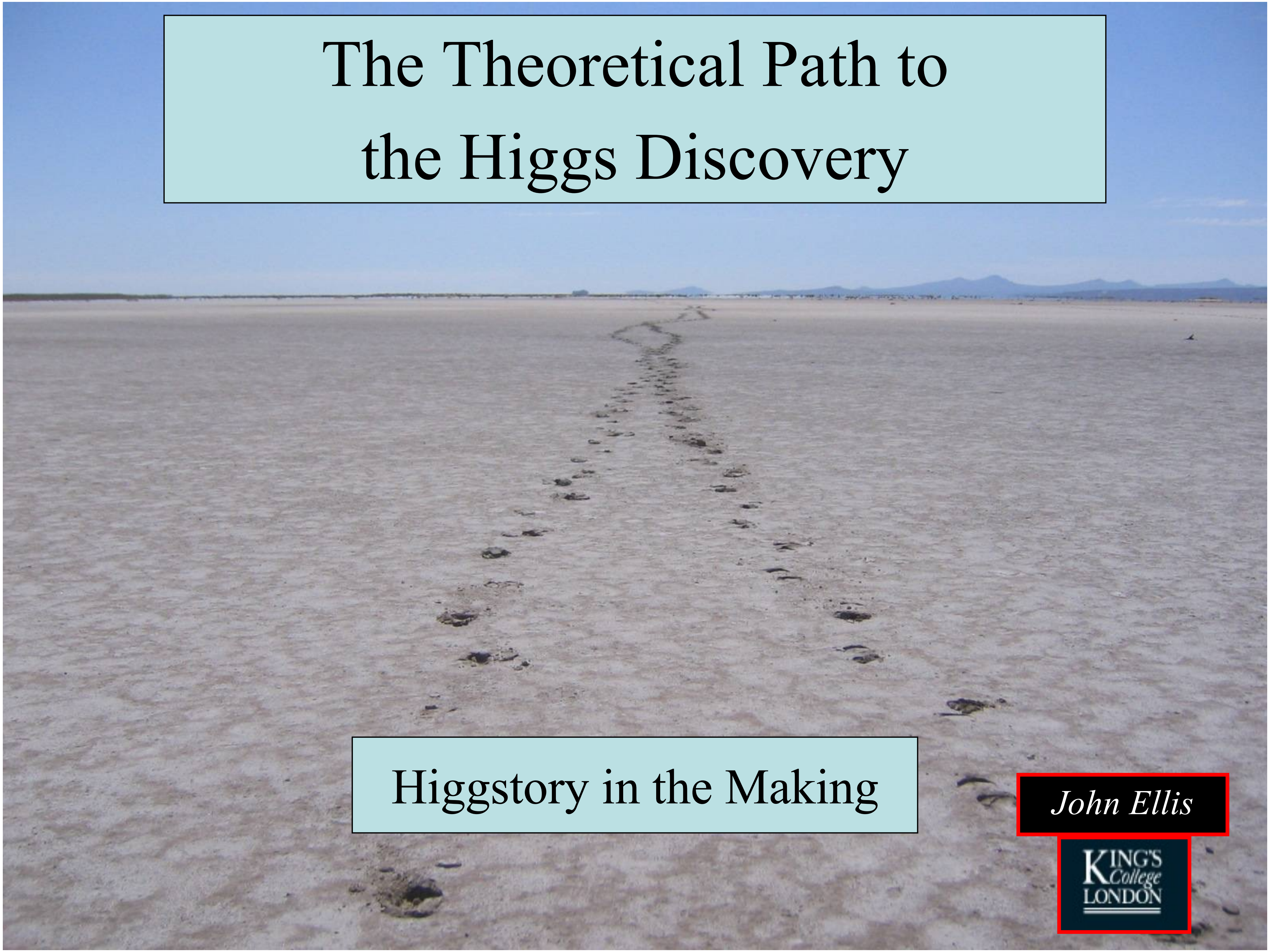
The Theoretical Path to the Higgs Discovery



Higgstory in the Making

John Ellis

King's College London

1957

The BCS Theory of Superconductivity

PHYSICAL REVIEW VOLUME 108, NUMBER 5 DECEMBER 1, 1957

Theory of Superconductivity*

J. BARDEEN, L. N. COOPER,† AND J. R. SCHRIEFFER‡
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(Received July 8, 1957)

A theory of superconductivity is presented, based on the fact that the interaction between electrons resulting from virtual exchange of phonons is attractive when the energy difference between the electrons states involved is less than the phonon energy, $\hbar\omega$. It is favorable to form a superconducting phase when this attractive interaction dominates the repulsive screened Coulomb interaction. The normal phase is described by the Bloch individual-particle model. The ground state of a superconductor, formed from a linear combination of normal state configurations in which electrons are virtually excited in pairs of opposite spin and momentum, is lower in energy than the normal state by amount proportional to an average $(\hbar\omega)^2$, consistent with the isotope effect. A mutually orthogonal set of excited states in one-to-one correspondence with those of the normal phase is obtained by specifying occupation of certain Bloch states and by using the rest to form a linear combination of virtual pair configurations. The theory yields a second-order phase transition and a Meissner effect in the form suggested by Pippard. Calculated values of specific heats and penetration depths and their temperature variation are in good agreement with experiment. There is an energy gap for individual-particle excitations which decreases from about $3.5kT_c$ at $T=0°\mathrm{K}$ to zero at T_c. Tables of matrix elements of single-particle operators between the excited-state superconducting wave functions, useful for perturbation expansions and calculations of transition probabilities, are given.

Condensate of electron pairs of due to phonon interactions

Lowest-energy state has charge density: breaks/hides $U(1)_{em}$

1959/62

Nambu, Anderson & “Spontaneous Breaking” of Gauge Symmetry

“Spontaneous symmetry breaking” = hidden symmetry

Gauge-invariant mass generation by plasmons in non-relativistic theory

PHYSICAL REVIEW VOLUME 117, NUMBER 3 FEBRUARY 1, 1960

Quasi-Particles and Gauge Invariance in the Theory of Superconductivity*

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(Received July 23, 1959)

Ideas and techniques known in quantum electrodynamics have been applied to the Bardeen-Cooper-Schrieffer theory of superconductivity. In an approximation which corresponds to a generalization of the Hartree-Fock fields, one can write down an integral equation defining the self-energy of an electron in an electron gas with phonon and Coulomb interaction. The form of the equation implies the existence of a particular solution which does not follow from perturbation theory, and which leads to the energy gap equation and the quasi-particle picture analogous to Bogoliubov's.

The gauge invariance, to the first order in the external electromagnetic field, can be maintained in the quasi-particle picture by taking into account a certain class of corrections to the charge-current operator due to the phonon and Coulomb interaction. In fact, generalized forms of the Ward identity are obtained between certain vertex parts and the self-energy. The Meissner effect calculation is thus rendered strictly gauge invariant, but essentially keeping the BCS result unaltered for transverse fields.

It is shown also that the integral equation for vertex parts allows homogeneous solutions which describe collective excitations of quasi-particle pairs, and the nature and effects of such collective states are discussed.

PHYSICAL REVIEW VOLUME 130, NUMBER 1 1 APRIL 1963

Plasmons, Gauge Invariance, and Mass

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(Received 8 November 1962)

Schwinger has pointed out that the Yang-Mills vector boson implied by associating a generalized gauge transformation with a conservation law (of baryonic charge, for instance) does not necessarily have zero mass, if a certain criterion on the vacuum fluctuations of the generalized current is satisfied. We show that the theory of plasma oscillations is a simple nonrelativistic example exhibiting all of the features of Schwinger's idea. It is also shown that Schwinger's criterion that the vector field $m\neq 0$ implies that the matter spectrum before including the Yang-Mills interaction contains $m=0$, but that the example of superconductivity illustrates that the physical spectrum need not. Some comments on the relationship between these ideas and the zero-mass difficulty in theories with broken symmetries are given.

1960

Nambu Introduces Spontaneous Symmetry Breaking into Particle Physics

AXIAL VECTOR CURRENT CONSERVATION IN WEAK INTERACTIONS*

Yoichiro Nambu
Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois
(Received February 23, 1960)

In analogy to the conserved vector current interaction in the beta decay suggested by Feynman and Gell-Mann, some speculations have been made about a possible conserved axial vector current.[1-3] One can formally construct an axial vector nucleon current, which satisfies a continuity equation,

$$\Gamma_\mu^A(p',p) = i\gamma_5\gamma_\mu - 2M\gamma_5 q_\mu/q^2, \quad q = p' - p, \qquad (1)$$

where p and p' are the initial and final nucleon momenta. Such an attempt has some appeal in view of the apparently modest renormalization effect on the axial vector beta decay constant ($g_A/g_V \approx 1.25$), although the second appealing point,[1] namely, the possible forbidding of $\pi \to e + \nu$, has now lost its relevance.

The expression (1), unfortunately, can be easily ruled out experimentally, as was pointed out by Goldberger and Treiman,[3] since it introduces a large admixture of pseudoscalar interaction.

- Spontaneous breaking of global chiral symmetry
- Pion as (almost) massless (Nambu-)Goldstone boson of chiral symmetry of strong interactions

The Founding Fathers

1964

The Englert-Brout-Higgs Mechanism

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

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)

5 citations before 1967

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES

A. A. MIGDAL and A. M.

Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966
J. Exptl.

The occurrence of massless particles in the presence of spontaneous symmetry breakdown is discussed. By summing all Feynman diagrams, one obtains for the difference of the mass

1964

Steps Towards the Higgs Boson

6

CAN ONE EVADE THE GOLDSTONE THEOREM?

P.W. ANDERSON POINTED OUT THAT IN A SUPERCONDUCTOR THE GOLDSTONE MODE BECOMES A MASSIVE "PLASMON" MODE DUE TO ITS ELECTROMAGNETIC INTERACTION, AND THAT THIS MODE IS JUST THE LONGITUDINAL PARTNER OF TRANSVERSELY POLARIZED ELECTROMAGNETIC MODES, WHICH ARE ALSO MASSIVE. (MEISSNER EFFECT!)

ANDERSON CONTINUED, "THE GOLDSTONE ZERO-MASS DIFFICULTY IS NOT A SERIOUS ONE, BECAUSE WE CAN PROBABLY CANCEL IT OFF AGAINST AN EQUAL YANG-MILLS ZERO-MASS PROBLEM"

BUT (a) HE DIDN'T DISCUSS THE <u>THEOREM</u>
(b) HE DIDN'T DISCUSS ANY RELATIVISTIC MODEL

7

1964 HOW TO EVADE GOLDSTONE'S THEOREM

GSW PROOF INVOLVES COMMUTATOR

$$i[\hat{Q}, \hat{\phi}_1] = \hat{\phi}_2 \quad (1)$$

$$\hat{Q} = \int d^3x\, \hat{j}_0(\underline{x}, t) \quad \text{(GENERATOR)}$$

AND $\partial_\mu \hat{j}^\mu = 0$ (2) (INVARIANCE OF $\hat{\mathcal{L}}$)

MANIFEST LORENTZ INVARIANCE $\Rightarrow$ 4D FOURIER TRANSFORM OF

$$\langle i[\hat{j}_\mu(x), \hat{\phi}_1(y)]\rangle_0$$

HAS FORM $k_\mu\,(\text{sign}\,k^0)\,\rho(k^2)$ [$\rho = 0$ FOR SPACELIKE k_μ]

(2) $\rightarrow k^2\rho(k^2) = 0 \Rightarrow \rho = C\,\delta(k^2)$

(1) $\rightarrow C = 2\pi\langle\hat{\phi}_2\rangle_0 \neq 0$ (ASYMMETRIC VACUUM)

MARCH 1964

A. KLEIN & B.W. LEE

FOR (e.g.) SUPERCONDUCTOR, F.T. HAS MORE GENERAL FORM

$$k_\mu\, \rho_1(k^2, n.k) + n_\mu\, \rho_2(k^2, n.k)$$

WHERE n_μ ($= (1,0,0,0)$) SPECIFIES REST FRAME OF IONIC BACKGROUND. PERHAPS THIS COULD HAPPEN IN TRULY RELATIVISTIC CASE?

JUNE 1964 W. GILBERT No!

JULY 1964 P.W.H. YES! — BUT ONLY IF GAUGE FIELD A_μ IS COUPLED TO THE CURRENT

8

1964 ACCIDENTAL BIRTH OF A BOSON

Th. 16 July — Phys. Rev. Letters (22 June), containing Gilbert's paper reaches Edinburgh.

F. 24 July — Broken Symmetries, Massless Particles and Gauge Fields (P.W.H.) sent to Physics Letters editor at CERN.
ACCEPTED

F. 31 July — Broken Symmetries and the Masses of Gauge Bosons (P.W.H.) sent to Physics Letters editor at CERN.
REJECTED

August — Paper revised by adding (inter alia) "It is worth noting that an essential feature of this type of theory is the prediction of incomplete multiplets of scalar and vector bosons"

31 August — Revised paper received by Physical Review Letters.
ACCEPTED

Referee (Nambu) draws to attention of PWH the paper by F. Englert & R. Brout, Broken Symmetry and the Mass of Gauge Vector Mesons (received by Phys. Rev. Letters 22 June, published 31 August)

1965/6

First Steps in Phenomenology

PHYSICAL REVIEW VOLUME 145, NUMBER 4 27 MAY 1966

Spontaneous Symmetry Breakdown without Massless Bosons*

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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 symmetry 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 equations themselves, is an attractive one. Within the framework of quantum field theory such a "spontaneous" breakdown of symmetry occurs if a Lagrangian, fully invariant under the internal symmetry group, has such a structure that the physical vacuum is a member of a set of (physically equivalent) states which transform according to a nontrivial representation of the group. This degeneracy of the vacuum permits nontrivial multiplets of scalar fields (which may be either fundamental dynamic variables or polynomials constructed from them) to have nonzero vacuum expectation values, whose appearance in Feynman diagrams leads to symmetry-breaking terms in propagators and vertices. That vacuum expectation values of scalar fields, or "vacuons," might play such a role in the breaking of symmetries was first noted by Schwinger[1] and by Salam and Ward.[2] Under the alternative name, "tadpole" diagrams, the graphs in which vacuons 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] that the BCS theory of superconductivity[6] is of this type, and was continued by Glashow[7] and others.[8] All these authors encountered the difficulty that their theories predicted, *inter alia*, the existence of a number of massless scalar or pseudoscalar bosons, named "zerons" by Freund and Nambu.[9] Since the models which they discussed, being inspired by the BCS theory, used an attractive interaction between massless fermions and antifermions as the mechanism of symmetry breakdown, it was at first unclear whether zerons occurred as a result of the approximations (including the usual cutoff for divergent integrals) involved in handling the models or whether they would still be there in an exact solution. Some authors,

* This work was partially supported by the U. S. Air Force Office of Scientific Research under grant No. AF-AFOSR-153-64.

† On leave from the Tait Institute of Mathematical Physics, University of Edinburgh, Scotland.

[1] J. Schwinger, Phys. Rev. 104, 1164 (1954); Ann. Phys. (N. Y.) 2, 407 (1957).
[2] A. Salam and J. C. Ward, Phys. Rev. Letters 5, 390 (1960); Nuovo Cimento 19, 167 (1961).
[3] S. Coleman and S. L. Glashow, Phys. Rev. 134, B671 (1964).
[4] Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122, 345 (1961); 124, 246 (1961); Y. Nambu and P. Pascual, Nuovo Cimento 30, 354 (1963).
[5] Y. Nambu, Phys. Rev. 117, 648 (1960).
[6] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 106, 162 (1957).
[7] M. Baker and S. L. Glashow, Phys. Rev. 128, 2462 (1962); S. L. Glashow, *ibid.* 130, 2132 (1962).
[8] M. Suzuki, Progr. Theoret. Phys. (Kyoto) 30, 138 (1963); 30, 627 (1963); N. Byrne, C. Iddings, and E. Shrauner, Phys. Rev. 139, B918 (1965); 139, B933 (1965).
[9] P. G. O. Freund and Y. Nambu, Phys. Rev. Letters 13, 221 (1964).

going states and associated complex conjugate wave functions.

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

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

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

$$M = -2iem_1b^{*\nu}(k_1)b_\nu^*(k_2) - iem_1^{-1}(p^2+m_0^2)\phi^*(k_1)\phi^*(k_2). \quad (16)$$

We have retained the last term, which we shall need in calculating scattering amplitudes; when the incident particle is on the mass shell it vanishes and we are left with the invariant expression

$$M = -2iem_1b^{*\nu}(k_1)b_\nu^*(k_2). \quad (17)$$

Conservation of angular momentum allows three possibilities for the spin states of the decay products: They may be both right-handed, both left-handed, or both longitudinal ($\sigma_1=\sigma_2=+1, -1$, or 0). With the help of the explicit vectors (14), we find

$$M(+1,+1) = M(-1,-1) = 2iem_1,$$
$$M(0,0) = ifm_0(1-2e^2/f^2).$$

We note that as $e\to 0$ the amplitudes for decay to transverse states tend to zero, but the amplitude $M(0,0)$ tends to the value ifm_0 which we would calculate from the vertex $-\frac{1}{2}fm_0\Phi^2X$ for the decay of one massive into two massless scalar bosons in the original Goldstone model. (The sign change arises from the factor i which is associated with the term in each b_μ.)

ii. Vector Boson-Vector Boson Scattering

Let k_1, k_2 be the incoming and k_1', k_2' the outgoing momenta. The process occurs as a second-order effect of the cubic vertices, by exchange of a scalar boson in the s, t, or u channel, where $s=-(p_1+p_2)^2$, $t=-(p_1-p_1')^2$, $u=-(p_1-p_2')^2$. It also occurs as a direct effect of two of the quartic vertices. Equation (16) enables us to write down

$$M_s = i^2\{-2em_1b_\mu^*(k_1')b^{*\mu}(k_2') + em_1^{-1}(s-m_0^2)\phi^*(k_1')\phi^*(k_2')\} \times i(s-m_0^2)^{-1}\{-2em_1b_\nu(k_1)b^\nu(k_2) + em_1^{-1}(s-m_0^2)\phi(k_1)\phi(k_2)\}$$

and similar expressions for M_t and M_u. The quartic vertices yield a contribution given by

$$M_{\text{direct}} = i(-2e^2)\{a_\mu^*(k_1')a^{*\mu}(k_2')\phi(k_1)\phi(k_2) + 5 \text{ similar terms}\} + i(-3f^2)\phi^*(k_1')\phi^*(k_2')\phi(k_1)\phi(k_2)$$
$$= -2ie^2\{b_\mu^*(k_1')b^{*\mu}(k_2')\phi(k_1)\phi(k_2) + 5 \text{ similar terms}\} + i(4e^2-3f^2)\phi^*(k_1')\phi^*(k_2')\phi(k_1)\phi(k_2).$$

It is only when we combine these four contributions that we obtain (after some algebra) the invariant expression

$$M_{\text{total}} = M_s + M_t + M_u + M_{\text{direct}}$$
$$= -4ie^2m_1^2\{(s-m_0^2)^{-1}b^{*\mu}(k_1')b^{*\mu}(k_2')b_\nu(k_1)b^\nu(k_2) + (t-m_0^2)^{-1}b_\mu^*(k_1')b^\mu(k_1)b_\nu^*(k_2')b^\nu(k_2) + (u-m_0^2)^{-1}b_\mu^*(k_1')b^\mu(k_2)b_\nu^*(k_2')b^\nu(k_1)\}. \quad (18)$$

iii. Vector Boson-Scalar Boson Scattering

Let k, p be the momenta of the incoming vector and scalar boson, respectively, and k', p' be their outgoing momenta. Again there are four contributions, M_s, M_t, M_u, and M_{direct}. In the s and u channels a vector boson is exchanged and it turns out that the various propagators, $(T^*A_\mu A_\nu)$, $(T^*A_\mu\Phi)$, and $(T^*\Phi\Phi)$, occur only in the combination $(T^*B_\mu B_\nu)$. We obtain the expression

$$M_s = i^2\{-2em_1b^{*\mu}(k') + ieq^\mu\phi^*(k')\}i(g_{\mu\nu} + m_1^{-2}q_\mu q_\nu) \times (s-m_1^2)^{-1}\{-2em_1b^\nu(k) - ieq^\nu\phi(k)\},$$

where $q=k+p$ and $s=-q^2$, and a similar expression for M_u. In the t channel a scalar boson is exchanged, and we find that

$$M_t = i^2\{-3fm_0\}i(t-m_0^2)^{-1}\{-2em_1b_\mu^*(k')b^\mu(k) + em_1^{-1}(t-m_0^2)\phi^*(k')\phi(k)\},$$

where $t=-(k-k')^2$. Finally, the contribution of the quartic vertices is given by

$$M_{\text{direct}} = i\{-2e^2[b_\mu^*(k') - im_1^{-1}k_\mu'\phi^*(k')] \times [b^\mu(k) + im_1^{-1}k^\mu\phi(k)] - f^2\phi^*(k')\phi(k)\}.$$

Again the four contributions sum to the invariant expression

$$M_{\text{total}} = -2im_1^2\{2e^2(s-m_1^2)^{-1}[b_\mu^*(k')b^\mu(k) + m_1^{-2}p_\mu'b^{*\mu}(k')p_\nu b^\nu(k)] + 3f^2(t-m_0^2)^{-1}b_\mu^*(k')b^\mu(k) + 2e^2(u-m_1^2)^{-1}[b_\mu^*(k')b^\mu(k) + m_1^{-2}p_\mu b^{*\mu}(k')p_\nu'b^\nu(k)]\} - 2ie^2b_\mu^*(k')b^\mu(k). \quad (19)$$

A similar matrix element may be written down for the process, vector pair ↔ scalar pair, by making appropriate interchanges of incoming and outgoing momenta and wave functions.

1966/7

The Non-Abelian Case

PHYSICAL REVIEW VOLUME 155, NUMBER 5 25 MARCH 1967

Symmetry Breaking in Non-Abelian Gauge Theories*

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(Received 24 October 1966)

According to the Goldstone theorem, any manifestly covariant broken-symmetry theory must exhibit massless particles. However, it is known from previous work that such particles need not appear in a relativistic theory such as radiation-gauge electrodynamics, which lacks manifest covariance. Higgs has shown how the massless Goldstone particles may be eliminated from a theory with broken $U(1)$ symmetry by coupling in the electromagnetic field. The primary purpose of this paper is to discuss the analogous problem for the case of broken non-Abelian gauge symmetries. In particular, a model is exhibited which shows how the number of massless particles in a theory of this type is determined, and the possibility of having a broken non-Abelian gauge symmetry with no massless particles whatever is established. A secondary purpose is to investigate the relationship between the radiation-gauge and Lorentz-gauge formalisms. The Abelian-gauge case is reexamined in order to show that, contrary to some previous assertions, the Lorentz-gauge formalism, properly handled, is perfectly consistent, and leads to physical conclusions identical with those reached using the radiation gauge.

V. A SIMPLE MODEL

As an illustration of the discussion in the preceding section, we shall consider here a simple model of broken $U(2)$ symmetry in which no massless particles remain. The model contains a complex three-component field $\phi=(\phi_i)$ and four vector fields A_μ and $\mathbf{A}_\mu=(A_{i\mu})$. It is

Also
Migdal & Polyakov
1965

1967

Weinberg: A Model of Leptons

- Electroweak sector of the Standard Model
- SU(2) x U(1)
- Mixing of Z, photon
- Neutral currents
- Higgs-lepton couplings
- No quarks

2 citations before 1971

and

$$\varphi_1 \equiv (\varphi^0 + \varphi^{0\dagger} - 2\lambda)/\sqrt{2} \quad \varphi_2 \equiv (\varphi^0 - \varphi^{0\dagger})/i\sqrt{2}. \qquad (5)$$

The condition that φ_1 have zero vacuum expectation value to all orders of perturbation theory tells us that $\lambda^2 \cong M_1^2/2h$, and therefore the field φ_1 has mass M_1 while φ_2 and φ^- have mass zero. But we can easily see that the Goldstone bosons represented by φ_2 and φ^- have no physical coupling. The Lagrangian is gauge invariant, so we can perform a combined isospin and hypercharge gauge transformation which eliminates φ^- and φ_2 everywhere[6] without changing anything else. We will see that G_e is very small, and in any case M_1 might be very large,[7] so the φ_1 couplings will also be disregarded in the following.

The effect of all this is just to replace φ everywhere by its vacuum expectation value

$$\langle\varphi\rangle = \lambda\binom{1}{0}. \qquad (6)$$

The first four terms in $\mathfrak{L}$ remain intact, while the rest of the Lagrangian becomes

$$-\tfrac{1}{8}\lambda^2 g^2[(A_\mu^{\ 1})^2 + (A_\mu^{\ 2})^2] - \tfrac{1}{8}\lambda^2(gA_\mu^{\ 3} + g'B_\mu)^2 - \lambda G_e \bar{e}e. \qquad (7)$$

We see immediately that the electron mass is λG_e. The charged spin-1 field is

$$W_\mu \equiv 2^{-1/2}(A_\mu^{\ 1} + iA_\mu^{\ 2}) \qquad (8)$$

and has mass

$$M_W = \tfrac{1}{2}\lambda g. \qquad (9)$$

The neutral spin-1 fields of definite mass are

$$Z_\mu = (g^2 + g'^2)^{-1/2}(gA_\mu^{\ 3} + g'B_\mu), \qquad (10)$$

$$A_\mu = (g^2 + g'^2)^{-1/2}(-g'A_\mu^{\ 3} + gB_\mu). \qquad (11)$$

Their masses are

$$M_Z = \tfrac{1}{2}\lambda(g^2 + g'^2)^{1/2}, \qquad (12)$$

$$M_A = 0, \qquad (13)$$

so A_μ is to be identified as the photon field. The interaction between leptons and spin-1 mesons is

$$\frac{ig}{2\sqrt{2}}\bar{e}\gamma^\mu(1+\gamma_5)\nu W_\mu + \text{H.c.} + \frac{igg'}{(g^2+g'^2)^{1/2}}\bar{e}\gamma^\mu e A_\mu + \frac{i(g^2+g'^2)^{1/2}}{4}\left[\left(\frac{3g'^2-g^2}{g'^2+g^2}\right)\bar{e}\gamma^\mu e - \bar{e}\gamma^\mu\gamma_5 e + \bar{\nu}\gamma^\mu(1+\gamma_5)\nu\right]Z_\mu. \qquad (14)$$

We see that the rationalized electric charge is

$$e = gg'/(g^2 + g'^2)^{1/2} \qquad (15)$$

and, assuming that W_μ couples as usual to hadrons and muons, the usual coupling constant of weak interactions is given by

$$G_W/\sqrt{2} = g^2/8M_W^{\ 2} = 1/2\lambda^2. \qquad (16)$$

Note that then the e-φ coupling constant is

$$G_e = M_e/\lambda = 2^{1/4}M_e G_W^{\ 1/2} = 2.07 \times 10^{-6}.$$

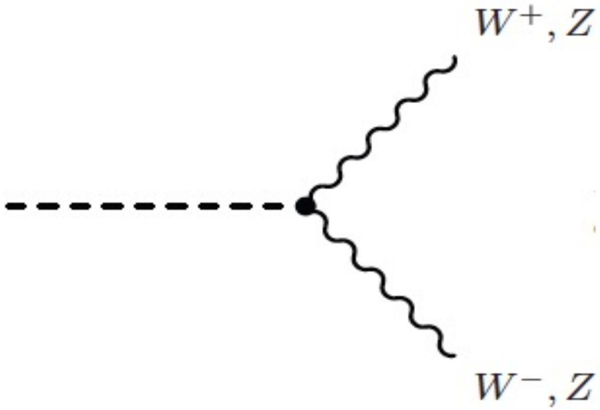
The coupling of φ_1 to muons is stronger by a factor M_μ/M_e, but still very weak. Note also that (14) gives g and g' larger than e, so (16) tells us that $M_W > 40$ BeV, while (12) gives $M_Z > M_W$ and $M_Z > 80$ BeV.

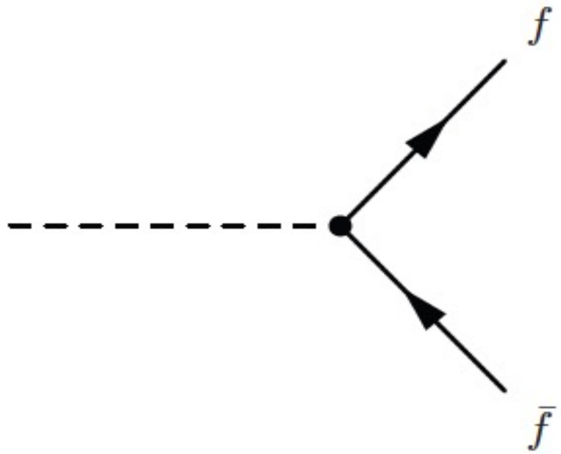
The only unequivocal new predictions made by this model have to do with the couplings of the neutral intermediate meson Z_μ. If Z_μ does not couple to hadrons then the best place to look for effects of Z_μ is in electron-neutron scattering. Applying a Fierz transformation to the W-exchange terms, the total effective e-ν interaction is

$$\frac{G_W}{\sqrt{2}}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu\left\{\frac{(3g^2-g'^2)}{2(g^2+g'^2)}\bar{e}\gamma^\mu e + \tfrac{3}{2}\bar{e}\gamma^\mu\gamma_5 e\right\}.$$

If $g \gg e$ then $g \gg g'$, and this is just the usual e-ν scattering matrix element times an extra factor $\frac{3}{2}$. If $g \simeq e$ then $g \ll g'$, and the vector interaction is multiplied by a factor $-\frac{1}{2}$ rather than $\frac{3}{2}$. Of course our model has too many arbitrary features for these predictions to be

Higgs Boson Couplings





$$g_2 M_W \,, \quad g_2 \frac{M_Z}{c_W}$$

$$\frac{m_f}{v} = \frac{g_2\, m_f}{2 M_W}$$

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_F M_H}{4\pi\sqrt{2}}\, m_f^2, \quad N_C = 3\,(1) \text{ for quarks (leptons)}$$

Weinberg 1967

$$\Gamma(H \to VV) = \frac{G_F M_H^3}{8\pi\sqrt{2}}\, F(r) \left(\frac{1}{2}\right)_Z, \quad r = \frac{M_V}{M_H}$$

Higgs 1966

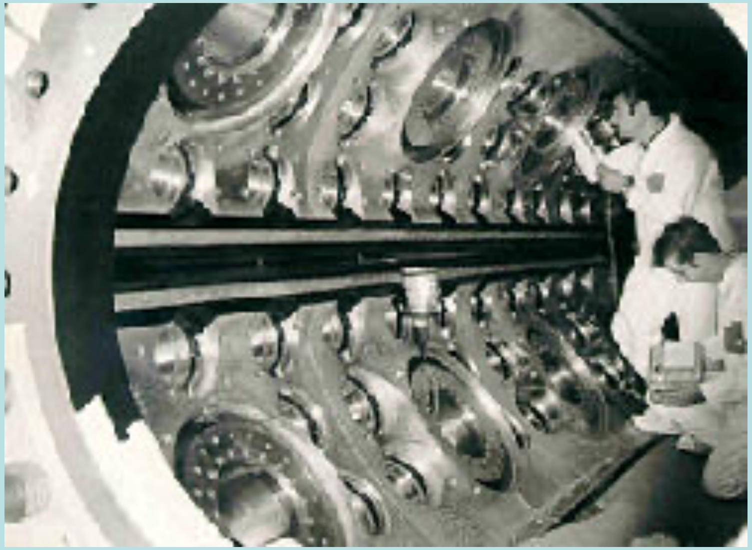
Gauge Theories taken Seriously

1971/2

- `t Hooft and Veltman: renormalizable

1973

- Kobayashi and Maskawa show how to include CP violation in the Standard Model



1973

- Neutral currents in Gargamelle

1974

- J/Ψ discovered

1975/6

- Tau lepton and charmed particles discovered

1975

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

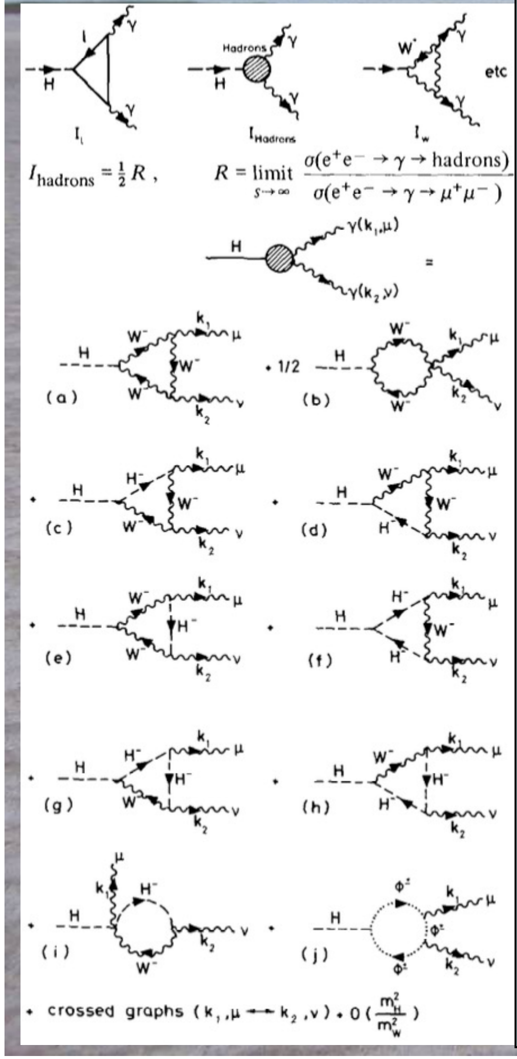
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

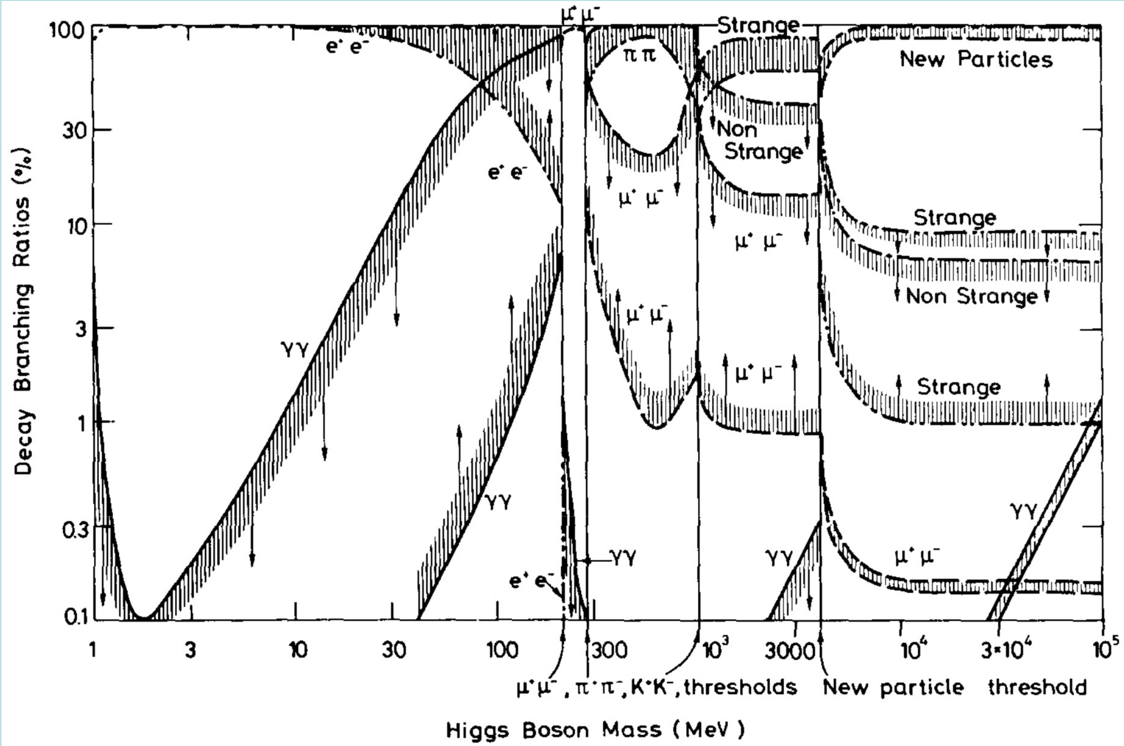
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

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.

A Phenomenological Profile of the Higgs Boson



- Previous mass limit ~ 15 MeV
- Decay into photons via loop diagrams



- Production in association with Z boson

1977/8

Next Steps in Phenomenology

VOLUME 40, NUMBER 11 PHYSICAL REVIEW LETTERS 13 MARCH 1978

Higgs Bosons from Two-Gluon Annihilation in Proton-Proton Collisions

H. M. Georgi, S. L. Glashow, M. E. Machacek, and D. V. Nanopoulos
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 27 December 1977)

We estimate the cross section for Higgs-boson production in proton-proton collisions. We find that most of the cross section comes from a two-gluon annihilation process, in which the gluons couple to Higgs bosons via heavy-quark loops.

PHYSICAL REVIEW D VOLUME 18, NUMBER 5 1 SEPTEMBER 1978

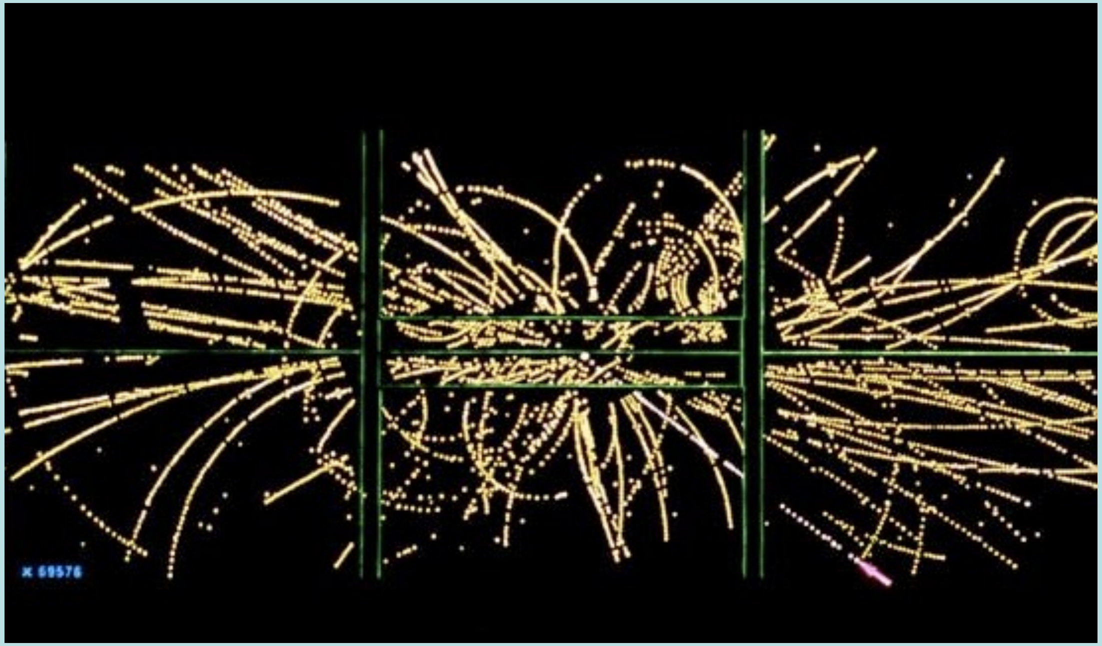
Associated production of Higgs bosons and *Z* particles

S. L. Glashow, D. V. Nanopoulos, and A. Yildiz
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 25 April 1978)

We estimate the cross section for Higgs-boson production via bremsstrahlung from intermediate vector bosons produced in pp and $\bar{p}p$ collisions.

1983

Discovery of the W and Z



How did they get so heavy?

- The top quark still undiscovered
- The search for the Higgs moved up the agenda

1984

Supercollider Phenomenology

Fermi National Accelerator Laboratory

FERMILAB-Pub-84/17-T
LBL-16875
DOE/ER/01545-345
February, 1984

Supercollider Physics

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P.O. Box 500, Batavia, IL 60510

D. Production of Higgs Bosons

In the standard electroweak theory, a single neutral scalar particle remains as a vestige of the spontaneous breakdown of the $SU(2)_L \otimes U(1)_Y$ gauge symmetry. As we have already noted in §I.B, the mass of this Higgs boson is not specified by the theory, but consistency arguments suggest (Linde, 1976; Weinberg, 1976a; Veltman, 1977; Lee, Quigg, and Thacker, 1977)

$$7\ \mathrm{GeV}/c^2 \lesssim M_H \lesssim 1\ \mathrm{TeV}/c^2. \tag{4.80}$$

The interactions of the Higgs boson are of course prescribed by the gauge symmetry. It is therefore straightforward to write down the partial widths for kinematically-allowed decays. The partial width for decay into a fermion-antifermion pair is

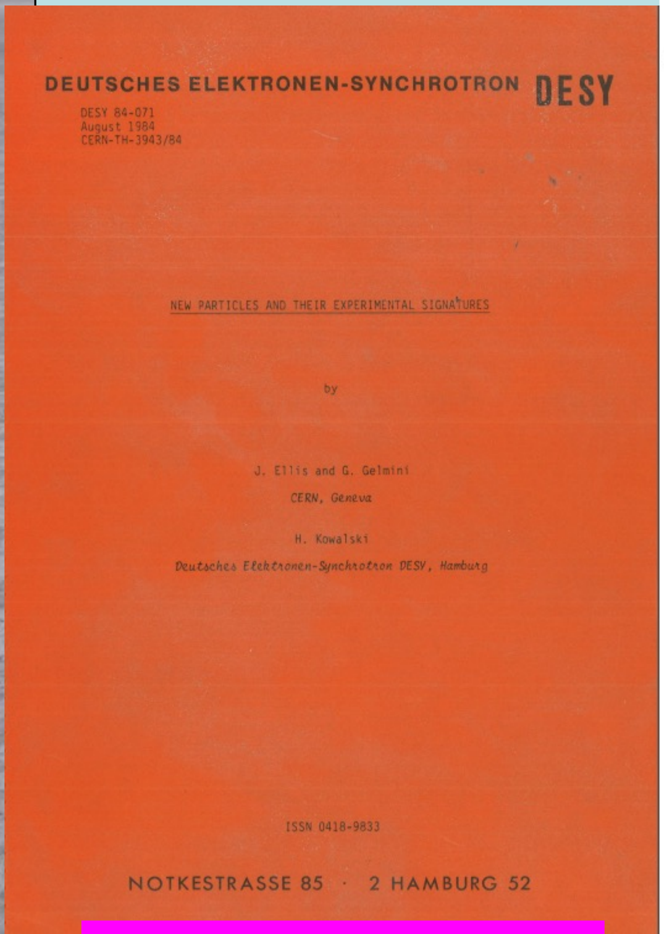
$$\Gamma(H \to f\bar{f}) = \frac{G_F m_f^2 M_H N_c}{4\pi\sqrt{2}} \left(1 - 4m_f^2/M_H^2\right)^{3/2}, \tag{4.81}$$

where N_c is the number of fermion colors. For $M_H \leq M_W$, the preferred decay of the Higgs boson is into the heaviest accessible pair of quarks or leptons.

1984

A Preview of the Higgs Boson @ LHC

- Presented at LHC Lausanne workshop 1984



DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 84-071
August 1984
CERN-TH-3943/84

NEW PARTICLES AND THEIR EXPERIMENTAL SIGNATURES

by

J. Ellis and G. Gelmini
CERN, Geneva

H. Kowalski
Deutsches Elektronen-Synchrotron DESY, Hamburg

ISSN 0418-9833

NOTKESTRASSE 85 · 2 HAMBURG 52

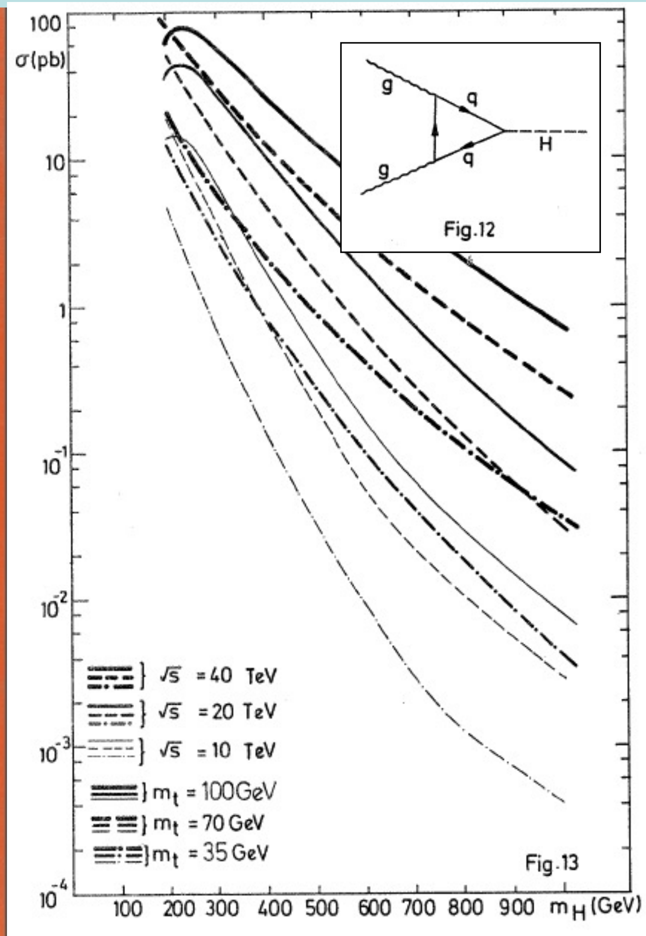


Fig.13

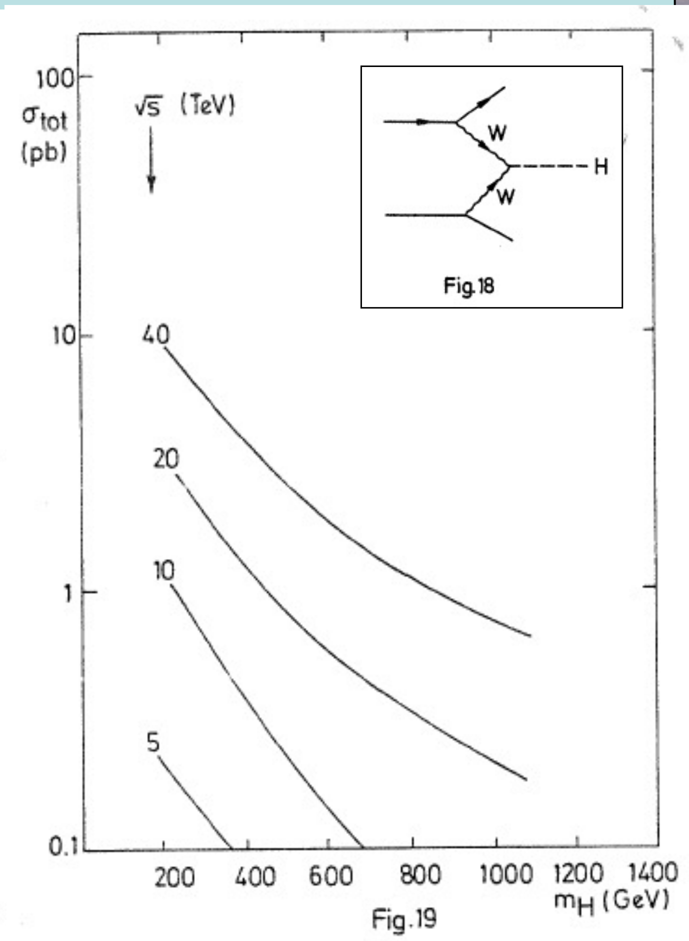


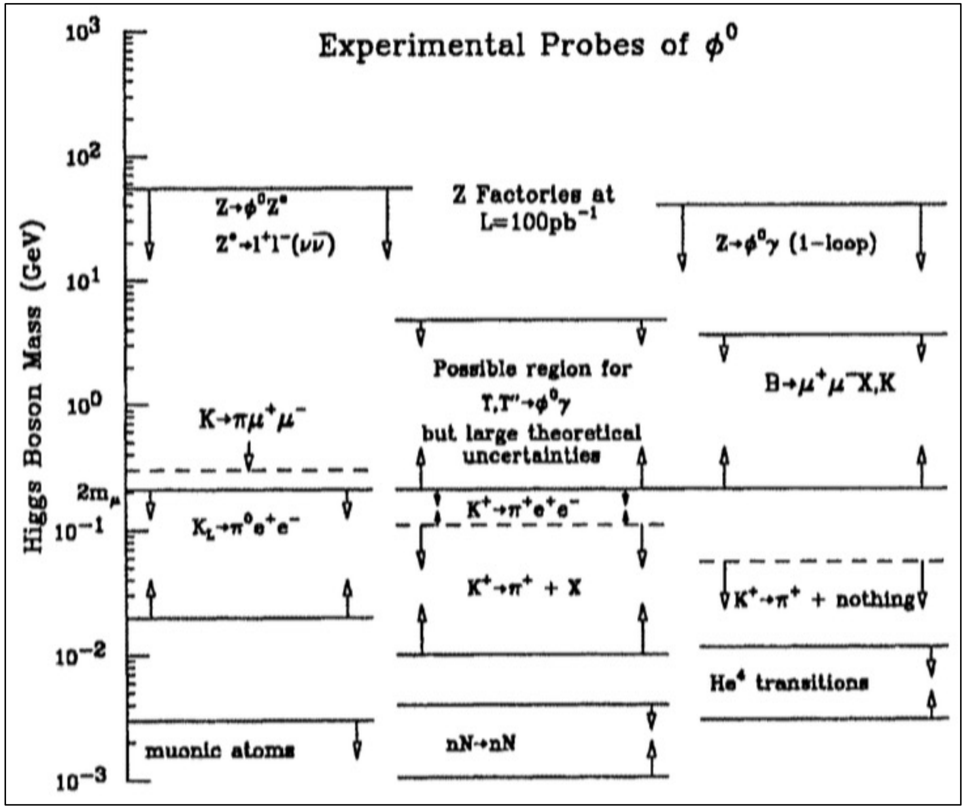
Fig.19

JE, Gelmini & Kowalski, 1984

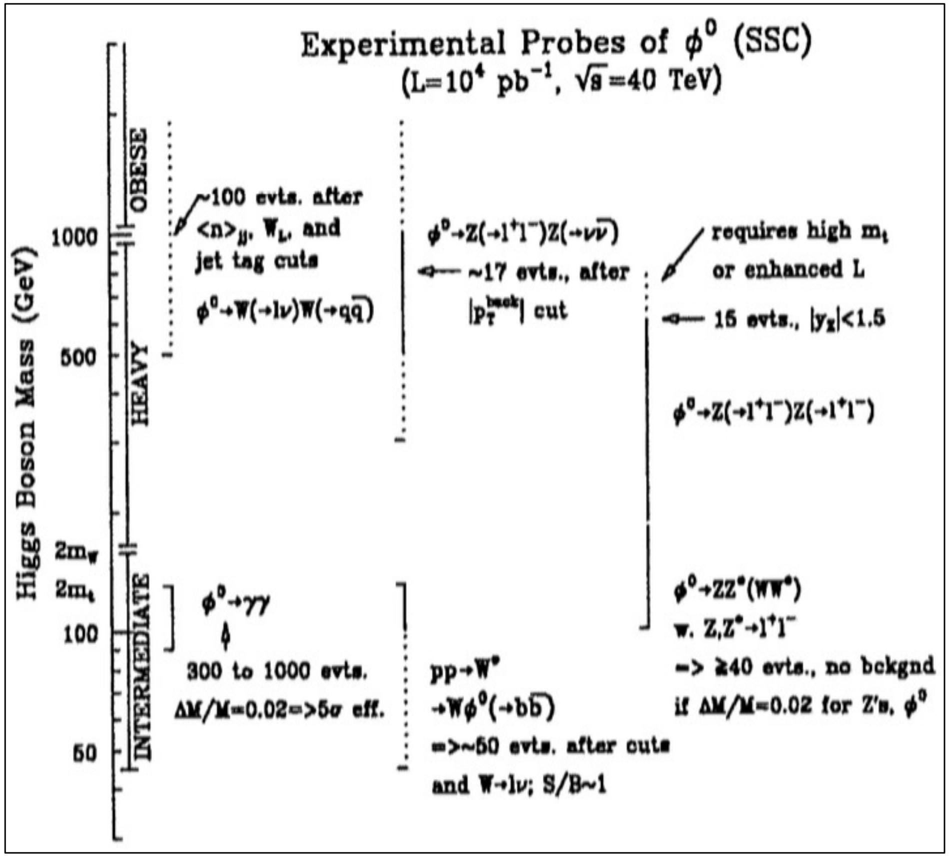
1989

The Higgs Hunter's Guide

Previous searches and prospects in e^+e^- collisions



Prospects at the SSC

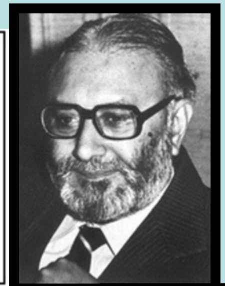


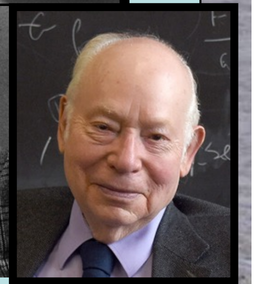
Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L, \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L, \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},-1)$
E_R	$e^-_R\ ,\ \mu^-_R\ ,\ \tau^-_R$	$(\mathbf{1},\mathbf{1},-2)$
Q_L	$\begin{pmatrix}u\\ d\end{pmatrix}_L, \begin{pmatrix}c\\ s\end{pmatrix}_L, \begin{pmatrix}t\\ b\end{pmatrix}_L$	$(\mathbf{3},\mathbf{2},+1/3)$
U_R	$u_R\ ,\ c_R\ ,\ t_R$	$(\mathbf{3},\mathbf{1},+4/3)$
D_R	$d_R\ ,\ s_R\ ,\ b_R$	$(\mathbf{3},\mathbf{1},-2/3)$

Ignored for several years





- Lagrangian:

$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} && \text{gauge interactions}\\
&+ i\bar{\psi}\, \not{D}\psi + h.c. && \text{matter fermions}\\
&+ \psi_i y_{ij} \psi_j \phi + h.c. && \text{Yukawa interactions}\\
&+ |D_\mu \phi|^2 - V(\phi) && \text{Higgs potential}
\end{aligned}
$$

High-precision tests at LEP, …

No direct evidence until 2012

Where are the top and Higgs?

Estimating Masses with Electroweak Data

- High-precision electroweak measurements are sensitive to quantum corrections

$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\mathrm{G}_F}(1+\Delta r)$$

Veltman

- Sensitivity to top mass is quadratic: $\frac{3\mathrm{G}_F}{8\pi^2\sqrt{2}} m_t^2$

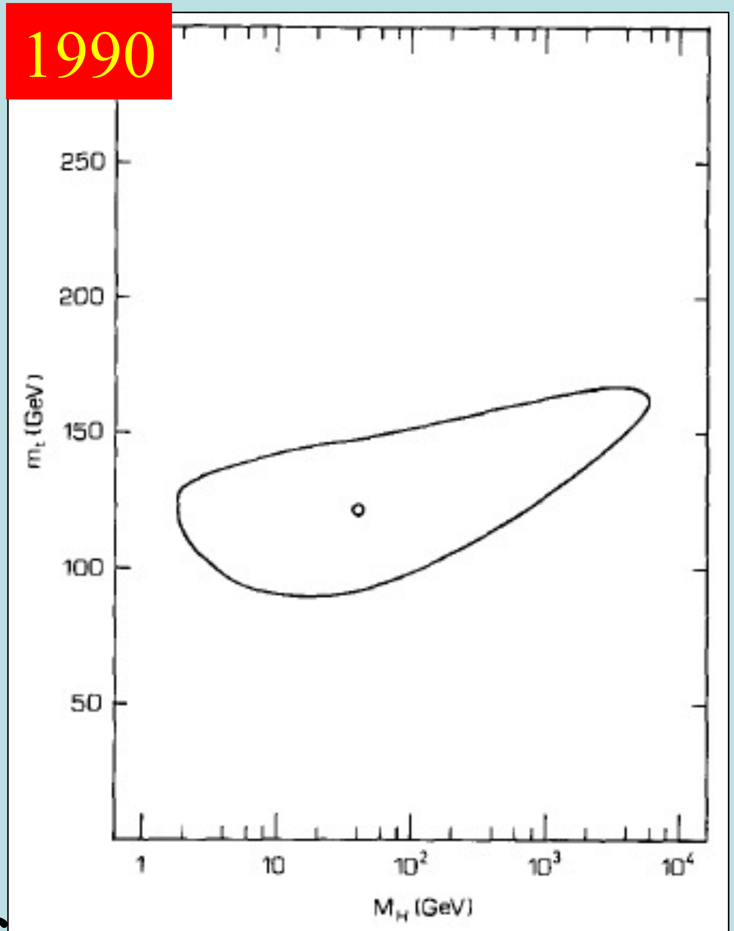
- Sensitivity to Higgs mass is logarithmic:

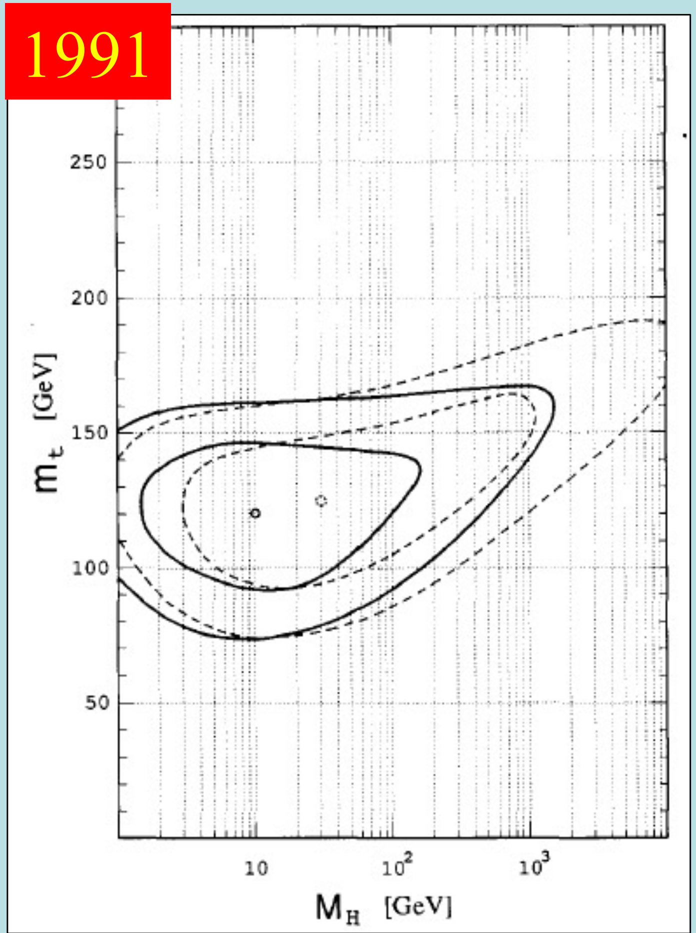
$$\frac{\sqrt{2}\mathrm{G}_F}{16\pi^2} m_W^2 \left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2} + \ldots\right),\ M_H >> m_W$$

- Measurements at LEP et al. gave indications first on top mass, then on Higgs mass $\Delta\rho = 0.0026\frac{M_t^2}{M_Z^2} - 0.0015\ln\left(\frac{M_H}{M_W}\right)$

Estimating the BEH mass

- Early attempts





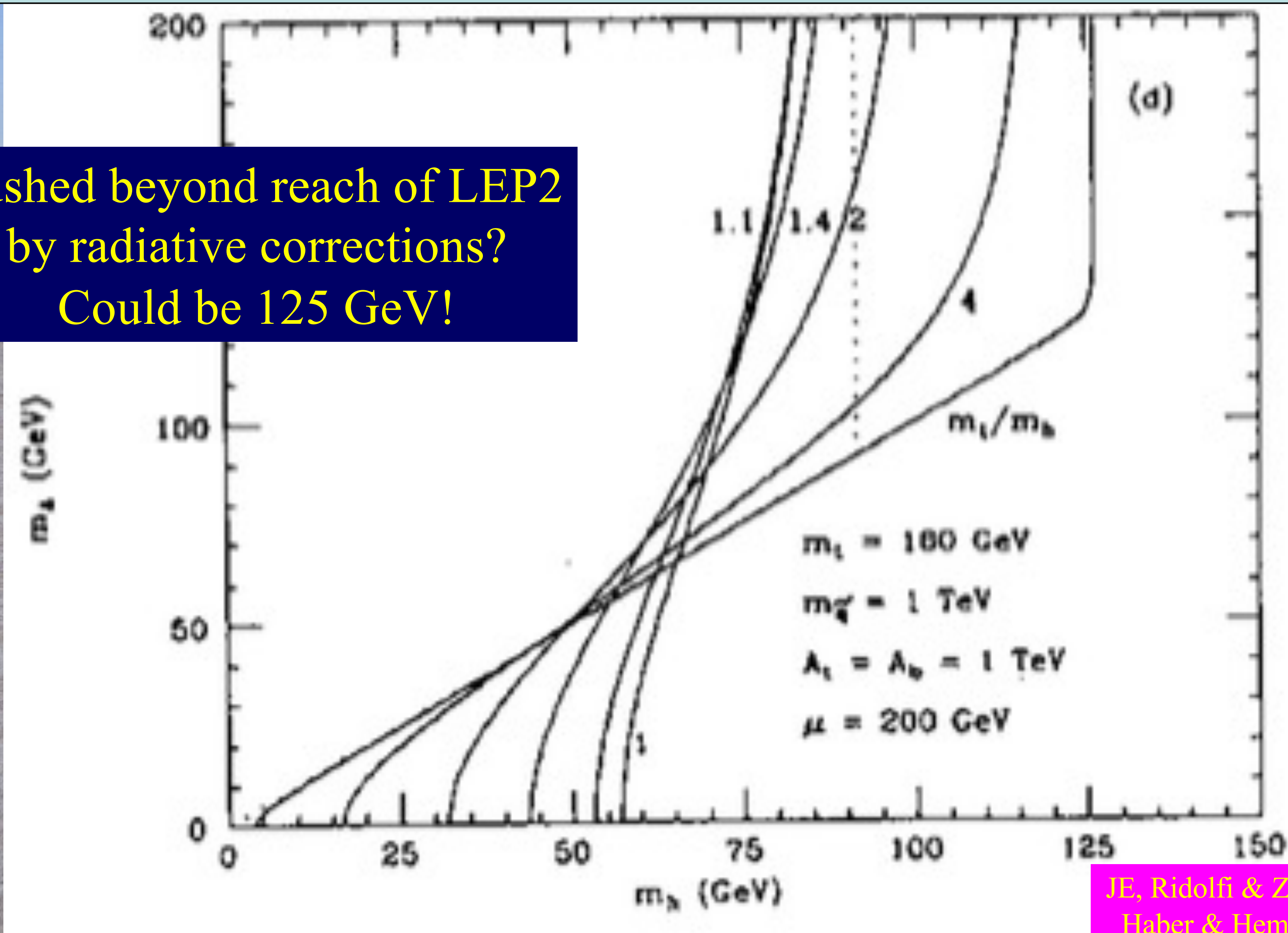
- Difficult before the discovery of the top quark

JE, Fogli & Lisii

1990/1

Higgs Mass in Supersymmetry

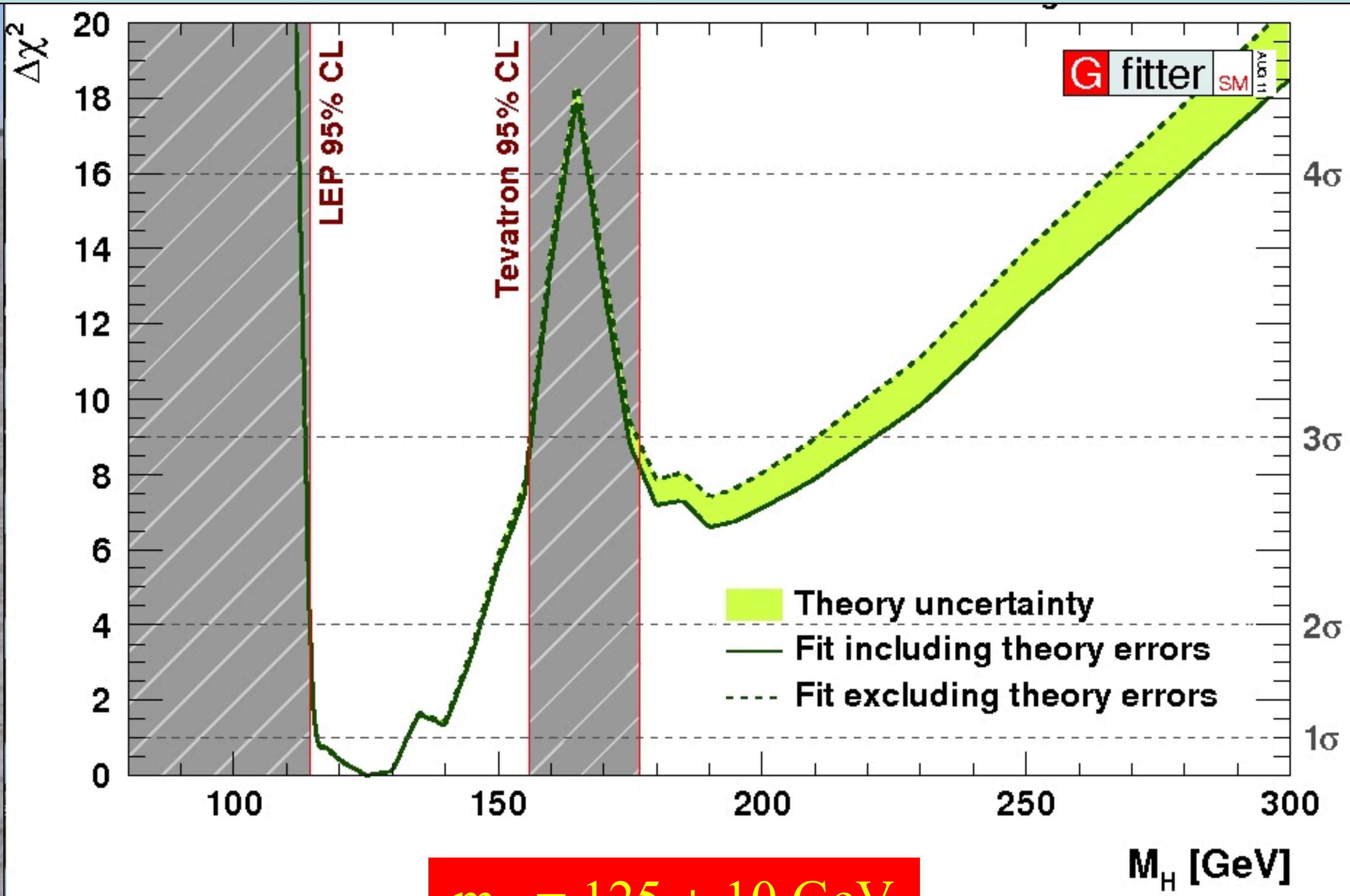
Pushed beyond reach of LEP2 by radiative corrections? Could be 125 GeV!



JE, Ridolfi & Zwirner; Haber & Hempfling

2011

Combining Information from Previous Direct Searches and Indirect Data



$m_H = 125 \pm 10$ GeV

Gfitter collaboration

"… we do not want to encourage big experimental searches for the Higgs boson, but …"

EGN 1975

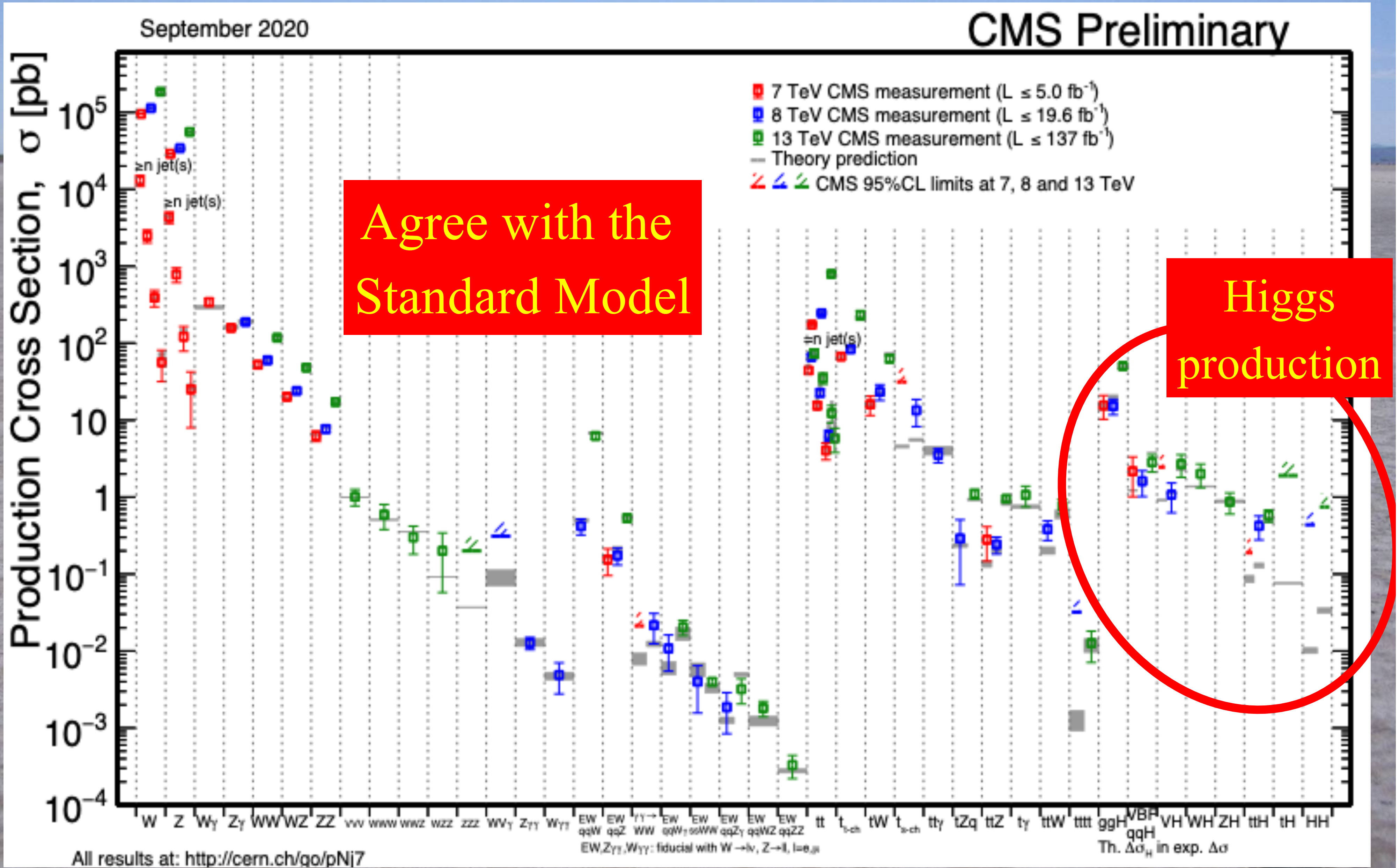
Higgsdependence Day!

The Particle Higgsaw Puzzle

Did the LHC find the missing piece?

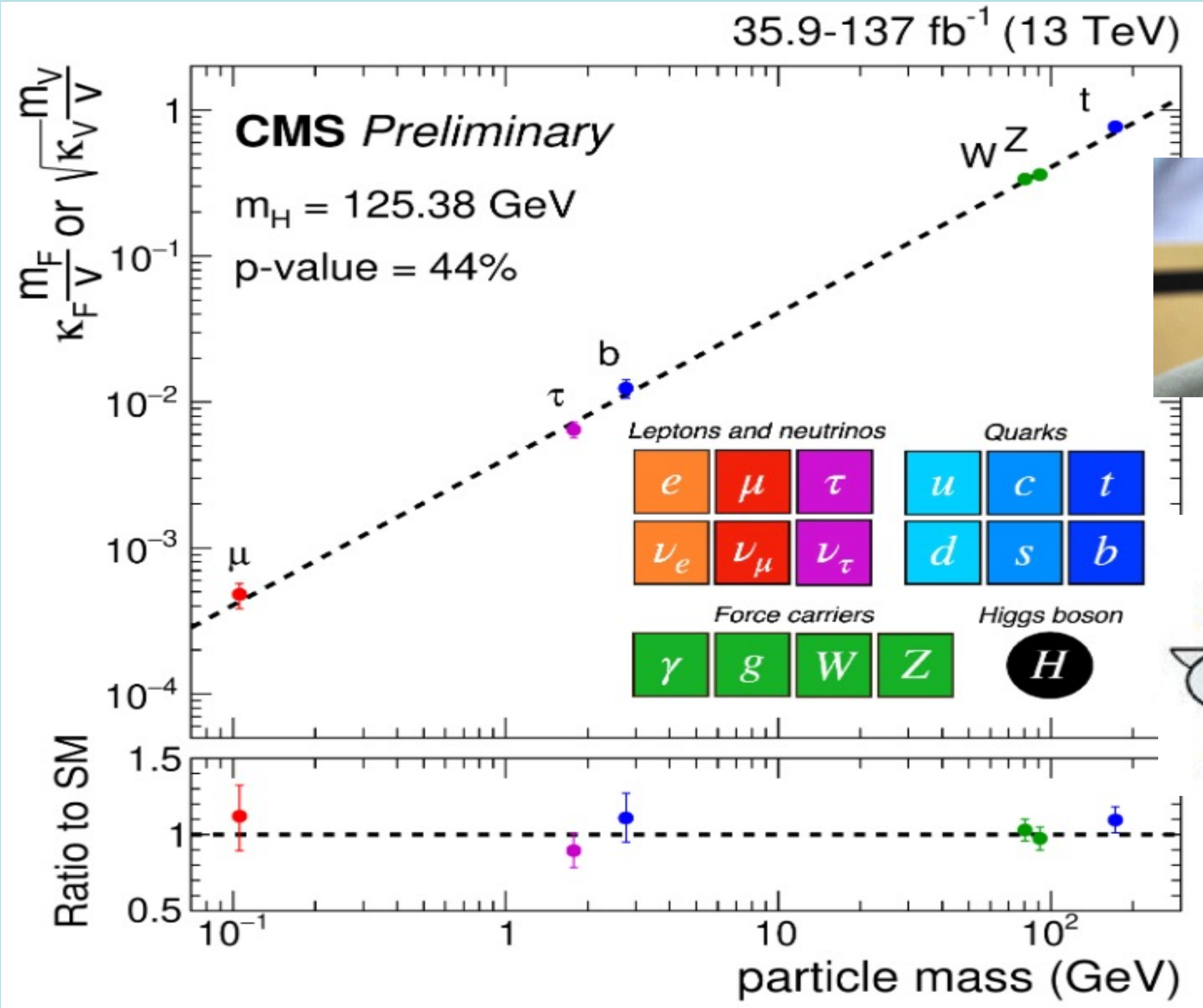
Is it the right shape? Does it have the right size?

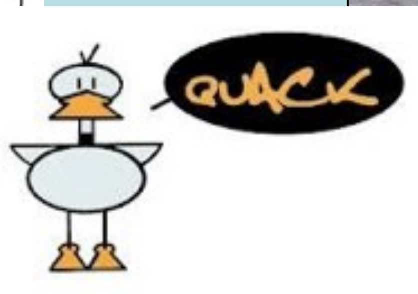
LHC Measurements



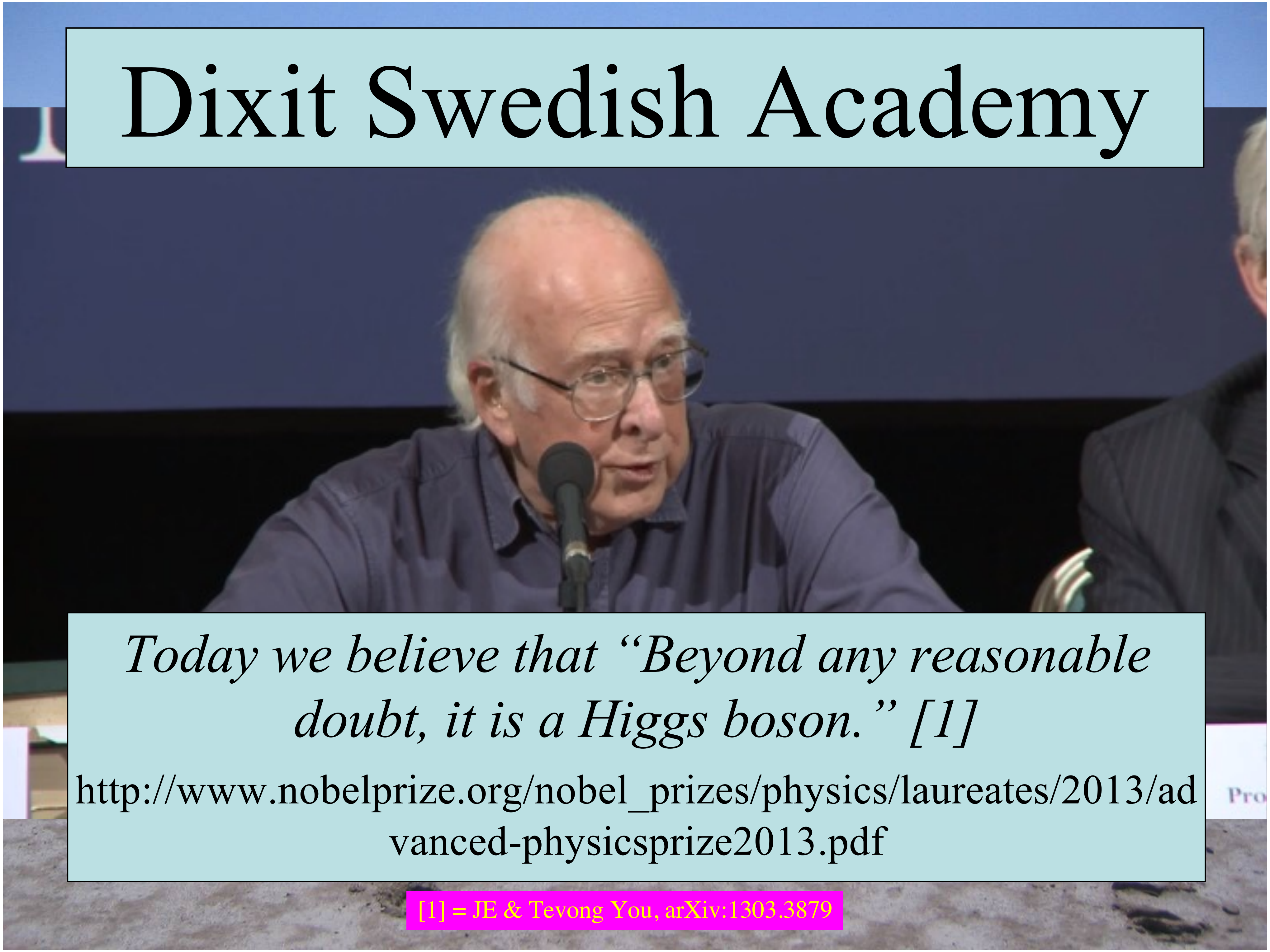
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?





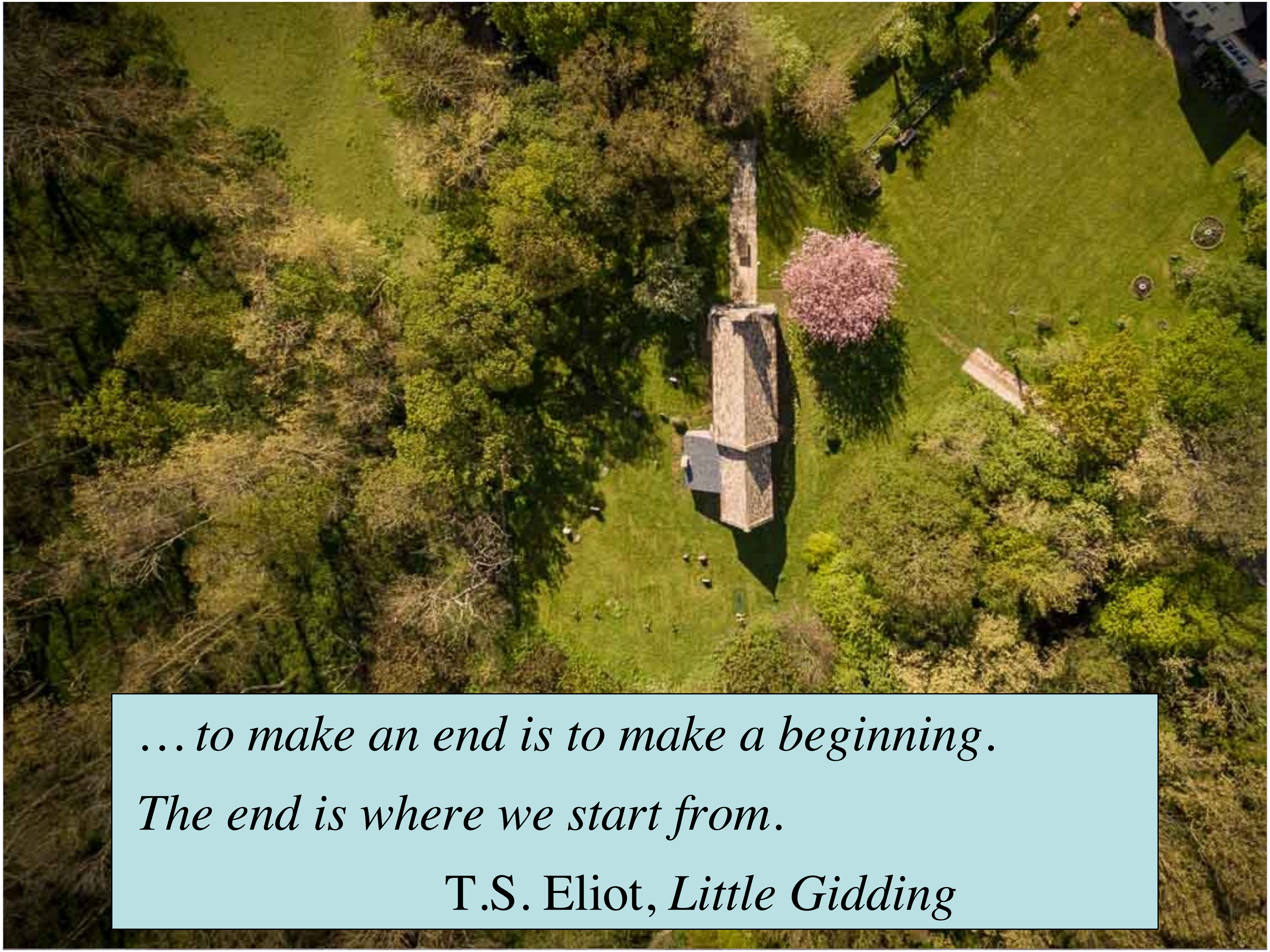
Dixit Swedish Academy



Today we believe that "Beyond any reasonable doubt, it is a Higgs boson." [1]

http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

[1] = JE & Tevong You, arXiv:1303.3879



…to make an end is to make a beginning.

The end is where we start from.

T.S. Eliot, *Little Gidding*

Everything about Higgs is Puzzling

$$\mathcal{L} = yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0 + \ldots$$

- Pattern of Yukawa couplings y:
  - **Flavour problem**
- Magnitude of mass term μ:
  - **Naturalness/hierarchy problem**
- Magnitude of quartic coupling λ:
  - **Stability of electroweak vacuum**
- Cosmological constant term V_0:
  - **Dark energy**

Higher-dimensional interactions?

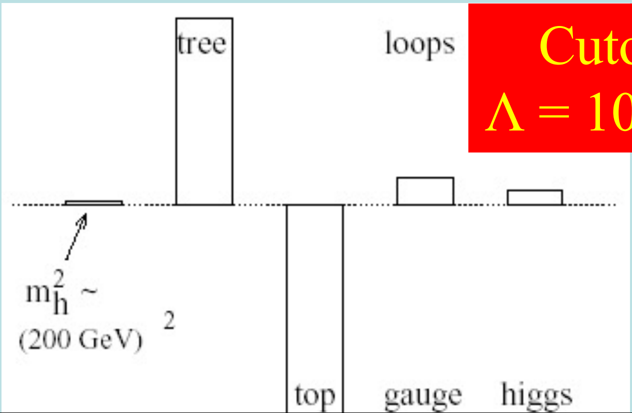
Theoretical worries about the Higgs boson

Elementary Higgs or Composite?

- Higgs field:

  $v = \langle 0|H|0\rangle \neq 0$

- Quantum loop problems
- M_h, v, other masses have quadratic divergences



Cutoff
Λ = 10 TeV

Cut-off $\Lambda \sim$ 1 TeV with **Supersymmetry?**

- Fermion-antifermion condensate?
- Just like π in QCD, Cooper pairs in BCS superconductivity
- Need new 'technicolour' force

- Heavy scalar resonance?
- **(Problems with precision electroweak data)**
- Pseudo-Nambu-Goldstone boson?

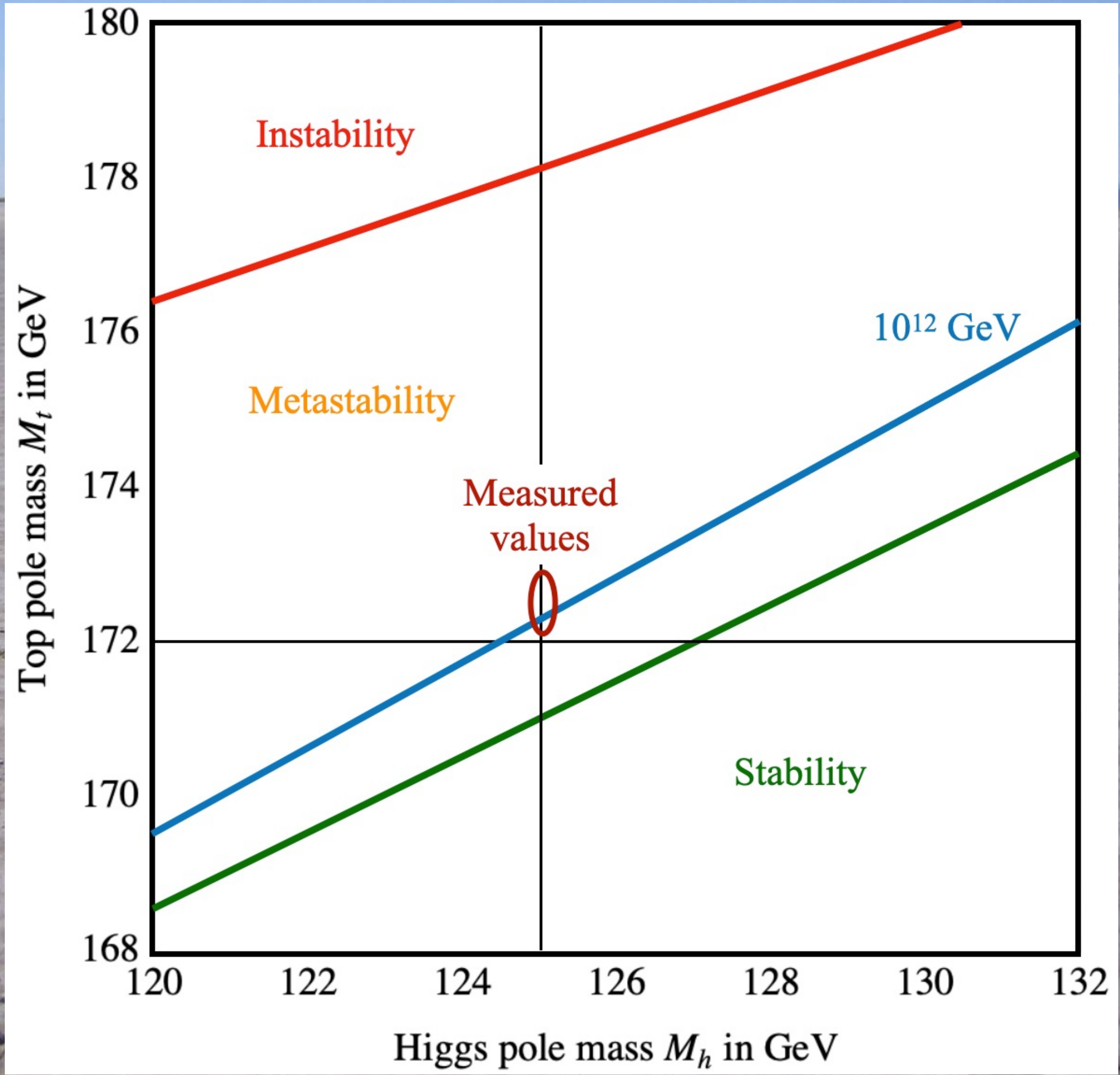
1979

Is "Empty Space" Unstable?

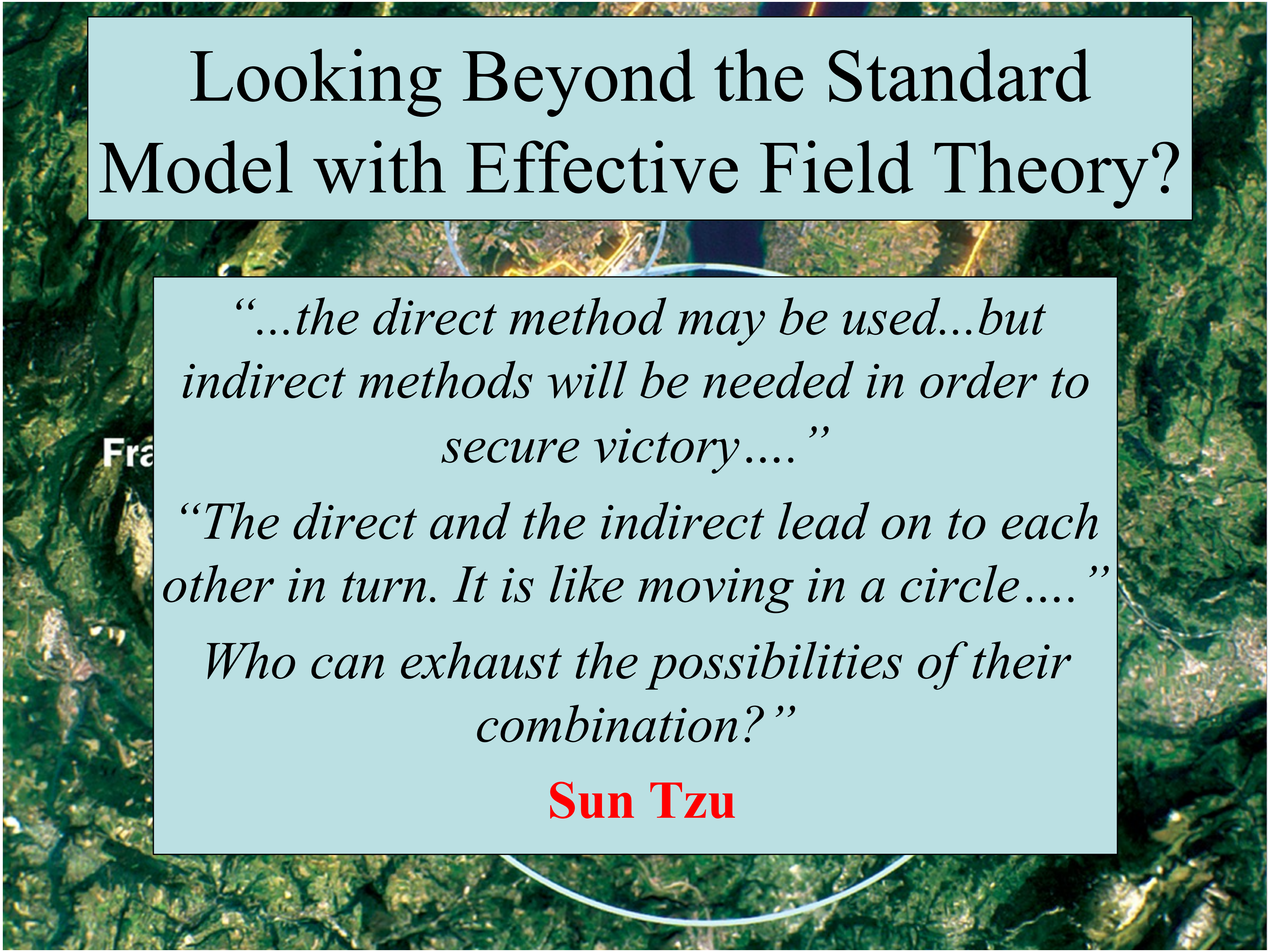
Politizer & Wolfram,
Hung,
Cabibbo, Maiani, Parisi & Petronzio;

Depends on masses of Higgs boson and top quark, strong coupling

Instability scale $\sim 10^{12}$ GeV



Buttazzo et al, arXiv:1307.3536;
Franceschini et al, 2203.17197



Looking Beyond the Standard Model with Effective Field Theory?

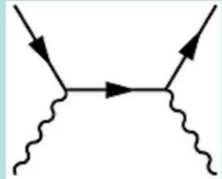
"...the direct method may be used...but indirect methods will be needed in order to secure victory...."

"The direct and the indirect lead on to each other in turn. It is like moving in a circle.... Who can exhaust the possibilities of their combination?"

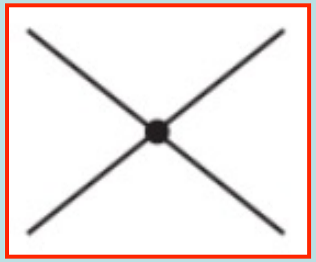
Sun Tzu

Effective Field Theories (EFTs)
a long and glorious History

- 1930's: "Standard Model" of QED had d=4

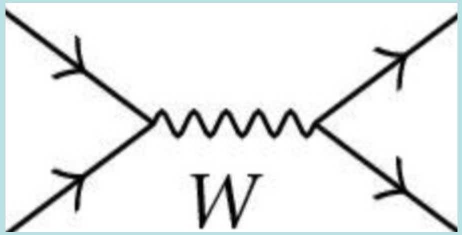


- **Fermi's four-fermion theory of the weak force**

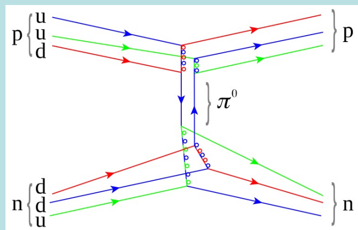


- Dimension-6 operators: form = S, P, V, A, T?
  – Due to exchanges of massive particles?

- V-A ➔ massive vector bosons ➔ gauge theory



- Yukawa's meson theory of the strong N-N force
  – Due to exchanges of mesons? ➔ pions



- Chiral dynamics of pions: (∂π∂π)ππ clue ➔ QCD

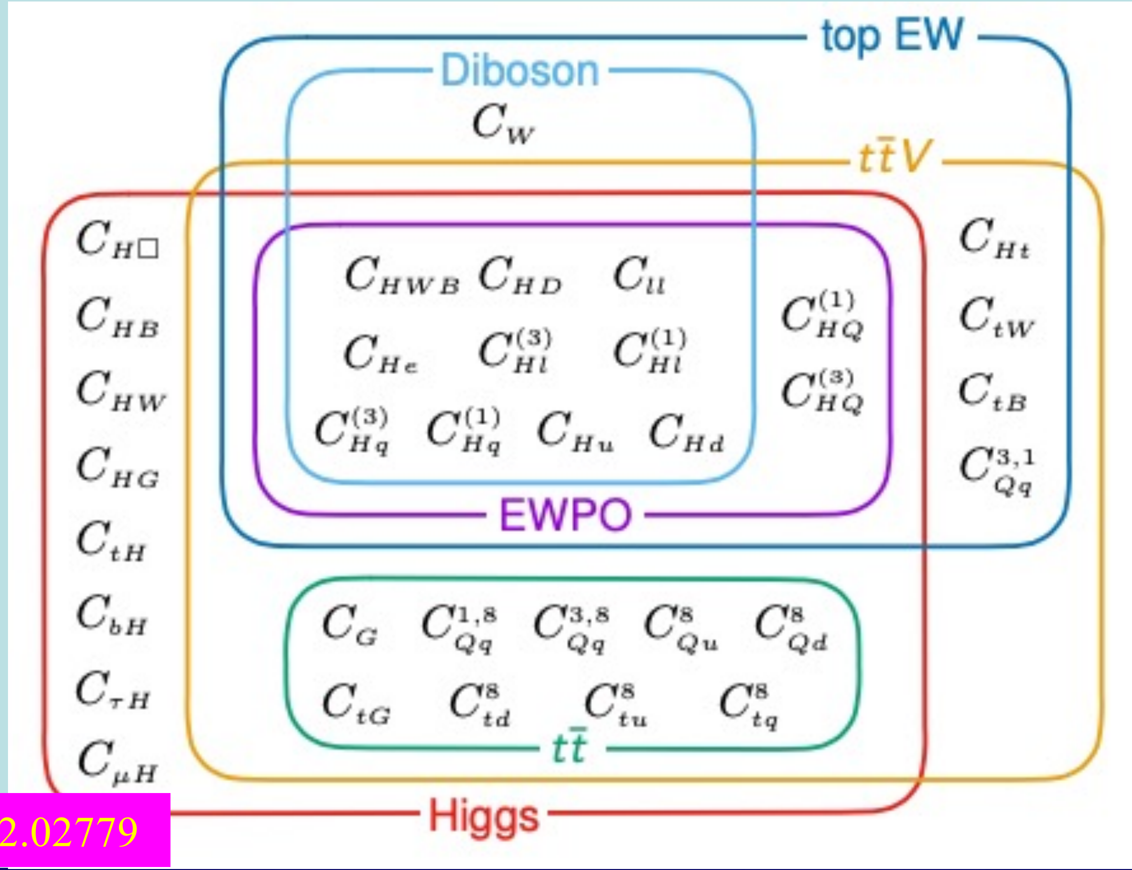
Standard Model Effective Field Theory

a more powerful way to analyze the data

- Assume the Standard Model Lagrangian is correct (quantum numbers of particles) but incomplete
- Look for additional interactions between SM particles due to exchanges of heavier particles
- Analyze Higgs data together with electroweak precision data and top data
- Most efficient way to extract largest amount of information from LHC and other experiments
- **Model-independent way to look for physics beyond the Standard Model (BSM)**

Global SMEFT Fit
to Top, Higgs, Diboson, Electroweak Data

- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level

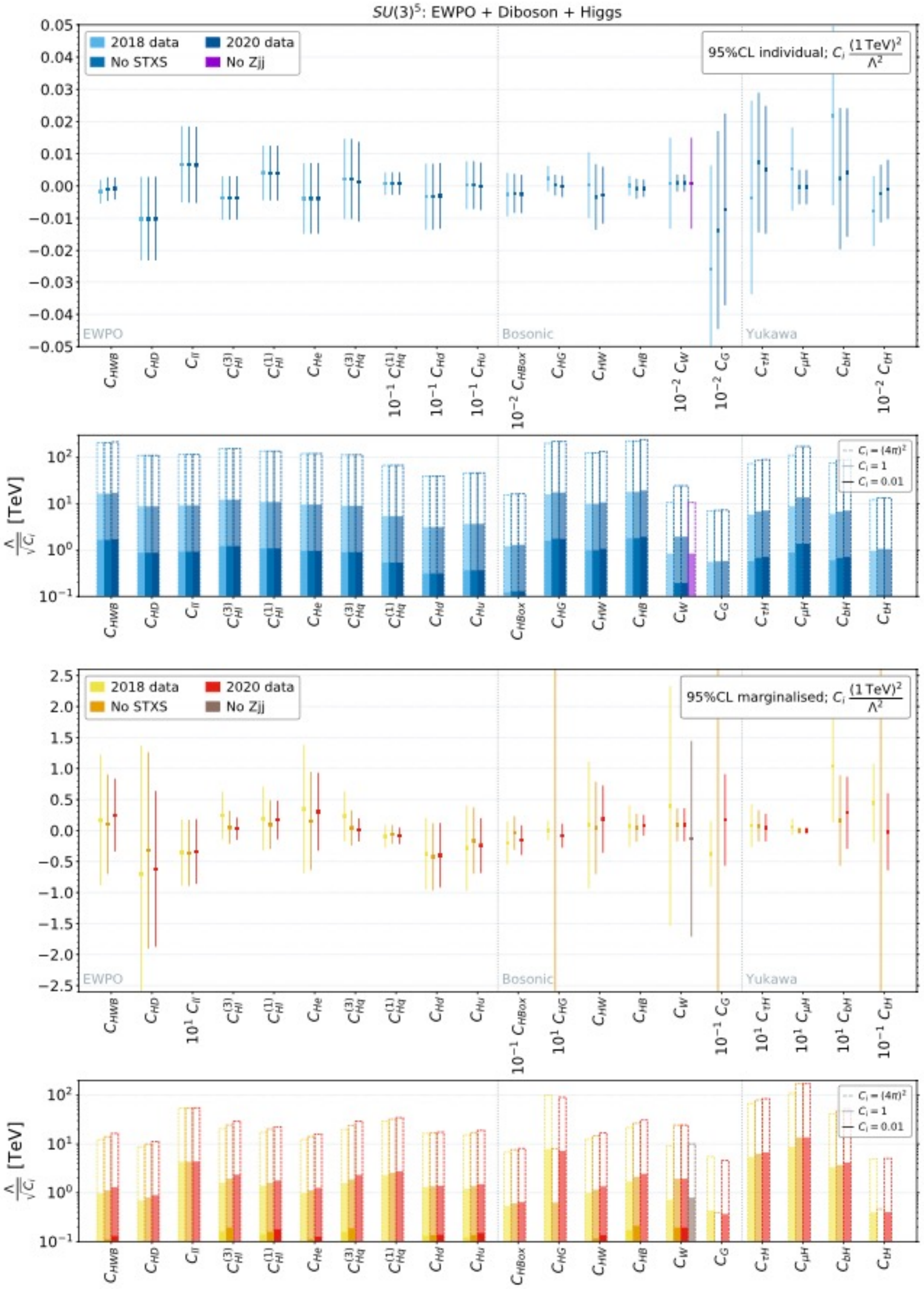


JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Dimension-6 Constraints with Flavour-Universal $SU(3)^5$ Symmetry

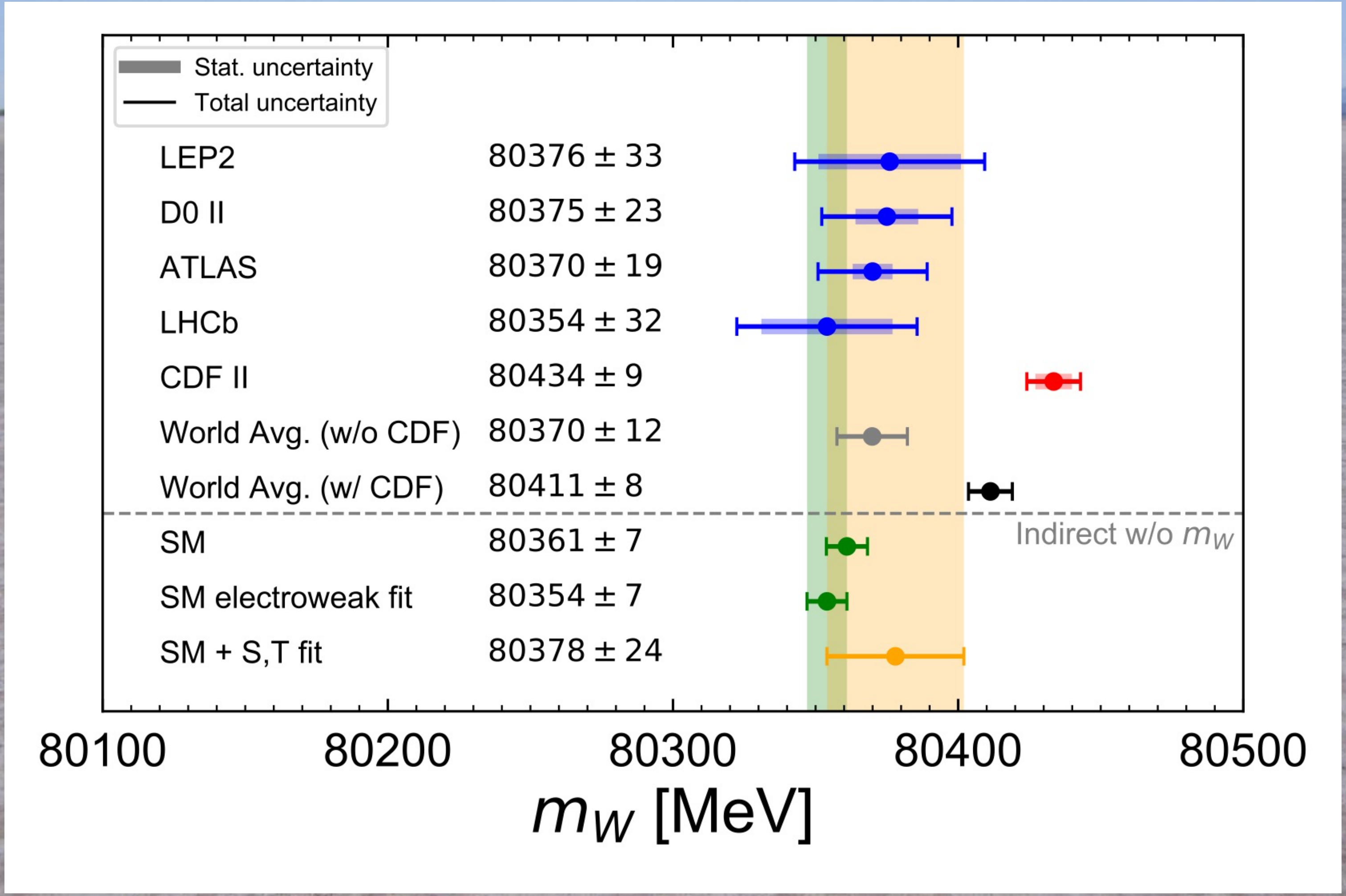
- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779



CDF Measurement of m_W

compared with previous measurements

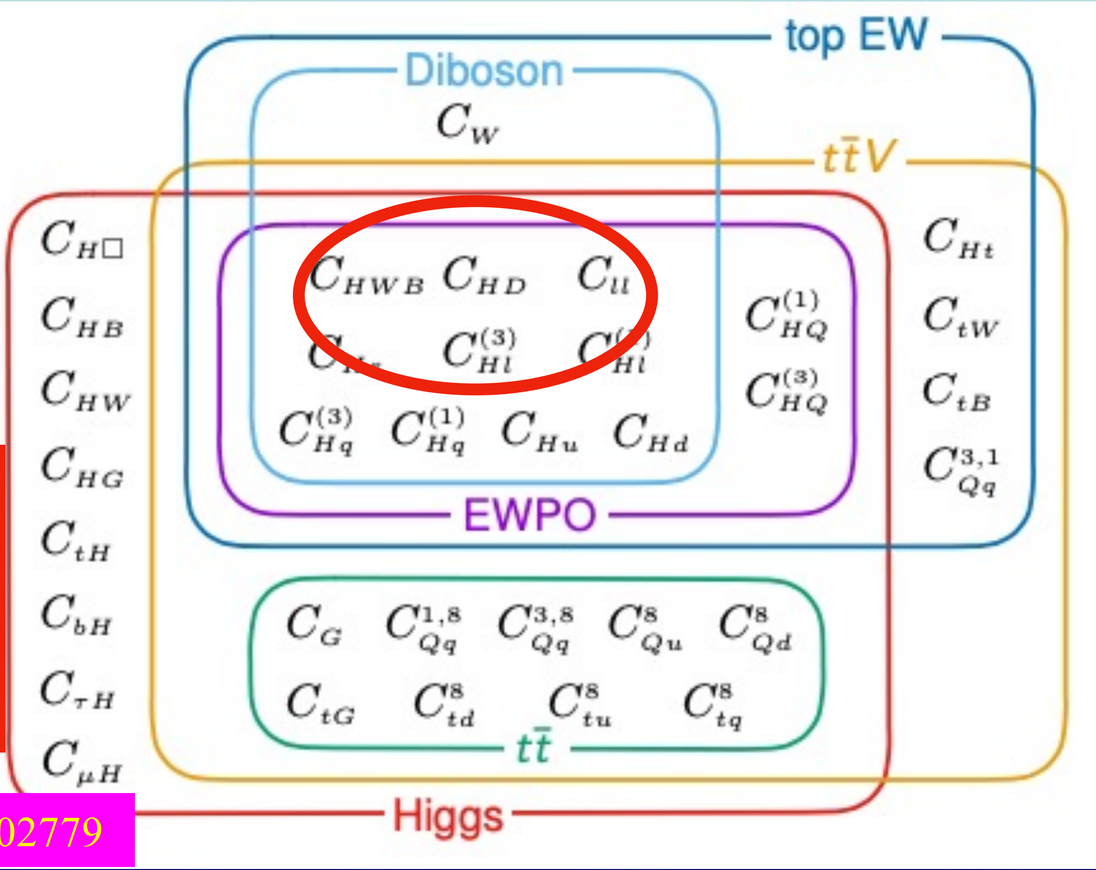


- Tension: 7-σ discrepancy with Standard Model?

Global SMEFT Fit
to Top, Higgs, Diboson, Electroweak Data

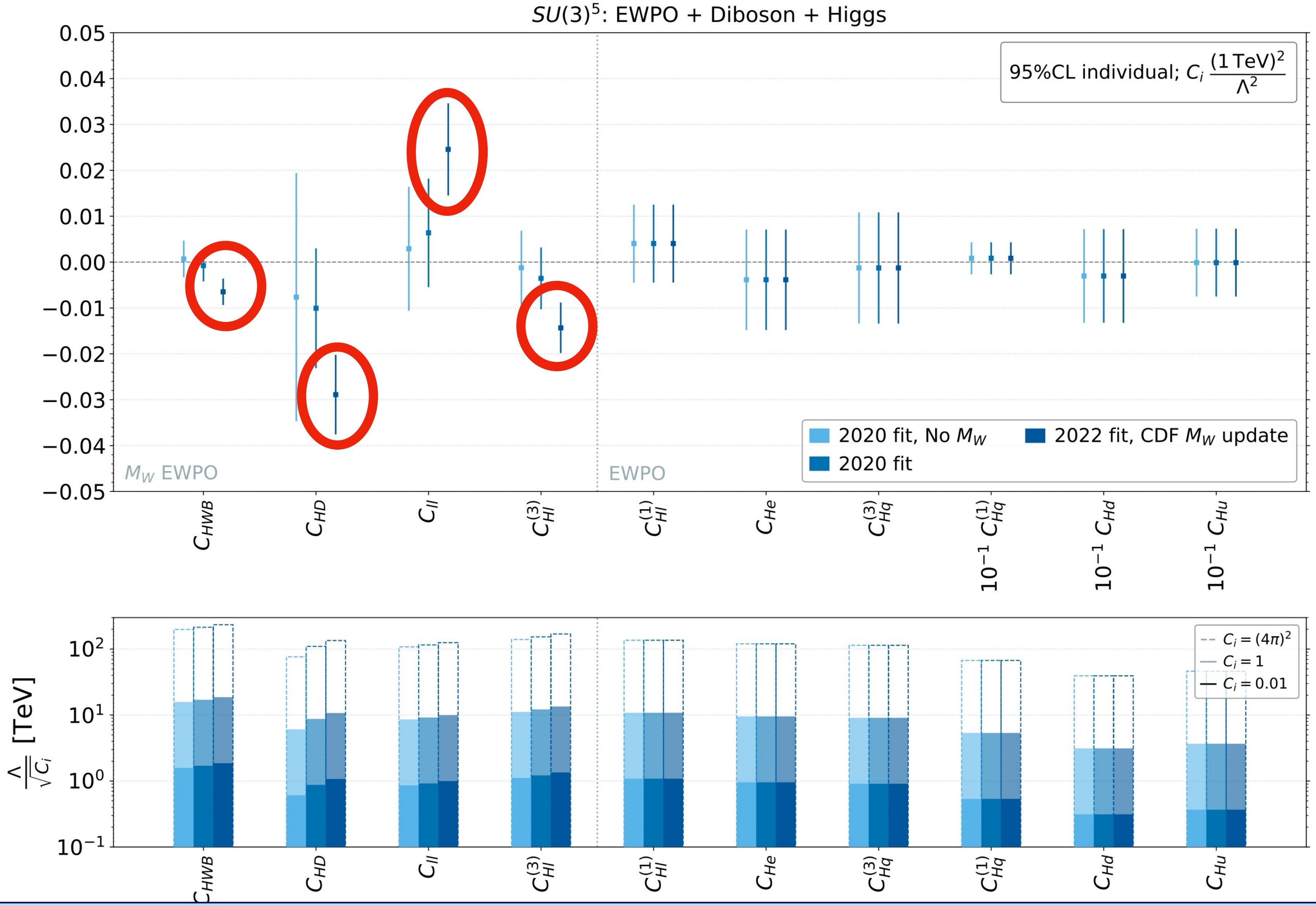
- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level

Positive contributions to mw



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

SMEFT Fit with the Mass of the W Boson



- Non-zero coefficients for any of four operators can fit W mass

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Single-Field Extensions of the Standard Model

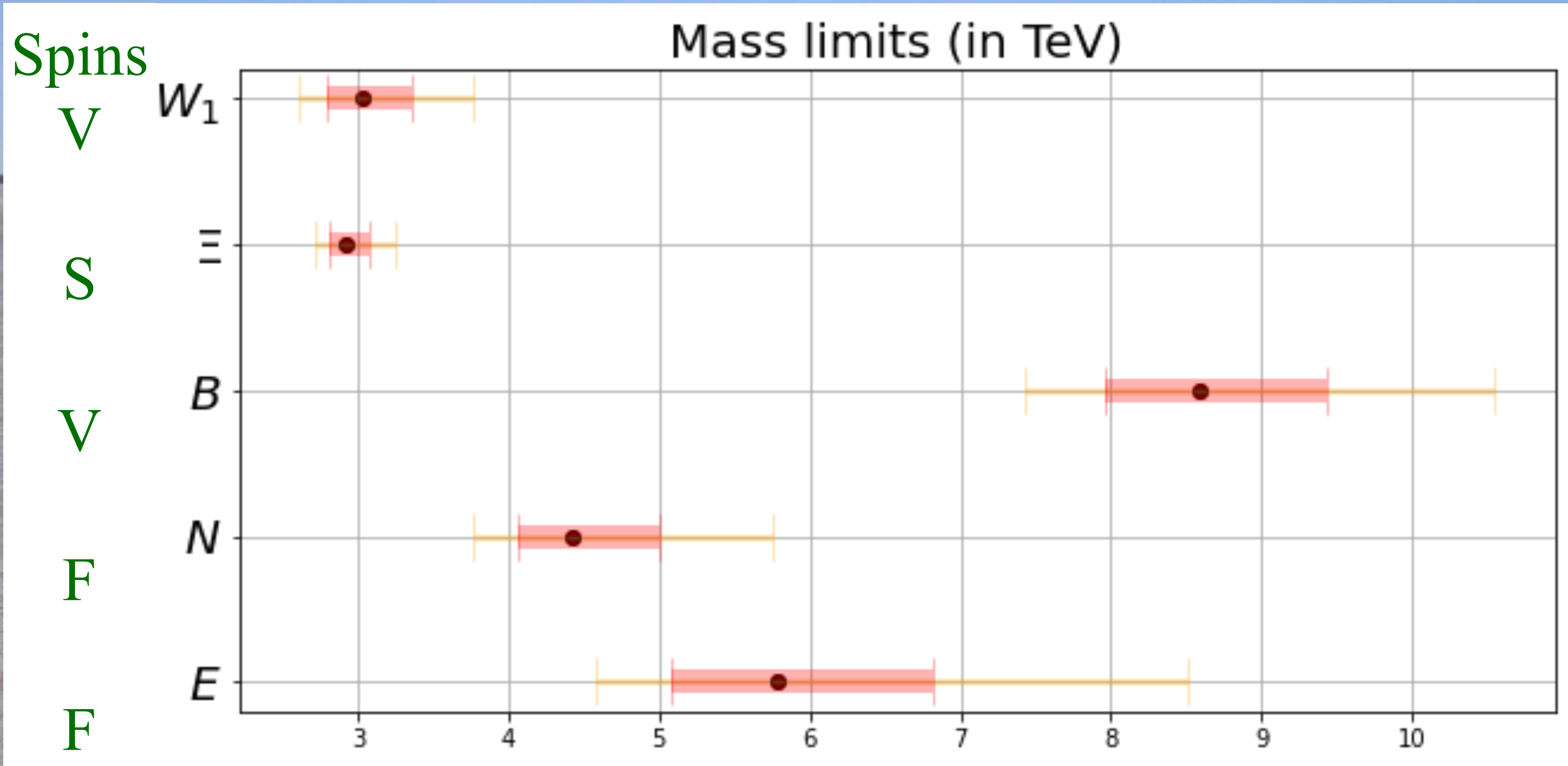
Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	[illegible]	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
B_1	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
W	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
W_1	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$

Spin zero

Vector

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Models Fitting the Mass of the W Boson



- 68 and 95% CL ranges of masses assuming unit coupling
- Masses proportional to couplings
- Large masses consistent with SMEFT approximation

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Higgstorical Summary

- Speculation
- Hypothesis
- Theory
- Search
- Discovery
- Building-block

Repeat?

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260