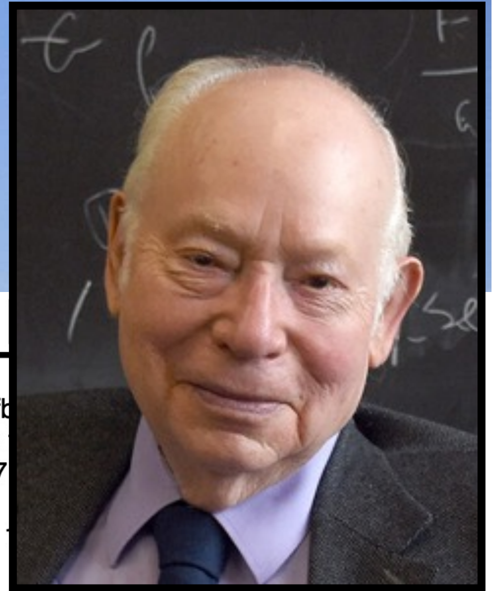
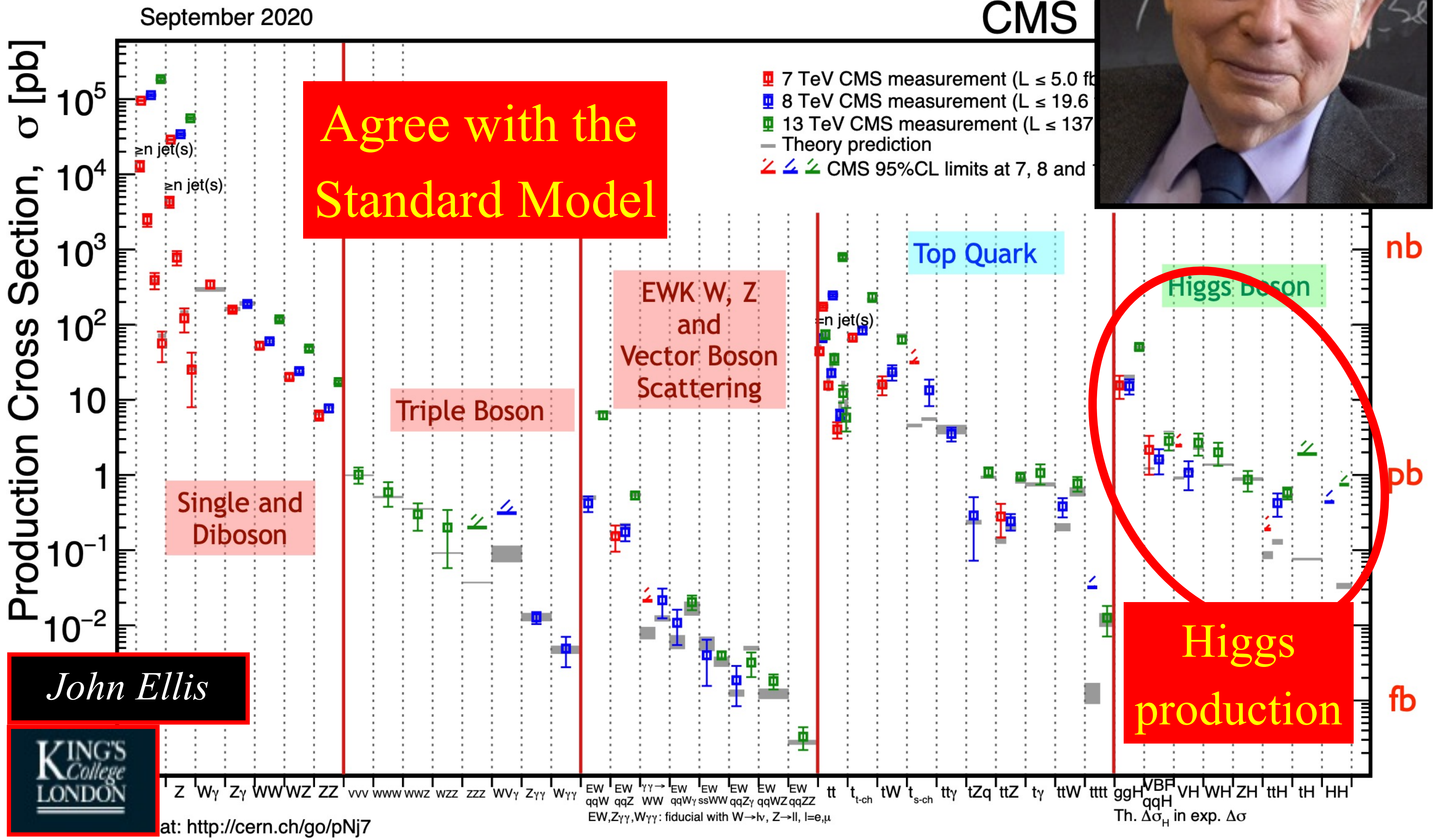
Status of the Standard Model





John Ellis

KING'S College LONDON

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. POLYAKOV

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J. Exptl. Theoret. Physics (U.S.S.R.) 51, 135-146 (July 1966)

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

1965/6

First Steps in 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 symmetry breakdown 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).
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[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 [illegible] (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

$$M = i\{e[a^{*\nu}(k_1)(-ik_{2\nu})\phi^*(k_2) + a^{*\nu}(k_2)(-ik_{1\nu})\phi^*(k_1)] - e(ip_\nu)[a^{*\nu}(k_1)\phi^*(k_2) + a^{*\nu}(k_2)\phi^*(k_1)] - 2em_1 a_\nu^*(k_1)a^{*\nu}(k_2) - fm_0\phi^*(k_1)\phi^*(k_2)\}.$$

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

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

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

$$M = -2iem_1 b^{*\nu}(k_1)b_\nu^*(k_2). \quad (17)$$

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 [illegible] associated with the [illegible] in each b_μ.)

ii. Vector Boson-Vector Boson Scattering

Let k_1, [illegible] the incoming and k_1', [illegible] 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

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

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

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

iii. Vector Boson-Scalar Boson Scattering

Let k, [illegible] be the momenta of the incoming [illegible] and scalar boson, [illegible] 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, $\langle T^*A_\mu A_\nu\rangle$, $\langle T^*A_\mu\Phi\rangle$, and $\langle T^*\Phi\Phi\rangle$, occur only in the combination $\langle T^*B_\mu B_\nu\rangle$. We obtain the expression

$$M_s = i^2\{-2em_1 b^{*\mu}(k') + ieq^\mu\phi^*(k')\}i(g_{\mu\nu} + m_1^{-2}q_\mu q_\nu) \times (s - m_1^2)^{-1}\{-2em_1 b^\nu(k) - ieq^\nu\phi(k)\},$$

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

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

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

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

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.

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

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

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

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

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

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

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

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

and has mass

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

The neutral spin-1 fields of definite mass are

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

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

Their masses are

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

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

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

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

We see that the rationalized electric charge is

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

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

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

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

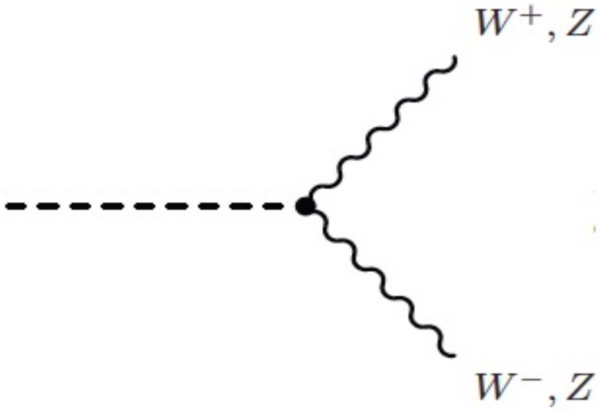
by this model have to do with the couplings of the neutral intermediate meson Z_μ. If Z_μ does not couple to hadrons then the best place to look for effects of Z_μ is in electron-neutron scattering. Applying a Fierz transformation to the W-exchange terms, the total effective e-ν interaction is

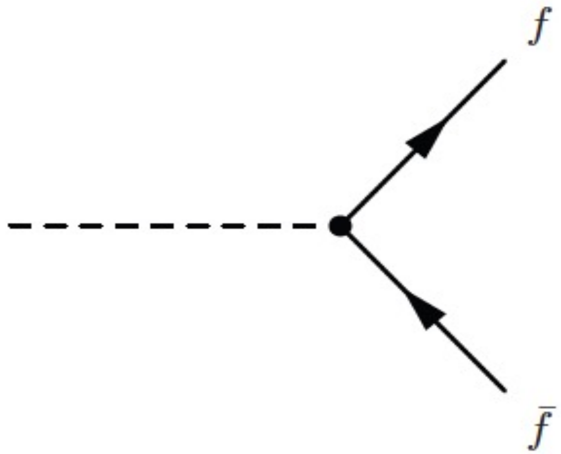
$$\frac{G_W}{\sqrt{2}}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu\left\{\frac{(3g^2-g'^2)}{2(g^2+g'^2)}\bar{e}\gamma^\mu e + \tfrac{3}{2}\bar{e}\gamma^\mu\gamma_5 e\right\}.$$

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."

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

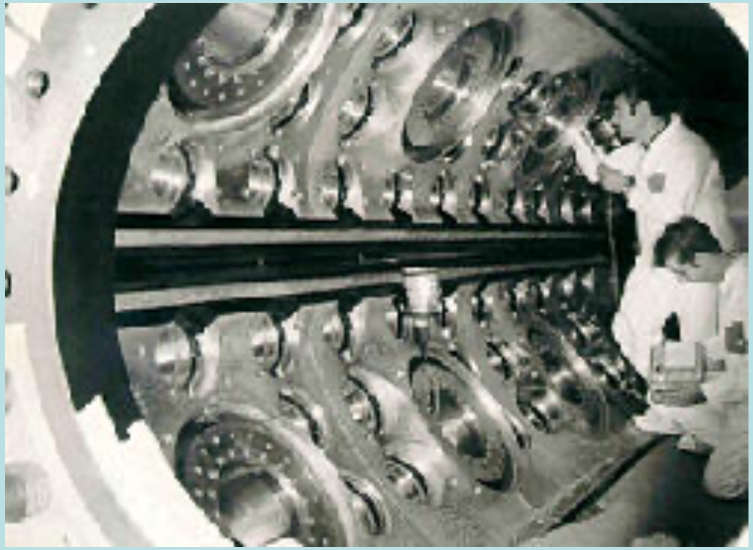
Gauge Theories taken Seriously

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

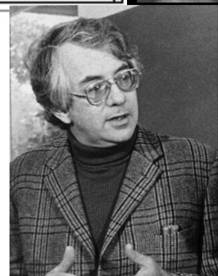
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons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

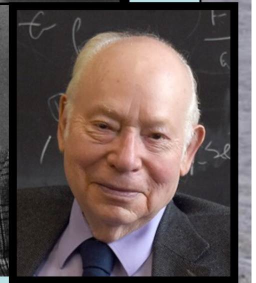
Summary of the Standard Model

- 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:

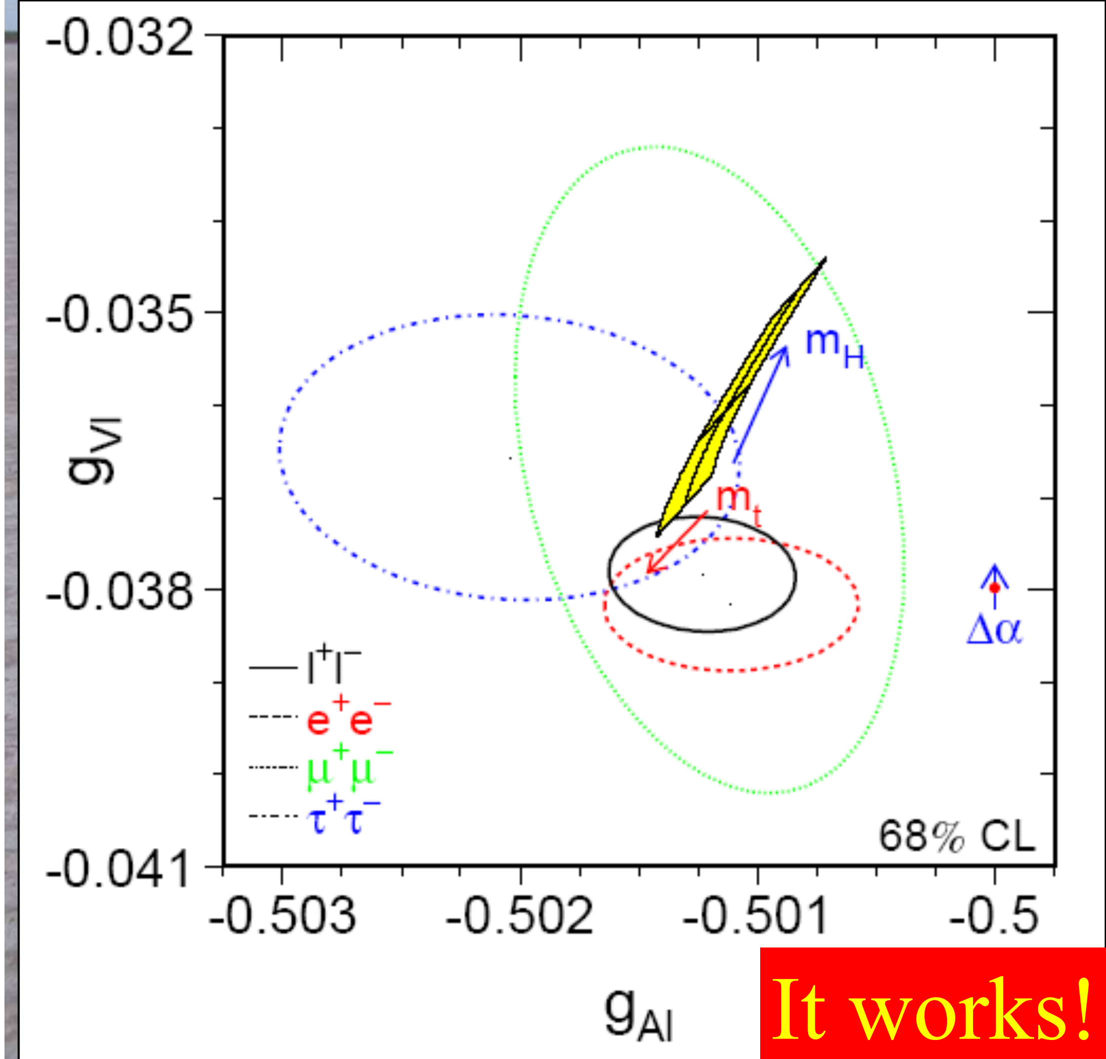
$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} && \text{gauge interactions} \\ &+ i\bar{\psi} \not{D}\psi + h.c. && \text{matter fermions} \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. && \text{Yukawa interactions} \\ &+ |D_\mu \phi|^2 - V(\phi) && \text{Higgs potential} \end{aligned}$$

High-precision tests at LEP, …

No direct evidence until 2012

Precision Tests of the Standard Model

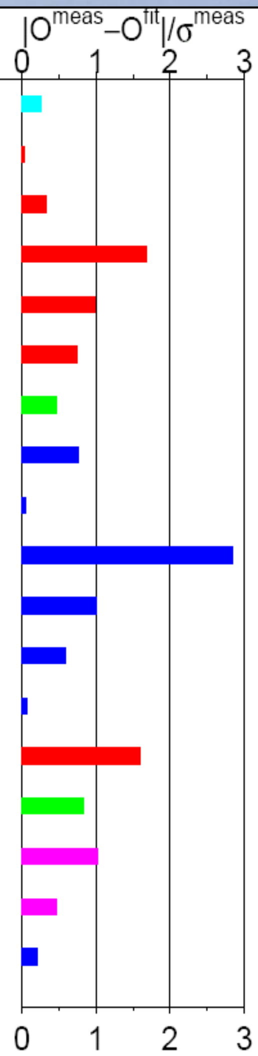
Lepton couplings



It works!

Pulls in global fit

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.410 ± 0.032	80.377
Γ_W [GeV]	2.123 ± 0.067	2.092
m_t [GeV]	172.7 ± 2.9	173.3



Where are the top and Higgs?

Estimating Masses with Electroweak Data

- High-precision electroweak measurements are sensitive to quantum corrections

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

Veltman

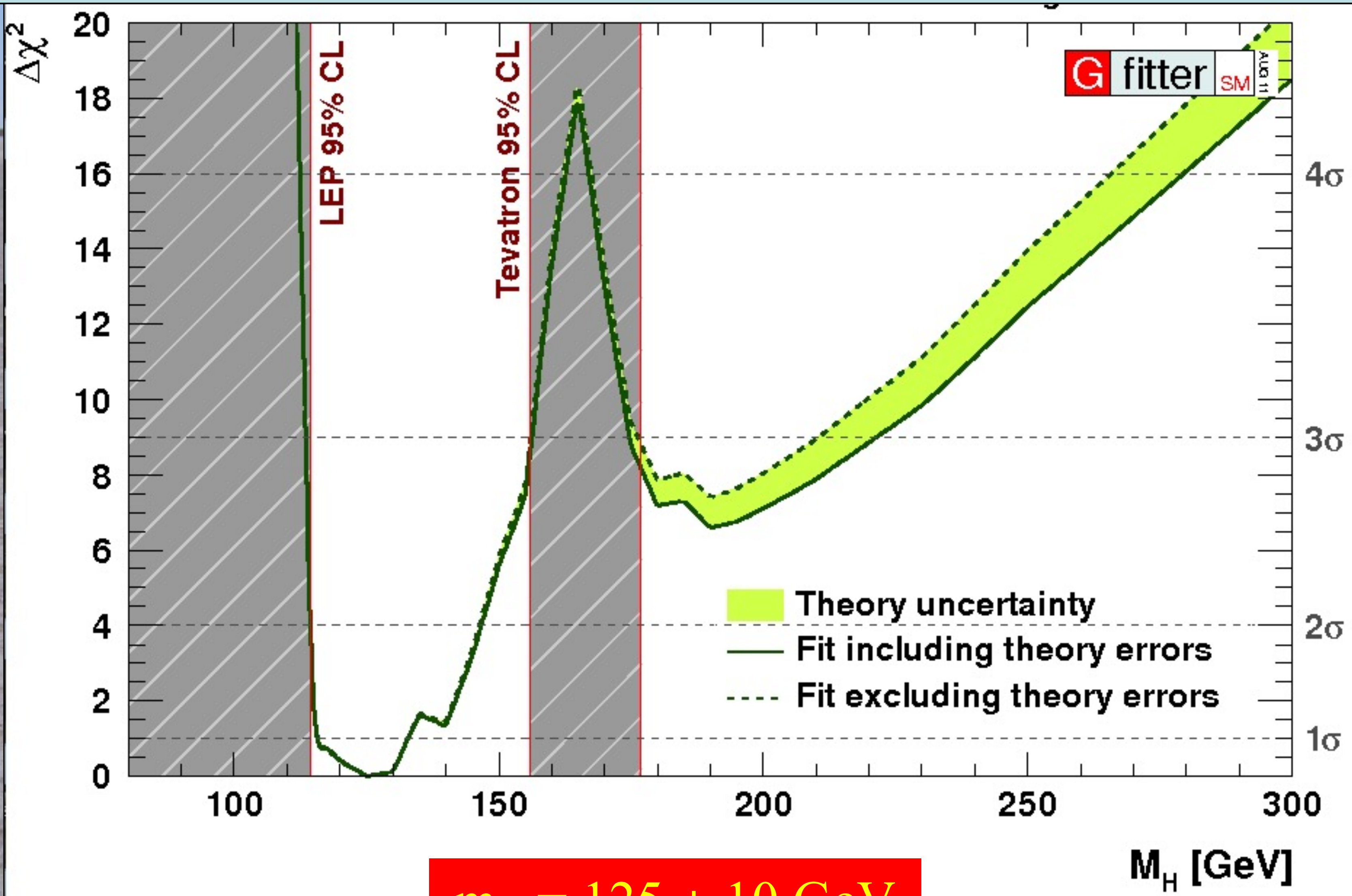
- Sensitivity to top mass is quadratic: $\frac{3G_F}{8\pi^2\sqrt{2}} m_t^2$

- Sensitivity to Higgs mass is logarithmic:

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

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

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

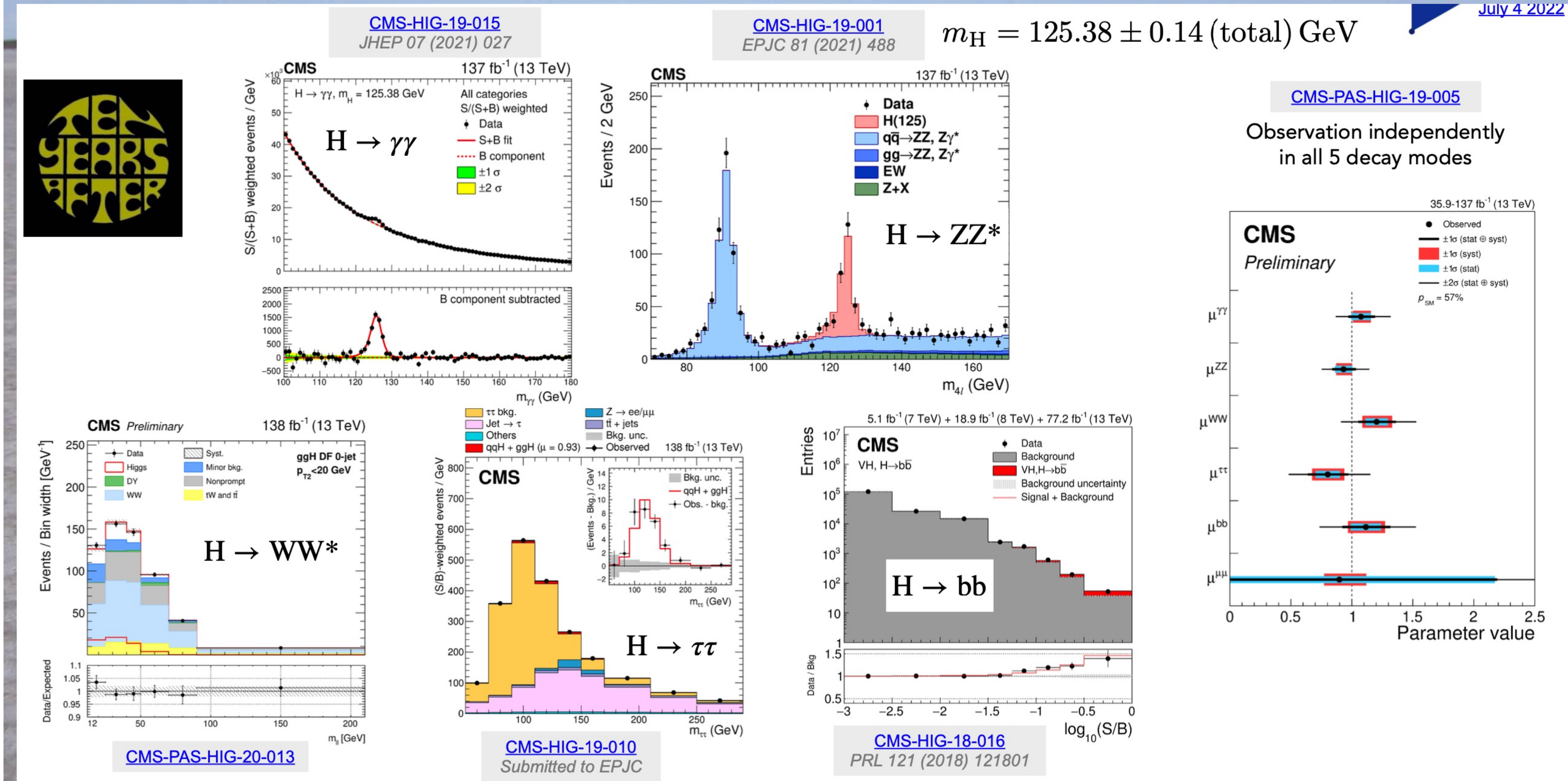
Higgsdependence Day!

The Particle Higgsaw Puzzle

Did the LHC find the missing piece?

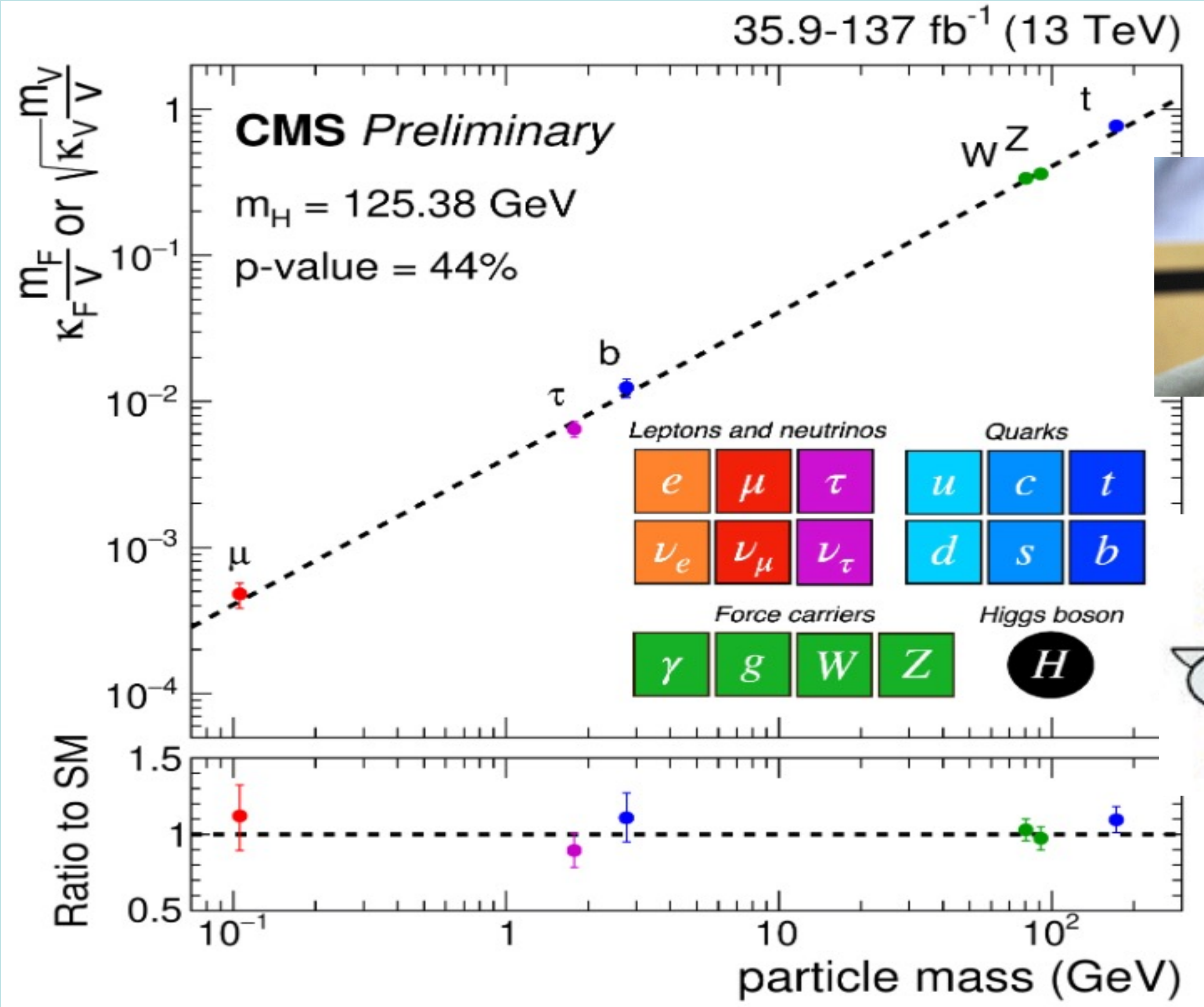
Is it the right shape? Does it have the right size?

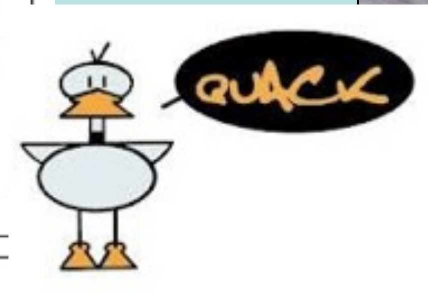
Higgs Measurements



It Walks and Quacks like a Higgs

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





…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

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

- 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?

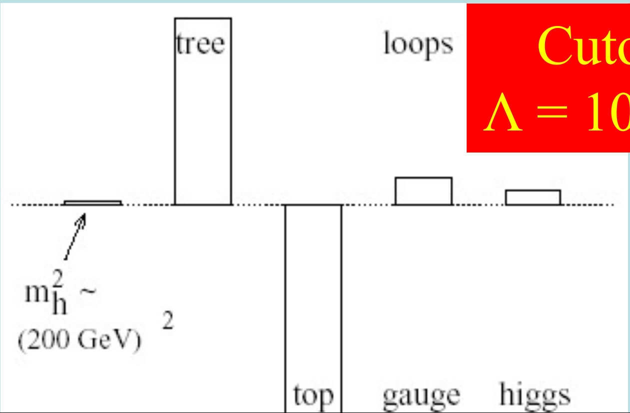
Theoretical worries about the Higgs boson

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
$\Lambda = 10$ 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?

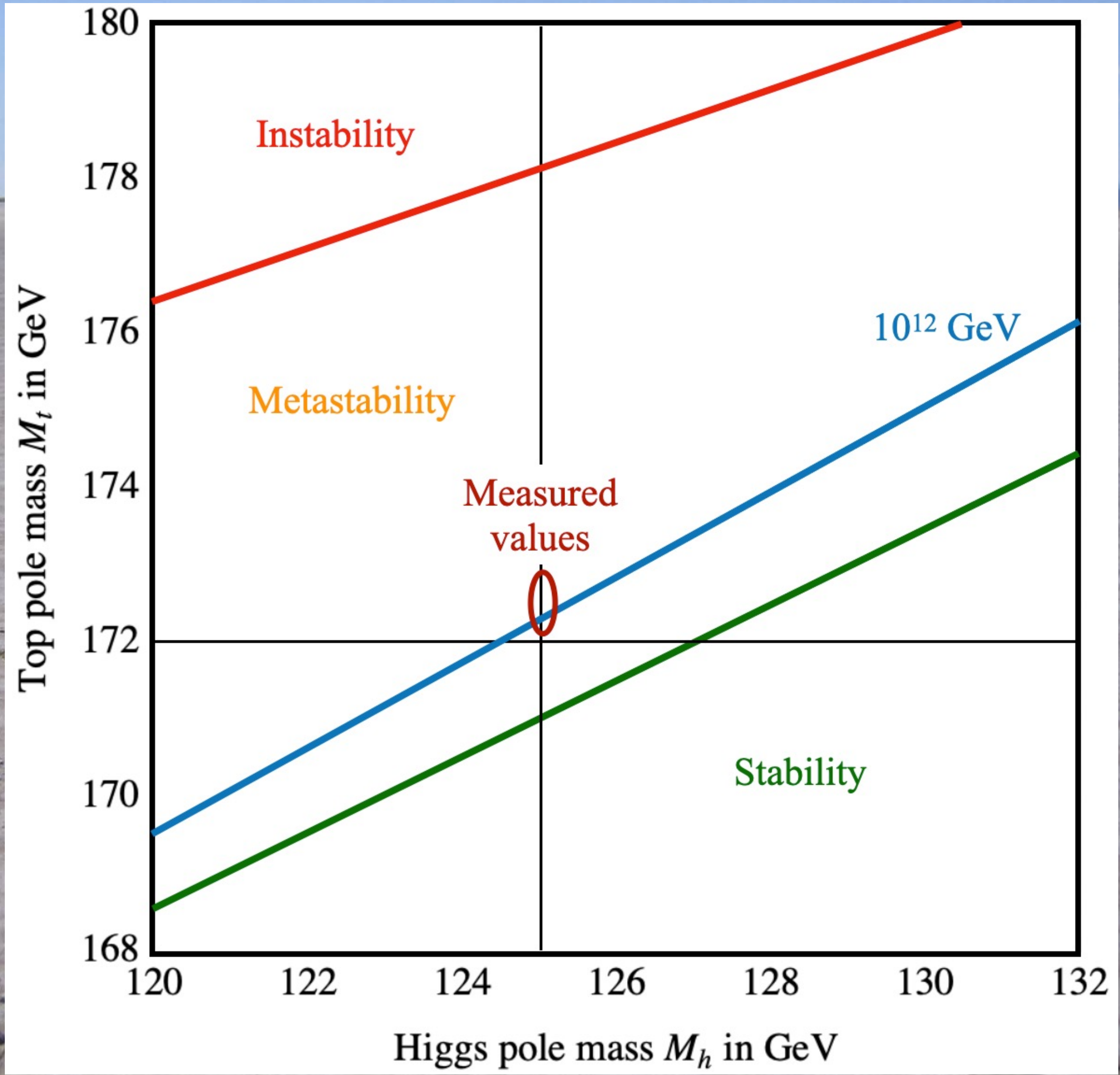
1979

Is “Empty Space” Unstable?

Politzer & 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

Is “Empty Space” Unstable?

- Dependence of instability scale on masses of Higgs boson and top quark, and strong coupling:

$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 10.5 - 1.3\left(\frac{m_t}{\mathrm{GeV}} - 172.6\right) + 1.1\left(\frac{m_H}{\mathrm{GeV}} - 125.1\right)\Big) + 0.6\left(\frac{\alpha_s(m_Z) - 0.1179}{0.0009}\right)$$

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

- New CMS value of m_t:

$$m_t = 171.77 \pm 0.38\mathrm{GeV}$$

CMS Collaboration, April 2022

- Particle Data Group values:

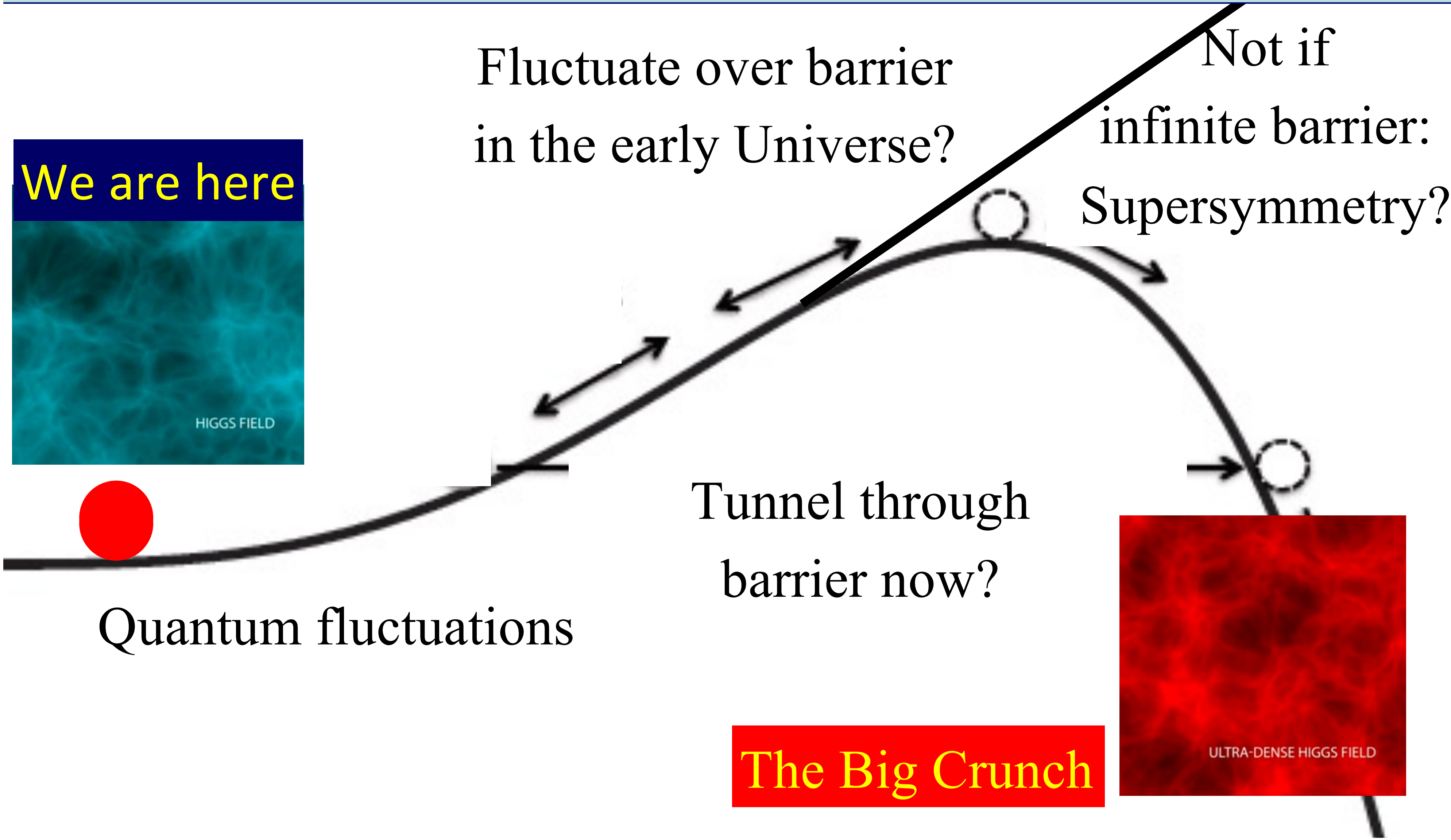
$$m_H = 125.25 \pm 0.17\mathrm{GeV}, \alpha_s(m_Z) = 0.1179 \pm 0.0009$$

- Instability scale:

$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 11.7 \pm 0.8$$

- Dominant uncertainties those in α_s and m_t

Will the Universe Collapse? Should it have Collapsed already?



1967

Weinberg: Anthropic Estimate of the Cosmological Constant

"… the laws of nature should allow the existence of intelligent beings that can ask about the laws of nature …"

The cosmological constant problem*

Steven Weinberg

Theory Group, Department of Physics, University of Texas, Austin, Texas 78712

Astronomical observations indicate that the cosmological constant is many orders of magnitude smaller than estimated in modern theories of elementary particles. After a brief review of the history of this problem, five different approaches to its solution are described.

CONTENTS

As I was going up the stair,
I met a man who wasn't there.
He wasn't there again today,
I wish, I wish he'd stay away.

Hughes Mearns

II. EARLY HISTORY

After completing his formulation of general relativity in 1915–1916, Einstein (1917) attempted to apply his new theory to the whole universe. His guiding principle was that the universe is static: "The most important fact that we draw from experience is that the relative velocities of the stars are very small as compared with the velocity of light." No such static solution of his original equations could be found (any more than for Newtonian gravitation), so he modified them by adding a new term involving a free parameter λ, the cosmological constant:[2]

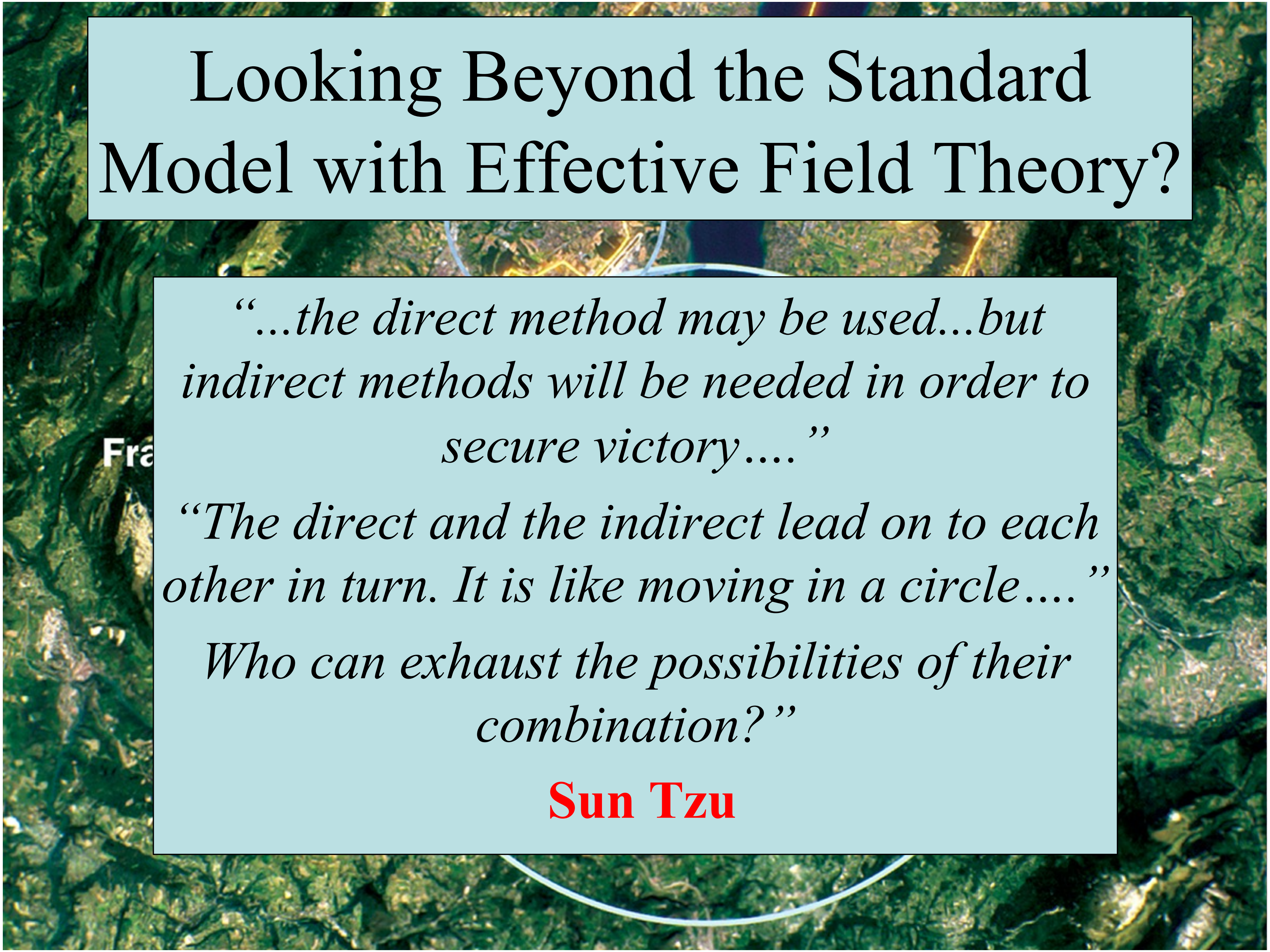
$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R - \lambda g_{\mu\nu} = -8\pi G T_{\mu\nu} \ . \qquad (2.1)$$

Now, for $\lambda > 0$, there was a static solution for a universe filled with dust of zero pressure and mass density

$$\rho = \frac{\lambda}{8\pi G} \ . \qquad (2.2)$$

Its geometry was that of a sphere S_3, with proper circumference $2\pi r$, where

Looking Beyond the Standard Model with Effective Field Theory?



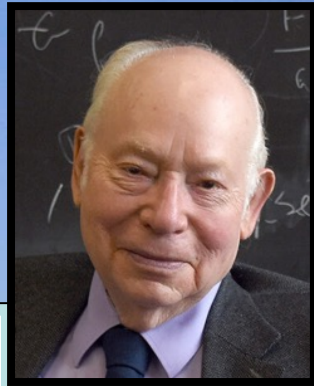
"...the direct method may be used...but indirect methods will be needed in order to secure victory...."

"The direct and the indirect lead on to each other in turn. It is like moving in a circle...."

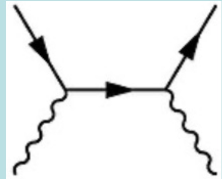
Who can exhaust the possibilities of their combination?"

Sun Tzu

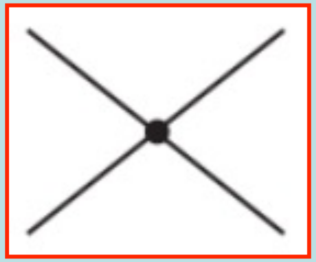
Effective Field Theories (EFTs)
a long and glorious History



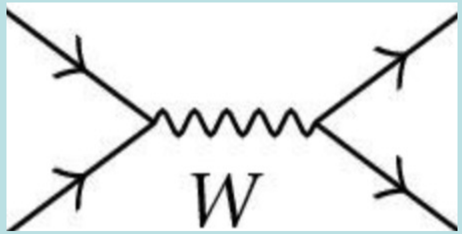
- 1930's: "Standard Model" of QED had d=4



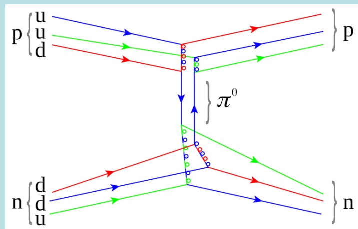
- **Fermi's four-fermion theory of the weak force**



- 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



1967

Weinberg: Effective Field Theory for the Strong Interactions

PHYSICAL REVIEW VOLUME 166, NUMBER 5 25 FEBRUARY 1968

Nonlinear Realizations of Chiral Symmetry*

STEVEN WEINBERG†
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 25 September 1967)

We explore possible realizations of chiral symmetry, based on isotopic multiplets of fields whose transformation rules involve only isotopic-spin matrices and the pion field. The transformation rules are unique, up to possible redefinitions of the pion field. Chiral-invariant Lagrangians can be constructed by forming isotopic-spin-conserving functions of a covariant pion derivative, plus other fields and their covariant derivatives. The resulting models are essentially equivalent to those that have been derived by treating chirality as an ordinary linear symmetry broken by the vacuum, except that we do not have to commit ourselves as to the grouping of hadrons into chiral multiplets; as a result, the unrenormalized value of g_A/g_V need not be unity. We classify the possible choices of the chiral-symmetry-breaking term in the Lagrangian according to their chiral transformation properties, and give the values of the pion-pion scattering lengths for each choice. If the symmetry-breaking term has the simplest possible transformation properties, then the scattering lengths are those previously derived from current algebra. An alternative method of constructing chiral-invariant Lagrangians, using ρ mesons to form covariant derivatives, is also presented. In this formalism, ρ dominance is automatic, and the current-algebra result from the ρ-meson coupling constant arises from the independent assumption that ρ mesons couple universally to pions and other particles. Including ρ mesons in the Lagrangian has no effect on the π-π scattering lengths, because chiral invariance requires that we also include direct pion self-couplings which cancel the ρ-exchange diagrams for pion energies near threshold.

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)**

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

Summarize Analysis Framework

- Include all leading dimension-6 operators?

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2}\mathcal{O}_i$$

- Simplify by assuming flavour $SU(3)^5$ or $SU(2)^2 \times SU(3)^3$ symmetry for fermions
- Work to linear order in operator coefficients, i.e. $\mathcal{O}(1/\Lambda^2)$
- Use G_F, M_Z, α as input parameters

Dimension-6 SMEFT Operators

- Including 2- and 4-fermion operators
- Different colours for different data sectors
- Grey cells violate SU(3)^5 symmetry
- Important when including top observables

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

X^3	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$\mathcal{O}_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

H^6 and H^4D^2	
$\mathcal{O}_H$	$(H^\dagger H)^3$
$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star (H^\dagger D_\mu H)$

$\psi^2 H^3$	
$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar l_p e_r H)$
$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar q_p d_r H)$

X^2H^2	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$\mathcal{O}_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$\mathcal{O}_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{HWB}$	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$

$\psi^2 XH$	
$\mathcal{O}_{eW}$	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$
$\mathcal{O}_{eB}$	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
$\mathcal{O}_{uG}$	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H G^A_{\mu\nu}$
$\mathcal{O}_{uW}$	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H W^I_{\mu\nu}$
$\mathcal{O}_{uB}$	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H B_{\mu\nu}$
$\mathcal{O}_{dG}$	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H G^A_{\mu\nu}$
$\mathcal{O}_{dW}$	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H W^I_{\mu\nu}$
$\mathcal{O}_{dB}$	$(\bar q_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$

Anomalous magnetic moments

$\psi^2 H^2 D$	
$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
$\mathcal{O}_{Hud}$	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$	
$\mathcal{O}_{ll}$	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$

Flavour anomalies

$(\bar RR)(\bar RR)$	
$\mathcal{O}_{ee}$	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$
$\mathcal{O}_{uu}$	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$
$\mathcal{O}_{dd}$	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$
$\mathcal{O}_{eu}$	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$
$\mathcal{O}_{ed}$	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$
$\mathcal{O}_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$
$\mathcal{O}_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LL)(\bar RR)$	
$\mathcal{O}_{le}$	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$\mathcal{O}_{lu}$	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$\mathcal{O}_{ld}$	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$\mathcal{O}_{qe}$	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$\mathcal{O}_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
$\mathcal{O}_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
$\mathcal{O}_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
$\mathcal{O}_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

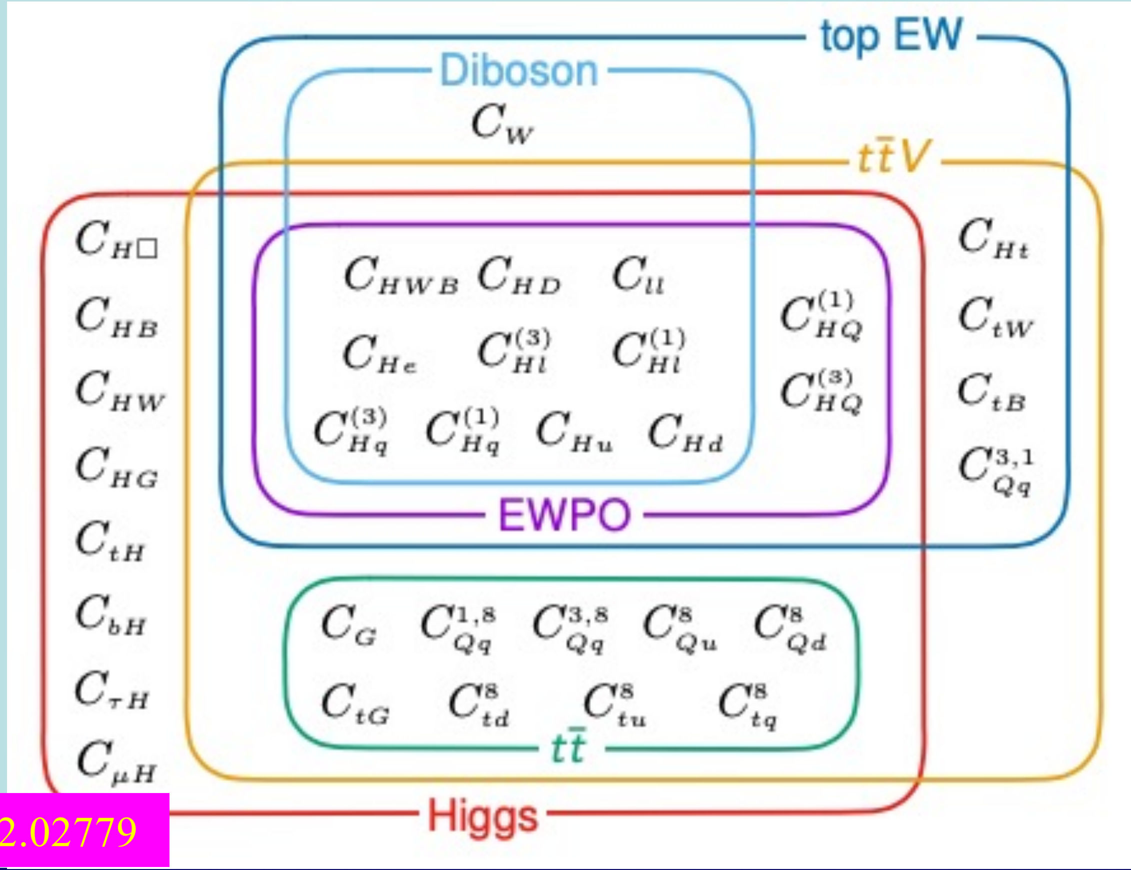
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$	
$\mathcal{O}_{ledq}$	$(\bar l_p^j e_r)(\bar d_s q_t^j)$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$

B-violating	
$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Baryon decay

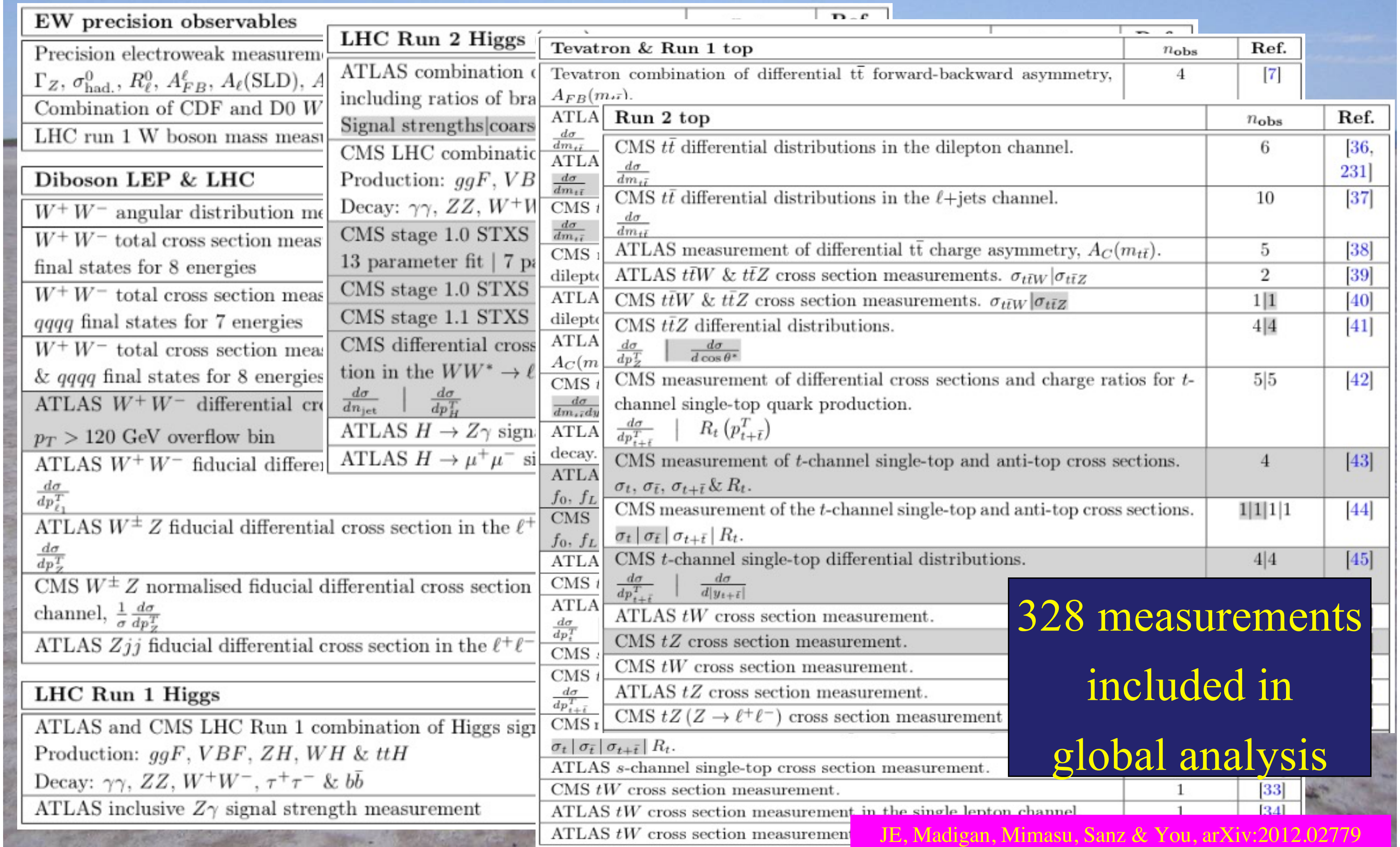
Global SMEFT Fit
to Top, Higgs, Diboson, Electroweak Data

- 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

Data included in Global Fit

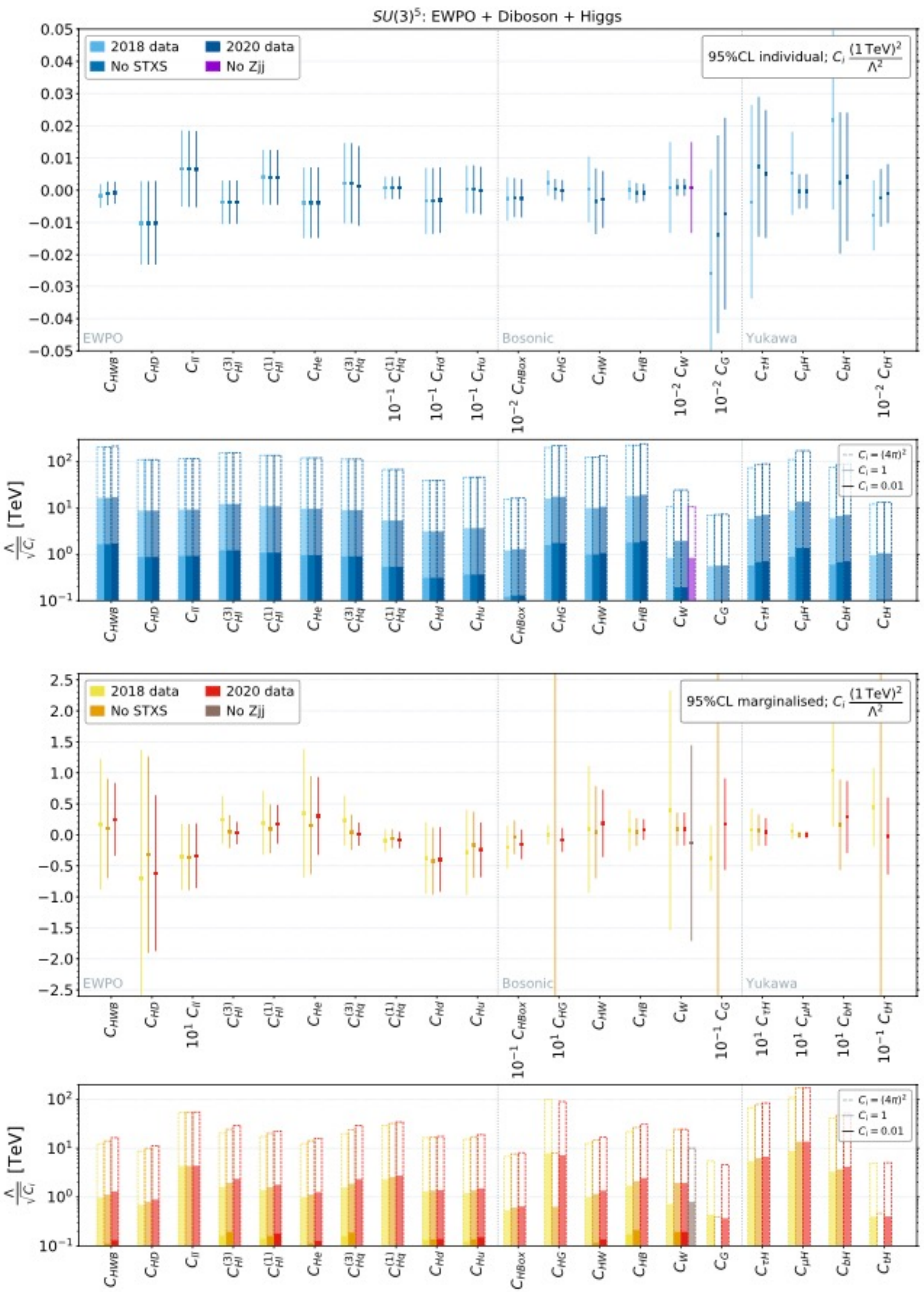


328 measurements included in global analysis

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

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

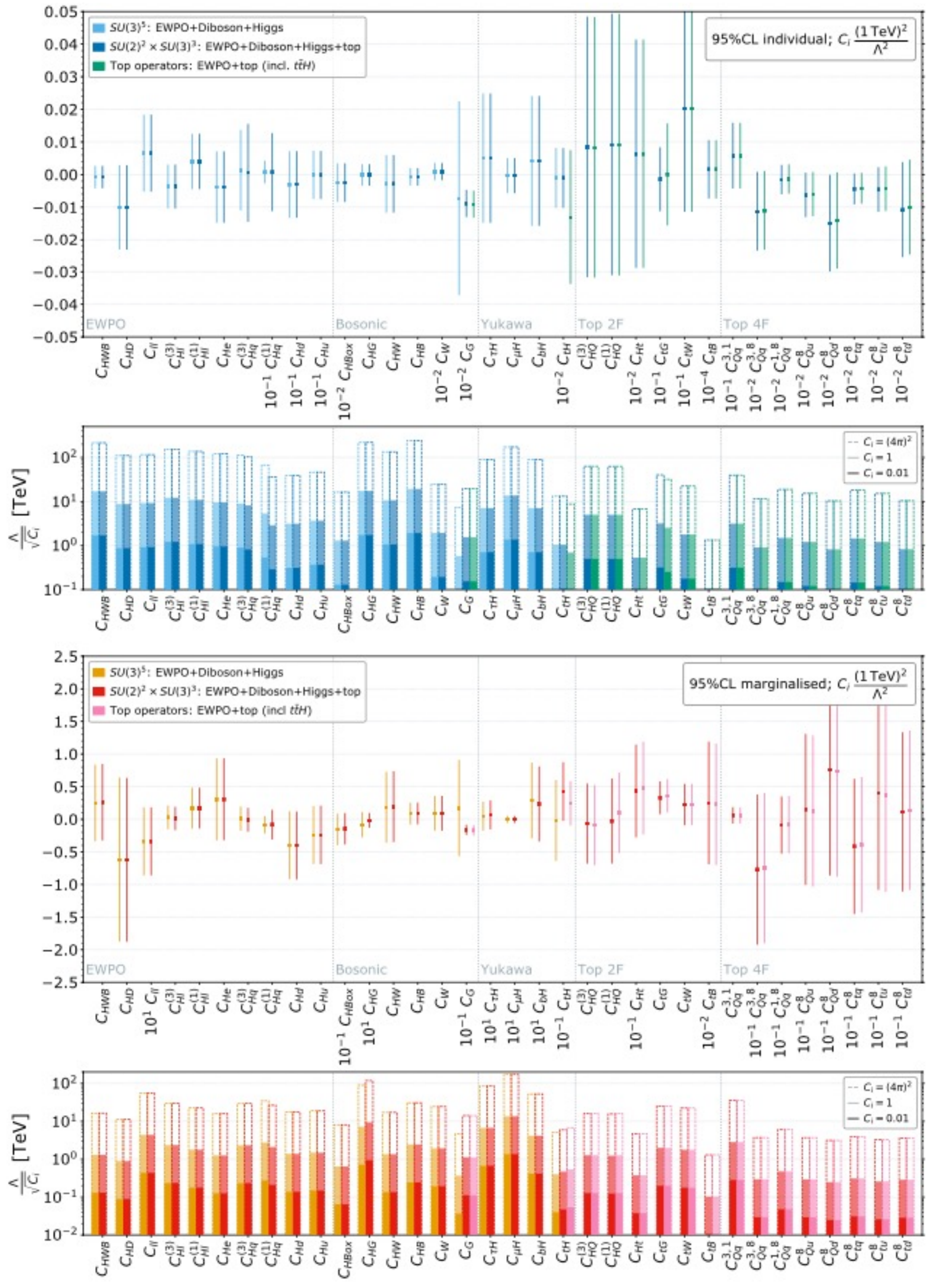
- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**



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

Dimension-6 Constraints with Top-Specific $SU(2)^2 \times SU(3)^3$

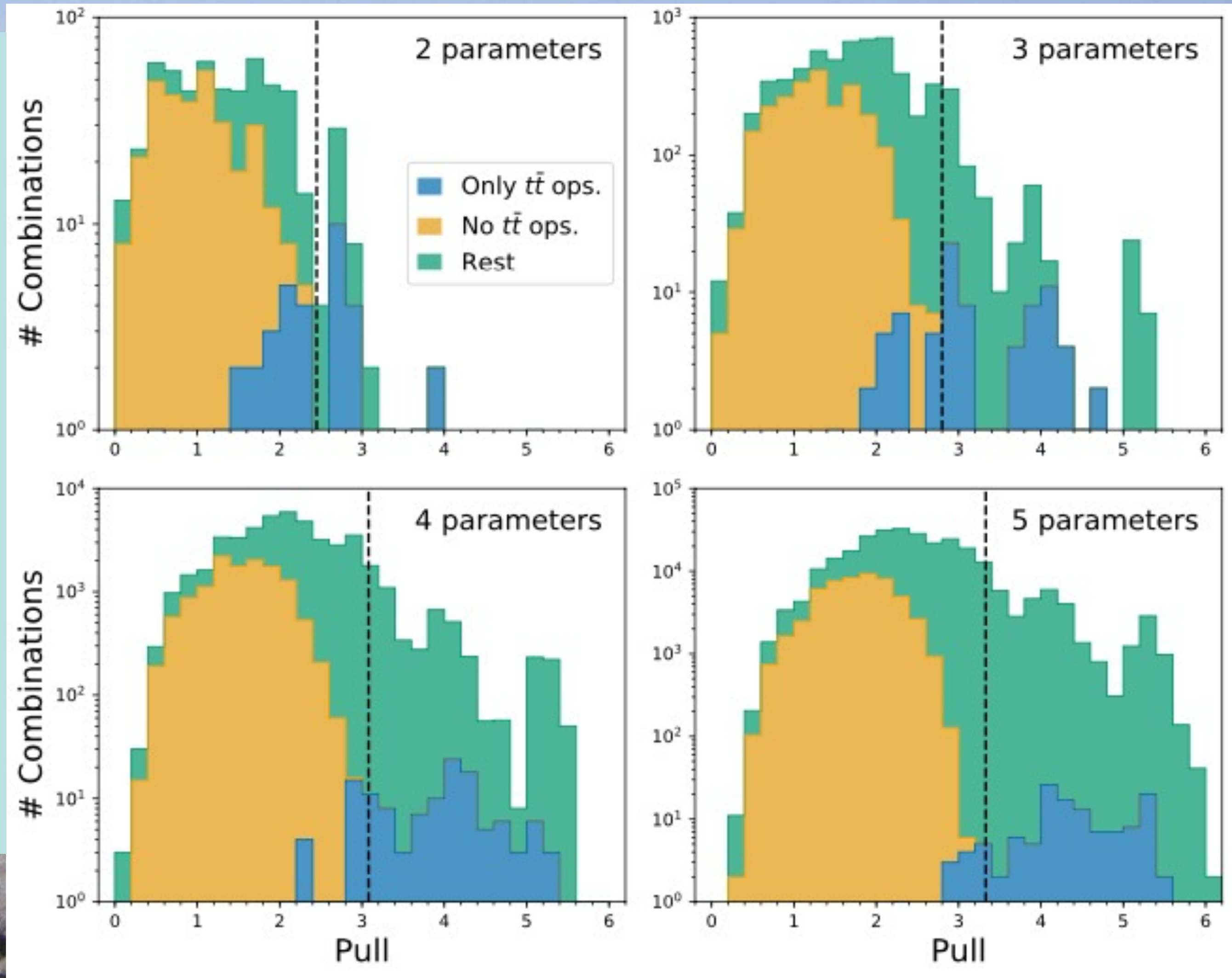
- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**



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

Model-Independent BSM Survey

- **Top-less sector fits SM very well**
- Top sector does not fit so well
- Overall, pulls not excessive
- **No hint of BSM**



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

CDF Collaboration, Science 376 (2022) p170

PARTICLE PHYSICS

High-precision measurement of the *W* boson mass with the CDF II detector

CDF Collaboration†‡, T. Aaltonen[1,2], S. Amerio[3,4], D. Amidei[5], A. Anastassov[6], A. Annovi[7], J. Antos[8,9], G. Apollinari[6], J. A. Appel[6], T. Arisawa[10], A. Artikov[11], J. Asaadi[12], W. Ashmanskas[6], B. Auerbach[13], A. Aurisano[12], F. Azfar[14], W. Badgett[6], T. Bae[15,16,17,18,19,20,21], A. Barbaro-Galtieri[22], V. E. Barnes[23], B. A. Barnett[24], P. Barria[25,26], P. Bartos[8,9], M. Bauce[3,4], F. Bedeschi[25], S. Behari[6], G. Bellettini[25,27], J. Bellinger[28], D. Benjamin[29], A. Beretvas[6], A. Bhatti[30], K. R. Bland[31], B. Blumenfeld[24], A. Bocci[29], A. Bodek[32], D. Bortoletto[23], J. Boudreau[33], A. Boveia[34], L. Brigliadori[35,36], C. Bromberg[37], E. Brucken[1,2], J. Budagov[11]§, H. S. Budd[32], K. Burkett[6], G. Busetto[3,4], P. Bussey[38], P. Butti[25,27], A. Buzatu[38], A. Calamba[39], S. Camarda[40], M. Campanelli[41], B. Carls[42], D. Carlsmith[28], R. Carosi[25], S. Carrillo[43]§, B. Casal[44], M. Casarsa[45], A. Castro[35,36], P. Catastini[46], D. Cauz[45,47,48], V. Cavaliere[42], A. Cerri[22], L. Cerrito[41], Y. C. Chen[49], M. Chertok[50], G. Chiarelli[25], G. Chlachidze[6], K. Cho[15,16,17,18,19,20,21], D. Chokheli[11], A. Clark[51], C. Clarke[52], M. E. Convery[6], J. Conway[50], M. Corbo[6], M. Cordelli[7], C. A. Cox[50], D. J. Cox[50], M. Cremonesi[25], D. Cruz[12], J. Cuevas[44], R. Culbertson[6], N. d'Ascenzo[6], M. Datta[6], P. de Barbaro[32], L. Demortier[30], M. Deninno[35]§, M. D'Errico[3,4], F. Devoto[1,2], A. Di Canto[25,27], B. Di Ruzza[6], J. R. Dittmann[31], S. Donati[25,27], M. D'Onofrio[53], M. Dorigo[45,54], A. Driutti[45,47,48], K. Ebina[10], R. Edgar[5], A. Elagin[34], R. Erbacher[50], S. Errede[42], B. Esham[42], S. Farrington[14], J. P. Fernández Ramos[55], R. Field[43], G. Flanagan[6], R. Forrest[50], M. Franklin[46], J. C. Freeman[6], H. Frisch[34], Y. Funakoshi[10], C. Galloni[25,27], A. F. Garfinkel[23], P. Garosi[25,26], H. Gerberich[42], E. Gerchtein[6], S. Giagu[56], V. 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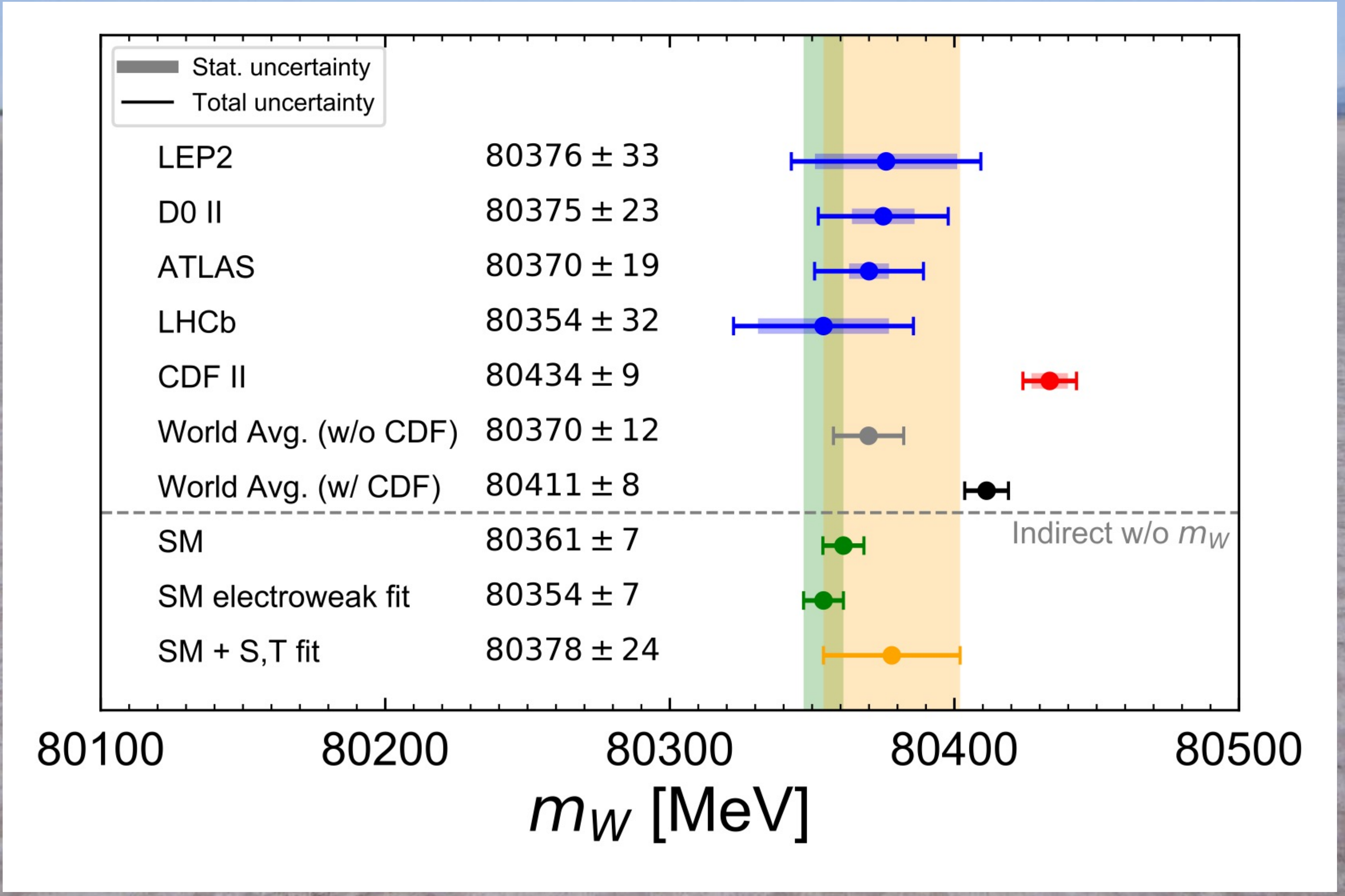
CDF Measurement of m_W

compared with previous measurements



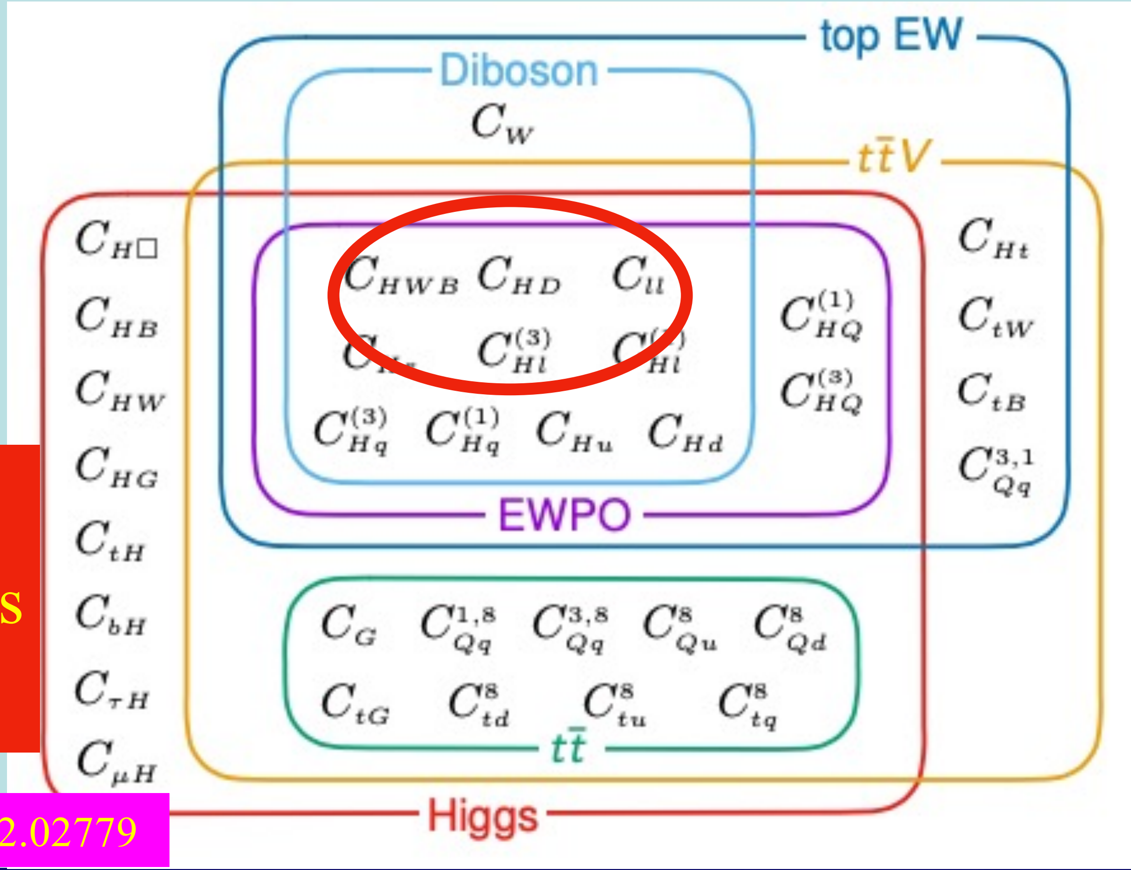
- Tension: 7-σ discrepancy with Standard Model?

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 Operators that can Contribute to W Mass

- Relevant SMEFT operators

$$\mathcal{O}_{HWB} \equiv H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}, \quad \mathcal{O}_{HD} \equiv \left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$$

$$\mathcal{O}_{\ell\ell} \equiv \left(\bar{\ell}_p \gamma_\mu \ell_r\right)\left(\bar{\ell}_s \gamma^\mu \ell_t\right), \quad \mathcal{O}^{(3)}_{H\ell} \equiv \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{\ell}_p \tau^I \gamma^\mu \ell_r\right)$$

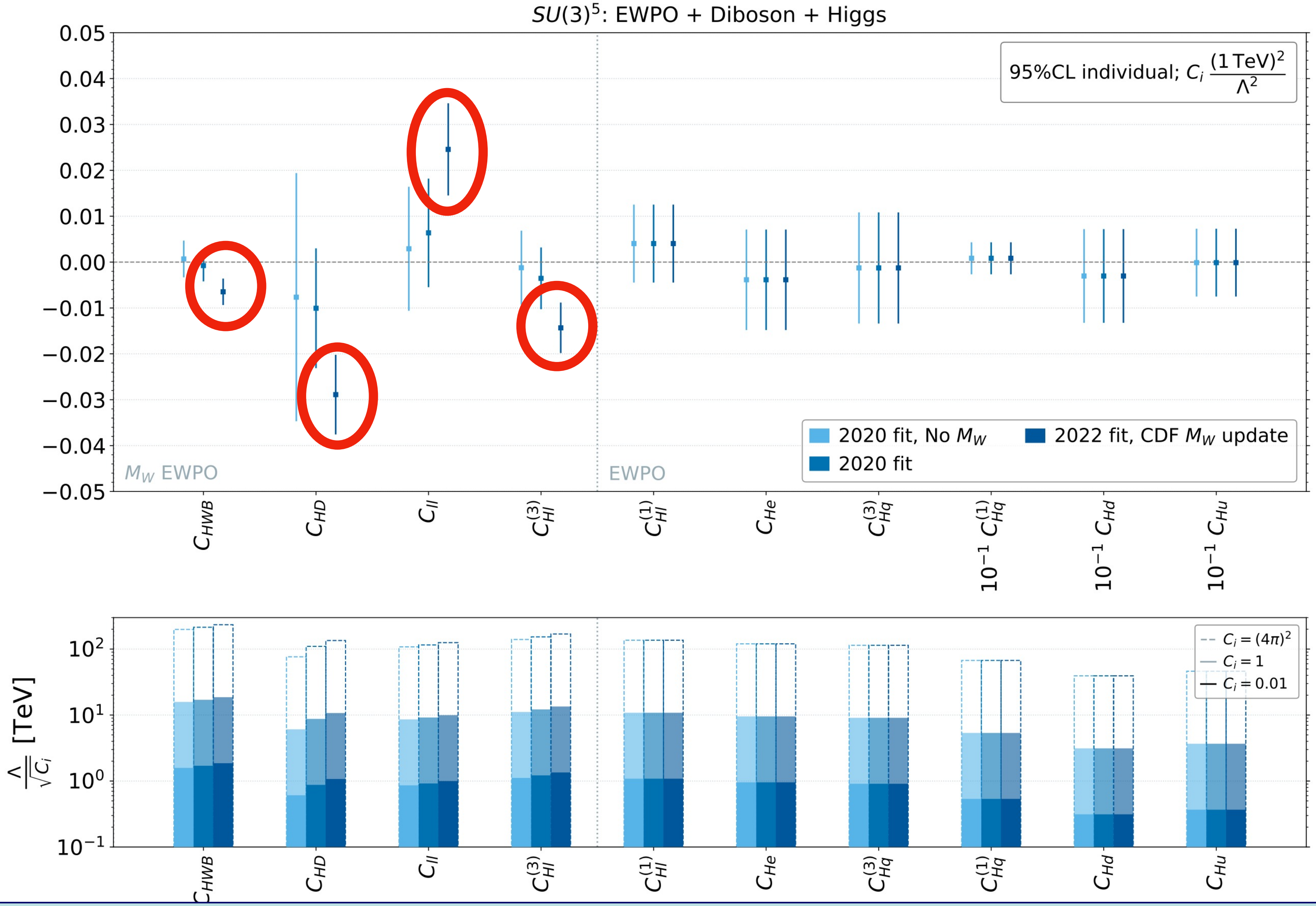
- Three out of four involve the Higgs field!
- Contributions to W mass

$$\frac{\delta m_W^2}{m_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w}\frac{v^2}{4\Lambda^2}\left(\frac{\cos\theta_w}{\sin\theta_w} C_{HD} + \frac{\sin\theta_w}{\cos\theta_w}\left(4C^{(3)}_{Hl} - 2C_{ll}\right) + 4C_{HWB}\right)$$

- Contributions to *S* and *T* oblique parameters

$$\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16\pi} S \quad , \quad \frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)} T$$

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

Single-Field Models that can Contribute to W Mass

Model	C_{HD}	C_{ll}	$C_{Hl}^{(3)}$	$C_{Hl}^{(1)}$	C_{He}	$C_{H\square}$	$C_{\tau H}$	C_{tH}	C_{bH}
S_1		X							
Σ			X	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	X					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
B	-2						$-y_\tau$	$-y_t$	$-y_b$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
W	X					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

Wrong sign

Right sign

Operators contributing to mw

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

Models Fitting the Mass of the W Boson

Spins

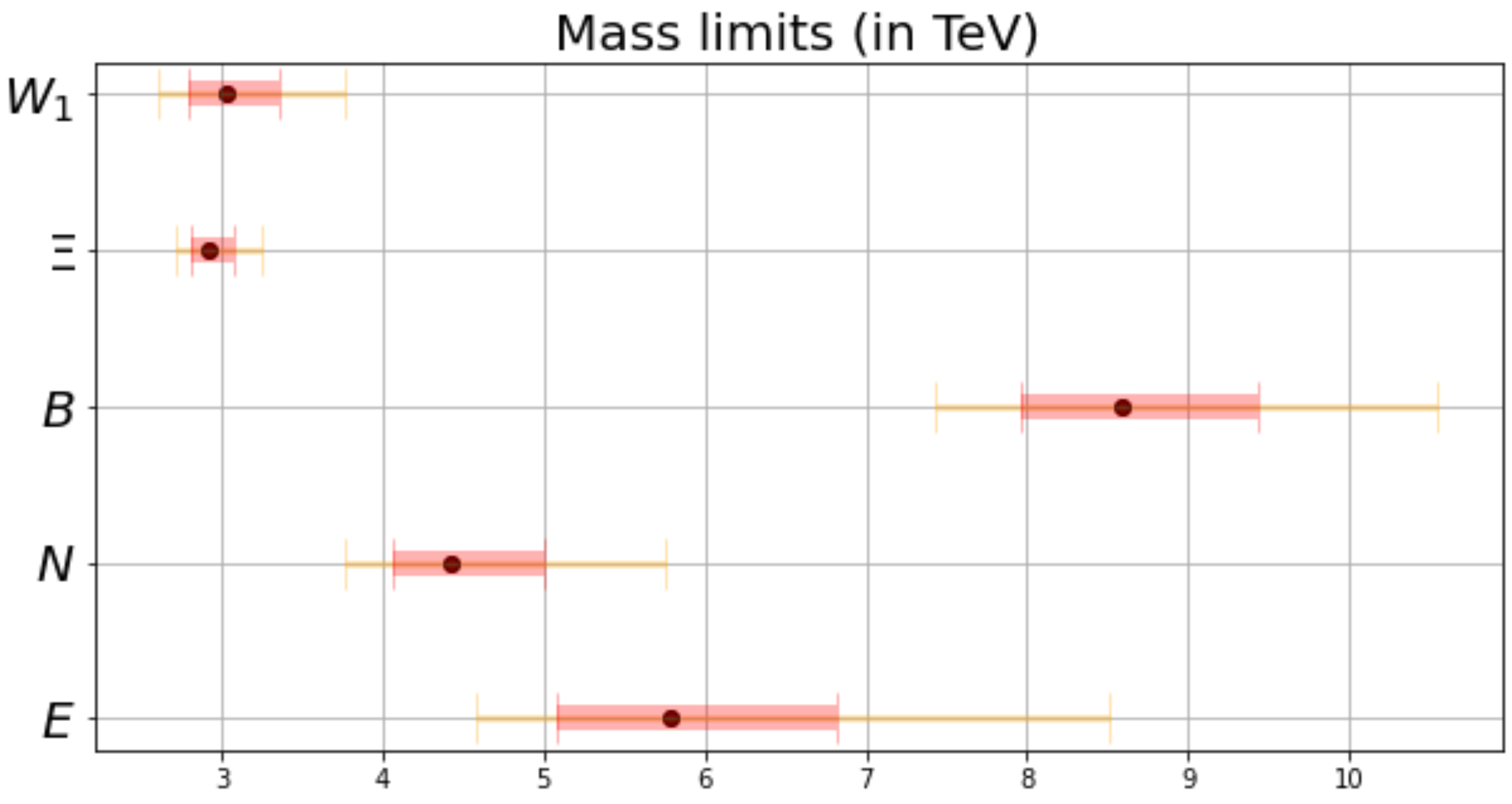
V

S

V

F

F



- 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

Searching for Models Fitting the Mass of the W Boson

- W: Isotriplet vector boson, mass ~ 3 TeV x coupling, electroweak production, accessible at LHC?
- B: Singlet vector boson, mass ~ 8 TeV x coupling, phenomenology depends on fermion couplings, too heavy for LHC?
- Ξ: Isotriplet scalar boson, mass ~ 3 TeV x coupling, detectable in LHC searches for heavy Higgs bosons?
- N: Isosinglet neutral fermion, mass ~ 4 TeV x coupling, similar to (right-handed) singlet neutrino
- E: Isosinglet charged fermion, mass ~ 6 TeV x coupling, similar to (right-handed) singlet electron

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

Some Final Words

"If there is no point in the universe that we discover by the methods of science, there is a point that we can give the universe by the way we live"

Steven Weinberg