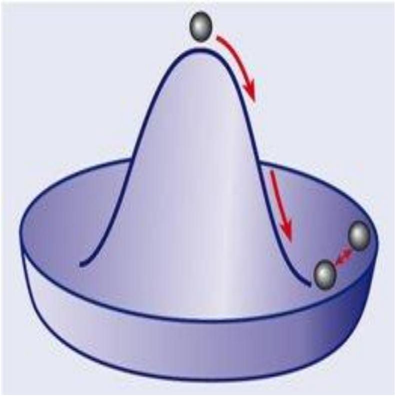
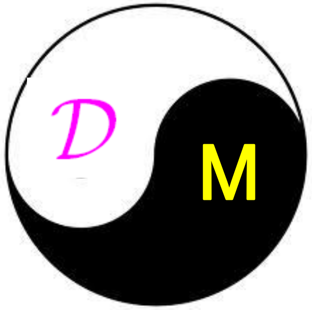
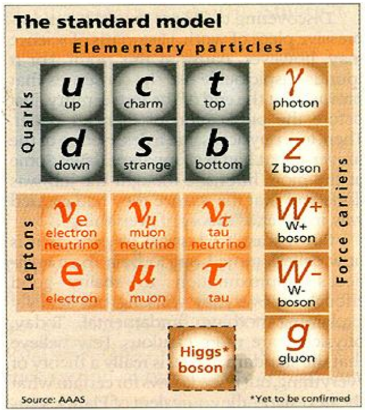
Particle Odyssey to Completing the Standard Model

S.Y. Choi (Chonbuk)







The standard model

Elementary particles

Quarks	u up	c charm	t top	γ photon
	d down	s strange	b bottom	Z Z boson
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	$W+$ W+ boson
	e electron	μ muon	τ tau	$W-$ W- boson
		Higgs* boson		g gluon

Force carriers

Source: AAAS

*Yet to be confirmed

Particle Physics
Symmetries
Symmetry Breaking
Exploration

Open KIAS PCSI, 2013

July 4, 2012, CERN : a memorable day in human history

Particle Physics

I can't promise that
my historical review
is fair and balanced.

Warning by Iliopoulos at Higgs Hunting 2012

Never read old papers with today's
knowledge for the purpose of
assigning credit.

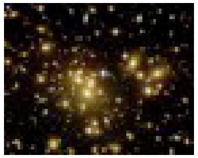
Read them to gain insights.

Hierarchy of Scales

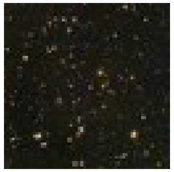
10^{7} m

10^{11} m

10^{20} m



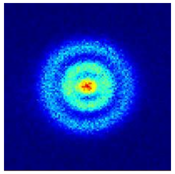
10^{23} m



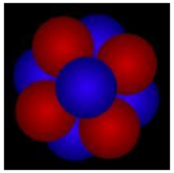
10^{27} m

10^{3} m

10^{-1} m



10^{-10} m



10^{-15} m

10^{-19} m

?

Two Pillars in Physics

Relativity (Einstein)
QM (Heisenberg, Schrodinger, …)

Very different way to describe nature from what most people are used to

The only way to combine them together is a theory of quantum fields.

Particle World

Quantum : particle © wave

$\lambda = h/p \qquad h = 6.6 \times 10^{-34}\,\mathrm{J\,s}$

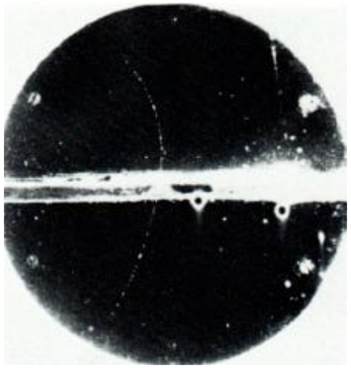
Relativity : energy © momentum © mass

$E^2 = p^2c^2 + m^2c^4 \qquad c = 3 \times 10^8\,\mathrm{m/s}$

Probing Nature at the smallest time/length demands the strongest energy/momentum.

100 GeV ⇔ 10^{-18} m ⇔ 10^{-26} s

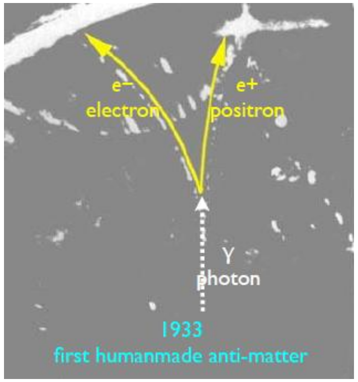
Terascale: 1000 GeV ⇔ 10^{-19} m ⇔ 10^{-27} sec



Relativistic Quantum Field Theory

particle ⇔ anti-particle

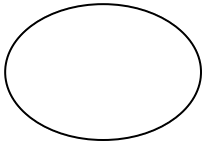
Heisenberg uncertainty principle



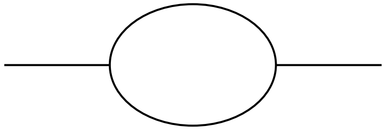
$$\Delta E \sim h/\Delta t$$

$$\Delta p \sim h/\Delta x$$

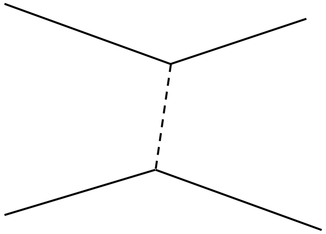
Dynamic vacuum



Pair creation/annihilation

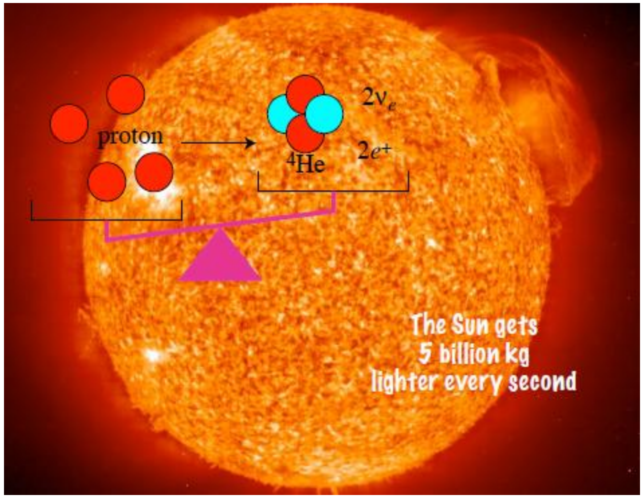


Interactions

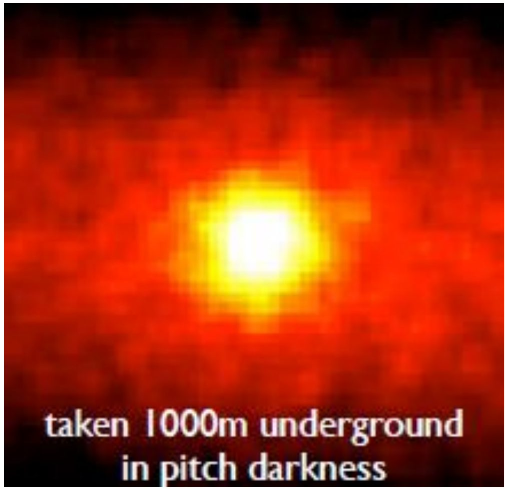


Interaction strengths vary with distance

Origin of Solar Energy



Trillions of neutrinos go through our body every second



Particle Physics

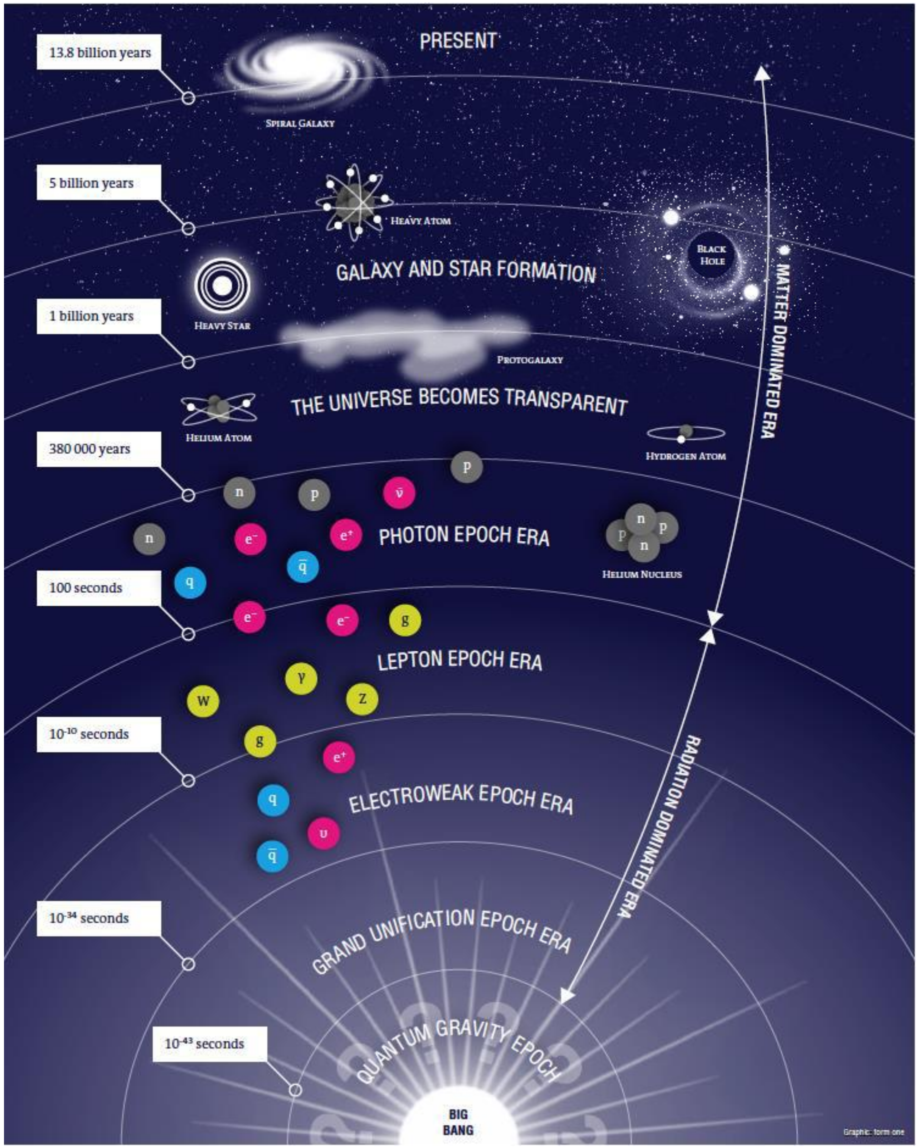
Study the constituents and the interactions
among them at the smallest time and length scales

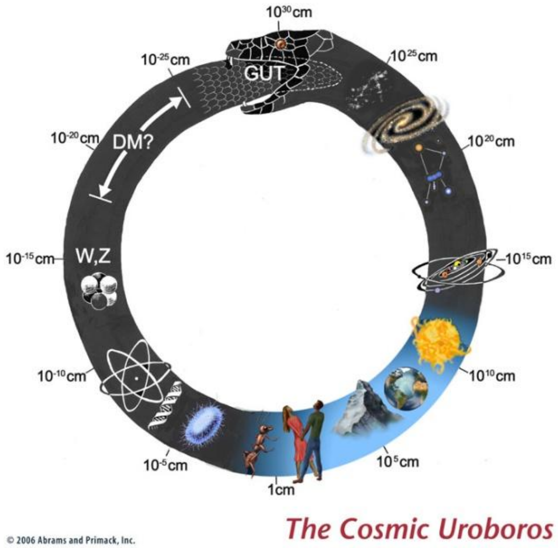
What is matter made of?
Why and how do they interact to build things?

Tear things down and see what come out
See how they interact with each other

Necessary to understand the Universe

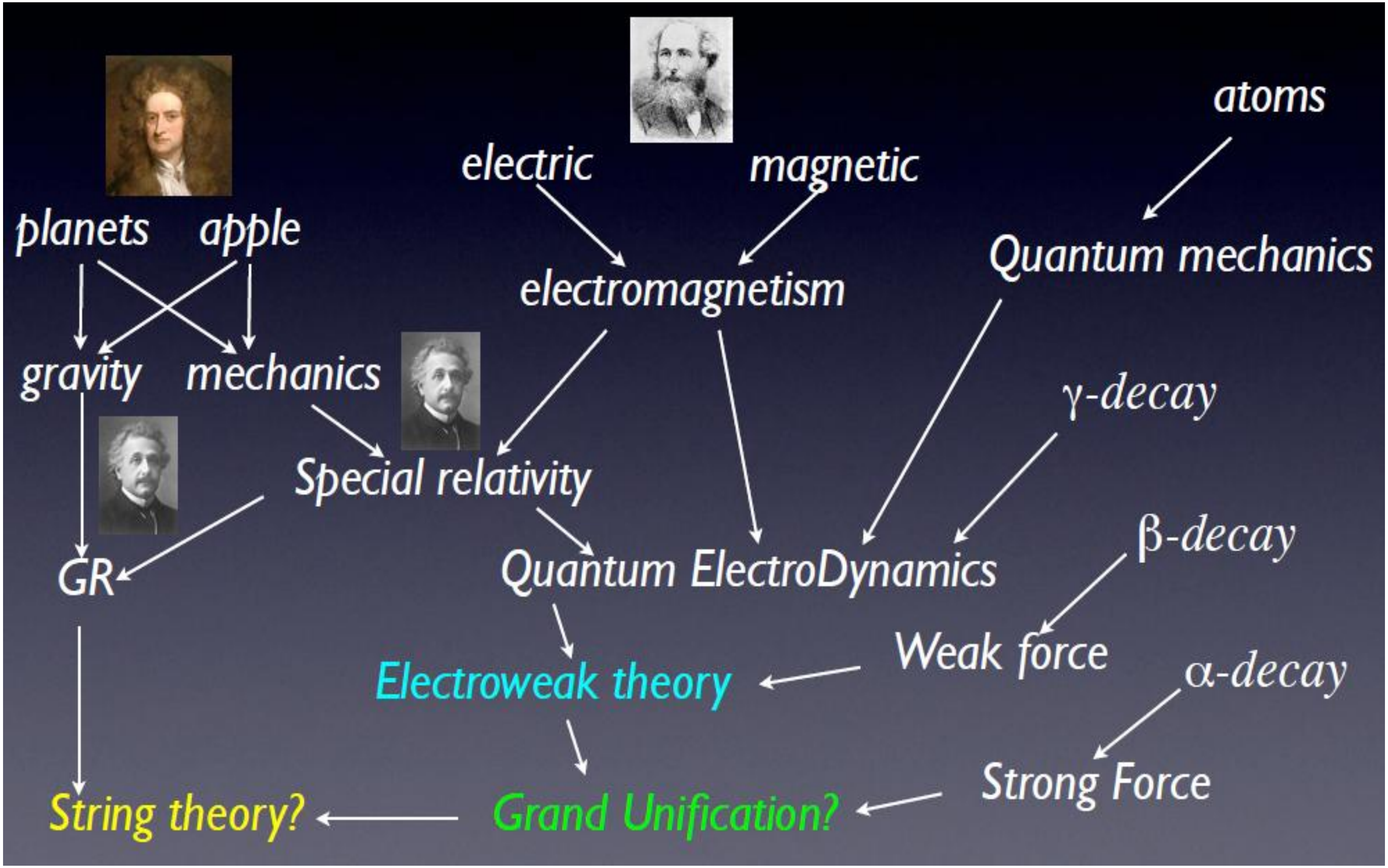
Cosmic Uroboros





Unification

[H. Murayama]



planets

apple

gravity

mechanics

electric

magnetic

electromagnetism

atoms

Quantum mechanics

Special relativity

GR

Quantum ElectroDynamics

γ-decay

β-decay

Weak force

α-decay

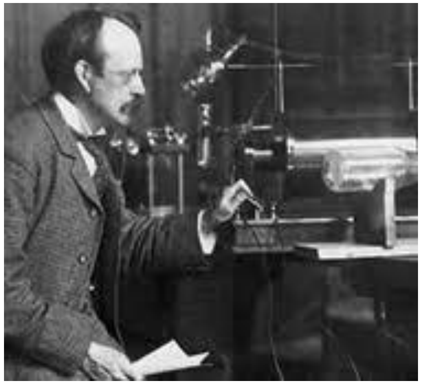
Electroweak theory

Strong Force

String theory?

Grand Unification?

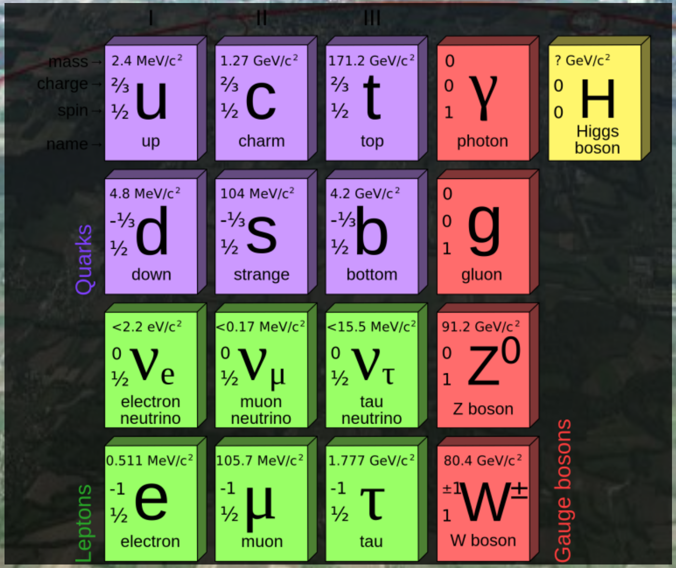
Evolution of Instruments



[1987]

[2013]

Standard Model



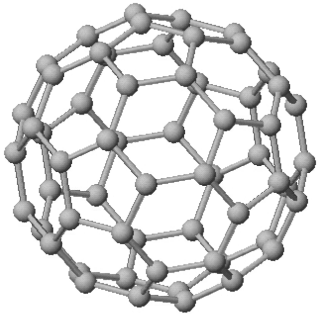
	I	II	III		
mass → charge → spin → name →	2.4 MeV/c² ⅔ ½ u up	1.27 GeV/c² ⅔ ½ c charm	171.2 GeV/c² ⅔ ½ t top	0 0 1 γ photon	? GeV/c² 0 0 H Higgs boson
Quarks	4.8 MeV/c² -⅓ ½ d down	104 MeV/c² -⅓ ½ s strange	4.2 GeV/c² -⅓ ½ b bottom	0 0 1 g gluon	
	<2.2 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<15.5 MeV/c² 0 ½ ν_τ tau neutrino	91.2 GeV/c² 0 1 Z^0 Z boson	
Leptons	0.511 MeV/c² -1 ½ e electron	105.7 MeV/c² -1 ½ μ muon	1.777 GeV/c² -1 ½ τ tau	80.4 GeV/c² ±1 1 $W^\pm$ W boson	Gauge bosons

$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{a\mu\nu} \\
& +\bar{Q}_i i\not{D} Q_i + \bar{u}_i i\not{D} u_i + \bar{d}_i i\not{D} d_i + \bar{L}_i i\not{D} L_i + \bar{e}_i i\not{D} e_i \\
& +Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H + |D_\mu H|^2 \\
& -\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}
\end{aligned}
$$

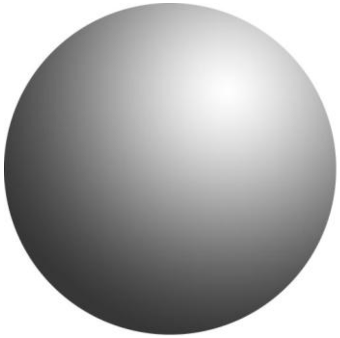
Symmetry

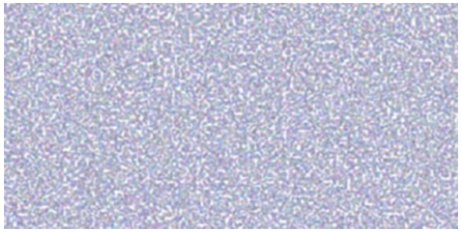
Symmetries

Indistinguishable
Unobservable
Disordered



Discrete ⬄ Continuous
Global ⬄ Local
External ⬄ Internal



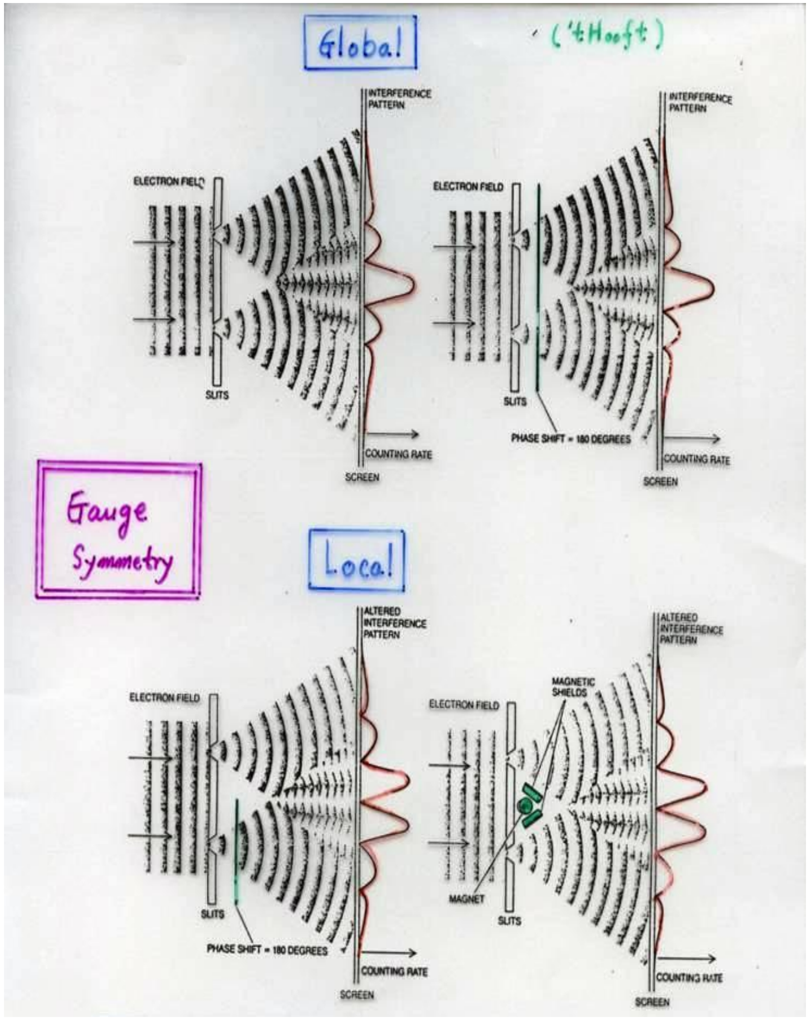


Symmetries ⇔ Conservation laws

Noether (1918)

Time translation	Energy
Spatial translation	Linear momentum
Rotational invariance	Angular momentum
QM phase	Charge

Local gauge symmetries dictate interactions



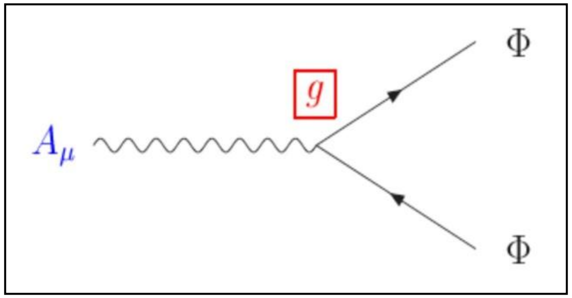
G. ’t Hooft

Local gauge symmetry

$\Phi(x) \rightarrow \Phi(x)\, e^{ig\alpha(x)}$

$A_\mu \rightarrow A_\mu + \partial_\mu \alpha(x)$

$$|(\partial_\mu - ig\, A_\mu)\Phi|^2$$



Quantum electrodynamics (QED)

[QM version of Maxwell equations]

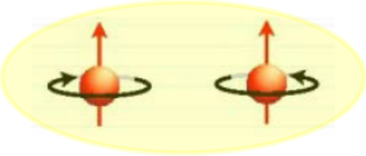
Maxwell (1861/2)

U(1)$_{EM}$ Abelian gauge symmetry

Massless spin-1 photon coupled to conserved charge

No obstacle to electron mass as L- and R-handed electrons have same charge

$$\bar{\psi}\psi = \bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L$$

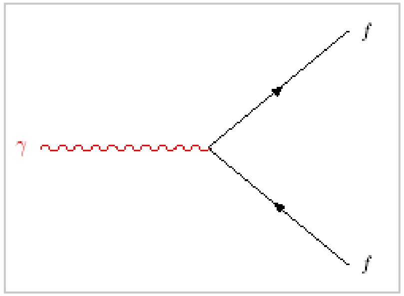


Local U(1)$_{\mathrm{EM}}$ gauge symmetry

$$\psi(x) \;\to\; e^{iq\alpha(x)}\psi(x)$$

$$A_\mu(x) \;\to\; A_\mu(x) - \partial_\mu\alpha(x)$$

$$D_\mu \;\equiv\; \partial_\mu + iqA_\mu(x)$$

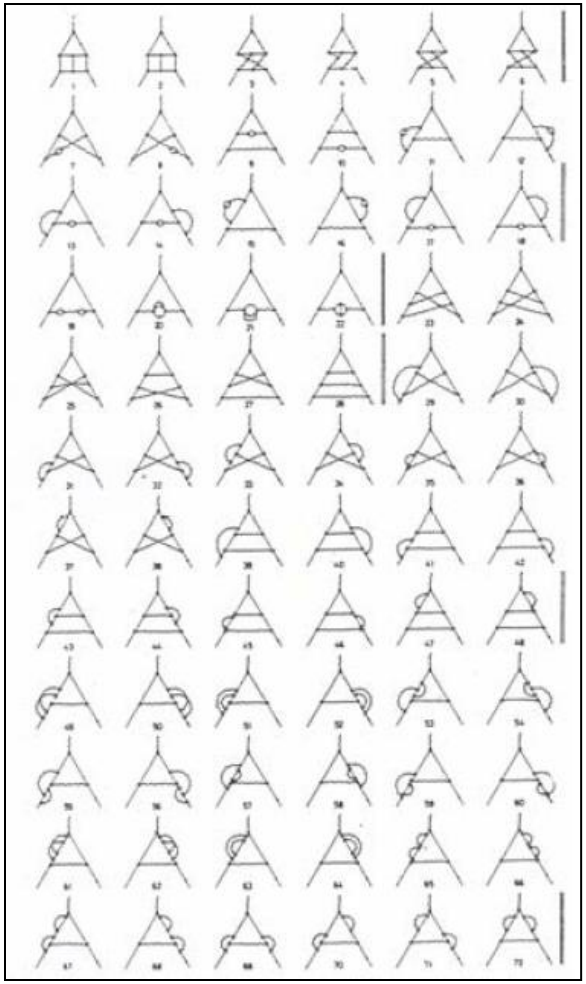


$$\begin{aligned}
\mathcal{L} &= \bar\psi(i\gamma^\mu D_\mu - m)\psi \\
&= \bar\psi(i\gamma^\mu\partial_\mu - m)\psi - \boxed{qA_\mu\bar\psi\gamma^\mu\psi} \\
&= \mathcal{L}_{\text{free}} - J^\mu A_\mu
\end{aligned}$$

Unbelievable precision

[electron anomalous magnetic moment]

Feynman Graphs		
$O(\alpha)$		1
$O(\alpha^2)$		7
$O(\alpha^3)$	analytically	72
$O(\alpha^4)$	numerically	891
til $O(\alpha^4)$		971



$$a_{e^-} = 0.001\,159\,652\,188\,4\,(43)$$

$$a_{e^+} = 0.001\,159\,652\,187\,9\,(43)$$

H. Dehmelt et al. 1987

$$a_e = 0.001\,159\,652\,180\,85\,(76)$$

G. Gabrielse et al. 2006

$$a_e = \frac{\alpha}{2\pi} - 0.328\ldots\left(\frac{\alpha}{\pi}\right)^2 + 1.182\ldots\left(\frac{\alpha}{\pi}\right)^3 - 1.505\ldots\left(\frac{\alpha}{\pi}\right)^4$$

Theory

$$a_e = 0.001\,159\,652\,133\,(290)$$

$$a_e = 0.001\,159\,652\,180\,85\,(76)$$

Symmetry restriction

Gauge-boson masses forbidden as the photon mass term violates gauge invariance

$$\boxed{A^\mu A_\mu \to (A^\mu - \partial^\mu \alpha)(A_\mu - \partial_\mu \alpha) \neq A^\mu A_\mu}$$

⇓

Massless photon predicted

⇑

Present experimental bound

$$m_\gamma \lesssim 10^{-22}\, m_e$$

Non-Abelian gauge symmetries [1954]

Mills CN Yang

[1954]

Shaw

[1955]

Conservation of isotopic spin and isotopic gauge invariance, PR 96, 191

Invariance under general isotopic gauge transformations. PhD thesis

SU(2) isospin gauge symmetry

Can one choose the convention to name proton and neutron Independently at each point in spacetime?

No obstacle to nucleon mass as L- and R-handed nucleons have same isospin

Local isospin symmetry implies $2^2 - 1 = 3$ "massless" gauge bosons coupled to isospin

What of YM (isospin) theory?

After SSB, still not the theory of nuclear strong forces
Right idea, wrong symmetry, wrong constituents

↓

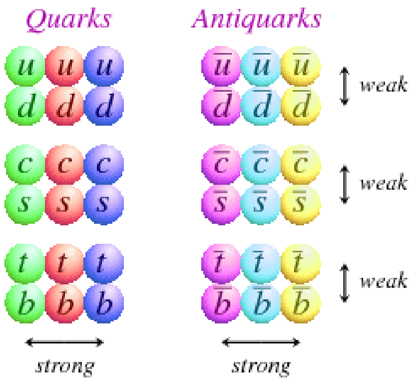
In contrast to biological evolution, unsuccessful lines in theoretical physics do not become extinguished.

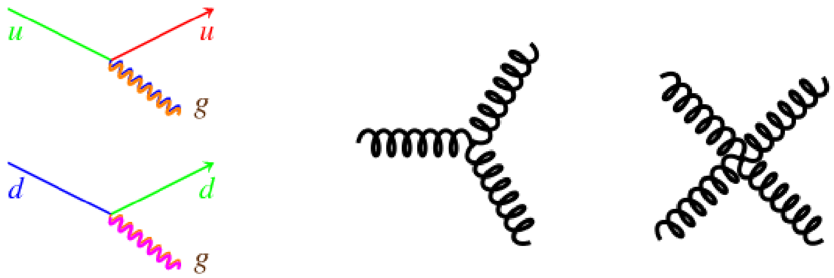
↓

Precursor of Quantum Chromodynamics (QCD) based on $SU(3)_C$ color gauge symmetry for interactions among quarks

QCD : SU(3) YM gauge theory

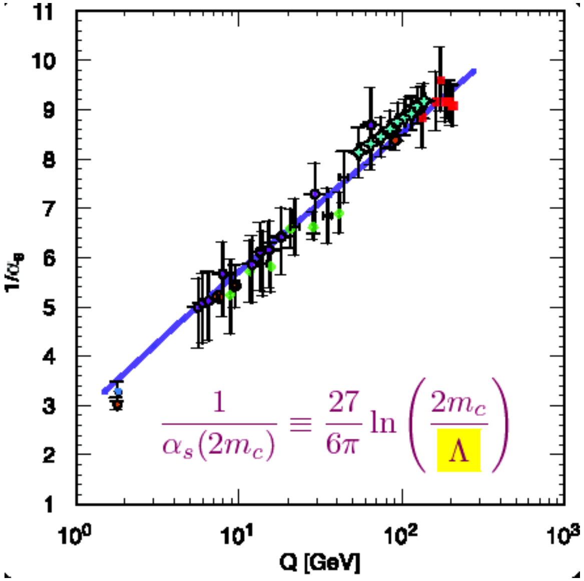
[C Kim's lectures]

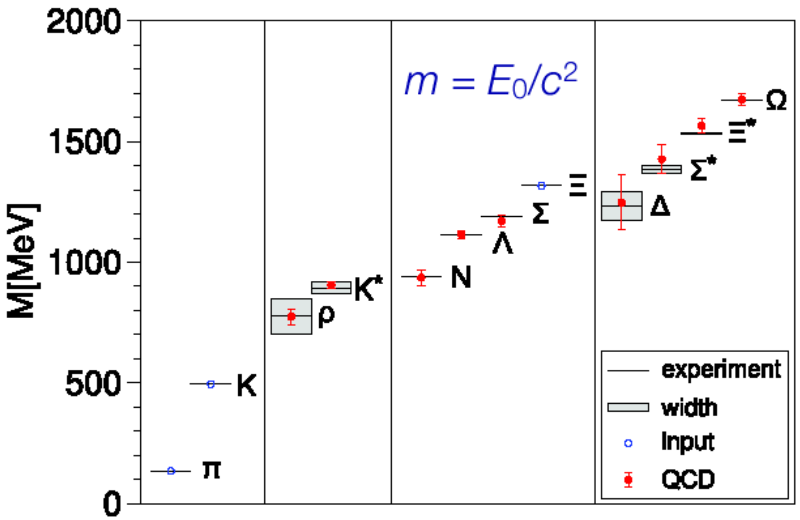




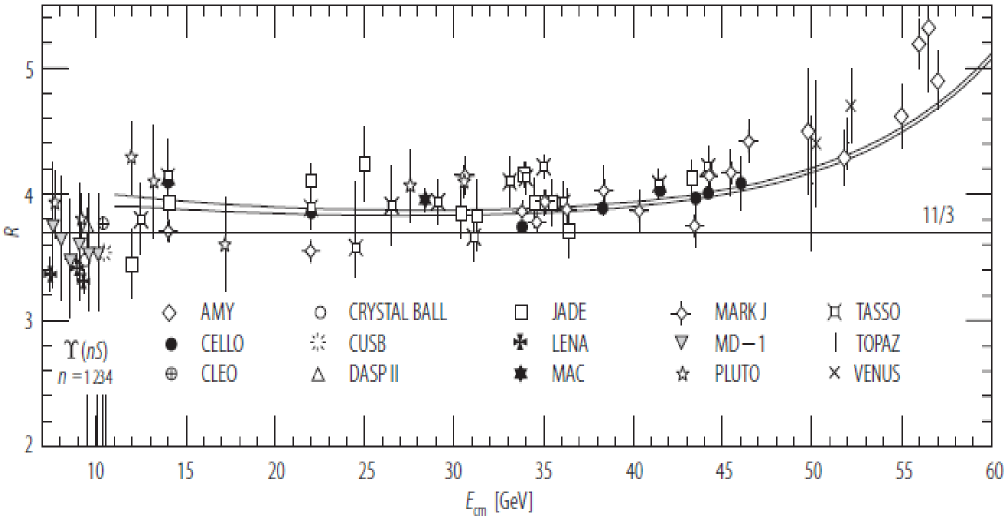
Asymptotic freedom in OCD

Most of visible mass for light hadrons





$$\boxed{\begin{aligned} R &\equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \\ &\approx N_C\left[2\cdot\frac{4}{9}+3\cdot\frac{1}{9}\right] \\ &\approx \frac{11}{9}N_c \quad \text{for} \quad q=u,c,d,s,b \end{aligned}}$$

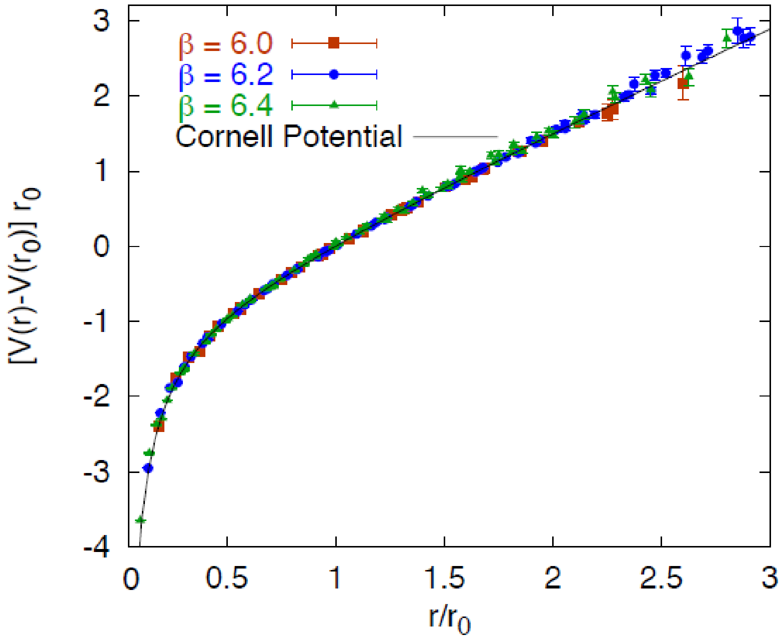


$$\text{Br}(W^- \to e^-\bar{\nu}_e) \approx 1/(3+2N_c) \quad \Leftrightarrow \quad 10.7\,\%\,[\text{exp.}]$$

$$\text{Br}(\tau^- \to e^-\bar{\nu}_e\nu_\tau) \approx 1/(2+N_c) \quad \Leftrightarrow \quad 18\,\%\,[\text{exp.}]$$

Potential ⇔ Confinement

[Lattice simulation]

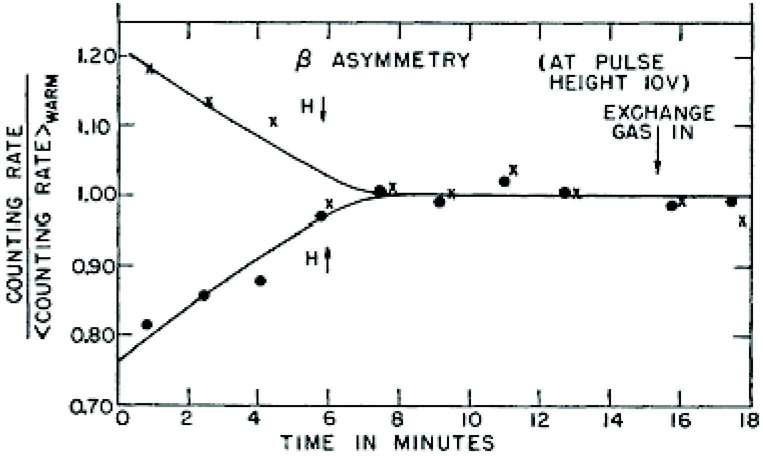


Parity violation in weak interactions

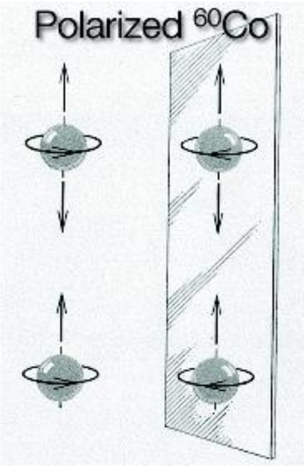
TD Lee

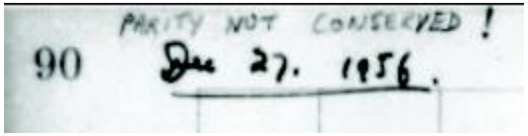
CN Yang

Question of Parity Conservation in
Weak Interactions, PR 104, 254 (1956)



CS Wu (1956)





PARITY NOT CONSERVED !

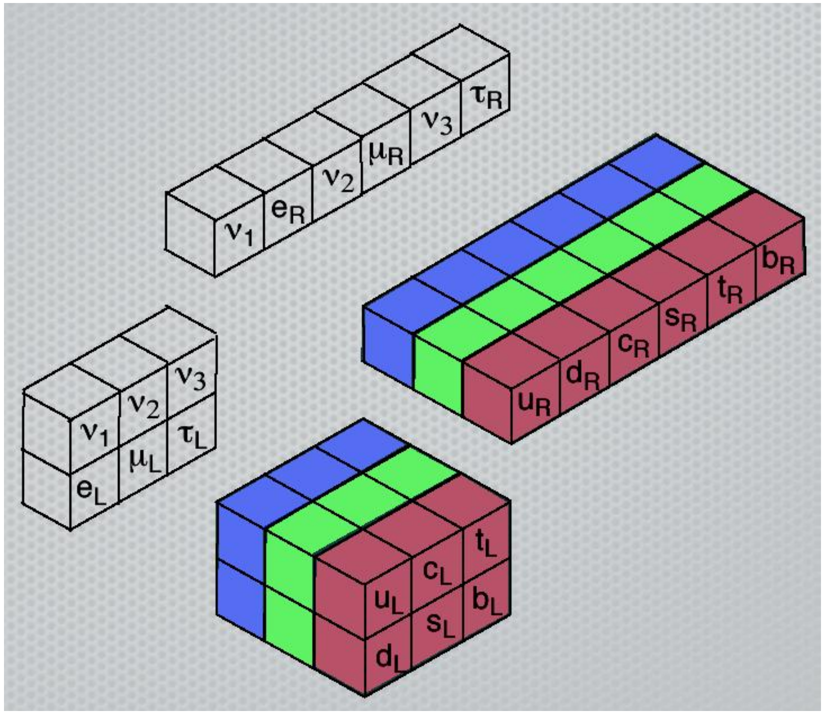
90 Dec 27. 1956.

Chiral quarks and leptons

L and R fermions have different quantum #'s

fermions	SU(2)	U(1)$_Y$
$(\nu\ ,\ e^-)_L$	2	-1
e^-_R	1	-2
$(u\ ,\ d)_L$	2	$1/3$
u_R	1	$4/3$
d_R	1	$-2/3$

$$Q = T_3 + \tfrac{1}{2}Y$$



A electroweak $SU(2)_L \times U(1)_Y$ theory

Glashow (1961)

Partial symmetries of
weak interactions,
NP 22, 579

Weak isospin (left-handed)
+
Weak hypercharge

3 massless gauge bosons
coupled to weak isospin

1 massless hyperphoton
coupled to weak hypercharge

Massless quarks and leptons

SM : a renormalizable QFT

Three generations of quarks and leptons

EM + weak + strong [+gravitational]

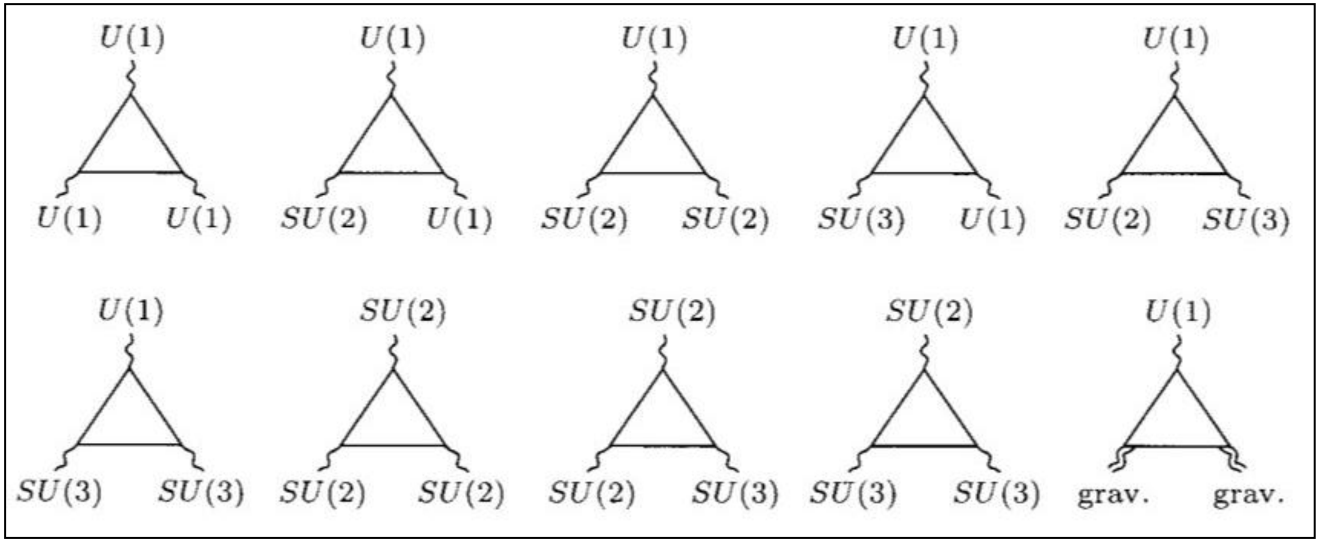
$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

states	**Q**	**d**	**u**	**L**	**e**	**B**	**W**	**g**	**H**	**G**
$SU(3)_C$	3	3	3	1	1	1	1	8	1	1
$SU(2)_L$	2	1	1	2	1	1	3	1	1	1
$U(1)_Y$	1/3	-2/3	4/3	-1	-2	0	0	0	1	0
spin	1/2	1/2	1/2	1/2	1/2	1	1	1	0	2
flavor	3	3	3	3	3	1	1	1	1	1
seen?	yes	yes	Yes	yes	yes	yes	yes	yes	yes	no

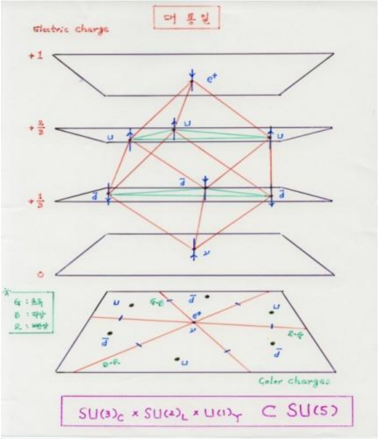
Gauge anomaly cancellation [Fujikawa + SM Lee]

Local gauge symmetry is crucial to keep quantum field theories (including SM) under control.

Triangle diagrams may spoil gauge invariance at quantum level ⇒ anomalies must all vanish for three gauge vertices (not for global currents)



Anomaly cancellation
$\Rightarrow$ nontrivial q-l connection



[H. Georgi]

$$\mathrm{U}(1)^3 \quad : \quad 3\cdot 2\left(\frac{1}{3}\right)^3 + 3\left(-\frac{4}{3}\right)^3 + 3\left(\frac{2}{3}\right)^3 + 2\,(-1)^3 + (2)^3 = 0$$

$$\mathrm{U}(1)(\text{gravity}) \quad : \quad 3\cdot 2\left(\frac{1}{3}\right) + 3\left(-\frac{4}{3}\right) + 3\left(\frac{2}{3}\right) + 2\,(-1) + (2) = 0$$

$$\mathrm{U}(1)(\mathrm{SU}(2))^2 \quad : \quad 3\cdot 2\left(\frac{1}{3}\right) + 2\,(-1)$$

$$\mathrm{U}(1)(\mathrm{SU}(3))^2 \quad : \quad 3\cdot 2\left(\frac{1}{3}\right) + 3\left(-\frac{4}{3}\right) + 3\left(\frac{2}{3}\right) = 0$$

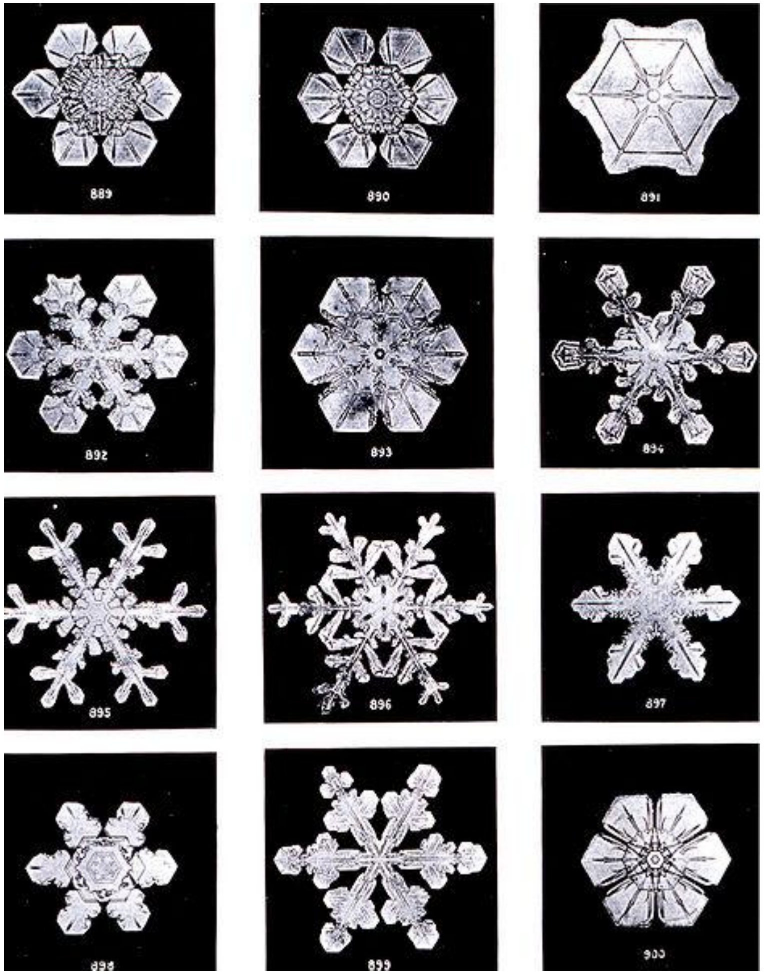
$$(\mathrm{SU}(3))^3 \quad : \quad \#\underline{3} - \#\underline{3}^* = 2 - 1 - 1 = 0$$

$$(\mathrm{SU}(2))^3 \quad : \quad \#\underline{2} = 3 + 1 = \text{even}$$

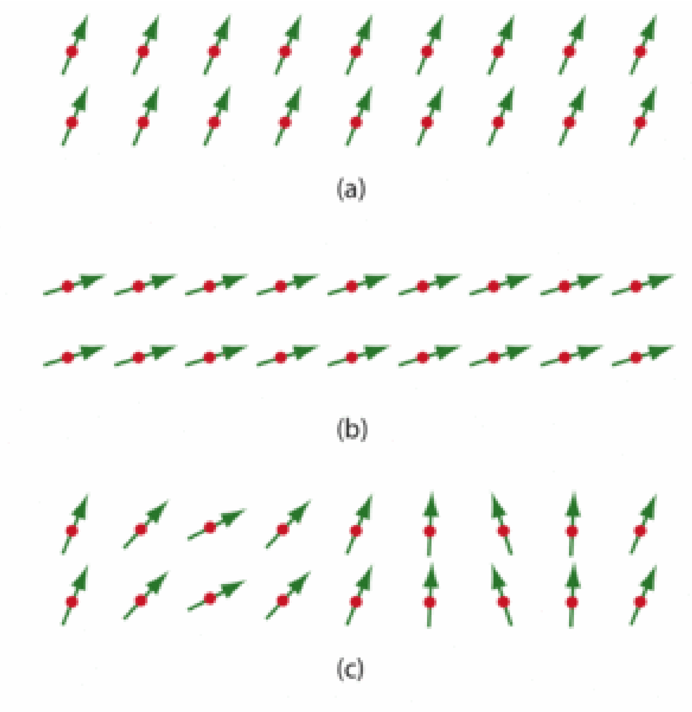
$$(\mathrm{SU}(2))^3,\ (\mathrm{SU}(3))^2\mathrm{SU}(2),\ \mathrm{SU}(3)(\mathrm{SU}(2))^2 \quad : \quad 0$$

Symmetry Breaking

Symmetric laws $\nRightarrow$ Symmetric outcomes



Ferromagnetism



Low-energy spin-wave excitation

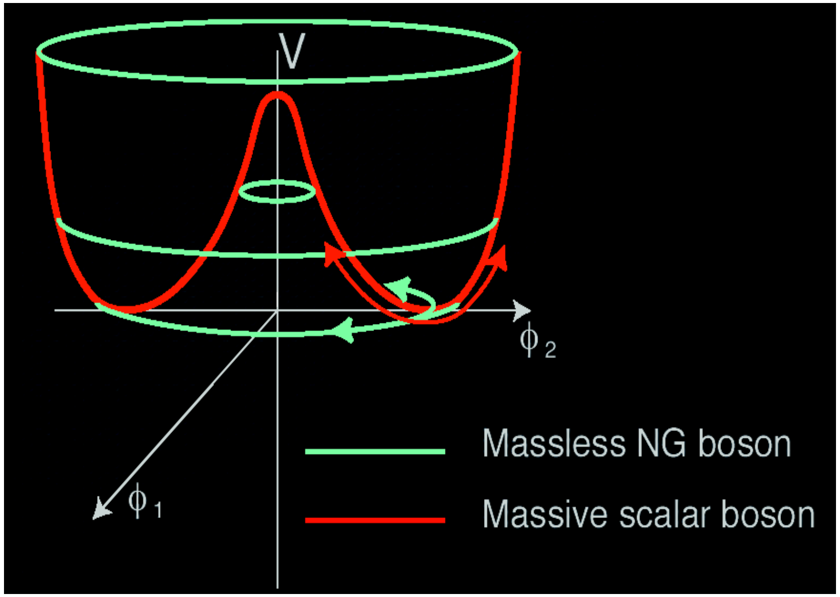
Nambu-Goldstone bosons (NGBs)

Nambu (1960)

Quasi-particles and gauge invariance
in the theory of superconductivity.
PR 117, 648

Field theories with superconductor
solutions, NCim 19, 154.

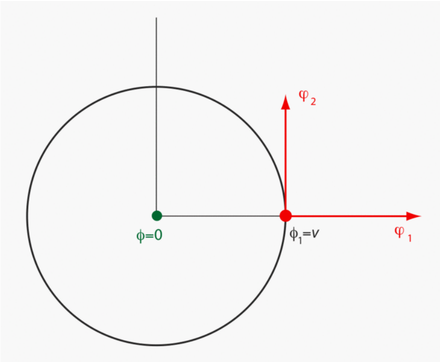
Goldstone (1961)



Whenever a continuous global symmetry is spontaneously broken, massless fields emerge

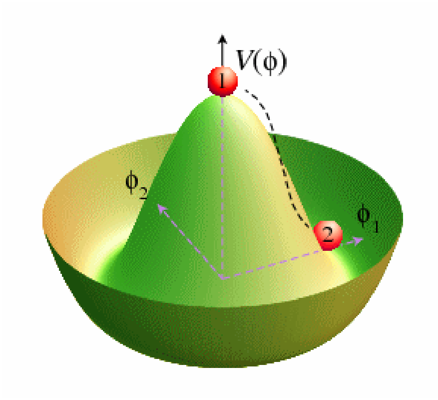
NGBs
spin waves, phonons,
pions, ...

Original Goldstone U(1) model



$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - V(\phi)$$

$$\phi(x) \to \phi(x)\, e^{i\alpha}$$



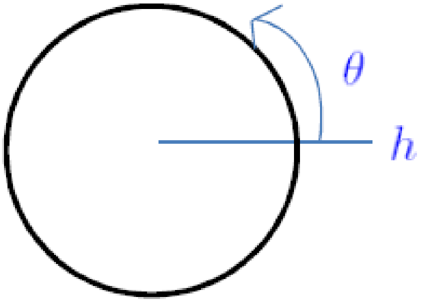
$$\phi(x) = \frac{1}{\sqrt{2}}(v + \varphi_1 + i\varphi_2) \xleftarrow{\boxed{\text{SSB}}} V(\phi) = \frac{\lambda}{2}\left(|\phi|^2 - \frac{v^2}{2}\right)^2$$

$$\downarrow$$

$$\mathcal{L} = \underbrace{\frac{1}{2}(\partial_\mu \varphi_1)^2 - \frac{1}{2}\lambda v^2 \varphi_1^2}_{\text{Massive scalar}} + \underbrace{\frac{1}{2}(\partial_\mu \varphi_2)^2}_{\text{Massless NGB}} - \frac{1}{2}\lambda v \varphi_1(\varphi_1^2 + \varphi_2^2) - \frac{\lambda}{8}(\varphi_1^2 + \varphi_2^2)^2$$

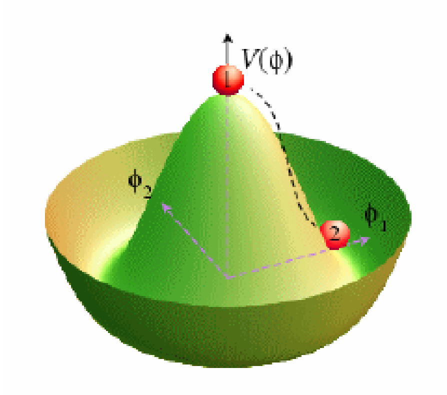
Goldstone U(1) model

[More transparent and clear description]



$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - V(\phi)$$

$$\phi(x) \rightarrow \phi(x)\, e^{i\alpha}$$



SSB

$$\phi(x) = \frac{1}{\sqrt{2}}(v+h)e^{i\theta/v}$$

$$V(\phi) = \frac{\lambda}{2}\left(|\phi|^2 - \frac{v^2}{2}\right)^2$$

$$\mathcal{L} = \underbrace{\frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}\lambda v^2 h^2}_{\text{Massive scalar}} + \frac{1}{2}(1+h/v)^2(\partial_\mu \theta)^2 - \frac{1}{2}\lambda v h^3 - \frac{\lambda}{8}h^4$$

Massless NGB

Proof 1 : Goldstone Theorem

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi^T \partial^\mu \phi - V(\phi^2) \quad \text{with} \quad \phi^2 = \phi^T \phi = \sum_{i=1}^{n} \phi_i^2$$

$$O(n) \,:\, \phi \to \phi' = \phi + \delta\phi \quad \text{with} \quad \delta\phi_i = i\,\delta\theta^a\, t^a_{ij}\phi_j$$

$$\text{Vacuum} \,:\, \left.\frac{\partial V}{\partial \phi_i}\right|_{\phi=\phi^0} = 0 \quad + \quad \left.\frac{\partial^2 V}{\partial\phi_k \partial\phi_i}\right|_0 t^a_{ij}\,\phi^0_j + \left.\frac{\partial V}{\partial\phi_i}\right|_0 t^a_{ik} = 0$$

⇓

$$\boxed{M^2\, t^a\, \phi^0 = 0 \quad \text{with} \quad (M^2)_{ki} = \left.\frac{\partial^2 V}{\partial\phi_k \partial\phi_i}\right|_0}$$

Each $t^a\phi^0 \neq 0$ is a zero-eigenvalue eigenstate of the squared mass matrix.
$\Rightarrow$ A massless mode or state is associated with each broken generator t^a.

Proof 2 : Goldstone Theorem

$$\text{Symmetry} \ : \ [Q, H] = QH - HQ = 0$$

$$\text{Vacuum} \ : \ H|0\rangle = E_{\text{min}}|0\rangle \quad \text{But } |0'\rangle \equiv Q|0\rangle \neq 0$$

$$(QH - HQ)|0\rangle = 0 = (E_{\text{min}} - H)|0'\rangle$$

$$\text{thus:} \ \ H|0'\rangle = E_{\text{min}}|0'\rangle$$

There is a new, non-symmetric state |0'>, which has a degenerate energy with the vacuum |0>, i.e. a m=0 Nambu-Goldstone boson

Hiding the symmetry helps?

Seems to add “massless” NGBs

to “massless” gauge bosons

Goldstone theorem proved
with ever-increasing rigor

Goldstone, Salam, Weinberg (1962)
Broken symmetries, PR 127, 965

Manifest Lorentz covariance?!

Klein, BW Lee (1964) : Does spontaneous breakdown of symmetry imply zero-mass particles?, PRL 10, 266

⟺

Gilbert (1964) : Broken symmetries and massless particles, PRL 12, 713

Avoidable

Unavoidable

Some hints

The gauge invariance of a vector field does not necessarily imply zero mass for an associated particle if the current vector coupling is sufficiently strong.

Schwinger (1962)

Gauge invariance and mass, PR 125, 397

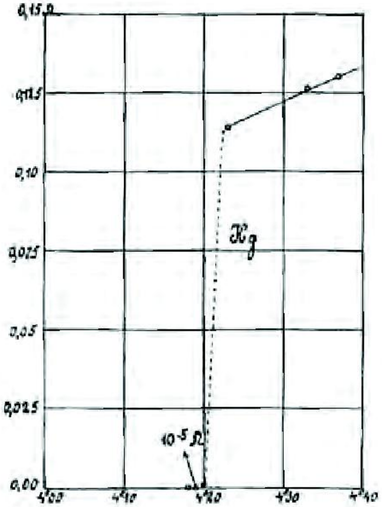
The plasmon theory is a simple non-relativistic example exhibiting all of the features of Schwinger's idea.

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.

Plasmons, gauge invariance and mass, PR 130, 439

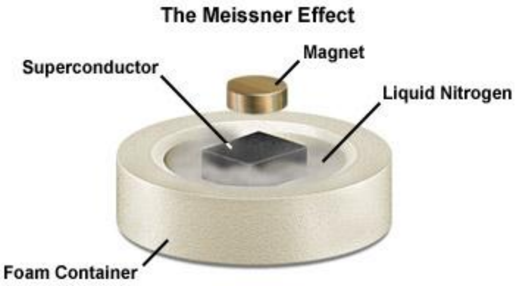
Anderson (1963)

Superconductivity (1911)



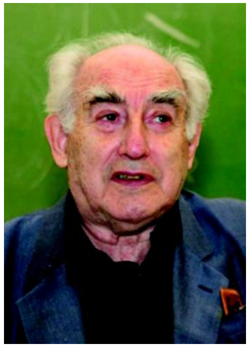
Onnes [1911]

Meissner effect



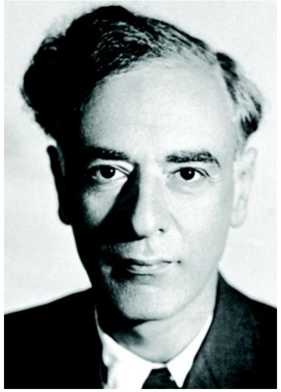
Magnetic fields excluded

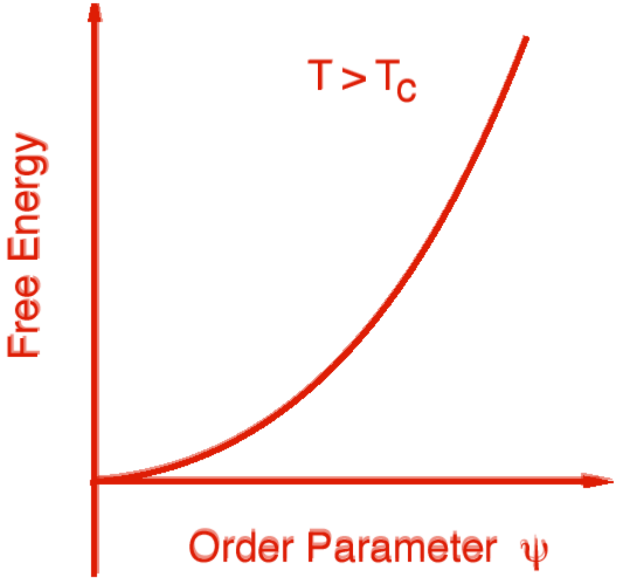
Meissner (1933)

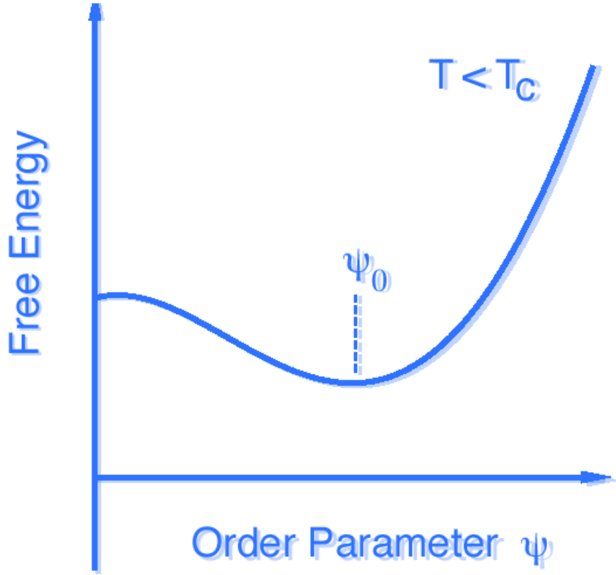


Ginzburg and Landau (1950)

On the theory of superconductivity,
JETP 20, 1064



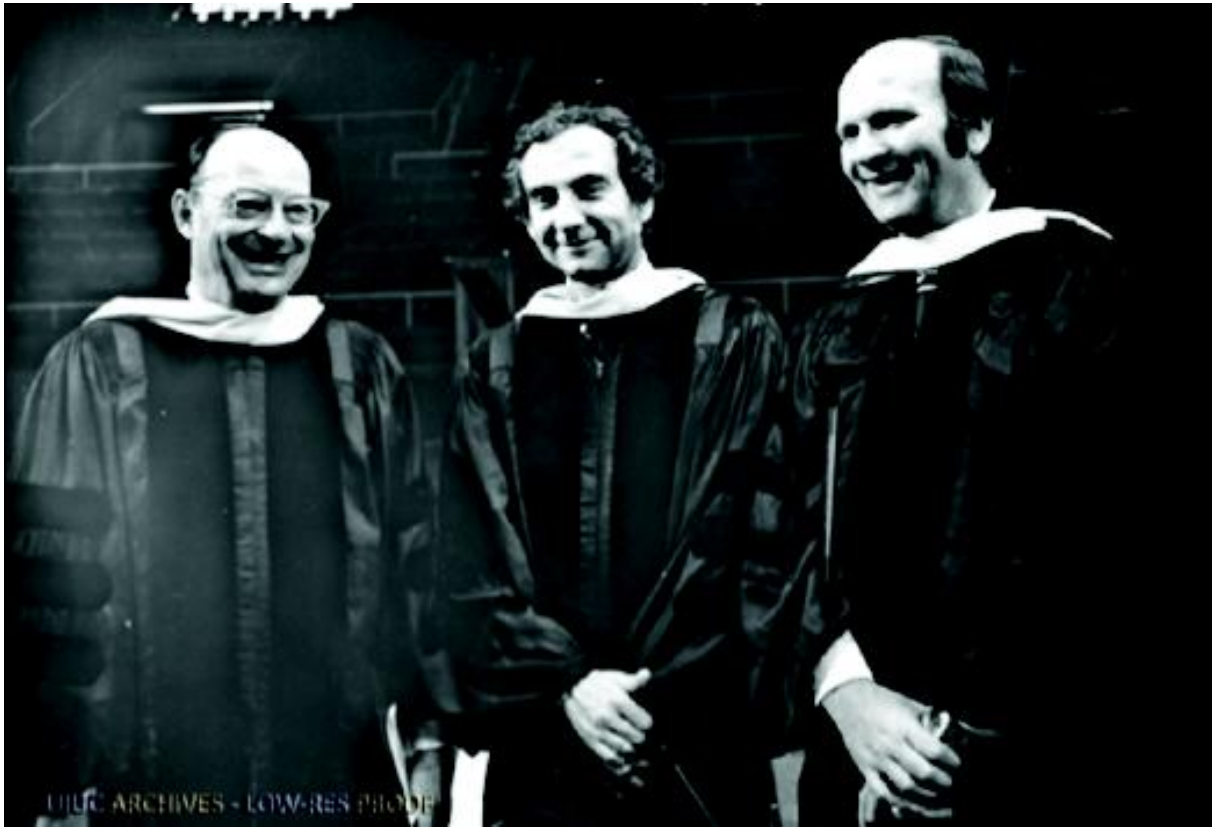




Photon acquires mass in superconductor!

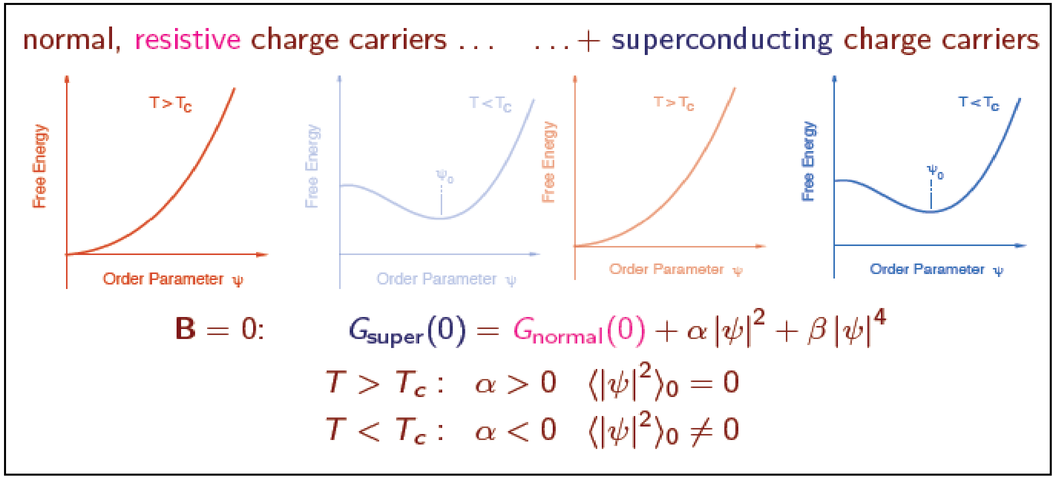
BCS Theory (1957)

Microscopic theory of superconductivity, PR 106, 162



Bardeen　　Cooper　　Schrieffer

Ginzburg-Landau phenomenological analysis



normal, resistive charge carriers . . . . . . + superconducting charge carriers

$\mathbf{B} = 0$: $G_{\text{super}}(0) = G_{\text{normal}}(0) + \alpha\,|\psi|^2 + \beta\,|\psi|^4$

$T > T_c: \quad \alpha > 0 \quad \langle|\psi|^2\rangle_0 = 0$

$T < T_c: \quad \alpha < 0 \quad \langle|\psi|^2\rangle_0 \neq 0$

Weak, slowly varying field:

$\psi \approx \psi_0 \neq 0,\ \nabla\psi \approx 0$

[Variational analysis]

BCS description (B ≒ 0)

$$G_{\text{super}}(\mathbf{B}) = G_{\text{super}}(0) + \frac{\mathbf{B}^2}{8\pi} + \frac{1}{2m^*}\left|-i\hbar\nabla\psi - \frac{e^*}{c}\mathbf{A}\psi\right|^2$$

$$\left.\begin{array}{l} e^* = -2 \\ m^* \end{array}\right\} \text{ of superconducting carriers}$$

$$\nabla^2\mathbf{A} - \frac{4\pi e^{*2}}{m^* c^2}\,|\psi_0|^2\,\mathbf{A} = 0$$

Massive photon
[Meissner effect]

Spontaneous symmetry breaking (SSB) (1964)

Higgs Kibble Guralnik Hagen Englert Brout*

Englert, Brout : Broken symmetry and the mass of gauge vector mesons, PRL 13, 321
Higgs : Broken symmetries, massless particles and gauge fields, PL 12, 132
Higgs : Broken symmetries and the masses of gauge bosons, PRL 13, 508
Guralnik, Hagen, Kibble : Global conservation laws and massless particles, PRL 13, 585

Goldstone theorem does NOT apply to gauge theories!

↑

Manifest Lorentz covariance is not guaranteed, e.g. in Coulomb gauge

[Scholarpedia : EBHGHK mechanism (history) by Kibble]

Abelian Higgs model

[Ginzburg-Landau in relativistic notation]

A massive photon
+
A massive scalar particle
(Higgs boson)

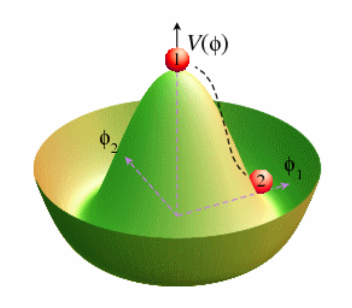
No mention of weak interactions

No question of fermion masses
(not an issue for LR-symmetric YM theory)

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad D_\mu\phi = \partial_\mu\phi + ieA_\mu\phi \qquad V(\phi) = \frac{\lambda}{2}\left(|\phi|^2 - \frac{v^2}{2}\right)^2$$

$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - D_\mu\phi^* D^\mu\phi - V(\phi)}$$

$$\phi(x) \rightarrow \phi(x)e^{i\alpha(x)} \qquad A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{e}\partial_\mu\alpha(x)$$



$$\xrightarrow{\text{SSB}}$$

$$\boxed{\phi(x) = \frac{1}{\sqrt{2}}(v + \varphi_1 + i\varphi_2)}$$

$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu\varphi_1)^2 - \frac{1}{2}\lambda v^2\varphi_1^2 + \frac{1}{2}(\partial_\mu\varphi_2 + evA_\mu)^2 + \ldots}$$

$$B_\mu = A_\mu + \frac{1}{ev}\partial_\mu\varphi_2 \qquad \downarrow \qquad F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\nu$$

1x2+2x1
= 1x3+1x1

$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu\varphi_1)^2 - \frac{1}{2}\lambda v^2\varphi_1^2 + \frac{1}{2}e^2v^2B_\mu B^\mu + \ldots}$$

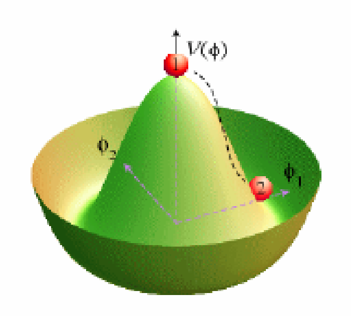
Massive scalar (Higgs) boson Massive gauge boson

Refined clear and transparent description

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad D_\mu\phi = \partial_\mu\phi + ieA_\mu\phi \qquad V(\phi) = \frac{\lambda}{2}\left(|\phi|^2 - \frac{v^2}{2}\right)^2$$

$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - D_\mu\phi^* D^\mu\phi - V(\phi)}$$

$$\phi(x) \rightarrow \phi(x)e^{i\alpha(x)} \qquad A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{e}\partial_\mu\alpha(x)$$



$$\xrightarrow{\text{SSB}}$$

$$\boxed{\phi(x) = \frac{1}{\sqrt{2}}(v+h)e^{i\theta/v}}$$

$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}\lambda v^2 h^2 + \frac{1}{2}(1+h/v)^2(\partial_\mu\theta + evA_\mu)^2 + \ldots}$$

$$B_\mu = A_\mu + \frac{1}{ev}\partial_\mu\theta \qquad \downarrow \qquad F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\nu$$

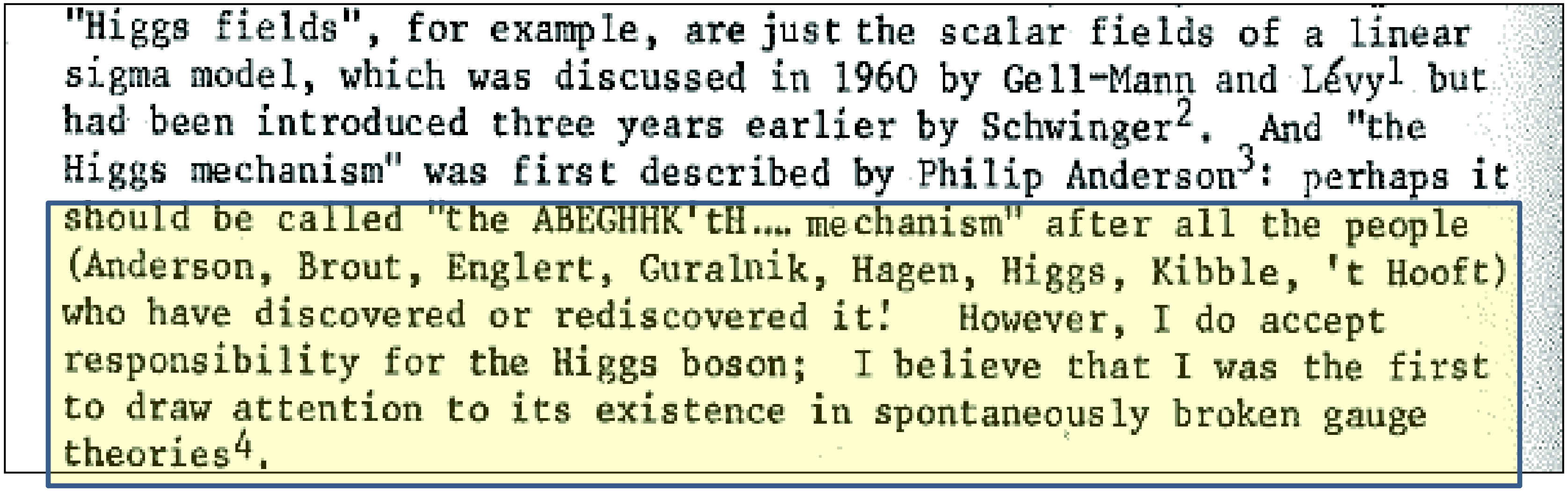
1x2+2x1
= 1x3+1x1

$$\boxed{\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \tfrac{1}{2}(\partial_\mu h)^2 - \tfrac{1}{2}\lambda v^2 h^2 + \tfrac{1}{2}e^2v^2 B_\mu B^\mu + \ldots}$$

Massive scalar (Higgs) boson Massive gauge boson

Who invented the Higgs boson?

Higgs : 50 years of Weak Interactions, Wingspread (1984)



"Higgs fields", for example, are just the scalar fields of a linear sigma model, which was discussed in 1960 by Gell-Mann and Lévy[1] but had been introduced three years earlier by Schwinger[2]. And "the Higgs mechanism" was first described by Philip Anderson[3]: perhaps it should be called "the ABEGHHK'tH.... mechanism" after all the people (Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble, 't Hooft) who have discovered or rediscovered it! However, I do accept responsibility for the Higgs boson; I believe that I was the first to draw attention to its existence in spontaneously broken gauge theories[4].

Adrian Cho : News Focus, Science 337, 1286 (2012)

Five living theorists have claims to having dreamed up the most famous subatomic particle in physics. But, what did they really do?

Franck Close : The Infinity Puzzle (2012)

…

An electroweak theory

Contrive a vacuum to hide EW symmetry
(need 4 new fields)

$$V(\Phi) = \tfrac{1}{2}\lambda(\Phi^\dagger\Phi - \tfrac{1}{2}v^2)^2$$

$$\Phi = \begin{pmatrix} \omega^+ \\ \frac{1}{\sqrt{2}}(v + h^0 + i\omega^3) \end{pmatrix}$$

Weinberg (1967)

A model of leptons
PRL 19, 1264

Massive W^+, W^-, Z^0
Massless photon

Massive Higgs boson

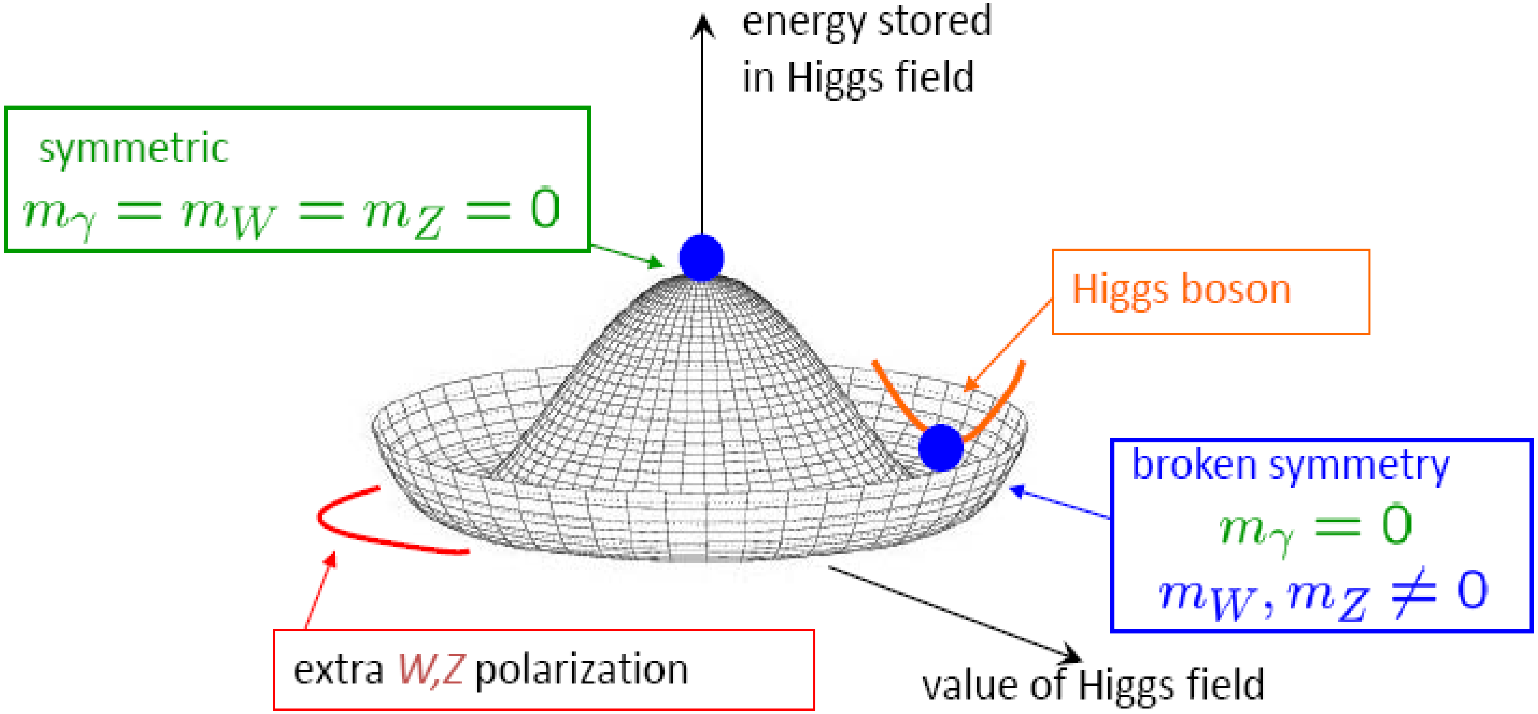
$3 \times 2 + 1 \times 4 = 3 \times 3 + 1$

Salam (1968)

Weak and electromagnetic
Interactions. Proc. of the
Nobel Symposium, 1968

Electroweak symmetry breaking

Higgs imagined a field filling all of space, with a “weak charge”.
Energy forces it to be **nonzero** at bottom of the “Mexican hat”.



energy stored
in Higgs field

symmetric
$m_\gamma = m_W = m_Z = 0$

Higgs boson

broken symmetry
$m_\gamma = 0$
$m_W, m_Z \neq 0$

extra *W,Z* polarization

value of Higgs field

$$\boxed{\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \rightarrow \mathrm{U}(1)_{\mathrm{EM}}}$$

$$m_W = \frac{1}{2} g v \qquad m_Z = \frac{1}{2}\sqrt{g^2+g'^2}\, v \qquad v = 246\,\mathrm{GeV}$$

$$\boxed{\tan\theta_W = \frac{g'}{g}} \qquad \sin / \cos\theta_W = \frac{g'/g}{\sqrt{g^2+g'^2}}$$

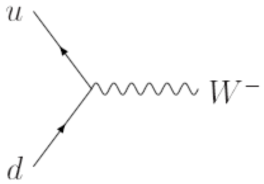
$$\begin{tikzcd}
 & \boxed{g_Z = \sqrt{g^2+g'^2}} \arrow[dl, "\times \cos\theta_W"'] \arrow[dr, "\times \sin\theta_W"] & \\
SU(2)_L \ \boxed{g} \arrow[dr, "\times \sin\theta_W"'] & & \boxed{g'} \ U(1)_Y \arrow[dl, "\times \cos\theta_W"] \\
 & \boxed{e = \frac{gg'}{\sqrt{g^2+g'^2}}} & \\
 & U(1)_{EM} &
\end{tikzcd}$$

Electroweak interactions

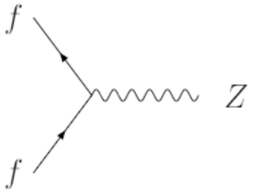
$$A_\mu = W_\mu^3 \, \sin\theta_W + B_\mu \, \cos\theta_W$$

$$Z_\mu = W_\mu^3 \, \cos\theta_W - B_\mu \, \sin\theta_W$$

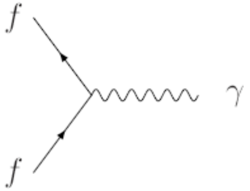
$$W_\mu^\pm = \frac{1}{\sqrt{2}} \left(W_\mu^1 \mp i \, W_\mu^2 \right)$$



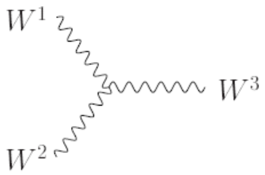
$$-\tfrac{i}{\sqrt{2}} g \gamma_\mu P_L$$



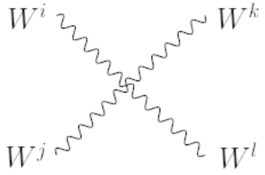
$$-i g_Z \gamma_\mu \left(I_3 P_L - Q \sin^2\theta_W \right)$$



$$-ieQ\gamma_\mu$$



$W^+W^-[Z/\gamma]$

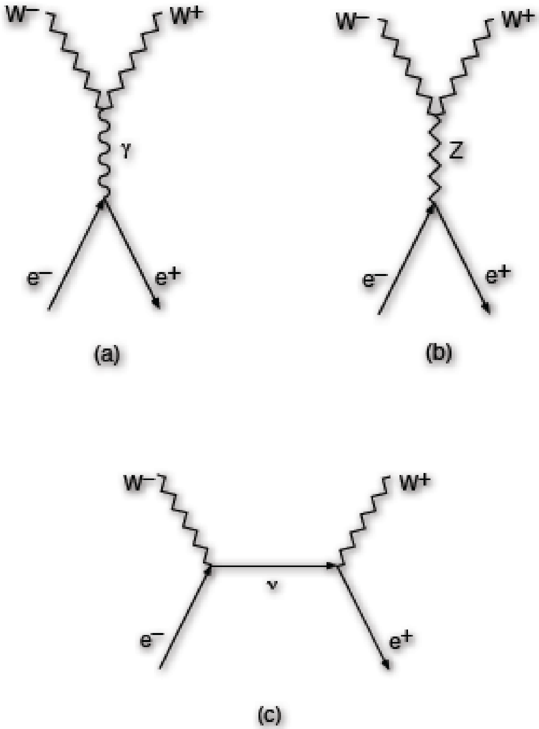


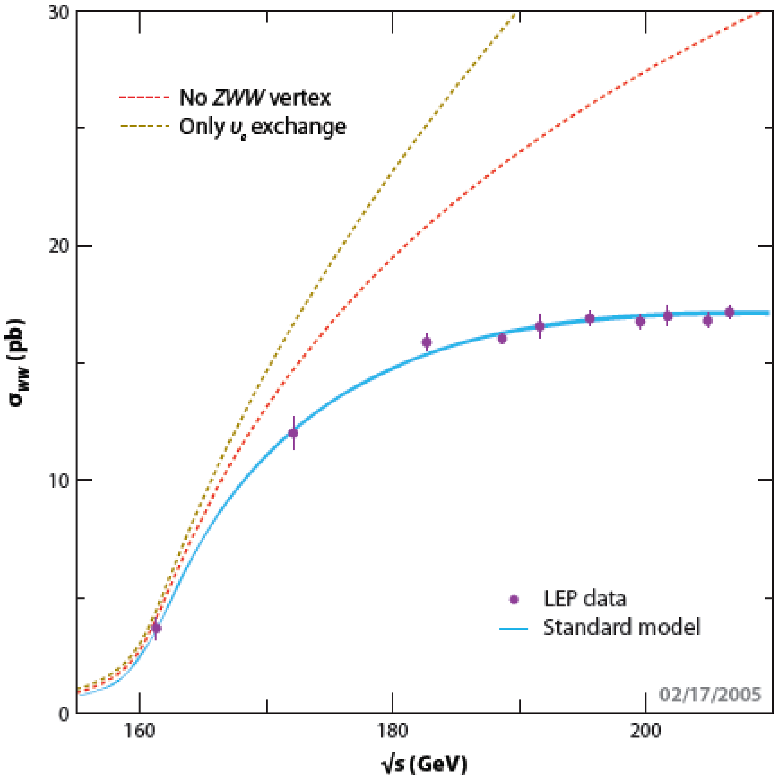
$W^+W^-[W^+W^-/ZZ/Z\gamma/\gamma\gamma]$

tri-linear and quadri-linear gauge-boson couplings

Gauge symmetry (group-theory structure)

$$e^+e^- \rightarrow W^+W^-$$

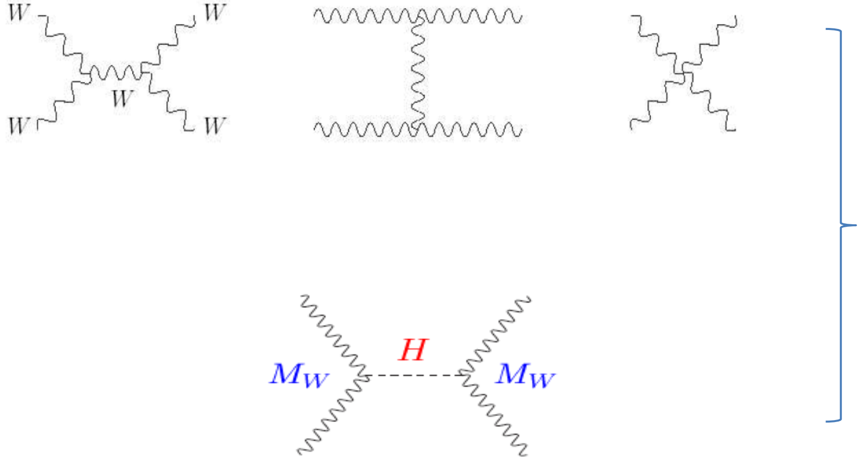




Miraculous adjustments due to electroweak symmetry!

High energy behavior of EW theory

$$W_L^+W_L^- \to W_L^+W_L^-, Z_LZ_L, Z_LH, HH$$



Unitarity

$$\mathcal{M} = -\sqrt{2}G_F m_H^2 \left(\frac{s}{s-m_h^2} + \frac{t}{t-m_h^2} \right)$$

$$m_H^2 \leq \frac{4\pi\sqrt{2}}{3G_F} \simeq (700\,\mathrm{GeV})^2$$

BW Lee, Quigg, Thacker (1777)
Weak Interactions at Very High Energies :
The Role of the Higgs Boson Mass, PRD 16, 1519

BW Lee

No-lose theorem

If the Higgs mass bound is respected, perturbation theory is “everywhere” reliable ✓

If not, weak interactions among W, Z and H bosons become strong at the TeV scale (Terascale)

↓

New phenomena are to be found @ Terascale

Fermion mass after SSB

Weinberg and Salam add interactions between fermions and scalars which give rise to quark and lepton masses

$$y_e \left[(\bar{e}_L \Phi) e_R + \bar{e}_R (\Phi^\dagger e_L) \right] \rightsquigarrow m_e = \frac{1}{\sqrt{2}} y_e v$$

y_e : picked to give right mass but not predicted

⇓

Fermion mass requires physics beyond the SM

Highly economical ⇔ Is it indeed true?

Four key tasks of the SM Higgs field

Hide EW symmetry, distinguishing EM and weak interactions

Give masses to W and Z gauge bosons

Give masses and mixings to fermions

Keep EW theory from misbehaving

World without SSB

Electron and quarks have no mass

QCD still confines quarks into hadrons
(Nucleon mass is little changed)

QCD hides EW symmetry by giving
tiny masses to W and Z bosons

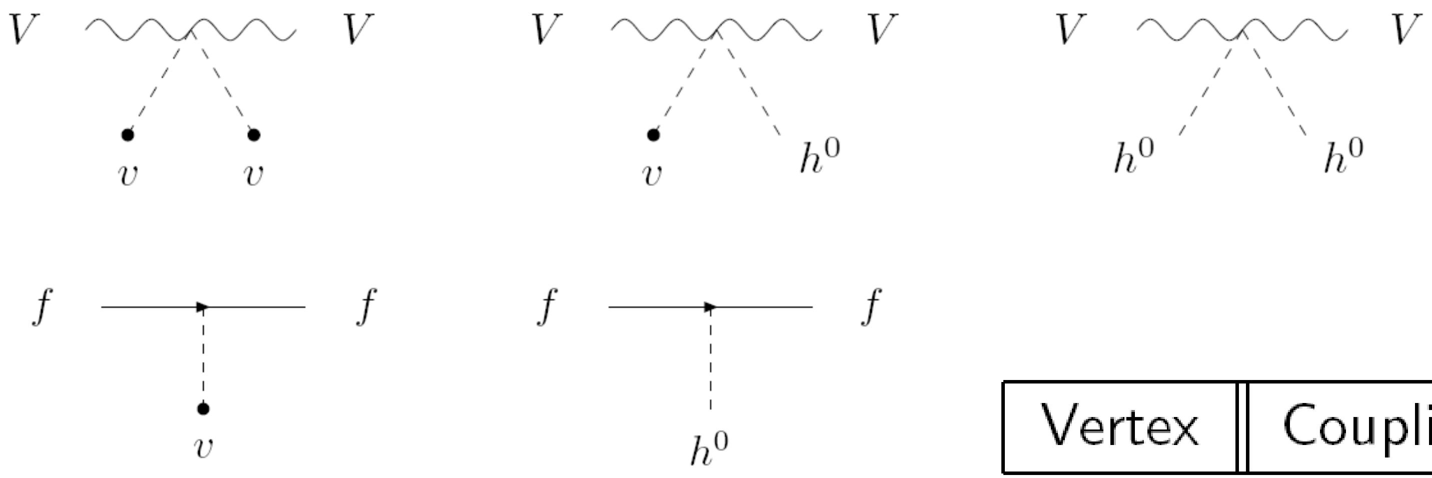
Massless electron ⇔ atoms lose integrity

No atoms mean no chemistry, i.e. no stable
composite structures like liquids, solids, …

…

Higgs couplings

[Tree diagrams]

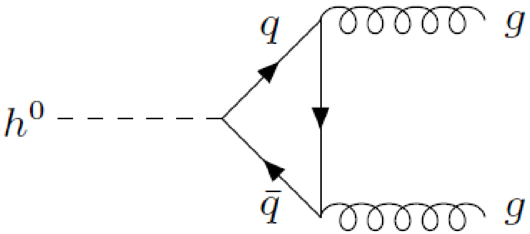


$$v \to v\left(1 + \frac{h}{v}\right)$$

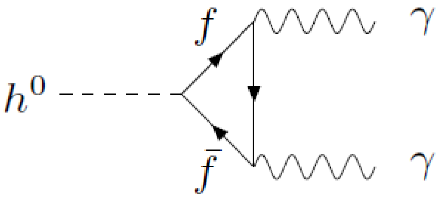
Vertex	Coupling
hVV	$2m_V^2/v$
$hhVV$	$2m_V^2/v^2$
hhh	$3m_h^2/v$
$hhhh$	$3m_h^2/v^2$
$hf\bar{f}$	m_f/v

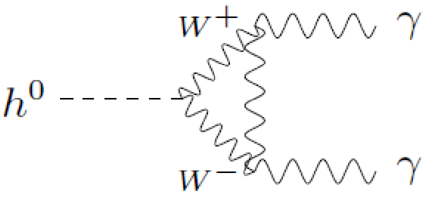
Higgs couplings

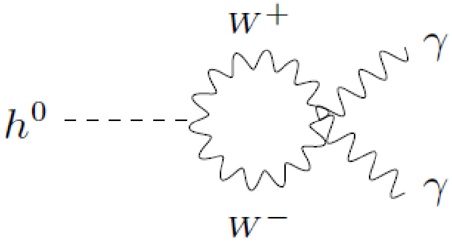
[Loop diagrams]



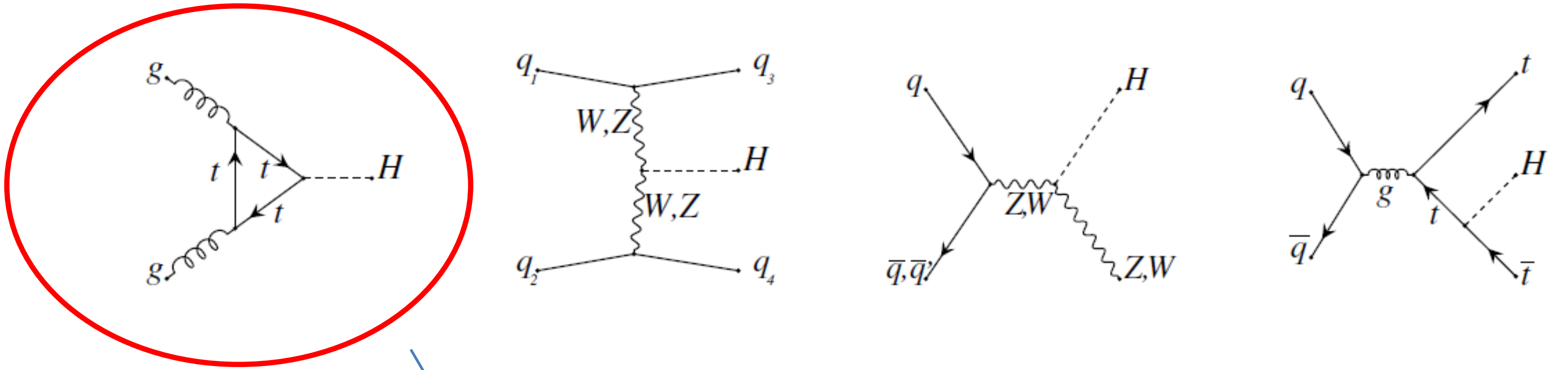
One-loop Vertex	identity of particles in the loop
hgg	quarks
$h\gamma\gamma$	$W^{\pm}$, quarks and charged leptons
$hZ\gamma$	$W^{\pm}$, quarks and charged leptons

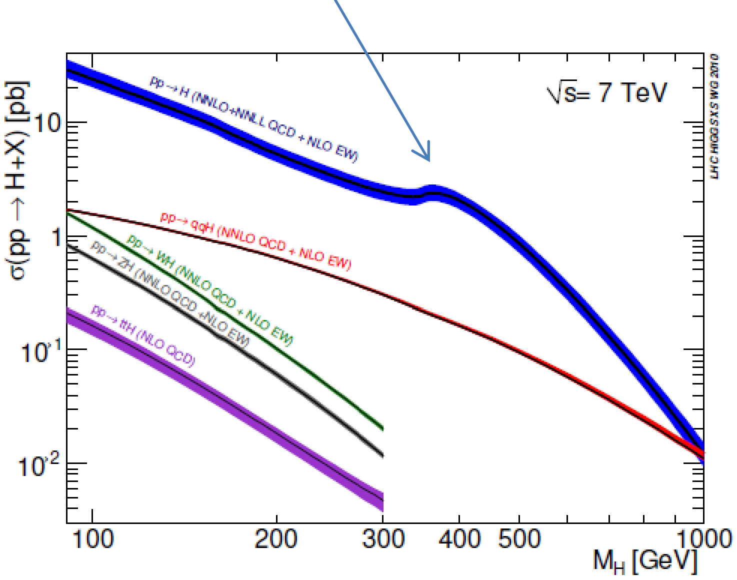


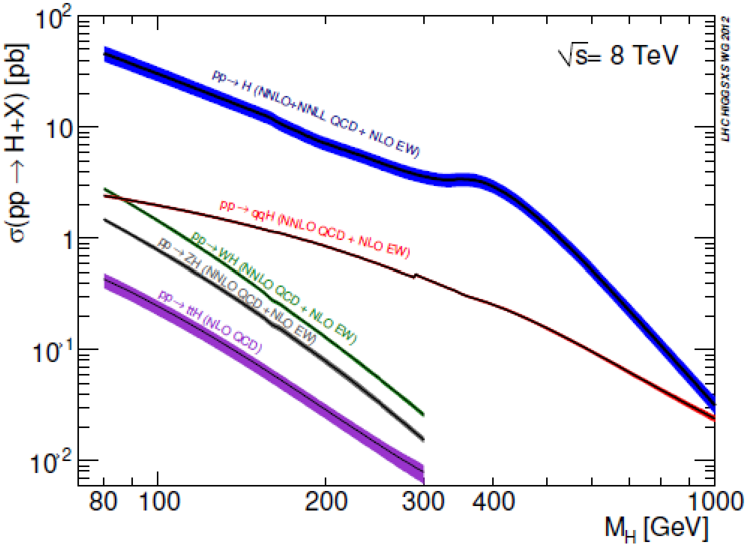




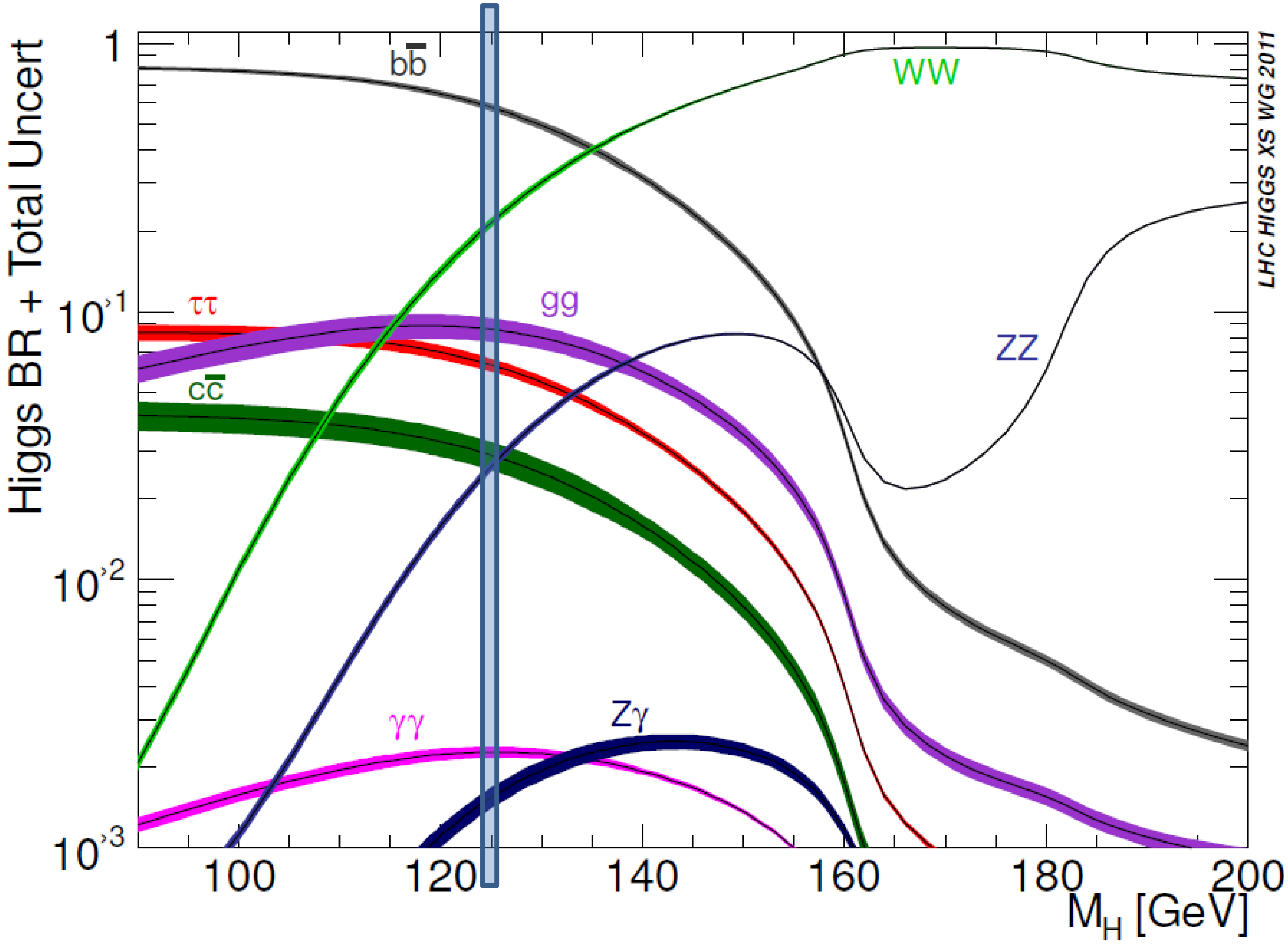
Production @ LHC





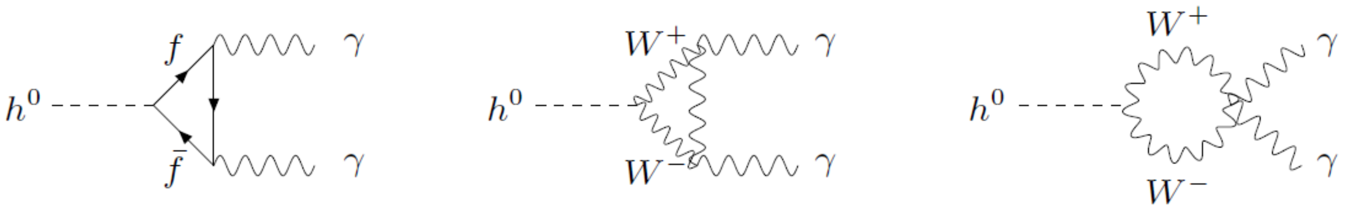


Branching ratios

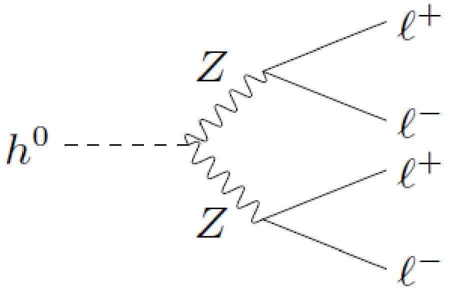


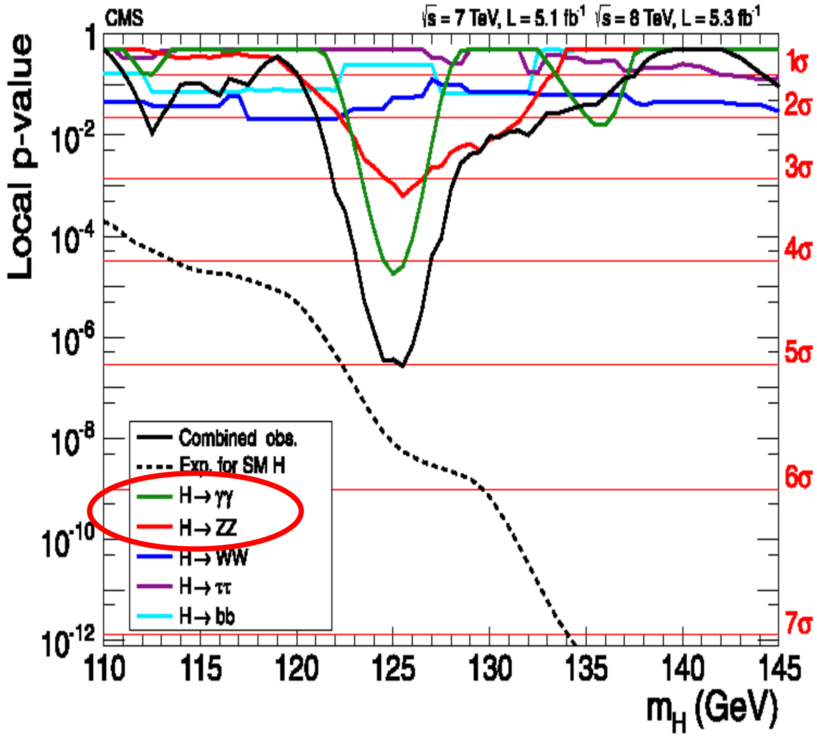
$$gg \to H \to \gamma\gamma,\ ZZ^*(\to \ell^+\ell^-\ell^+\ell^-)$$

Most promising



Golden





Exploration

The new world with a new-boson discovery is here.

Time to explore!

Urgent experimental checks for the SM Higgs boson or not

$$\mathrm{J}^{\mathrm{P}} = 0^{+}$$

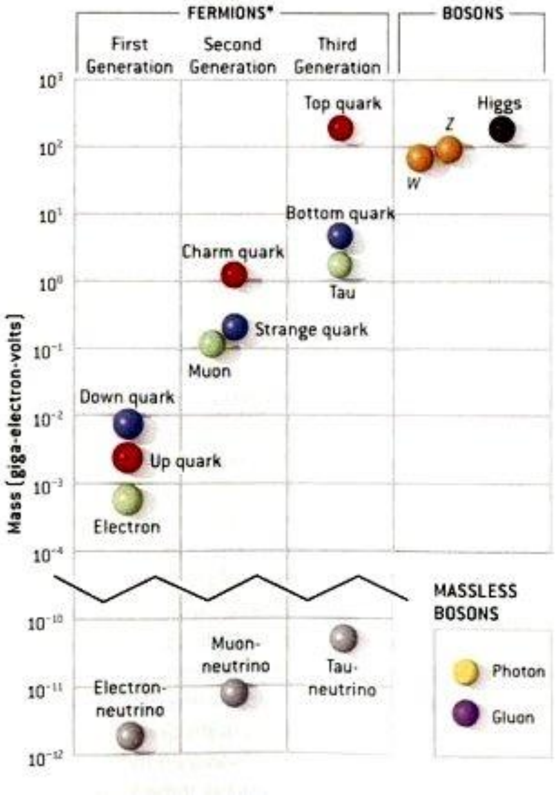
[My talk at the 2012 KPS fall meeting]

(1 + n) ?

Vertex	Coupling
hVV	$2m_V^2/v$
$hhVV$	$2m_V^2/v^2$
hhh	$3m_h^2/v$
$hhhh$	$3m_h^2/v^2$
$hf\bar{f}$	m_f/v

. . .

EWSB and other questions



Origin of fermion masses/mixings

Meaning of CP violation

Lessons for cosmic inflation?

Connection to dark matter?

Insights for dark energy problem?

Link with extra spacetime dimensions

Connection to gravity through SUSY

After more than 40 years of theory and simulation, we have now entered the era of Higgs boson experimental physics, completing the Standard Model.

↓

Hopefully this lasts another 40 years and more, giving us unexpected and profound insights into the theory of the fundamental particles and their interactions and the origin and structure of the universe.

For more comprehensive and broad information
visit the 40th SLAC summer institute site
[http://www-conf.slac.stanford.edu/ssi/2012/]