The standard Model and its possible extensions

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USTC. ICTS. Mar. 26. 2004

Outline

* The standard Model As a Theory

*. Experimental Signs to go beyond the standard Model

* Symmetry and hierarchy problem

* possible extensions

* Conclusions

The Particle Adventure

Home Glossary

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What is Fundamental? **Eternal Questions**

People have long asked,

"What is the world made of?"

and

"What holds it together?"

Question: What is the name of this statue and who sculpted it?
[Answer]

The Particle Adventure

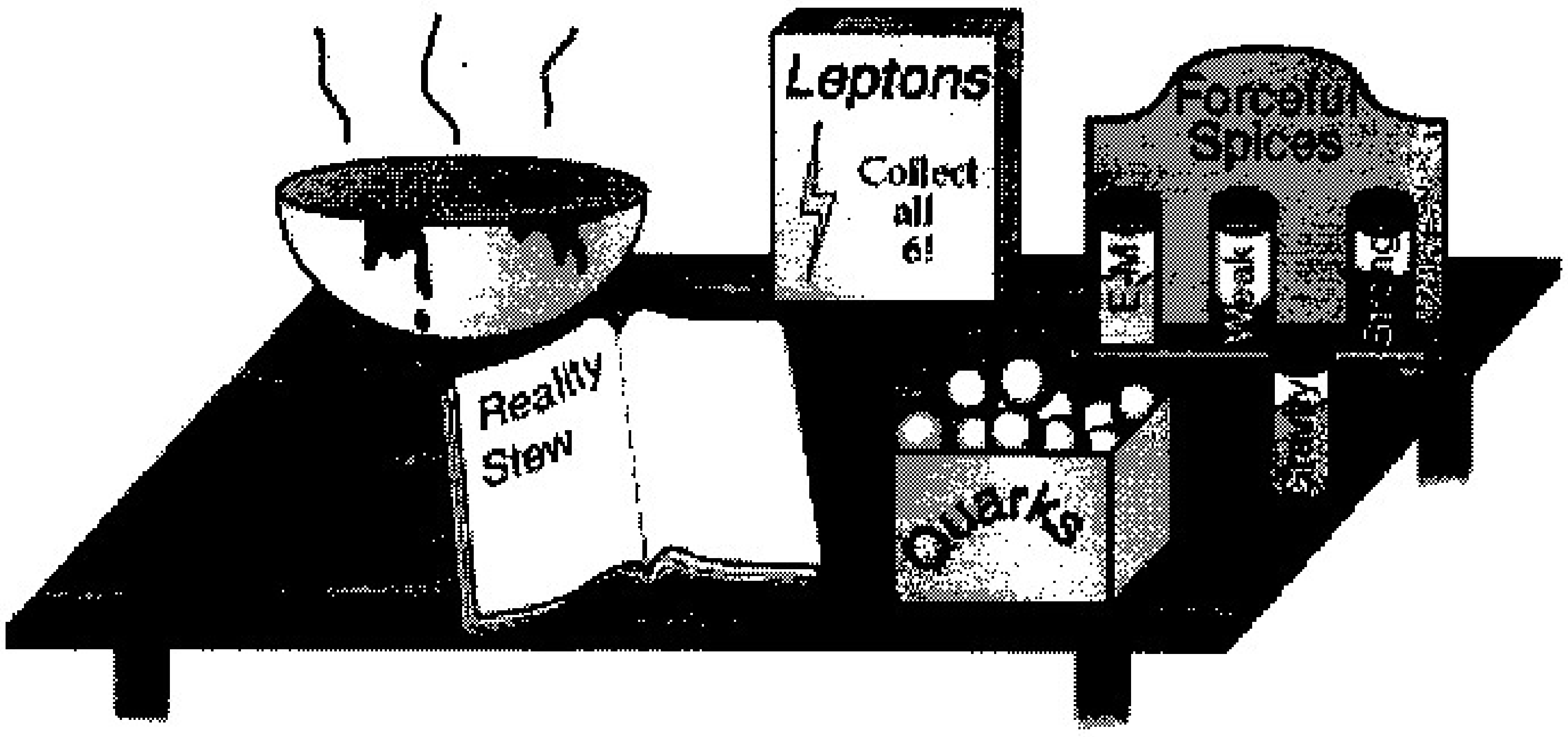
What is Fundamental? **The Standard Model**

The Standard Model

Physicists have developed a theory called **The Standard Model** that explains what the world is and what holds it together. It is a simple and comprehensive theory that explains all the hundreds of particles and complex interactions with only:

- **6 quarks**.
- **6 leptons**. The best-known lepton is the electron. We will talk about leptons in just a few pages.
- **Force carrier particles**, like the photon. We will talk about these particles later.

All the known matter particles are composites of quarks and leptons, and they interact by exchanging force carrier particles.



The Standard Model is a good **theory**. Experiments have verified its predictions to incredible precision, and all the particles predicted by this theory have been found. But it does not explain everything. For example, gravity is not included in the Standard Model.

This site will explore the Standard Model in greater detail and will describe the experimental techniques that gave us the data to support this theory. We will also explore the intriguing questions that lie outside our current understanding of how the universe works.

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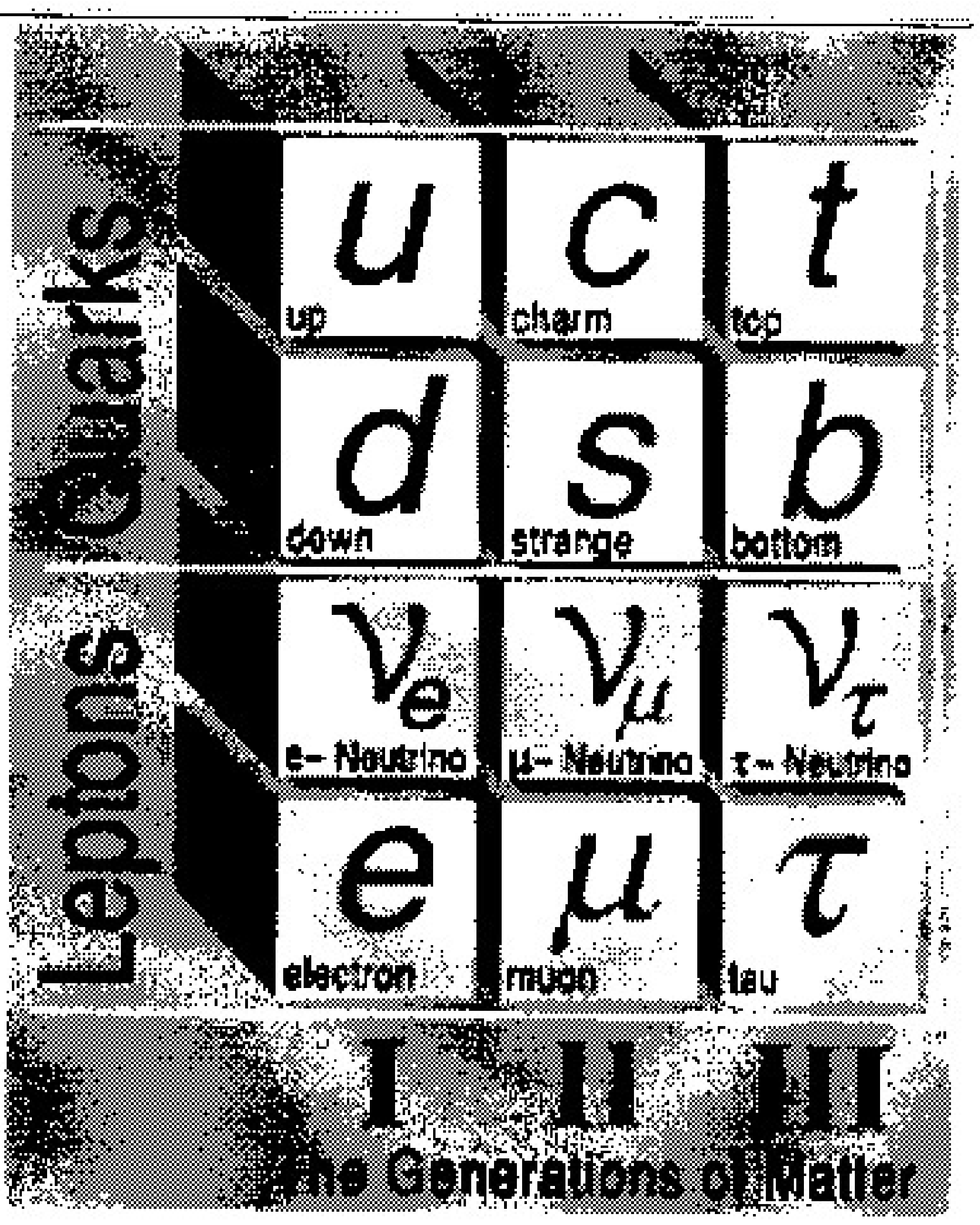
What is the World Made of? The Generations of Matter

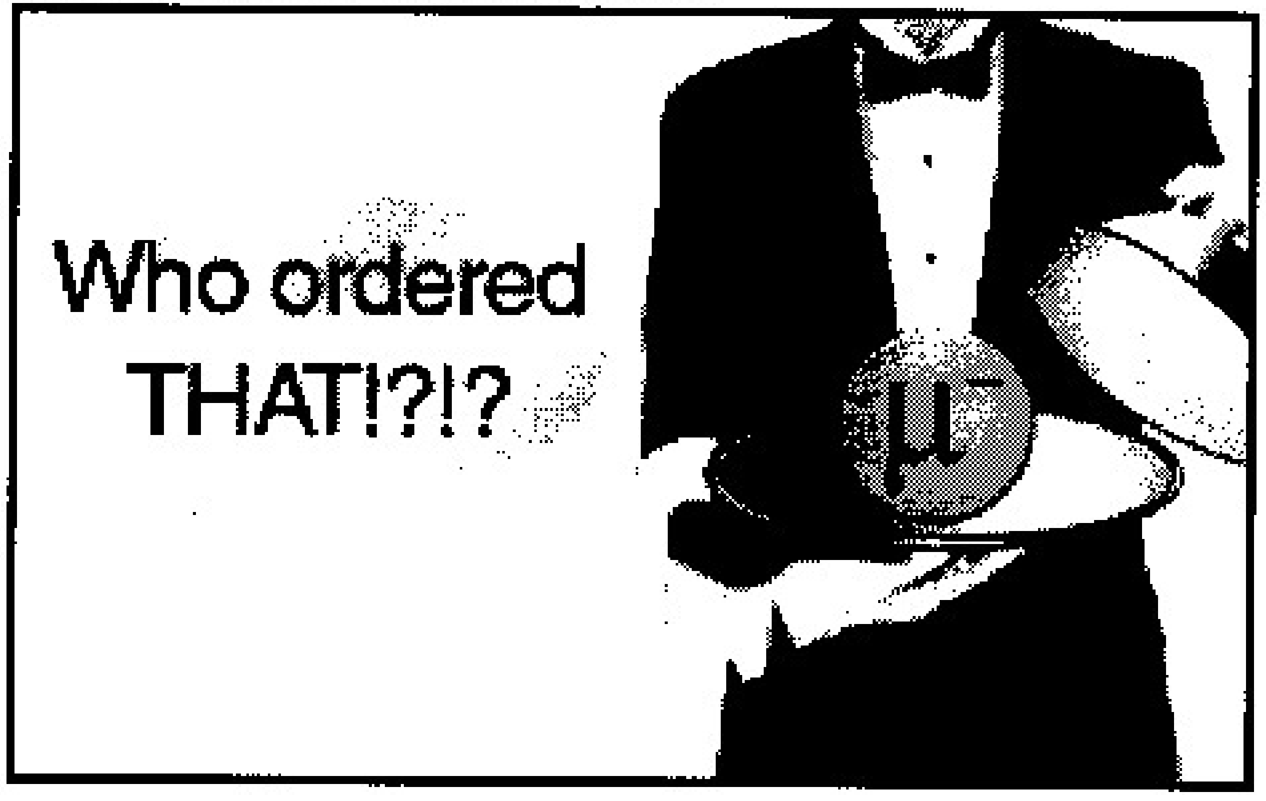


Note that both quarks and leptons exist in three distinct sets. Each set of quark and lepton charge types is called a **generation** of matter (charges +2/3, -1/3, 0, and -1 as you go down each generation). The generations are organized by increasing mass.

All visible matter in the universe is made from the first generation of matter particles -- up quarks, down quarks, and electrons. This is because all second and third generation particles are unstable and quickly decay into stable first generation particles.

Wait a minute. If the higher generations of matter decay quickly, are rarely observed, and do not make up any of the stable matter around us, why do they exist at all?

Good question. In fact, when the muon was discovered physicist I.I. Rabi asked,



So why do we have generations of matter at all? Why three of them? We don't know. And without understanding why the second and third generation particles exist, we cannot rule out the possibility that there are yet more quarks and leptons that we have not discovered yet. Or perhaps the answer is that quarks and leptons aren't fundamental, but are made up of even more elementary particles whose composite particles we observe as quarks.

The Particle Adventure

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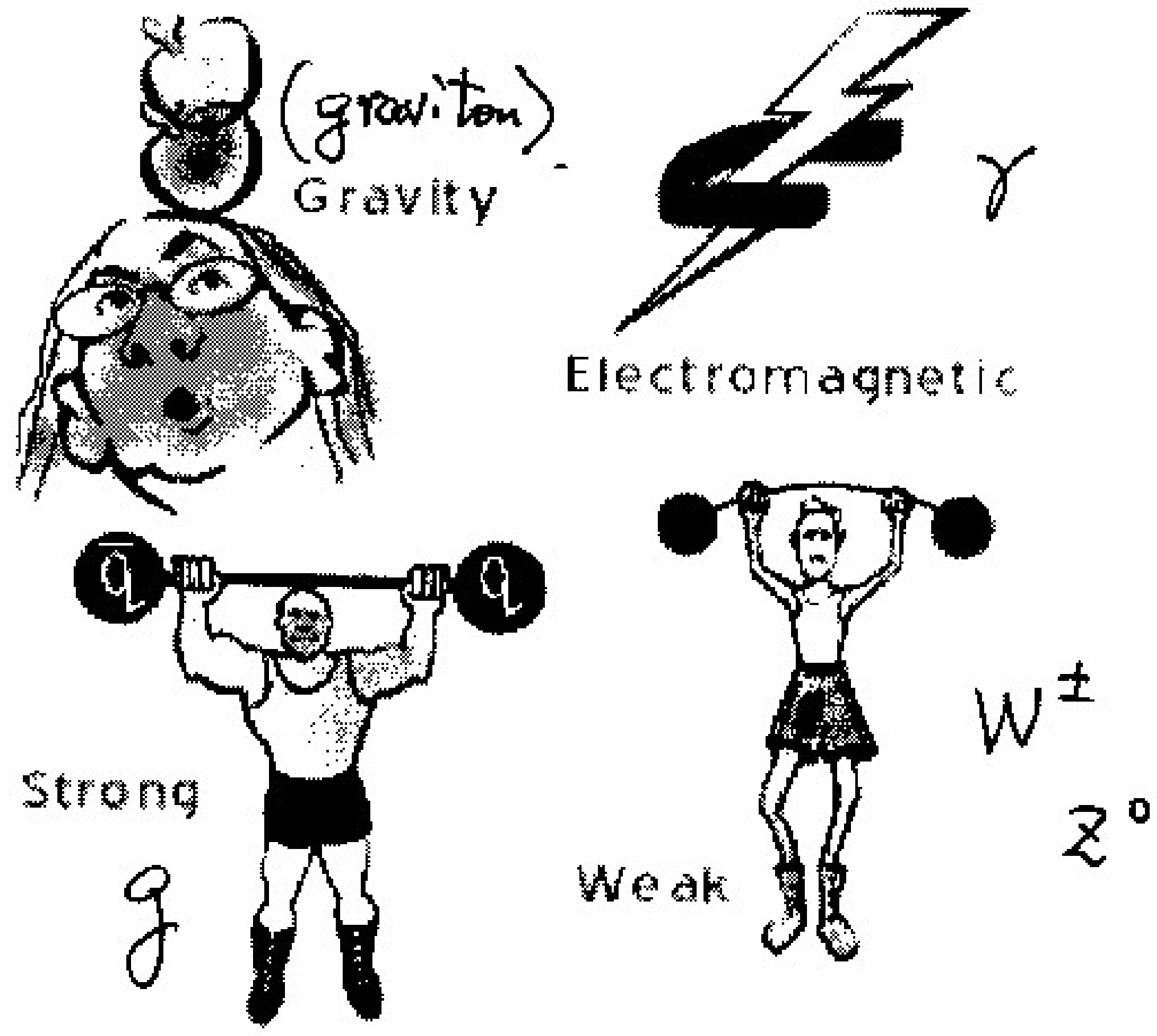
What Holds it Together? The Four Interactions

Now we think we have a good idea of what the world is made of: quarks and leptons. So...

What holds it together?

The universe, which we know and love, exists because the fundamental particles interact. These interactions include attractive and repulsive forces, decay, and annihilation.

There are four fundamental interactions between particles, **and all forces in the world can be attributed to these four interactions!**



That's right: Any force you can think of -- friction, magnetism, gravity, nuclear decay, and so on -- is caused by one of these four fundamental interactions.

What's the difference between a force and an interaction?

This is a hard distinction to make. Strictly speaking, a **force** is the effect on a particle due to the presence of other particles. The **interactions** of a particle include all the forces that affect it, but also include decays and annihilations that the particle might go through. (We will spend the next chapter discussing these decays and annihilations in more depth.)

The reason this gets confusing is that most people, even most physicists, usually use "force" and "interaction" interchangeably, although "interaction" is more correct. For instance, we call the particles which carry the interactions force carrier particles. You will usually be okay using the terms interchangeably, but you should know that they are different.

* The standard Model As a Theory

describing

strong Weak electromagnetic interactions

$SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge theory

Leptons	ν_e	ν_μ	ν_τ	Massless neutrinos
	e	μ	τ	
Quarks	u	c	t	
	d	s	b	
	I	II	III	three generations
Gauge Boson	g	$W^\pm$ Z^0	γ	

Higgs Boson Ⓗ ??? not observed yet.

Scalar particle which is for electroweak symmetry breaking

The standard Model provides a very good description of almost all phenomena observed by experiments up to now.
$\leq 1\text{TeV}$

It is a good Theory $\leq 1\text{TeV}$

Beyond the Standard Model. Why?

many ....

a) it is incomplete . not including gravity

b) Some questions such as

(i) Why the standard model predict a particle's mass?

(ii) Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

(iii) why are there three generations of quarks and lepton?

⋮

Also why not?

* Experimental Signs to go beyond the standard Model.

A. Some exotic narrow states observed in hadron physics in 2003

(i) Japan LEPS Collaboration. January 2003

Narrow $S = +1$ Baryon Resonance. 5 quark pentaquark state. ($uudd\bar{s}$)

(ii) USA BaBar Collaboration April 2003

A narrow meson state named $D_s(2317)$ containing quark content $c\bar{s}$, however, the $c\bar{s}$ configuration of this state contradicts current models of charm meson spectroscopy. So either these models need modification or the observed state is of different type. Such as four-quark state.

(iii) Japan. Belle Collaboration September 2003.

A narrow charmonium-like meson state. $X(3872)$ which is higher than the expected values from current models of charmonium meson spectroscopy, thus may be different from $c\bar{c}$. . Can be as $c\bar{c}g$. or four-quark states
or D-D^* molecule.

(iv). China. BES Collaboration. Mar. 2003.

A narrow enhancement near $2m_p$ in the invariant mass spectrum of $p\bar{p}$ in $J/\psi \to \gamma p\bar{p}$ decays. In the case of the S-wave fit the peak mass is below $2m_p$. at $M \doteq 1859$. $\Gamma < 30$ MeV. These mass and width values are not consistent with the properties of any known particle.

Traditionally. Meson $q\bar{q}$

Baryon qqq

It seems that the above states Contradict this picture

But not QCD (the theory of strong interaction)

Since this is now nonperturbative region of strong interactio

So. the above experiments would help to understand the nonperturbative Dynamics of strong interaction.

But. cannot be regarded as Signs to go beyond the standard Model.

B. Some possible experimental Signs beyond the SM

(1) The Anomalous magnetic moment of Muon.

$$a_\mu^{Exp} = \frac{g-2}{2} = 11659203\ (8) \times 10^{-10}$$ 2002. BNL

theoretical: $a_\mu^{SM} = 11658470.35 \times 10^{-10}$ (QED)

$+ 684(7) \times 10^{-10}$ (had. Vac)

$+ 8(4) \times 10^{-10}$ (had. light by light) ?

$+ 15.4(2) \times 10^{-10}$ (EW)

$\sim 2\sigma$

(ii) NuTeV anomaly

Fermilab NuTeV Collaboration. νN DIS.

measure

$$\sin^2\theta_W(\text{NuTeV}) = \underset{\text{Stat}}{0.2276 \pm 0.0013} \pm \underset{\text{Sym}}{0.0006} \qquad \left(\begin{array}{l} e = g\sin\theta_W \\ \sin^2\theta_W = 1 - \dfrac{m_W^2}{m_{Z_0}^2} \end{array} \right)$$

which is 2.8 σ away from the result of the global fit

$$\sin^2\theta_W = 0.2229 \pm 0.0004.$$

Uncertainties: a) in the parton distribution function.

b) NLO QCD corrections

c) Electroweak corrections.

(iii) $\sin 2\beta\ (\phi_1)$ in Belle. $\left\{ \begin{array}{ll} \sin 2\beta & \text{BaBar} \\ \sin 2\phi_1 & \text{Belle.} \end{array} \right.$

$\sin 2\beta(\phi_1)$ is a quantity characterized CP violation in B meson decay, which can be measured in $B \to J/\psi K_S$ or $B \to \phi K_S$ decays.

In the SM. $\left| (\sin 2\underset{\phi_1}{\beta})_{J/\psi K_S} - (\sin 2\underset{\phi_1}{\beta})_{\phi K_S} \right| \leq O(\lambda^2)$ with $\lambda \simeq 0.22$

BaBar $(\sin 2\beta)_{J/\psi K_S} = 0.741 \pm 0.067 \pm 0.033$

Belle $(\sin 2\phi_1)_{J/\psi K_S} = 0.733 \pm 0.057 \pm 0.028$

In the SM. the global fit shows

$0.6 \lesssim \sin 2\beta(\phi_1) \lesssim 0.9$ Consistent with the direct measurement

from $B \to \phi K_S$

BaBar 2002 : $(\sin 2\beta)_{\phi K_S} = -0.18 \pm 0.51 \pm 0.09$

Belle 2002 : $(\sin 2\phi_1)_{\phi K_S} = -0.73 \pm 0.64 \pm 0.22$

→ going close to SM

BaBar 2003 : $(\sin 2\beta)_{\phi K_S} = +0.45 \pm 0.43 \pm 0.07$

Belle 2003 : $(\sin 2\phi_1)_{\phi K_S} = -0.96 \pm 0.50 {}^{+0.09}_{-0.11}$

away from $(\sin 2\beta)_{J/\psi K_S}$ $\boxed{3.5\sigma}$

New physics beyond the SM

Or not ?

文部科学省 高エネルギー加速器研究機構 K
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZA

Indication of New Physics from the Belle Experiment

August 13, 2003
High Energy Accelerator Research Organization (KEK)

The High Energy Accelerator Research Organization (KEK) announced that the Belle collaboration, an international research team working at the KEKB accelerator, found evidence for a new phenomenon that cannot be explained by the Standard Model of elementary particles.

The KEKB accelerator is a device for generating a large number of very shortlived subatomic particles called B mesons as well as their anti-matter counterparts. These particles, each with a mass somewhat greater than that of the helium atom, disintegrate after about a few trillionths of a second into lighter and more long-lived daughters, and these decay products are detected by the Belle detector.

Studies of these B meson decays play a crucial role in our understanding of the behavior of matter at its most elementary level, notably in investigating the origin of the tiny difference that is known to exist between matter and anti-matter, called CP violation.

The first clear evidence that such CP violation occurs in B meson decays was reported two years ago by the Belle and the BaBar collaborations, the latter working at the Stanford Linear Accelerator Center in California. Since then, the Belle team has been expanding the scope of its investigation into the ways that CP violation might manifest itself. A new and surprising finding has arisen recently in the course of this work.

In one particular and infrequent process, the B meson (or its anti-matter counterpart) decays into exactly two daughters named the J/ψ meson and the K_S meson, and the size of the CP violation is characterized by a quantity called $\sin 2\phi_1$. (This quantity would be zero if there were no CP violation, but could be as strong as ±1 according to the Standard Model.) This quantity is now known to be 0.731 with an accuracy of ± 0.056, and is in excellent agreement with what can be inferred indirectly from a host of other data with the assumption of one single source of CP violation as envisioned by M. Kobayashi and T. Maskawa in 1973.

If the Standard Model is correct, several other rarer B meson decay processes will show CP violation of a size that is determined by this same $\sin 2\phi_1$.

Using the entire data sample of 150 million pairs of B and anti-B mesons recorded over the past four years, the Belle team found 68 cases of an alternate CP-sensitive process where the B meson decays into a ϕ meson plus a K_S meson. Surprisingly, the measurement of $\sin 2\phi_1$ in this process gave -0.96 ± 0.50, in contrast to the well established value of $+0.731 \pm 0.056$.

The observed asymmetry data, from which the value of $\sin 2\phi_1$ is determined, is shown in Figure 1. The observed asymmetry data shown by the dots (with vertical lines) are clearly different from what is expected by the Standard Model, whose prediction is indicated by the

(IV) Neutrino Mass.

SM. massless neutrino

The most reasonable explanation for the experimental observations: atmospheric neutrio and Solar anomaly is neutrino oscillation. which reqaire neutrino massive.

This will implies evidence for new physics beyond the standard model. !!!

Now. Two Conclusions. (totally Contrary)

① Open and optimistic.

Obviously. there are signs to go beyond the SM.

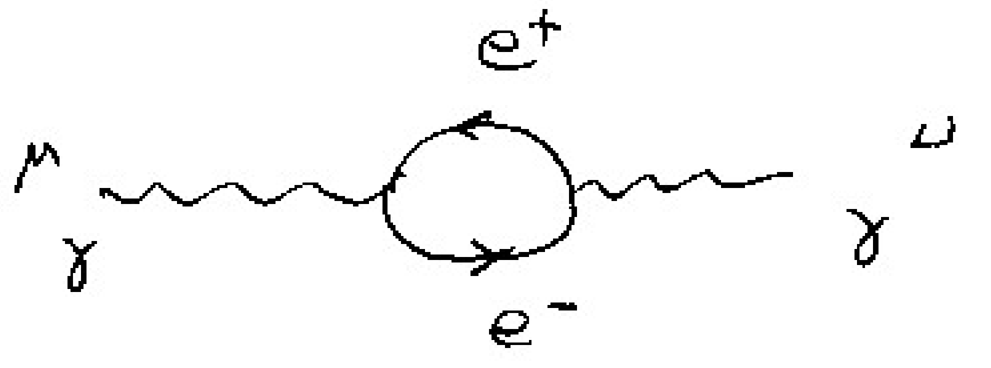
② Conservative and/or pessimistic.

Obviously. there are no any signs to go beyond. Since no confirmed evidence.

*. Symmetry and hierarchy problem

Quantum Field theory will lead to Self-energy of particles, At the One-loop level.
which will be related to the Mass of particles

1. photon.



For simplicity. assuming vanishing external momentum

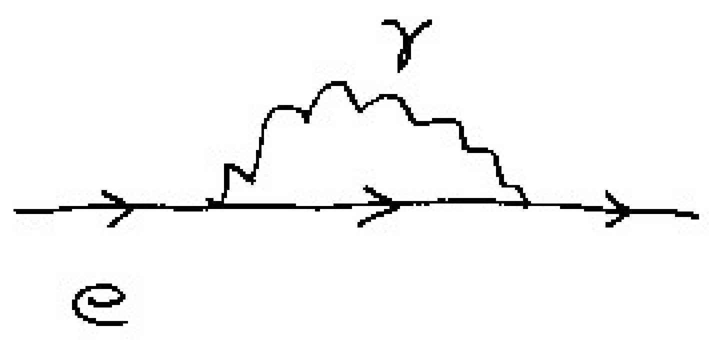
$$\Pi^{\mu\nu}_{\gamma\gamma}(0) = -\int \frac{d^4k}{(2\pi)^4}\, tr\left[(-ie\gamma^\mu)\frac{i}{\not{k}-m_e}(-ie\gamma^\nu)\frac{i}{\not{k}-m_e}\right]$$

$$= -4e^2\int\frac{d^4k}{(2\pi)^4}\frac{2k^\mu k^\nu - g^{\mu\nu}(k^2-m_e^2)}{(k^2-m_e^2)^2}$$

$= 0.$ in the regularization scheme preseving gauge invariance

Gauge invariance ensures the photon remains massless in all orders in perturbation theory.

2. electron.



$$\Pi_{ee}(0) = \int\frac{d^4k}{(2\pi)^4}(-ie\gamma_\mu)\frac{i}{\not{k}-m_e}(-ie\gamma_\nu)\frac{-ig^{\mu\nu}}{k^2}$$

$$= -e^2\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2(k^2-m_e^2)}\gamma_\mu(\not{k}+m_e)\gamma^\mu$$

$$= -4e^2 m_e\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2(k^2-m_e^2)}$$

Logarithmic divergence at large

given a CutOff Λ.

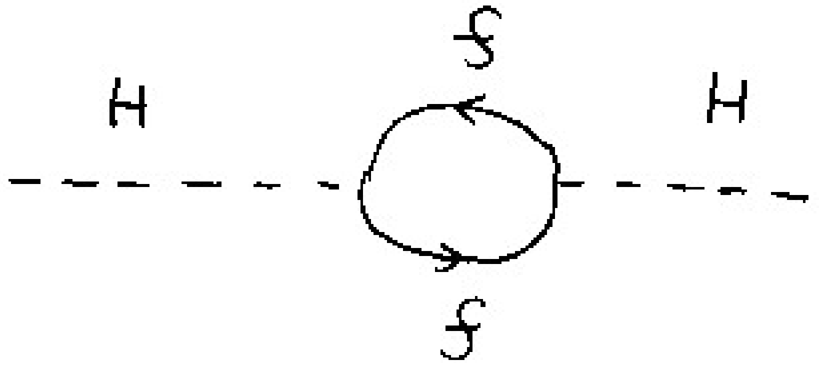
$$\delta m_e \simeq 2\frac{\alpha_{em}}{\pi} m_e \,\mathrm{Log}\frac{\Lambda}{m_e}$$

If we set $\Lambda = M_{pl}$. $\delta m_e \simeq 0.24\, m_e$ not very large.

$$\delta m_e \sim m_e$$

The fact can be understood from a symmetry: in the limit of $m_e \to 0$, there is chiral symmetry in QED (SM). If ~~this~~ symmetry were exact, the correction of $\Pi_{ee}(0)$ should be absent.

3. Higgs boson



→ coupling

$\frac{1}{\sqrt{2}}\lambda_f H f\bar f$

$$\Pi^f_{HH}(0) = -3\int\frac{d^4k}{(2\pi)^4}\,\mathrm{tr}\left[\left(i\frac{\lambda_f}{\sqrt{2}}\right)\frac{i}{\not k - m_f}\left(i\frac{\lambda_f}{\sqrt{2}}\right)\frac{i}{\not k - m_f}\right]$$

$$= -6\lambda_f^2\int\frac{d^4k}{(2\pi)^4}\left[\underbrace{\frac{1}{k^2-m_f^2}}_{\text{Quadratically divergent}} + \frac{2m_f^2}{(k^2-m_f^2)^2}\right]$$

$\Pi^f_{HH}(0) \propto \Lambda^2$ $\quad\Lambda \to M_{pl}$. 10^{19}

Then the correction from $\Pi^f_{HH}(0)$ would be 30 orders of magnitude larger than the physical SM Higgs mass

$$m_H \lesssim 1000\ \mathrm{GeV}$$

- fine tuning is needed to get physical Higgs mass

Hierachy problem

Gauge Symmetry protects photon mass (gauge boson mass)

Chiral Symmetry protects electron mass (fermion mass)

Unfortunately, no any symmetry protects the Scalar particle mass. Since $m_H = 0$ cannot lead to any symmetry.

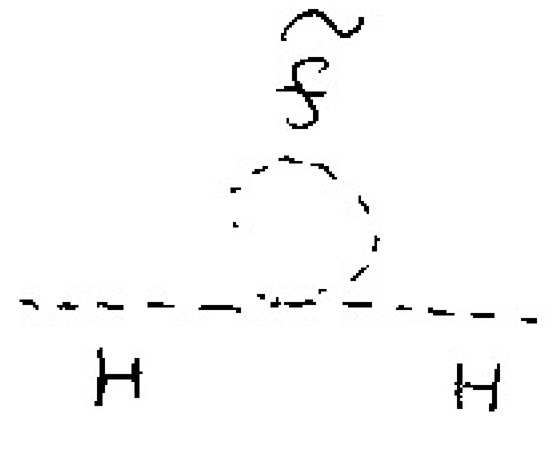
Need symmetry. ?

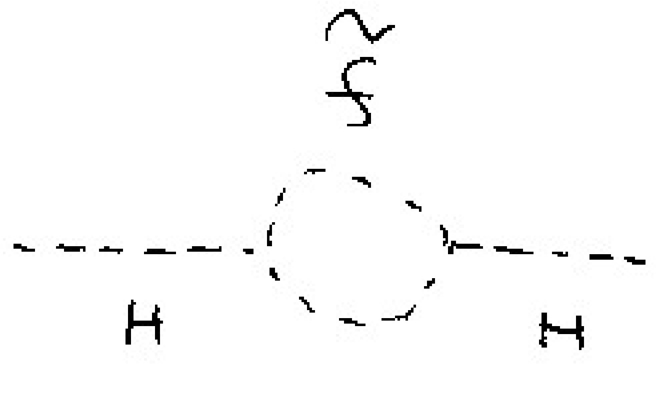
↓

*. possible extensions.

1\. Supersymmetry {

	Standard model.	Super partner
	fermion	~~Boson~~ Sfermion
	Gauge boson	Gaugino
	Higgs	Higgsino





which will cancel the quadratic divergence from the fermion loop.

(Since there exist different sign between fermion loop and Boson loop)

2. other extensions from SM

(i) extended fermion sector.

IV generation or vector-like quark model

(ii) extended gauge Boson Sector

$W_L \Rightarrow W_L . \ W_R .$

$SU(2)_L \Rightarrow SU(2)_L \times SU(2)_R$

(iii) extended Scalar Sector

One Higgs doublet. ⟶ $\left.\begin{matrix}\text{two}\\ \text{multi}\end{matrix}\right\}$ Higgs doublet.

3. Extra dimensions

$3+1 + \underset{1,2\ldots}{ⓝ}$

* Conclusions

? ? ?

Thank you!