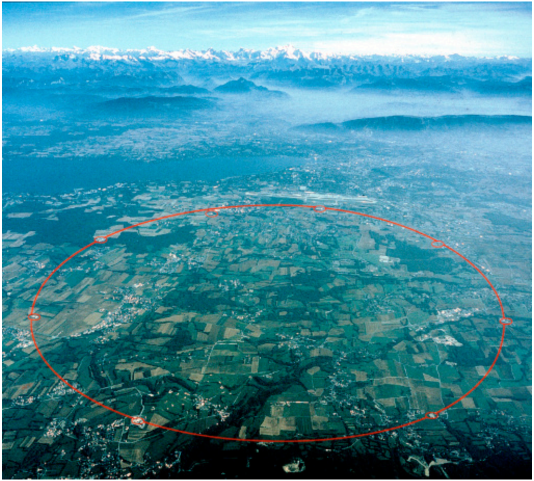
Theory with and for the LHC

Tilman Plehn

Universität Heidelberg

Münster, 4/2017

The LHC

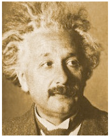


The LHC


Neasden
Dollis Hill
Willesden Green
Kilburn
Golders Green
Hampstead
Hampstead Heath
Gospel Oak
Tufnell Park
Upper Holloway
Finsbury Park
Arsenal
Holloway Road
Kentish Town
Kentish Town West
Belsize Park
Finchley Road & Frognal
Chalk Farm
Camden Road
Caledonian Road
Highbury & Islington
Canonbury
Caledonian Road & Barnsbury
Brondesbury Park
Brondesbury
West Hampstead
Finchley Road
Swiss Cottage
St. John's Wood
Camden Town
Mornington Crescent
King's Cross St. Pancras
Kilburn High Road
South Hampstead
Paddington
Edgware Road
Baker Street
Great Portland Street
Euston
Angel
Old Street
Marylebone
Warren Street
Euston Square
Farringdon
Regent's Park
Liverpool Street
Bayswater
Russell Square
Barbican
Shoreditch
Holland Park
Notting Hill Gate
Lancaster Gate
Bond Street
Oxford Circus
Goodge Street
Chancery Lane
Moorgate
Holborn
Tottenham Court Road
Queensway
Marble Arch
St. Paul's
Bank
Aldgate East
Aldgate
Covent Garden
Cannon Street
High Street Kensington
Hyde Park Corner
Green Park
Leicester Square
Mansion House
Piccadilly Circus
Monument
Tower Hill
Tower Gateway
Knightsbridge
Charing Cross
Blackfriars
Gloucester Road
Sloane Square
St. James's Park
Temple
River Thames
Rotherhithe
Earl's Court
South Kensington
Victoria
Westminster
Embankment
London Bridge
Bermondsey
Canada Water
Surrey Quays
Fulham Broadway
Waterloo
Southwark
Borough
Pimlico
Lambeth North
East London line is closed for major line extension work to become part of the London Overground network.

The LHC

Einstein: beam energy to particle mass $E = mc^2$



– smash 7.5 TeV protons onto 7.5 TeV protons [energy unit GeV: proton mass]
produce anything that interacts with quarks and gluons
search for it in decay products
repeat every 25-50 ns

– huge detectors, actual data, commuting to CERN $\longrightarrow$ experiment
field theory, strong opinions, working in villas $\longrightarrow$ theory

The LHC

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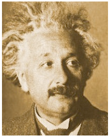

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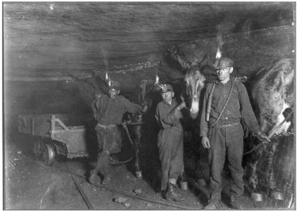
life as an experimentalist



life as a theorist

The LHC

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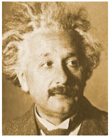

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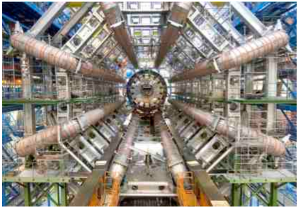

life as a theorist

The LHC

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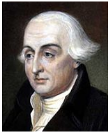

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- language: Lagrangian

Quantity	Symbol, equation	Value	Uncertainty (ppb)
speed of light in vacuum	c	1	exact
Planck constant	h	1	exact
Planck constant, reduced	$\hbar = h/2\pi$	1	exact
electron charge magnitude	e	1	exact
conversion constant	$\hbar c$	1	exact
conversion constant	$(\hbar c)^2$	1	exact
electron mass	m_e	1	exact
proton mass	m_p	1	exact
deuteron mass	m_d	1	exact
unified atomic mass unit	(mass ^{12}C atom)/12 = (1 g)/(N_A mol)	1	exact
permettivity of free space	$\epsilon_0 = 1/\mu_0 c^2$	1	exact
permeability of free space	μ_0	1	exact
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	1	exact
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c$	1	exact
(e^- Compton wavelenght)/2π	$\lambda_e/2\pi = \hbar/m_e c = r_e\alpha^{-1}$	1	exact
Bohr radius ($m_{\text{nucleus}} = \infty$)	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$	1	exact
wavelenght of 1 eV/c particle	$hc/(1\text{ eV})$	1	exact
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$	1	exact
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	1	exact
Bohr magneton	$\mu_B = e\hbar/2m_e$	1	exact
nuclear magneton	$\mu_N = e\hbar/2m_p$	1	exact
electron cyclotron freq./field	$\omega^e_{\text{cycl}}/B = e/m_e$	1	exact
proton cyclotron freq./field	$\omega^p_{\text{cycl}}/B = e/m_p$	1	exact
gravitational constant	G_N	1	exact
standard gravitational accel.	g_n	1	exact
Avogadro constant	N_A	1	exact
Boltzmann constant	k	1	exact
molar volume, ideal gas at STP	$N_A k(273.15\text{ K})/(101\,325\text{ Pa})$	1	exact
Wien displacement law constant	$b = \lambda_{\max} T$	1	exact
Stefan-Boltzmann constant	$\sigma = \pi^2 k^4/60\hbar^3 c^2$	1	exact

Higgs mechanism

Quantum theory with famous problem

– Lagrangian

(quantum) electrodynamics $[F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu]$

$$\mathcal{L} = \underbrace{i\,\overline{\psi}\gamma_\mu\partial^\mu\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{kinetic terms}} - \underbrace{m\,\overline{\psi}\psi}_{\text{electron mass}} - \underbrace{e\,\overline{\psi}\gamma_\mu A^\mu\psi}_{ee\gamma\text{ interaction}}$$

symmetries of Lagrangian = symmetries of theory

Higgs mechanism

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symmetries of Lagrangian = symmetries of theory

– exact and broken symmetries
massless exchange particle: Coulomb potential $V(r) \propto -1/r$
massive exchange particle: Yukawa potential $V(r) \propto -e^{-mr}/r$
symmetry restauration $m \to 0$?

– problem 1: massive gauge theories
massless gauge bosons have 2 polarizations, massive have 3, and $3 \neq 2$

– problem 2: Goldstone's theorem
breaking $SU(2)$ produces 3 massless unobserved scalars

Higgs boson

Solving that problem [also Brout & Englert; Guralnik, Hagen, Kibble]

1964 combining two problems to one predictive solution [Stueckelberg mass]

$$\mathcal{L} = \underbrace{-\frac{1}{4} F_{\mu\nu} F^{\mu\nu}}_{\text{massless photon}} + \underbrace{\frac{1}{2} (\partial_\mu \phi)^2}_{\text{massless scalar}} + \frac{f^2}{2} A_\mu^2 - f A_\mu \partial^\mu \phi = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \underbrace{\frac{f^2}{2} \left(A_\mu - \frac{1}{f} \partial_\mu \phi \right)^2}_{\text{photon mass}}$$

similar for $W^\pm$ and Z masses, structurally only complex 2-vector possible

$\Rightarrow$ remaining scalar: Higgs boson

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

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

Higgs boson

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A detailed discussion of these questions will be presented elsewhere.

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

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[1]P. W. Higgs, to be published.

[2]J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).

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1966 original Higgs phenomenology

PHYSICAL REVIEW VOLUME 145, NUMBER 4 27 MAY 1966

Spontaneous Symmetry Breakdown without Massless Bosons*

PETER W. HIGGS†
Department of Physics, University of North Carolina, Chapel Hill, North Carolina
(Received 27 December 1965)

We examine a simple relativistic theory of two scalar fields, first discussed by Goldstone, in which as a result of spontaneous breakdown of $U(1)$ symmetry one of the scalar bosons is massless, in conformity with the Goldstone theorem. When the symmetry group of the Lagrangian is extended from global to local $U(1)$ transformations by the introduction of coupling with a vector gauge field, the Goldstone boson becomes the longitudinal state of a massive vector boson whose transverse states are the quanta of the transverse gauge field. A perturbative treatment of the model is developed in which the major features of these phenomena are present in zero order. Transition amplitudes for decay and scattering processes are evaluated in lowest order, and it is shown that they may be obtained more directly from an equivalent Lagrangian in which the original symmetry is no longer manifest. When the system is coupled to other systems in a $U(1)$ invariant Lagrangian, the other systems display an induced symmetry breakdown, associated with a partially conserved current which interacts with itself via the massive vector boson.

I. INTRODUCTION

THE idea that the apparently approximate nature of the internal symmetries of elementary-particle physics is the result of asymmetries in the stable solutions of exactly symmetric dynamical equations, rather than an indication of asymmetry in the dynamical

appear have been used by Coleman and Glashow[3] to account for the observed pattern of deviations from $SU(3)$ symmetry.

The study of field theoretical models which display spontaneous breakdown of symmetry under an internal Lie group was initiated by Nambu,[4] who had noticed[5]

Higgs boson

Solving that problem [also Brout & Englert; Guralnik, Hagen, Kibble]

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II. THE MODEL

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

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

In Eq. (1) the metric tensor $g^{\mu\nu} = -1$ ($\mu=\nu=0$), $+1$ ($\mu=\nu\neq0$) 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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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

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1966 original Higgs phenomenology

1976 Higgs physics for colliders

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 boson may be visible in the reaction $pp \to H + X$, $H \to \mu^+\mu^-$. If the Higgs boson has a mass $\lesssim 2m_\mu$, the decays $H \to e^+e^-$ and $H \to \gamma\gamma$ dominate, and the lifetime is $O(6 \times 10^{-4}$ to $2 \times 10^{-12})$ seconds. As thresholds for heavier particles (pions, strange particles, new particles) are crossed, decays into them become dominant, and the lifetime decreases rapidly

Higgs boson

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A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

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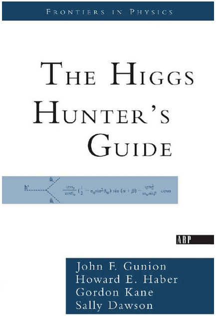
2012 Higgs discovery

$\Rightarrow$ LHC: really just one Higgs doublet?



Electroweak Standard Model

Crucial: boson and fermion masses

– fundamental symmetry: $SU(2)_L \times U(1)_Y$
observed unbroken: electromagnetism $U(1)_Q$

– forbidden by $SU(2)_L$: $m_{W,Z}$ and $m_{t,b,\tau}$

$\Rightarrow$ masses proportional to Higgs VEV $\langle\phi\rangle = v = 246$ GeV

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– complex $SU(2)$ doublet ϕ

  3 Nambu-Goldstone modes 'eaten' by W and Z
  4th mode $\phi = v + H$

$\Rightarrow$ Higgs particle coupling proportional to mass

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Depar
Massachusetts Institute of Technology, Cambridge, Ma

(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

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Electroweak Standard Model

Crucial: boson and fermion masses

– fundamental symmetry: $SU(2)_L \times U(1)_Y$
observed unbroken: electromagnetism $U(1)_Q$

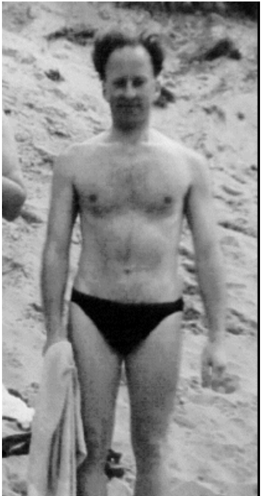
– forbidden by $SU(2)_L$: $m_{W,Z}$ and $m_{t,b,\tau}$

⇒ masses proportional to Higgs VEV $\langle\phi\rangle = v = 246$ GeV

– complex $SU(2)$ doublet ϕ

3 Nambu-Goldstone modes 'eaten' by W and Z
4th mode $\phi = v + H$

⇒ Higgs particle coupling proportional to mass



Higgs potential

– Standard Model

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

$$\frac{\partial V}{\partial |\phi|^2} = 0 \quad \Rightarrow \quad \frac{v^2}{2} = -\frac{\mu^2}{2\lambda}$$

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

⇒ LHC: why not more terms?

$$V = \mu^2 |\phi|^2 + \lambda_4 |\phi|^4 + \frac{\lambda_6}{M^2} |\phi|^6 + \cdots$$

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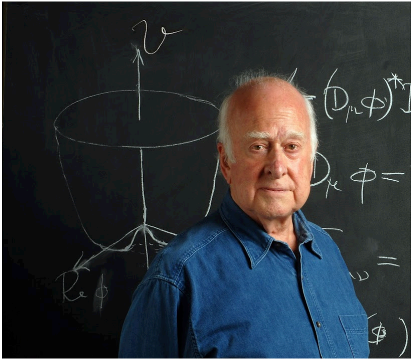
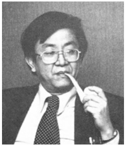


Modern language



Unitarity [Lee, Quigg, Thacker]

– predicted transition amplitudes finite for all Higgs masses

$$\sigma_{WW\to WW} \sim \frac{m_H^2}{v^2} \qquad \Rightarrow \qquad m_H \lesssim 1\text{ TeV}$$

⇒ LHC: Higgs couplings unitary?

AL REVIEW D VOLUME 16, NUMBER 5 1 SEPTEMB

Weak interactions at very high energies: The role of the Higgs-boson mass

Benjamin W. Lee,* C. Quigg,† and H. B. Thacker
Fermi National Accelerator Laboratory,‡ *Batavia, Illinois 60510*

(Received 20 April 1977)

We give an S-matrix-theoretic demonstration that if the Higgs-boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$, parital-wave unitarity is not respected by the tree diagrams for two-body scattering of gauge bosons, and the weak interactions must become strong at high energies. We exhibit the relation of this bound to the structure of the Higgs-Goldstone Lagrangian, and speculate on the consequences of strongly coupled Higgs-Goldstone systems. Prospects for the observation of massive Higgs scalars are noted.

Modern language

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⇒ LHC: Higgs couplings unitary?

Renormalizability ['t Hooft & Veltman]

– absence of UV cutoff scale defining ‘fundamental theory’

– couplings with inverse mass dimension problematic

$$\mathcal{L} \sim \frac{1}{M^2}\, \partial_\mu(\phi^\dagger\phi)\, \partial^\mu(\phi^\dagger\phi) \qquad \Rightarrow \qquad g_{HHH} \propto \frac{p^2 v}{M^2}$$

⇒ LHC: Higgs sector renormalizable?

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RENORMALIZABLE LAGRANGIANS FOR MASSIVE YANG-MILLS FIELDS

G.'t HOOFT

Institute for Theoretical Physics, University of Utrecht

Received 13 July 1971

Abstract: Renormalizable models are constructed in which local gauge invariance is broken spontaneously. Feynman rules and Ward identities can be found by means of a path integral method, and they can be checked by algebra. In one of these models, which is studied in more detail, local SU(2) is broken in such a way that local U(1) remains as a symmetry. A renormalizable and unitary theory results, with photons, charged massive vector particles, and additional neutral scalar particles. It has three independent parameters.

Another model has local SU(2)$\otimes$U(1) as a symmetry and may serve as a renormalizable theory for ρ-mesons and photons.

In such models electromagnetic mass-differences are finite and can be calculated in perturbation theory.

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REGULARIZATION AND RENORMALIZATION OF GAUGE FIELDS

G. 't HOOFT and M. VELTMAN
*Institute for Theoretical Physics *, University of Utrecht*

Received 21 February 1972

Abstract: A new regularization and renormalization procedure is presented. It is particularly well suited for the treatment of gauge theories. The method works for theories that were known to be renormalizable as well as for Yang-Mills type theories. Overlapping divergencies are disentangled. The procedure respects unitarity, causality and allows shifts of integration variables. In non-anomalous cases also Ward identities are satisfied at all stages. It is transparent when anomalies, such as the Bell-Jackiw-Adler anomaly, may occur.

1. INTRODUCTION

Recently it has been shown [1] that it is possible to formulate renormalizable theories of charged massive vector bosons. The derived Feynman rules involve ghost particles, and in order to establish unitarity and causality of the S-matrix Ward identities are needed. The necessary combinatorial techniques were given in ref. [2], in the treatment of massless Yang-Mills fields. It was emphasized that these same techniques work also in the case of massive vector boson theories obtained from the massless theory by means of the Higgs-Kibble [3] mechanism. Stated somewhat di-

Modern language

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$$\mathcal{L} \sim \frac{1}{M^2} \, \partial_\mu (\phi^\dagger \phi) \, \partial^\mu (\phi^\dagger \phi) \qquad \Rightarrow \qquad g_{HHH} \propto \frac{p^2 v}{M^2}$$

⇒ LHC: Higgs sector renormalizable?

Weakly or strongly interacting Higgs? [Weinberg; Georgi, Kaplan (Dimopoulos)]

– same as: fundamental or composite scalar?

– unitarity ensured by composite Higgs sector

– renormalizability not required with composite Higgs sector

⇒ LHC: Higgs scalar fundamental?

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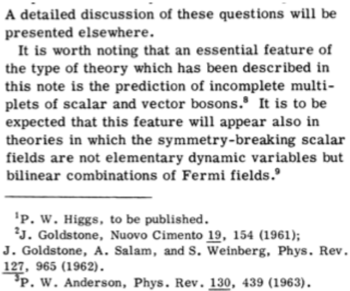
A detailed discussion of these questions will be presented elsewhere.

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]

[1] P. W. Higgs, to be published.

[2] J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).

[3] P. W. Anderson, Phys. Rev. 130, 439 (1963).

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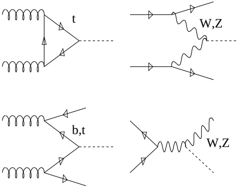
⇒ LHC: Higgs scalar fundamental?

1. Introduction. The recent discovery of the W and Z bosons confirm the belief that a spontaneously broken SU(2) × U(1) gauge group correctly describes the electroweak interactions. But how is SU(2) × U(1) broken? Nobody knows. In the standard model, the scalar Higgs doublet acquires a VEV, and the spectrum includes heavy gauge bosons and the massive, neutral uneaten scalar. Hypercolor models offer an alternative scenario for breaking SU(2) × U(1): strongly interacting hyperquarks form a condensate which transforms nontrivially under SU(2) × U(1) [1]. In

Higgs couplings



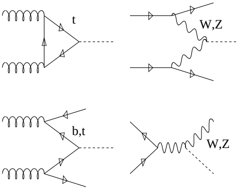
Standard-Model with free Higgs couplings [Dührssen]

– assume: narrow CP-even scalar
  Standard Model particles
  Higgs couplings proportional to masses?
– couplings from production & decay combinations
– Higgs Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible} + \text{unobservable}$$

Production		Coupling		Decay
$gg \to H$ $gg \to Hj$ (boosted) $gg \to H^*$ (off-shell) $qq \to qqH$ $gg \to t\bar{t}H$ $qq' \to VH$	$\longleftrightarrow$	$g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)$	$\longleftrightarrow$	$H \to ZZ$ $H \to WW$ $H \to b\bar{b}$ $H \to \tau^+\tau^-$ $H \to \gamma\gamma$ $H \to$ invisible

Higgs couplings



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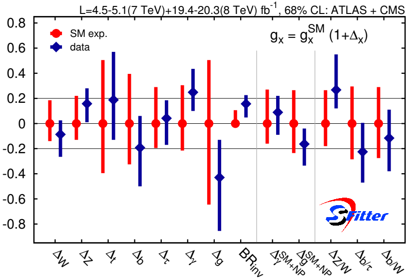
Exactly the 1964 prediction? [Butter, Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch, Zerwas]



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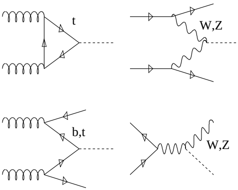

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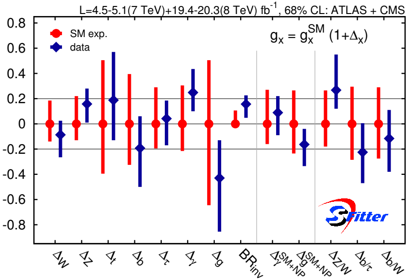
Exactly the 1964 prediction? [Butter, Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch, Zerwas]

- renormalizability/unitarity broken
- total rates only
- hard to relate to gauge sector
- not related to new physics scale

$\Rightarrow$ LHC: better framework?



Higgs-gauge effective theory

Learning from flavor physics: effective theory

– resolved mass scale $m_H \approx 126$ GeV
new physics mass scale $M \gg m_H$

– 'linear realization' meaning Higgs-Goldstone doublet ϕ

– Lagrangian from particle content and symmetries
start with mass dimension 6

$$\mathcal{L}^{HVV} = -\frac{\alpha_s v}{8\pi}\frac{f_g}{M^2}\mathcal{O}_{GG} + \frac{f_{BB}}{M^2}\mathcal{O}_{BB} + \frac{f_{WW}}{M^2}\mathcal{O}_{WW} + \frac{f_B}{M^2}\mathcal{O}_B + \frac{f_W}{M^2}\mathcal{O}_W + \frac{f_{\phi,2}}{M^2}\mathcal{O}_{\phi,2}$$

– operator basis [as any basis not unique]

$$\mathcal{O}_{BB} = \phi^\dagger B_{\mu\nu} B^{\mu\nu}\phi \qquad \mathcal{O}_{WW} = \phi^\dagger W_{\mu\nu} W^{\mu\nu}\phi \qquad \mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu}$$

$$\mathcal{O}_B = (D_\mu\phi)^\dagger B^{\mu\nu}(D_\nu\phi) \qquad \mathcal{O}_W = (D_\mu\phi)^\dagger W^{\mu\nu}(D_\nu\phi) \qquad \mathcal{O}_{\phi,2} = \partial^\mu(\phi^\dagger\phi)\partial_\mu(\phi^\dagger\phi)$$

– plus fermion couplings $f_{t,b,\tau}$: 9 operators

7 Δ-like coupling shifts, 4 new Lorentz structures

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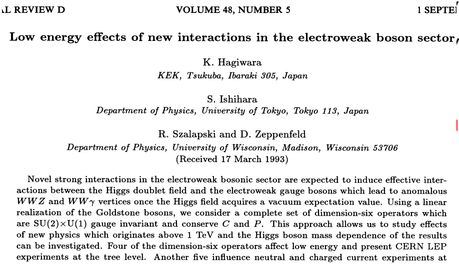
L REVIEW D VOLUME 48, NUMBER 5 1 SEPTE

Low energy effects of new interactions in the electroweak boson sector

K. Hagiwara
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S. Ishihara
Department of Physics, University of Tokyo, Tokyo 113, Japan

R. Szalapski and D. Zeppenfeld
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706
(Received 17 March 1993)

Novel strong interactions in the electroweak bosonic sector are expected to induce effective interactions between the Higgs doublet field and the electroweak gauge bosons which lead to anomalous WWZ and $WW\gamma$ vertices once the Higgs field acquires a vacuum expectation value. Using a linear realization of the Goldstone bosons, we consider a complete set of dimension-six operators which are SU(2)×U(1) gauge invariant and conserve C and P. This approach allows us to study effects of new physics which originates above 1 TeV and the Higgs boson mass dependence of the results can be investigated. Four of the dimension-six operators affect low energy and present CERN LEP experiments at the tree level. Another five influence neutral and charged current experiments at

$^{\mu\nu}\phi$ $\qquad \mathcal{O}_{GG} = \phi^\dagger\phi G^a_{\mu\nu}G^{a\mu\nu}$

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The other five operators are

$$\mathcal{O}_{WWW} = \mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_\rho{}^\mu], \quad (2.7a)$$

$$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi, \quad (2.7b)$$

$$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi, \quad (2.7c)$$

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi), \quad (2.7d)$$

$$\mathcal{O}_B = (D_\mu\Phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\Phi)\,. \quad (2.7e)$$

As we shall see they all contribute to four-fermion amplitudes at the one-loop level. In addition $\mathcal{O}_{WWW}$, $\mathcal{O}_W$, and $\mathcal{O}_B$ give rise to nonstandard triple gauge boson couplings. Conventionally the WWV vertices ($V = Z,\gamma$) are parametrized by the effective Lagrangian [2]

$$\mathcal{L}_{\text{eff}}^{WWV} = i\,g_{WWV}\left(g_1^V(W^+_{\mu\nu}W^{-\,\mu} - W^{+\,\mu}W^-_{\mu\nu})V^\nu + \kappa_V\,W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2}W^{+\,\nu}_\mu W^{-\,\rho}_\nu V_\rho{}^\mu\right), \quad (2.8)$$

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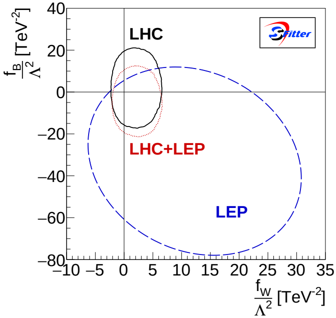
New physics in Higgs sector?

- Higgs couplings re-written as operators

  theoretically sound
  distributions included
- gauge bosons included

  LHC exceeding LEP
  many analyses not done



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- Higgs couplings re-written as operators

  theoretically sound
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  LHC exceeding LEP
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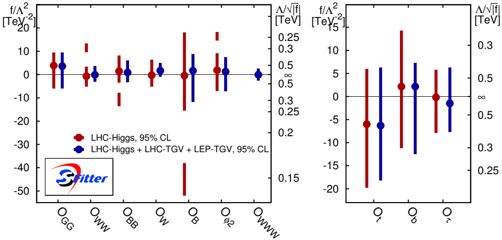
$\Rightarrow$ new physics $M \gtrsim 500$ GeV

[strongly interaction models heavier]



More effective theories

Effective theory of top sector [Glasgow TopFitter]

- all available top production and decay measurements
- dimension-6 operators

$$\mathcal{O}_{qq} = \bar{q}\gamma_\mu q \, \bar{t}\gamma^\mu t \qquad \mathcal{O}_G = f_{abc} G_\mu^{a\nu} G_\nu^{b\lambda} G_\lambda^{c\mu} \qquad \mathcal{O}_{\phi G} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \cdots$$

- similar to Higgs-gauge analysis

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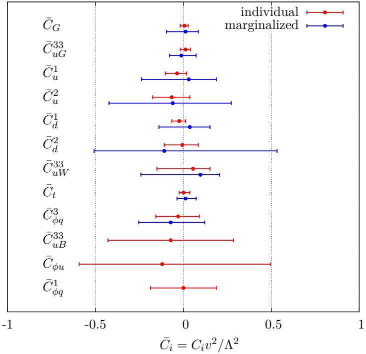

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Effective theory of QCD [with Sherpa]

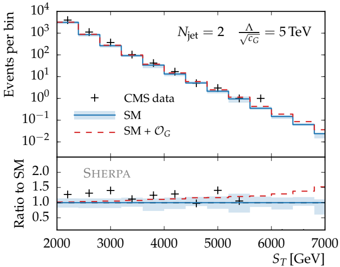
– multi-jet production rates

$$S_T \approx \sum_{j=1}^{N_\text{jets}} E_{T,j}$$

– dimension-6 operators of the kind

$$\mathcal{O}_{qq} = \bar{q}\gamma_\mu q \, \bar{q}'\gamma^\mu q' \qquad \mathcal{O}_G = f_{abc} G^{a\nu}_\mu G^{b\lambda}_\nu G^{c\mu}_\lambda$$

– 4-fermion operator for $N_\text{jets} = 2, 3$
gluon operator for $N_\text{jets} \geq 5$



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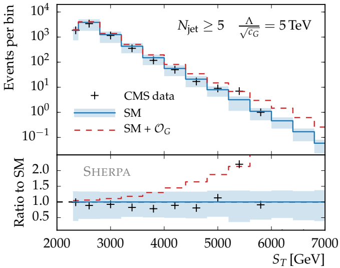

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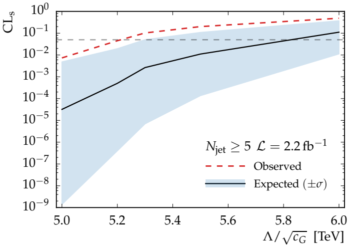
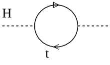
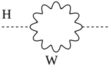
gluon operator for $N_\text{jets} \geq 5$

$\Rightarrow$ new physics $M \gtrsim 5$ TeV, QCD rules!



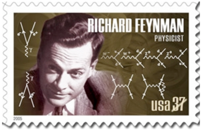
Naturalness





Problem with scalars

– quantum corrections to Higgs mass... [$\Delta t \, \Delta E < 1$]



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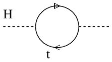

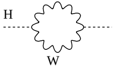

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– quantum corrections to Higgs mass

$$m_H^2 \longrightarrow m_H^2 - \frac{g^2}{(4\pi)^2}\,\frac{3}{2}\,\frac{\Lambda^2}{m_W^2}\left[m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right] + \cdots$$

– Higgs mass pulled to cut-off $\Lambda \gg 126$ GeV [where Higgs at Λ does not work]

no protecting symmetry in Standard Model [no idea where Higgs field comes from]

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Renormalization Group and Strong Interactions*

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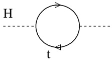
and
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850†

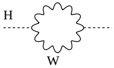
(Received 30 November 1970)

The renormalization-group method of Gell-Mann and Low is applied to field theories of strong interactions. It is assumed that renormalization-group equations exist for strong interactions which involve one or several momentum-dependent coupling constants. The further assumption that these coupling constants approach fixed values as the momentum goes to infinity is discussed in detail. However, an alternative is suggested, namely, that these coupling constants approach a limit cycle in the limit of large momenta. Some results of this paper are: (1) The e^+-e^- annihilation experiments above 1-GeV energy may distinguish a fixed point from a limit cycle or other asymptotic behavior. (2) If electrodynamics or weak interactions become strong above some large momentum Λ, then the renormalization group can be used (in principle) to determine the renormalized coupling constants of strong interactions, except for $U(3)\times U(3)$ symmetry-breaking parameters. (3) Mass terms in the Lagrangian of strong, weak, and electromagnetic interactions must break a symmetry of the combined interactions with zero mass. (4) The $\Delta I=\frac{1}{2}$ rule in nonleptonic weak interactions can be understood assuming only that a renormalization group exists for strong interactions.

This discussion can be summarized by saying that mass or symmetry-breaking terms must be "protected" from large corrections at large momenta due to various interactions (electromagnetic, weak, or strong). A symmetry-breaking term, such as $h_{1\lambda}$, $h_{2\lambda}$, or $h_{3\lambda}$, is protected if, in the renormalization-group equation for $h_{1\lambda}$, $h_{2\lambda}$, or $h_{3\lambda}$, the right-hand side is proportional to $h_{1\lambda}$, $h_{2\lambda}$, $h_{3\lambda}$ or other small coupling constants even when high-order strong, electromagnetic, or weak corrections are taken into account. The mass terms for the electron and muon and the weak boson, if any, must also be protected. This requirement means that weak interactions cannot be mediated by scalar particles.[36]

Naturalness





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no protecting symmetry in Standard Model [no idea where Higgs field comes from]

$\Rightarrow$ valid theoretical guiding principle?

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS

CHIRAL SYMMETRY BREAKING

G. 't Hooft

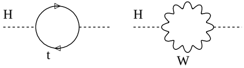
Institute for Theoretical Fysics

Utrecht, The Netherlands

ABSTRACT

A properly called "naturalness" is imposed on gauge theories. It is an order-of-magnitude restriction that must hold at all energy scales μ. To construct models with complete naturalness for elementary particles one needs more types of confining gauge theories besides quantum chromodynamics. We propose a search program for models with improved naturalness and concentrate on

Naturalness



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If Higgs mass is a problem...

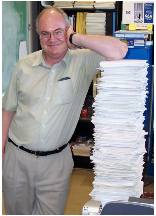
– protecting symmetries: supersymmetry?

– low cut-off in composite models?

– something totally different?

– maybe combined with dark matter particle?

$\Rightarrow$ LHC theory beyond precision QCD and EFT...



Higgs portal

Higgs as portal to new physics

- renormalizable, extended scalar potential

$$V(\Phi, S) = \mu_1^2\, (\Phi^\dagger\, \Phi) + \lambda_1\, |\Phi^\dagger \Phi|^2 + \mu_2^2\, |S|^2 + \lambda_2\, |S|^4 + \lambda_3\, |\Phi^\dagger\, \Phi|\, |S|^2$$

- $\langle S \rangle \neq 0$: mixing with Higgs particle
  $\langle S \rangle = 0$: weak-scale dark matter candidate
- LHC and direct detection based on the same *ggH* coupling
- $m_S < m_H/2$: invisible Higgs decays

$\Rightarrow$ nicest dark matter model ever!

The Minimal Model of nonbaryonic dark matter: a singlet scalar

C.P. Burgess [a,b], Maxim Pospelov [c], Tonnis ter Veldhuis [c]

[a] The Institute for Advanced Study, Princeton, NJ 08540, USA
[b] Physics Department, McGill University, 3600 University St., Montréal, PQ, Canada H3A 2T8
[c] Department of Physics, University of Minnesota, Minneapolis, MN 55455, USA

Received 17 January 2001; accepted 9 October 2001

Abstract

We propose the simplest possible renormalizable extension of the Standard Model—the addition of just one singlet scalar field—as a minimalist model for nonbaryonic dark matter. Such a model

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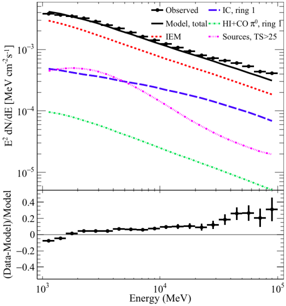
Leading dark matter anomaly: Fermi galactic center excess [Goodenough, Hooper]

– anomalous photon spectrum



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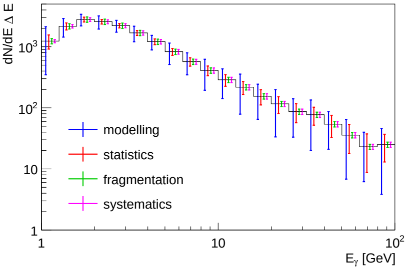

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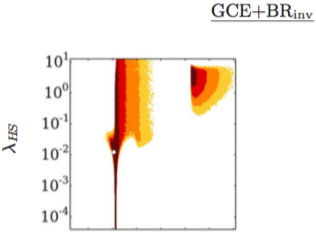
– explained by Higgs portal dark matter [Cuoco, Eiteneuer, Heisig, Krämer]

– constrained by Fermi and LHC



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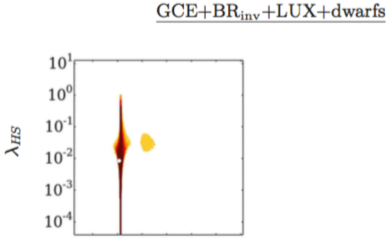
– more constrained by direct detection

$\Rightarrow$ there is interesting data around...



More Hooperon candidates

Supersymmetric dark matter candidates [Michael's favorite]

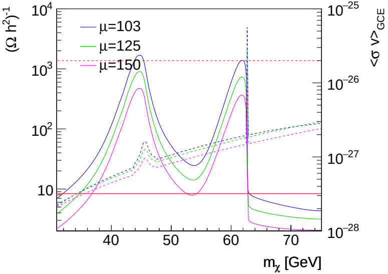
– superposition of $SU(2)_L$ representations: neutralinos/charginos

singlet — bino, singlino
double-doublet — higgsino
triplet — wino

– annihilation $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to b\bar{b}, W^+W^-, t\bar{t}$

– Higgs portal to Majorana fermions

– direct detection key



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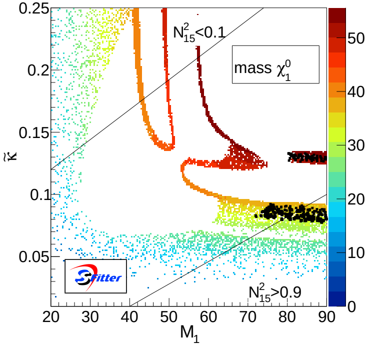
Link to invisible Higgs decays

– no Fermi-Higgs link in MSSM

– strong correlation for NMSSM



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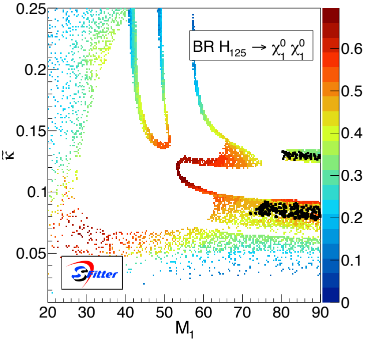
– BR($H \to$ inv) $\approx$ 10 ... 30% expected

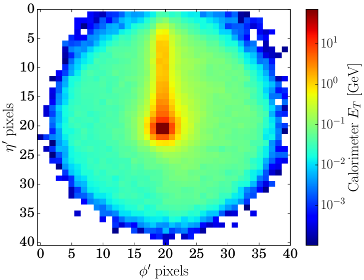
$\Rightarrow$ LHC physics not only QCD and EFT

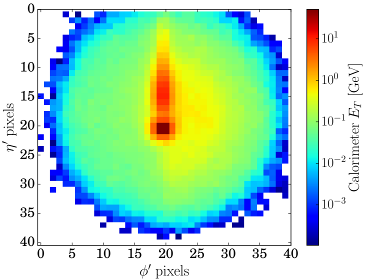


Theory for/at the LHC

Data driven era of weak-scale physics

- requiring experts, not preachers
- Higgs physics a triumph, LHC one of the great experiments
- lots of open questions, some very old, but data is new
- currently no 'hot' anomaly [as far as I am concerned]
  but who knows what happens next
- new ideas still crucial, welcome, and acknowledged





Lectures on LHC Physics, arXiv:0910.4182 *Yet Another Introduction to Dark Matter*, arXiv:170?.????
both updated under `www.thphys.uni-heidelberg.de/~plehn/`