BEYOND THE STANDARD MODEL OF PARTICLE PHYSICS

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LECTURE 1.

THE STANDARD MODEL OF PARTICLE PHYSICS :

WHAT IS IT AND WHY DO WE NEED TO GO BEYOND?

AIM OF PARTICLE PHYSICS :
EXPLAIN (OR AT LEAST DESCRIBE) ALL THE VARIOUS INTERACTIONS OBSERVED

- ELECTROMAGNETIC
- STRONG
- WEAK
- GRAVITY

} KNOWN INTERACTIONS

- GRAVITY MUCH WEAKER THAN OTHER 3 : WILL NEGLECT IN FIRST TWO LECTURES

WHAT FRAMEWORK TO USE TO DESCRIBE ELECTROMAGNETIC / STRONG / WEAK INT'S?

GAUGE THEORIES

GENERALIZATIONS OF MAXWELL'S THEORY OF ELECTROMAGNETISM

$A_\mu(x)$ VECTOR FIELD $(\mu = 0,1,2,3)$

$F_{\mu\nu}(x) = \partial_\mu A_\nu - \partial_\nu A_\mu$ FIELD STRENGTH

DERIVABLE FROM ACTION

$S = \int d^4x \, \mathcal{L}$ $\quad \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$

- $F_{\mu\nu}$ INVARIANT UNDER GAUGE TRANSFORMATION

$$A_\mu(x) \to A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x)$$

- INTERACTION WITH MATTER (ELECTRON)

ALSO TRANSFORM UNDER GAUGE TRANSFORMATION

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

← LOCAL U(1) SYMMETRY

- TO MAKE LAGRANGIAN GAUGE INVARIANT (= INVARIANT UNDER LOCAL SYMMETRIES)

NEED TO USE COVARIANT DERIVATIVE

$$D_\mu \psi \to e^{i\alpha(x)} D_\mu \psi$$

$$D_\mu \psi = (\partial_\mu + ieA_\mu)\psi$$

- ELECTRODYNAMICS (QED):

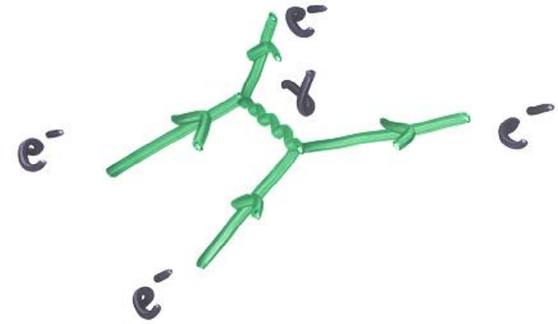
$$\mathcal{L} = -1/4\, F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\not{D} - m)\psi$$

Dirac action for fermion

MAIN FEATURES

- MASS TERM FOR GAUGE BOSON NOT ALLOWED ($A_\mu A^\mu$ NOT GAUGE INVARIANT)

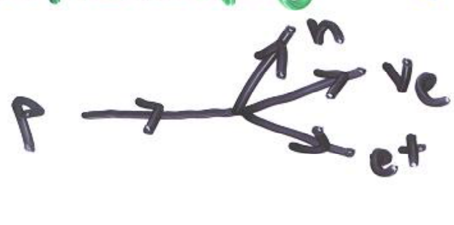
- PHOTON MEDIATES INTERACTION OF ELECTRONS



TRY GENERALIZE TO WEAK AND STRONG INTERACTIONS

WEAK
- INTERACTION HAS FINITE RANGE

- AT LOW ENERGIES WELL DESCRIBED BY CURRENT-CURRENT INTERACTIONS (4-FERMI OPERATORS)



$$\sim \bar{\Psi}_p \gamma_\mu (1-\gamma_5) \Psi_n \cdot \bar{\Psi}_e \gamma^\mu (1-\gamma_5) \Psi_\nu$$

SUGGESTS DESCRIBED BY EXCHANGE OF **MASSIVE** GAUGE BOSONS

W^+, W^-

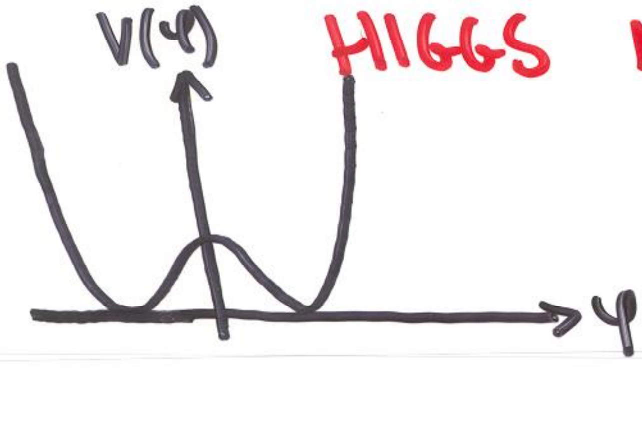
HOW TO GET MASSIVE GAUGE BOSONS WITHOUT GIVING UP ON GAUGE INVARIANCE?

SPONTANEOUS SYMMETRY BREAKING

- LAGRANGIAN INVARIANT
- VACUUM STATE NOT INVARIANT

NEED A SCALAR FIELD THAT TRANSFORMS UNDER GAUGE SYMMETRY, AND NON-ZERO VEV:

HIGGS MECHANISM

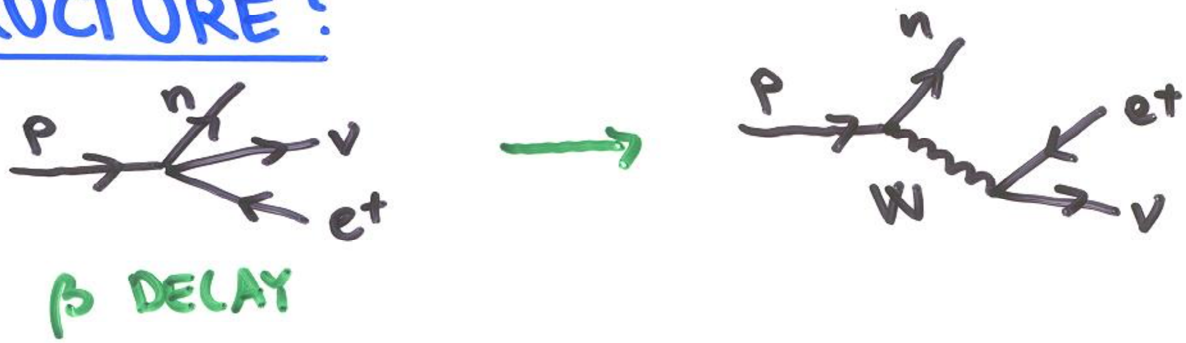


FOR $U(1)$

$$D_\mu H^\dagger D^\mu H = (\partial_\mu - igA_\mu)H^\dagger(\partial^\mu + igA^\mu)H$$

$$\supset g^2 A_\mu A^\mu \langle H^\dagger\rangle\langle H\rangle$$

SO WHAT SHOULD BE THE STRUCTURE?



- W NEEDS TO CARRY ELECTROM. CHARGE
- IN ORDINARY MAXWELL (U(1)) GAUGE THEORIES GAUGE BOSONS DO NOT INTERACT

NEED TO GENERALIZE U(1) GAUGE THEORIES TO THEORIES WITH

- MORE
- INTERACTING

GAUGE BOSONS

NON-ABELIAN GAUGE THEORY (YANG-MILLS THEORY)

- U(1) SYMMETRY $\psi \to e^{i\alpha(x)}\psi$

  SIMPLE PHASE TRANSF.

  MORE COMPLICATED:

  ALSO MIXES UP COMPONENTS OF MATTER FIELD

  $$\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} \to U\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$$

  (U:) 2×2 UNITARY MATRIX, det = 1
  SU(2) TRANSFORM.

- BIGGER GAUGE GROUP → MORE PARAMETERS TO DESCRIBE TRANSFORM.

- EVERY TRANSFORMATION PARAMETER
  (~3 EULER ANGLES IN SU(2))
  ~ "EVERY GENERATOR T^a"

  ↕

  A SEPARATE GAUGE BOSON

  A^a_μ

- SU(2) GAUGE THEORY: 3 GAUGE BOSONS

- NON-ABELIAN GAUGE THEORIES:
  GAUGE BOSONS ALSO CARRY CHARGE

  GROUP GENERATOR $U = e^{i\epsilon^a T^a}$

$$[T^a, T^b] = i f^{abc} T^c$$

- COVARIANT DERIVATIVE

$$D_\mu \psi = (\partial_\mu - i g T^a A_\mu^a)\psi$$

g: analog of electric charge, "gauge coupling"

T^a: generator

- FIELD STRENGTH

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c$$

$g f^{abc} A_\mu^b A_\nu^c$: RESPONSIBLE FOR SELF-INTERACTION

- LAGRANGIAN

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^a F^{a\,\mu\nu} + \bar{\psi}(i\not{D} - m)\psi$$

FORMALLY SAME AS FOR QED

- WEAK INTERACTIONS:

W^+, W^-, γ SIMPLEST POSSIBILITY

SU(2) 3 GENERATORS ~ $W^\pm, \gamma$

DOES NOT WORK

$SU(2) \to U(1)_{EM}$ BY HIGGS SCALAR WOULD IMPLY $\binom{\nu}{e}$ HAVE TO BE IN 3 DIMENSIONAL IRREP.

- NEXT SIMPLEST POSSIBILITY

WEINBERG - SALAM - GLASHOW MODEL

IF SU(2) DOESN'T WORK, TAKE $SU(2) \times U(1) \to U(1)_{EM}$

$U(1)_{EM}$ NEEDS TO BE PART OF SU(2) & U(1), OTHERWISE W NOT CHARGED.

THE MODEL

- A HIGGS SCALAR IN FUND'L OF SU(2)

  $2_{1/2}$ GETS A VEV

$$SU(2)_L \times U(1)_Y$$

$$\downarrow \qquad \downarrow$$

$$g \qquad g'$$

GAUGE COUPLINGS

- NOW THERE ARE 4 GAUGE BOSONS

  $W^{\pm}, \gamma, Z$

- GAUGE BOSON MASSES FROM HIGGS VEV

$$H = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

UNBROKEN GENERATOR

$$Q \equiv T_3 + Y$$

↑ E&M

$$\begin{pmatrix} 1/2 & \\ & -1/2 \end{pmatrix} + \begin{pmatrix} 1/2 & \\ & 1/2 \end{pmatrix} = \begin{pmatrix} 1 & \\ & 0 \end{pmatrix}$$

$$D_\mu H^+ D^\mu H \longrightarrow M_W^2 W_\mu^+ W^{\mu -} + \frac{M_Z^2}{2} Z_\mu Z^\mu$$

$$M_W^2 = \frac{g^2 v^2}{4} \qquad M_Z^2 = \frac{g^2 + g'^2}{4} v^2$$

- PHOTON : MIXTURE OF W_3 & B

$\uparrow$ $U(1)_Y$ GB

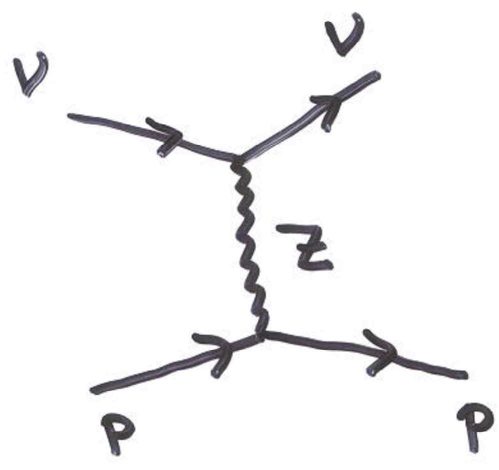
$$A = \sin\theta_W W_3 + \cos\theta_W B$$

$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2}$$ WEAK MIXING ANGLE

- Z : THE OPPOSITE COMBINATION

$$Z = \cos\theta_W W_3 - \sin\theta_W B$$

- EXISTENCE OF Z : "NEUTRAL CURRENTS"



WOULD NOT HAPPEN OTHERWISE

- HOW DO MATTER FIELDS COUPLE?

EXPERIMENTAL FACT:

ONLY LEFT-HANDED PARTICLES COUPLE TO $W^\pm$. $\psi_L = \frac{1-\gamma_5}{2}\psi$

ψ: DIRAC FERMION, 4 COMPONENTS

ψ_L: "WEYL FERMION", ONLY 2 COMP'S

$\psi_R = \frac{1+\gamma_5}{2}$ ALSO WEYL FERMION OF "OPPOSITE CHIRALITY"

- SUGGESTS: L & R FERMIONS HAVE <u>DIFFERENT</u> GAUGE QUANTUM NUMBERS UNDER $SU(2) \times U(1)$

L COUPLES TO $W^\pm$ → DOUBLET OF $SU(2)$

R COUPLES TO E&M & Z → SINGLET OF $SU(2)$

CHARGE ASSIGNMENTS OF ELECTROWEAK THEORY

$Q = T_3 + Y$

	$SU(2)_L$	$\times\, U(1)_Y$
$E = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$	2	$-1/2$
e_R	1	-1
$Q = \begin{pmatrix} u \\ d \end{pmatrix}_L$	2	$1/6$
u_R	1	$2/3$
d_R	1	$-1/3$
H	2	$1/2$

Leptons (E, e_R): 3 FAMILIES e, μ, τ; ν_e, ν_μ, ν_τ

Quarks (Q, u_R, d_R): 3 FAMILIES $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$

- CHIRAL GAUGE THEORY MEANING L & R TRANSFORM DIFFERENTLY UNDER GAUGE SYMMETRIES

CAN NOT WRITE DOWN A MASS TERM FOR FERMIONS

- BUT CAN USE HIGGS TO ALSO GENERATE MASSES FOR FERMIONS

- THE YUKAWA COUPLINGS:

$$\mathcal{L}_{Yuk} = -\lambda_d^{ij}\,\bar{Q}^i_L H d^j_R - \lambda_u^{ij}\,\epsilon^{ab}\,\bar{Q}^i_{La} H^\dagger_b u^j_R + h.c.$$

IN PRINCIPLE λ_d^{ij}, λ_u^{ij} ARBITRARY COMPLEX 3x3 MATRICES (NOT SYMMETRIC)

- NOT NECESSARILY DIAGONALIZABLE BY SINGLE UNITARY TRANSFORMATION!

BUT

$$\begin{cases} \lambda_u \lambda_u^\dagger = U_u D_u^2 U_u^\dagger \\ \lambda_u^\dagger \lambda_u = W_u D_u^2 W_u^\dagger \end{cases}$$

POSITIVE DEF. HERMITIAN

$$\lambda_u = U_u D_u W_u^\dagger$$

DIAGONALIZED BY BI-UNITARY TRANSFORM.

- REDEFINE

$$\left.\begin{aligned} u_R^i &\to W_u^{ij} u_R^j \\ d_R^i &\to W_d^{ij} d_R^j \end{aligned}\right\}$$

W_u, W_d disappear, since u_R, d_R SU(2) SINGLETS

- SIMILAR REDEFINITION OF L FIELDS

$$u_L^i \to U_u^{ij} u_L^j$$
$$d_L^i \to U_d^{ij} d_L^j$$

} SINCE $\begin{pmatrix} u \\ d \end{pmatrix}_L$ SU(2) DOUBLET,

INTERACTION WITH $W^\pm$

$$\frac{1}{\sqrt{2}} g W_\mu^+ \bar{u}_L^i \gamma^\mu d_L^i$$

DOES NOT CANCEL OUT

$$\downarrow$$

$$\frac{1}{\sqrt{2}} g W_\mu^+ \bar{u}_L^i \gamma^\mu \underbrace{(U_u^\dagger U_d)^{ij}}_{V^{ij}} d_L^j$$

CKM MATRIX

- CHARGED CURRENT NOT FLAVOR DIAGONAL (WHILE NEUTRAL CURRENT IS)
- CKM: 3x3 UNITARY MATRIX

HOWEVER SOME PHASES CAN BE REMOVED BY $q_L^i \to e^{i\alpha} q_L^i$

(EXCEPT OVERALL PHASE)

- FOR 3 GENERATIONS, CAN REMOVE 6-1=5 PHASES.

- NUMBER OF PARAMETERS IN CKM: 3x3 UNITARY

9 PARAMETERS
=
3 ANGLES
6 PHASES − 5 UNPHYSICAL

→ 3 ANGLES + 1 PHASE

- IN ELECTROWEAK THEORY

P : $e_L^- \leftrightarrow e_R^-$ BROKEN

C : $e_L^- \leftrightarrow e_L^+$ BROKEN (DIFFERENT QUANTUM #'S)

BUT

CP : $e_L^- \leftrightarrow e_R^+$ COULD BE A SYMMETRY (IS A SYMMETRY OF GAUGE INTERACTIONS

- BUT UNDER CP

$$\lambda_u \longleftrightarrow \lambda_u^*$$

$$\lambda_d \longleftrightarrow \lambda_d^*$$

WHETHER OR NOT CP PRESERVED: COMES DOWN TO WHETHER CKM MATRIX REAL OR COMPLEX

- FOR 3 FAMILIES: SINGLE PHASE IN CKM MATRIX, COULD BE RESPONSIBLE FOR OBSERVED CP VIOLATION

STRONG INTERACTIONS
(VERY BRIEF)

- FACTS
  - CLASSIFICATION OF HADRONS IMPLIES QUARKS AS FUND'L PARTICLES $\begin{pmatrix} u \\ d \\ s \end{pmatrix}$ AS 3 OF SU(3) FLAVOR
  - DEEP INELASTIC SCATTERING ON PROTONS : AT LARGE ENERGIES QUARKS ALMOST FREE "ASYMPTOTIC FREEDOM"
  - QUARK SPECTROSCOPY + + PAULI PRINCIPLE IMPLIES ADDITIONAL COLOR QUANTUM #

- ASYMPTOTIC FREEDOM: COUPLING DECREASES WITH ENERGY

  OPPOSITE TO USUAL SCREENING, CAN ONLY HAPPEN IN VERY SPECIAL THEORIES SELF-INTERACTIONS OF GB'S → MUST BE ANOTHER NON-ABELIAN GT.

- USE COLOR DEGREE OF FOR NON-ABELIAN GT.

STRONG INTERACTION ≡ SU(3) GAUGE THEORY FOR COLOR ≡ QCD

COMPLETE STANDARD MODEL

	$SU(3)_c$ ×	$SU(2)_L$ ×	$U(1)_Y$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$	1	2	$-1/2$
e_R	1	1	-1
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	3	2	$1/6$
u_R	3	1	$2/3$
d_R	3	1	$-1/3$
H	1	2	$1/2$

$$\mathcal{L}_{Yuk} = -\lambda_d^{ij} \bar{Q}_L^i H d_R^j - \lambda_u^{ij} \epsilon^{ab} \bar{Q}_{La}^i H_b^{+} u_R^j - \lambda_e^{ij} \bar{E}_L^i H e_R^j$$

$$\mathcal{L}_{Higgs} = \mathcal{L}_{kin} + \mu^2 H^+ H - \lambda (H^+ H)^2$$

THE PARAMETERS OF THE SM

GAUGE COUPLINGS	g, g', g_3	3
FERMION MASSES	m_e, m_μ, m_τ m_u, m_c, m_t m_d, m_s, m_b	9
HIGGS MASS, HIGGS COUPLING	μ λ	2
CKM MATRIX	3 angles, 1 phase	4
STRONG CP PARAMETER	$\theta F\tilde{F}$	1
		19

+ NEUTRINO SECTOR (UNTIL NOW ASSUMED MASSLESS)

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	-1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	-1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	-1

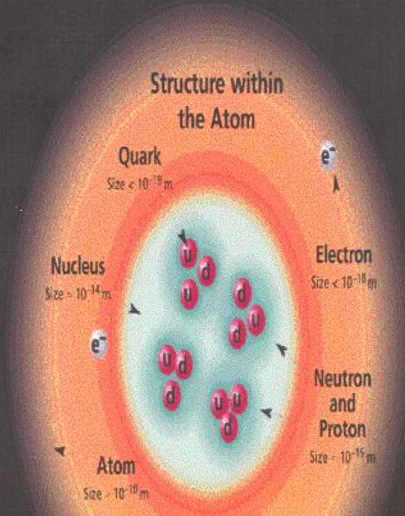
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
b bottom	4.3	-1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	-1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and **W** and **Z** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons.** This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

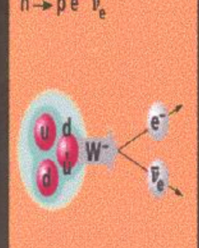
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

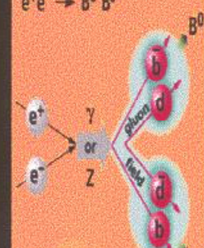
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



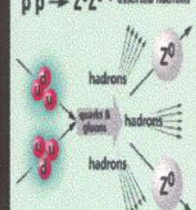
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\,\bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\,p \rightarrow Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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PDG. LBL. GOV

THE (UNREASONABLE) SUCCESS OF THE STANDARD MODEL

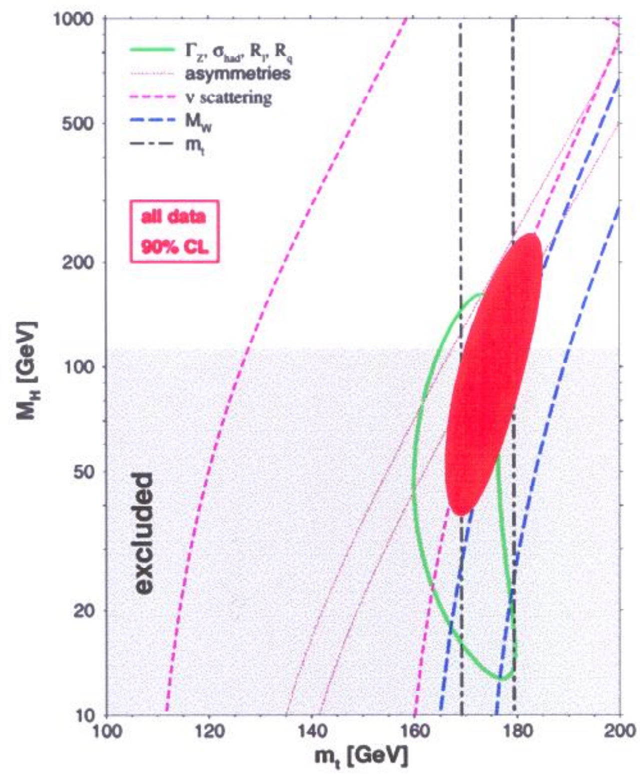
- TILL NOW NO EXPERIMENT IN DISAGREEMENT WITH SM
- LEP : ~0.1% VERIFICATION OF SM PREDICTIONS SENSITIVE TO ELECTROWEAK LOOP CORRECTIONS
- HIGGS NOT YET(?) FOUND

  $m_h \gtrsim 115$ GeV

- SINCE LEP SENSITIVE TO LOOP CORRECTIONS → INDIRECT BOUND ON HIGGS MASS

  $m_h \lesssim 200$ GeV

M_H and m_t for various observables are shown in Fig. 10.1.



INDIRECT EVIDENCE FOR LIGHT HIGGS

Figure 10.1: One-standard-deviation (39.35%) uncertainties in M_H as a function of m_t for various inputs, and the 90% CL region ($\Delta\chi^2 = 4.605$) allowed by all data. $\alpha_s(M_Z) = 0.120$ is assumed except for the fits including the Z-lineshape data. The 95% direct lower limit from LEP 2 is also shown.

Table 10.4: Principal Z-pole and other observables, compared with the Standard Model predictions for the global best fit values $M_Z = 91.1874 \pm 0.0021$ GeV, $M_H = 98^{+51}_{-35}$ GeV, $m_t = 175.3 \pm 4.4$ GeV, $\alpha_s(M_Z) = 0.1200 \pm 0.0028$, and $\widehat{\alpha}(M_Z)^{-1} = 127.922 \pm 0.027$. The LEP averages of the ALEPH, DELPHI, L3, and OPAL results include common systematic errors and correlations [83]. The heavy flavour results of LEP and SLD are based on common inputs and correlated, as well [83]. $\bar{s}^2_\ell(A^{(0,q)}_{FB})$ is the effective angle extracted from the hadronic charge asymmetry. The values of $\Gamma(\ell^+\ell^-)$, $\Gamma(\text{had})$, and $\Gamma(\text{inv})$ are not independent of Γ_Z, the R_ℓ, and σ_{had}. The first M_W value is from CDF, DØ, and UA2 [112] while the second one is from LEP 2 [28]. The first M_W and M_Z are correlated, but the effect is negligible due to the tiny M_Z error. The three values of A_e are (i) from A_{LR} for hadronic final states [80]; (ii) from A_{LR} for leptonic final states and from polarized Bhabba scattering [82]; and (iii) from the angular distribution of the τ polarization. The two A_τ values are from SLD and the total τ polarization, respectively. The two values of R^ν from deep-inelastic scattering (DIS) are from CDHS [49] and CHARM [50], respectively; κ^ν (proportional to R^ν) is from CCFR [51]; and R^- from NuTeV [55]. The two values for $g^{\nu e}_{V,A}$ are from CHARM II [58] and the world average. The second errors in Q_W, DIS, and $g-2$ are theoretical. In the Standard Model predictions, the uncertainty is from M_Z, M_H, m_t, $\widehat{\alpha}(M_Z)^{-1}$, and α_s, and their correlations have been accounted for. The errors in Γ_Z, $\Gamma(\text{had})$, R_ℓ, and σ_{had} are largely dominated by the uncertainty in α_s.

Quantity	Value	Standard Model	Pull
m_t [GeV]	174.3 ± 5.1	175.3 ± 4.4	-0.2
M_W [GeV]	80.451 ± 0.061	80.391 ± 0.019	1.0
	80.446 ± 0.040		1.4
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966 ± 0.0016	-0.6
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7429 ± 0.0015	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.76 ± 0.14	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.019 ± 0.027	—
σ_{had} [nb]	41.541 ± 0.037	41.477 ± 0.014	1.7
R_e	20.804 ± 0.050	20.744 ± 0.018	1.2
R_μ	20.785 ± 0.033	20.744 ± 0.018	1.2
R_τ	20.764 ± 0.045	20.790 ± 0.018	-0.6
R_b	0.21664 ± 0.00068	0.21569 ± 0.00016	1.4
R_c	0.1729 ± 0.0032	0.17230 ± 0.00007	0.2
$A^{(0,e)}_{FB}$	0.0145 ± 0.0025	0.01637 ± 0.00026	-0.8
$A^{(0,\mu)}_{FB}$	0.0169 ± 0.0013		0.4
$A^{(0,\tau)}_{FB}$	0.0188 ± 0.0017		1.4
$A^{(0,b)}_{FB}$	0.0982 ± 0.0017	0.1036 ± 0.0008	-3.2
$A^{(0,c)}_{FB}$	0.0689 ± 0.0035	0.0740 ± 0.0006	-1.5
$A^{(0,s)}_{FB}$	0.0976 ± 0.0114	0.1037 ± 0.0008	-0.5
$\bar{s}^2_\ell(A^{(0,q)}_{FB})$	0.2322 ± 0.0010	0.23143 ± 0.00015	0.8

FROM PDG. LBL. GOV

Table 10.4: (continued)

Quantity	Value	Standard Model	Pull
A_e	0.15138 ± 0.00216	0.1478 ± 0.0012	1.7
	0.1544 ± 0.0060		1.1
	0.1498 ± 0.0048		0.4
A_μ	0.142 ± 0.015		-0.4
A_τ	0.136 ± 0.015		-0.8
	0.1439 ± 0.0041		-0.9
A_b	0.921 ± 0.020	0.9347 ± 0.0001	-0.7
A_c	0.667 ± 0.026	0.6681 ± 0.0005	0.0
A_s	0.895 ± 0.091	0.9357 ± 0.0001	-0.4
R^-	$0.2277 \pm 0.0021 \pm 0.0007$	0.2300 ± 0.0002	-1.1
κ^ν	$0.5820 \pm 0.0027 \pm 0.0031$	0.5833 ± 0.0004	-0.3
R^ν	$0.3096 \pm 0.0033 \pm 0.0028$	0.3093 ± 0.0002	0.1
	$0.3021 \pm 0.0031 \pm 0.0026$		-1.7
$g_V^{\nu e}$	-0.035 ± 0.017	-0.0398 ± 0.0003	—
	-0.040 ± 0.015		-0.1
$g_A^{\nu e}$	-0.503 ± 0.017	-0.5065 ± 0.0001	—
	-0.507 ± 0.014		0.0
$Q_W(\mathrm{Cs})$	$-72.65 \pm 0.28 \pm 0.34$	-73.10 ± 0.03	1.0
$Q_W(\mathrm{Tl})$	$-114.8 \pm 1.2 \pm 3.4$	-116.67 ± 0.05	0.5
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to ce\nu)}$	$3.26^{+0.75}_{-0.68} \times 10^{-3}$	$3.14^{+0.17}_{-0.16} \times 10^{-3}$	0.2
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$4510.55 \pm 1.51 \pm 0.51$	4506.55 ± 0.36	2.5

IF EVERYTHING WORKS THIS WELL, WHY AM I TALKING ABOUT BEYOND THE SM?

REASONS TO GO BEYOND

- HIERARCHY PROBLEM
- WHY THOSE 3 GAUGE GROUPS?
- FERMION MASS HIERARCHY
- NEUTRINO MASSES
- DARK MATTER
- DARK ENERGY & CC. PROBLEM
- BARYOGENESIS
- STRONG CP PROBLEM

⋮

SOME OF THESE NATURALNESS PROBLEMS : CERTAIN PARAMETERS MUCH SMALLER FOR NO APPARENT REASON THAN YOU WOULD EXPECT

CONCEPTUALLY MOST IMPORTANT

HIERARCHY PROBLEM

OR WHAT BREAKS THE $SU(2) \times U(1)$ SYMMETRY

SM: HIGGS SCALAR H

HIGGS POTENTIAL:

$$V(H) = -\mu^2 (H^+ H) + \lambda (H^+ H)^2$$

HIGGS VEV: $v^2 = \frac{\mu^2}{\lambda}$ $v \simeq 246\,\text{GeV}$

μ SETS SCALE OF EWSB, M_W, M_Z, ETC.

HOWEVER, LOOP CORRECTIONS TO HIGGS POTENTIAL:

$$\Delta m_H^2 \sim -\frac{\lambda_t^2}{16\pi^2}\cdot 3\cdot 4\,\Lambda^2 + \frac{\lambda}{16\pi^2}\Lambda^2 + \frac{g^2}{16\pi^2}\cdot 3\cdot 3\,\Lambda^2 + \dots$$

DIAGRAMS QUADRATICALLY DIVERGENT

HIGGS MASS <u>EXTREMELY SENSITIVE</u> TO ANY NEW PHYSICS.

FOR EXAMPLE, $\Lambda \sim M_{Pl}$ SCALE OF GRAVITY $\rightarrow$ WOULD EXPECT

$$\mu^2 \sim M_{Pl}^2 \sim (10^{19})^2 (\mathrm{GeV})^2$$

HIERARCHY PROBLEM: WHY

$$\frac{m_{weak}}{M_{Pl}} \sim 10^{-17}, \text{ NAIVELY } \sim 1$$

WEAK SCALE NOT STABLE UNDER RADIATIVE CORRECTIONS

REASON: SCALAR MASS **NOT** PROTECTED BY SYMMETRY.

FERMION: $m\bar{\psi}\psi$, if $m \to 0$

$\psi \to e^{i\alpha\gamma_5}\psi$ NEW CHIRAL SYMMETRY

$\Delta m \sim m$, NATURAL

GAUGE BOSON: $m^2 A_\mu A^\mu$ $m \to 0$

gauge symmetry restored

$\Delta m \sim m$ NATURAL

SCALAR $m^2 H^\dagger H$ $m \to 0$

NO NEW SYMMETRY!

SUGGESTS: THERE SHOULD BE NEW PHYSICS COMING IN WELL BEFORE $\Lambda \sim M_{Pl}$.

$v \sim 246\,GeV$ NATURAL ONLY IF

$\Lambda \sim TeV$

SHOULD BE NEW PHYSICS AT ~TeV ENERGIES THAT STABILIZES HIGGS MASS.

- TECHNICOLOR
- SUPERSYMMETRY (LECTURE II.)
- EXTRA DIMENSIONS (LECTURE III)

TECHNICOLOR

- PERHAPS MOST ELEGANT IDEA FOR RESOLVING HIERARCHY PROBLEM.

  ELECTROWEAK SYMMETRY NOT BROKEN BY FUNDAMENTAL SCALAR HIGGS, BUT BY CONDENSATE OF FERMIONS.

- MOTIVATION: STRONG INTERACTION QCD 2 FLAVORS $\begin{pmatrix} u \\ d \end{pmatrix}$. FOR SMALL QUARK MASSES $m_u, m_d \to 0$ $SU(2)_L \times SU(2)_R$ CHIRAL SYMMETRY

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \to U_L \begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_R \to U_R \begin{pmatrix} u \\ d \end{pmatrix}_R$$

- BUT HADRON SPECTRUM ONLY SHOWS $SU(2)_V$ SYMMETRY $\to$ $SU(2)_A$ BROKEN

- $\underbrace{SU(2)_L \times SU(2)_R}_{SU(2)_D} \supset \underbrace{SU(2)_L \times U(1)_Y}_{U(1)_{EM}}$

- STRONG DYNAMICS GIVES EXACTLY THE RIGHT STRUCTURE FOR EWSB, EXCEPT $v \sim m_{proton} \sim \Lambda_{QCD} \sim 1\,GeV$

- WOULD NEED $\Lambda_{TC} \sim 1\,TeV$ TO GET $v \sim 100\,GeV$

  NEED TO POSTULATE EVEN STRONGER ANALOG OF QCD

  TECHNI COLOR

- BEAUTIFUL, BUT
  - FERMION MASSES?
  - LARGE CORRECTIONS TO EW PRECISION

  } NOT A MAIN FOCUS, BUT POSSIBLE

WHY THESE GAUGE GROUPS?

NOT VERY APPEALING $SU(3) \times SU(2) \times U(1)$ ~ PUT TOGETHER BY HAND. MORE FUNDAMENTAL STRUCTURE?

$SU(3) \times SU(2) \times U(1) \subset SU(5)$ GUT

WILL SEE IN SUSY THAT THIS IS INDEED A VERY APPEALING POSSIBILITY

FERMION MASS HIERARCHY

$m_{top} = 174 \pm 5$ GeV $\qquad m_\tau = 1.7$ GeV

$m_{bottom} = 4 \sim 4.5$ GeV

$m_c = 1 \sim 1.4$ GeV $\qquad m_\mu = 105$ MeV

$m_s = 80 \sim 150$ MeV

$m_d = 5 \sim 8$ MeV $\qquad m_e = 511$ keV

$m_u = 1.5 \sim 4.5$ MeV $\qquad \frac{m_e}{m_t} \simeq 10^{-6}$

$\boxed{m_f \sim \lambda_f v}$ top ONLY natural. WHY?

NEUTRINO MASSES

- LAST ~ 5 YEARS : NEUTRINOS ALSO HAVE MASSES, MIXINGS ... $m_{\nu_e} < 3\,eV$ TINY

  STRICTLY WITHIN PREVIOUS "SM" $m_\nu = 0$

- BUT : CAN ADD COMPLETE $SU(2) \times U(1)$ SINGLET ν_R'S

  AND ADD ANOTHER MASS TERM

  $$\bar{E}_L H^* \nu_R$$

  OR WITHOUT NEW PARTICLES, BUT HIGHER DIMENSION OP:

$$\mathcal{L} \sim \frac{1}{\Lambda} \bar{E}^i \epsilon_{ij} H^{*j} \; E_i \epsilon^{ij} H_j \supset$$

$$\frac{v^2}{\Lambda} \bar{\nu}_L^c \nu_L$$

MAJORANA MASS FOR ν $\quad \Lambda \gtrsim 10^{13}\,GeV$

STRONG CP PROBLEM

- ANOTHER NATURALNESS PROBLEM
- $\mathcal{L}'_{QCD} = \theta \, F^a_{\mu\nu} F^a_{\alpha\beta} \, \epsilon^{\mu\nu\alpha\beta}$

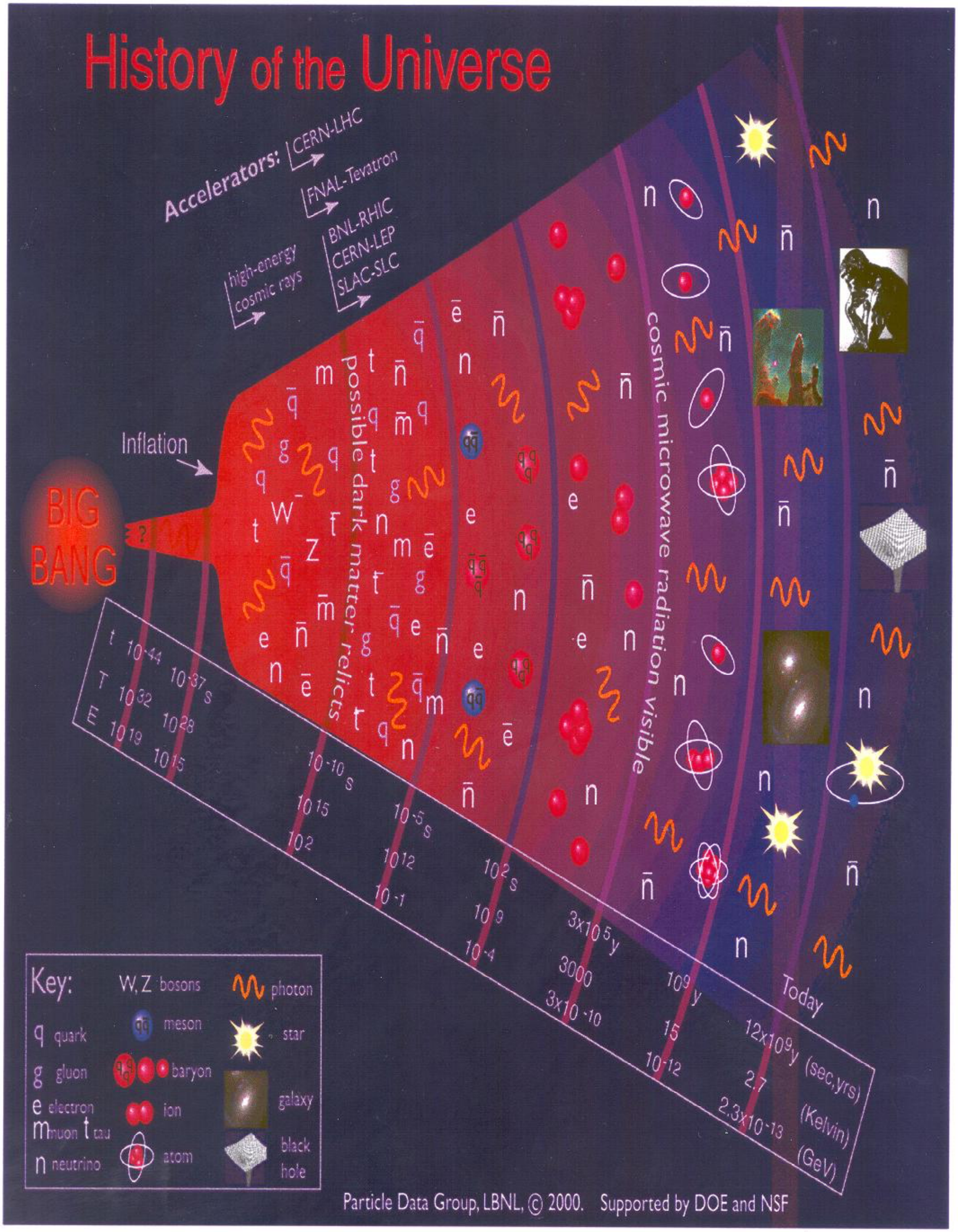
POSSIBLE.

- INVOLVES STRONG INTERACTIONS & VIOLATES CP, NOT OBSERVED

$$\theta \lesssim 10^{-9}$$ WHY?

- POSSIBLE WAY OUT: PECCEI-QUINN MECHANISM → EXISTENCE OF AXION LIGHT PSEUDOSCALAR PARTICLE

COULD BE DARK MATTER, IMPORTANT FOR COSMOLOGY ...


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

DARK MATTER & DARK ENERGY

- $\Omega_{tot} \sim 1$ (CMB)
- $\Omega_{matter} \sim 0.3$ (HERE "matter" = $p=0$ COMPONENT)
- FROM NUCLEOSYNTH., CMB

  $\Omega_{baryon} \sim 0.03$

- WHAT MAKES UP $\Omega = 0.3$?

  DARK MATTER

- FOR STRUCTURE FORMATION USUALLY NEED COLD DARK MATTER (HEAVY SEMISTABLE PARTICLES PRODUCED AFTER BIG BANG)

  NO SUCH PARTICLE IN SM

  SEE SUSY, EXTRA DIM'S

- WHAT MAKES UP $\Omega \sim 0.7$ $p<0$?

  DARK ENERGY WHAT IS IT? CC.? SCALAR FIELD?

  NO GOOD EXPLANATION

SUMMARY OF LECTURE I.

- STANDARD MODEL $SU(3) \times SU(2) \times U(1)$

  VERY SOLID FOUNDATIONS
- VERY STRONG EXPERIMENTAL VERIFICATION IN PARTICLCE PHYSICS
- SEVERAL THEORETICAL / AESTHETICAL ISSUES UNRESOLVED
  - HIERARCHY
  - UNIFICATION
  - FERMION MASS
  - STRONG CP...
- COSMOLOGICAL ISSUES
  - DARK MATTER
  - DARK ENERGY
  - BARYOGENESIS

  UNRESOLVED