# Some Thoughts about Higgs Physics

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Universität Heidelberg

Siegen, January 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 $3 \neq 2$

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

- 1964: combining two problems to one predictive solution

VOLUME 13, NUMBER 16 — PHYSICAL REVIEW LETTERS — 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

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

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

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– 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]

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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

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

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

#### i. Decay of a Scalar Boson into Two Vector Bosons

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

$$M = i\{e[a^{*\mu}(k_1)(-ik_{2\mu})\phi^*(k_2) + a^{*\mu}(k_2)(-ik_{1\mu})\phi^*(k_1)] - e(ip_\mu)[a^{*\mu}(k_1)\phi^*(k_2) + a^{*\mu}(k_2)\phi^*(k_1)] - 2em_1 a_\mu^*(k_1) a^{*\mu}(k_2) - f m_0 \phi^*(k_1)\phi^*(k_2)\} .$$

By using Eq. (15), conservation of momentum, and the transversality ($k_\mu b^\mu(k) = 0$) of the vector wave functions we reduce this to the form

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– 1964: combining two problems to one predictive solution

– 1966: original Higgs phenomenology

– 1976 etc: collider phenomenology

**A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON**

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

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^- p \to Hn$ or $\gamma p \to Hp$ near threshold. If its mass is $\lesssim$300 MeV, the Higgs boson may be present in the decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one of the new particles: $3.7 \to 3.1 + H$ with a branching ratio $O(10^{-4})$. If its mass is $\lesssim$4 GeV, the Higgs

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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.

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$\Rightarrow$ Higgs boson based on field theory consistency

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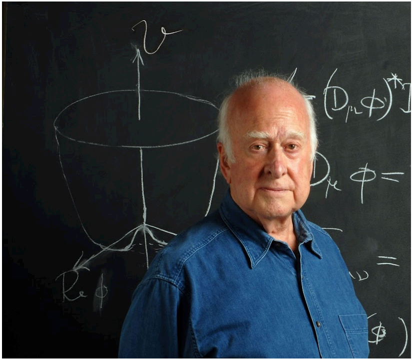
## In terms of mexican hat potential



# Higgs discovery

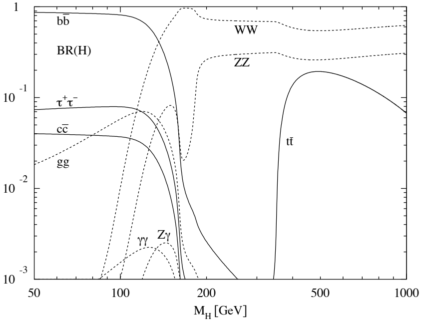
## Higgs decays easy [Hdecay]

– weak-scale scalar coupling proportional to mass

– off-shell decays below threshold

– decay to $\gamma\gamma$ via $W$ and top loop [destructive interference]

$\Rightarrow$ $m_H = 126$ GeV perfect



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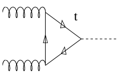
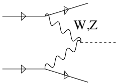
## Higgs production hard [7-8 TeV, 5-15/fb]

– quantum effects needed

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



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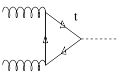


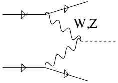


- easy channels for 2011-2012

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

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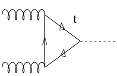


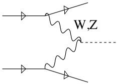


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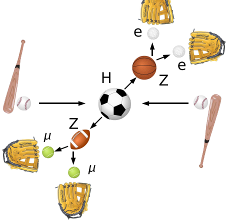
$\Rightarrow$ fun still waiting

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

# Questions




1. What is the 'Higgs' Lagrangian? [Maggi's seminar]
   - 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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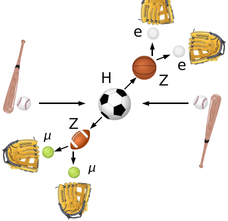


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   – 'coupling' after fixing operator basis

   – Standard Model Higgs vs anomalous couplings

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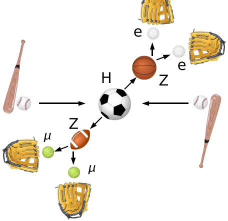


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   - weakly interacting two-Higgs-doublet models?
   - TeV-scale new physics?

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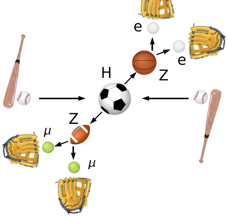


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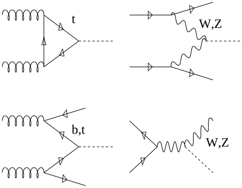
## 4. What is the future?

- QCD challenges?
- new analysis tools?

# Couplings




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

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

– couplings from production & decay rates

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

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

| |
|---|
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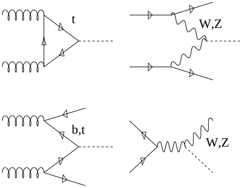


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## Total width

– non-trivial scaling

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

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

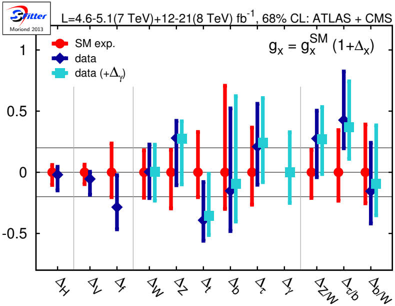
– $WW \to WW$ unitarity: $g_{WWH} \lesssim g_{WWH}^{\text{SM}} \to \Gamma_H|_{\text{max}}$

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

# Couplings now and in the future

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

- focus SM-like [secondary solutions possible]
- six couplings and ratios from data
  $g_b$ from width
  $g_g$ vs $g_t$ not yet possible
  [similar: Ellis etal, Djouadi etal, Strumia etal, Grojean etal]
- poor man's analyses: $\Delta_H, \Delta_V, \Delta_f$



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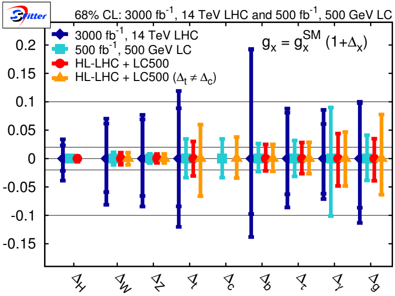
– LHC extrapolations unclear

– interplay in loop-induced couplings



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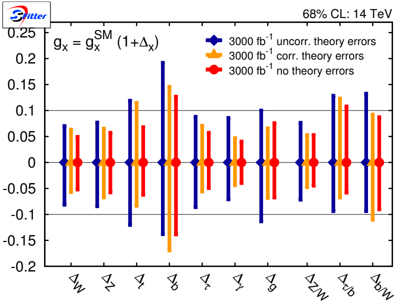

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- obvious ILC case:

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

# Error analysis

## Sources of uncertainty [Cranmer, Kreiss, Lopez-Val, TP]

- statistical error: Poisson
  systematic error: Gaussian, if measured
  theory error: not Gaussian [no statistical interpretation, just a range; ATLAS & CMS too optimistic]
- simple argument
  LHC rate 10% off: no problem
  LHC rate 30% off: no problem
  LHC rate 300% off: Standard Model wrong
- theory likelihood flat centrally and zero far away
- profile likelihood construction: RFit [CKMFitter]

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

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

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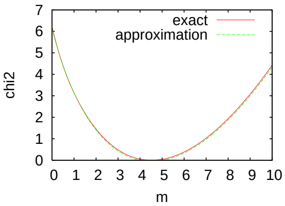
## Efficient combination of errors

- Gaussian ⊗ Gaussian: half width added in quadrature
  Gaussian/Poisson ⊗ flat: RFit, linear
  flat ⊗ flat: RFit, linear
  Gaussian ⊗ Poisson: ??
- approximate formula

$$\frac{1}{\log\mathcal{L}_{\text{comb}}} = \frac{1}{\log\mathcal{L}_{\text{Gauss}}} + \frac{1}{\log\mathcal{L}_{\text{Poisson}}}$$

⇒ error bars from toy measurements



# 2HDM as weakly interacting completion

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

– assume the Higgs really is 'a Higgs'

– allow for coupling modifications

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

⇒ how would 2HDMs look?

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

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⇒ how would 2HDMs look?

## Physical parameters

- angle $\beta = \text{atan}(v_2/v_1)$
  angle $\alpha$ 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 $\Phi_2$
  type-II: up-type fermions with $\Phi_2$
  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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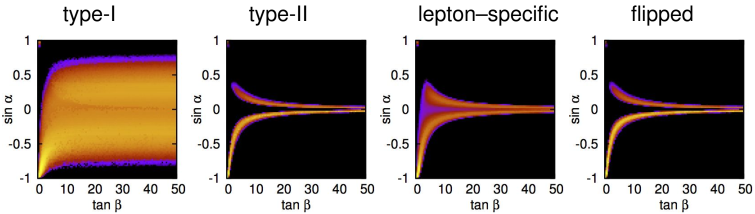
⇒ how would 2HDMs look?

## 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

- $\Delta_V \leftrightarrow (\beta - \alpha)$ $\Delta_{b,t,\tau} \leftrightarrow \{\beta, \gamma_{b,\tau}\}$ $\Delta_\gamma \leftrightarrow m_{H\pm}$
- $\Delta_g$ 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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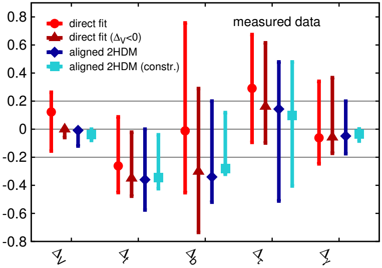
## UV-complete vs SM coupling fits

- 2HDM close to perfect at tree level
- $\Delta_W \neq \Delta_Z > 0$ through loops

$\Rightarrow$ free SM couplings well defined



# Jet counting

## Counting jets: Poisson scaling

– generating function for exclusive jet number

$$\Phi = \sum_{n=1}^{\infty} u^n P_{n-1} \qquad \text{with} \quad P_{n-1} = \frac{\sigma_{n-1}}{\sigma_{\text{tot}}} = \frac{1}{n!} \frac{d^n}{du^n} \Phi \bigg|_{u=0}$$

– with DGLAP-like evolution equation

$$\Phi_i(t) = \Delta_i(t, t_0) \Phi_i(t_0) + \int_{t_0}^{t} \frac{dt'}{t'} \Delta_i(t, t') \sum_{i \to j,k} \int_0^1 dz \frac{\alpha_s}{2\pi} \hat{P}_{i \to jk}(z) \; \Phi_j(z^2 t') \Phi_k((1-z)^2 t')$$

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– solution for quarks for large logarithm

$$\Phi_q(t) = u \exp\left[ \int_{t_0}^{t} dt' \; \Gamma_{q \leftarrow q}(t, t') \left( \Phi_g(t') - 1 \right) \right] \simeq u \exp\left[ \int_{t_0}^{t} dt' \; \Gamma_{q \leftarrow q}(t, t') \, (u - 1) \right]$$

– Poisson form

$$\Phi_{q,g}(t) = u \; \Delta_{q,g}(t)^{1-u} \qquad R_{(n+1)/n} = \frac{\sigma_{n+1}}{\sigma_n} = \frac{|\log \Delta_{q,g}(t)|}{n+1}$$

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– gluons for small logarithms

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$$\simeq \Phi_g(t) \, \frac{C_A}{2\pi} \, \frac{\alpha_s(t)}{t} \left( \log \frac{t}{t_0} - \frac{11}{6} \right) (\Phi_g(t) - 1) \equiv \Phi_g(t) \, \tilde{\Gamma}_{g \leftarrow g}(t, t_0) \; (\Phi_g(t) - 1)$$

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– staircase form $[\tilde{\Delta}_g(t) = \exp(-\int dt' \tilde{\Gamma}_{g\leftarrow g}(t',t_0))]$

$$\Phi_g(t) = \frac{1}{1 + \dfrac{1-u}{u \tilde{\Delta}_g(t)}} \qquad R_{(n+1)/n} = \frac{\sigma_{n+1}}{\sigma_n} = 1 - \tilde{\Delta}_g(t) = \text{constant}$$

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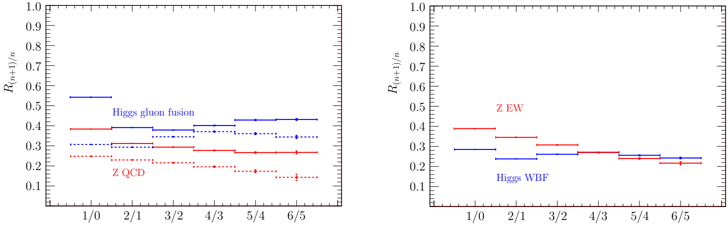
⇒ first principles QCD: either Possion or staircase scaling

# Jet veto

## Example: WBF $H \to \tau\tau$ [Englert, Gerwick, TP, Schichtel, Schumann]

– staircase scaling before WBF cuts [QCD and e-w processes]

– e-w $Zjj$ production with too many structures



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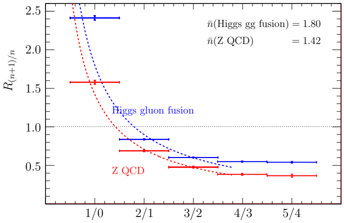
## Understanding a jet veto

- count add'l jets to reduce backgrounds

$$p_T^{\text{veto}} > 20 \text{ GeV} \qquad \min y_{1,2} < y^{\text{veto}} < \max y_{1,2}$$

- Poisson for QCD processes ['radiation' pattern]



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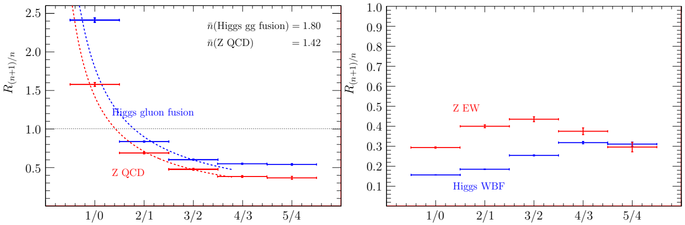
– Poisson for QCD processes ['radiation' pattern]
– (fairly) staircase for e-w processes [cuts keeping signal]
– features understood, now test experimentally...



# MadMax

## Understanding modern analyses

– hardly any counting experiments left

– more and more $x$-axes with NN or BDT output

– number of useful observables ever increasing

– theory uncertainties increasingly relevant

– relevant information still (mostly) in hard process

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

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## 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]

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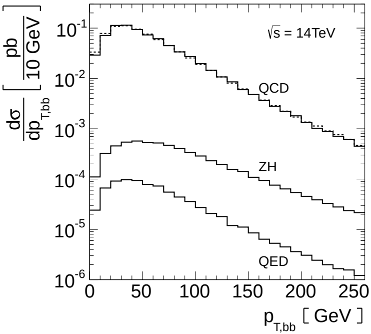
– boosted Higgs the key
– modern analyses imminent
– $p_{T,bb}$ distributions



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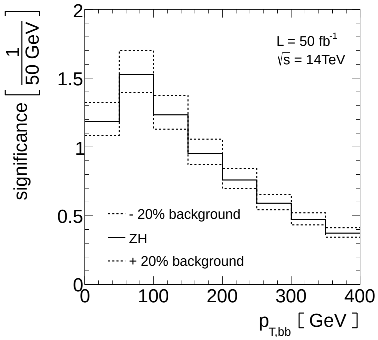

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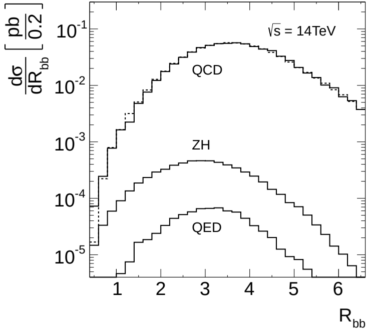

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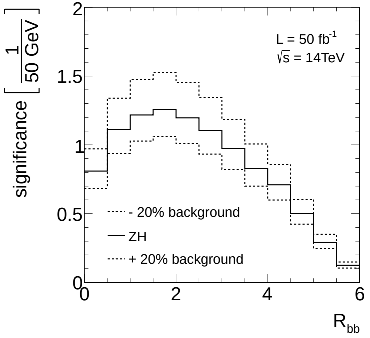

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– boosted Higgs the key

– modern analyses imminent

– $p_{T,bb}$ distributions

– $R_{bb}$ distributions

$\Rightarrow$ anyone having a question for our answer?

# 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

– who wants to compute backgrounds?

– 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

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

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first operator, wave function renormalization

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

proper normalization of combined kinetic term [LSZ]

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

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second operator, minimum condition to fix $v$

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

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

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

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

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

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 $v \sim g^2 f/(2\pi)$]

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$$
\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} .
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& - \frac{c_6}{(3f)^2} \left( H^\dagger H \right)^3 + \left( \frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.} \right) \\
& + \frac{i c_W}{(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}
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## Anomalous Higgs couplings [Hagiwara etal; Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

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

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

– 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]

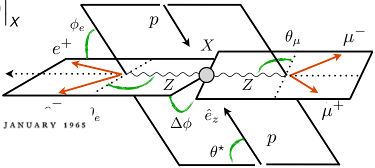
– Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles for $H \to ZZ$

[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 $\pi$-$\pi$ Phase Shifts***

NICOLA CABIBBO† AND ALEXANDER MAKSYMOWICZ
*Lawrence Radiation Laboratory, University of California, Berkeley, California*

(Received 1 September 1964)

The study of correlations in $K_{e4}$ 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 $\delta_0$-$\delta_1$ between the $S$- and $P$-wave $\pi$-$\pi$ phase shifts at that energy. Information about the average value of $\delta_0$-$\delta_1$ 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 $\pi$-$\pi$ scattering. We discuss in particular two such models: (a) the Chew-Mandelstam effective-range description of $S$-wave scattering and (b) the Brown-Faier $\sigma$-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 $\sigma$-resonance model is correct, these measurements should yield a value for the mass of the resonance.

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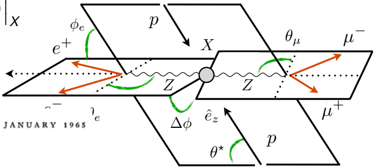


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* This work was done under the auspices of the U. S. Atomic Energy Commission.
† On leave from the Frascati National Laboratory, Frascati, Italy; present address: CERN, Geneva, Switzerland.

[1] L. B. Okun' and E. P. Shabalin, Zh. Eksperim. i Teor. Fiz. **37**, 1775 (1959) [English transl.: Soviet Phys.—JETP **10**, 1252 (1960)].
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[4] E. P. Shabalin, Zh. Eksperim. i Teor. Fiz. **39**, 345 (1960) [English transl.: Soviet Phys.—JETP **12**, 245 (1961)].
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dominated by the postulated $\sigma$ 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

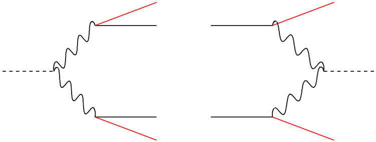
## Measurements of operator structures [learning from the flavor people]

– 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 $(\eta, \phi)$ in WBF [Breit: boost into space-like]

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



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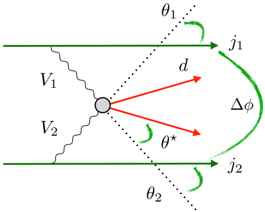

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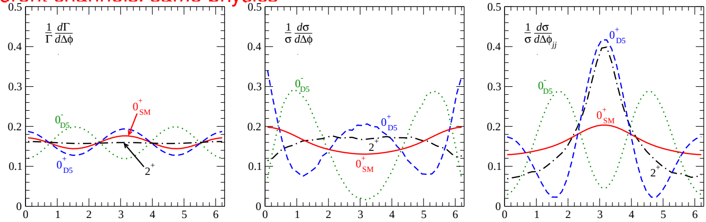
– possible scalar couplings

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

$\Rightarrow$ different channels, same physics



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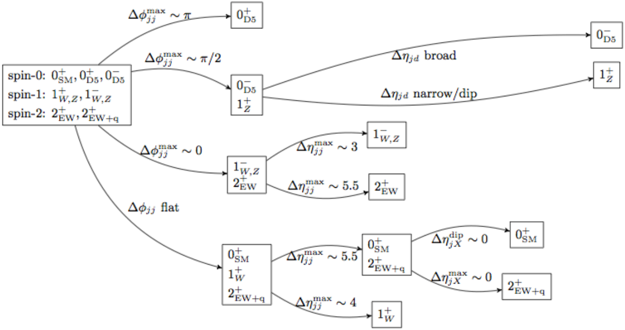

# Error analysis

## Sources of uncertainty

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

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

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

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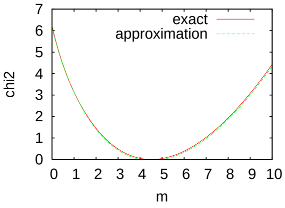
## Efficient combination of errors

– Gaussian $\otimes$ Gaussian: half width added in quadrature
  Gaussian/Poisson $\otimes$ flat: RFit scheme
  Gaussian $\otimes$ Poisson: ??

– approximate formula

$$\frac{1}{\log\mathcal{L}_{\text{comb}}} = \frac{1}{\log\mathcal{L}_{\text{Gauss}}} + \frac{1}{\log\mathcal{L}_{\text{Poisson}}}$$

$\Rightarrow$ error bars from toy measurements



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## Systematic uncertainties

| | |
|---|---|
| luminosity measurement | 5 % |
| detector efficiency | 2 % |
| lepton reconstruction efficiency | 2 % |
| photon reconstruction efficiency | 2 % |
| WBF tag-jets / jet-veto efficiency | 5 % |
| $b$-tagging efficiency | 3 % |
| $\tau$-tagging efficiency (hadronic decay) | 3 % |
| lepton isolation efficiency ($H \to 4\ell$) | 3 % |

| | $\Delta B^{\text{(syst)}}$ |
|---|---|
| $H \to ZZ$ | 1% |
| $H \to WW$ | 5% |
| $H \to \gamma\gamma$ | 0.1% |
| $H \to \tau\tau$ | 5% |
| $H \to b\bar{b}$ | 10% |

# Meaning

## TeV scale

– fourth chiral generation excluded

– strongly interacting models retreating [Goldstone protection]

– extended Higgs sectors wide open

– no final verdict on the MSSM

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

$\Rightarrow$ do not know

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## High scales

- Planck-scale extrapolation [Holthausen, Lim, Lindner; 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 $\lambda/\lambda_t^2$ fixing $m_H^2/m_t^2$ [with gravity: Shaposhnikov, Wetterich]

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

- IR fixed points phenomenological nightmare

$\Rightarrow$ do not know

# Exercise: top–Higgs renormalization group

## Running of coupling/mass ratios

Higgs self coupling and top Yukawa with stable zero IR solutions

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

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

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

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

# Jet counting

## Counting jets: Poisson scaling

– generating function for exclusive jet number

$$\Phi = \sum_{n=1}^{\infty} u^n P_{n-1} \qquad \text{with} \quad P_{n-1} = \frac{\sigma_{n-1}}{\sigma_{\text{tot}}} = \frac{1}{n!} \frac{d^n}{du^n} \Phi \Big|_{u=0}$$

– with DGLAP-like evolution equation

$$\Phi_i(t) = \Delta_i(t, t_0)\Phi_i(t_0) + \int_{t_0}^{t} \frac{dt'}{t'} \Delta_i(t, t') \sum_{i \to j,k} \int_0^1 dz \frac{\alpha_s}{2\pi} \hat{P}_{i \to jk}(z) \, \Phi_j(z^2 t')\Phi_k((1-z)^2 t')$$

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– solution for quarks for large logarithm

$$\Phi_q(t) = u \exp\left[\int_{t_0}^{t} dt'\; \Gamma_{q\leftarrow q}(t,t')\,(\Phi_g(t')-1)\right] \simeq u \exp\left[\int_{t_0}^{t} dt'\; \Gamma_{q\leftarrow q}(t,t')\,(u-1)\right]$$

– Poisson form

$$\Phi_{q,g}(t) = u\; \Delta_{q,g}(t)^{1-u} \qquad R_{(n+1)/n} = \frac{\sigma_{n+1}}{\sigma_n} = \frac{|\log \Delta_{q,g}(t)|}{n+1}$$

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## Counting jets: staircase scaling

– gluons for small logarithms

$$\frac{d\Phi_g(t)}{dt} = u \, \frac{d}{dt} \, \exp \left[ \int_{t_0}^{t} dt' \; \Gamma_{g\leftarrow g}(t,t') \left( \Phi_g(t') - 1 \right) \right]$$

$$\simeq \Phi_g(t) \, \frac{C_A}{2\pi} \, \frac{\alpha_s(t)}{t} \left( \log \frac{t}{t_0} - \frac{11}{6} \right) \left( \Phi_g(t) - 1 \right) \equiv \Phi_g(t) \, \tilde{\Gamma}_{g\leftarrow g}(t,t_0) \, \left( \Phi_g(t) - 1 \right)$$

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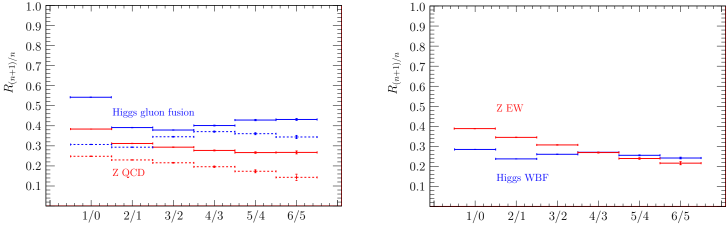
$\Rightarrow$ first principles QCD: Possion or staircase scaling

# Jet veto

## Example: WBF $H \to \tau\tau$ [Englert, Gerwick, TP, Schichtel, Schumann]

– staircase scaling before WBF cuts [QCD and e-w processes]

– e-w $Zjj$ production with too many structures



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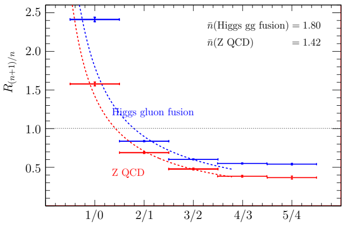
## Understanding a jet veto

- count add'l jets to reduce backgrounds

$$p_T^{\text{veto}} > 20 \text{ GeV} \qquad \min y_{1,2} < y^{\text{veto}} < \max y_{1,2}$$

- Poisson for QCD processes ['radiation' pattern]



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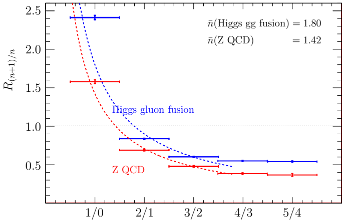
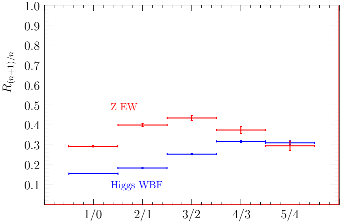
– Poisson for QCD processes ['radiation' pattern]

– (fairly) staircase for e-w processes [cuts keeping signal]

– features understood, now test experimentally...



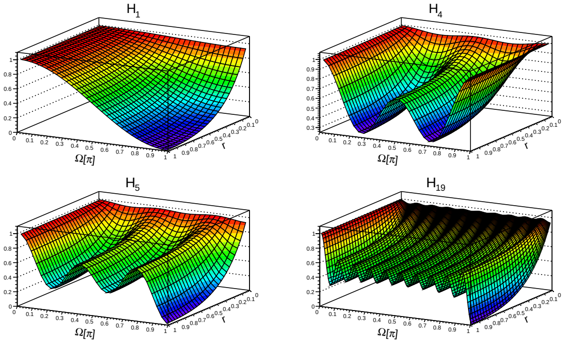
# Fox-Wolfram moments

## 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 $\ell$ | forbidden | democratic | ordered, collinear, back-to-back |
| odd $\ell$ | back-to-back | democratic | collinear, ordered |

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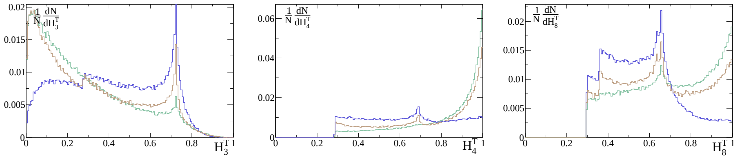
– applied to tagging jets in WBF [$m_{jj} > 600$ GeV]



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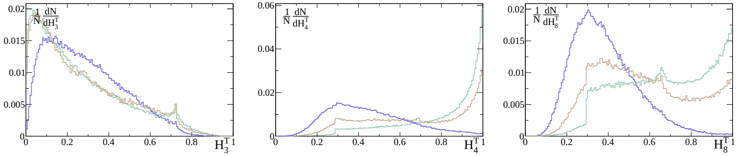
– applied to all jets in WBF



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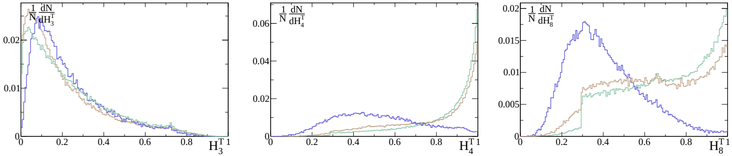
– applied to all jets in WBF

– applied to all jets after WBF cuts



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$\Rightarrow$ might be useful, bachelor project!