

Random Thoughts about Higgs Measurements

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Berlin, June 2014

Higgs boson

Higgs boson

Questions

Couplings

ggH vertex

MadMax

BSM

Meaning

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 $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

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

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A detailed discussion of these questions will be presented elsewhere.

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.⁸ It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.⁹

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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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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

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

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

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

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We examine a simple solution

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i. Decay of a Scalar Boson into Two Vector Bosons

The process occurs in first order (four of the five cubic vertices contribute), provided that $m_0 > 2m_1$. Let p be the incoming and k_1, k_2 the outgoing momenta. Then

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

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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- 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 $\pi^- p \rightarrow H n$ or $\gamma p \rightarrow H p$ 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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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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 mass of
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 $p \rightarrow Hn$ or
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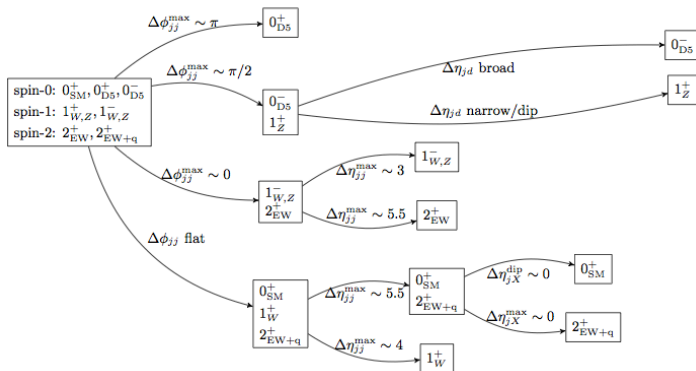
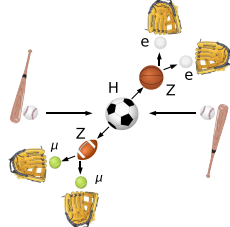
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- ⇒ **Higgs boson based on field theory**

Questions

1. What is the 'Higgs' Lagrangian?

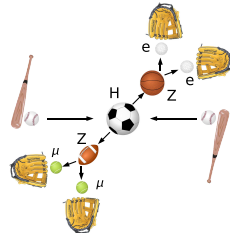
- psychologically: looked for Higgs, so found a Higgs
- CP-even spin-0 scalar expected, which operators?
spin-1 vector unlikely
spin-2 graviton unexpected
- **ask flavor colleagues** [Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles]



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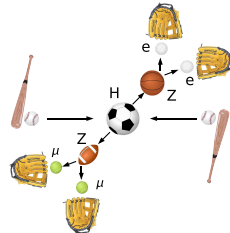
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- 'coupling' after fixing operator basis
- Standard Model Higgs vs anomalous couplings

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2. What are the coupling values?

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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

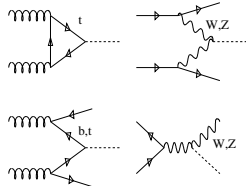
$$\begin{aligned} gg &\rightarrow H \\ qq &\rightarrow qqH \\ gg &\rightarrow ttH \\ qq' &\rightarrow VH \end{aligned}$$

 \longleftrightarrow

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

 \longleftrightarrow

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



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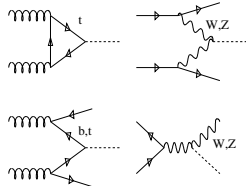
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Total width

- non-trivial scaling

$$N = \sigma BR \propto \frac{g_p^2}{\sqrt{\Gamma_{\text{tot}}}} \frac{g_d^2}{\sqrt{\Gamma_{\text{tot}}}}$$

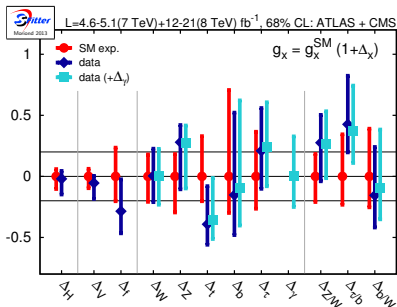
- sum of partial widths: $\sum \Gamma_i(g^2) < \Gamma_{\text{tot}} \rightarrow \Gamma_H|_{\text{min}}$
- $WW \rightarrow WW$ unitarity: $g_{WWH} \lesssim g_{WWH}^{\text{SM}} \rightarrow \Gamma_H|_{\text{max}}$ [HiggsSignals]
- **SFitter assumption** $\Gamma_{\text{tot}} = \sum_{\text{obs}} \Gamma_j$ [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 et al, Djouadi et al, Strumia et al, Grojean et al]
- poor man's analyses: Δ_H , Δ_V , Δ_f

⇒ **six couplings and ratios from data**



Couplings now and in the future

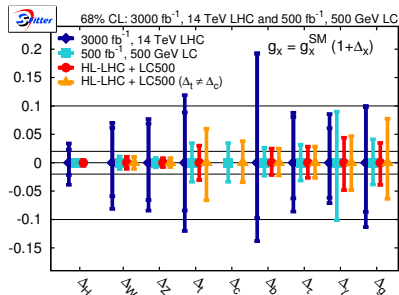
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- LHC extrapolations unclear



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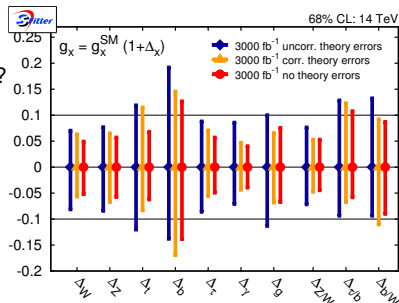
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- **obvious ILC case:**
rate measurement σ_{ZH}
no QCD theory error bars
etc

Resolving the ggH vertex

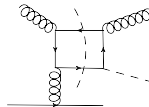
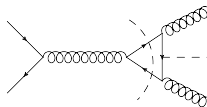
Non-pointlike-ness of ggH vertex [Ellis, Hinchliffe, Soldate, v d Bij; Baur & Glover]

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

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

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

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



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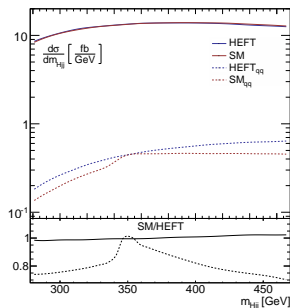
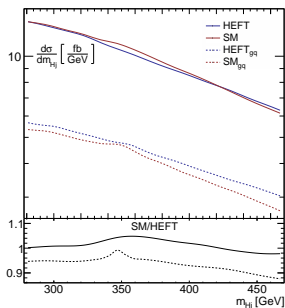
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- high- p_T logarithmic structure instead [Banfi etal; Azatov etal; Grojean etal]

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

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

- check m_{jj} , p_z in Hjj production, nothing...
- instead same as Hj process

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

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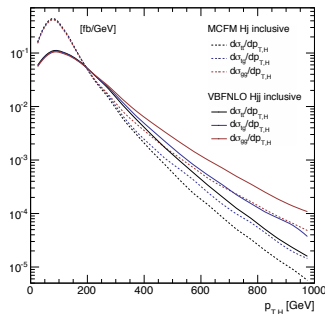
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- Hjj most promising with $H \rightarrow WW$
 - Hjj with more events in relevant regime
- ⇒ distributions the future



MadMax-izing 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?

MadMax-izing theory understanding

Modern analyses vs phase space

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- ⇒ **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 et al]

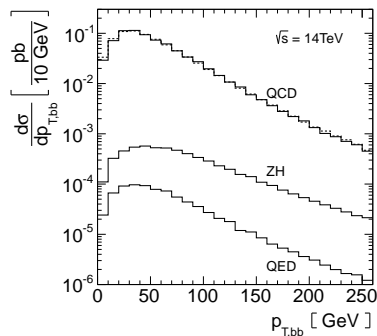
MadMax-izing theory understanding

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: $ZH, H \rightarrow b\bar{b}$ [same for $t\bar{t}H$]

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



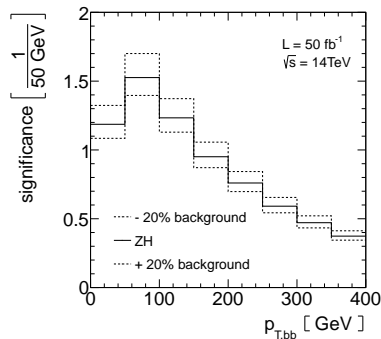
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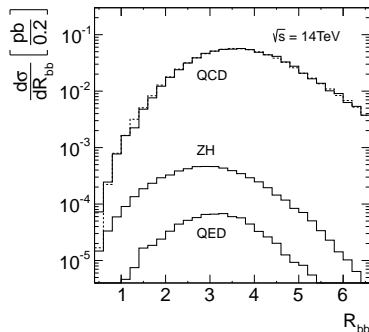
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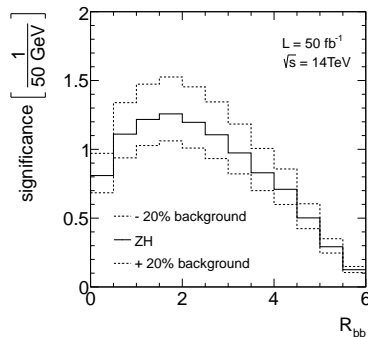
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- ⇒ **poor man's MEM at parton level**



Simple extended models

One-dimensional description of signal strengths [Cranmer, Kreiss, Lopez-Val, TP]

- decoupling defined through the massive gauge sector

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

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$$\Gamma_{\text{inv}} = \xi^2 \Gamma_{\text{SM}}$$

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

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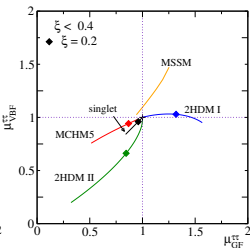
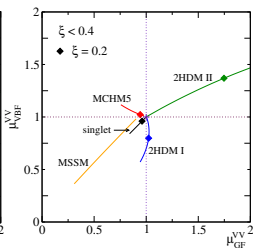
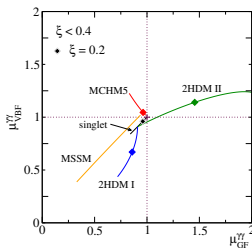
- MSSM [plus $\tan \beta$]

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

Simple extended models

Effect on signal strengths

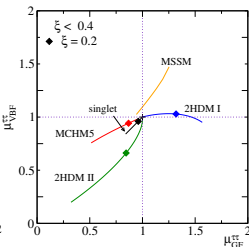
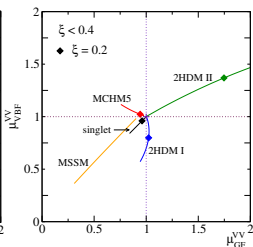
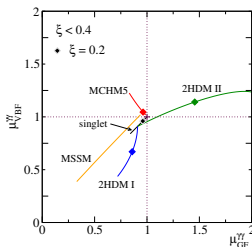
- decay–diagonal and production–diagonal correlations
- new physics scenarios in 2 dimensions



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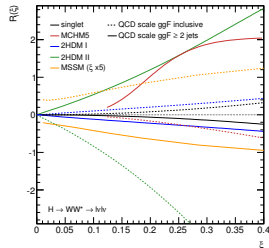
Effect on signal strengths

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



- theory uncertainties with direction

⇒ **robustness measure**



2HDM as example

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

- assume the Higgs really is ‘a Higgs’
- allow for coupling modifications

⇒ **how would 2HDMs look?**

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

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- assume the Higgs really is ‘a Higgs’
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- ⇒ **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 $\lambda_{6,7}$

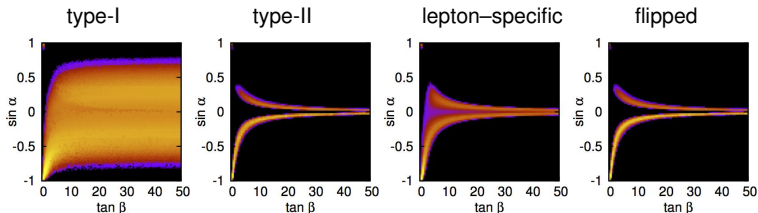
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- ⇒ **how would 2HDMs look?**

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

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Yukawa-aligned 2HDM

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

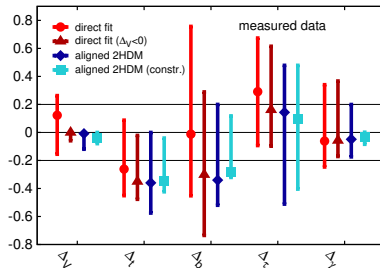
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UV-complete vs SM coupling fits

- 2HDM close to perfect at tree level
 - $\Delta_W \neq \Delta_Z > 0$ through loops
- ⇒ **free SM couplings well defined**



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 fundamental scalar discovered]

⇒ **whatever...**

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High scales

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

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

- vacuum stability right at edge
- $\lambda = 0$ 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

⇒ **whatever...**

High scale exercise

Running of coupling/mass ratios [\[Wetterich\]](#)

Higgs self coupling and top Yukawa with stable zero IR solutions

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

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

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

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

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

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

My bet or hope: 1:3

Higgs boson

Questions

Couplings

ggH vertex

MadMax

BSM

Meaning



Higgs Physics

Tilman Plehn

Higgs boson

Questions

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Meaning

Exercise: what operators can do

Higgs sector including dimension-6 operators

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

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first operator, wave function renormalization

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

proper normalization of combined kinetic term [LSZ]

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

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second operator, minimum condition to fix v

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

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physical Higgs mass

$$\begin{aligned} \mathcal{L}_{\text{mass}} &= -\frac{\mu^2}{2} \tilde{H}^2 - \frac{3}{2} \lambda v^2 \tilde{H}^2 - \frac{f_2}{\Lambda^2} \frac{15}{24} v^4 \tilde{H}^2 \stackrel{!}{=} -\frac{m_H^2}{2} H^2 \\ \Leftrightarrow \quad m_H^2 &= 2\lambda v^2 \left(1 - \frac{f_1 v^2}{\Lambda^2} + \frac{f_2 v^2}{2\Lambda^2 \lambda} \right) \end{aligned}$$

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Higgs self couplings momentum dependent

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

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

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

field renormalization, strong multi-Higgs interactions

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

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]
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- adding specific D6 operator set

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- adding specific D6 operator set

$$\begin{aligned}
 \mathcal{L}_{\text{SILH}} = & \frac{c_H}{2f^2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + \frac{c_T}{2f^2} (H^\dagger \overleftrightarrow{D}^\mu H) (H^\dagger \overleftrightarrow{D}_\mu H) \\
 & - \frac{c_6 \lambda}{f^2} (H^\dagger H)^3 + \left(\frac{c_Y y_f}{f^2} H^\dagger H \tilde{t}_L H f_R + \text{h.c.} \right) \\
 & + \frac{ic_W g}{2m_\rho^2} (H^\dagger \sigma^i \overleftrightarrow{D}^\mu H) (D^\nu W_{\mu\nu})^i + \frac{ic_B g'}{2m_\rho^2} (H^\dagger \overleftrightarrow{D}^\mu H) (\partial^\nu B_{\mu\nu}) \\
 & + \frac{ic_{HW} g}{16\pi^2 f^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{ic_{HB} g'}{16\pi^2 f^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
 & + \frac{c_\gamma g'^2}{16\pi^2 f^2} \frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2} \frac{y_t^2}{g_\rho^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}.
 \end{aligned}$$

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 & - \frac{c_6}{(3f)^2} (H^\dagger H)^3 + \left(\frac{c_Y y_f}{f^2} H^\dagger H \bar{l}_L H f_R + \text{h.c.} \right) \\
 & + \frac{ic_W}{(16f)^2} (H^\dagger \sigma^i \overleftrightarrow{D}^\mu H) (D^\nu W_{\mu\nu})^i + \frac{ic_B}{(16f)^2} (H^\dagger \overleftrightarrow{D}^\mu H) (\partial^\nu B_{\mu\nu}) \\
 & + \frac{ic_{HW}}{(16f)^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{ic_{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_{\mu\nu}^a G^{a\mu\nu}.
 \end{aligned}$$

Higher-dimensional operators

Higgs boson

Questions

Couplings

ggH vertex

MadMax

BSM

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- **collider phenomenology of $(H^\dagger H)$**

Anomalous Higgs couplings [Hagiwara et al.; Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

- assume Higgs is largely Standard Model
- additional higher-dimensional couplings

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

- plus e-w precision data and triple gauge couplings

⇒ **before measuring couplings remember what your operators are!**

Angular Correlations

Measurements of operator structures [learning from the flavor people]

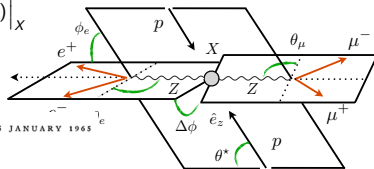
– Cabibbo–Maksymowicz–Dell’Aquila–Nelson angles for $H \rightarrow ZZ$

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

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

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

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



PHYSICAL REVIEW

VOLUME 137, NUMBER 2B

25 JANUARY 1965

Angular Correlations in $K_{\pi 4}$ Decays and Determination of Low-Energy $\pi-\pi$ Phase Shifts*

NICOLA CABIBBO† and ALEXANDER MAKSYMOWICZ

Lawrence Radiation Laboratory, University of California, Berkeley, California

(Received 1 September 1964)

The study of correlations in $K_{\pi 4}$ decays can give unique information on low-energy $\pi-\pi$ scattering. To this end we introduce a particularly simple set of correlations. We show that the measurement of these correlations at any fixed $\pi-\pi$ c.m. energy allows one to make a model-independent determination of the difference $\delta_S - \delta_P$ between the S - and P -wave $\pi-\pi$ 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 $\pi-\pi$ 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]

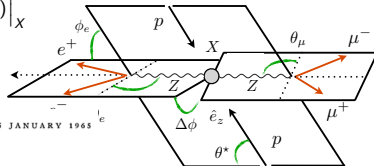
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$$\cos \phi_e = (\hat{p}_{\text{beam}} \times \hat{p}_{Z\mu}) \cdot (\hat{p}_{Z\mu} \times \hat{p}_{e^-}) \Big|_{Z_e}$$

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* 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)].

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

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

II. KINEMATICS AND CORRELATIONS

Our approach to the kinematics of the reaction $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ 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.

* The usefulness of angular correlations in the determination of $\pi_0-\pi_0$ was first recognized by E. P. Shabalin, Zh. Eksperim. i Teor. Fiz. **44**, 765 (1963) [English transl.: Soviet Phys.—JETP **17**, 517 (1963)]. See also erratum, Zh. Eksperim. i Teor. Fiz. **45**, 2085 (1963).

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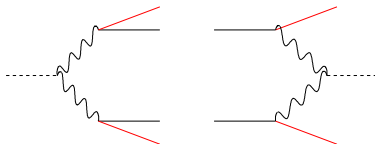
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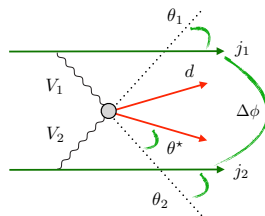
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$$\cos \theta_1 = \hat{p}_{j_1} \cdot \hat{p}_{V_2} \Big|_{V_1 \text{ Breit}} \quad \cos \theta_2 = \hat{p}_{j_2} \cdot \hat{p}_{V_1} \Big|_{V_2 \text{ Breit}} \quad \cos \theta^* = \hat{p}_{V_1} \cdot \hat{p}_d \Big|_X$$

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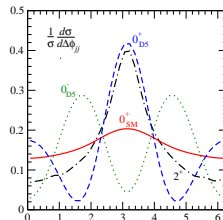
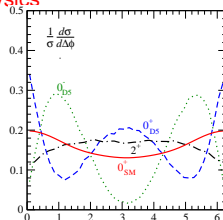
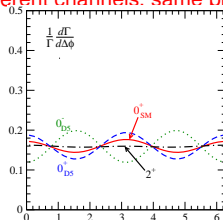
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- possible scalar couplings

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

⇒ different channels. same physics



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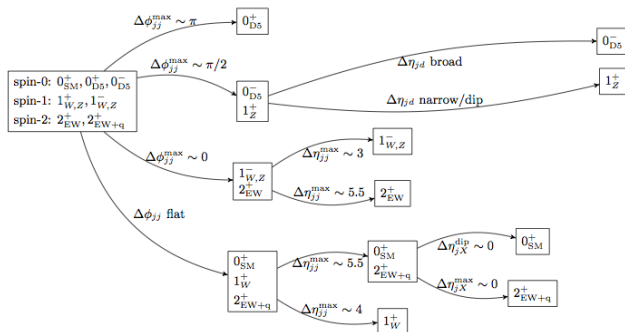
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⇒ different channels, same physics



Longitudinal WW scattering

WW scattering at high energies [Tao et al; Dawson]

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

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

- still useful after Higgs discovery?

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Tagging jet observables [Brehmer, Jäckel, TP]

- polarization defined in Higgs frame
- transverse momenta

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

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

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- 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 et al.; Dawson]

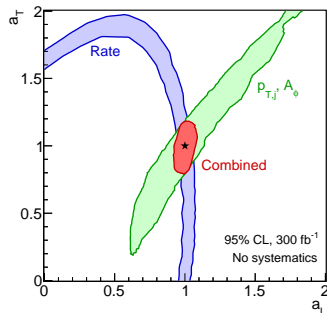
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- polarization defined in Higgs frame
 - transverse momenta
 - azimuthal angle
 - total rate $\sigma \sim (A_L a_L^2 + A_T a_T^2)$
- ⇒ simple question, clear answer



Fox-Wolfram moments

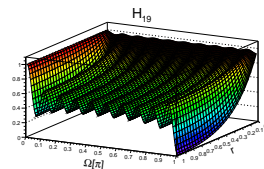
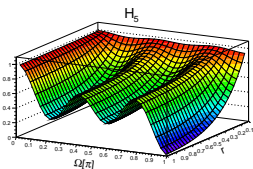
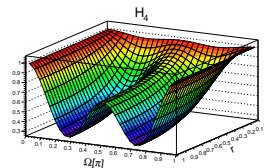
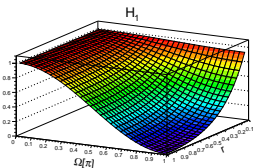
Weighted series in spherical harmonics [Field, Kanev, Tayebnejad; Bernaciak, Buschmann, Butter, TP]

- 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

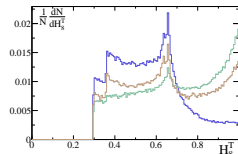
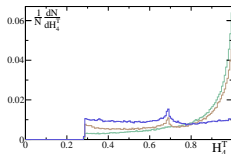
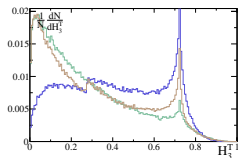
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- tunable for forward jets
- applied to tagging jets in WBF $[m_{jj} > 600 \text{ GeV}]$



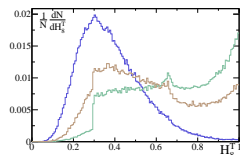
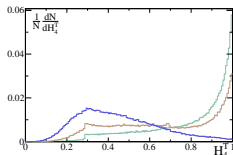
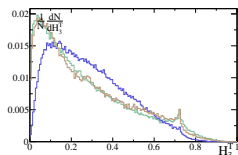
Fox-Wolfram moments

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 $[m_{jj} > 600 \text{ GeV}]$
- applied to all jets in WBF



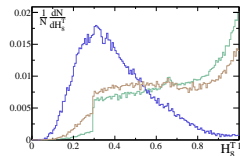
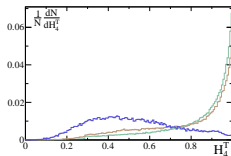
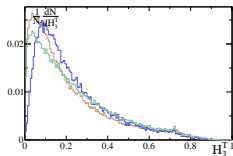
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- tunable for forward jets
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 - applied to all jets after WBF cuts
- ⇒ might be useful, bachelor project!