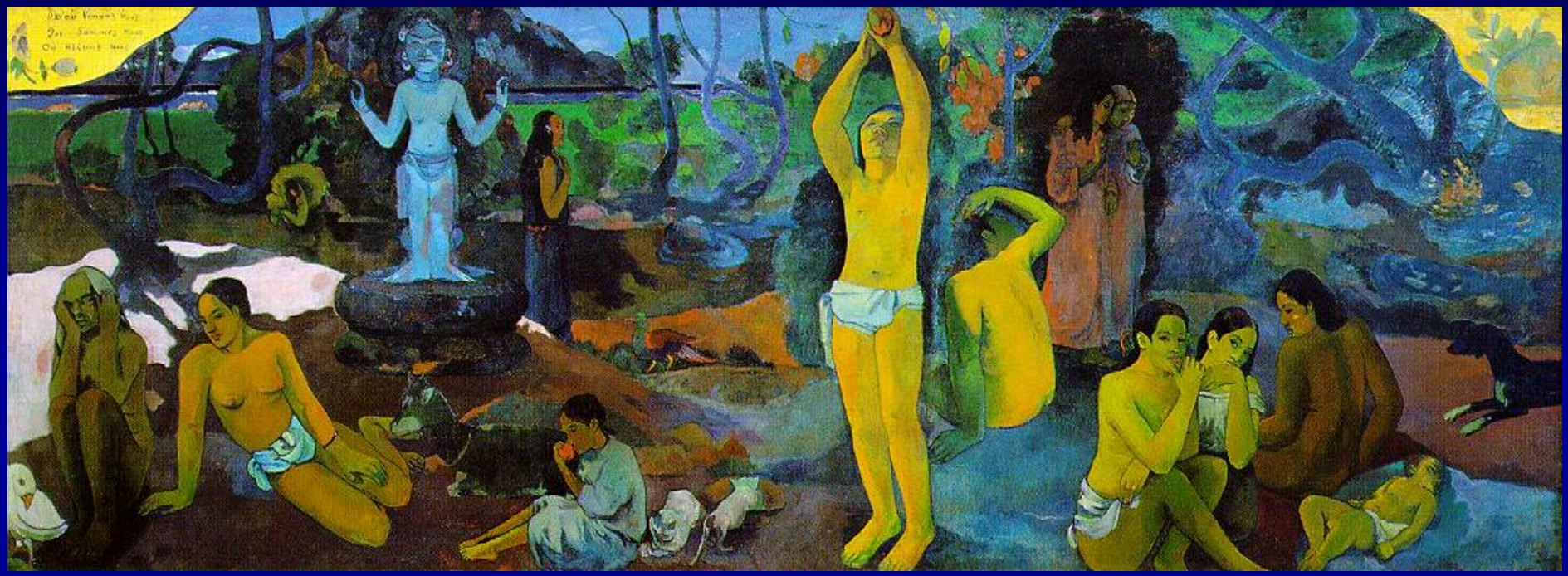
The Standard Model and Beyond

Harrison B. Prosper

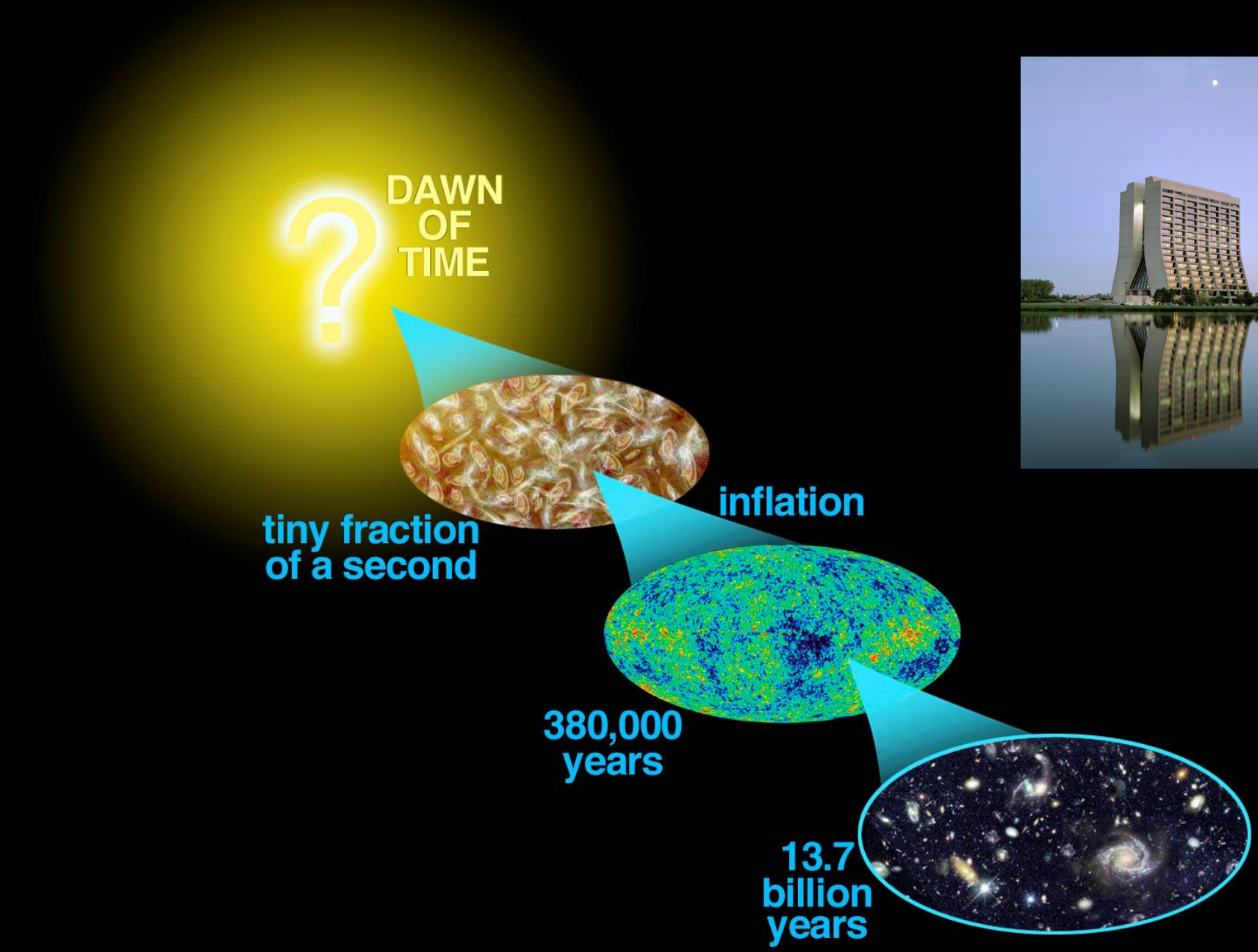
17 June, 2008

Fermilab Summer Lecture Series



Where Do We Come From?
What Are We?
Where Are We Going?

Paul Gauguin (1897)
Museum of Fine Arts, Boston


DAWN
OF
TIME
tiny fraction
of a second
inflation
380,000
years
13.7
billion
years

The Standard Model

A Century of Particle Physics

J.J Thomson

Discovery, Electron – 1897

E. Rutherford

Discovery, Proton – 1909

J. Chadwick, Discovery Neutron – 1932

Chemical Heritage Foundation Collection

A Century of Particle Physics

1897 – ELECTRON	discovery	Thomson
1909 – PROTON	discovery	Rutherford
1928 – ANTIMATTER	theory	Dirac
1930 – NEUTRINO	theory	Pauli
1932 – NEUTRON	discovery	Chadwick
1932 – POSITRON	discovery	Anderson
1935 – EXCHANGE	theory	Yukawa
1948 – QED	theory	Feynman,…
1961 - ELECTROWEAK	theory	Glashow
1964 – QUARK	theory	Gell-Man, Zweig
1964 – HIGGS	theory	Higgs, Englert,…
1967 – ELECTROWEAK	theory	Weinberg, Salam,…

A Century of Particle Physics

1971 – CONSISTENCY PROOF	theory	't Hooft, Veltman
1972 – QCD	theory	Gell-Man, Frizsch
1973 – ASYMPTOTIC FREEDOM	theory	Gross, Wilzcek, Politzer

A Century of Particle Physics

1974 – CHARM	discovery	Ting, Richter
1977 – BOTTOM	discovery	Lederman
1979 – GLUON	discovery	TASSO, JADE, MARK-J, PLUTO
1983 – W & Z	discovery	Rubbia/UA1, UA2
1995 – TOP	discovery	DØ & CDF

FERMILAB
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NEWS RELEASE

News Release - March 2, 1995

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PHYSICISTS DISCOVER TOP QUARK

Batavia, IL--Physicists at the Department of Energy's Fermi National Accelerator Laboratory today (March 2) announced the discovery of the subatomic particle called the top quark, the last undiscovered quark of the six predicted by current scientific theory. Scientists worldwide had sought the top quark since the discovery of the bottom quark at Fermilab in 1977. The discovery provides strong support for the quark theory of the structure of matter.

Foundations

The Standard Model is a
Quantum Field Theory, based on:

- Quantum Mechanics
- Special Relativity
- Symmetry Principles

It describes the low-energy excitations of various quantum fields in spacetime. The excitations are interpreted as particles.

Foundations

There are two kinds of quantum field:

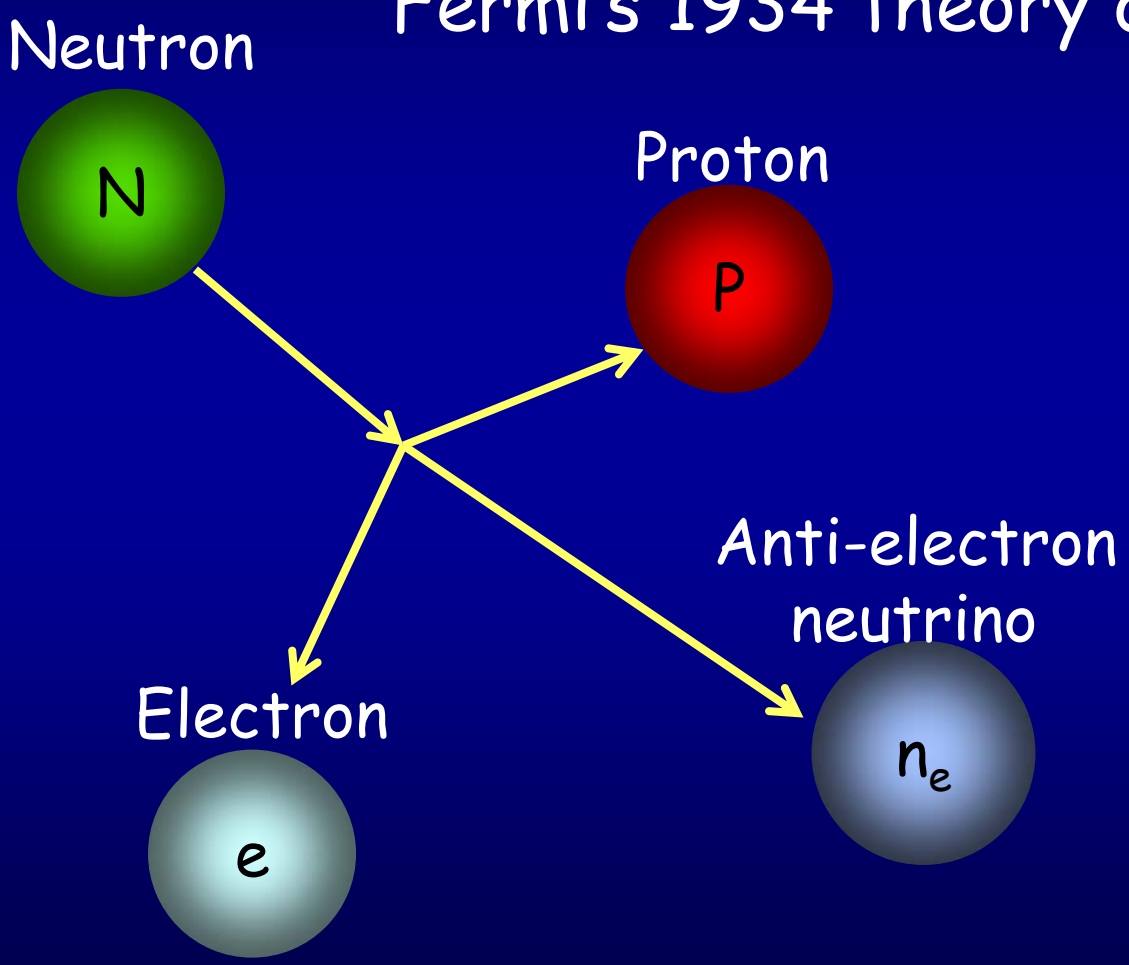
bosonic -> bosonic excitations
(e.g., photons)

fermionic -> fermionic excitations
(e.g., electrons)

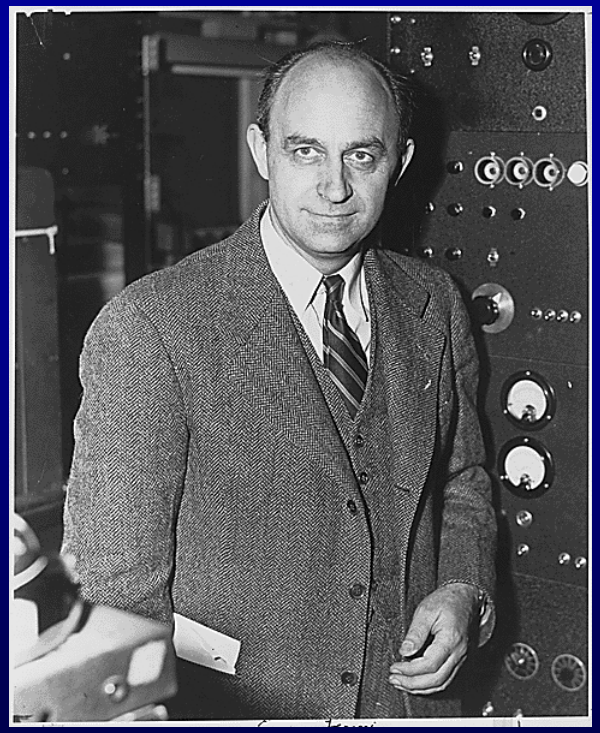
bosons tend to flock together
fermions tend to stay apart -> structure

Radioactivity

Fermi's 1934 theory of β-decay



Enrico Fermi
1901 - 1954



4th of December 1930

Dear Radioactive Ladies and Gentlemen,

… I have hit upon a desperate remedy to save …. the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles,……, which have spin 1/2 and obey the exclusion principle….The mass….should be of the same order of magnitude as the electron mass…

Your humble servant
W. Pauli

http://wwwlapp.in2p3.fr/neutrinos/aplettre.html

Exchange Theory

1935, Hideki Yukawa showed that the potential energy between particles has the form

$$U(R) = -\frac{g^2}{4\pi R}\exp\left(-\frac{R}{hc/mc^2}\right)$$

m is the mass of the quanta exchanged between the them

hc/mc^2 is the range of the force

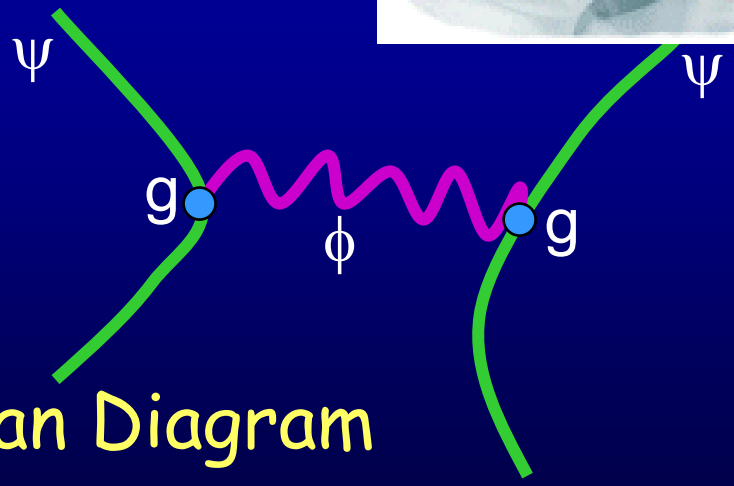
Hideki Yukawa
1907 - 1981

Quantum Electrodynamics

Feynman invented

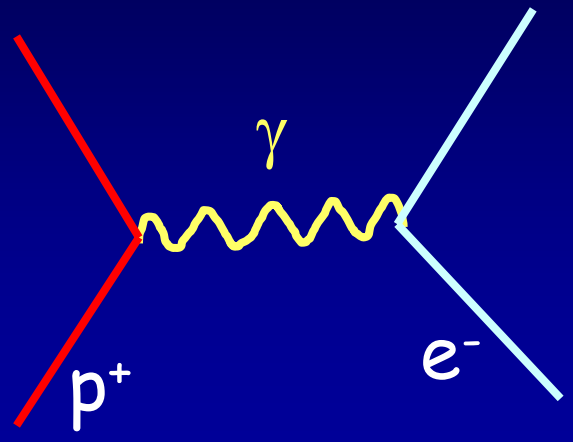
a systematic way to calculate the interactions between electrically charged particles

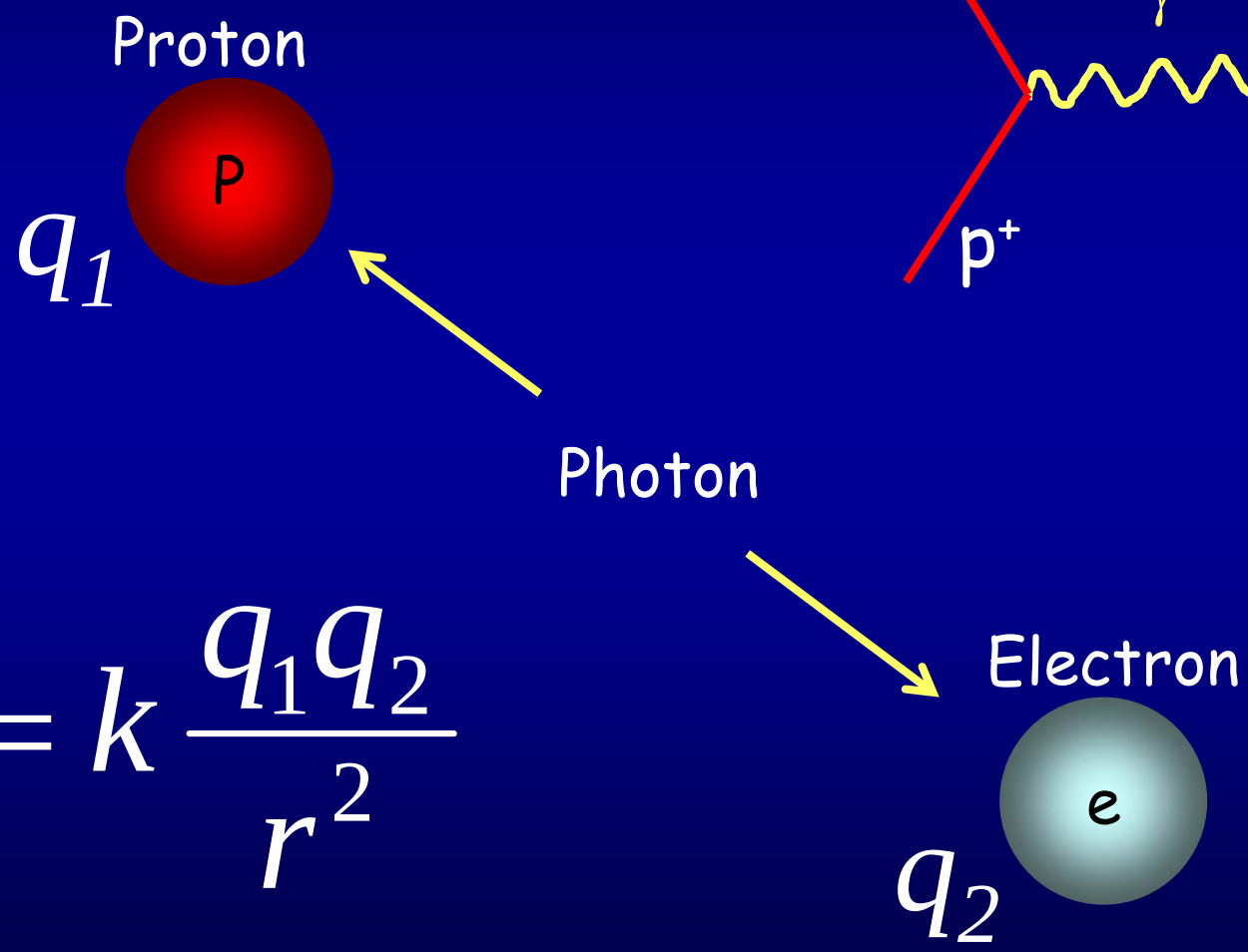
Richard P. Feynman
1918 - 1988



Feynman Diagram

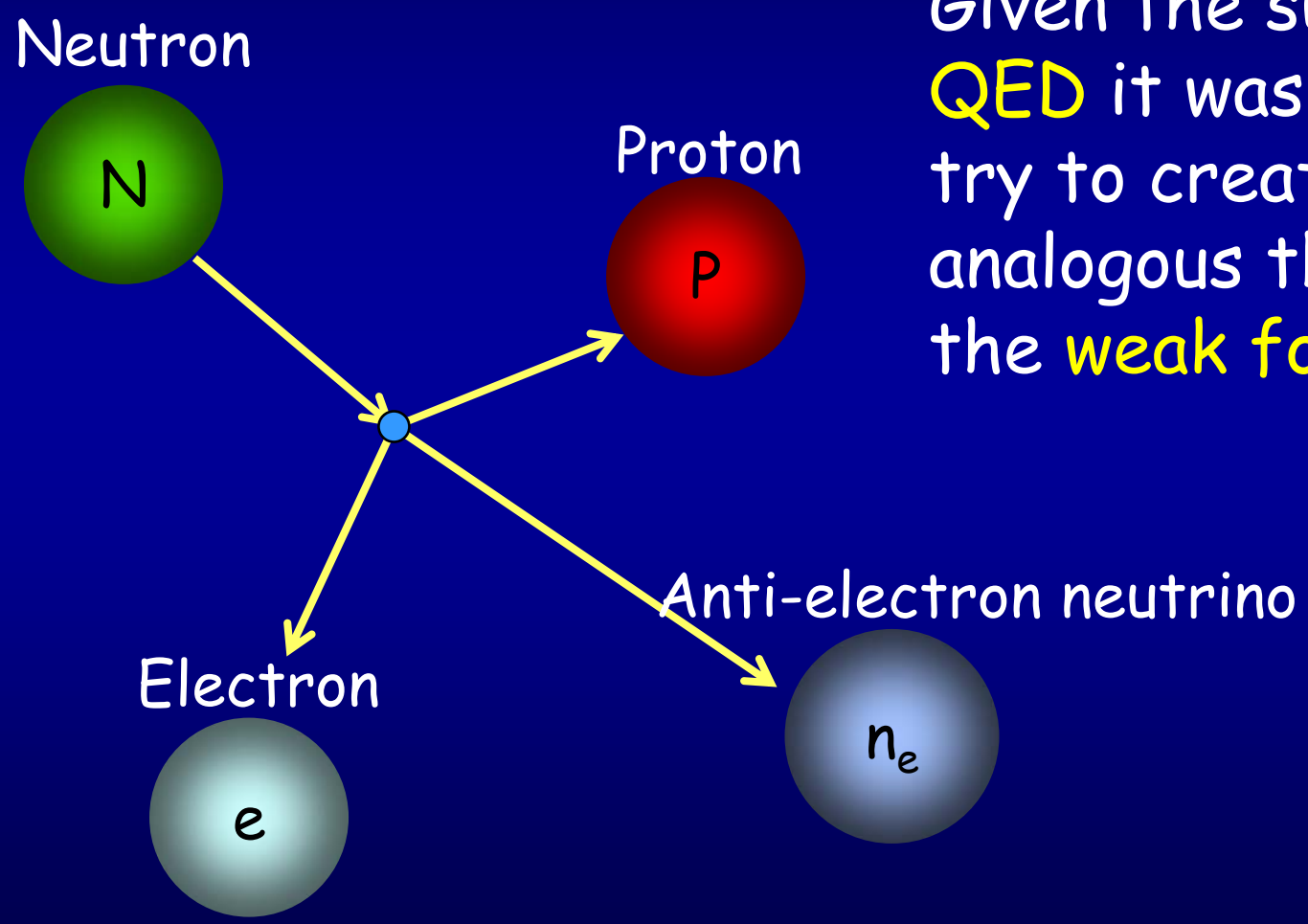
QED – The Coulomb Force





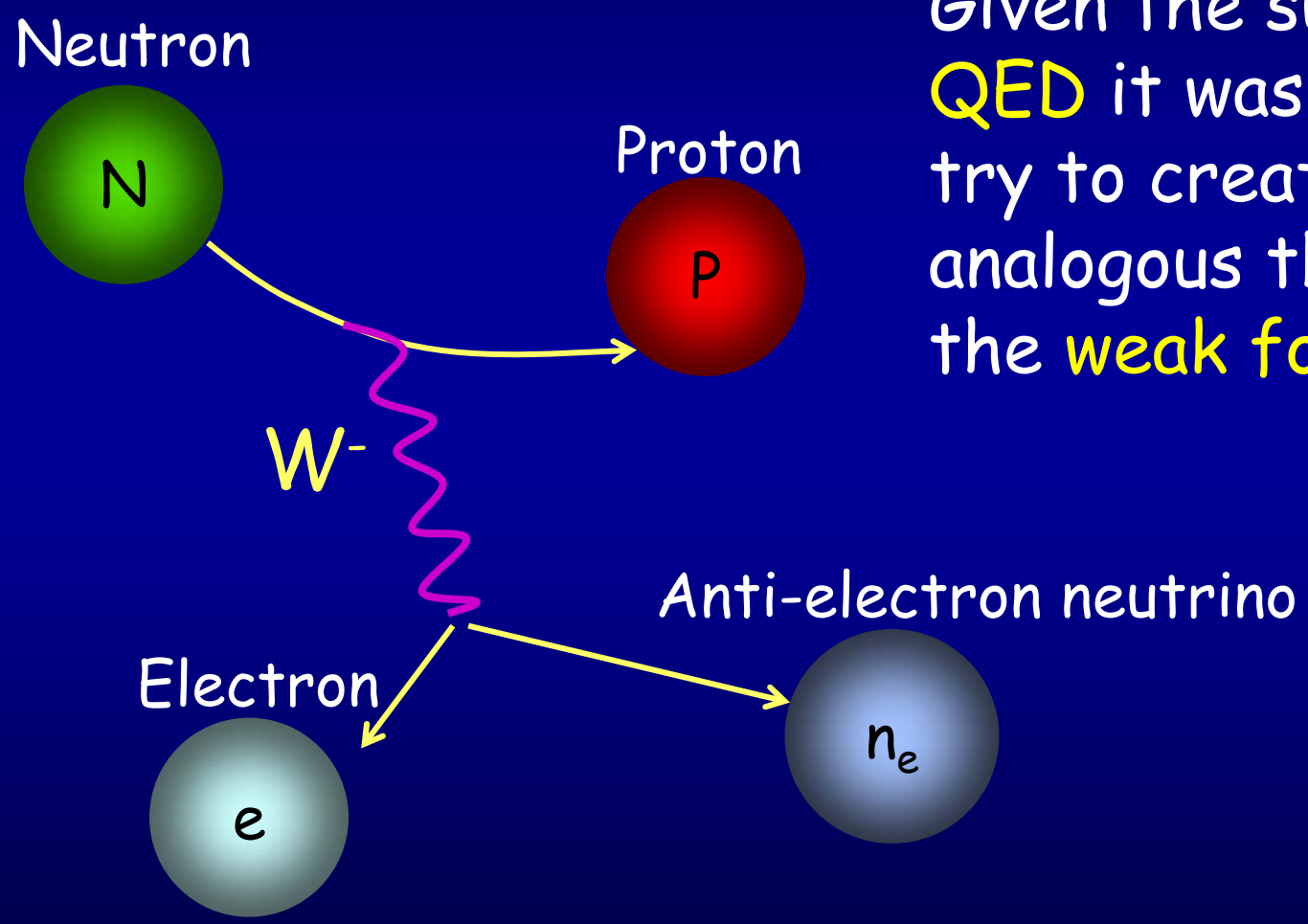
$$F = k\frac{q_1 q_2}{r^2}$$

The Weak Force



Given the success of QED it was natural to try to create an analogous theory of the weak force

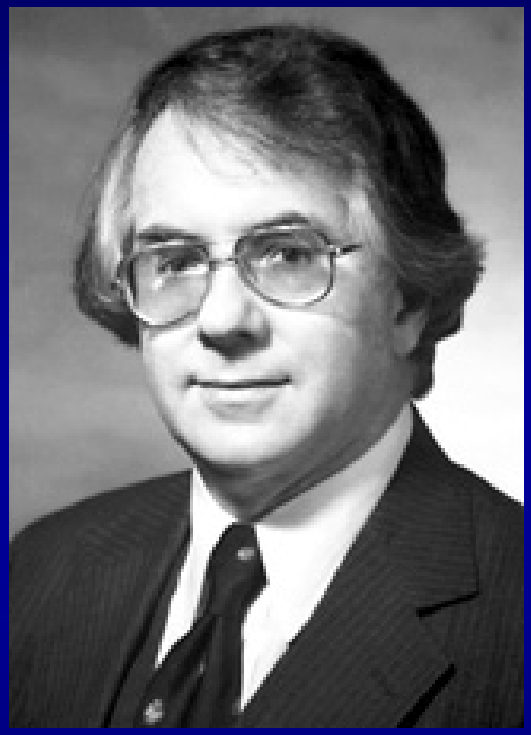
The Weak Force



Given the success of QED it was natural to try to create an analogous theory of the weak force

The Electroweak Theory – Take 1

1961, Sheldon Glashow created a unified theory of the weak and electromagnetic forces that contained 4 bosonic fields:



$$W^+ = (W_1 - i\,W_2) / \sqrt{2}$$
$$W^- = (W_1 + i\,W_2) / \sqrt{2}$$
$$Z = c\,W_3 - s\,B$$
$$\gamma = s\,W_3 + c\,B$$

But, alas, in this theory all the bosons are massless!

The Electroweak Theory – Take 2

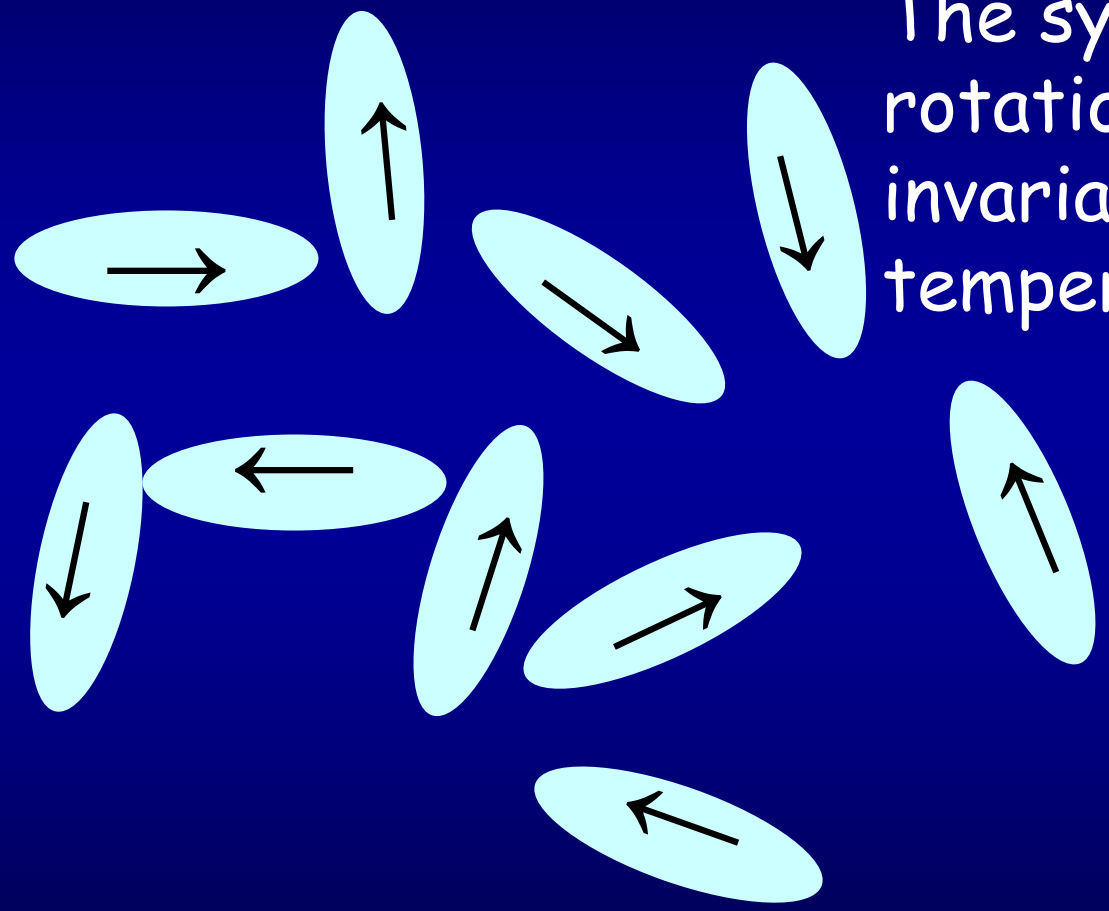
Steven Weinberg

Abdus Salam

Glashow Theory + Higgs Theory

Electroweak Theory
(1967)

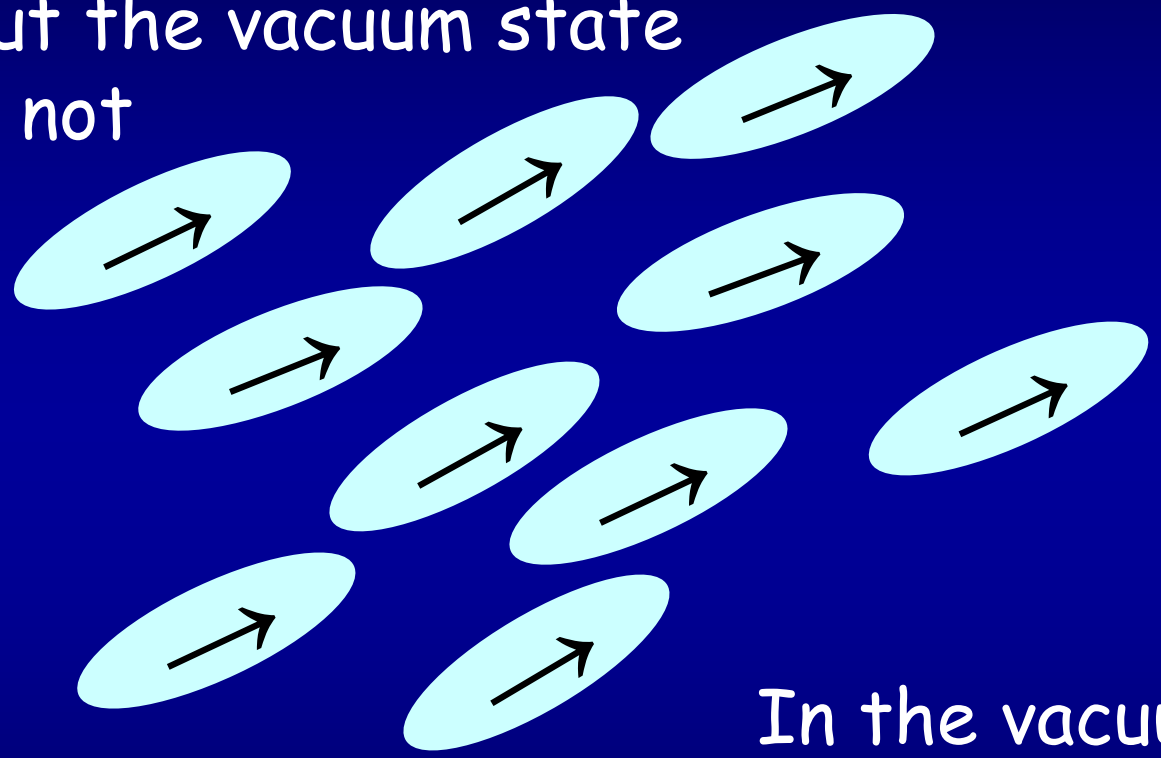
Spontaneous Symmetry Breaking



The system is rotationally invariant at high temperatures

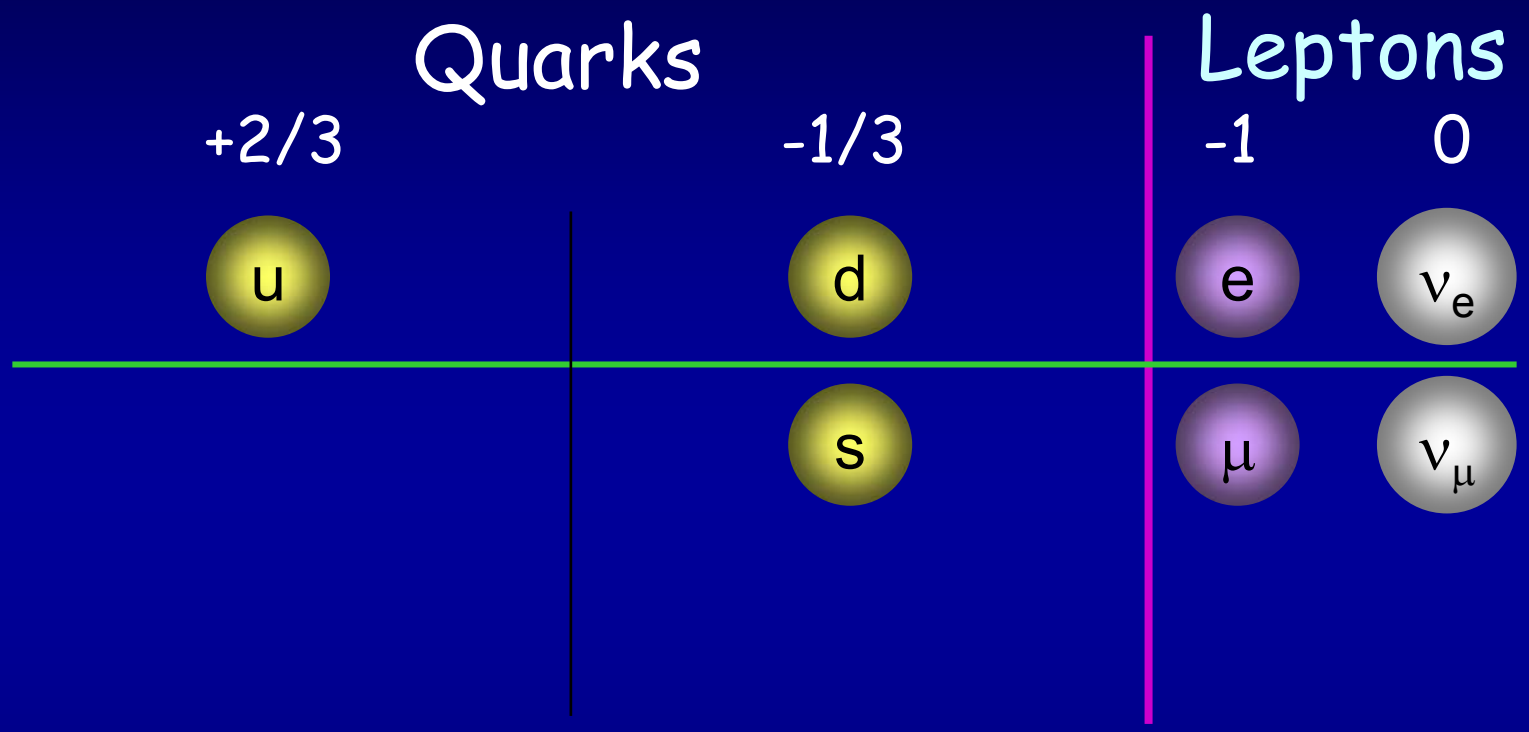
Spontaneous Symmetry Breaking

But the vacuum state is not



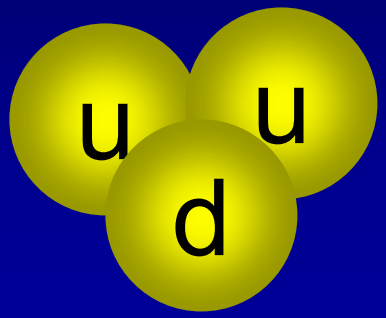
In the vacuum state of the Standard Model, the propagation of the massless W and Z fields is severely attenuated

The Quark Model

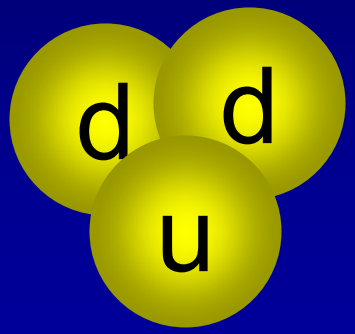


1964, Gell-Man and Zweig proposed, independently, a model in which all particles consist of elementary ones called quarks: up, down, and strange

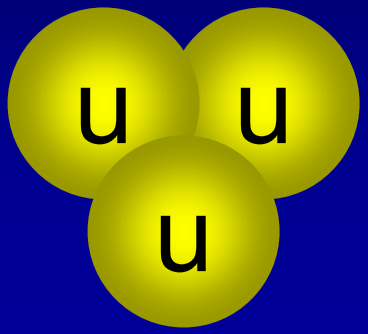
The Quark Model



Proton



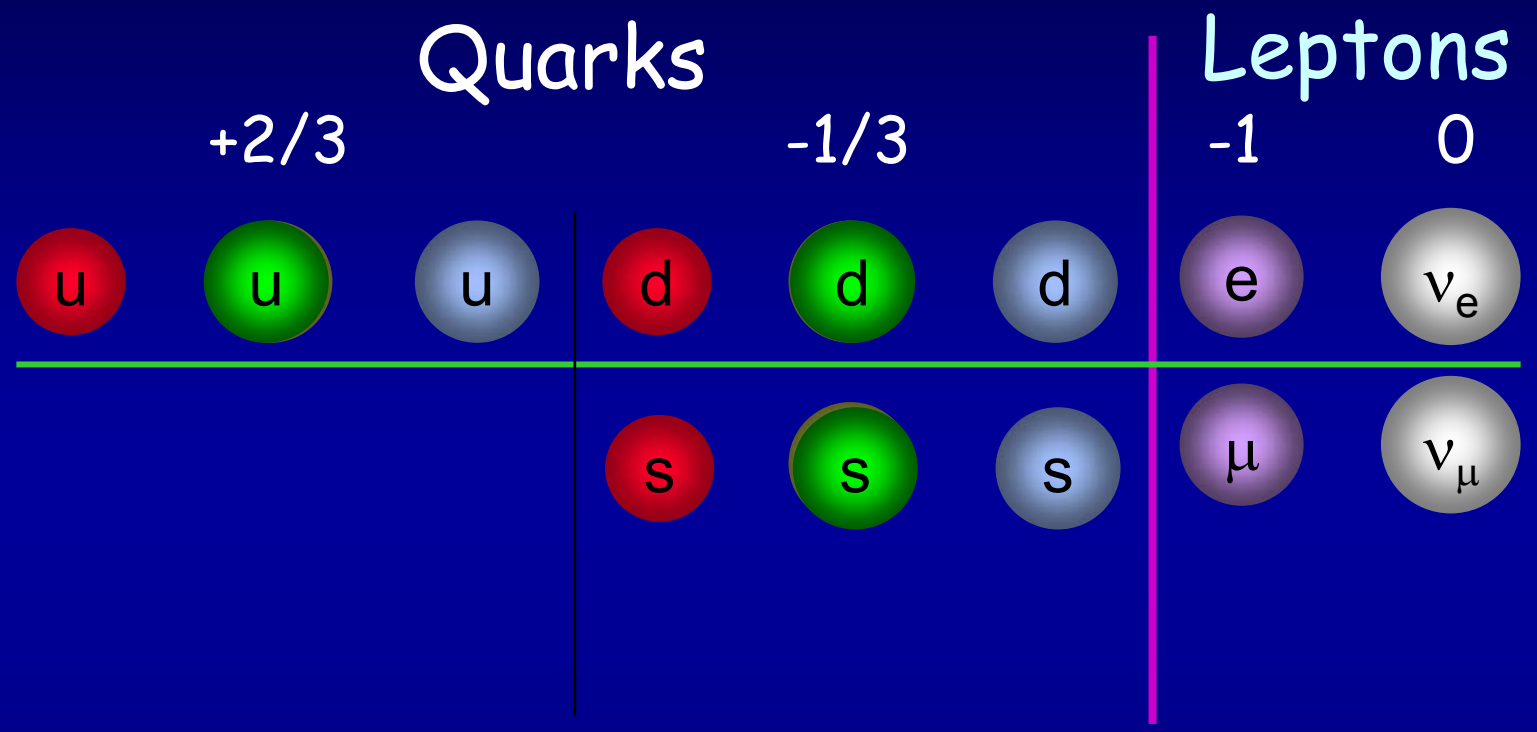
Neutron



Delta++

The Delta++ seemed to violate the Pauli exclusion principle, which forbids more than one fermion occupying the same state

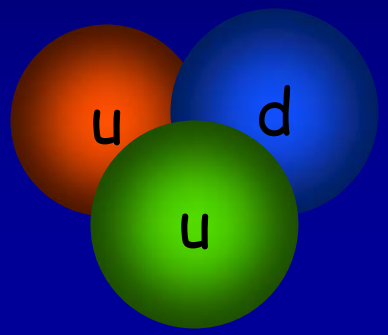
The Quark Model



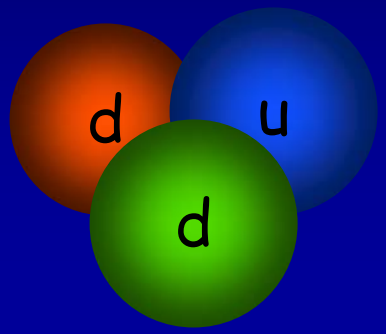
One possible solution (Greenberg, Frizsch, Gell-Man, Leutwyler) : each quark possesses another degree of freedom: color charge

Color Neutral States

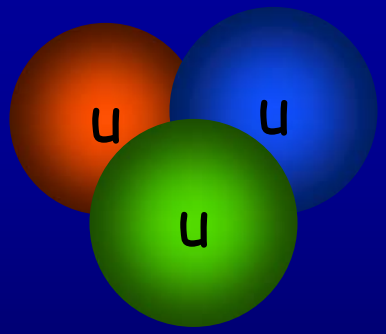
Proton



Neutron

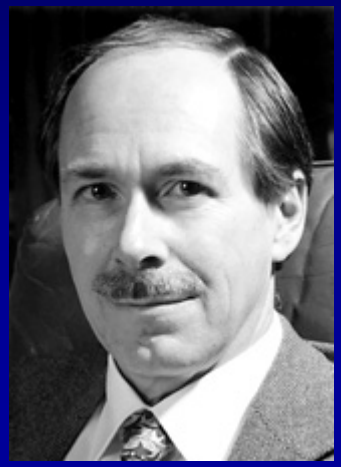


Delta++



Major Breakthrough

Martinus Veltman

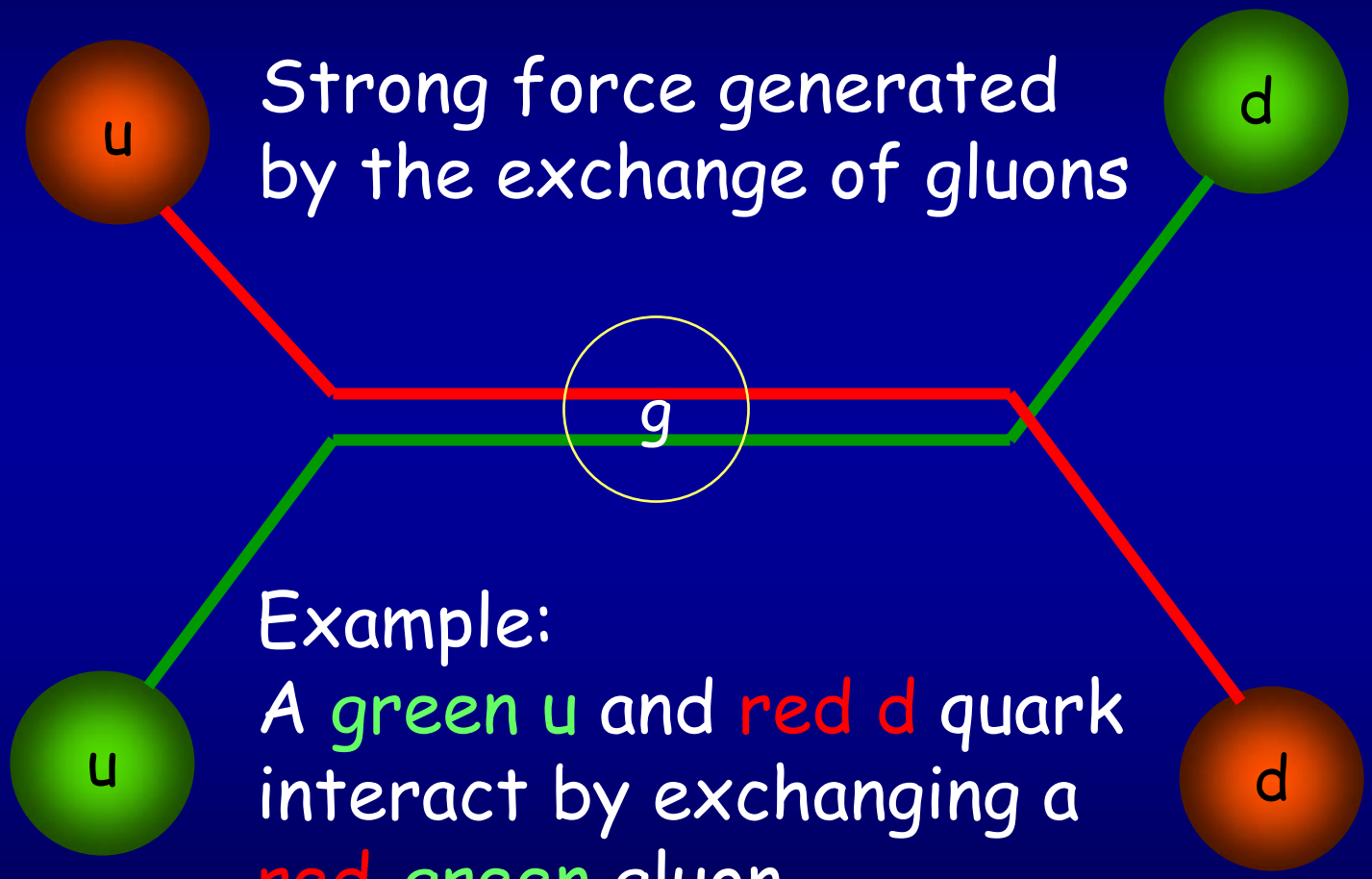


Gerard 't Hooft

1971 - Proved that theories of the sort created by Glashow, Weinberg and Salam are mathematically consistent

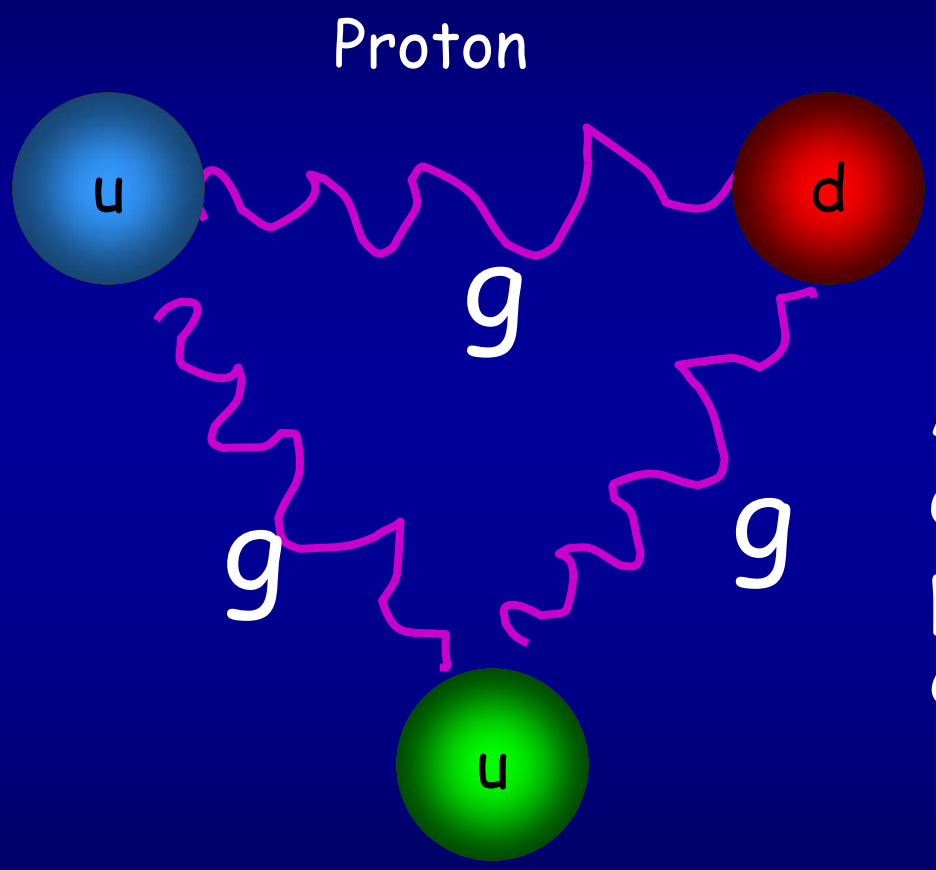
The Strong Force

Strong force generated by the exchange of gluons



Example:
A green u and red d quark interact by exchanging a red-green gluon

The Strong Force

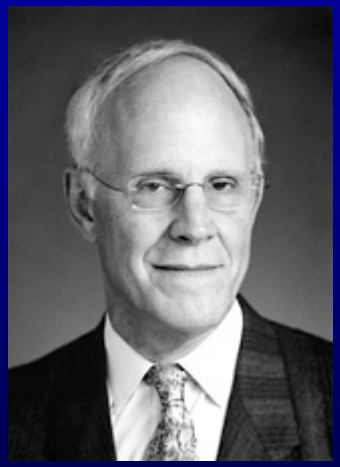


As gluons are exchanged the proton remains color neutral

Quantum Chromodynamics

1972, Gell-Man and Frizsch worked out the details of a new theory of the strong force, QCD

1973, Gross, Politzer and Wilczek showed the theory to be asymptotically free

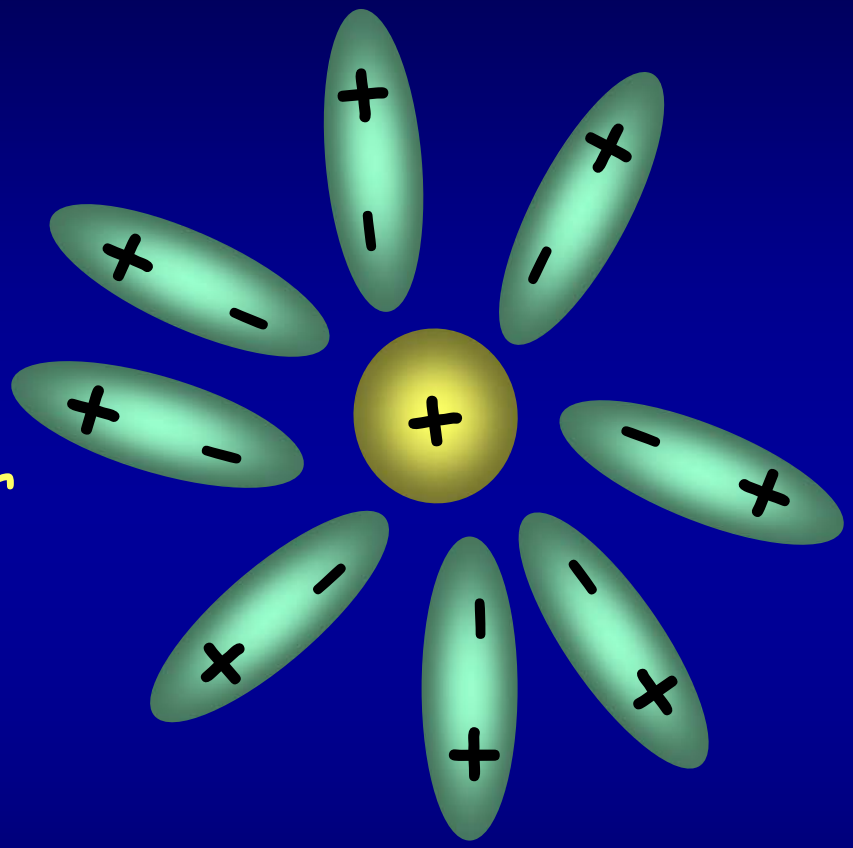


Asymptotic Freedom

The vacuum acts like a polarizable medium

An electric charge seen from afar appears weaker

A color charge seen from afar appears stronger



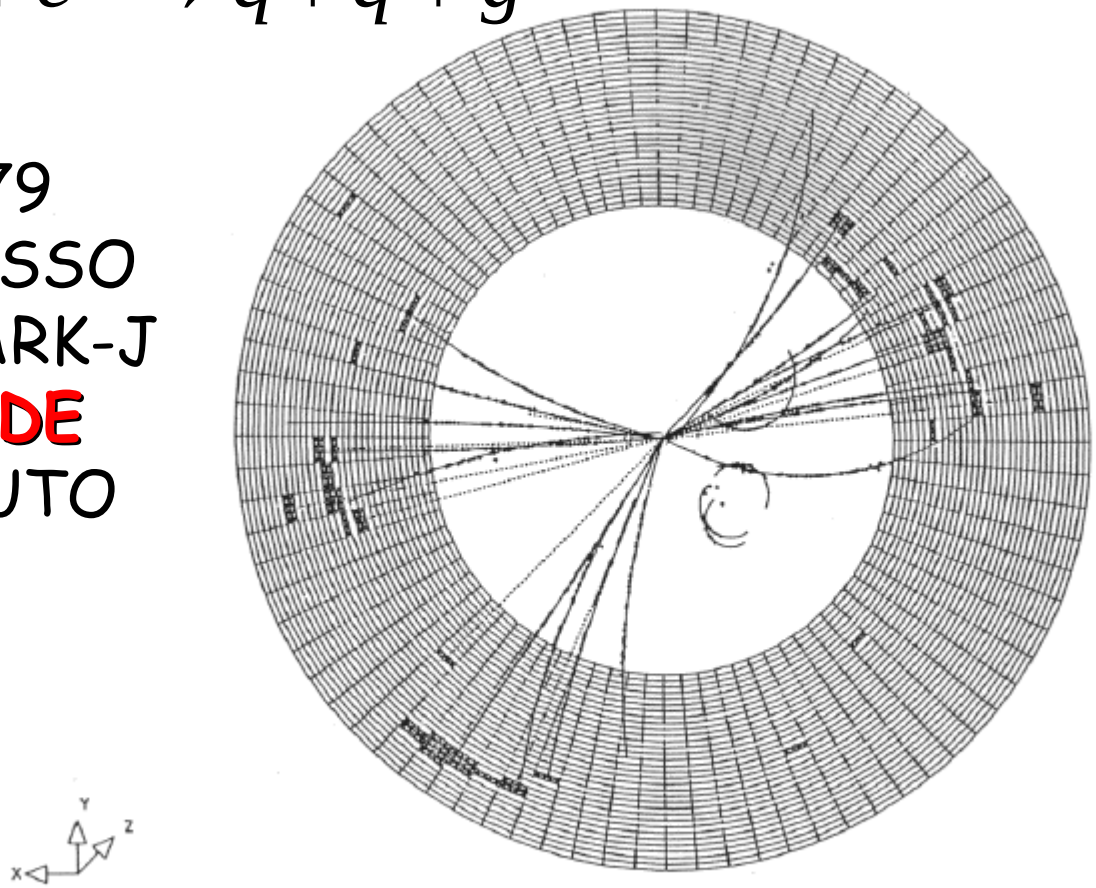
So, as two color charges get closer the force between them weakens –> asymptotic freedom

Discovery of the Gluon

$$e^+ + e^- \rightarrow q + \bar{q} + g$$

DESY
Hamburg,
Germany

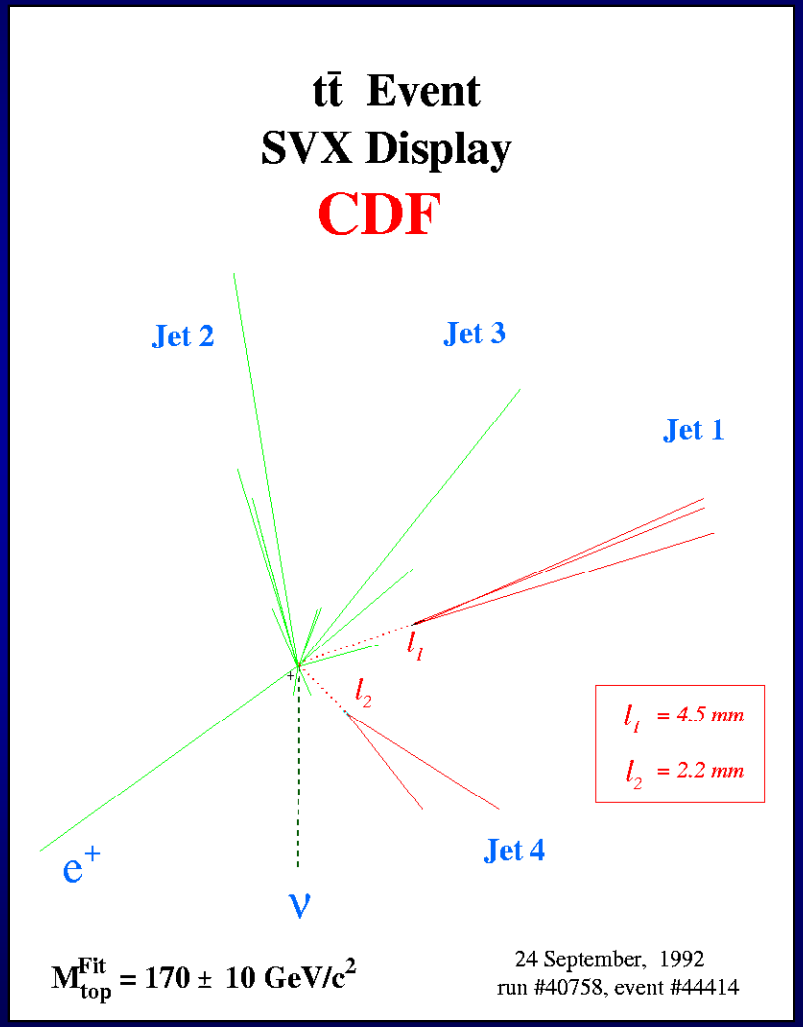
1979
TASSO
MARK-J
JADE
PLUTO



*** SUMS (GEV) *** PTOT 35.768 PTRANS 29.964 PLONG 15.700 CHARGE -2
TOTAL CLUSTER ENERGY 15.169 PHOTON ENERGY 4.893 NR OF PHOTONS 11

Discovery of Top the Quark

1995
CDF
DØ

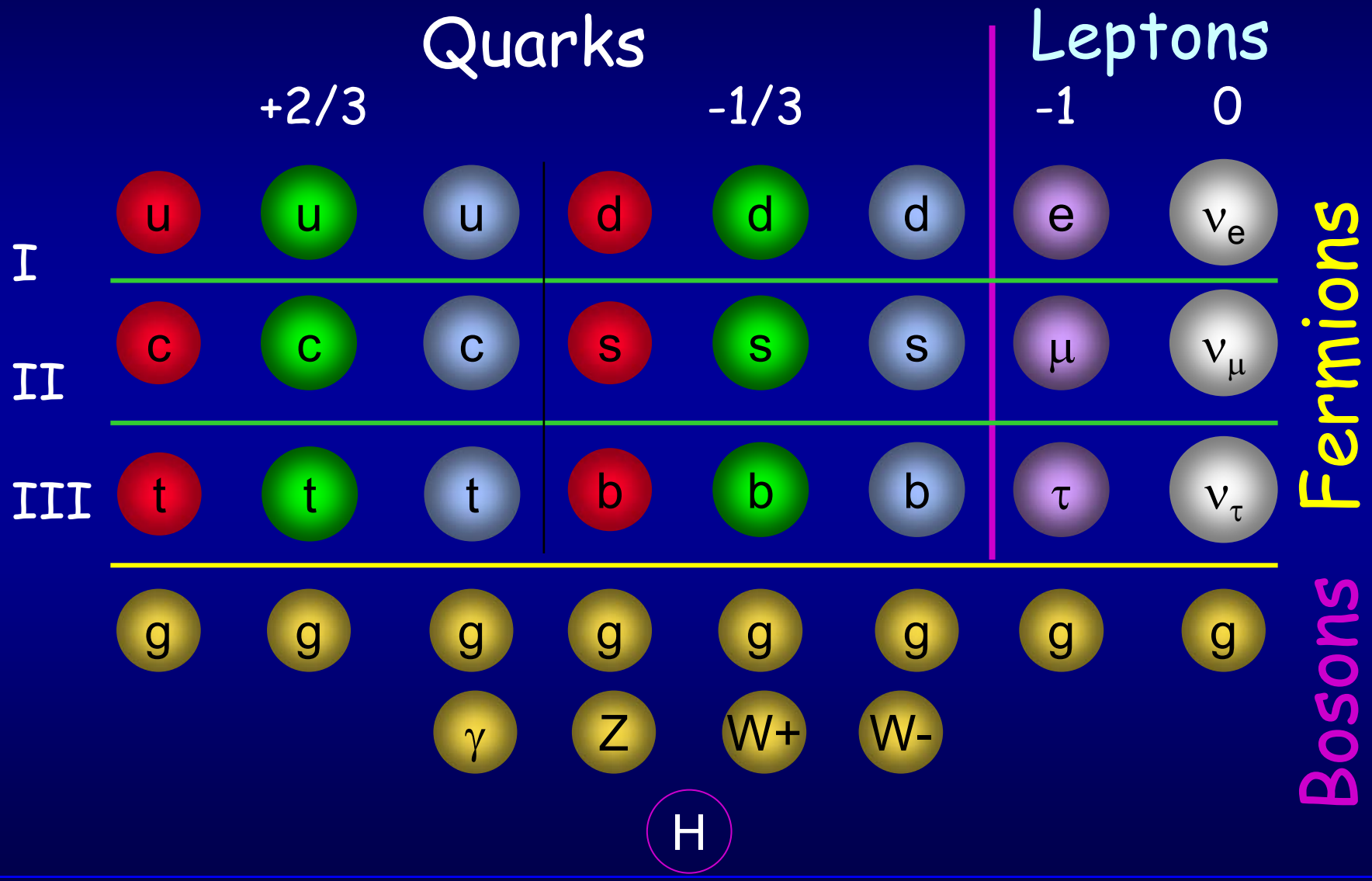


Fermilab

$$p + \bar{p} \rightarrow t \rightarrow e^+ + \nu_e + b$$

$$\bar{t} \rightarrow q + \bar{q}' + \bar{b}$$

The Standard Model



…And Beyond

Puzzles & Mysteries

The Identity Puzzle

What makes a top quark a top quark, an electron and electron, and a neutrino a neutrino?

Chris Quigg, 2007

The Mass Puzzle

What is the origin of mass?

The Matter Puzzle

What is the origin of the matter/anti-matter asymmetry?

The Dark Matter Puzzle

What is it?

Puzzles & Mysteries

The Just-So Puzzle

What determines the values of the 19 Standard Model parameters?

The Force Puzzle

Why strong: em: weak: gravity = 1: 10^{-2}: 10^{-5}: 10^{-39} ?

The Gravity Puzzle

Why is gravity so weak?

The Dark Energy Puzzle

Why is the vacuum nearly empty?

The Just-So Puzzle

What determines these masses?

Nucleon	Mass [MeV]
N (udd)	939.6
P (duu)	938.3
	1.3

Particle	Mass [MeV]
electron	0.51
muon	105.65
tau	1776.99
u	2.25
d	5.00
s	95 .00
c	1250 .00
b	4200 .00
t	171,000 .00

The Dark Energy Puzzle

According to the Standard Model, the energy density of the vacuum should be > 100 GeV/fm^3

According to observation, the energy density of the vacuum is < 10^{-52} GeV/fm^3

Oops!

The Gravity Puzzle

10^{-39}

Current Speculations

Supersymmetry

Technicolor

Extra dimensions

Strings

Branes

Quantum gravity

: :

The Planck Scale

General relativity predicts the existence of singularities, that is, boundaries in spacetime:

at the Big Bang

and within black holes

So if we wish to understand the origin of spacetime, we need to understand Nature on the smallest scale: the Planck scale

The Planck Scale

The Fundamental Parameters of Nature

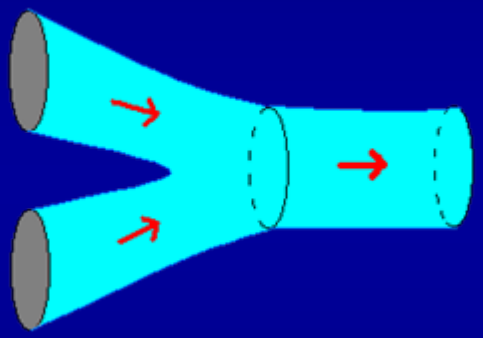
- h Planck's constant
- c Speed of light in vacuum
- G Newton's gravitational constant

$$l_P = \sqrt{\frac{hG}{c^3}}$$

$l_p \sim 4 \times 10^{-35}$ m The Planck Length

Strings

In 1974, Joel Scherk and John Schwarz created a theory in which the basic entities are tiny strings



that move in spacetime. The harmonics of strings correspond to what we interpret as particles.

Strings

But, it was quickly discovered that strings can exist only in 10-spacetime dimensions!

Which prompted further questions:

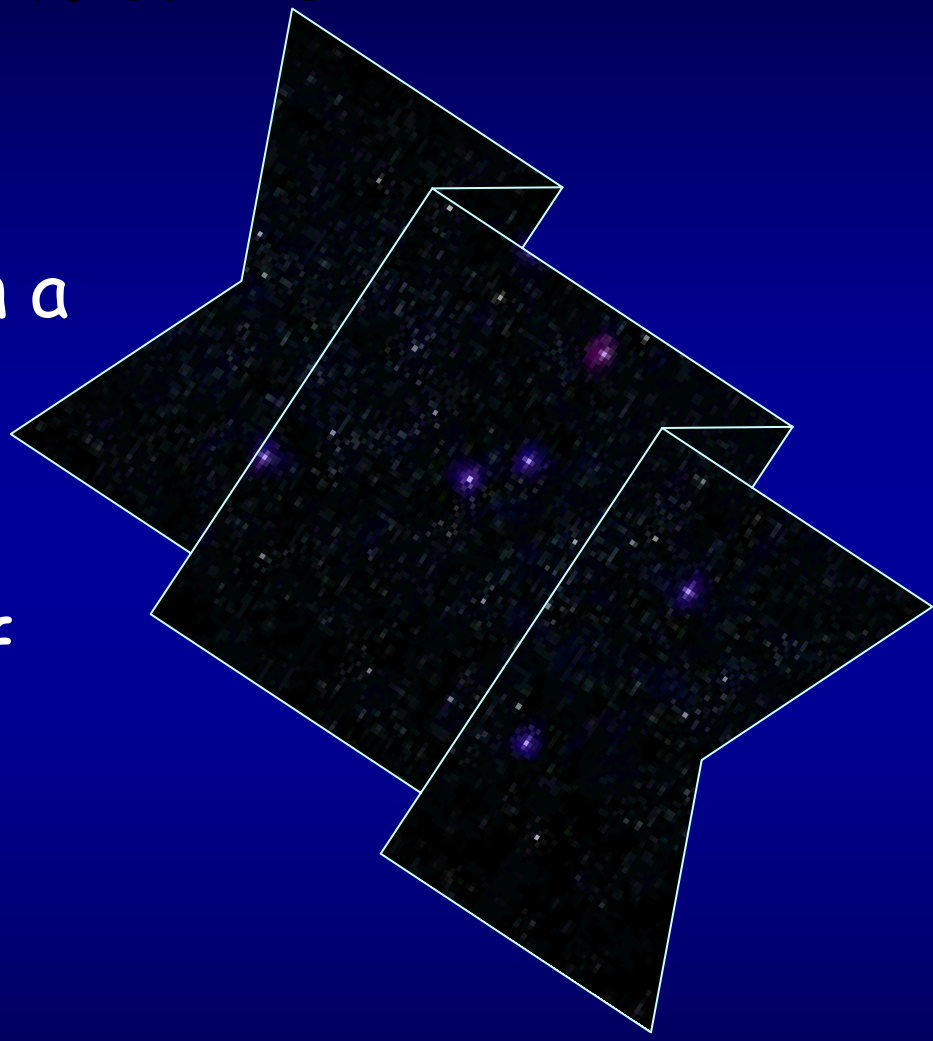
Where are the extra dimensions?

Are they large or are they small?

If they are small, what caused the collapse of spacetime to 4 dimensions?

Brane Worlds

Our 3-dimensional space could be embedded within a higher dimensional space



Perhaps ours is but one of numerous brane worlds

Perhaps brane worlds can collide (the Big Bang?)!

October, 2008
The Era of the LHC Begins