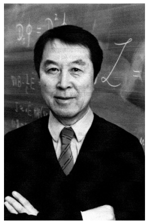
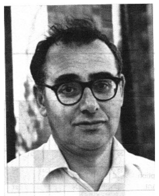
The Story of the Higgs Boson

A personal perspective

Higgs story intertwined with stories of spontaneous symmetry breaking and (non-Abelian) gauge theories

- Spontaneous symmetry breaking and (pseudo) Nambu-Goldstone bosons
  & their role in the making of the Standard Model
- The Higgs mechanism & the electroweak theory
- Searching for the Higgs: theory
- Searching for the Higgs: experiment
- Where are we today and where are we going?

1960  1961  SSB in condensed matter & particle physics: massless scalar

1962 Formal proof of Goldstone theorem — Goldstone, Salam & Weinberg

Mid 1960's: SSB becomes mainstream in particle physics: current algebra & PCAC Wikipedia: "archaic term for spontaneously broken chiral symmetry"

quark condensation: $\langle \bar{q}q \rangle = \langle \bar{q}_R q_L + \bar{q}_L q_R \rangle \neq 0$ $\quad q^T = (u, d)$

spontaneously breaks $SU(2)_L \otimes SU(2)_R : \quad q_L \to U_L q_L, \quad q_R \to U_R q_R$ to $SU(2)$: $U_L = U_R$

Nambu-Goldstone boson $= \pi$: $m_\pi^2 = (m_u + m_d)\langle \bar{q}q \rangle / f_\pi^2 \to 0$ if $m_{u,d} \to 0$

Small explicit breaking from $\quad \mathcal{L}_{\text{mass}} = -\bar{q}Mq, \quad M = \text{diag}(m_u, m_d)$

(Current understanding: M arises from quark couplings to Higgs!)

Tests of spontaneously broken chiral symmetry in low energy pion physics:

$\surd$ π-π and π-N scattering lengths $\Rightarrow$ strong couplings chiral invariant — Weinberg

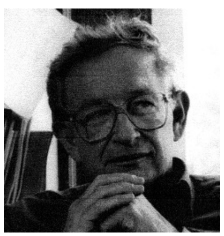
$\Rightarrow$ mediated by vector boson exchange (like QED)

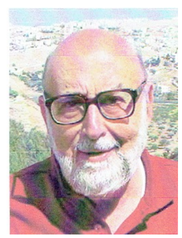
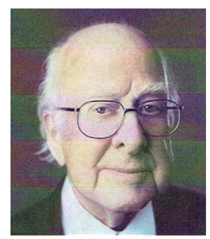
1968-71: scaling in DES $\Rightarrow$ asymptotic freedom $\Rightarrow$ non-Abelian gauge theory: 1973 QCD

Meanwhile 1960's: CA + PCAC applied to weak decays confirms chiral symmetry of strong couplings + $V - A$ structure of weak couplings — Cabbibo theory

1961 Glashow, 1964 Salam & Ward: 1st formulations of electroweak theory

symmetry breaking "by hand"

1963 

1964    $\times 2^*$

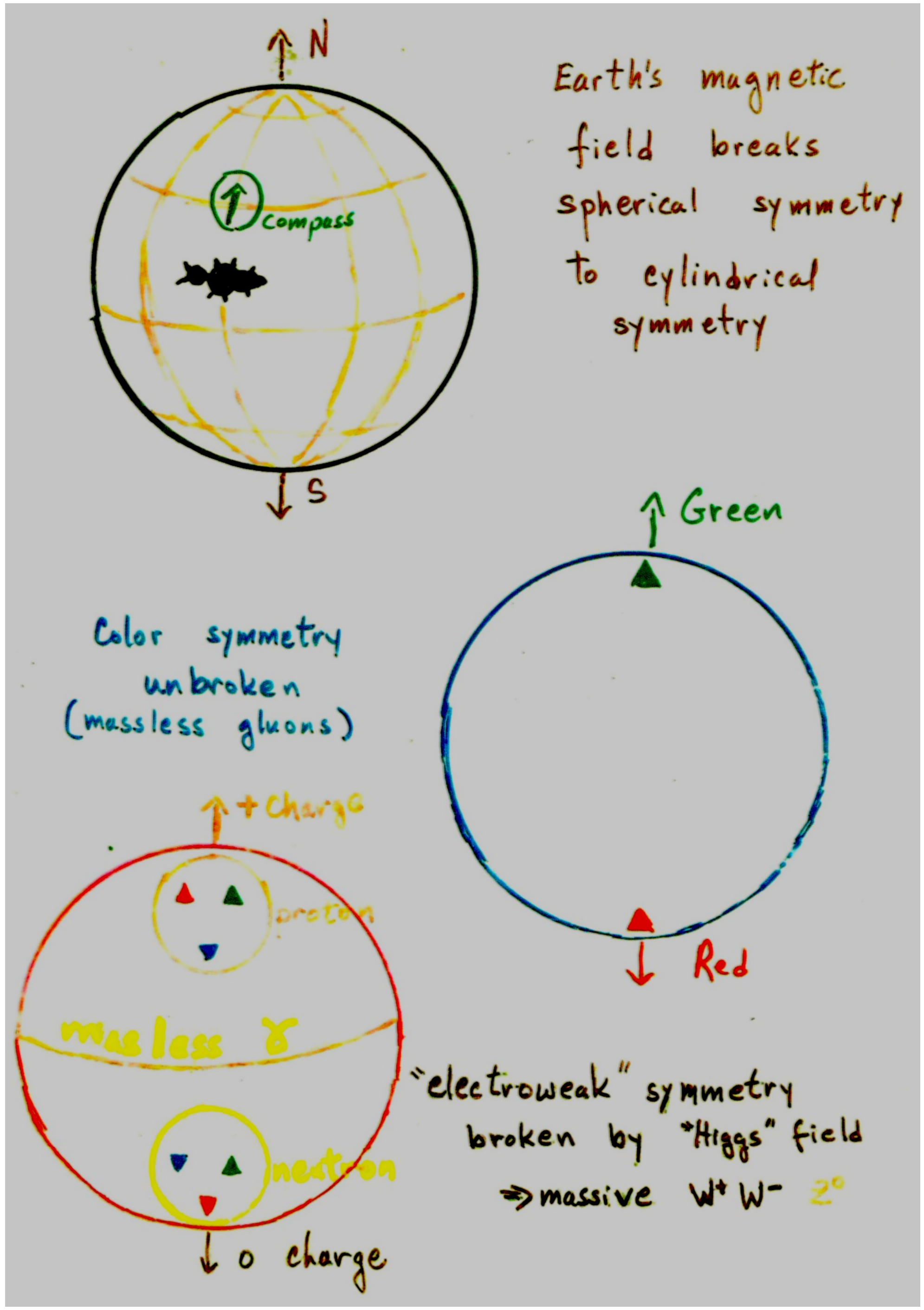
Guralnik, Hagen & Kibble

"Higgs" mechanism in CM

"Higgs" mechanism in QFT

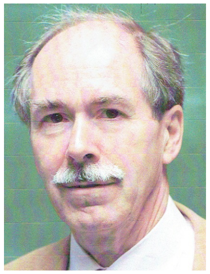
* Higgs particle

Spontaneously broken gauge theory: would-be Nambu-Goldstone bosons become longitudinal components of now massive gauge bosons



N
S
compass
Earth's magnetic field breaks spherical symmetry to cylindrical symmetry
Green
Red
Color symmetry unbroken (massless gluons)
+ Charge
proton
massless γ
neutron
0 charge
"electroweak" symmetry broken by "Higgs" field
⇒ massive W+ W- Z0

1967 Weinberg, 1968 Salam: electroweak theory with Higgs mechanism

1971-72  

Lee & Zinn-Justin

proof of renormalizability of

(spontaneously broken or not)

non-Abelian gauge theories

Revival of "A theory of leptons" (Weinberg 1967)

• Incorporation of hadrons needed CHARM to suppress strangeness changing neutral currents

Glashow Iliopoulos & Maiani

• BOTH quarks and leptons needed for full renormalization: anomaly cancellation

$\sum Q_q + \sum Q_\ell = 0$ Bouchiat Iliopoulos & Meyer

$\Rightarrow$ 1975-6 Discovery of τ requires new quarks: t, b

Nov. 1975 (preprint) "A Phenomenological Profile of the Higgs Boson" Ellis, G & Nanopoulos

Why not "Search for Higgs"?

August 1974 (preprint) “Search for Charm” G, Lee & Rosner

November 1974: J/ψ, June 1976 $D^{\pm}$ < 2 years!

Circa 1976 to present: picture of elementary particle and forces

Force	matter	mediator	
strong	uuu, ddd, sss, ccc, bbb, ttt	ggg ggg gg	
electroweak	above + $e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$	$\gamma, W^{\pm}, Z$	H
gravitational	all	h	

1977: b 1983: W, Z July 4, 2012: H ← almost 38 years!

1980: g (gluon jets) 1995: t February 11, 2016: h? (waves)

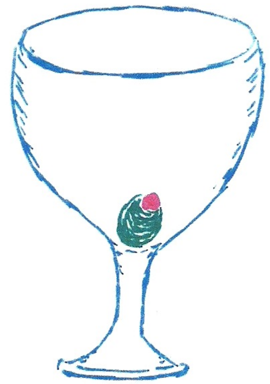
*We should perhaps finish our paper with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson,. . . , and for not being sure** of its coupling to other particles*, except that they are probably all very small. For these reasons we do not want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

EGN

*Uncertainties in strong interaction effects

*Light hadrons

SYMMETRY



Wine Glass:
Cylindrical Symmetry

Cocktail Glass

Symmetric Solution
UNSTABLE

Stable Solution:
Spontaneously broken Symmetry

Stirred Cocktail
Symmetry restauration

PHENOMENOLOGY

Higgs potential: $V(\Phi) = \frac{\lambda}{4}\left(|\Phi|^2 - v^2\right)^2, \qquad \Phi = \begin{pmatrix} \varphi_1 + i\varphi_2 \\ v + H + i\varphi_3 \end{pmatrix}$ $\quad [SU(2) \otimes SU(2)]$

$$V = \frac{\lambda}{4}\left(\sum_i \varphi_i^2 + 2vH + H^2\right)^2 = \lambda v^2 H^2 + O(H,\varphi_i)^3 = \frac{1}{2}m^2 H^2 + V_{\text{interaction}}(H,\varphi_i)$$

$\Rightarrow \quad m_H = \sqrt{2\lambda}v$, $m_{\varphi_i} = 0$, H = physical Higgs particle, 3 φ_i eaten by massive $W^\pm, Z$

Masses of other particles $\propto$ • value v of Higgs field • strength g_H of particle coupling to Higgs:

vector bosons: $m_V = g_V v/\sqrt{2}$, $\quad$ fermions: $m_f = g_{f\bar{f}H} v$

v known since late 1940's: $\tau_\mu \propto 2G_F^{-2} = 64 m_W^4/g_W^4 = 16v^4 \approx (\text{TeV})^4/16$

All Higgs couplings to elementary particles with known masses known

BUT m_H, λ = Higgs self-coupling unknown in absence of Higgs discovery!

Circa 1975: $m_H \gtrsim 20$ MeV: $\begin{cases} > .6\text{MeV} & n\text{-}e \text{ \& } d\text{-}e \text{ scattering} \\ > .7\text{MeV} & \text{Higgs from neutron stars} \\ < 1\text{MeV or } > 18\text{MeV} & \text{Higgs from } ^{16}\text{O}, ^4\text{He decay} \\ > 15\text{MeV} & n\text{-nucleus scattering} \end{cases}$

Theoretical guidance?

If $m_H >$ TeV $\lambda > O(1)$: strongly coupled Higgs $([W^\pm, Z]_{\text{longitudinal}})$ sector $\quad \left[\varphi_i \sim \pi_i^T\right]$

If $m_H^{\text{tree}} = 0$ and $m_q \ll m_W$ $\forall q$ (!!) loop corrections (S.Coleman & E.Weinberg potential)

contribute $m_H^{\text{loop}} \approx 10$ GeV: represent(ed) effective lower limit $\quad$ Post EGN observation

EGN considered Higgs production and decay modes including

$H \to \gamma\gamma$ important decay mode for Higgs discovery sans t, b

$$e^+e^- \to \begin{cases} Z \to H + \bar{f}f \\ Z + H \end{cases}$$

also Bjorken 1976

also Ioffe & Khoze 1976

important LEP search modes

Precision SLC & LEP data & FNAL top mass: $m_H = 100 \pm 30$ GeV Veltman 1977

Direct LEP searches: $m_H > 114.4$ GeV

Production modes at FNAL/LHC $\begin{cases} gg \to H \\ W^\pm, Z + H \\ W^+W^-, ZZ \to H \end{cases}$

Georgi, Glashow, Machacek & Nanopoulos 1978

Glashow, Nanopoulos & Yildiz 1978

Cahn & Dawson 1984

CDF & D0: $m_H < 156$ GeV or > 177 GeV Tevatron shut down September 2011

Late 2009 LHC takes first data reaches 7 TeV CM by March 2011

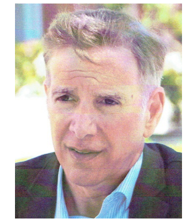
~ 5/fb by end of 2011: hint of bump at $\sim$ 120-125 GeV

2012: ~ 20/fb at 8 TeV CM

July 4, 2012: new particle announced

$m \sim 125$ GeV

Is it the Higgs boson?



- $m_H = 125.09 \pm 0.24$ consistent with inference from precision measurements

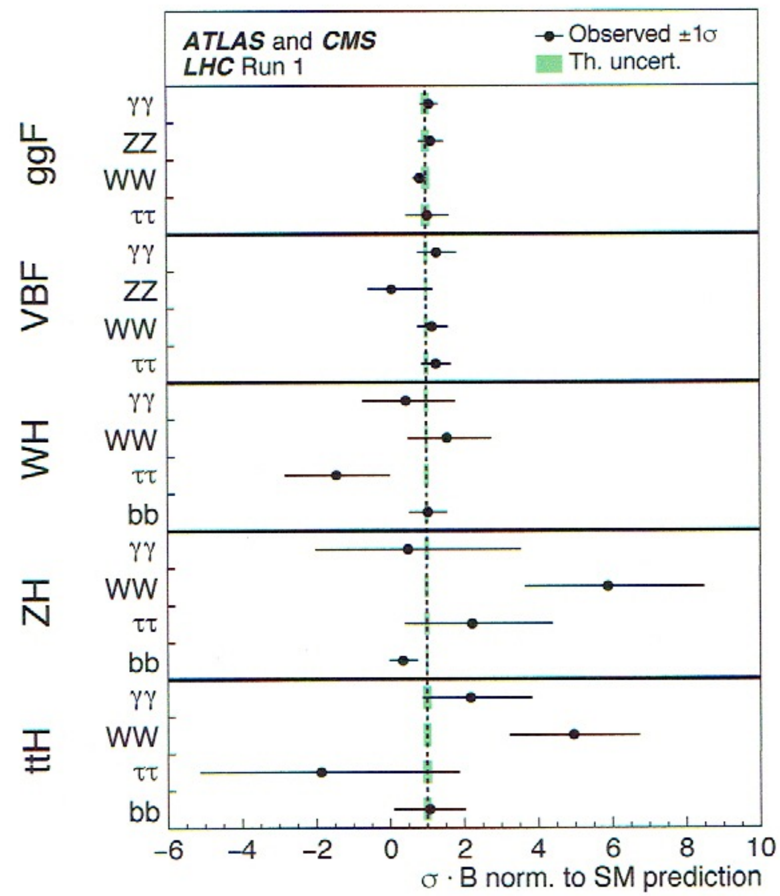
  Spin = 0? $H \to 2\gamma : S = 0$ or 2. Angular distribution favors $S = 0$ + other tests

- Parity = + 1? favored by H-V invariant mass in production by "Higgsstrahlung" from $V = W, Z$ + other tests

- Couplings to SM particles? $g_h = m/v(\times\sqrt{2})$ for fermions (vector bosons)?

  including loop-induced processes: $H \to \gamma\gamma$, $gg \to H$

Various parametrizations constrain a variety of postulated deviations from Standard Model Higgs properties



ATLAS and CDF collaborations, arXive 1606.02266 (7 & 8 TeV CME)

Run II @ 13 TeV: more data, so far still consistent with SM

Standard Model complete! End of story? NO!

- neutrino masses and mixing CP violation?

  dark matter where/what is it??

- dark energy even more mysterious!

We don't understand

- origin of matter-antimatter imbalance in the universe CP violation in ν sector??

  What drives inflation?

- hierarchy of fermion masses and quark mixing

- hierarchy of scales: electroweak breaking vs gauge coupling unification/strong gravity

  We all expected something besides SM Higgs to show up at TeV energies!

We need new physics to

- Cancel large quadratically divergent contributions to Higgs mass/vev
- Stabilize electroweak vacuum?

  W, Z loops: $\Delta\lambda > 0 \quad \Rightarrow m_H \gtrsim 10$ GeV

top loops: $\Delta\lambda < 0 \quad \Rightarrow$ with $m_H \approx 125$ GeV, $\lambda(\mu) \to 0$ for $\mu \approx 10^{10}$ GeV $\Rightarrow$

we live in metastable vacuum if SM all there is

Many proposed candidates for BSM physics (see Carlos, Gia, Marcela, Howie)

Many proposed scenarios for deviations from SM Higgs

technicolor, compositeness, extra dimensions, little Higgs...

Or my favorite: Supersymmetry

- most elegant

  remarkable cancellation of divergences

- needed (at some scale) for consistency of string theory–at present most promising candidate for unifying SM with gravity

The higher the SUSY breaking scale in MSSM

- the more closely lightest scalar resembles SM higgs  at least consistent!

- the more difficulty SUSY has in explaining hierarchy of scales 

WHAT NEXT?

Some BSM issues being addressed by

- underground experiments
- long beam-line neutrino experiments
- cosmological/astrophysical obervation

Energy frontier?

- Maybe someting will still show up at LHC
- (Probably) a Higgs factory to look for small deviations from SM model predictions for Higgs properties
- $\sim$ 100 TeV proton collider?

Depends on LHC results, techology  and politics!