Higgs, Top & Beyond

Why the Higgs boson?
What can the Higgs & top tell us?
Looking beyond them

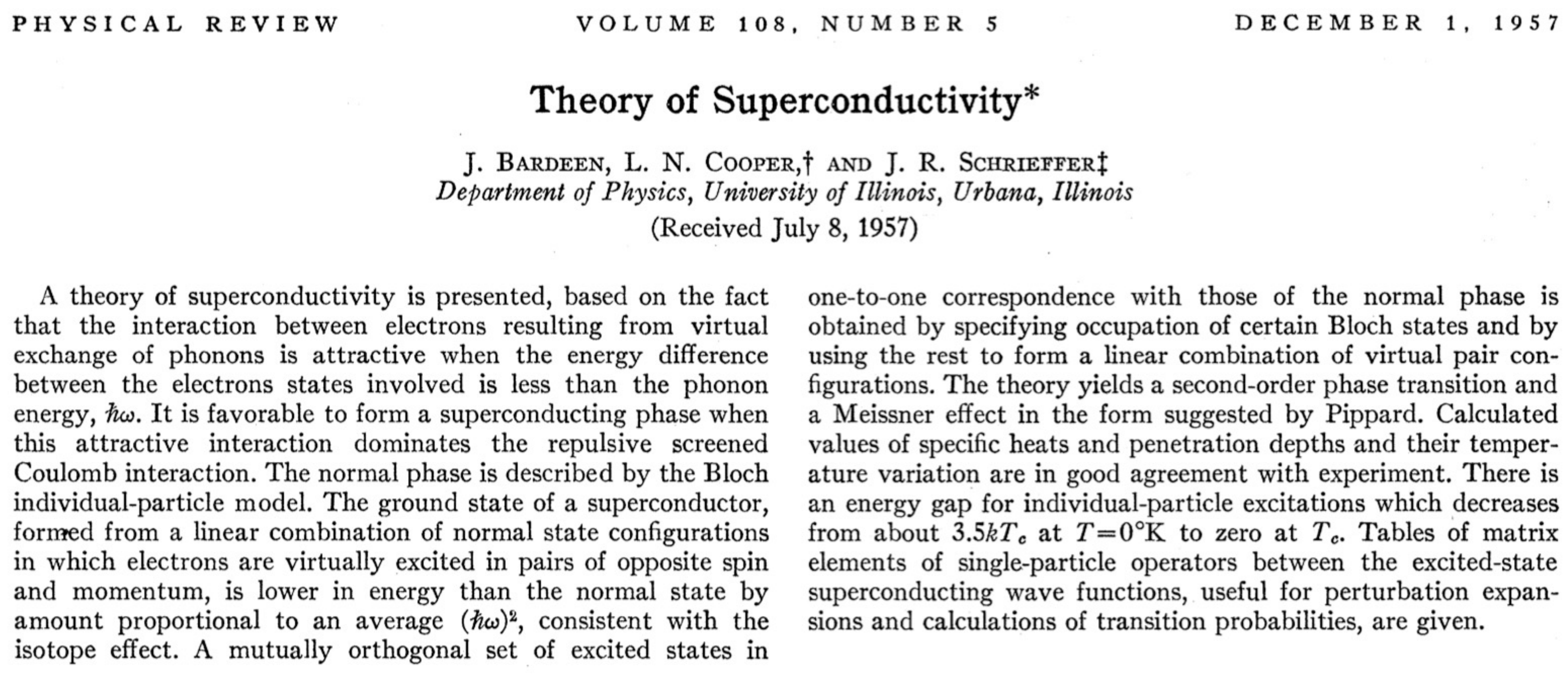
John Ellis

KING'S College LONDON

Remember the lectures by Jonas Lindert

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‡
Department of Physics, University of Illinois, Urbana, Illinois

(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 $T=0°\text{K}$ 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

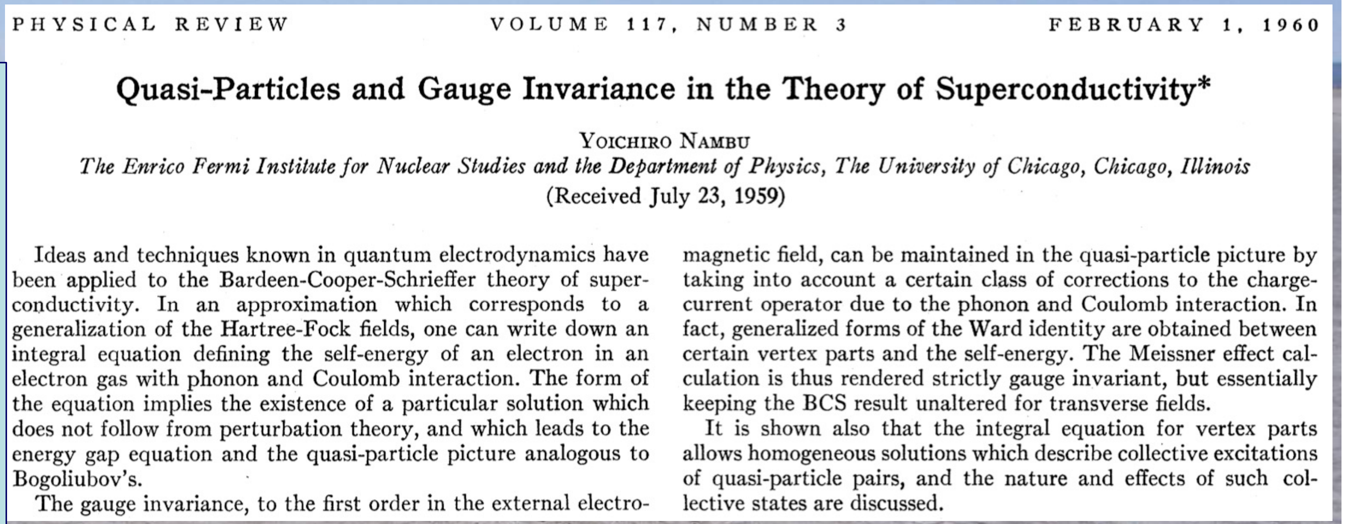
Lowest-energy state has charge density: breaks/hides $\text{U}(1)_{\text{em}}$

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*

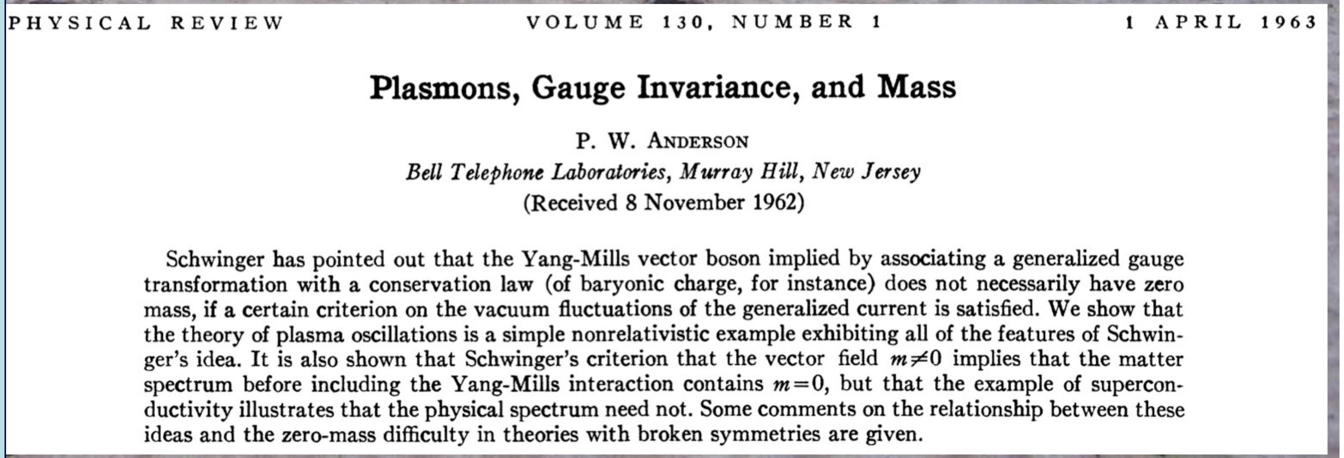
YOICHIRO NAMBU
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois

(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

P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received 8 November 1962)

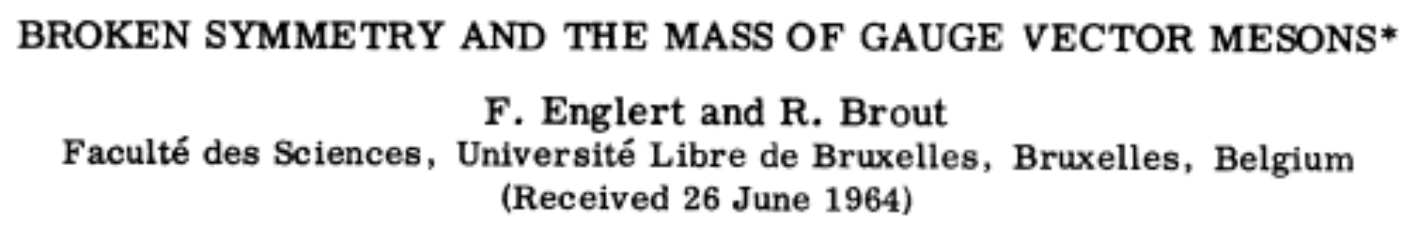
Schwinger has pointed out that the Yang-Mills vector boson implied by associating a generalized gauge transformation with a conservation law (of baryonic charge, for instance) does not necessarily have zero mass, if a certain criterion on the vacuum fluctuations of the generalized current is satisfied. 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.

1964

The Founders

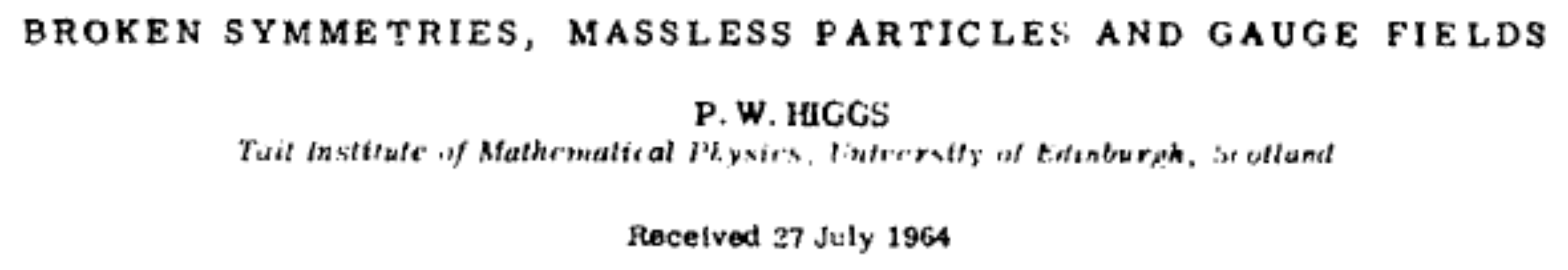
1964

The (GN)AEBHGHKMP Mechanism



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

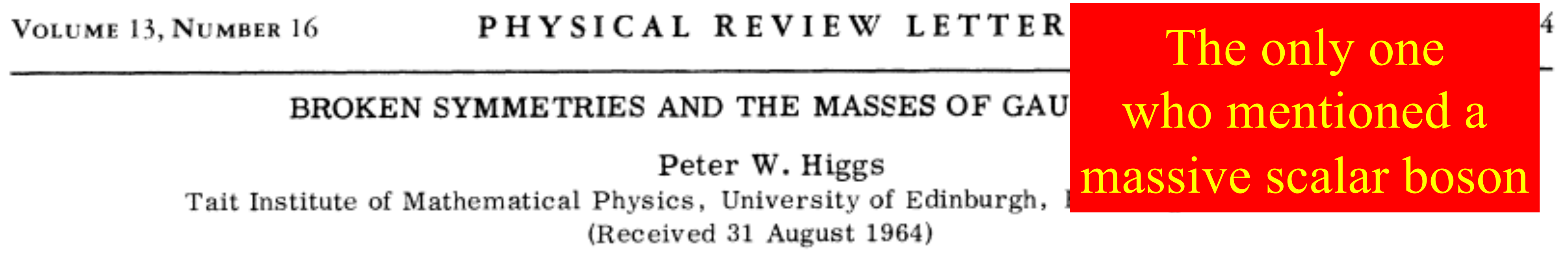
F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)



BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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

Received 27 July 1964

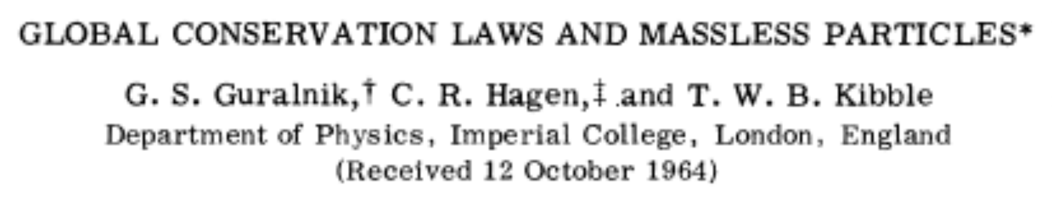


VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTER

BROKEN SYMMETRIES AND THE MASSES OF GAU

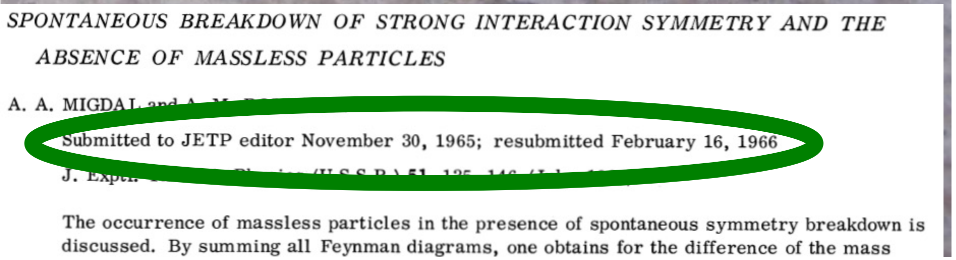
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh,
(Received 31 August 1964)

The only one who mentioned a massive scalar boson



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

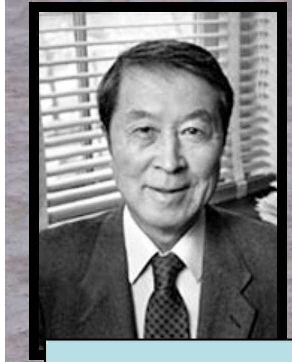
A. A. MIGDAL

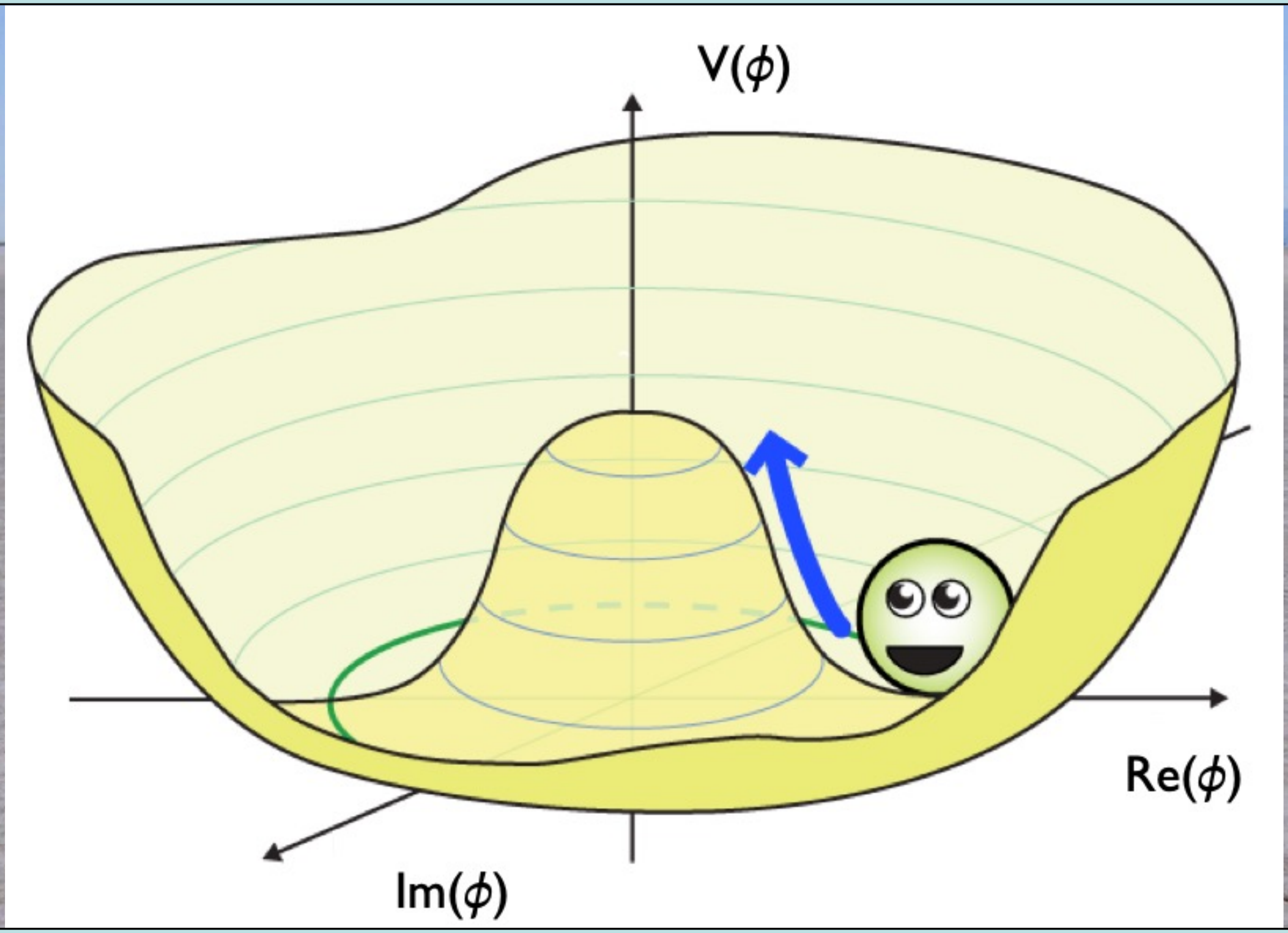
Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966

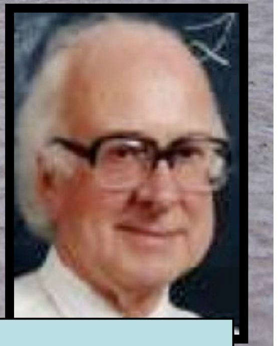
J. Exptl.

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

Nambu EB, H, GHK & Higgs



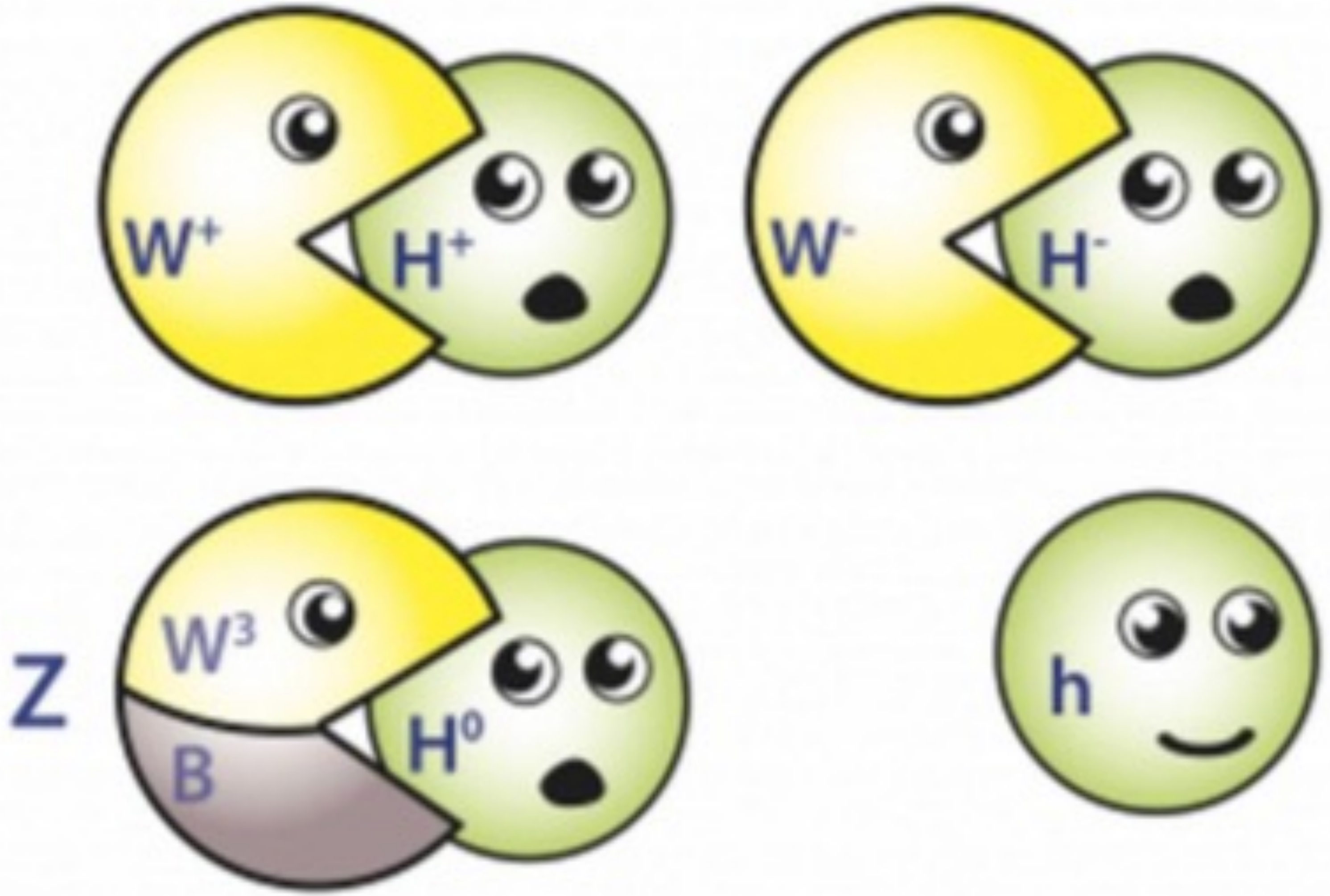




Spontaneous symmetry breaking: massless Nambu-Goldstone boson‘eaten’ by massless gauge boson

Accompanied by massive scalar particle

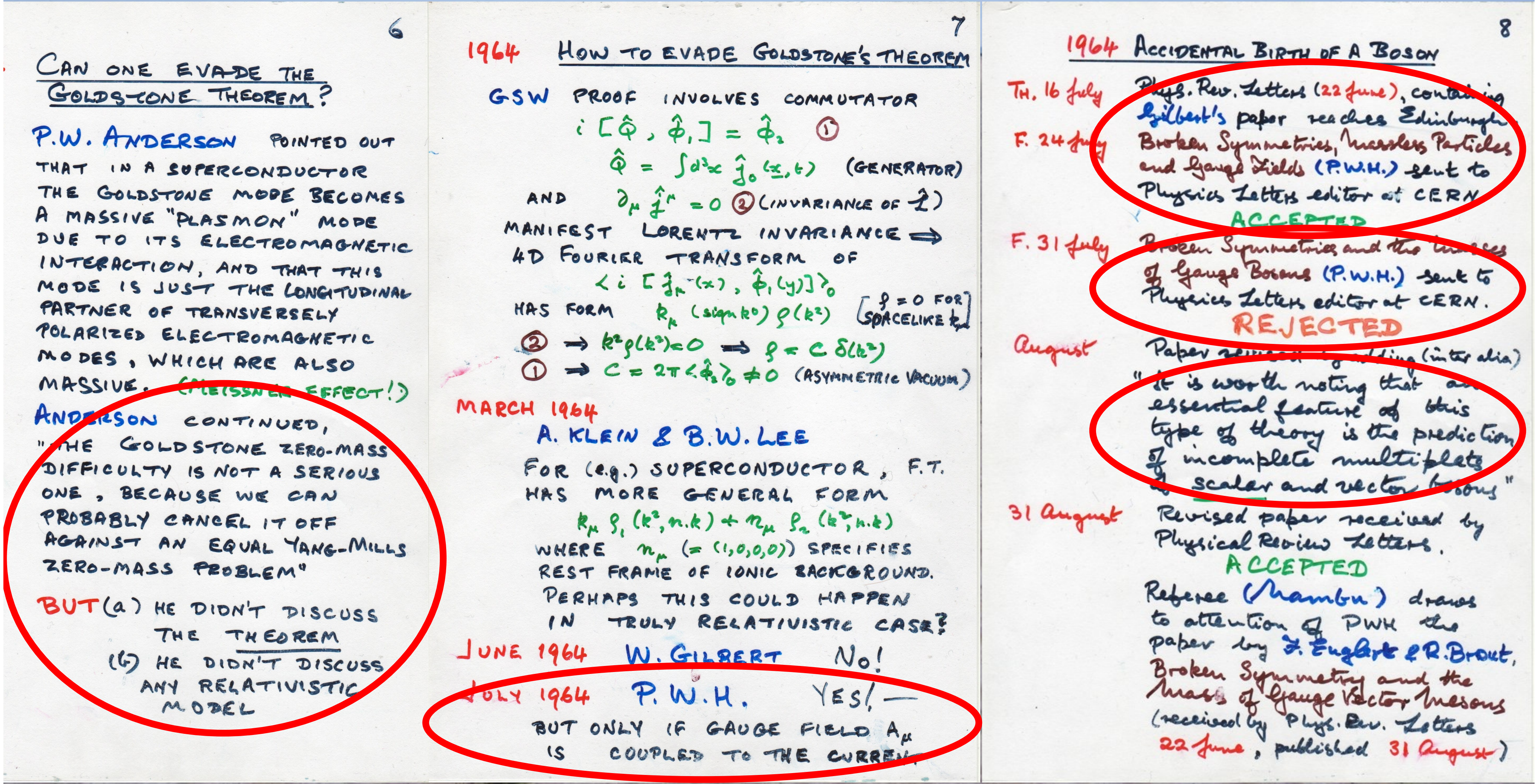
Hungry for Higgs



(FLIP TANEDO / QUANTUM DIARIES)

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 THEOREM
(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 ⟹ 4D FOURIER TRANSFORM OF

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

HAS FORM $k_\mu(\mathrm{sign}\,k^0)\rho(k^2)$ [$\rho = 0$ 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"

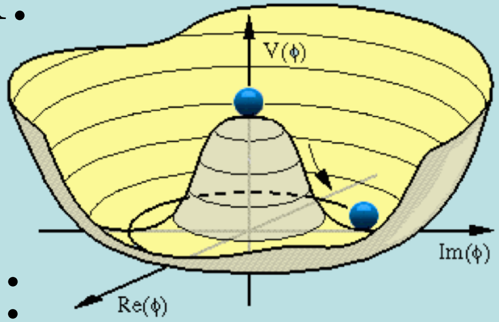
31 August — Revised paper received by Physical Review Letters.
ACCEPTED

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)

The Nambu-Goldstone Mechanism

- Postulated effective scalar potential:

$$V[\phi] = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

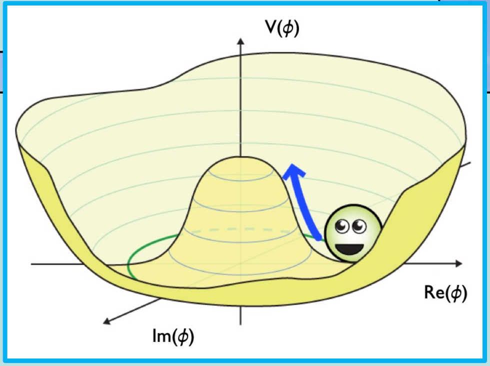


- Minimum energy at non-zero value:

$$\phi_0 =< 0|\phi|0 >= \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ +v \end{pmatrix} \quad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

- Components of scalar field: $\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma(x))e^{i\pi(x)}$
- π massless, σ massive: $m_H^2 = 2\mu^2 = 2\lambda v$

Abelian EBH Mechanism



- Lagrangian with U(1) gauge boson:

$$\mathcal{L} = (D_\mu\phi)^+(D^\mu\phi) - V(|\phi|) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad D_\mu = \partial_\mu - ieA_\mu$$

- Gauge transformation

$$\phi'(x) = e^{i\alpha(x)}\,\phi(x) = e^{i\alpha(x)}\,e^{i\theta(x)}\eta(x)$$

$$A'_\mu(x) = A_\mu(x) + \frac{1}{e}\partial_\mu\alpha(x)$$

- Choose $\alpha(x) = -\theta(x)$: $\quad \phi'(x) = \eta(x)$
- Rewrite Lagrangian: $\mathcal{L} = |(\partial - ieA'_\mu)\eta|^2 - V(\eta) - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu}$

$$\begin{aligned}\mathcal{L} &= |(\partial_\mu - ieA'_\mu)(v + \tfrac{1}{\sqrt{2}}H)|^2 - \tfrac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - V \\ &= \underbrace{-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + v^2e^2\,A'_\mu A'^\mu}_{\text{massive A-field, } m_A \sim ev} + \underbrace{\frac{1}{2}[(\partial_\mu H)^2 - m_H^2 H^2]}_{\text{neutral scalar, } m_H \neq 0} + \cdots\end{aligned}$$

Think of a Snowfield

Skier moves fast:
Like particle without mass
e.g., photon = particle of light

Snowshoer sinks into snow,
moves slower:
Like particle with mass
e.g., electron

Hiker sinks deep,
moves very slowly:
Particle with large mass

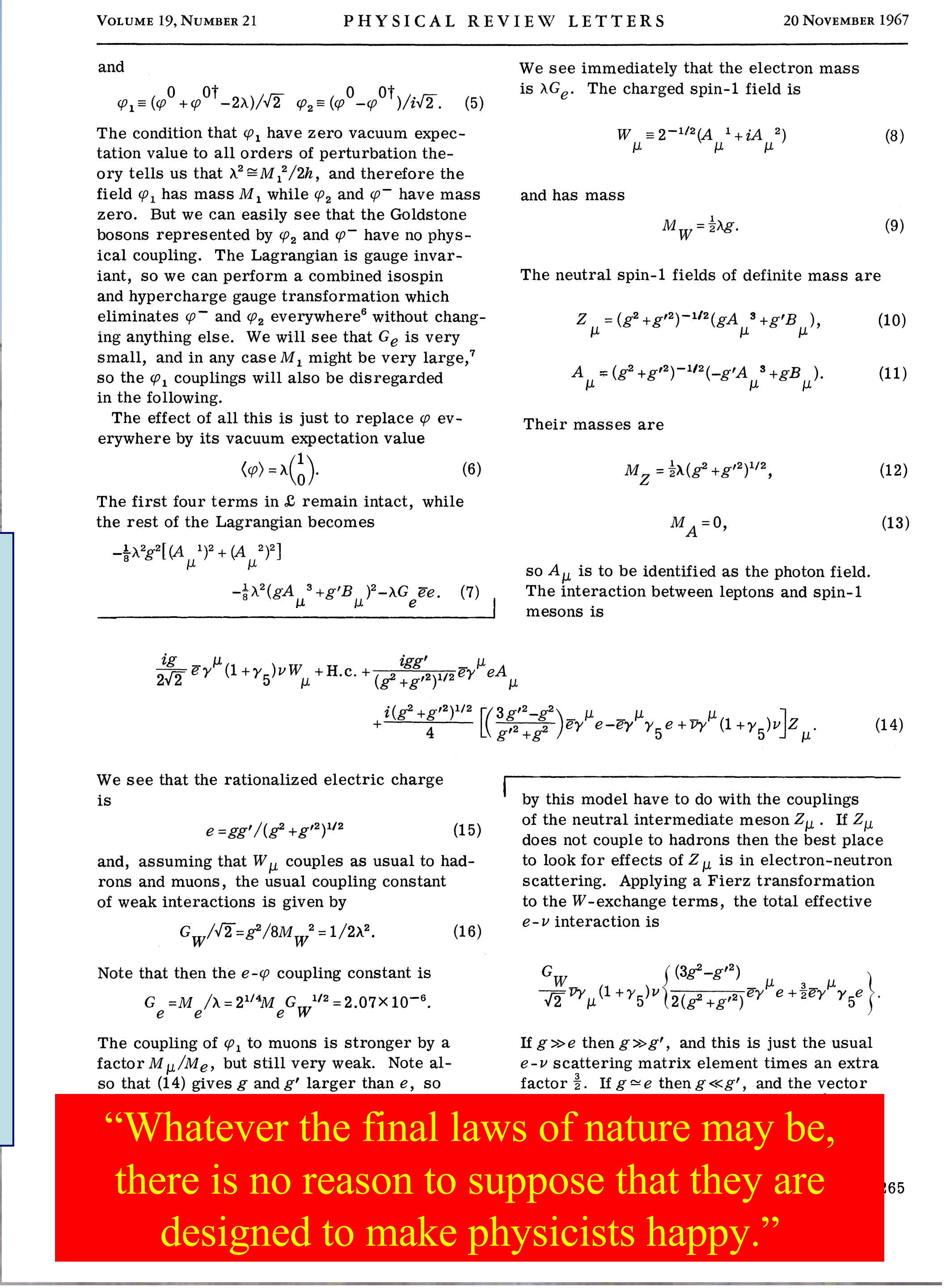
**The LHC discovered
the snowflake:
The Higgs Boson**

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

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

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

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

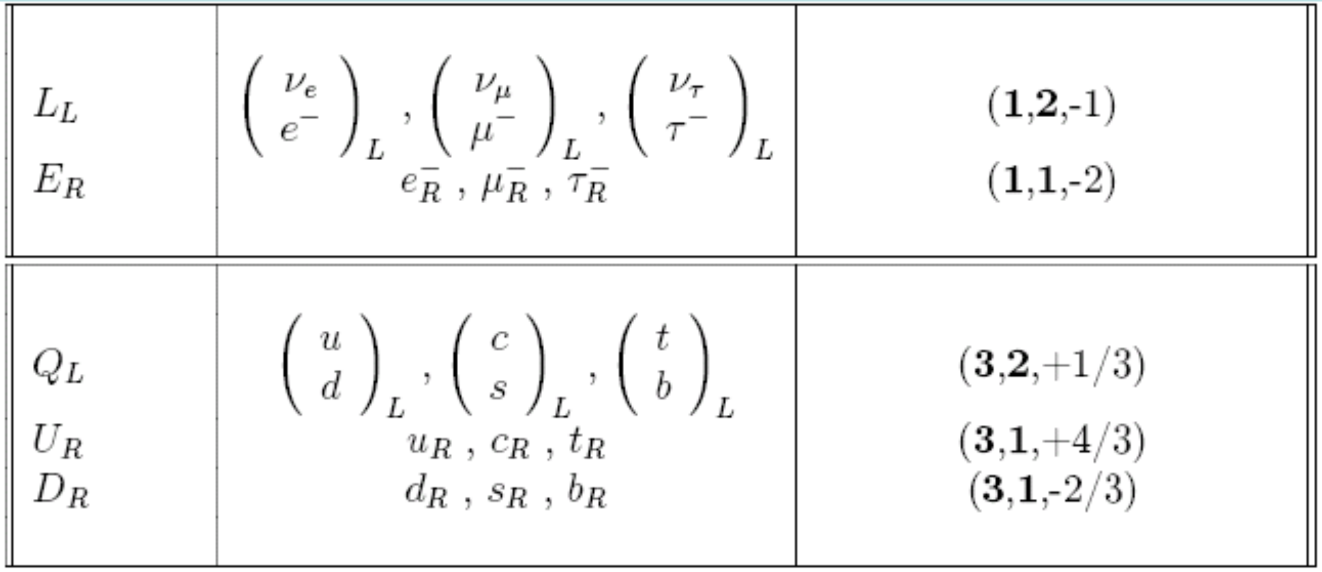
$$\frac{G_W}{\sqrt{2}}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu\left\{\frac{(3g^2-g'^2)}{2(g^2+g'^2)}\bar{e}\gamma^\mu e + \tfrac{3}{2}\bar{e}\gamma^\mu\gamma_5 e\right\}.$$

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

"Whatever the final laws of nature may be, there is no reason to suppose that they are designed to make physicists happy."

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	$(\mathbf{3},\mathbf{1},-2/3)$

- Lagrangian:

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

gauge interactions

matter fermions

Yukawa interactions

Higgs potential

Tested < 0.1% before LHC

Testing now in progress

Parameters of the Standard Model

- Gauge sector:
  - 3 gauge couplings: g_3, g_2, g'
  - 1 strong CP-violating phase
- Yukawa interactions:
  - 3 charged-lepton masses
  - 6 quark masses
  - 4 CKM angles and phase
- Higgs sector:
  - 2 parameters: μ, λ
- **Total: 19 parameters**

Unification?

Flavour?

Mass?

The Standard Model Lagrangian

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \quad ,$$

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D^L_\mu Q_L + \bar{q}_R i\gamma^\mu D^R_\mu q_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R$$

$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu}$$

✓ Experiment: accuracy < %

$$\mathcal{L}_H = (D^L_\mu \phi)^\dagger (D^{L\mu} \phi) - V(\phi)$$

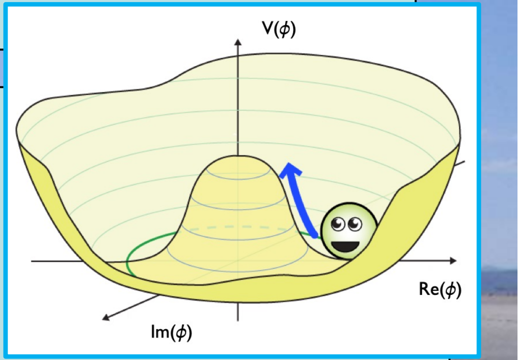
$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q^d_R + y_u \bar{Q}_L \phi^c q^u_R + y_L \bar{L}_L \phi l_R +$$

No direct evidence until July 4, 2012

$$D^L_\mu = \partial_\mu - igW^a_\mu T^a - iYg' B_\mu \quad , \quad D^R_\mu = \partial_\mu - iYg' B_\mu$$

$$V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4 \quad .$$

Masses for SM Gauge Bosons



- Kinetic terms for SU(2) and U(1) bosons:

$$\mathcal{L} = -\frac{1}{4}\, G^i_{\mu\nu} G^{i\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

where $G^i_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + ig\epsilon_{ijk} W^j_\mu W^k_\nu$ $F_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu$

- Kinetic term for Higgs field:

$$\mathcal{L}_\phi = -|D_\mu \phi|^2 \quad D_\mu \equiv \partial_\mu - i\, g\, \sigma_i\, W^i_\mu - i\, g'\, Y\, B_\mu$$

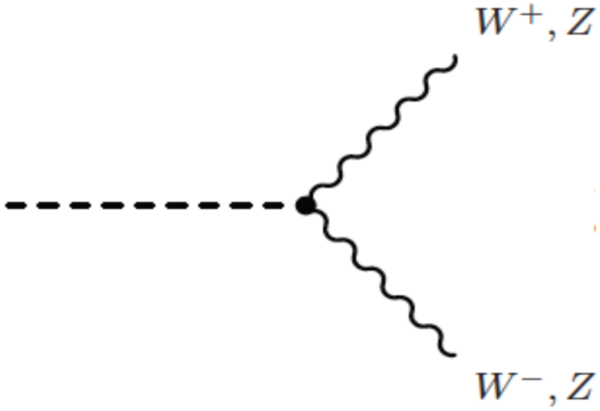
- Expanding around vacuum: $\phi =< 0|\phi|0 > + \hat{\phi}$

$$\mathcal{L}_\phi \ni -\frac{g^2 v^2}{2}\; W^+_\mu\, W^{\mu-} - g'^2\, \frac{v^2}{2}\, B_\mu\, B^\mu + g\, g' v^2\, B_\mu\, W^{\mu 3} - g^2\, \frac{v^2}{2}\, W^3_\mu\, W^{\mu 3}$$

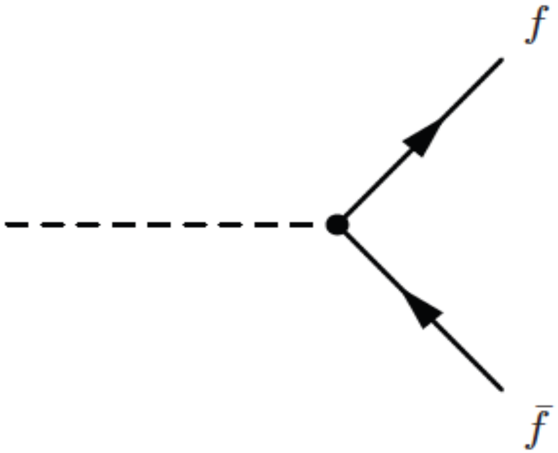
- Boson masses:

$$m_{W^\pm} = \frac{gv}{2} \quad Z_\mu = \frac{g W^3_\mu - g' B_\mu}{\sqrt{g^2 + g'^2}} \;:\; m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v\;; \quad A_\mu = \frac{g' W^3_\mu + g B_\mu}{\sqrt{g^2 + g'^2}} \;:\; m_A = 0$$

Higgs Boson Couplings



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



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

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

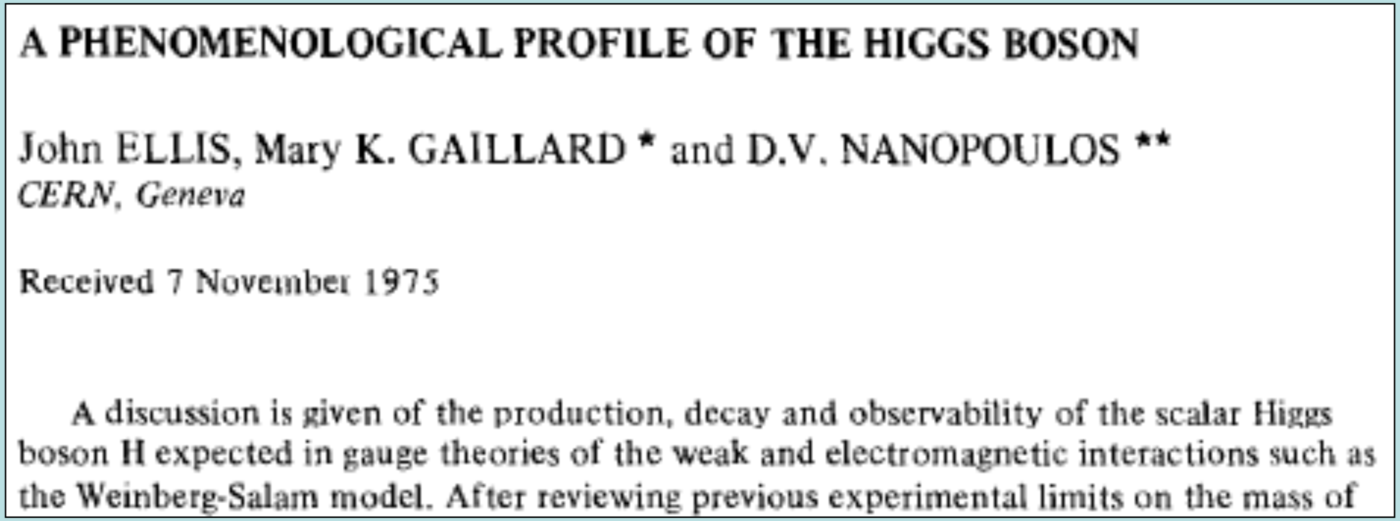
Weinberg 1967

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

Higgs 1966

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

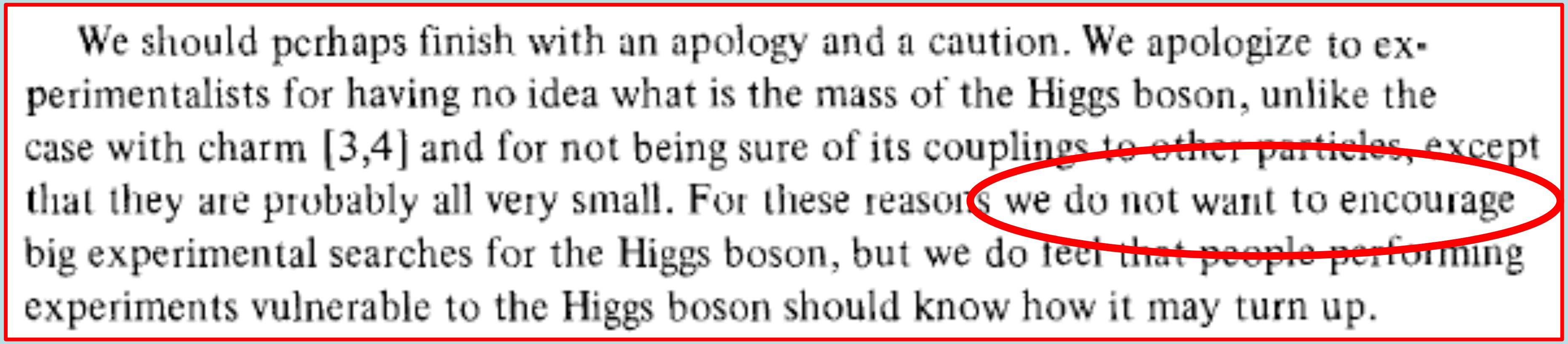


A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

Received 7 November 1975

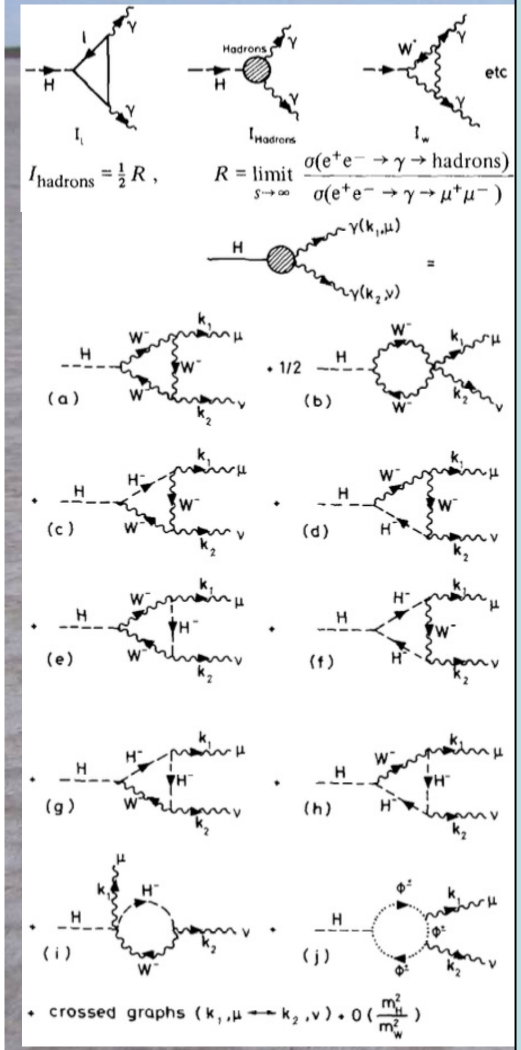
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of



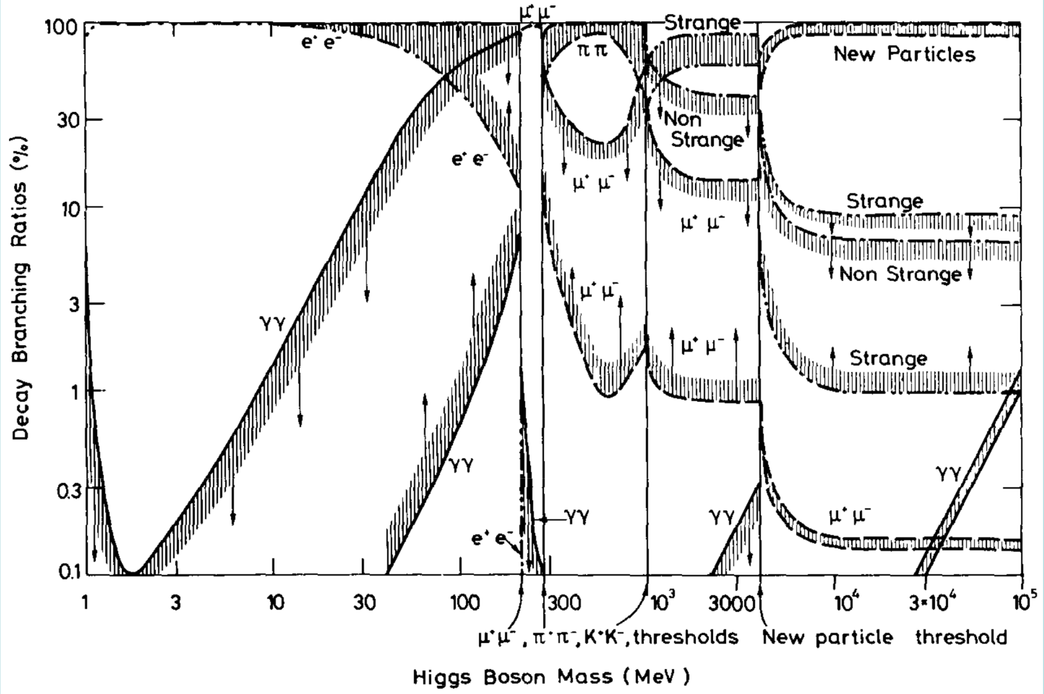
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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.

1975

A Phenomenological Profile of the Higgs Boson



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



- Look for pp → (H → $\mu\mu$) + X production
- H + Z associated production

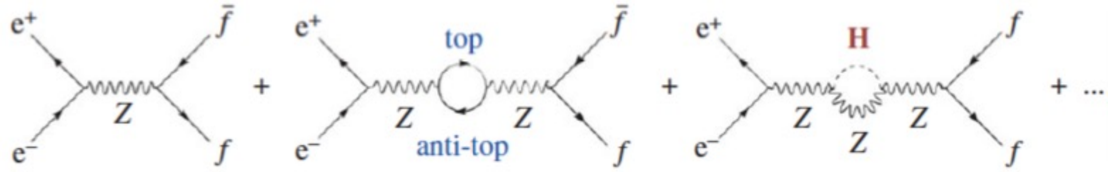
2011

Status of the Standard Model before the LHC

- Perfect agreement with all *confirmed* accelerator data
- Consistency with precision electroweak data (LEP et al) *only if there is a Higgs boson*
- Agreement seems to require *a relatively light Higgs boson* weighing < ~ 180 GeV
- Raises many unanswered questions:

mass? flavour? unification?

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:

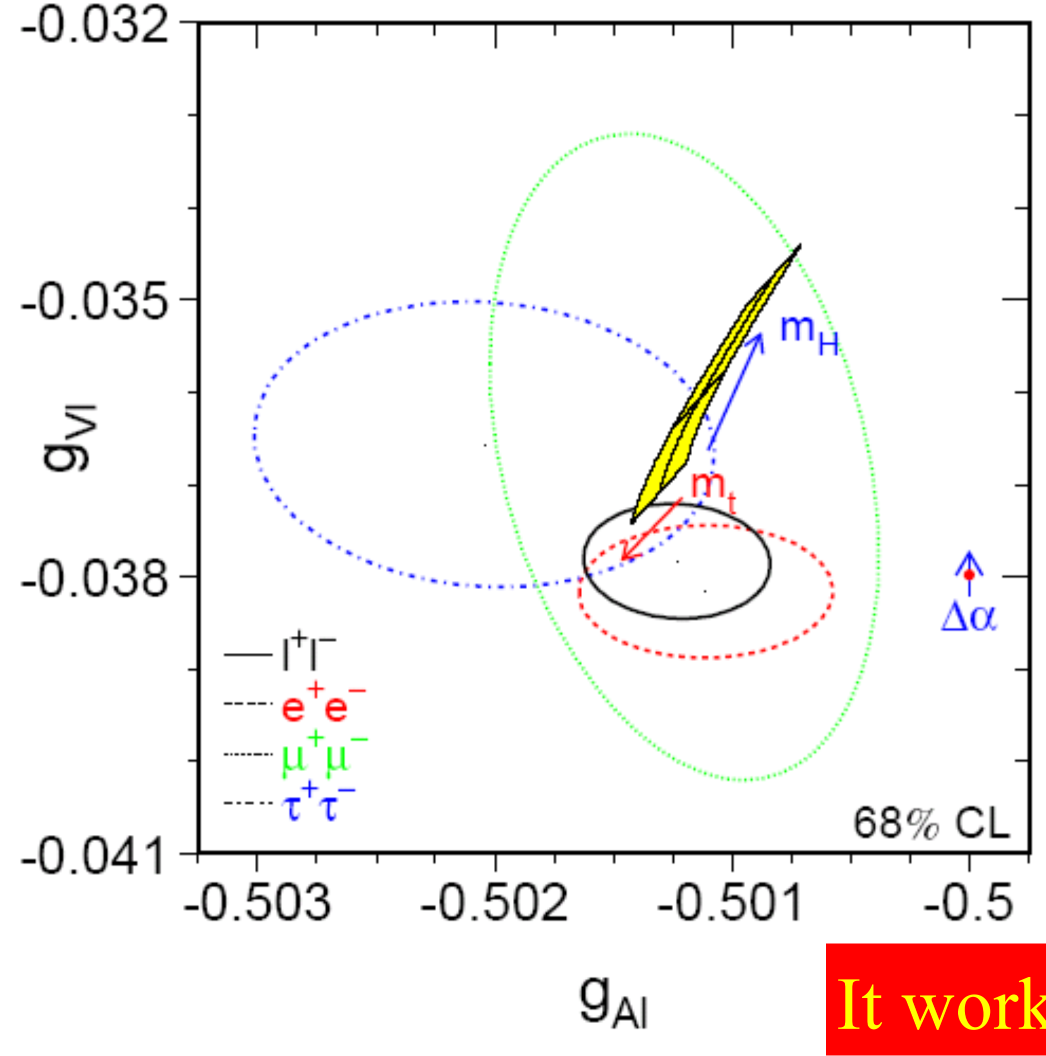
$$\frac{\sqrt{2}\mathrm{G}_F}{16\pi^2}m_W^2\left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2} + \ldots\right),\ M_H >> m_W$$

- Measurements at LEP et al. gave indications first on top mass, then on Higgs mass

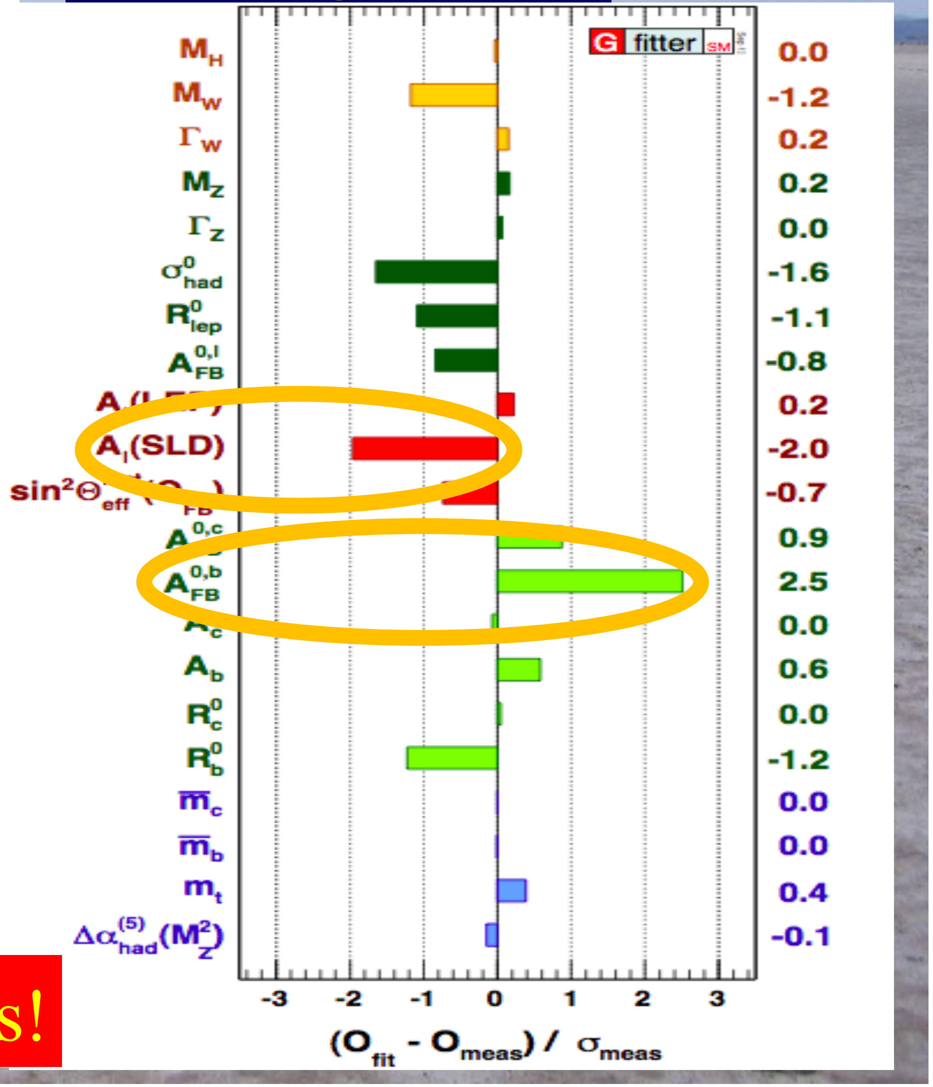
$$\Delta\rho = 0.0026\frac{M_t^2}{M_Z^2} - 0.0015\ln\left(\frac{M_H}{M_W}\right)$$

Precision Tests of the Electroweak Sector of the Standard Model

Lepton couplings



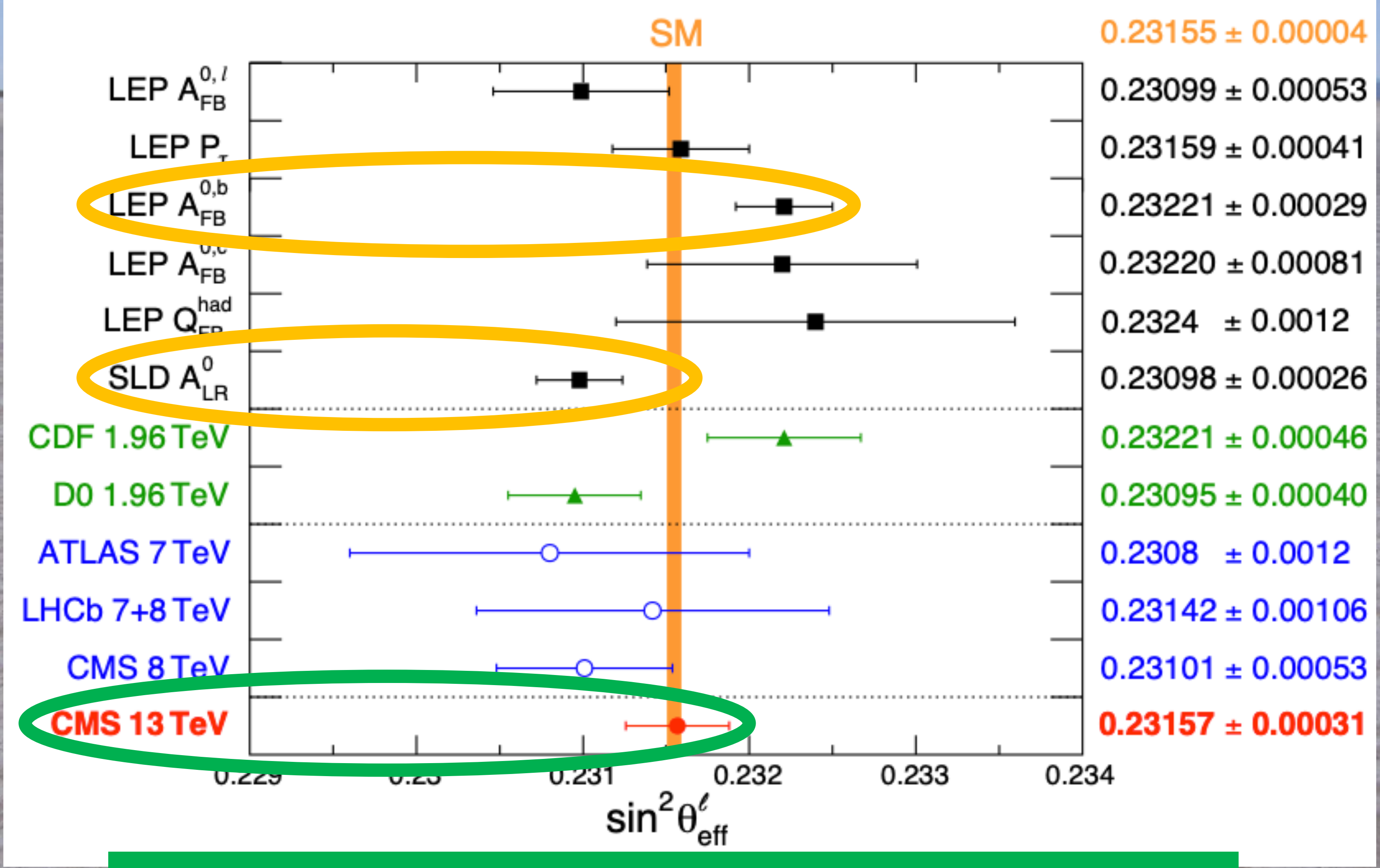
Pulls in global fit



It works!

CMS Collaboration, arXiv:2408.07622

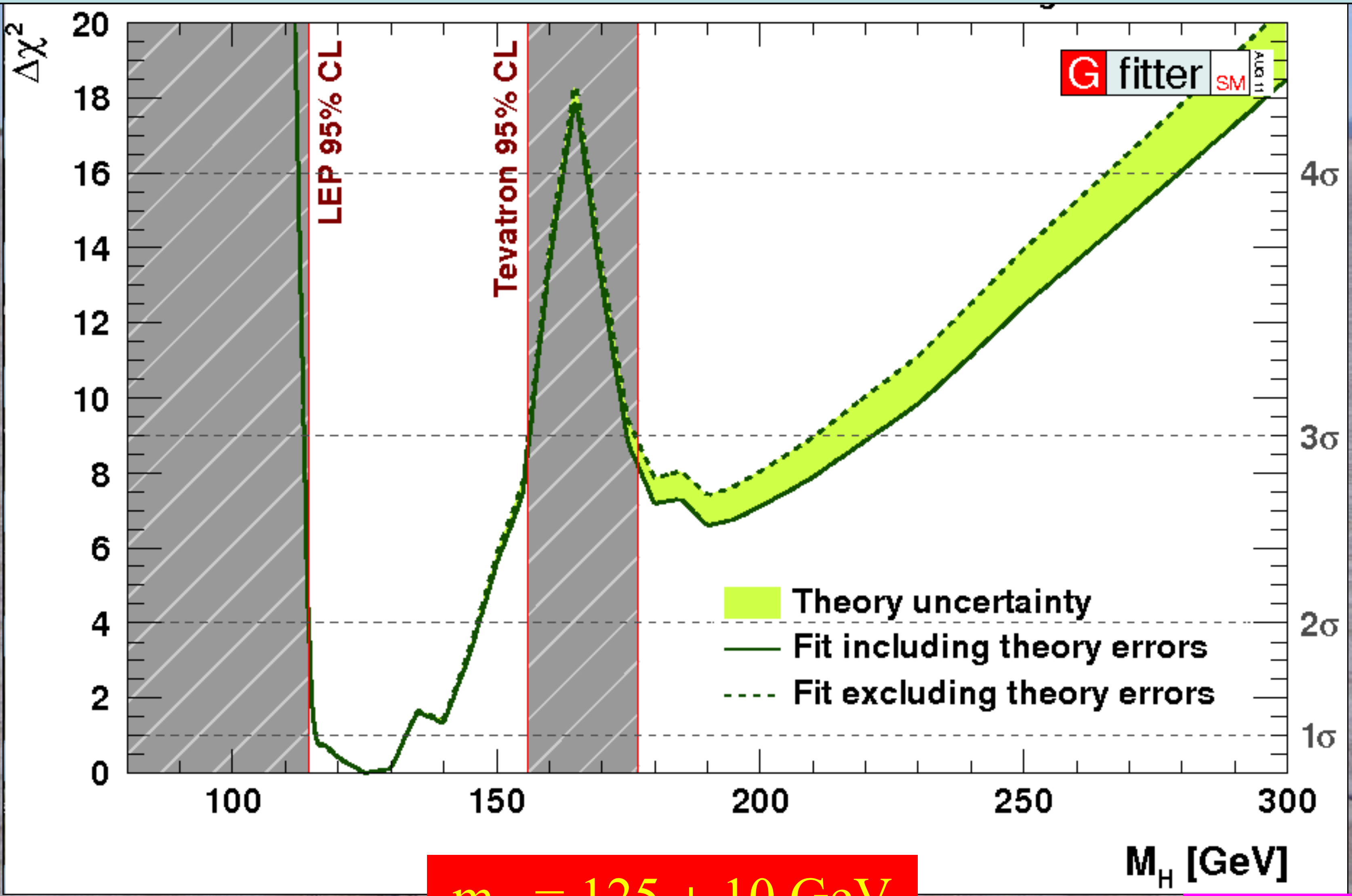
New Precision Measurement of Electroweak Mixing Angle



Splits the difference between LEP and SLD

2011

Combining Information from Previous Direct Searches and Indirect Data



$m_H = 125 \pm 10$ GeV

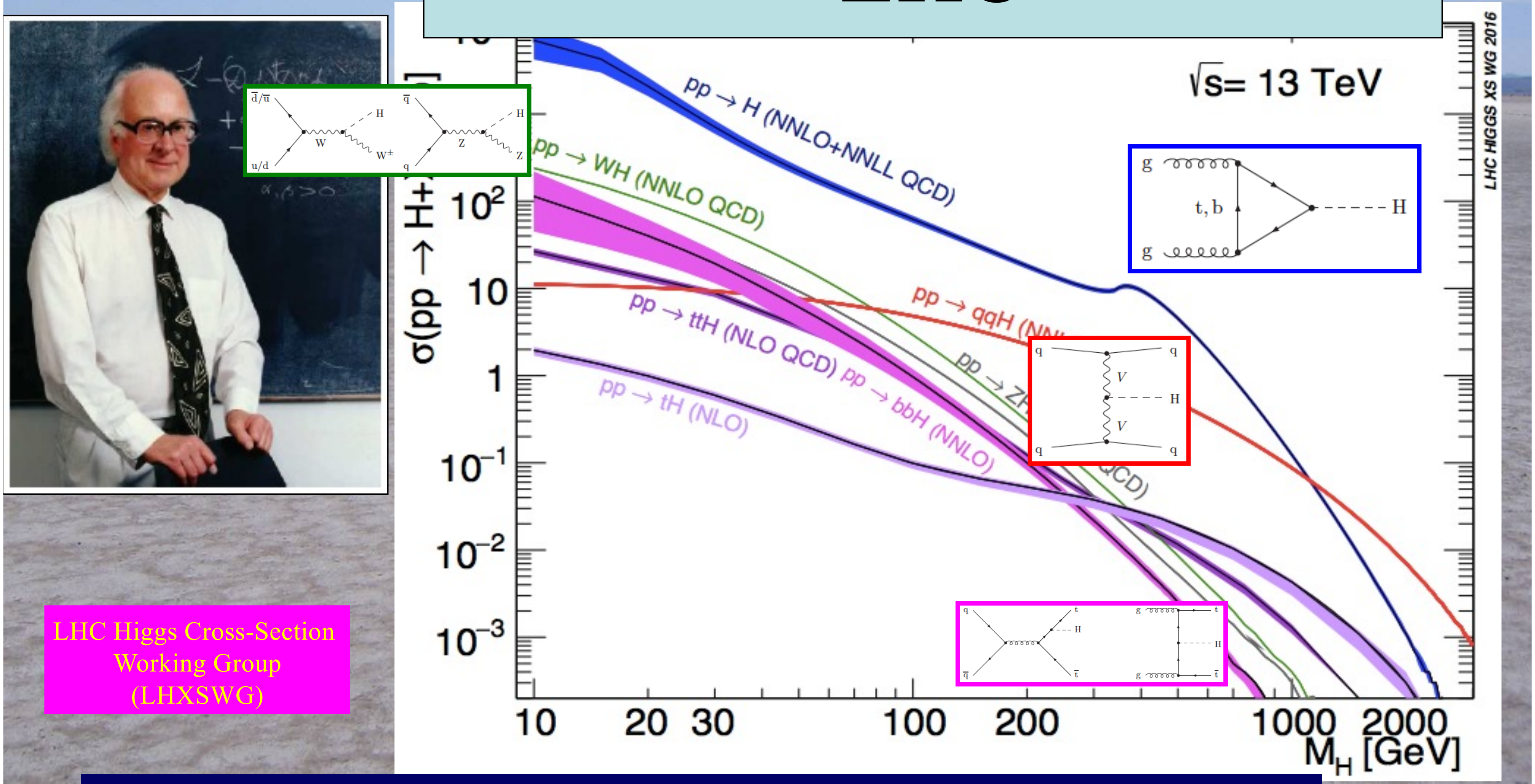
Gfitter collaboration

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

EGN 1975

A la recherche du
Higgs perdu …

Higgs Production at the LHC

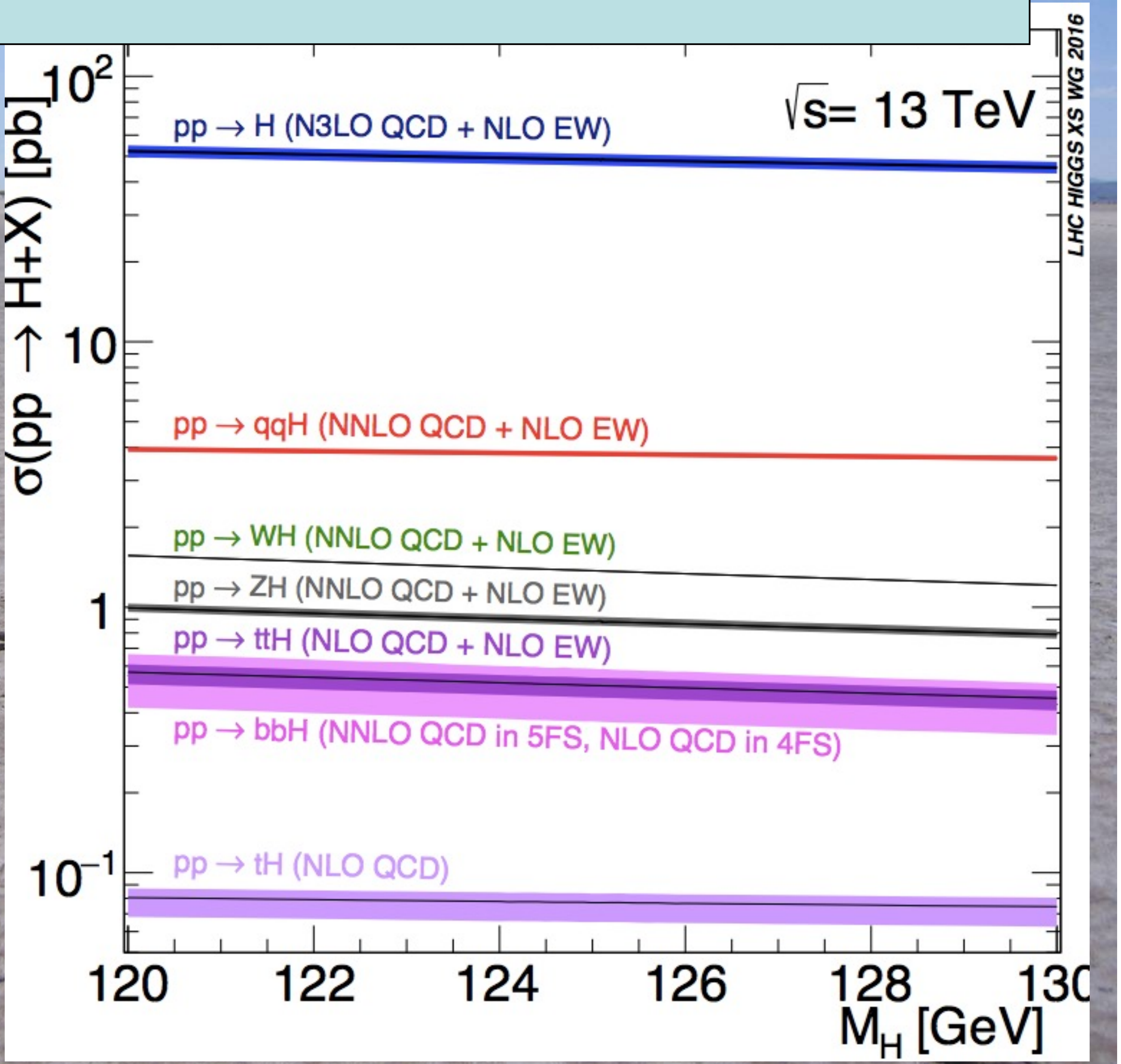


LHC Higgs Cross-Section Working Group (LHXSWG)

Many production modes measurable if $M_h \sim 125$ GeV

Higgs Production at the LHC

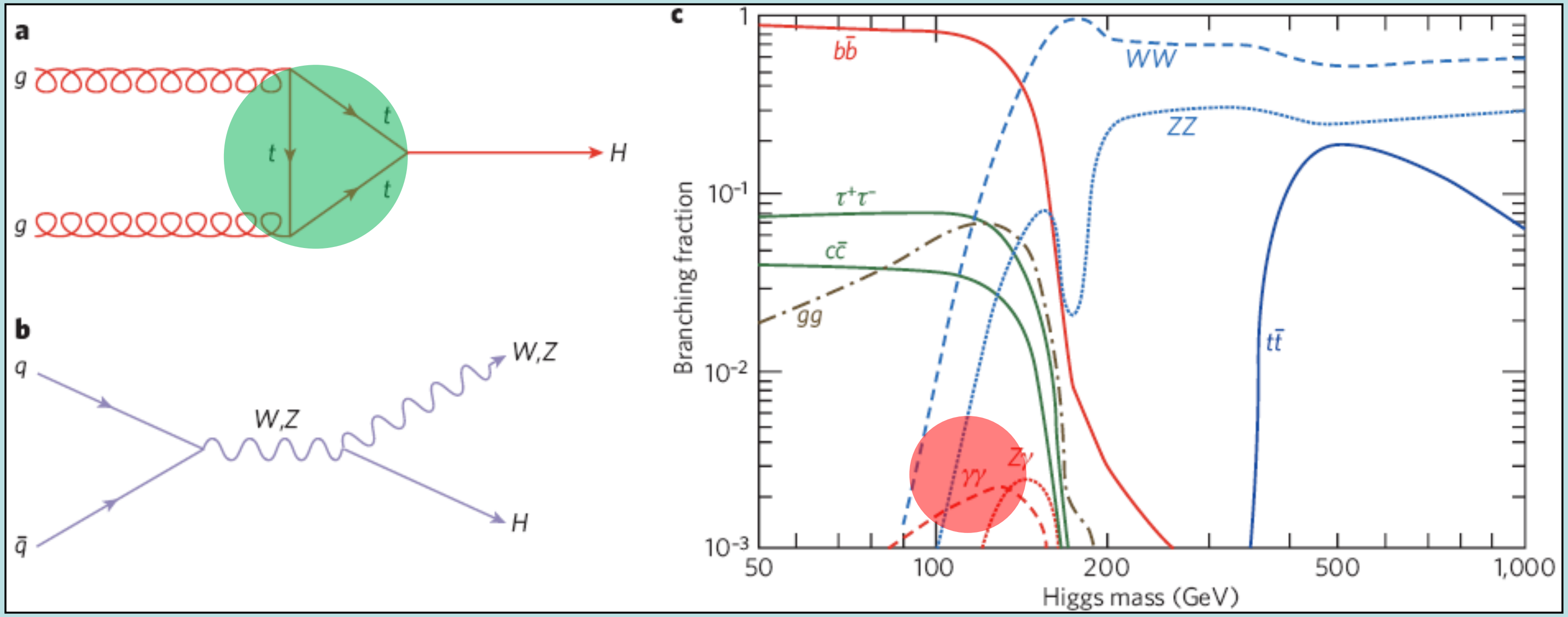
Cross sections for Higgs mass near 125 GeV



LHC Higgs Cross-Section Working Group (LHXSWG)

Higgs Decay Branching Ratios

- Couplings proportional to masses (?)



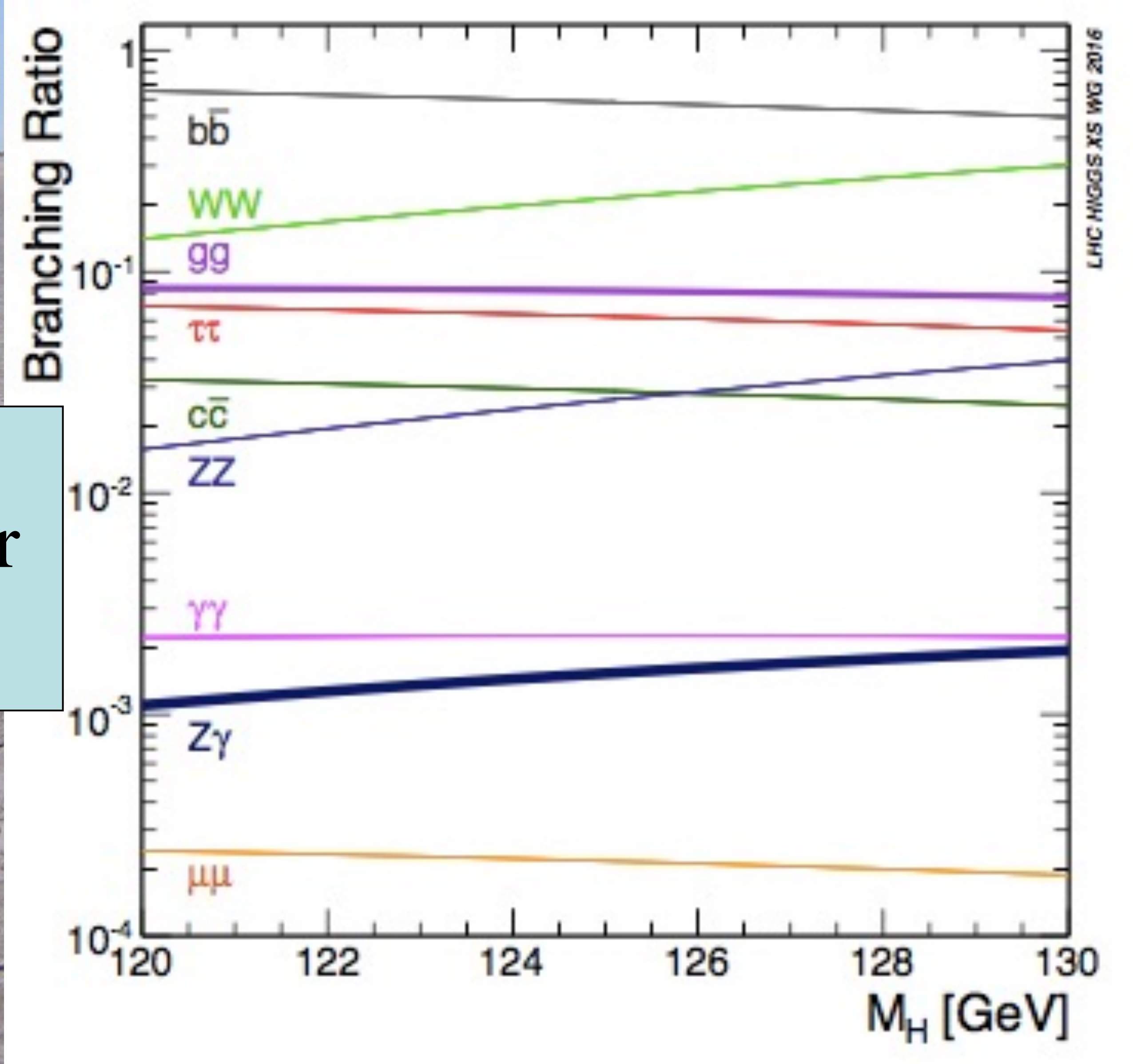
- Important couplings through (quantum) loops:
  - gluon + gluon → Higgs → γγ

Many decay modes measurable if M_h ~ 125 GeV

Higgs Decay Branching Ratios

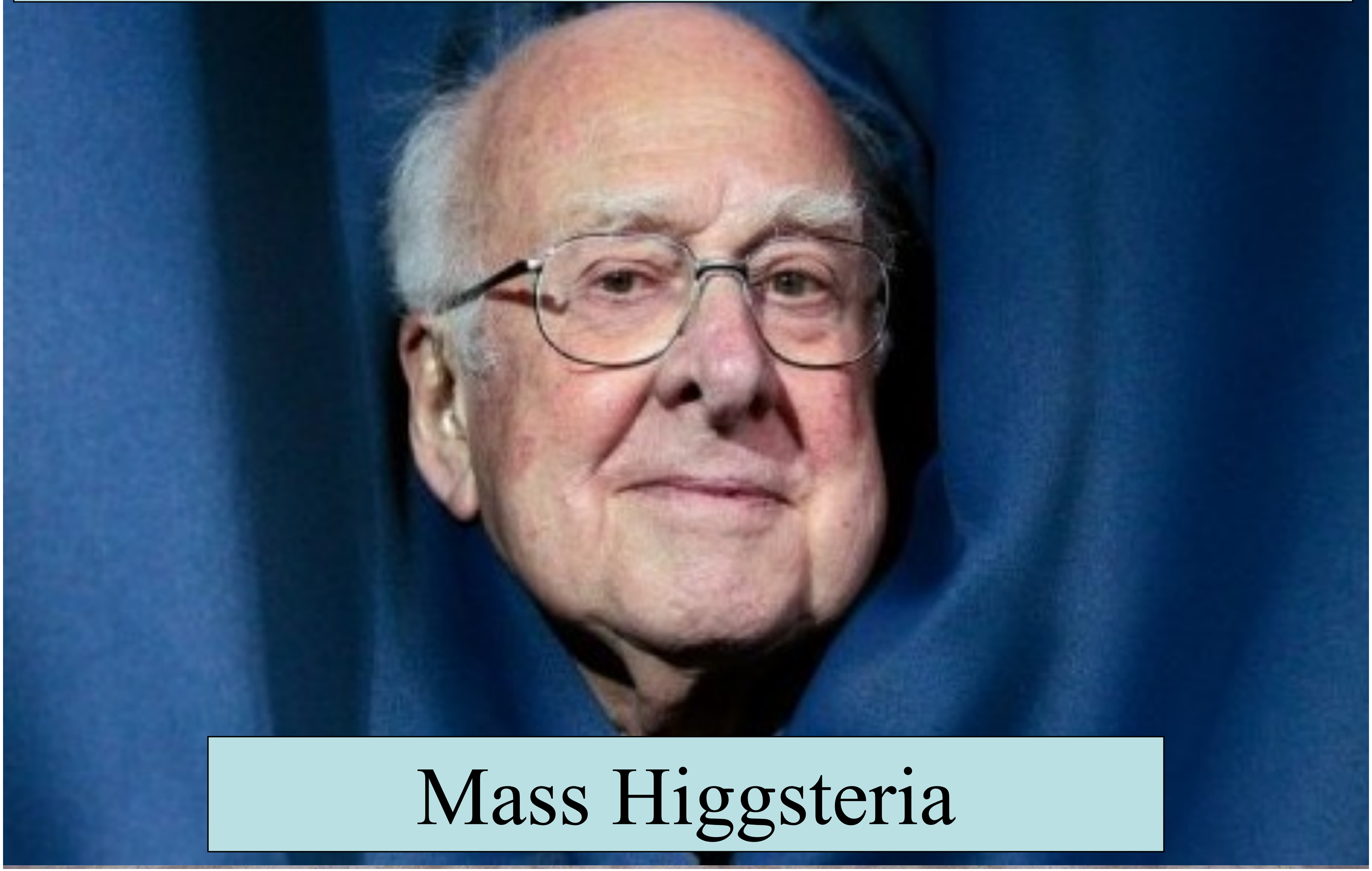
Dominant decay branching ratios for $m_H \sim 125$ GeV

LHC Higgs Cross-Section Working Group (LHXSWG)



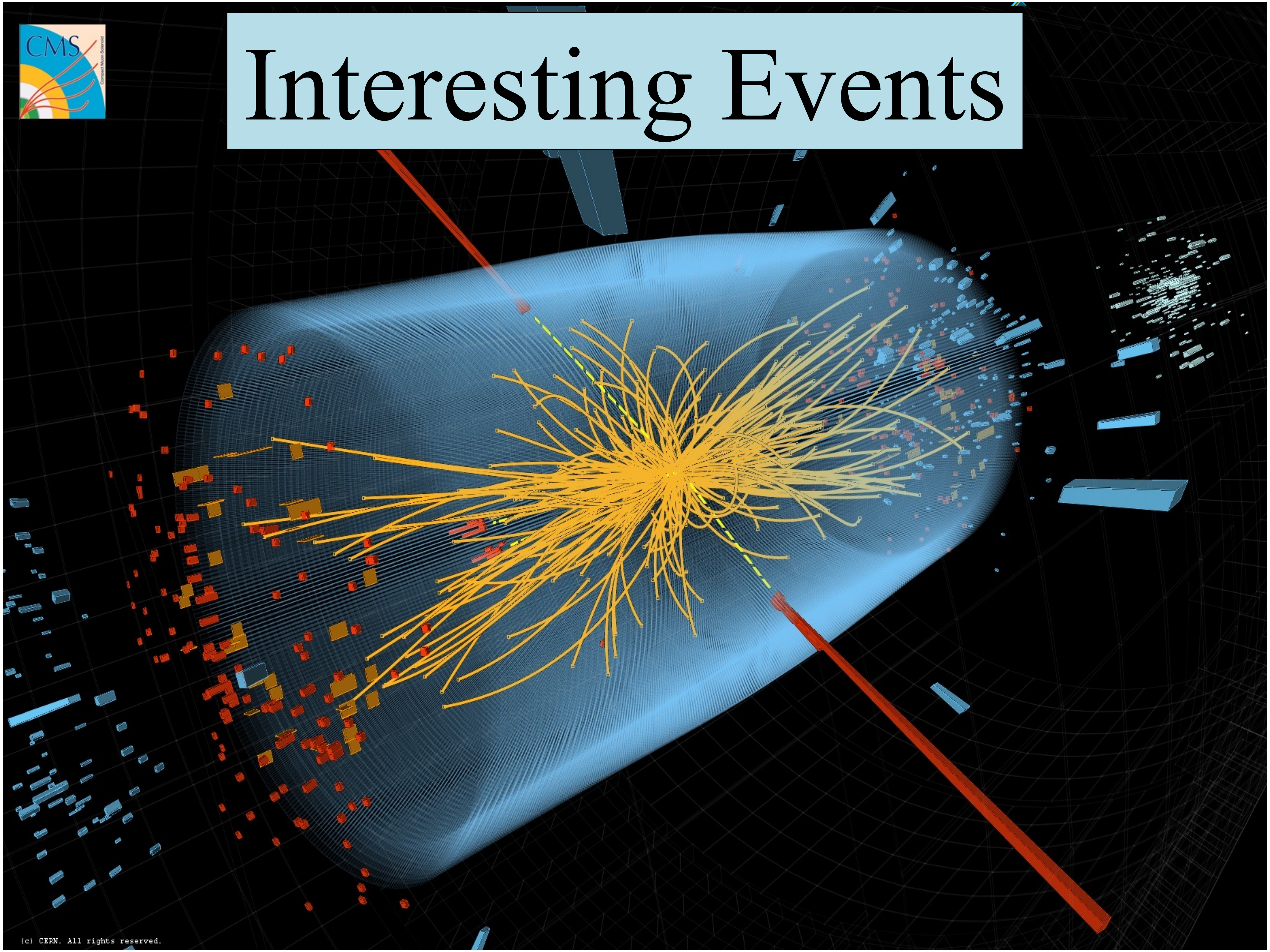
2012

The Discovery of the Higgs Boson



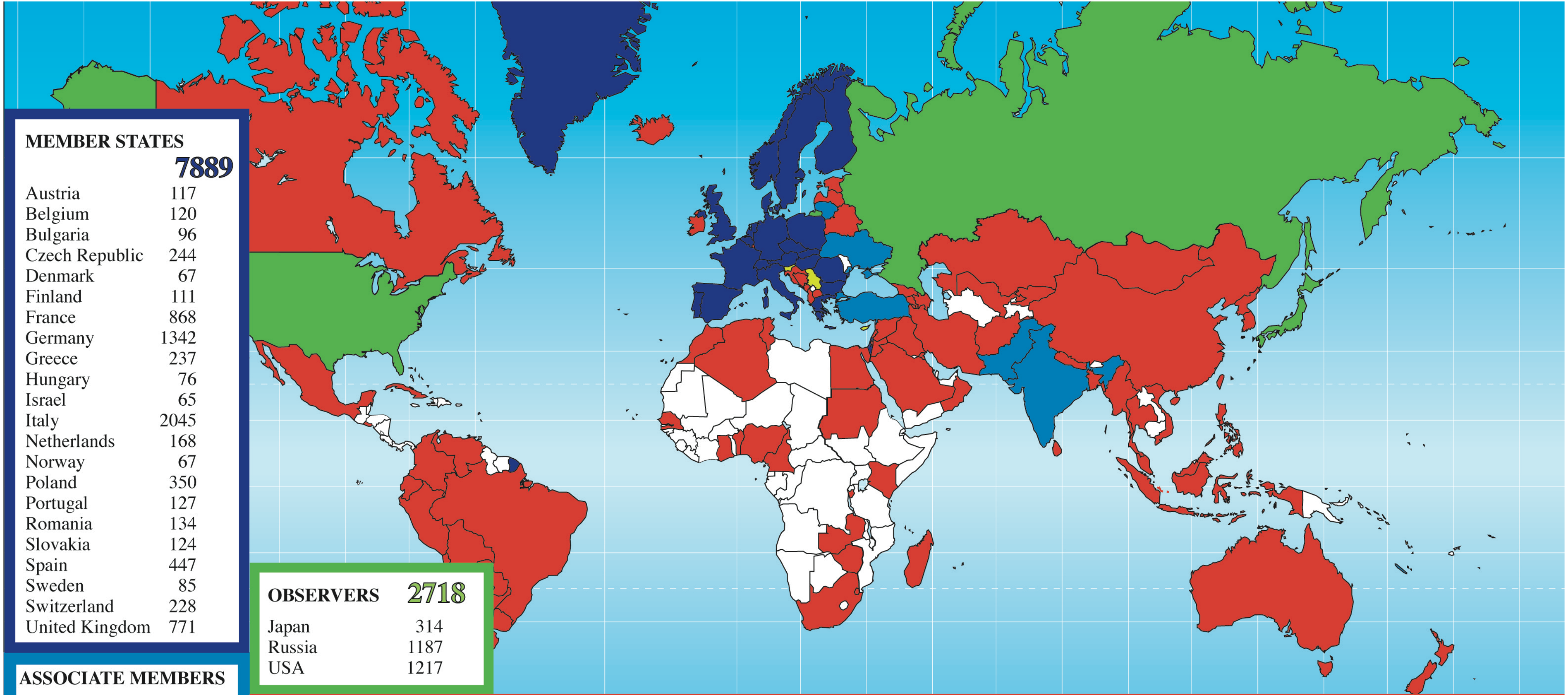
Mass Higgsteria

Interesting Events



Higgsdependence Day!

Scientists from around the World



MEMBER STATES **7889**

Austria	117
Belgium	120
Bulgaria	96
Czech Republic	244
Denmark	67
Finland	111
France	868
Germany	1342
Greece	237
Hungary	76
Israel	65
Italy	2045
Netherlands	168
Norway	67
Poland	350
Portugal	127
Romania	134
Slovakia	124
Spain	447
Sweden	85
Switzerland	228
United Kingdom	771

ASSOCIATE MEMBERS **745**

India	357
Lithuania	35
Pakistan	65
Turkey	173
Ukraine	115

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP **118**

Cyprus	26
Serbia	57
Slovenia	35

OBSERVERS **2718**

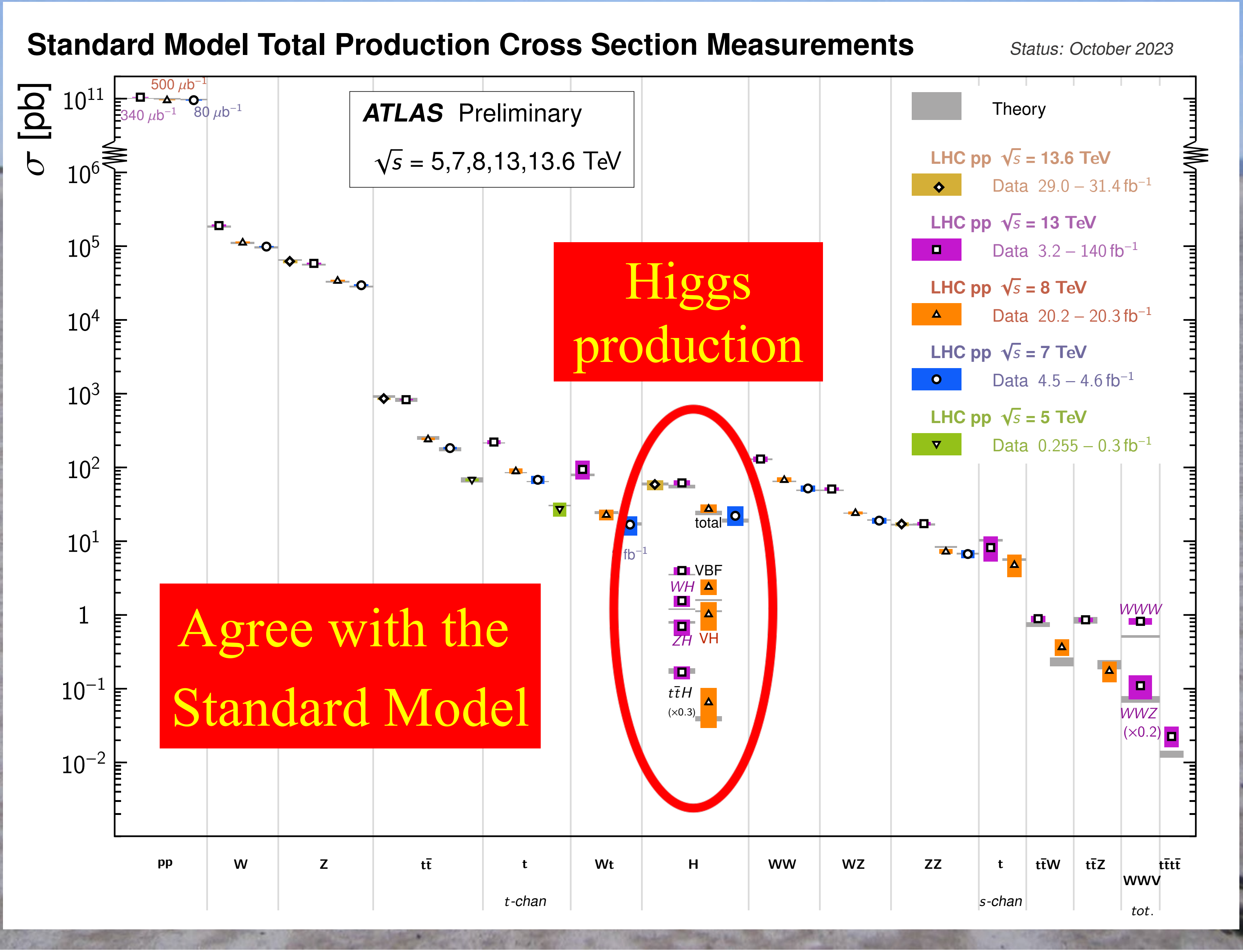
Japan	314
Russia	1187
USA	1217

OTHERS **1872**

Afghanistan	1
Albania	3
Algeria	14
Argentina	27
Armenia	19
Australia	31
Azerbaijan	10
Bangladesh	11
Belarus	48
Benin	1
Bolivia	4
Bosnia & Herzegovina	2
Brazil	135
Burundi	1
Cameroon	1
Canada	161
Chile	20
China	510
Colombia	45
Croatia	41
Cuba	12
Ecuador	6
Egypt	31
El Salvador	1
Estonia	15
Georgia	46
Ghana	1
Hong Kong	1
Iceland	3
Indonesia	11
Iran	51
Iraq	1
Ireland	16
Jordan	1
Kazakhstan	5
Kenya	3
Korea Rep.	185
Kyrgyzstan	1
Latvia	2
Lebanon	23
Luxembourg	2
Madagascar	4
Malaysia	15
Malta	9
Mauritius	1
Mexico	82
Mongolia	2
Montenegro	11
Morocco	20
Myanmar	1
Nepal	10
New Zealand	5
Nigeria	3
North Korea	1
Oman	3
Palestine (O.T.).	7
Paraguay	2
Peru	7
Philippines	3
Saint Kitts and Nevis	1
Saudi Arabia	2
Senegal	1
Singapore	4
South Africa	56
Sri Lanka	6
Sudan	1
Swaziland	1
Syria	1
Taiwan	51
Thailand	22
T.F.Y.R.O.M.	2
Tunisia	5
Uruguay	1
Uzbekistan	4
Venezuela	10
Viet Nam	13
Zambia	1
Zimbabwe	2

Russian naval shells reused in the CMS experiment

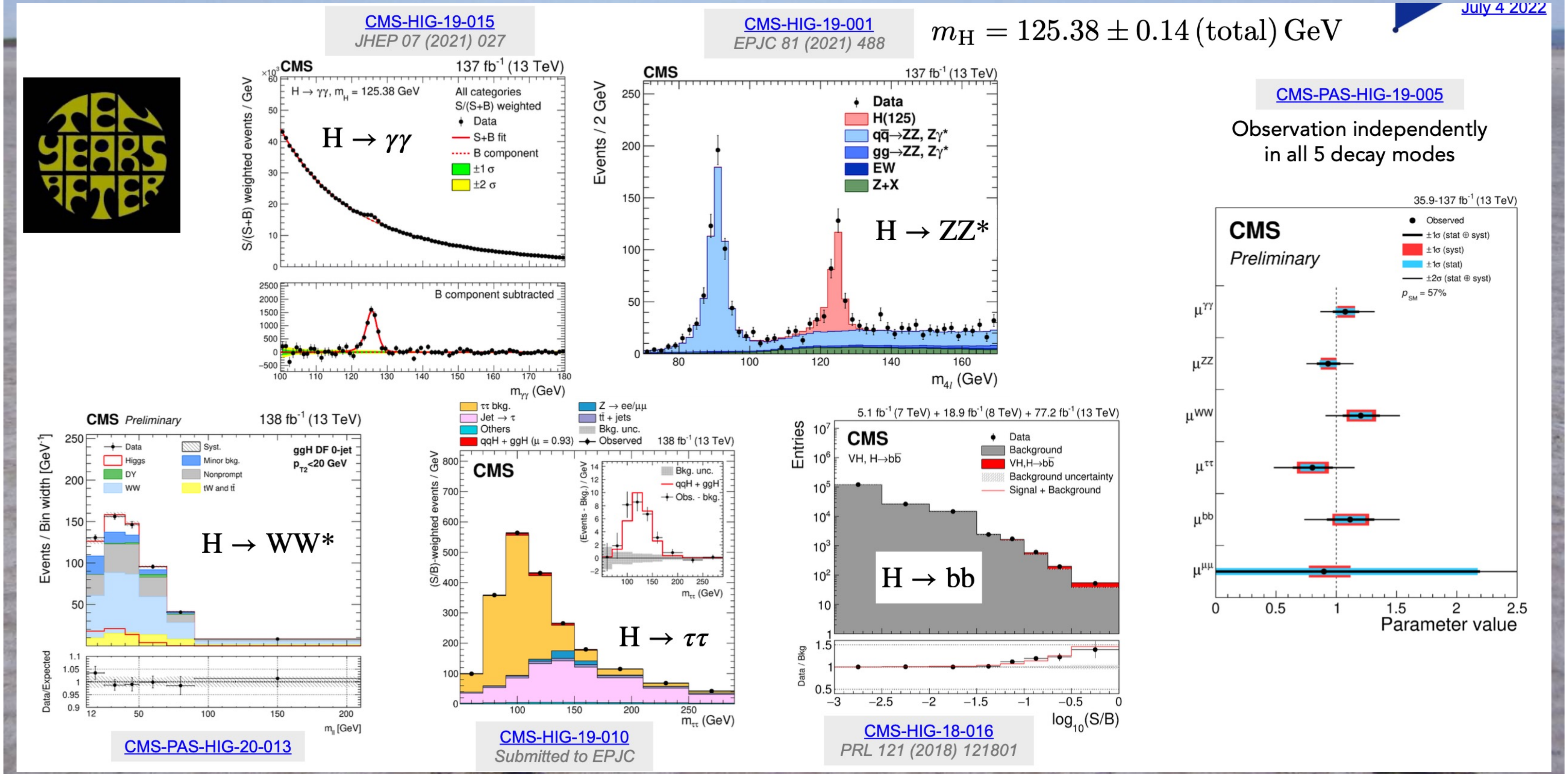
LHC Measurements



Higgs production

Agree with the Standard Model

Higgs Measurements



July 4 2022

CMS-HIG-19-015
JHEP 07 (2021) 027

CMS-HIG-19-001
EPJC 81 (2021) 488

$$m_{\mathrm{H}} = 125.38 \pm 0.14\,(\text{total})\,\mathrm{GeV}$$

CMS-PAS-HIG-19-005

Observation independently in all 5 decay modes

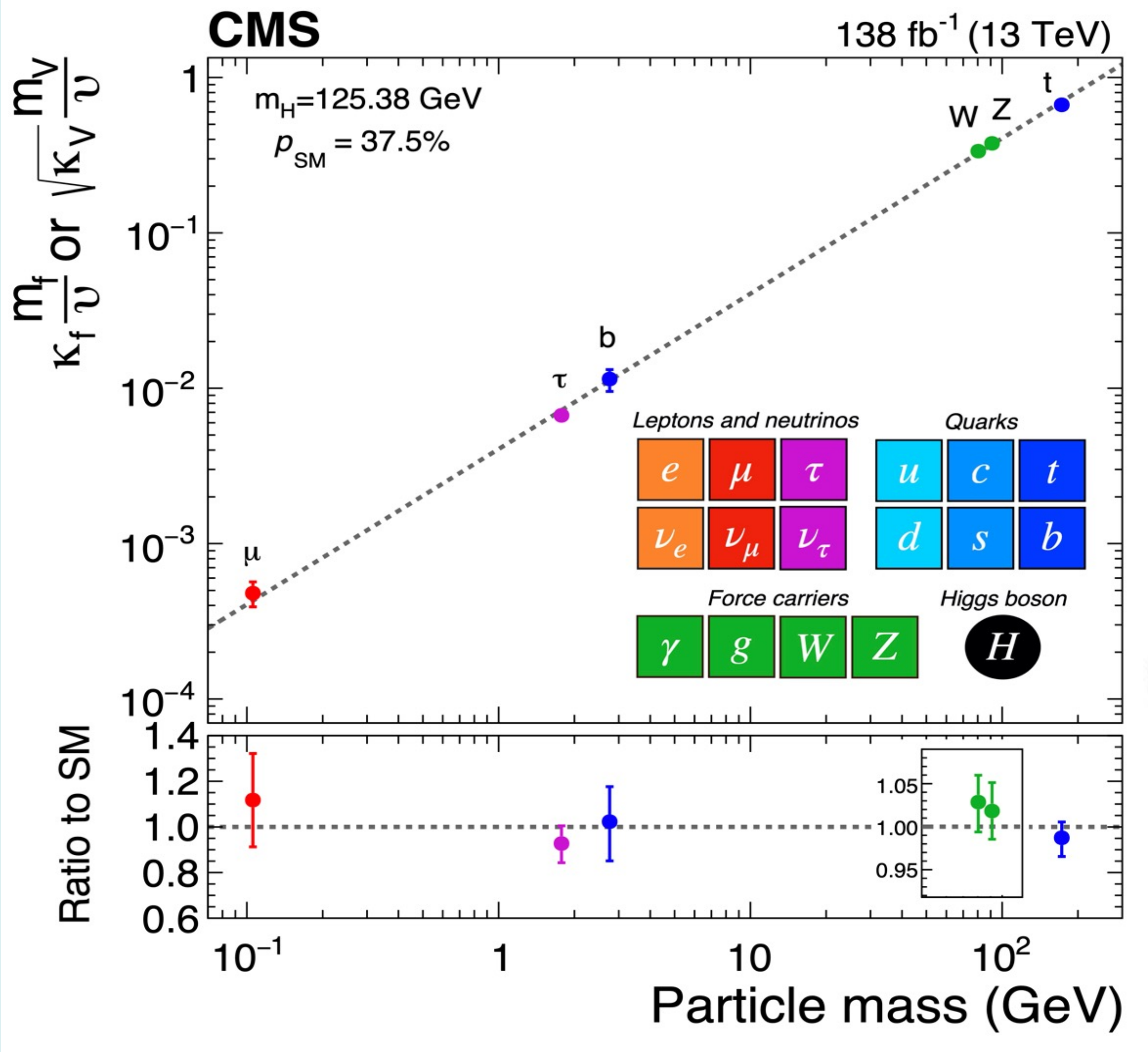
CMS-PAS-HIG-20-013

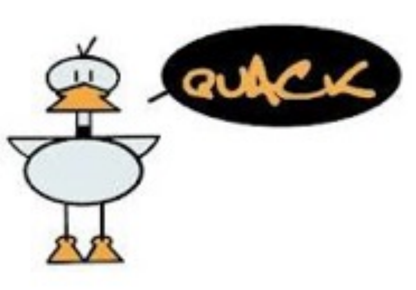
CMS-HIG-19-010
Submitted to EPJC

CMS-HIG-18-016
PRL 121 (2018) 121801

It Walks and Quacks like a Higgs

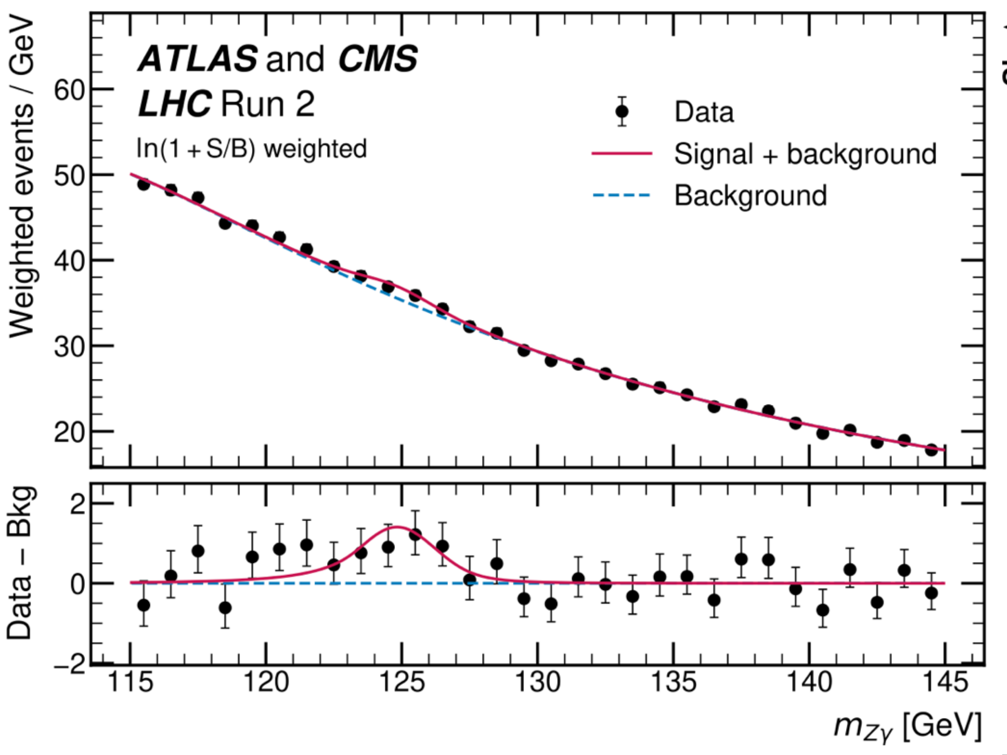
- Do couplings scale ~ mass? With scale = v?

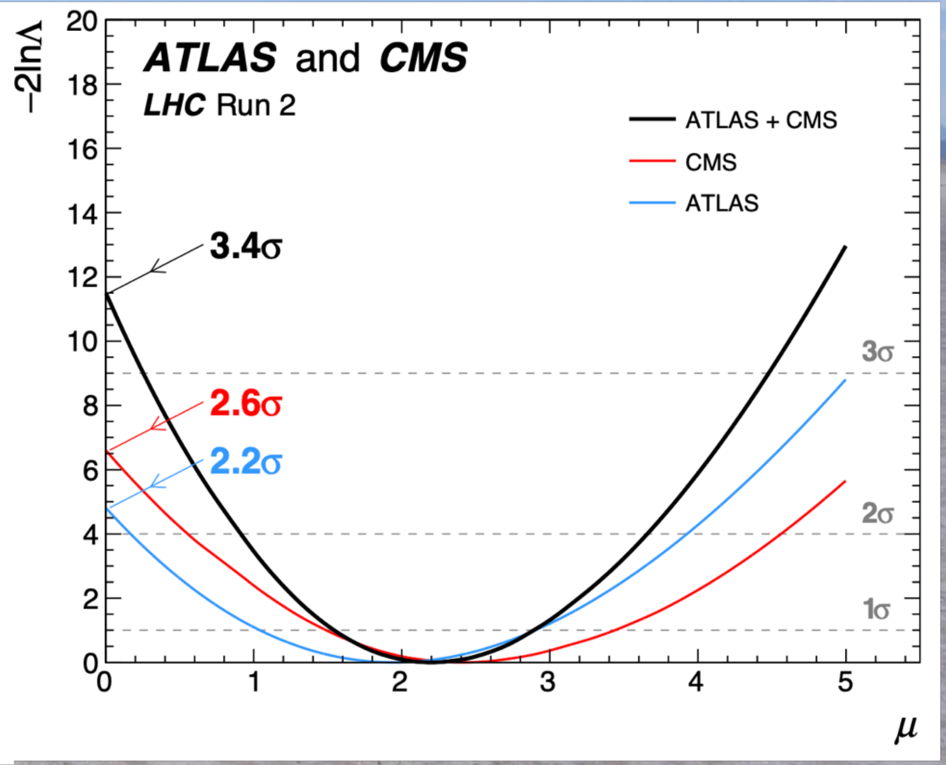




ATLAS & CMS, arXiv:2309.03501

Emerging Decay Mode: $H \to Z\gamma$





Signal strength $\mu = 2.2 \pm 0.7$ times Standard Model value

Negligible change in NLO QCD

Buccioni, Devoto, Djouadi, JE, Quevillon, Tancredi, arXiv:2312.12384

Higher-order EW unimportant

Chen, Chen, Qiao & Zhu, arXiv:2404.114441

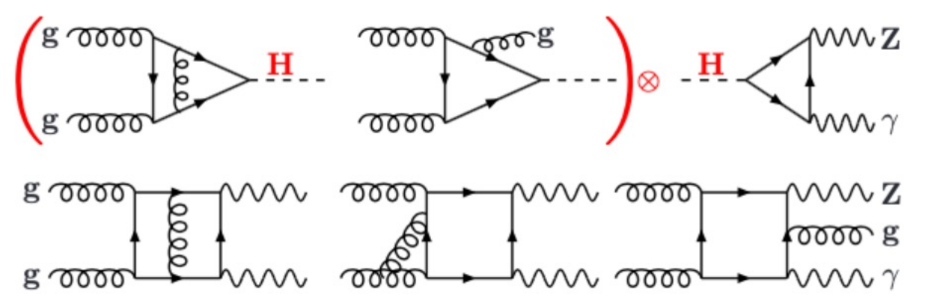
Statistics? BSM physics?

Boto, Das, Romão, Saha & Silva, arXiv:2312.13050

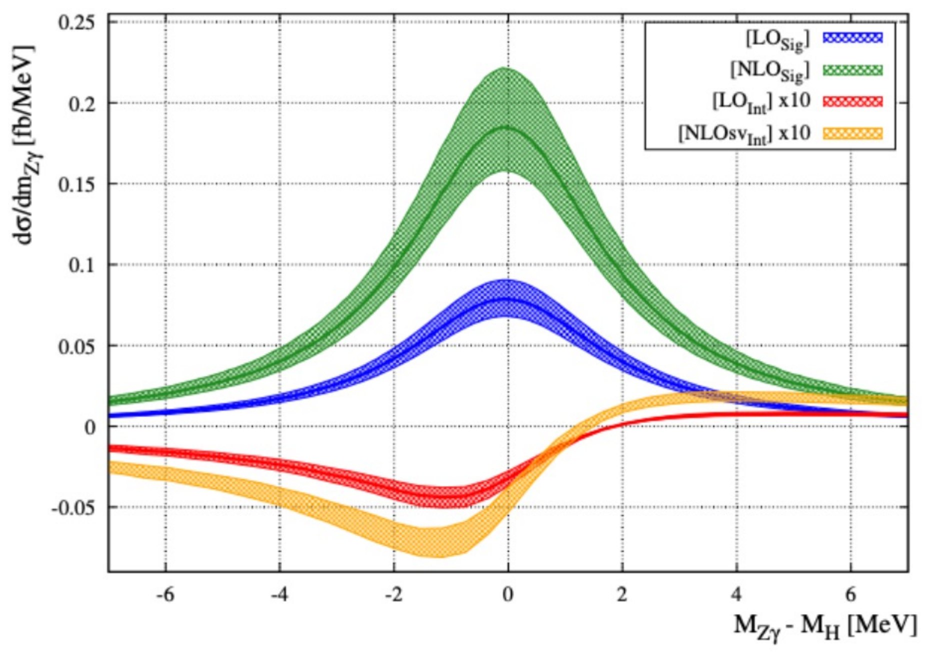
Buccioni, Devoto, Djouadi, JE, Quevillon, Tancredi, arXiv:2312.12384

QCD Corrections to $H \to Z\gamma$

NLO QCD diagrams for signal and background



NLO QCD increases cross-section by factor ~ 2



Negative interference – but blown up by factor 10 in plot

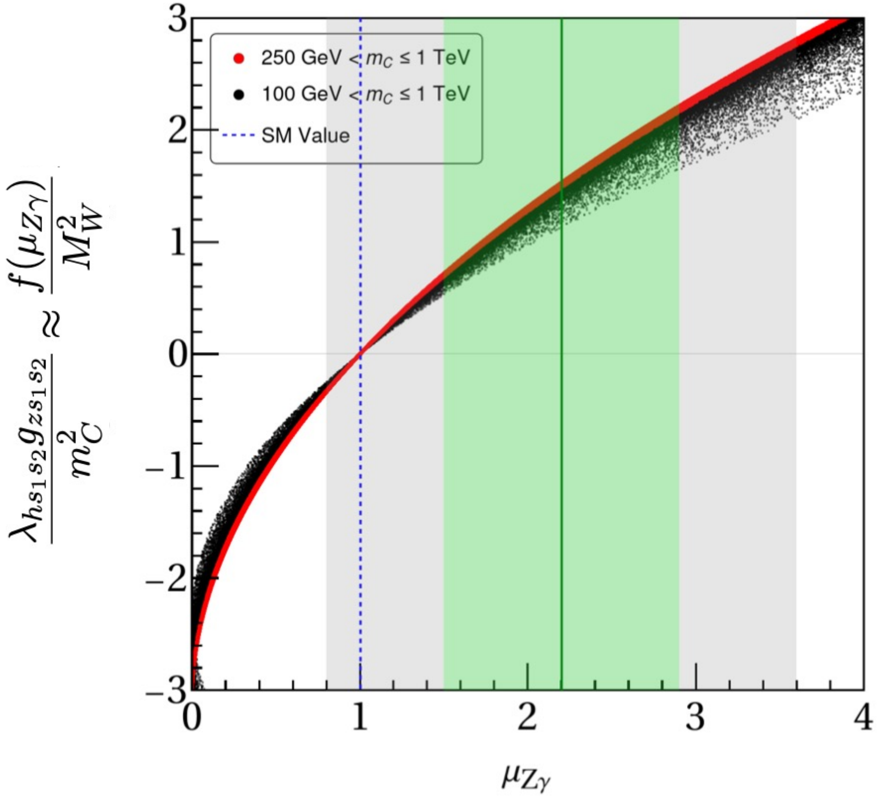
Reduces cross-section by 3%

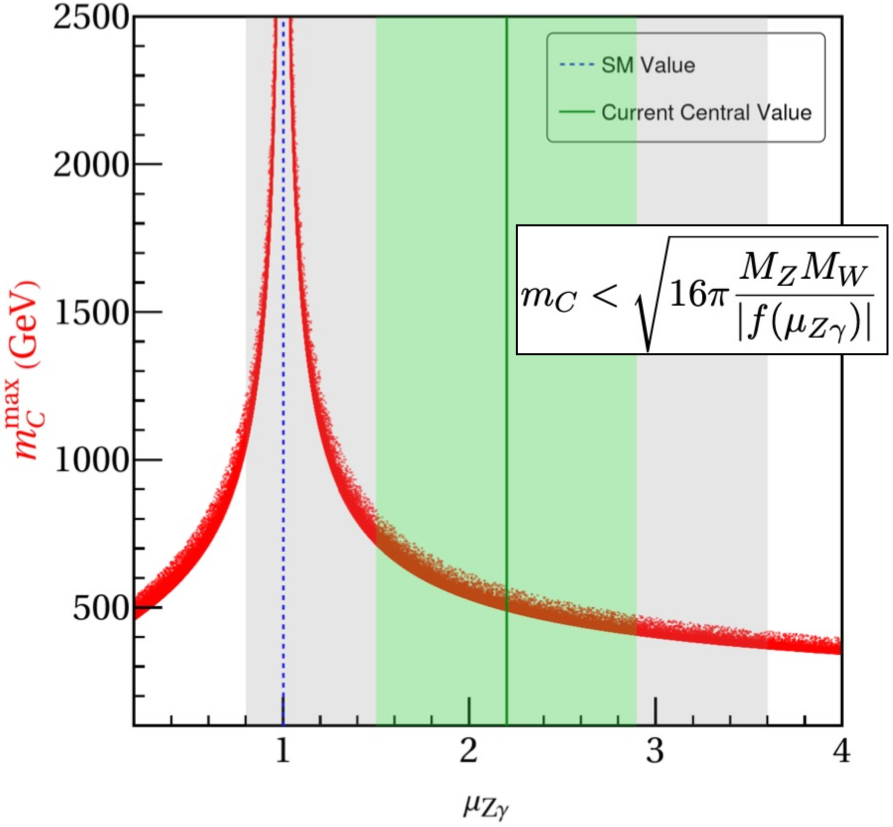
$$\sigma^{\rm NLO}_{\rm Sig} = 1.207^{+20\%}_{-15\%}\ {\rm fb},\ \ \sigma^{\rm NLO_{SV}}_{\rm Int} = -0.0344^{+12\%}_{-12\%}\ {\rm fb}$$

BSM Scenario for $H \to Z\gamma$

$$\mathscr{L}_S^{\text{int}} = \lambda_{hs_is_j} M_W\, h\, S_i^{+Q} S_j^{-Q} + i\, g_{zs_is_j} Z^\mu \left\{ \left(\partial_\mu S_i^{+Q}\right) S_j^{-Q} - \left(\partial_\mu S_j^{-Q}\right) S_i^{+Q} \right\}$$
$$+ eQ g_{zs_is_j} A^\mu Z_\mu S_i^{+Q} S_j^{-Q} + g_{zzs_is_j} Z^\mu Z_\mu S_i^{+Q} S_j^{-Q} + \text{h.c.}\,,$$

Mixing parameter: $\dfrac{\lambda_{hs_1s_2} g_{zs_1s_2}}{m_C^2} \approx \dfrac{f(\mu_{Z\gamma})}{M_W^2}$





$$m_C < \sqrt{16\pi \frac{M_Z M_W}{|f(\mu_{Z\gamma})|}}$$

Boto, Das, Romão, Saha & Silva, arXiv:2312.13050

Higher-Order Higgs Couplings

- Standard Model Lagrangian contains $HHH, VVHH$ couplings in Higgs potential $V(H)$, Higgs kinetic term $|D_\mu H|2$, respectively

- Directly related to (m_H, mW) and VVH, respectively

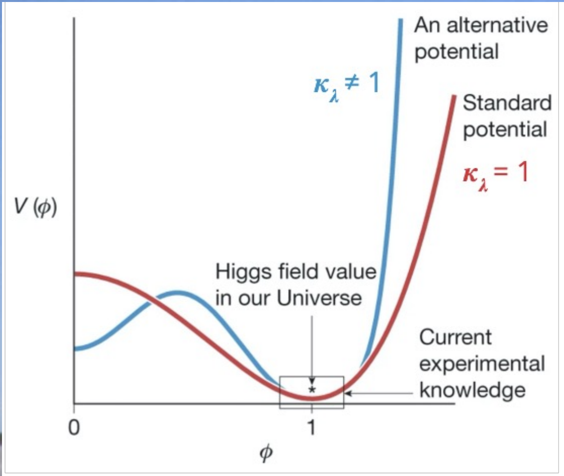
- Absence/modification would destroy consistency (renormalizability) of Standard Model

- Could be modified by, e.g., higher-order terms in effective field theory, e.g., H^6 or $|H|2|D_\mu H|2$

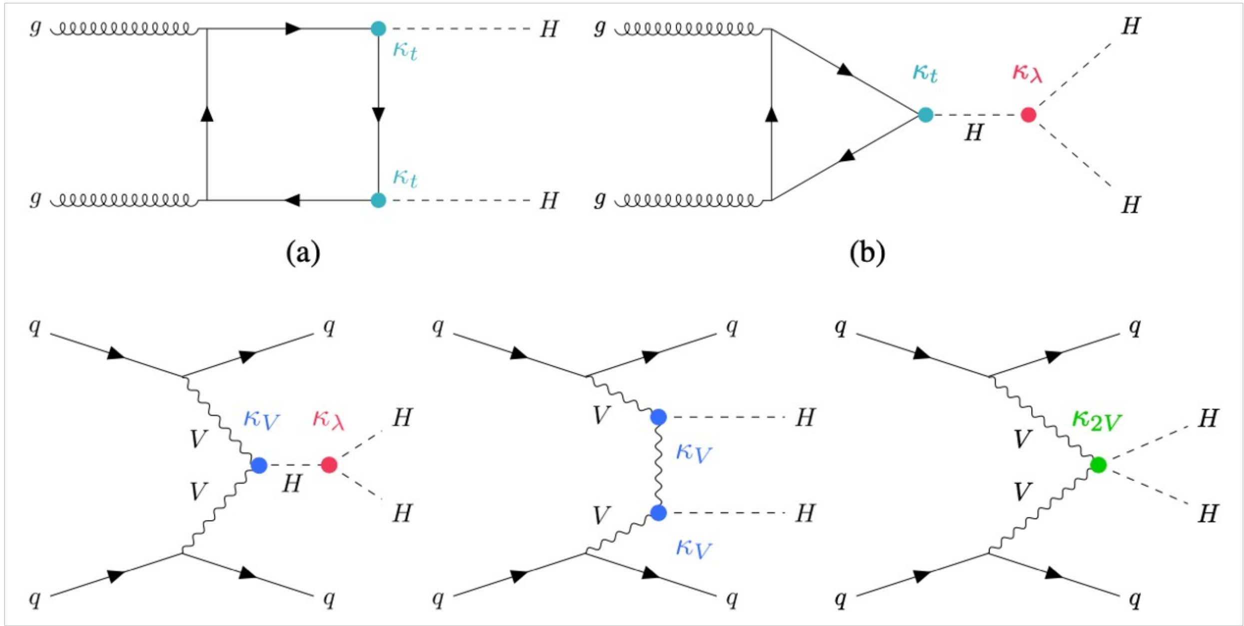
- Parameterized by $\kappa_\lambda, \kappa_{2V}$, respectively

- **Measuring them is next frontier in Higgs measurements**

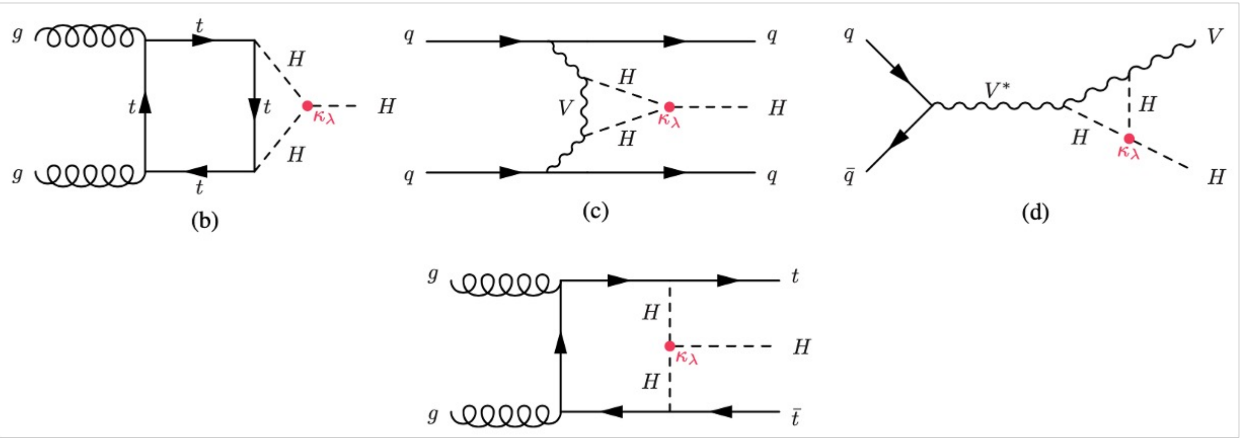
Search for Triple-H Coupling



Diagrams for double-Higgs production



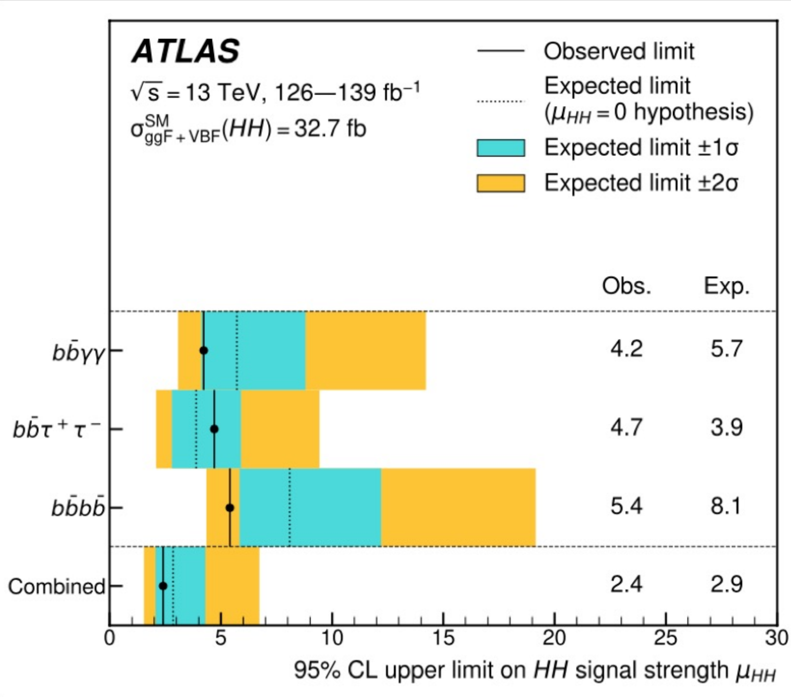
Loop corrections to single Higgs production



ATLAS Collaboration, arXiv: 2211.01216

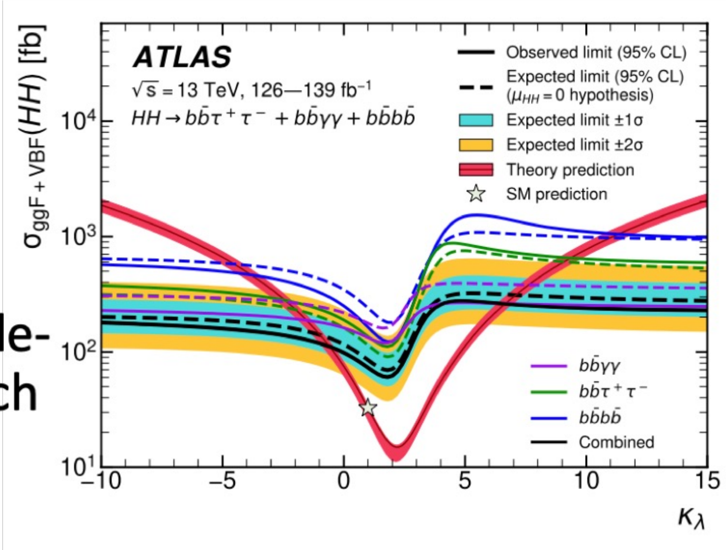
Search for HHH Coupling

Limit on double-Higgs production

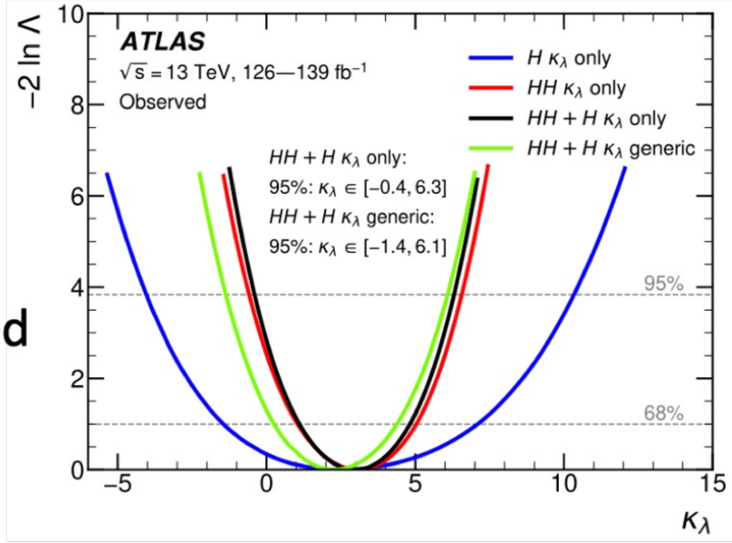


Limits on triple-Higgs coupling

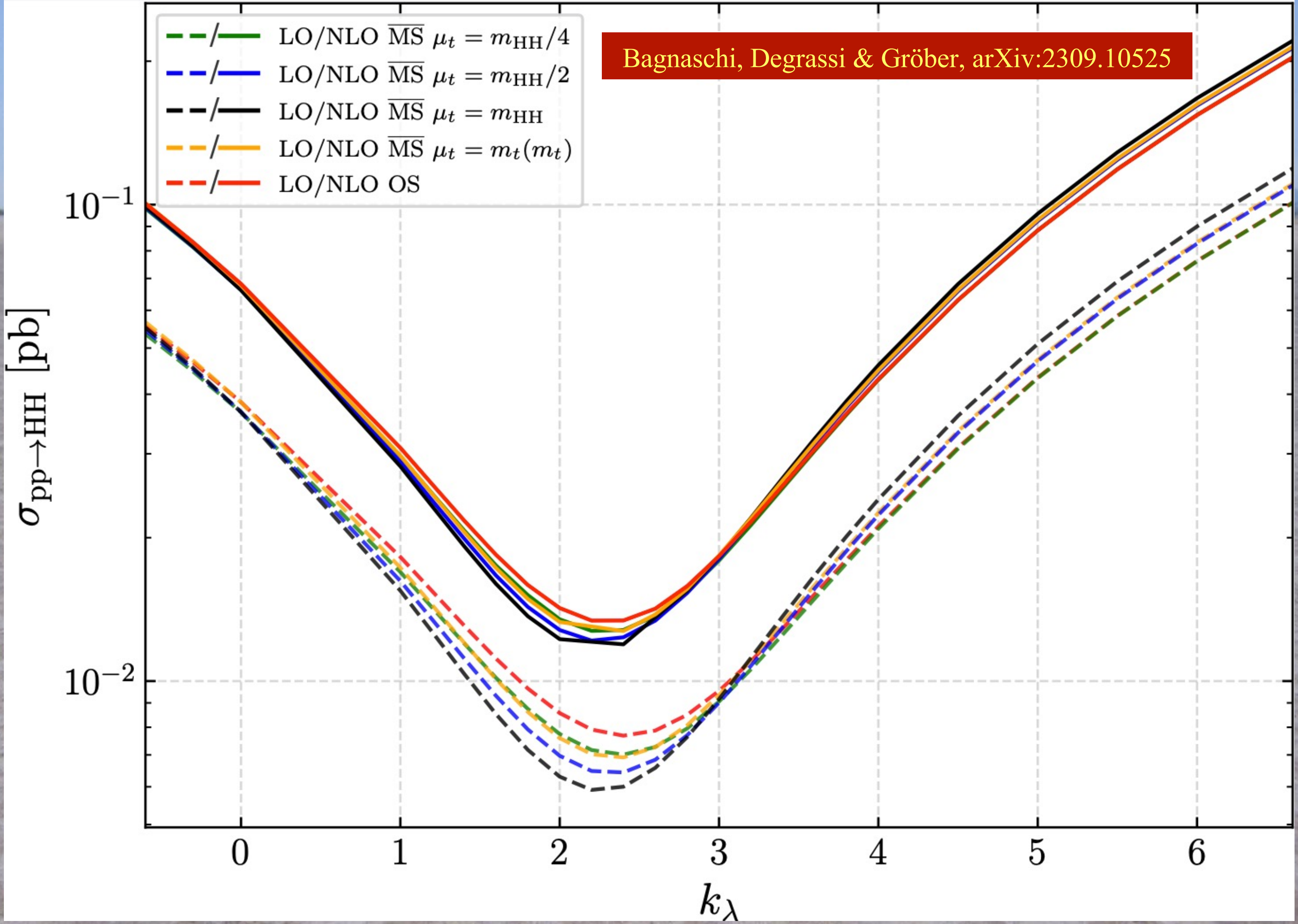
From double-Higgs search



Combined limit



NLO Corrections to Di-Higgs Production

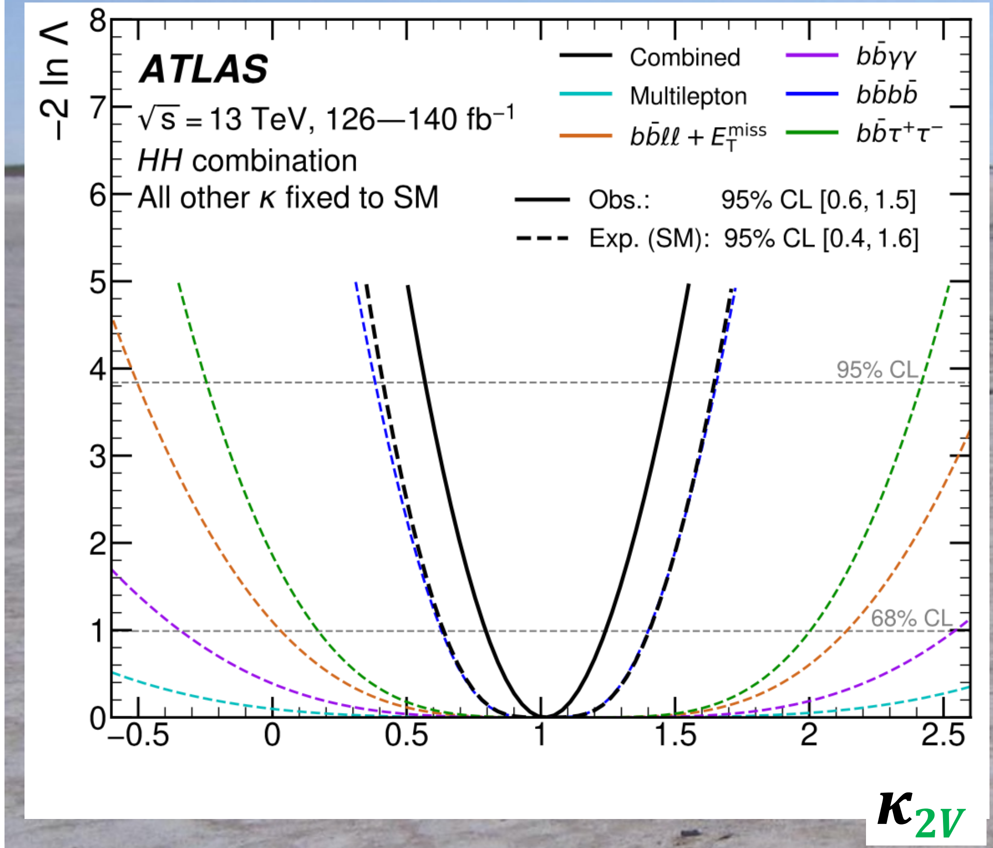


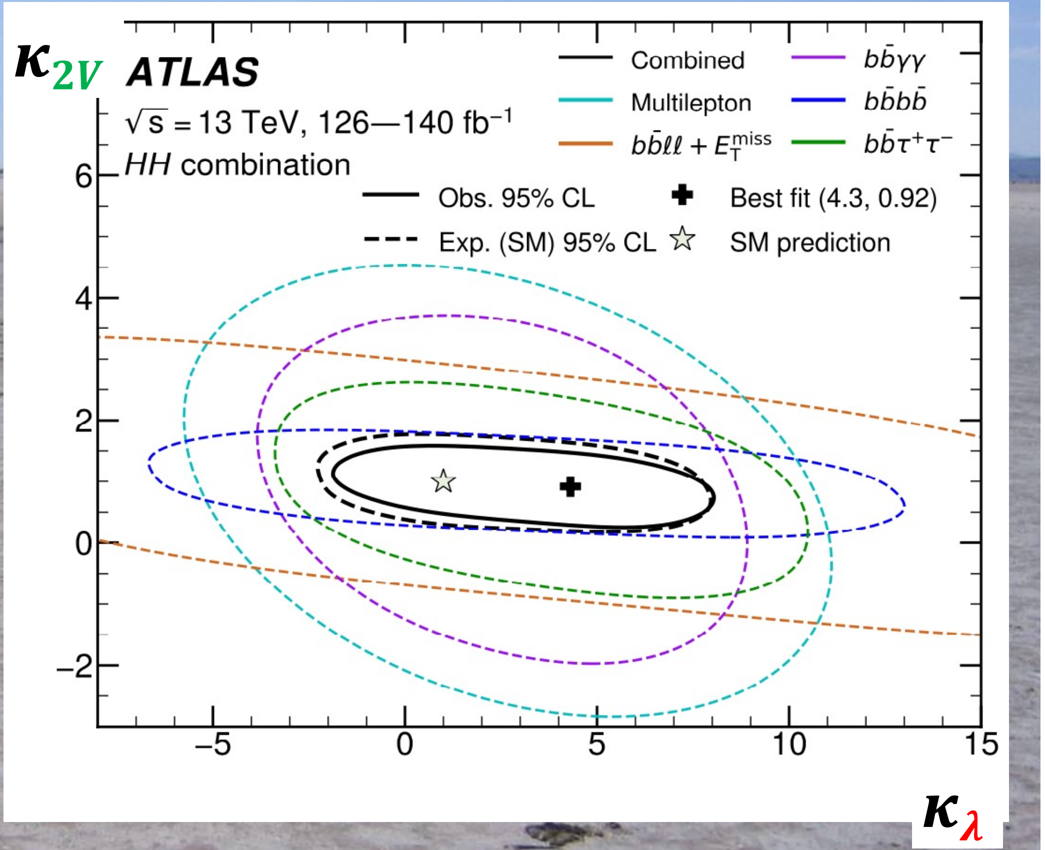
Bagnaschi, Degrassi & Gröber, arXiv:2309.10525

Important corrections

Insensitive to choice of renormalization scale

Evidence for VVHH Coupling

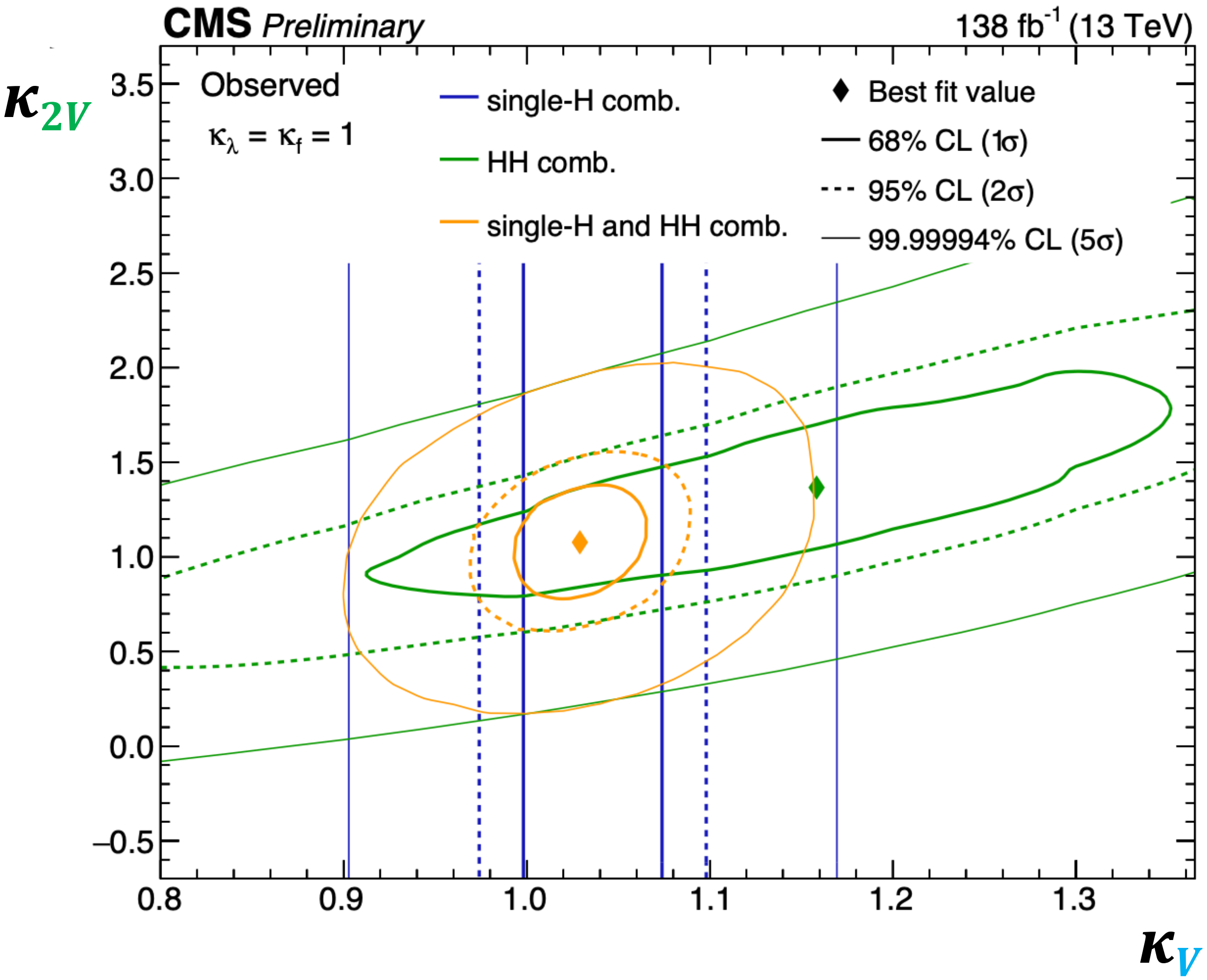




$\kappa_{2V} = 1.02 \pm 0.23$ if other Higgs couplings have Standard Model values

ATLAS Collaboration, arXiv:2406.09971

Evidence for VVHH Coupling

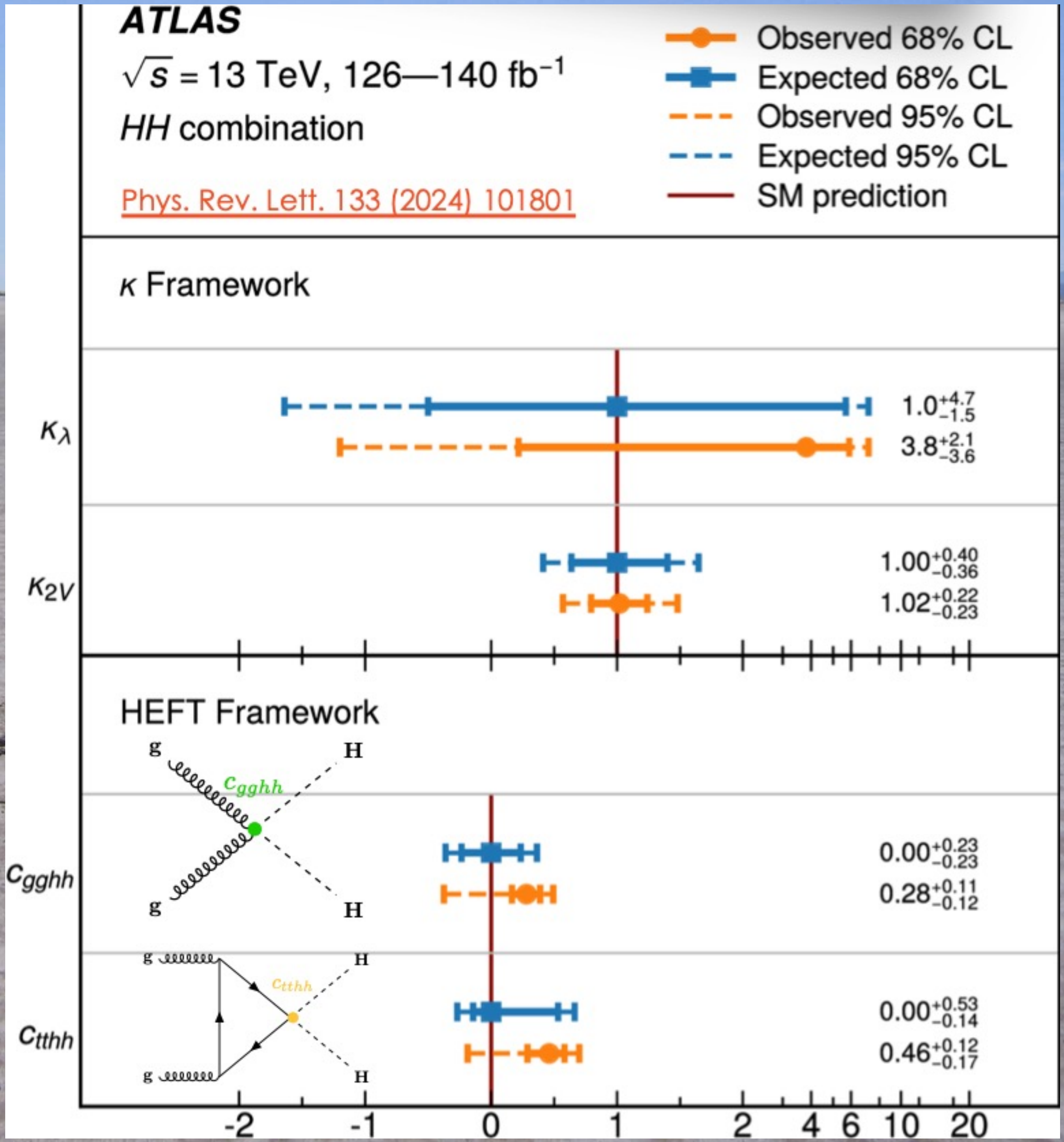


$5-\sigma$ exclusion of $\kappa_{2V} = 0$ if other Higgs couplings have Standard Model values

CMS Collaboration, arXiv:2407.13554

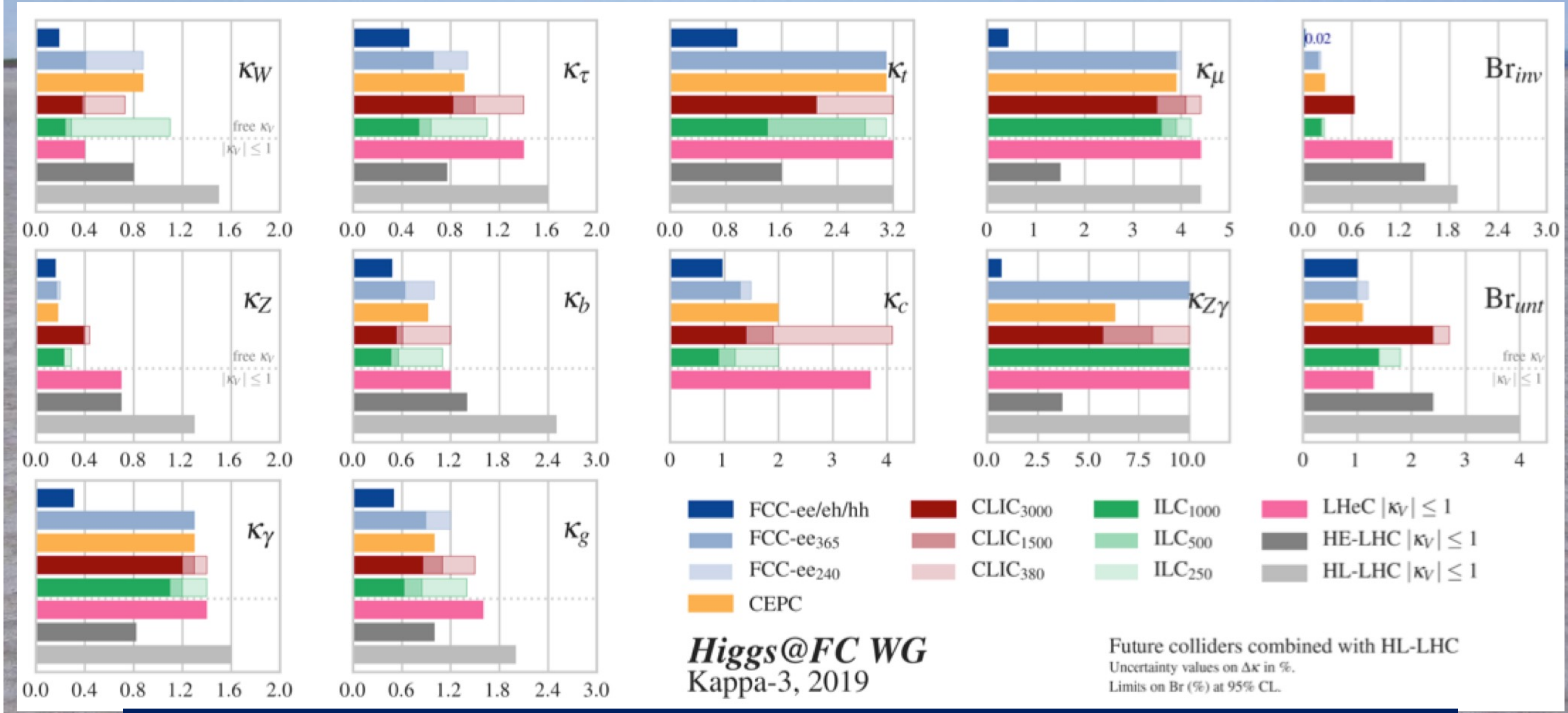
Constraints on Di-Higgs Couplings

- Coupling modifiers
- Higher-dimensional couplings



ATLAS Collaboration, PRL 133 (2024) 10181

Prospects for Future Higgs Measurements



Coupling modifiers κ_i: strengths relative to SM predictions

R.K. Ellis et al (European Strategy), arXiv:1910.11775