Electroweak Theory and Higgs Physics

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A Decade of Discovery Past . . .

- ▷ Electroweak theory $\rightarrow$ law of nature
- ▷ Higgs-boson influence observed in the vacuum
- ▷ Neutrino flavor oscillations: $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\mu/\nu_\tau$
- ▷ Understanding QCD
- ▷ Discovery of top quark
- ▷ Direct $\mathcal{CP}$ violation in $K \rightarrow \pi\pi$
- ▷ B-meson decays violate $\mathcal{CP}$
- ▷ Flat universe dominated by dark matter, energy
- ▷ Detection of ν_τ interactions
- ▷ Quarks & leptons structureless at TeV scale

A Decade of Discovery Past . . .

- ▷ Electroweak theory → law of nature
  $[Z,\ e^+e^-,\ \bar{p}p,\ \nu N,\ (g-2)_\mu,\ \ldots]$
- ▷ Higgs-boson influence observed in the vacuum
  [EW experiments]
- ▷ Neutrino flavor oscillations: $\nu_\mu \to \nu_\tau$,
  $\nu_e \to \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}, reactors]
- ▷ Understanding QCD
  [heavy flavor, Z^0, $\bar{p}p$, νN, ep, ions, lattice]
- ▷ Discovery of top quark [$\bar{p}p$]
- ▷ Direct $\mathcal{CP}$ violation in $K \to \pi\pi$ [fixed-target]
- ▷ B-meson decays violate $\mathcal{CP}$ [$e^+e^- \to B\bar{B}$]
- ▷ Flat universe dominated by dark matter, energy
  [SN Ia, CMB, LSS]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Quarks & leptons structureless at TeV scale
  [mainly colliders]

Goal: Understanding the Everyday

- ▷ Why are there atoms?
- ▷ Why chemistry?
- ▷ Why stable structures?
- ▷ What makes life possible?

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▷ Why are there atoms?

▷ Why chemistry?

▷ Why stable structures?

▷ What makes life possible?

What would the world be like, without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons?

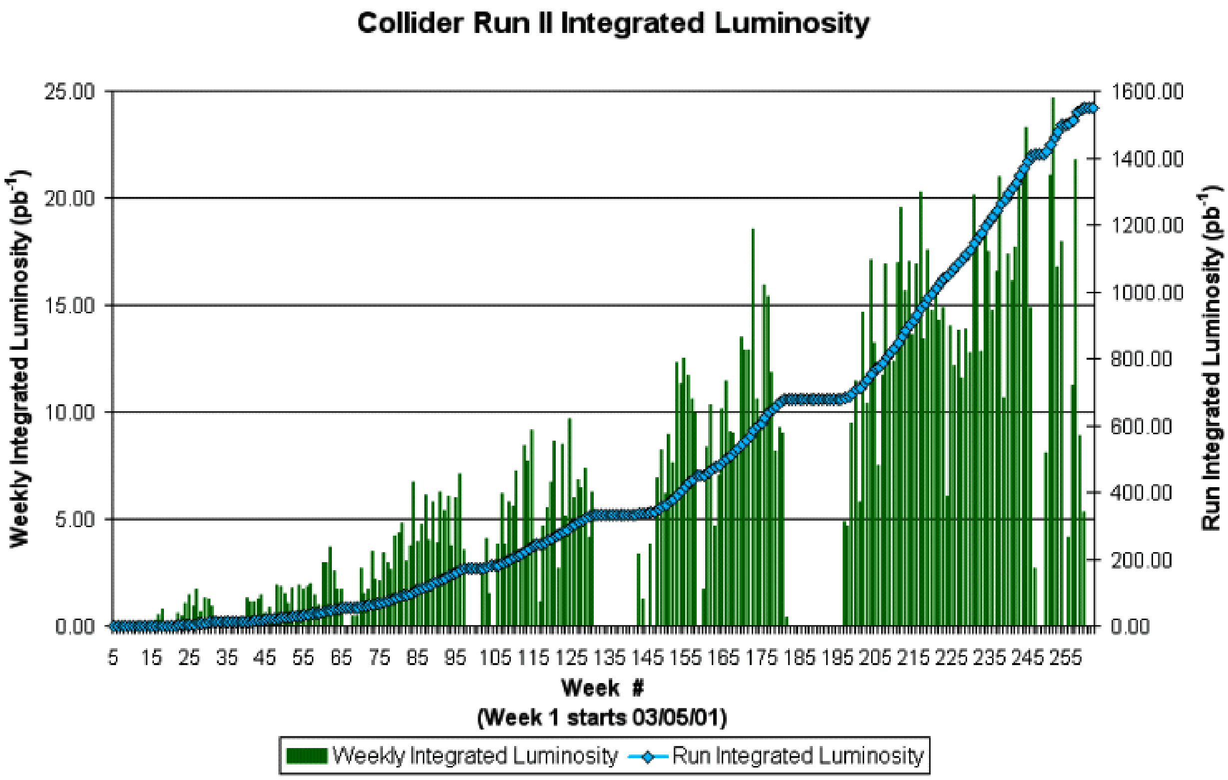
Searching for the mechanism of electroweak symmetry breaking, we seek to understand

why the world is the way it is.

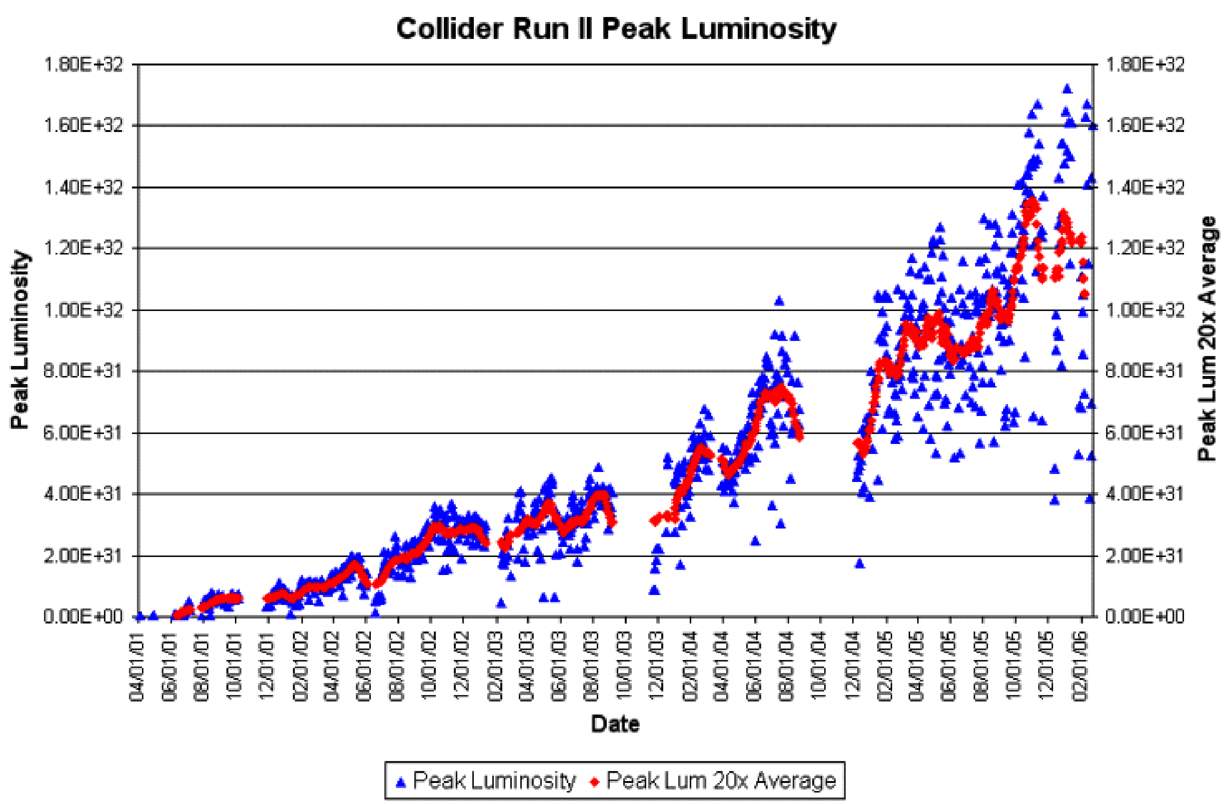
This is one of the deepest questions humans have ever pursued, and

it is coming within the reach of particle physics.

Tevatron Collider is running *now*, breaking new ground in sensitivity



Collider Run II Integrated Luminosity
Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity



Collider Run II Peak Luminosity
Peak Luminosity
Peak Lum 20x Average
Date
Peak Luminosity
Peak Lum 20x Average

Tevatron Collider in a Nutshell

980-GeV protons, antiprotons

(2π km)

frequency of revolution $\approx 45\,000$ s^{-1}

392 ns between crossings

($36 \otimes 36$ bunches)

collision rate $= \mathcal{L} \cdot \sigma_{\text{inelastic}} \approx 10^7$ s^{-1}

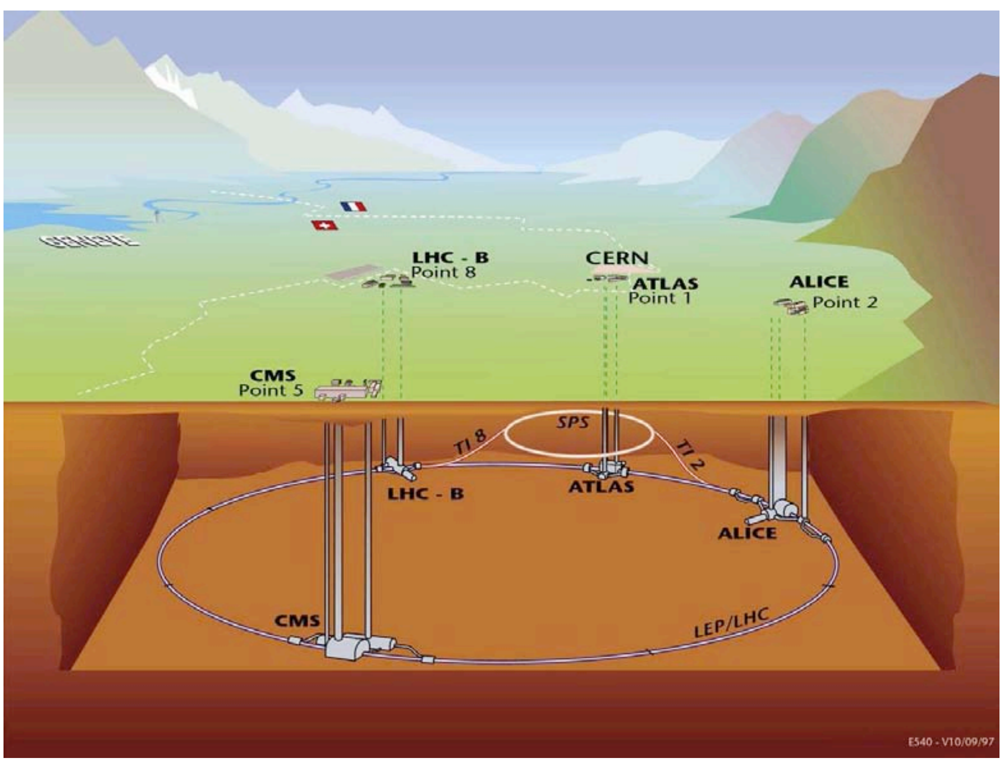
$c \approx 10^9$ km/h; $v_p \approx c - 495$ km/h

Record $\mathcal{L}_{\text{init}} = 1.64 \times 10^{32}$ cm^{-2} s^{-1}

[CERN ISR: pp, 1.4]

Maximum $\bar{p}$ at Low β: 1.661×10^{12}

The LHC will operate *soon*, breaking new ground in energy and sensitivity



LHC in a nutshell

7-TeV protons on protons (27 km);

$v_p \approx c - 10$ km/h

Novel two-in-one dipoles (≈ 9 teslas)

Startup: 43 $\otimes$ 43 $\longrightarrow$ 156 $\otimes$ 156 bunches, $\mathcal{L} \approx 6 \times 10^{31}$ cm^{-2} s^{-1}

Early: 936 bunches, $\mathcal{L} \gtrsim 5 \times 10^{32}$ cm^{-2} s^{-1} [75 ns]

Next phase: 2808 bunches, $\mathcal{L} \longrightarrow 2 \times 10^{33}$ cm^{-2} s^{-1}

25 ns bunch spacing

Eventual: $\mathcal{L} \gtrsim 10^{34}$ cm^{-2} s^{-1}: 100 fb^{-1}/year

Tentative Outline ...

- $SU(2)_L \otimes U(1)_Y$ theory

  Gauge theories

  Spontaneous symmetry breaking

  Consequences: $W^{\pm}$, Z^0/NC, H, m_f?

  Measuring $\sin^2\theta_W$ in νe scattering

  GIM / CKM

- Phenomena at tree level and beyond

  Z^0 pole

  W mass and width

  Vacuum energy problem

. . . Outline

▷ The Higgs boson and the 1-TeV scale

  Why the Higgs boson must exist

  Higgs properties, constraints

  How well can we anticipate M_H?

  Higgs searches

▷ The problems of mass

▷ The EW scale and beyond

  Hierarchy problem

  Why is the EW scale so small?

  Why is the Planck scale so large?

▷ Outlook

General References

- ▷ C. Quigg, "Nature's Greatest Puzzles," hep-ph/0502070
- ▷ C. Quigg, "The Electroweak Theory," hep-ph/0204104 (TASI 2000 Lectures)
- ▷ C. Quigg, *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions*
- ▷ I. J. R. Aitchison & A. J. G. Hey, *Gauge Theories in Particle Physics*
- ▷ R. N. Cahn & G. Goldhaber, *Experimental Foundations of Particle Physics*
- ▷ G. Altarelli & M. Grünewald, "Precision Electroweak Tests of the SM," hep-ph/0404165
- ▷ F. Teubert, "Electroweak Physics," ICHEP04
- ▷ S. de Jong, "Tests of the Electroweak Sector of the Standard Model," EPS HEPP 2005

Problem sets: http://lutece.fnal.gov/TASI/default.html

Our picture of matter

Pointlike constituents ($r < 10^{-18}$ m)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

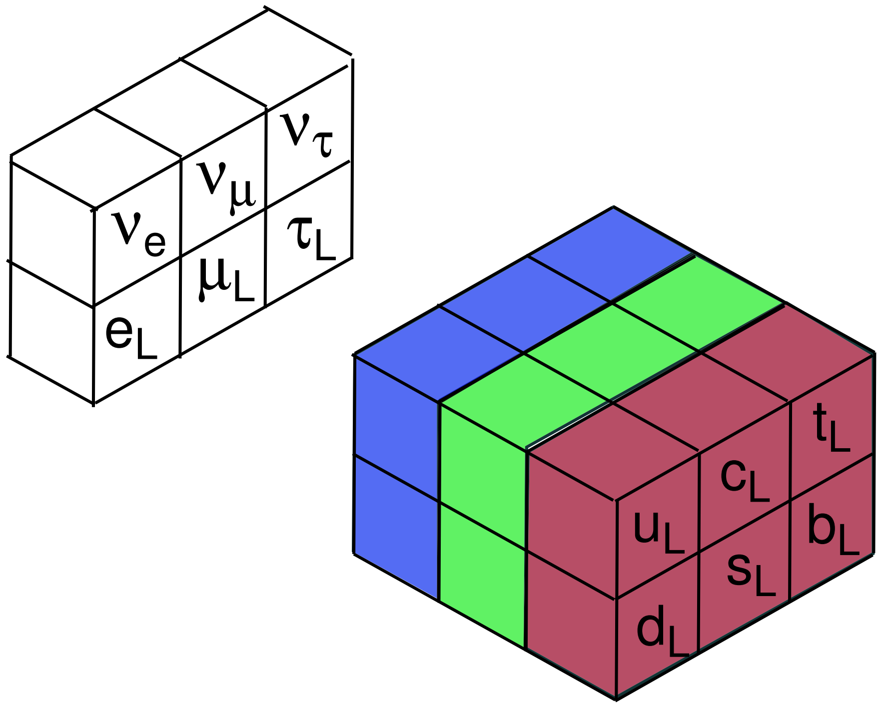
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

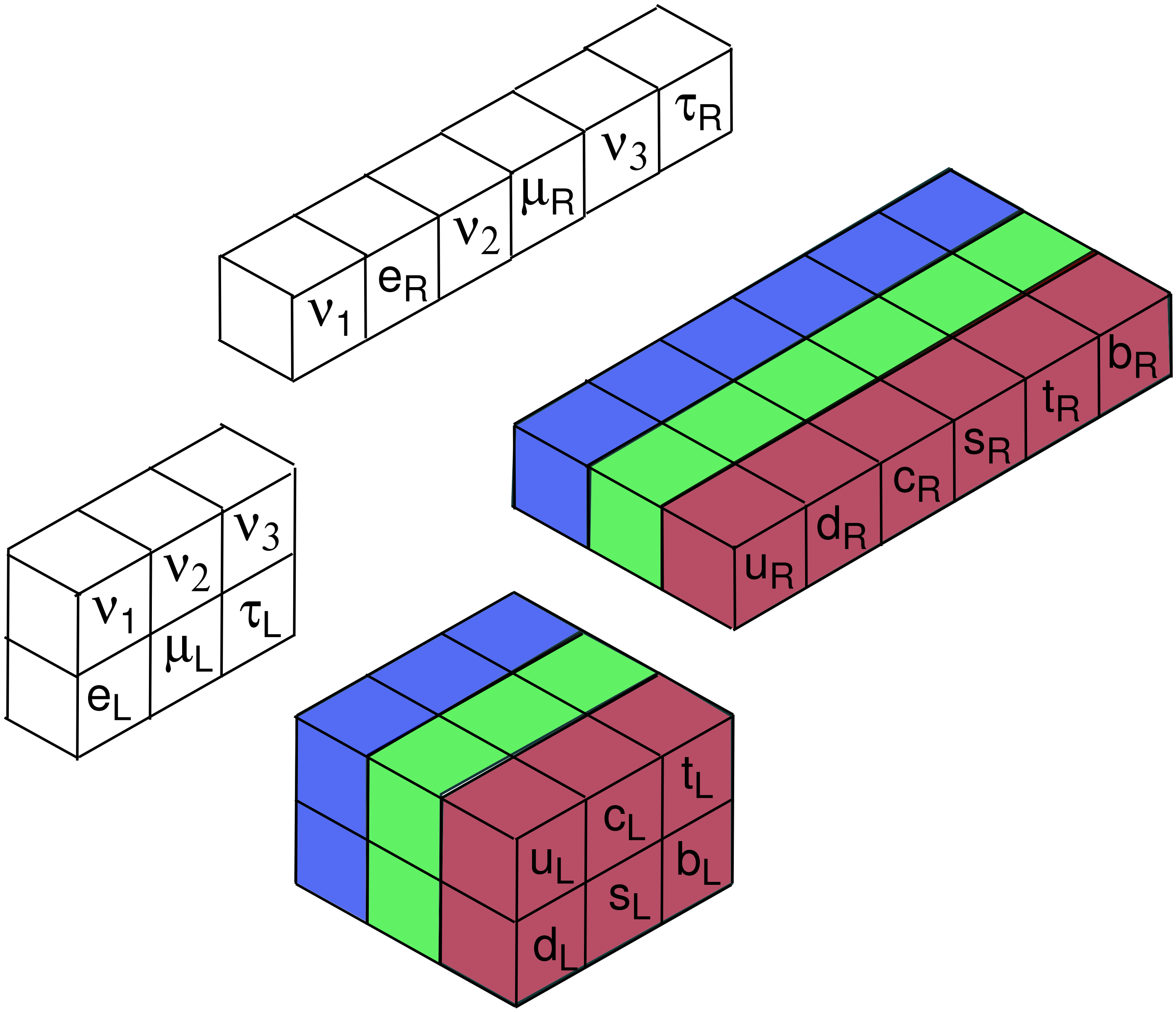
Few fundamental forces, derived from gauge symmetries

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Electroweak symmetry breaking

Higgs mechanism?


ν_τ
ν_μ
ν_e
τ_L
μ_L
e_L
t_L
c_L
u_L
b_L
s_L
d_L


ν_1 e_R ν_2 μ_R ν_3 τ_R
ν_1 ν_2 ν_3
e_L μ_L τ_L
u_R d_R c_R s_R t_R b_R
u_L c_L t_L
d_L s_L b_L

SYMMETRIES $\Longrightarrow$ INTERACTIONS
Phase Invariance (Symmetry) in Quantum Mechanics

QM STATE: COMPLEX SCHRÖDINGER WAVE FUNCTION $\psi(x)$

OBSERVABLES

$$\langle O \rangle = \int d^n x \psi^* O \psi$$

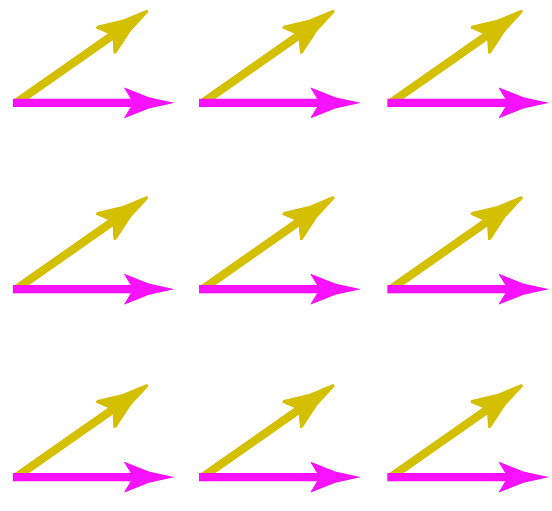
ARE UNCHANGED

UNDER A GLOBAL PHASE ROTATION

$$\psi(x) \to e^{i\theta}\psi(x)$$
$$\psi^*(x) \to e^{-i\theta}\psi^*(x)$$

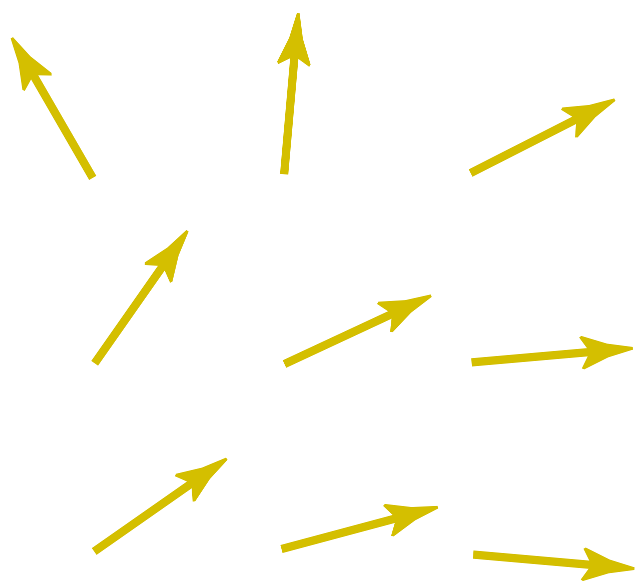
- Absolute phase of the wave function cannot be measured (is a matter of convention).
- Relative phases (interference experiments) are unaffected by a global phase rotation.

GLOBAL ROTATION — SAME EVERYWHERE



MIGHT WE CHOOSE ONE PHASE CONVENTION IN RIO AND ANOTHER IN BATAVIA?

A DIFFERENT CONVENTION AT EACH POINT?



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

THERE IS A PRICE.

Some variables (e.g., momentum) and the Schrödinger equation itself contain derivatives. Under the transformation

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

the gradient of the wave function transforms as

$$\nabla\psi(x) \to e^{iq\alpha(x)}[\nabla\psi(x)+iq(\nabla\alpha(x))\psi(x)]$$

The $\nabla\alpha(x)$ term spoils local phase invariance.

TO RESTORE LOCAL PHASE INVARIANCE . . .

Modify the equations of motion and observables.

$$\boxed{\text{Replace } \nabla \text{ by } \nabla + iq\vec{A}}$$

"Gauge-covariant derivative"

If the vector potential $\vec{A}$ transforms under local phase rotations as

$$\vec{A}(x) \to \vec{A}'(x) \equiv \vec{A}(x) - \nabla\alpha(x),$$

then $(\nabla + iq\vec{A})\psi \to e^{iq\alpha(x)}(\nabla + iq\vec{A})\psi$ and $\psi^*(\nabla + iq\vec{A})\psi$ is invariant under local rotations.

NOTE . . .

- $\vec{A}(x) \to \vec{A}'(x) \equiv \vec{A}(x) - \nabla\alpha(x)$ has the form of a gauge transformation in electrodynamics.
- The replacement $\nabla \to (\nabla + iq\vec{A})$ corresponds to $\vec{p} \to \vec{p} - q\vec{A}$

FORM OF INTERACTION IS DEDUCED
FROM LOCAL PHASE INVARIANCE

$\Longrightarrow$ MAXWELL'S EQUATIONS

DERIVED

FROM A SYMMETRY PRINCIPLE

QED is the gauge theory based on
$U(1)$ phase symmetry

GENERAL PROCEDURE

- Recognize a symmetry of Nature.
- Build it into the laws of physics.
  (Connection with conservation laws)
- Impose symmetry in stricter (local) form.

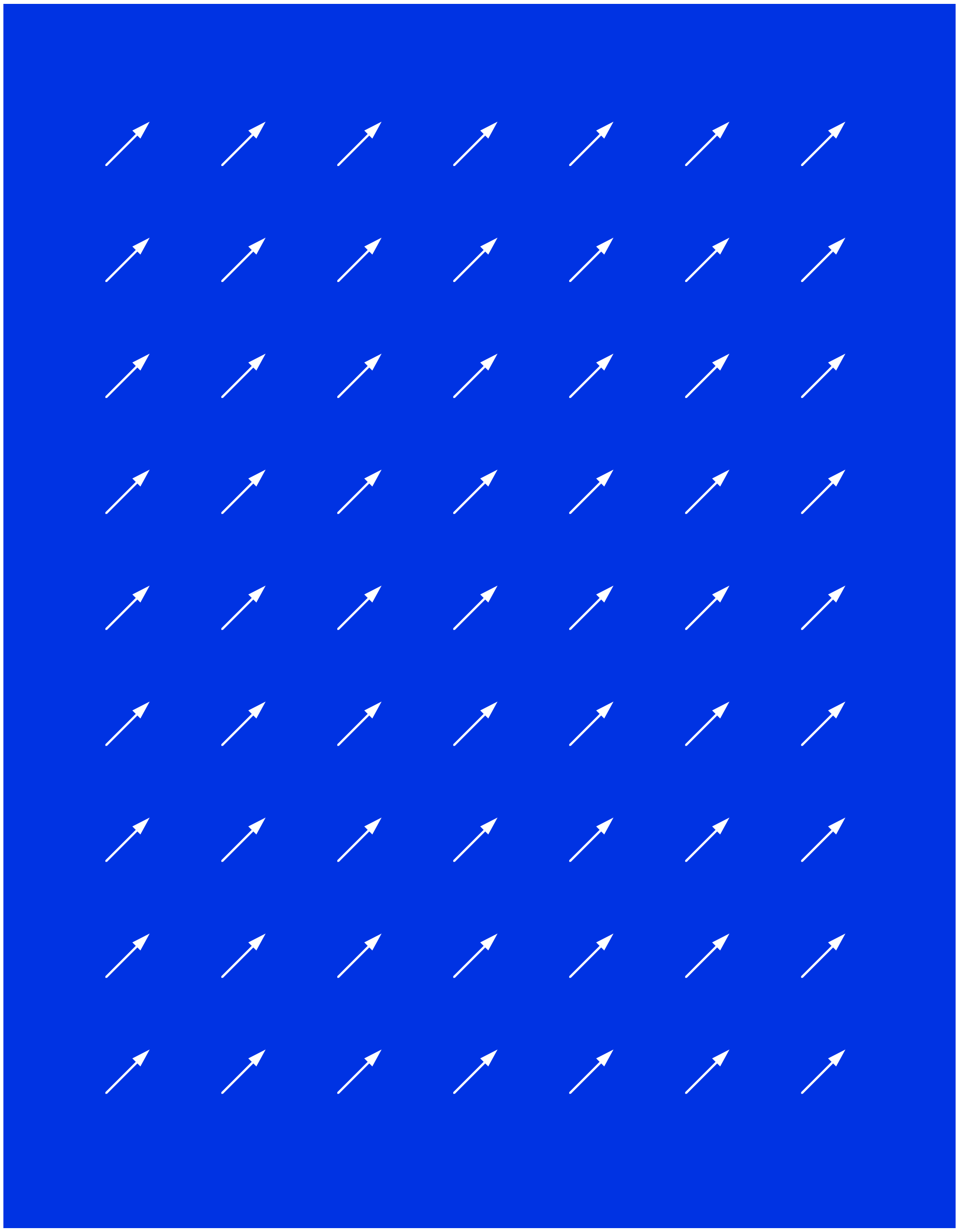
$\Longrightarrow$ INTERACTIONS

- Massless vector fields (gauge fields)
- Minimal coupling to the conserved current
- Interactions among the gauge fields, if symmetry is non-Abelian

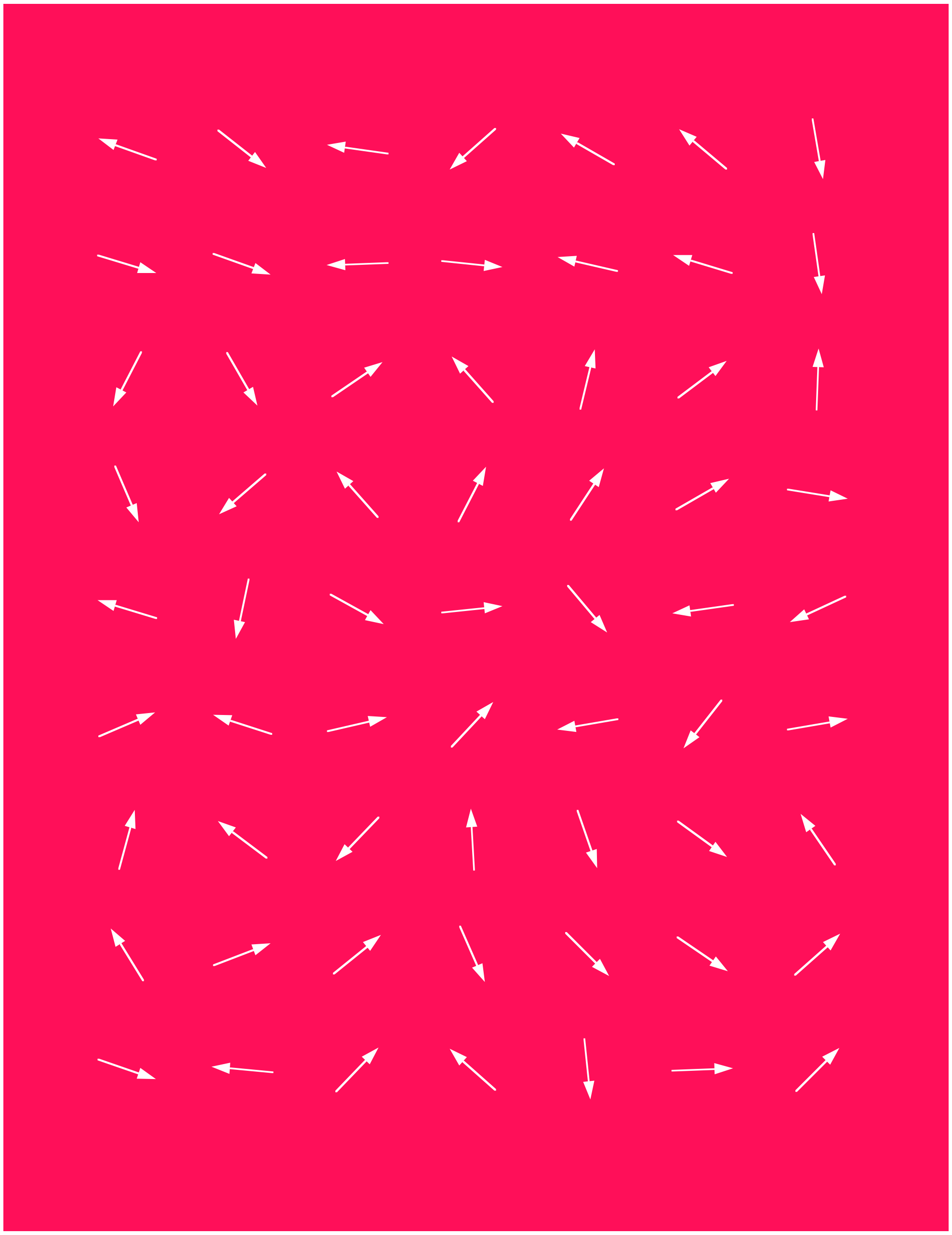
Posed as a problem in mathematics, construction of a gauge theory is always possible (at the level of a classical $\mathcal{L}$; consistent quantum theory may require additional vigilance).

Formalism is no guarantee that the gauge symmetry was chosen wisely.

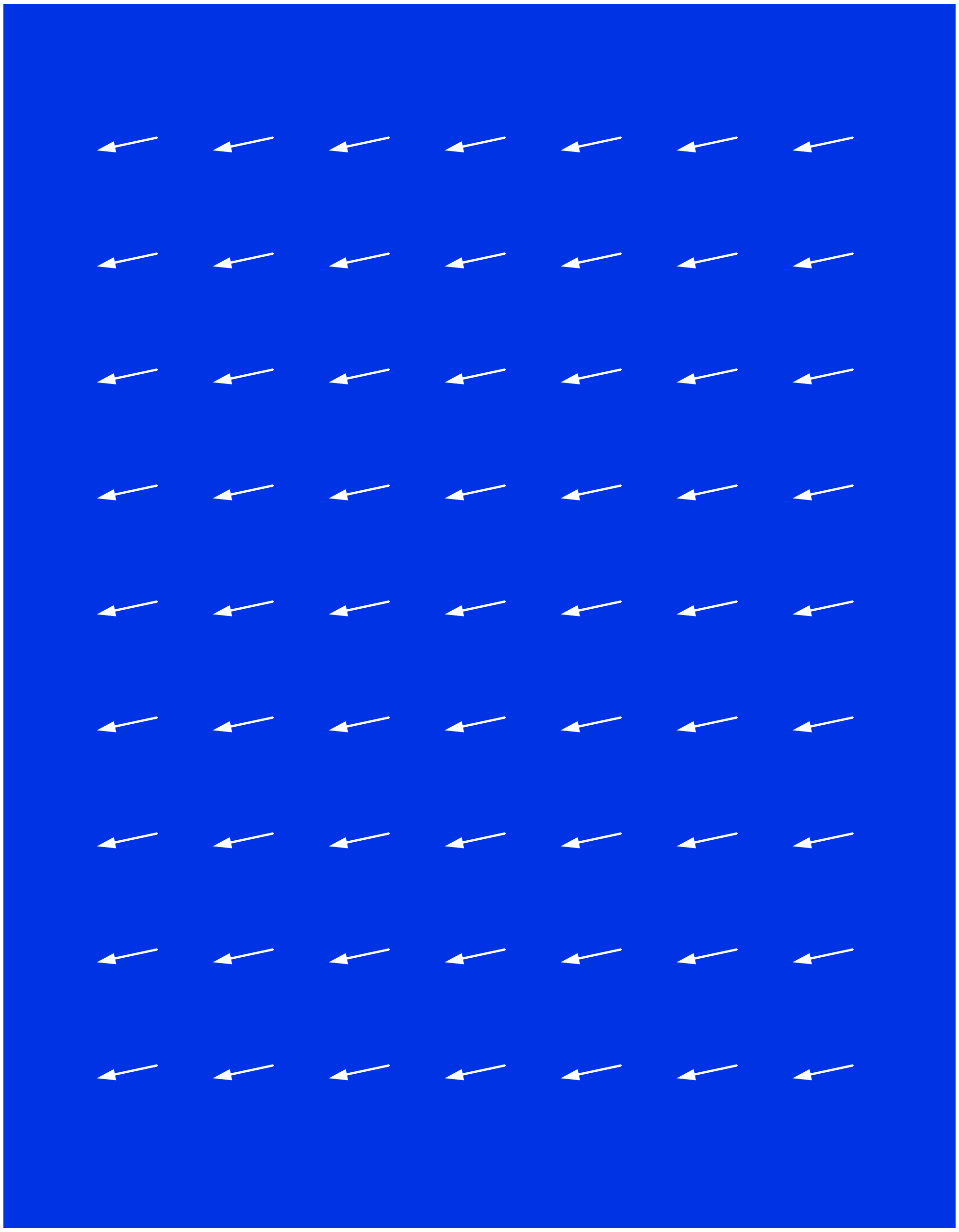
The Crystal World



The Crystal World



The Crystal World



The Perfect World

The Real World

Massive Photon? *Hiding Symmetry*

Recall $\boxed{2}$ miracles of superconductivity:

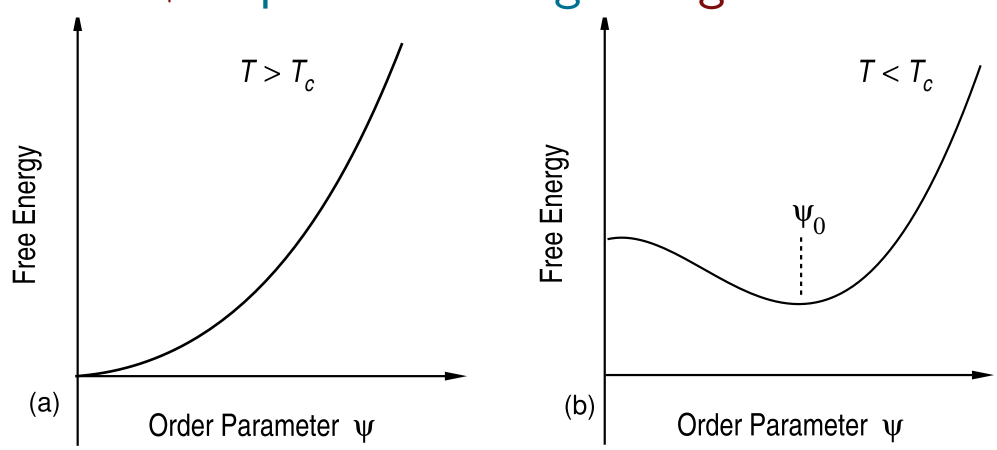
▷ No resistance

▷ Meissner effect (exclusion of $\mathbf{B}$)

Ginzburg–Landau Phenomenology
(not a theory from first principles)

normal, resistive charge carriers . . .

. . . + superconducting charge carriers



$\mathbf{B} = 0$:

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

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

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

NONZERO MAGNETIC FIELD

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

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

Weak, slowly varying field

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

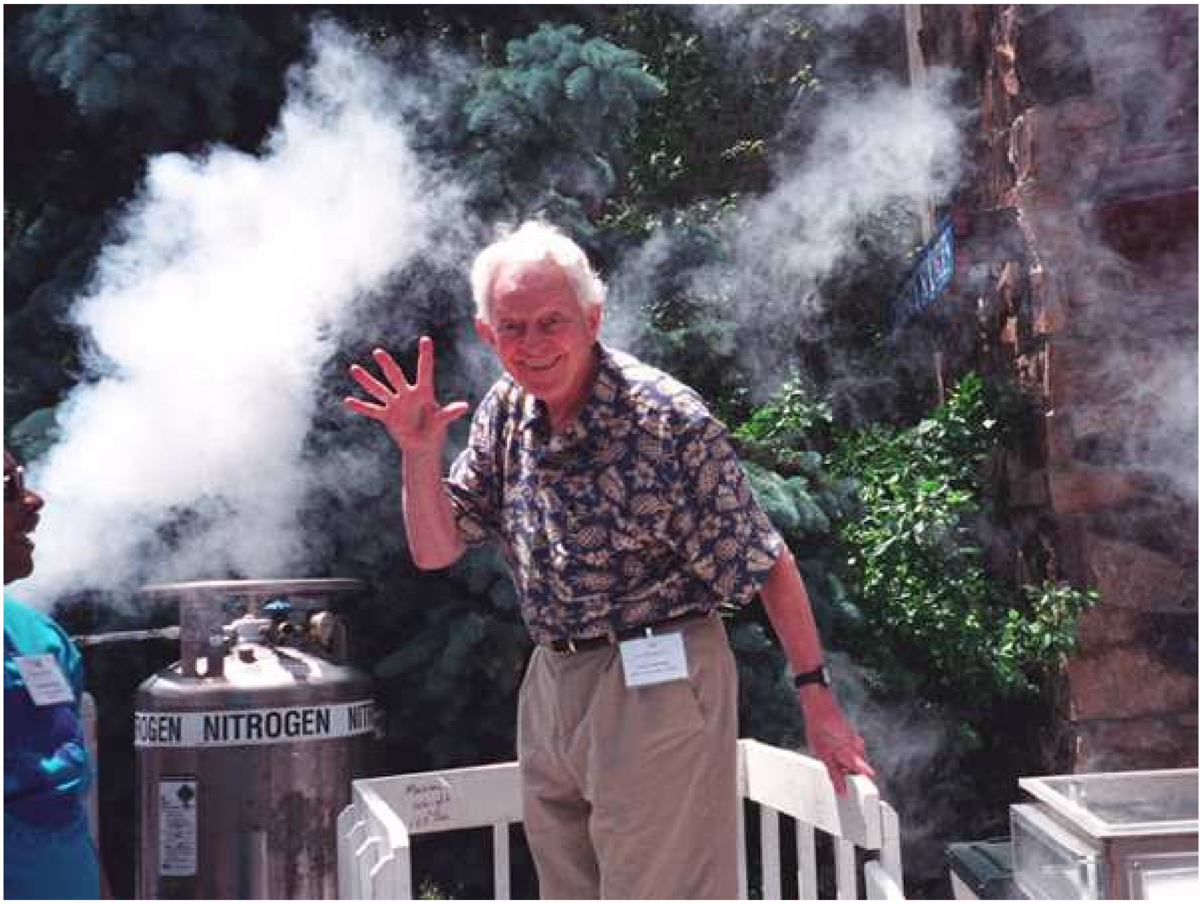
Variational analysis $\Longrightarrow$

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

wave equation of a *massive photon*

Photon— *gauge boson* — acquires mass within superconductor

origin of Meissner effect



Meissner effect levitates Lederman, Snowmass 2001

Formulate electroweak theory

three crucial clues from experiment:

▷ Left-handed weak-isospin doublets,

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

and

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s' \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b' \end{pmatrix}_L ;$$

▷ Universal strength of the (charged-current) weak interactions;

▷ Idealization that neutrinos are massless.

$\boxed{\text{First two clues suggest } SU(2)_L \text{ gauge symmetry}}$

A theory of leptons

$$\mathsf{L} = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \mathsf{R} \equiv e_R$$

weak hypercharges $Y_L = -1$, $Y_R = -2$
Gell-Mann–Nishijima connection, $Q = I_3 + \frac{1}{2}Y$

$SU(2)_L \otimes U(1)_Y$ gauge group $\Rightarrow$ gauge fields:

⋆ weak isovector $\vec{b}_\mu$, coupling g

⋆ weak isoscalar $\mathcal{A}_\mu$, coupling $g'/2$

Field-strength tensors

$$F^\ell_{\mu\nu} = \partial_\nu b^\ell_\mu - \partial_\mu b^\ell_\nu + g\varepsilon_{jk\ell} b^j_\mu b^k_\nu \ , SU(2)_L$$

and

$$f_{\mu\nu} = \partial_\nu \mathcal{A}_\mu - \partial_\mu \mathcal{A}_\nu \ , U(1)_Y$$

Interaction Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{leptons}} \ ,$$

with

$$\mathcal{L}_{\text{gauge}} = -\tfrac{1}{4}F^{\ell}_{\mu\nu}F^{\ell\mu\nu} - \tfrac{1}{4}f_{\mu\nu}f^{\mu\nu},$$

and

$$\begin{aligned}\mathcal{L}_{\text{leptons}} &= \overline{\mathsf{R}}\, i\gamma^{\mu}\left(\partial_{\mu} + i\frac{g'}{2}\mathcal{A}_{\mu}Y\right)\mathsf{R} \\ &+ \overline{\mathsf{L}}\, i\gamma^{\mu}\left(\partial_{\mu} + i\frac{g'}{2}\mathcal{A}_{\mu}Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_{\mu}\right)\mathsf{L}.\end{aligned}$$

Electron mass term

$$\mathcal{L}_e = -m_e(\bar{e}_{\mathsf{R}}e_{\mathsf{L}} + \bar{e}_{\mathsf{L}}e_{\mathsf{R}}) = -m_e\bar{e}e$$

would violate local gauge invariance Theory has four massless gauge bosons

$$\mathcal{A}_{\mu} \quad b^1_{\mu} \quad b^2_{\mu} \quad b^3_{\mu}$$

Nature has but one (γ)

Hiding EW Symmetry

Higgs mechanism: relativistic generalization of Ginzburg-Landau superconducting phase transition

▷ Introduce a complex doublet of scalar fields

$$\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad Y_\phi = +1$$

▷ Add to $\mathcal{L}$ (gauge-invariant) terms for interaction and propagation of the scalars,

$$\mathcal{L}_{\rm scalar} = (\mathcal{D}^\mu\phi)^\dagger(\mathcal{D}_\mu\phi) - V(\phi^\dagger\phi),$$

where $\mathcal{D}_\mu = \partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_\mu$ and

$$\boxed{V(\phi^\dagger\phi) = \mu^2(\phi^\dagger\phi) + |\lambda|\,(\phi^\dagger\phi)^2}$$

▷ Add a Yukawa interaction

$$\mathcal{L}_{\rm Yukawa} = -\zeta_e\left[\overline{\mathsf{R}}(\phi^\dagger\mathsf{L}) + (\overline{\mathsf{L}}\phi)\mathsf{R}\right]$$

- ▷ Arrange self-interactions so vacuum corresponds to a broken-symmetry solution: $\mu^2 < 0$
  Choose minimum energy (vacuum) state for vacuum expectation value

$$\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad v = \sqrt{-\mu^2/|\lambda|}$$

Hides (breaks) $SU(2)_L$ and $U(1)_Y$

but preserves $U(1)_{\mathrm{em}}$ invariance

Invariance under $\mathcal{G}$ means $e^{i\alpha\mathcal{G}}\langle\phi\rangle_0 = \langle\phi\rangle_0$, so $\mathcal{G}\langle\phi\rangle_0 = 0$

$$\tau_1\langle\phi\rangle_0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_2\langle\phi\rangle_0 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} -iv/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_3\langle\phi\rangle_0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 \\ -v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$Y\langle\phi\rangle_0 = Y_\phi\langle\phi\rangle_0 = +1\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

Examine electric charge operator Q on the (electrically neutral) vacuum state

$$
\begin{aligned}
Q\langle\phi\rangle_0 &= \tfrac{1}{2}(\tau_3 + Y)\langle\phi\rangle_0 \\
&= \tfrac{1}{2}\begin{pmatrix} Y_\phi + 1 & 0 \\ 0 & Y_\phi - 1 \end{pmatrix}\langle\phi\rangle_0 \\
&= \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \\
&= \begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad \textit{unbroken!}
\end{aligned}
$$

Four original generators are broken

electric charge is not

▷ $SU(2)_L \otimes U(1)_Y \to U(1)_{\mathrm{em}}$ (will verify)

▷ Expect massless photon

▷ Expect gauge bosons corresponding to

$$\tau_1,\ \tau_2,\ \tfrac{1}{2}(\tau_3 - Y) \equiv K$$

to acquire masses