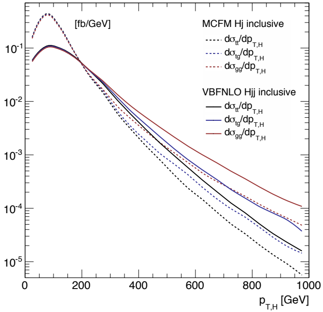
– check m_{jj}, p_z in *Hjj* production, nothing...

– instead same as *Hj* process

$$|\mathcal{M}_{Hjj}|^2 \propto \frac{m_t^4}{Q^4}\, \log^4 \frac{Q^2}{m_t^2} \sim \frac{m_t^4}{p_T^4}\, \log^4 \frac{p_T^2}{m_t^2}$$

– *Hjj* most promising with $H \to WW$

⇒ *Hjj* with more events in relevant regime



MadMax-imizing theory understanding

Modern analyses vs phase space

– hardly any counting experiments left [NN or BDT output instead]

– theory uncertainties increasingly relevant

– relevant information still (mostly) in hard process

$\Rightarrow$ how do we understand experimental results?

MadMax-imizing theory understanding

Modern analyses vs phase space

– hardly any counting experiments left [NN or BDT output instead]

– theory uncertainties increasingly relevant

– relevant information still (mostly) in hard process

⇒ how do we understand experimental results?

Differential significance distribution [TP, Schichtel, Wiegand]

– Neyman–Pearson lemma
log-likelihood ratio the best discriminator

– maximum significance through PS integral [Cranmer & TP]

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

– evaluated in parallel to cross sections [in Madgraph]

– translated into significance via LEPStats4LHC [Cranmer etal]

MadMax-imizing theory understanding

Modern analyses vs phase space

– hardly any counting experiments left [NN or BDT output instead]

– theory uncertainties increasingly relevant

– relevant information still (mostly) in hard process

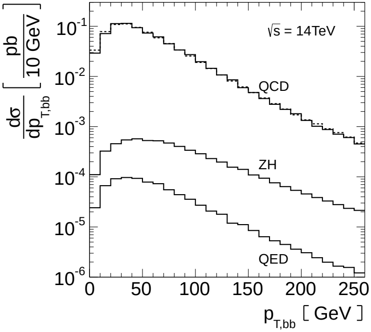
⇒ how do we understand experimental results?

Link to Higgs couplings: ZH, $H \to b\bar{b}$ [same for $t\bar{t}H$]

– boosted Higgs the key

– modern analyses imminent

– $p_{T,bb}$ distributions



MadMax-imizing theory understanding

Modern analyses vs phase space

– hardly any counting experiments left [NN or BDT output instead]

– theory uncertainties increasingly relevant

– relevant information still (mostly) in hard process

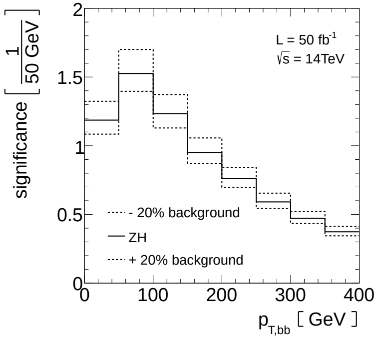
⇒ how do we understand experimental results?

Link to Higgs couplings: ZH, $H \to b\bar{b}$ [same for $t\bar{t}H$]

– boosted Higgs the key

– modern analyses imminent

– $p_{T,bb}$ distributions



MadMax-imizing theory understanding

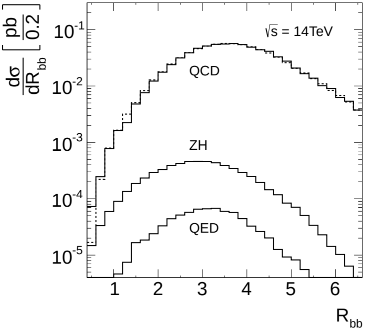
Modern analyses vs phase space

- hardly any counting experiments left [NN or BDT output instead]
- theory uncertainties increasingly relevant
- relevant information still (mostly) in hard process

⇒ how do we understand experimental results?

Link to Higgs couplings: ZH, $H \to b\bar{b}$ [same for $t\bar{t}H$]

- boosted Higgs the key
- modern analyses imminent
- $p_{T,bb}$ distributions
- R_{bb} distributions



MadMax-imizing theory understanding

Modern analyses vs phase space

– hardly any counting experiments left [NN or BDT output instead]

– theory uncertainties increasingly relevant

– relevant information still (mostly) in hard process

$\Rightarrow$ how do we understand experimental results?

Link to Higgs couplings: ZH, $H \to b\bar{b}$ [same for $t\bar{t}H$]

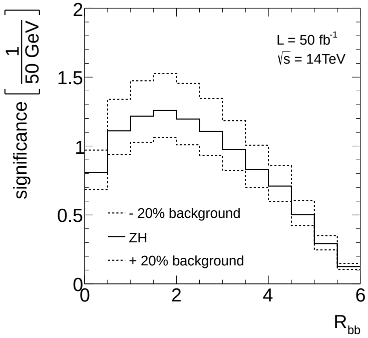
– boosted Higgs the key

– modern analyses imminent

– $p_{T,bb}$ distributions

– R_{bb} distributions

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



2HDM as weakly interacting completion

Extended Higgs models [Lopez-Val, TP, Rauch; many, many, many papers, ask Dr No]

– assume the Higgs really is ‘a Higgs’

– allow for coupling modifications

$\Rightarrow$ how would 2HDMs look?

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

2HDM as weakly interacting completion

Extended Higgs models [Lopez-Val, TP, Rauch; many, many, many papers, ask Dr No]

– assume the Higgs really is ‘a Higgs’

– allow for coupling modifications

$\Rightarrow$ how would 2HDMs look?

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 $\lambda_{6,7}$

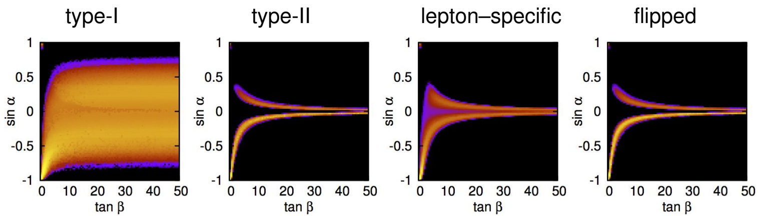
2HDM as weakly interacting completion

Extended Higgs models [Lopez-Val, TP, Rauch; many, many, many papers, ask Dr No]

– assume the Higgs really is ‘a Higgs’
– allow for coupling modifications
⇒ how would 2HDMs look?

Facing data

– fit including single heavy Higgs mass
– decoupling regime $\sin^2\alpha \sim 1/(1+\tan^2\beta)$
⇒ 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,...
- weak UV theory 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
  (3) compare to free SM couplings fit

2HDM as a consistent UV completion

How to think of SFitter coupling results

- $\Delta_x \neq 0$ violating renormalization, unitarity,...
- weak UV theory 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
  (3) compare to free SM couplings fit

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 $\tan\beta \ll 1$
  $\Delta_W \neq \Delta_Z > 0$ possible

2HDM as a consistent UV completion

How to think of SFitter coupling results

– $\Delta_x \neq 0$ violating renormalization, unitarity,...

– weak UV theory experimentally irrelevant, only QCD matters
theoretically (supposedly) of great interest

– EFT approach:

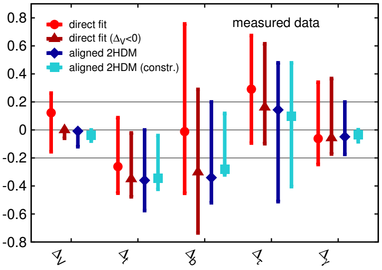
(1) define consistent 2HDM, decouple heavy states
(2) fit 2HDM model parameters, plot range of SM couplings
(3) compare to free SM couplings fit

UV-complete vs SM coupling fits

– 2HDM close to perfect at tree level

– $\Delta_W \neq \Delta_Z > 0$ through loops

$\Rightarrow$ free SM couplings well defined



Similar models

One-dimensional description of signal strengths $\Gamma_{p,d}$ [Cranmer, Kreiss, Lopez-Val, TP]

– decoupling defined through the massive gauge sector

$$\frac{g_V}{g_V^{\text{SM}}} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \qquad \Leftrightarrow \qquad \Delta_V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3)$$

Similar models

One-dimensional description of signal strengths $\Gamma_{p,d}$ [Cranmer, Kreiss, Lopez-Val, TP]

– decoupling defined through the massive gauge sector

$$\frac{g_V}{g_V^{\text{SM}}} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \qquad \Leftrightarrow \qquad \Delta_V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3)$$

– dark singlet

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

Similar models

One-dimensional description of signal strengths $\Gamma_{p,d}$ [Cranmer, Kreiss, Lopez-Val, TP]

– decoupling defined through the massive gauge sector

$$\frac{g_V}{g_V^{\text{SM}}} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \qquad \Leftrightarrow \qquad \Delta_V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3)$$

– dark singlet

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

– mixing singlet [Jose's portal, no anomalous decays]

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

Similar models

One-dimensional description of signal strengths $\Gamma_{p,d}$ [Cranmer, Kreiss, Lopez-Val, TP]

– decoupling defined through the massive gauge sector

$$\frac{g_V}{g_V^{\rm SM}} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \qquad \Leftrightarrow \qquad \Delta_V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3)$$

– dark singlet

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

– mixing singlet [Jose's portal, no anomalous decays]

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

– composite Higgs

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

Similar models

One-dimensional description of signal strengths $\Gamma_{p,d}$ [Cranmer, Kreiss, Lopez-Val, TP]

– decoupling defined through the massive gauge sector

$$\frac{g_V}{g_V^{\text{SM}}} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \qquad \Leftrightarrow \qquad \Delta_V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3)$$

– dark singlet

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

– mixing singlet [Jose's portal, no anomalous decays]

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

– composite Higgs

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

– additional doublet [type-X fermion sector]

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

Similar models

One-dimensional description of signal strengths $\Gamma_{p,d}$ [Cranmer, Kreiss, Lopez-Val, TP]

– decoupling defined through the massive gauge sector

$$\frac{g_V}{g_V^{\text{SM}}} = 1 - \frac{\xi^2}{2} + \mathcal{O}(\xi^3) \qquad \Leftrightarrow \qquad \Delta_V = -\frac{\xi^2}{2} + \mathcal{O}(\xi^3)$$

– dark singlet

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

– mixing singlet [Jose's portal, no anomalous decays]

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

– composite Higgs

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

– additional doublet [type-X fermion sector]

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

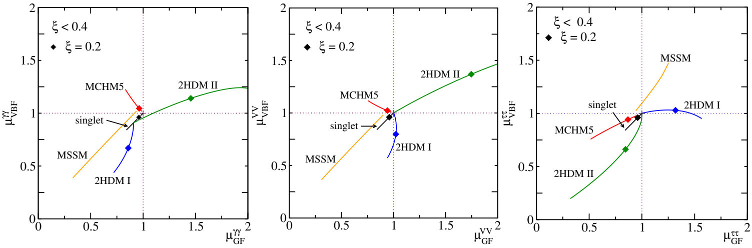
– MSSM [plus tan β]

$$\xi^2 =\simeq \frac{m_h^2\,(m_Z^2 - m_h^2)}{m_A^2(m_H^2 - m_h^2)} \sim \frac{m_Z^4\,\sin^2(2\beta)}{m_A^4}$$

Extended Higgs sectors

Effect on signal strengths

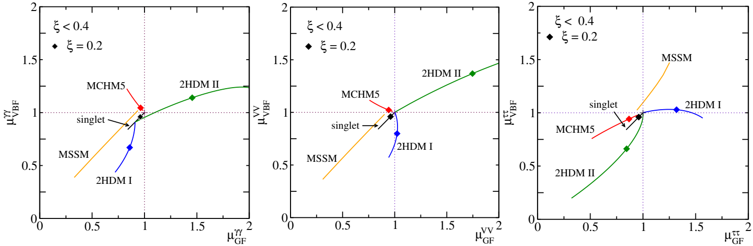
- decay–diagonal and production–diagonal correlations
- new physics scenarios in 2 dimensions



Extended Higgs sectors

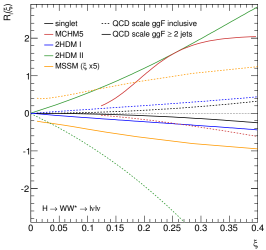
Effect on signal strengths

– decay–diagonal and production–diagonal correlations
– new physics scenarios in 2 dimensions



– theory uncertainties with direction

⇒ robustness measure



Meaning

TeV scale

- fourth chiral generation excluded
- strongly interacting models retreating [Goldstone protection]
- extended Higgs sectors wide open
- no final verdict on the MSSM
- hierarchy problem worse than ever [light fundemental scalar discovered]

$\Rightarrow$ whatever...

Meaning

TeV scale

– fourth chiral generation excluded

– strongly interacting models retreating [Goldstone protection]

– extended Higgs sectors wide open

– no final verdict on the MSSM

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

$\Rightarrow$ whatever...

High scales

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

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

– vacuum stability right at edge

– $\lambda = 0$ at finite energy?

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

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

– IR fixed points phenomenological nightmare

$\Rightarrow$ whatever...

Exercise: top–Higgs renormalization group

Running of coupling/mass ratios [Wetterich]

Higgs self coupling and top Yukawa with stable zero IR solutions

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

Exercise: top–Higgs renormalization group

Running of coupling/mass ratios [Wetterich]

Higgs self coupling and top Yukawa with stable zero IR solutions

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

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

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

Exercise: top–Higgs renormalization group

Running of coupling/mass ratios [Wetterich]

Higgs self coupling and top Yukawa with stable zero IR solutions

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

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

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

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

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

Questions

Big questions

– is it really the Standard Model Higgs?

– is there new physics outside the Higgs sector?

Small questions

– what are good alternative 'Higgs' test hypotheses?

– how can we improve the couplings fit precision?

– how can we measure the bottom Yukawa?

– how can we measure the top Yukawa?

– how can we measure the Higgs self coupling?

– how do we avoid theory dominating uncertainties

– can QCD really be fun?

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

Much of this work was funded by the BMBF Theorie-Verbund which is ideal for relevant LHC work

Bundesministerium für Bildung und Forschung

Exercise: what operators can do

Higgs sector including dimension-6 operators

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

Exercise: what operators can do

Higgs sector including dimension-6 operators

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

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]

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

Exercise: what operators can do

Higgs sector including dimension-6 operators

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

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]

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

second operator, minimum condition to fix v

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

Exercise: what operators can do

Higgs sector including dimension-6 operators

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

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]

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

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

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

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

Exercise: what operators can do

Higgs sector including dimension-6 operators

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

Higgs self couplings momentum dependent

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

Exercise: what operators can do

Higgs sector including dimension-6 operators

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

Higgs self couplings momentum dependent

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

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, Pomarol, Rattazzi, Galloway,...]

- strongly interacting models not looking like that [Bardeen, Hill, Lindner]
- 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

Higher-dimensional operators

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

– strongly interacting models not looking like that [Bardeen, Hill, Lindner]

– 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

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

Higher-dimensional operators

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

– strongly interacting models not looking like that [Bardeen, Hill, Lindner]
– 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

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

Higher-dimensional operators

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

- strongly interacting models not looking like that [Bardeen, Hill, Lindner]
- 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
- collider phenomenology of $(H^\dagger H)$

Higher-dimensional operators

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

– strongly interacting models not looking like that [Bardeen, Hill, Lindner]
– 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
– collider phenomenology of $(H^\dagger H)$

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
$\Rightarrow$ before measuring couplings remember what your operators are!

Angular Correlations

Measurements of operator structures [learning from the flavor people]

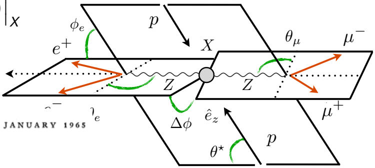
– Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles for $H \to ZZ$

[Melnikov etal; Lykken etal; v d Bij etal; Choi etal; Fabio 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 [learning from the flavor people]

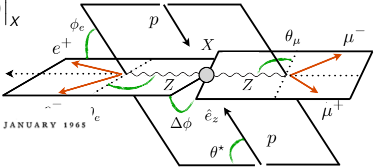
– Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles for $H \to ZZ$

[Melnikov etal; Lykken etal; v d Bij etal; Choi etal; Fabio 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 i
end we introduce a particularly simple set of correlations. '
tions at any fixed π-π c.m. energy allows one to make a mc
δ_0-δ_1 between the S- and P-wave π-π phase shifts at that
δ_0-δ_1 can be obtained from a measurement of the same c
Measurement of the average correlations is particularly suit
scattering. We discuss in particular two such models: (a) tl
of S-wave scattering and (b) the Brown-Faier σ-resonance
description is adequate, the suggested measurements shoul
in the $I=0$ state. If the σ-resonance model is correct, these n
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.
[1] L. B. Okun' and E. P. Shabalin, Zh. Eksperim. i Teor. Fiz. **37**, 1775 (1959) [English transl.: Soviet Phys.—JETP **10**, 1252 (1960)].
[2] K. Chadan and S. Oneda, Phys. Rev. Letters **3**, 292 (1959).
[3] V. S. Mathur, Nuovo Cimento **14**, 1322 (1959).
[4] E. P. Shabalin, Zh. Eksperim. i Teor. Fiz. **39**, 345 (1960) [English transl.: Soviet Phys.—JETP **12**, 245 (1961)].
[5] R. W. Birge, R. P. Ely, G. Gidal, G. E. Kalmus, A. Kernan, W. M. Powell, U. Camerini, W. F. Fry, J. Gaidos, R. H. March, and S. Natali, Phys. Rev. Letters **11**, 35 (1963). Members of this group have kindly communicated to us that the total of 11 events reported in this paper has now increased to at least 80.
[6] G. Ciocchetti, Nuovo Cimento **25**, 385 (1962).
[7] L. M. Brown and H. Faier, Phys. Rev. Letters **12**, 514 (1964).
[8] B. A. Arbuzov, Nguyen Van Hieu, and R. N. Faustov, Zh. Eksperim. i Teor. Fiz. **44**, 329 (1963) [English transl.: Soviet Phys.—JETP **17**, 225 (1963)].

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

II. KINEMATICS AND CORRELATIONS

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

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

Angular Correlations

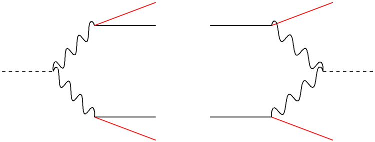
Measurements of operator structures [learning from the flavor people]

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

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



Angular Correlations

Measurements of operator structures [learning from the flavor people]

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

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

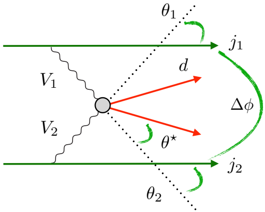
– Breit frame or hadron collider (η, ϕ) in WBF [Breit: boost into space-like]

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

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

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

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



Angular Correlations

Measurements of operator structures [learning from the flavor people]

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

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

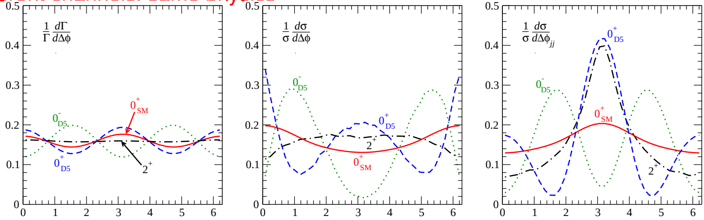
– Breit frame or hadron collider (η, ϕ) in WBF [Breit: boost into space-like]

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

– 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



Angular Correlations

Measurements of operator structures [learning from the flavor people]

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

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

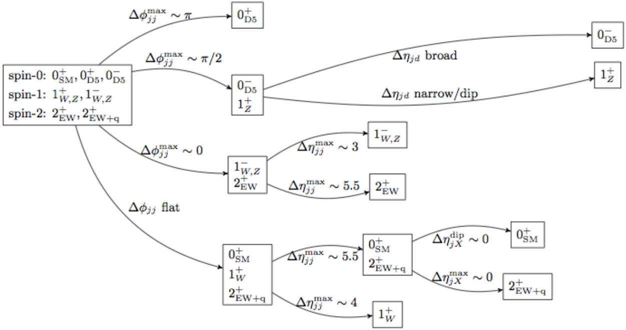
– Breit frame or hadron collider (η, ϕ) in WBF [Breit: boost into space-like]

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

– 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



Longitudinal WW scattering

WW scattering at high energies [Tao etal; Dawson]

– historically alternative to light Higgs

– *WW* scattering at high energies [via Goldstones]

$$g_V \; H \; \left(a_L V_{L\mu} V_L^\mu + a_T V_{T\mu} V_T^\mu \right)$$

– still useful after Higgs discovery?

Longitudinal WW scattering

WW scattering at high energies [Tao etal; Dawson]

– historically alternative to light Higgs

– *WW* scattering at high energies [via Goldstones]

$$g_V \; H \; \left(a_L V_{L\mu} V_L^{\mu} + a_T V_{T\mu} V_T^{\mu} \right)$$

– still useful after Higgs discovery?

– high energy signal reduced by Higgs

– tagging jets as Higgs pole observables instead

Longitudinal WW scattering

WW scattering at high energies [Tao etal; Dawson]

– historically alternative to light Higgs
– *WW* scattering at high energies [via Goldstones]

$$g_V \; H \;\; \left(a_L V_{L\mu} V_L^\mu + a_T V_{T\mu} V_T^\mu \right)$$

– still useful after Higgs discovery?
– high energy signal reduced by Higgs
– tagging jets as Higgs pole observables instead

Tagging jet observables [Brehmer, Jäckel, TP]

– polarization defined in Higgs frame
– transverse momenta

$$P_T(x, p_T) \sim \frac{1+(1-x)^2}{x} \; \frac{p_T^3}{((1-x)m_W^2 + p_T^2)^2}$$

$$P_L(x, p_T) \sim \frac{1-x}{x} \; \frac{2(1-x)m_W^2 p_T}{((1-x)m_W^2 + p_T^2)^2}$$

Longitudinal WW scattering

WW scattering at high energies [Tao etal; Dawson]

– historically alternative to light Higgs

– *WW* scattering at high energies [via Goldstones]

$$g_V \; H \; \left(a_L V_{L\mu} V_L^\mu + a_T V_{T\mu} V_T^\mu \right)$$

– still useful after Higgs discovery?

– high energy signal reduced by Higgs

– tagging jets as Higgs pole observables instead

Tagging jet observables [Brehmer, Jäckel, TP]

– polarization defined in Higgs frame

– transverse momenta

– azimuthal angle

$$A_\phi = \frac{\sigma(\Delta\phi_{jj} < \frac{\pi}{2}) - \sigma(\Delta\phi_{jj} > \frac{\pi}{2})}{\sigma(\Delta\phi_{jj} < \frac{\pi}{2}) + \sigma(\Delta\phi_{jj} > \frac{\pi}{2})}$$

Longitudinal WW scattering

WW scattering at high energies [Tao etal; Dawson]

- historically alternative to light Higgs
- *WW* scattering at high energies [via Goldstones]

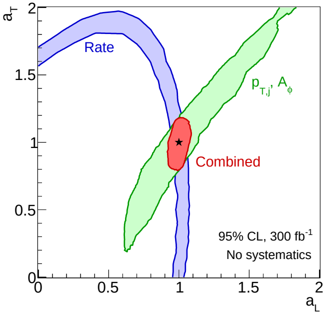
$$g_V \; H \; \left(a_L V_{L\mu} V_L^\mu + a_T V_{T\mu} V_T^\mu \right)$$

- still useful after Higgs discovery?
- high energy signal reduced by Higgs
- tagging jets as Higgs pole observables instead

Tagging jet observables [Brehmer, Jäckel, TP]

- polarization defined in Higgs frame
- transverse momenta
- azimuthal angle
- total rate $\sigma \sim (A_L a_L^2 + A_T a_T^2)$

$\Rightarrow$ simple question, clear answer



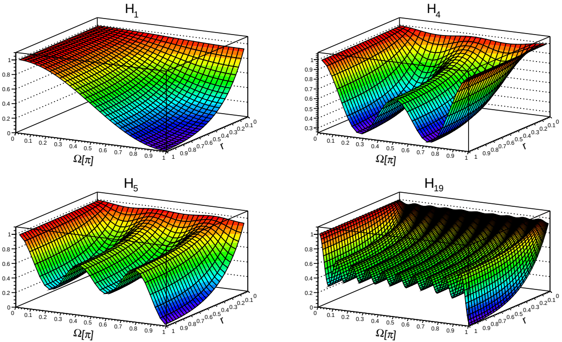
Fox-Wolfram moments

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

Fox-Wolfram moments

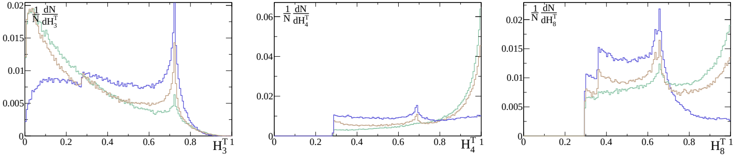
Weighted series in spherical harmonics [Field, Kanev, Tayebnejad; Bernaciak, Buschmann, Butter, TP]

– 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

– applied to tagging jets in WBF [$m_{jj} > 600$ GeV]



Fox-Wolfram moments

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

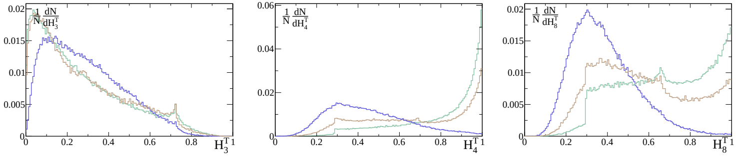
– originally alternative to event shapes

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

– tunable for forward jets

– applied to tagging jets in WBF [$m_{jj} > 600$ GeV]

– applied to all jets in WBF



Fox-Wolfram moments

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

– originally alternative to event shapes

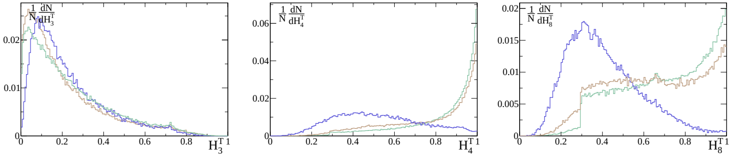
$$H_\ell^T = \frac{4\pi}{2\ell+1} \sum_{m=-\ell}^{\ell} \left| \sum_{i=1}^{N} Y_\ell^m(\Omega_i) \, \frac{p_{T,i}}{p_{T,\text{tot}}} \right|^2 = \sum_{i,j=1}^{N} \frac{p_{T,i} p_{T,j}}{p_{T,\text{tot}}^2} P_\ell(\cos \Omega_{ij})$$

– tunable for forward jets

– applied to tagging jets in WBF [$m_{jj} > 600$ GeV]

– applied to all jets in WBF

– applied to all jets after WBF cuts



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

– applied to tagging jets in WBF [$m_{jj} > 600$ GeV]

– applied to all jets in WBF

– applied to all jets after WBF cuts

$\Rightarrow$ might be useful, bachelor project!