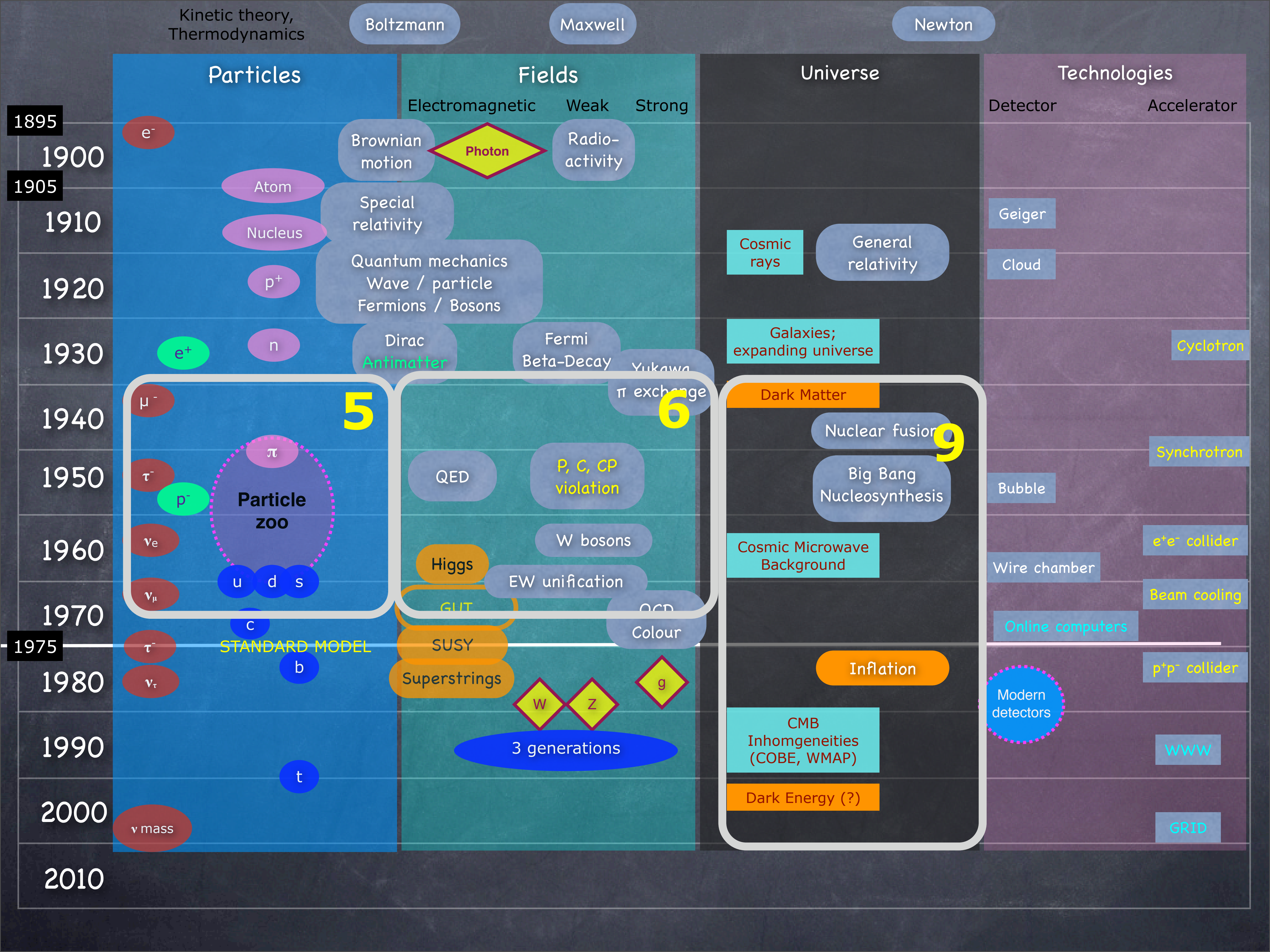
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P, C, CP violation
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Higgs
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Cosmic rays
General relativity
Galaxies; expanding universe
Dark Matter
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Cosmic Microwave Background
Inflation
CMB Inhomgeneities (COBE, WMAP)
Dark Energy (?)
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Wire chamber
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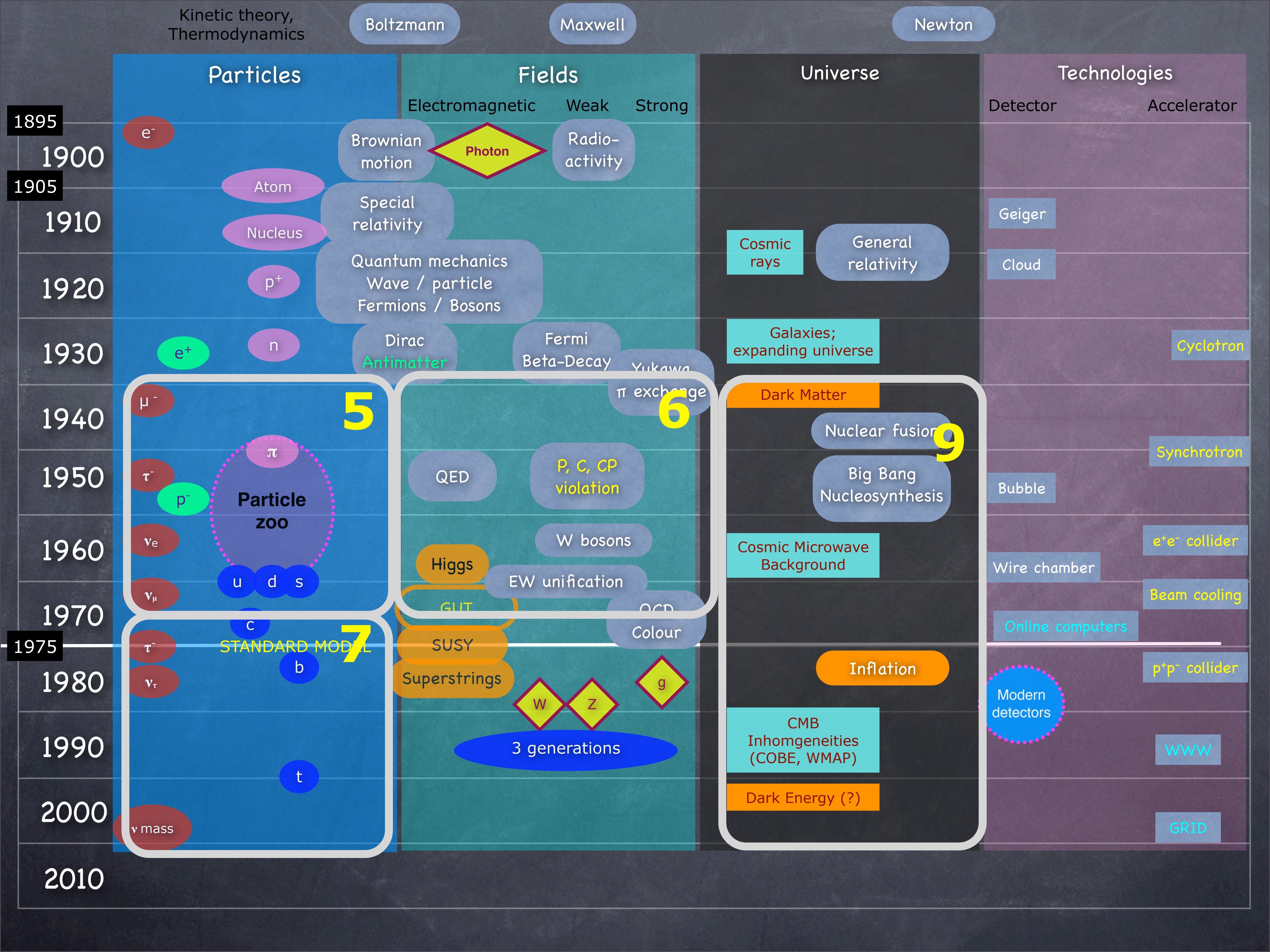
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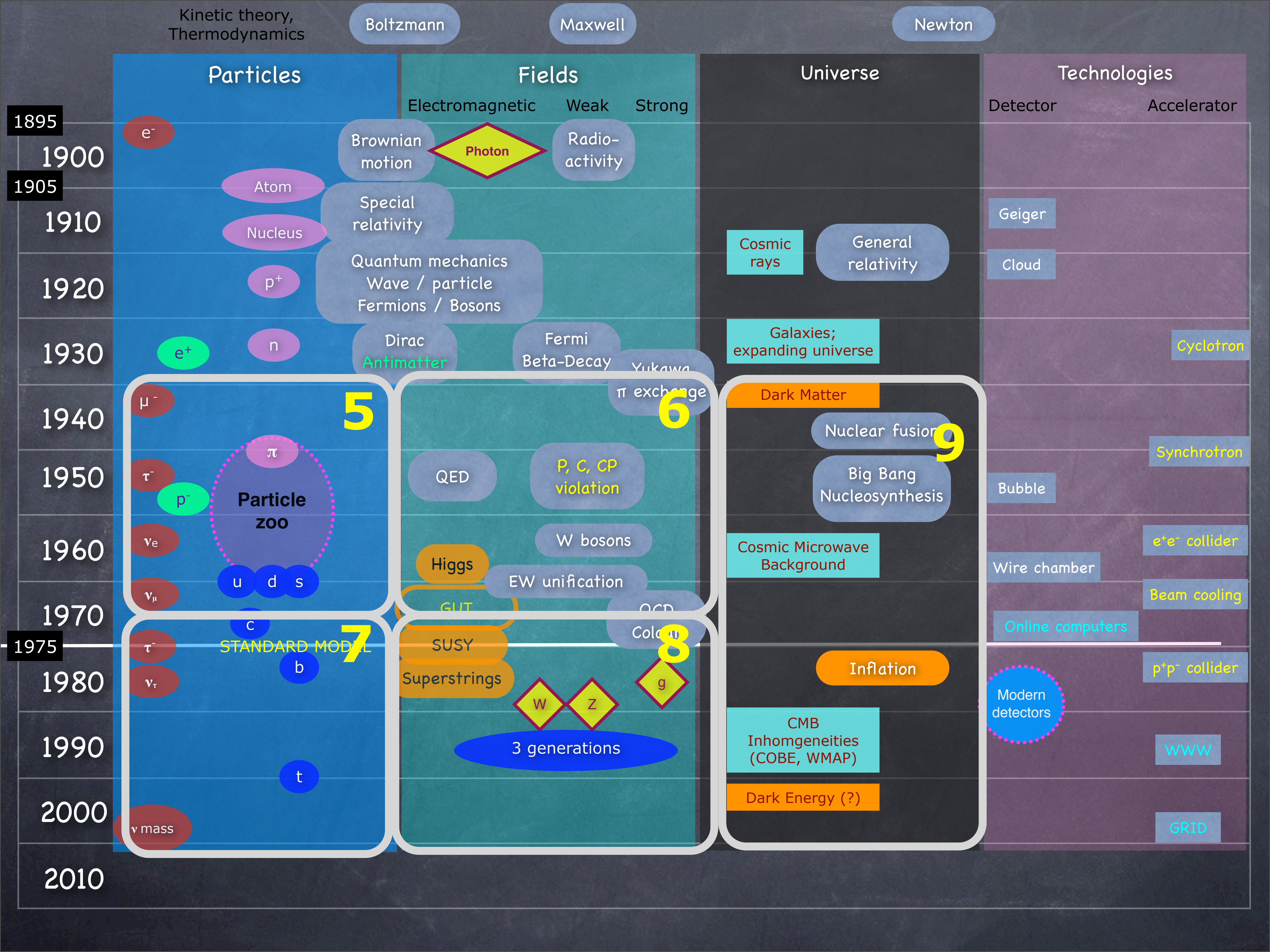

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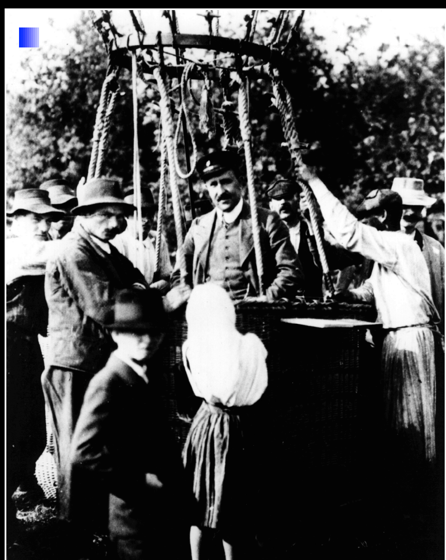
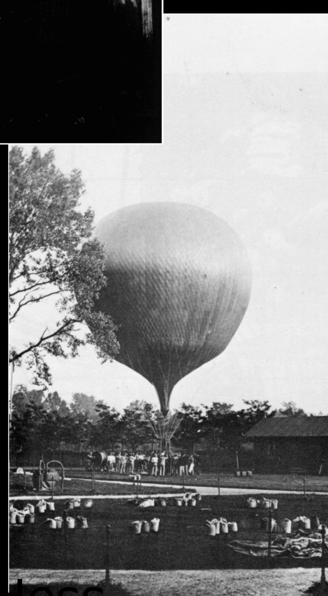
Universe

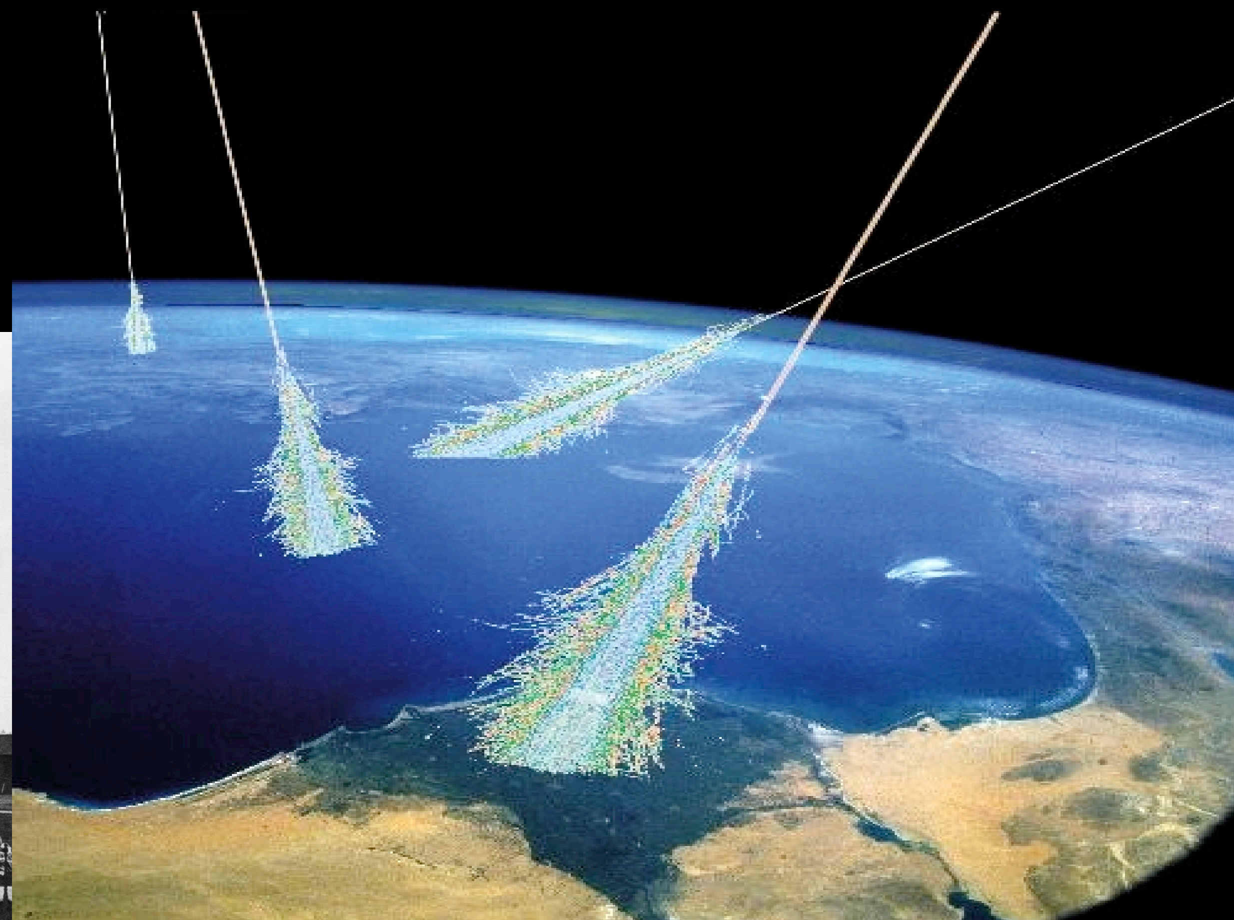
In 1913, first hints of a violent universe appeared

Discovery of cosmic rays



Victor Hess





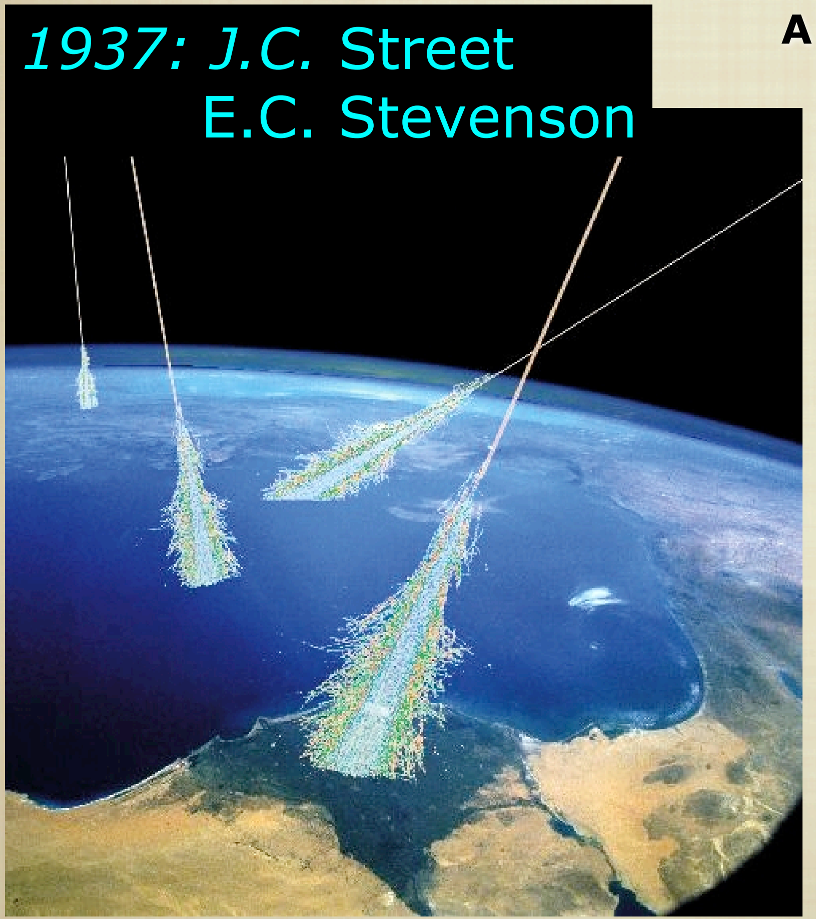
PARTICLE SPECTRUM

μ $^-$

1937

After Yukawa's prediction of a 'pion' (1934), everybody was searching for this particle (100-200 MeV).

There was no accelerator with sufficient energy available (yet). So physicists went on mountain tops to search for tracks in their photographic emulsions.



A new particle was discovered in the right mass range

Very long range in matter !! ?

No strong interaction with nuclei
>> Not Yukawa’s pion !

Muon - ‘heavy electron’ (206 x m_e)

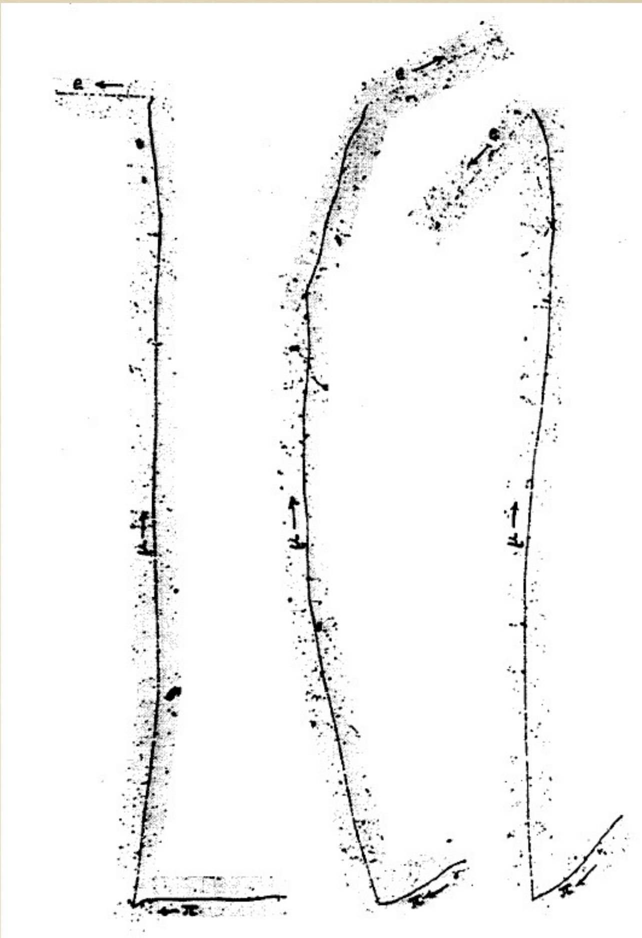
I. Rabi: “WHO ORDERED THAT ?”

PARTICLE SPECTRUM

Discovery of the (charged) pion

Cecil Powell

Ouff!



Photographic emulsion technique

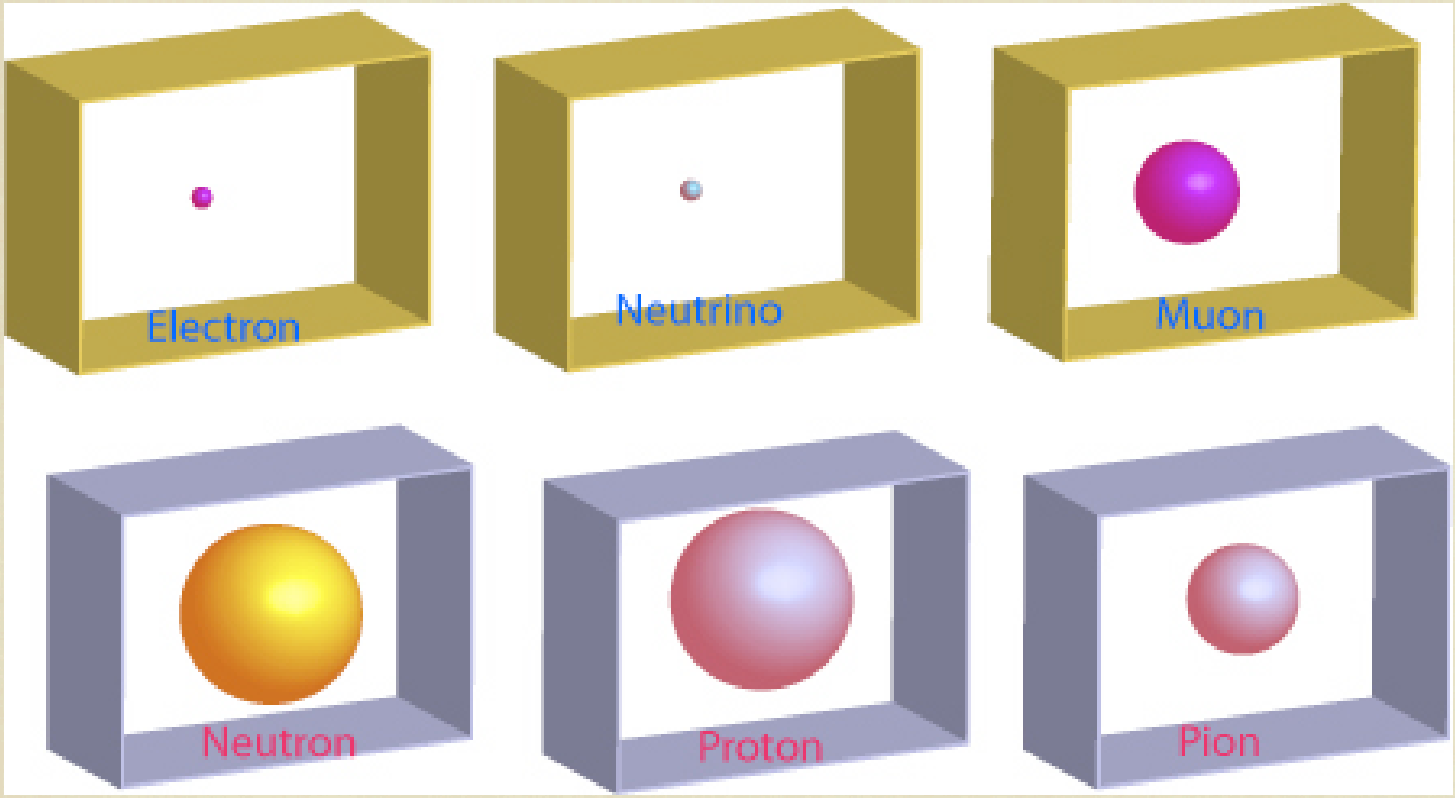
Cosmic rays at **high altitude** (Pic du Midi, Pyrenees)

Pion tracks identified under microscope

One year later: Pions produced at Berkeley cyclotron (Alpha+Carbon)

PARTICLE SPECTRUM

1948



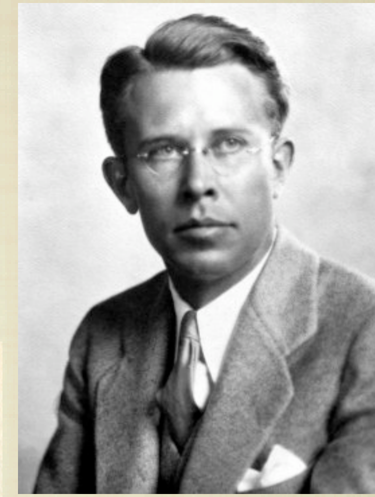
PARTICLE SPECTRUM

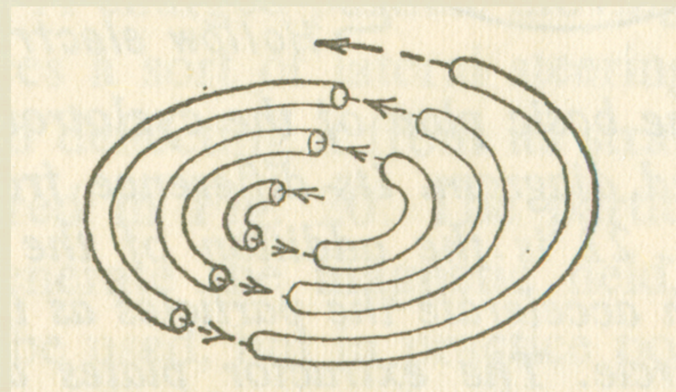
Accelerators

"Man-made cosmic rays"

Rolf Wideroe, 1928

Ernest Lawrence, 1931





Cyclotron

Linear accelerator

Accelerate particles between electrode gaps
Tune RF frequency to match particle motion

Use magnetic field to bend particles into circular orbit
Particles pass through same accelerating gap many times and reach higher energies

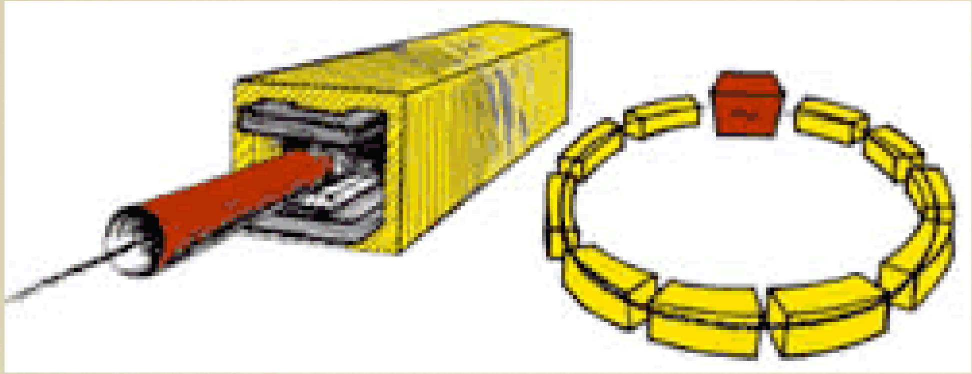
1931: 80 keV
1932: 1000 keV
1939: 19 MeV*
1946: 195 MeV ("synchrocyclotron")

* first limitations by relativistic mass increase

PARTICLE SPECTRUM

1931 - 1955

Accelerators (2)



Synchrotron

Similar to cyclotron, but change magnetic
field to keep particles on the same orbit
(also overcomes relativistic mass increase)

1947: US constructs two 'synchrotrons'

Brookhaven (1952) - 3 GeV

Berkeley (1954) - 6.2 GeV ('antiproton')

1954: Europe competes with US

CERN (1959) - 24 GeV

Brookhaven (1960) - 30 GeV

Detectors

Geiger counters
Cloud chambers
Emulsions
Bubble chambers

Cerenkov counters
Photomultipliers
Spark chambers

After 1967:

Wire chambers
Drift chambers
Calorimeters

PARTICLE SPECTRUM

Particle zoo

1950- 1968

With new accelerators and detectors, the "particle zoo" grew to more than ~ 200 'elementary particles'

MESONS

π^+ π^- π^0

Pions

K^+ K^- K^0

Kaons

η'

Eta-Prime

η

Eta

ϕ

Phi

ϱ^+ ϱ^- ϱ^o

Rho

BARYONS

$\Delta^{++}, \Delta^+, \Delta^0, \Delta^-$

Delta

Λ^0

Lambda (strange!)

$\Sigma^+, \Sigma^0, \Sigma^-$

Sigma (strange!)

Ξ^0, Ξ^-

Sigma(very strange!)

What was the underlying structure ?

PARTICLE SPECTRUM

1963

SU(3) - Classification scheme based on 'quarks'

Fig. 6.35 Murray Gell-Mann (b.1929).

Gell-Mann, 1963

(G. Zweig, 1963, CERN)

1) 3 types of "quarks" : up, down, strange

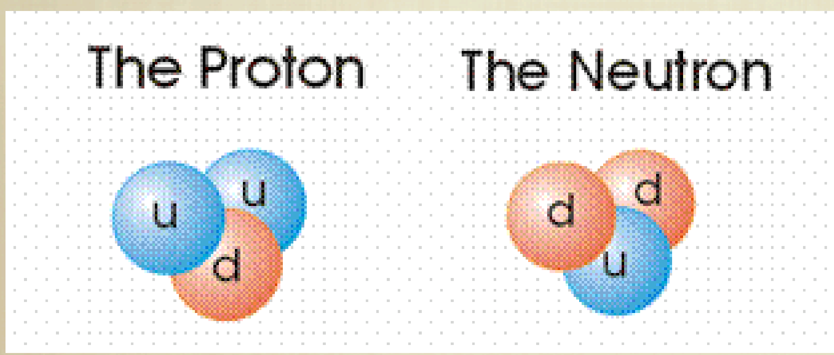
2) Carry electric charges: +2/3, -1/3, -1/3

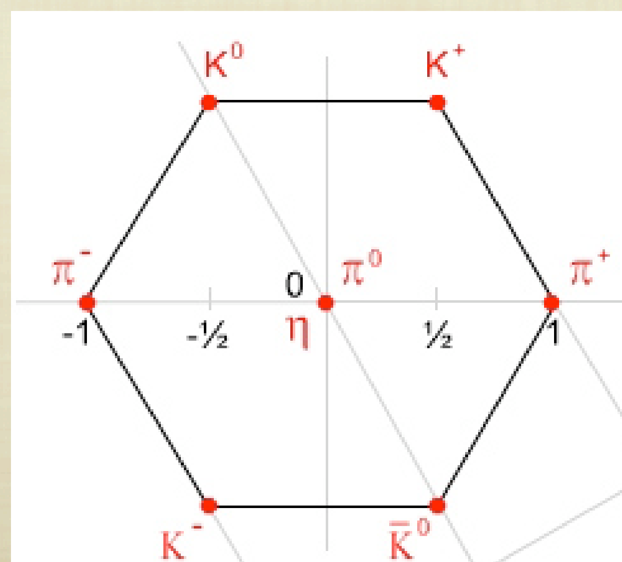
3) Appear in combinations:

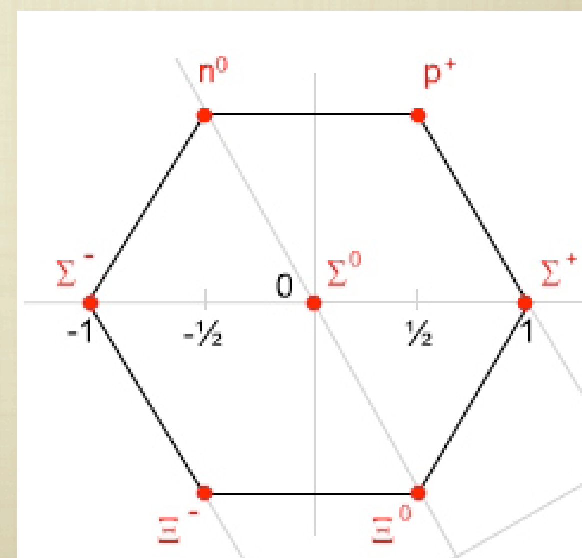
Meson = quark+antiquark

Baryon = quark(1) + quark(2) + quark(3)

4) Existing hadrons fit nicely into this scheme



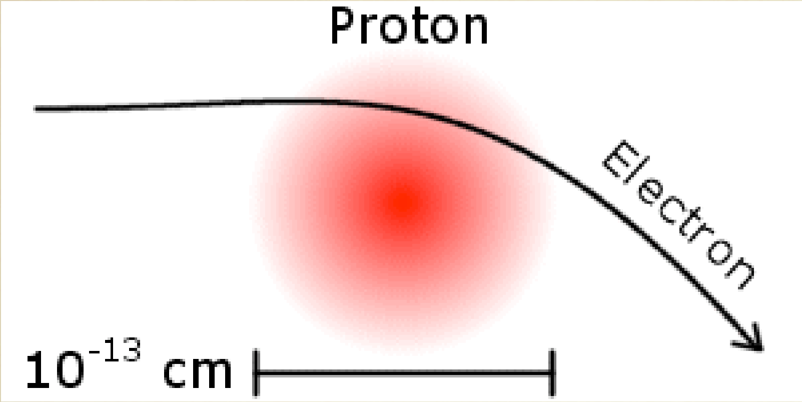




PARTICLE SPECTRUM

Discovery of quarks

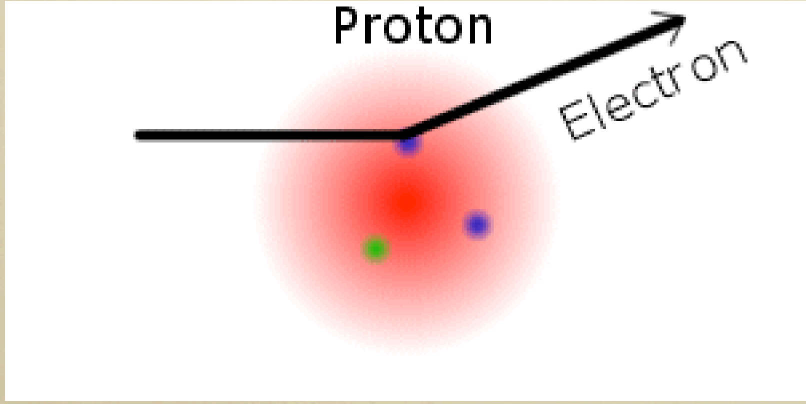
Electron-Proton scattering



1956 Hofstadter: measured finite proton radius

Stanford Linear Accelerator Centre

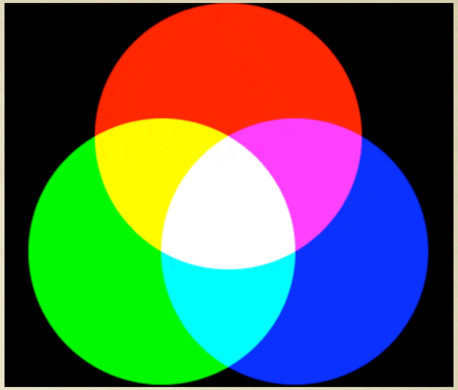
1967 Friedmann, Kendall, Taylor (SLAC):
'hard scattering' of electron on three 'point-like particles'



Measured cross-sections perfectly compatible with presence of 2 up- and 1 down-quark in proton

PARTICLE SPECTRUM

1973



Colour charge

Δ^{++} (u,u,u) three up-quarks with parallel spin, in a symmetric state

But: three fermions not allowed to be in identical states (Pauli exclusion principle)

The three quarks must be different in one quantum number: "colour"

(Bardeen, Fritzsch, Gell-Mann)

Only colour-neutral bound states are allowed

MESONS = Quark-Antiquark

BARYONS = 3-Quark states

Positive pion

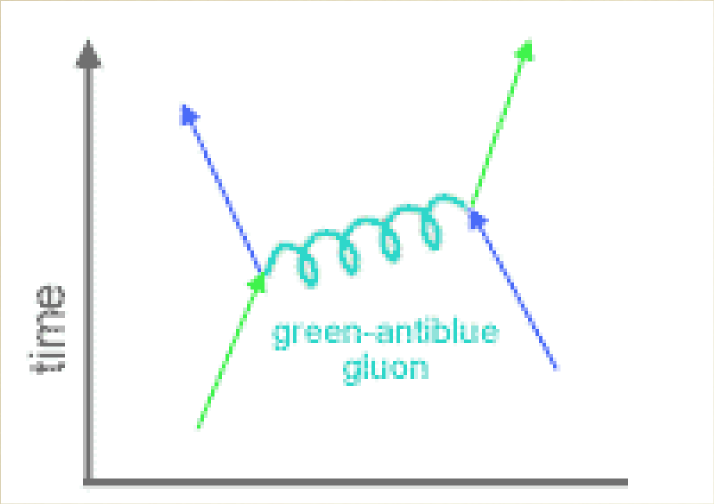
Colour-force transmitted by (eight) gluons

GLUONS CARRY COLOUR CHARGE - SELF-INTERACTION !

PARTICLE SPECTRUM

1973

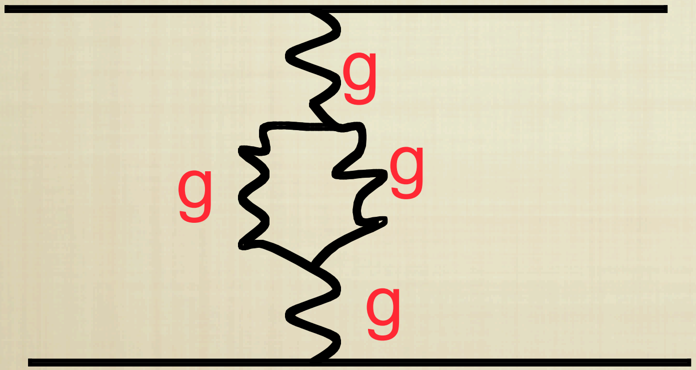
Gluons



Gluons are massless carriers of the strong force

There are 3 x 3 - 1 = 8 different gluons

Gluons carry colour charge -> self-interaction



Self-interaction of gluons

Potential rises linearly with distance (for large r)

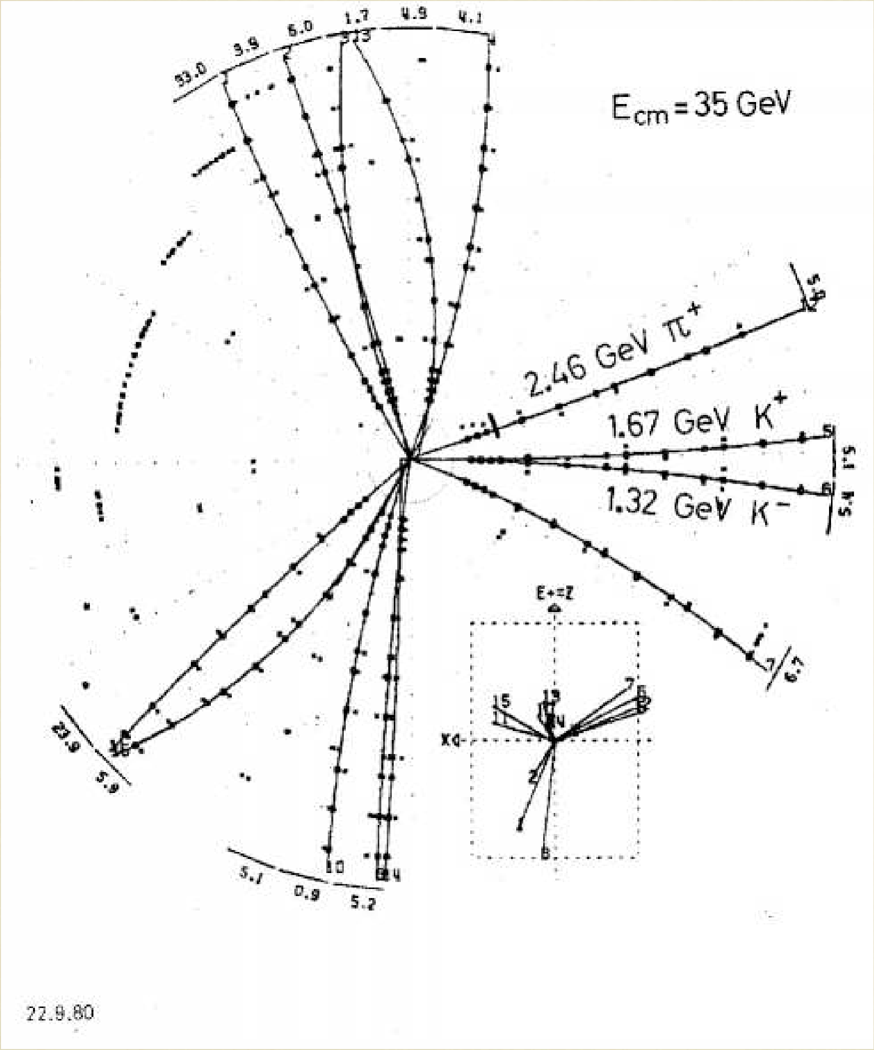
$$V_{QCD} = -\tfrac{4}{3}\frac{\alpha_s}{r} + kr$$

Small distances: asymptotic freedom

PARTICLE SPECTRUM

1973

Discovery of Gluons



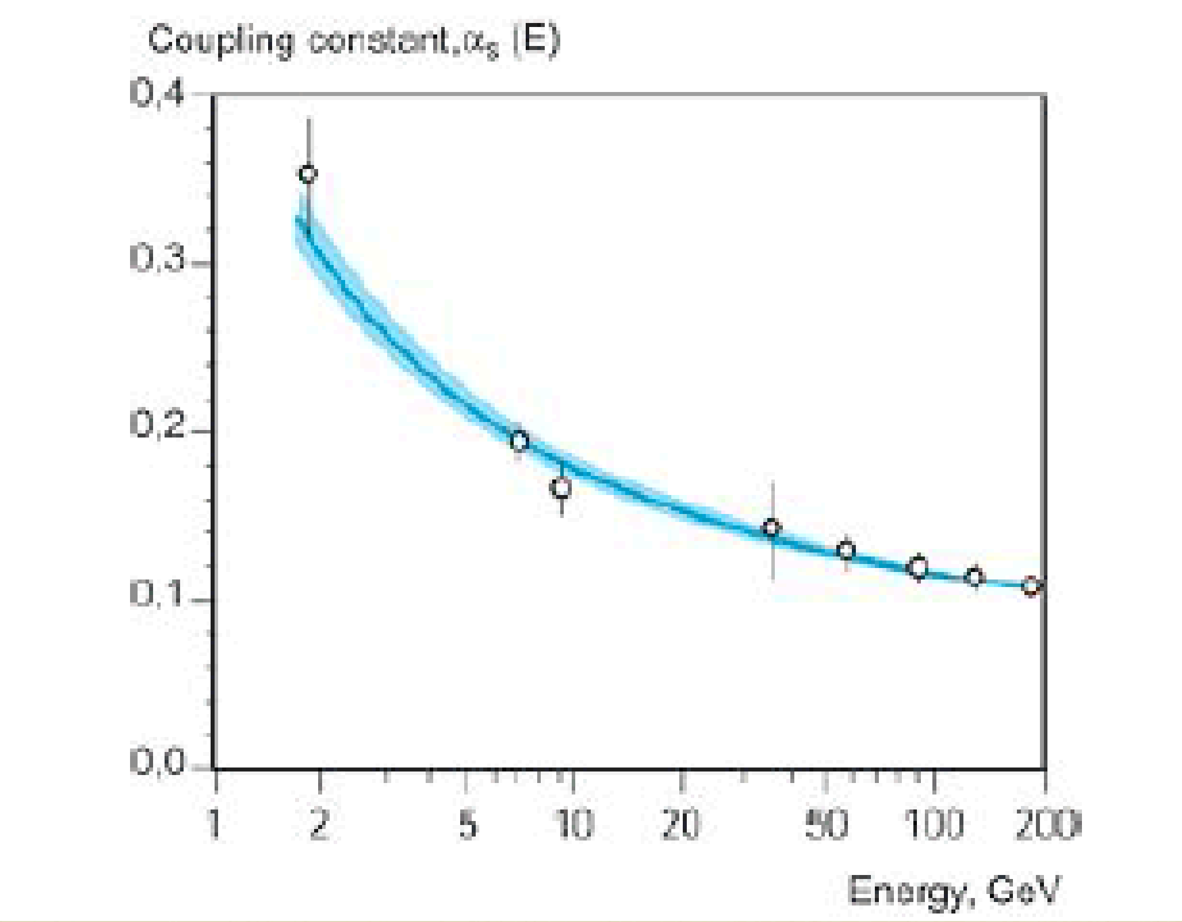
PETRA Storage Ring, 1979, DESY (Hamburg)

PARTICLE SPECTRUM

1973

Running coupling constant

The self-interaction of gluons produces an 'anti-shielding effect' - the force becomes smaller at shorter distances



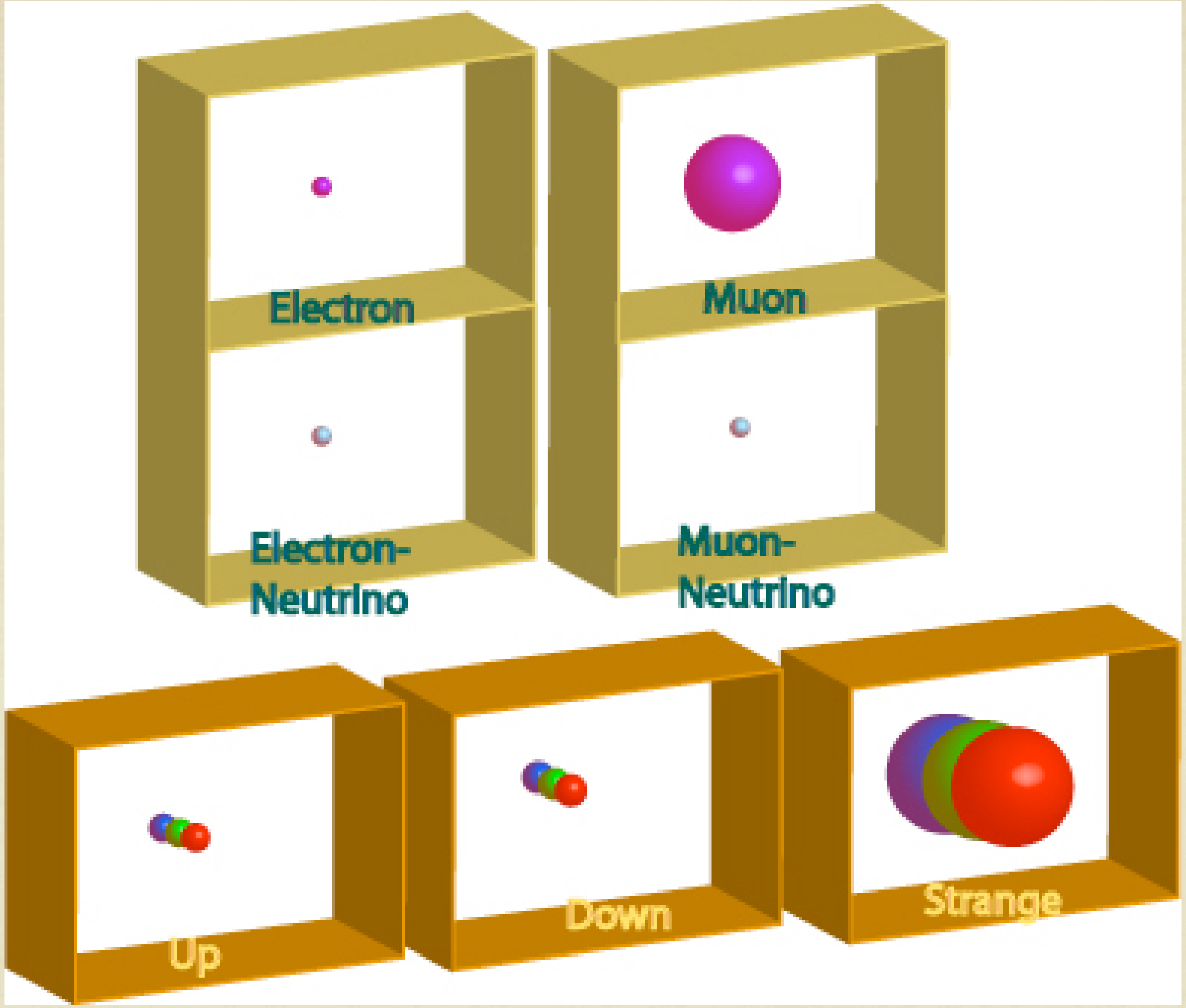
Verified by experiments (LEP/CERN at high energies)

PARTICLE SPECTRUM

1973

LEPTONS

QUARKS



Connection?

KEY: 'electroweak' interaction and the 'flavour' of elementary particles

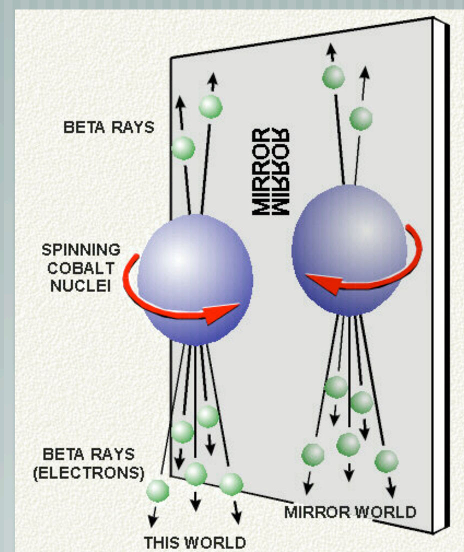
Fields

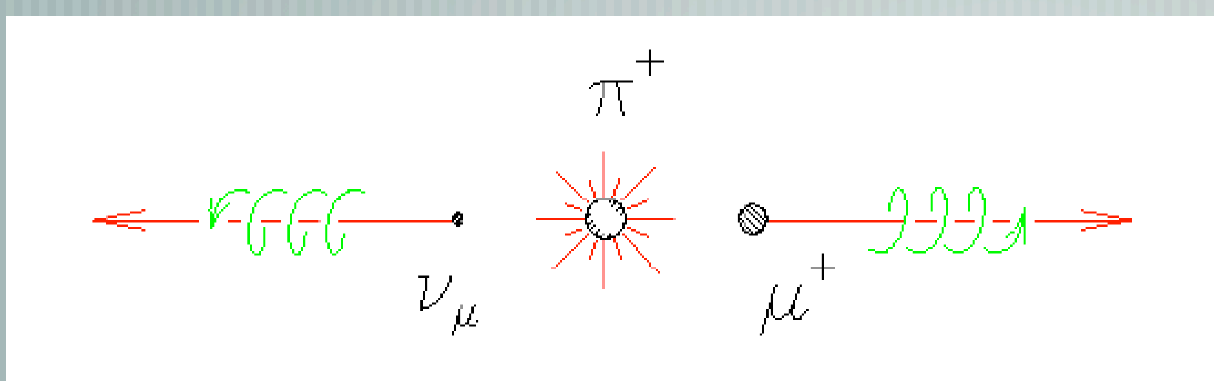
Broken Symmetries -
Neutrinos are born left-handed

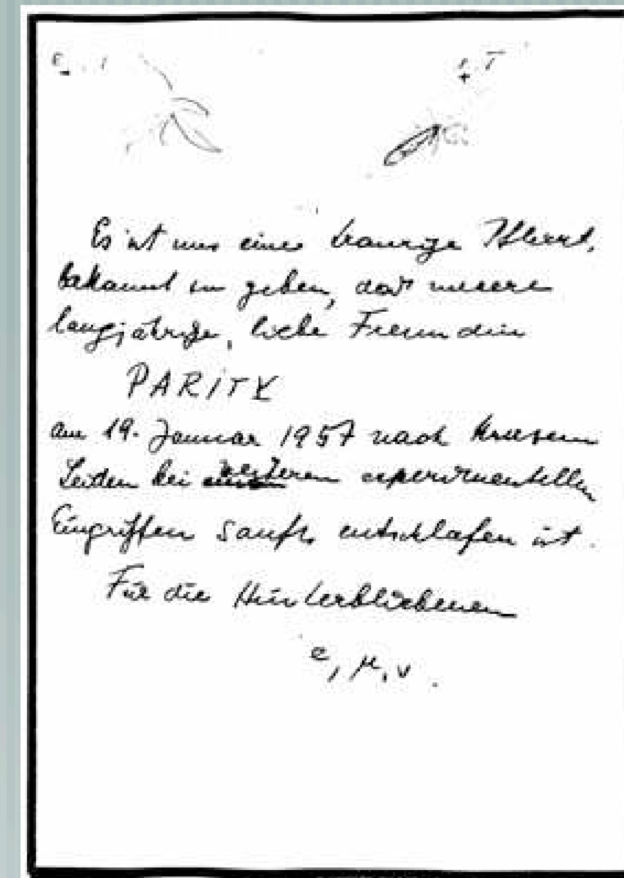
"Parity violation"
(Nature distinguishes left and right)

1956: C.S. Wu
(parity violation in Co-60 decay)

1957: L. Ledermann et al.
(Pion decay - 100% parity violation)





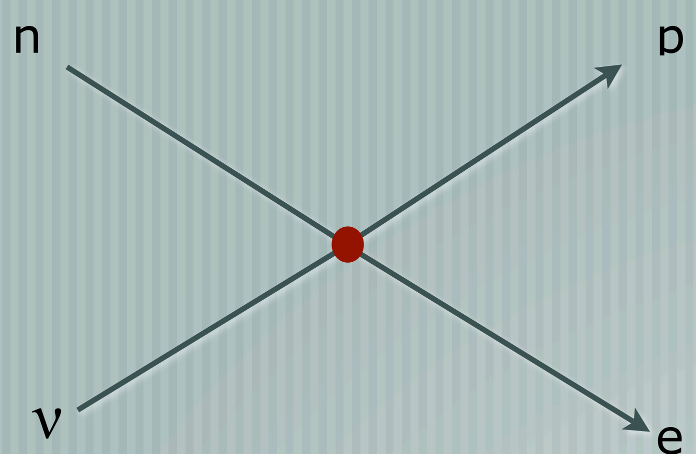

Es ist uns eine traurige Pflicht, bekannt zu geben, daß unsere langjährige, liebe Freundin
PARITY
am 19. Januar 1957 nach kurzem Leiden bei weiteren experimentellen Eingriffen sanft entschlafen ist.
Für die Hinterbliebenen
e, μ, ν.

Wolfgang Pauli's letter
on the Downfall of Parity

Fields

Big problem: Neutrino-Proton cross-section ~ ($G_F E_\nu$) violates conservation of probability for E > 300 GeV

$G_F = (1/294\ \mathrm{GeV})^2$

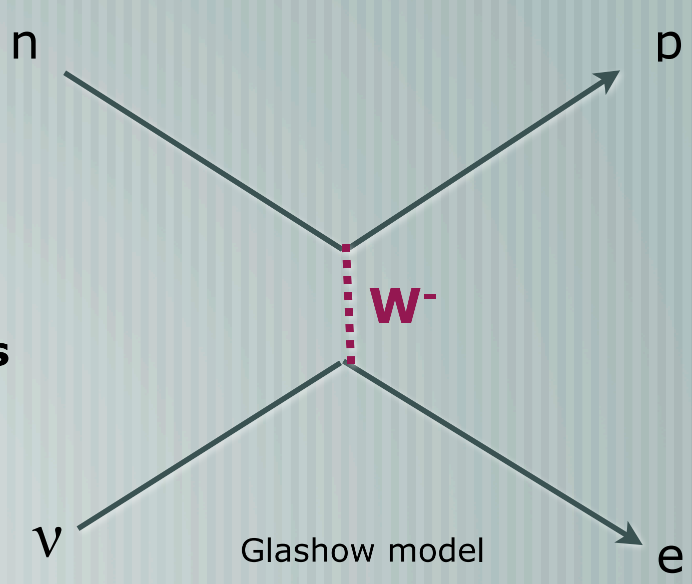


Fermi model

1958 Sheldon Glashow

Weak interaction transmitted by massive vector bosons (in analogy to photon exchange!)

Large mass (>40 GeV) explains short range and small cross-sections

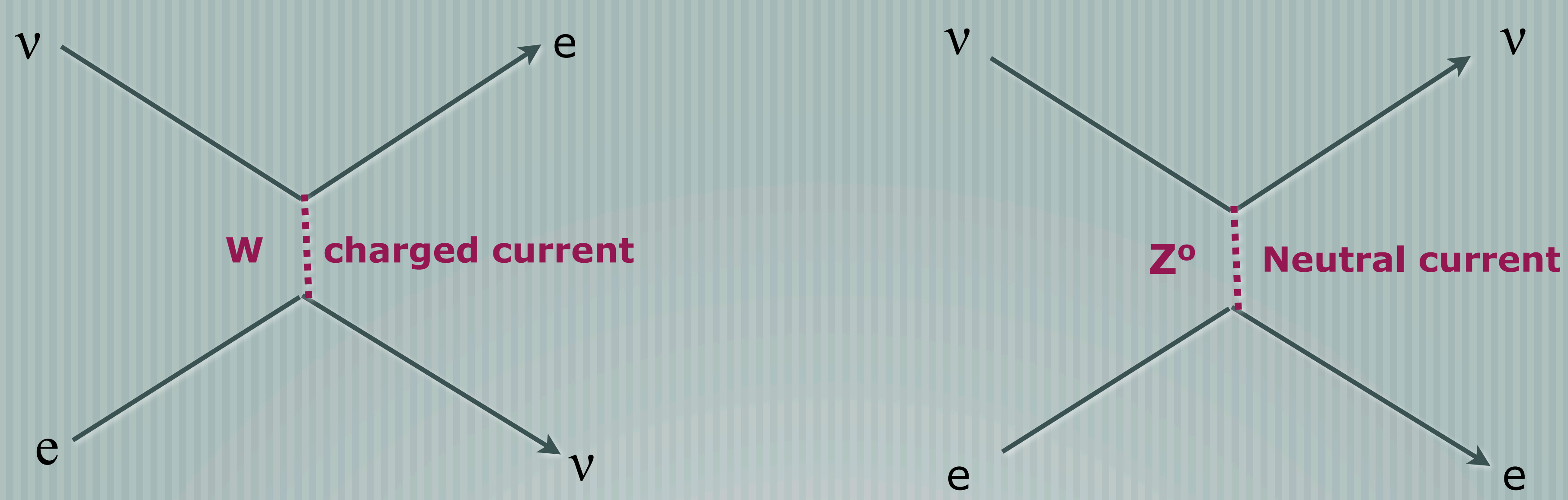


Glashow model

Fields

Electroweak Interaction

1968

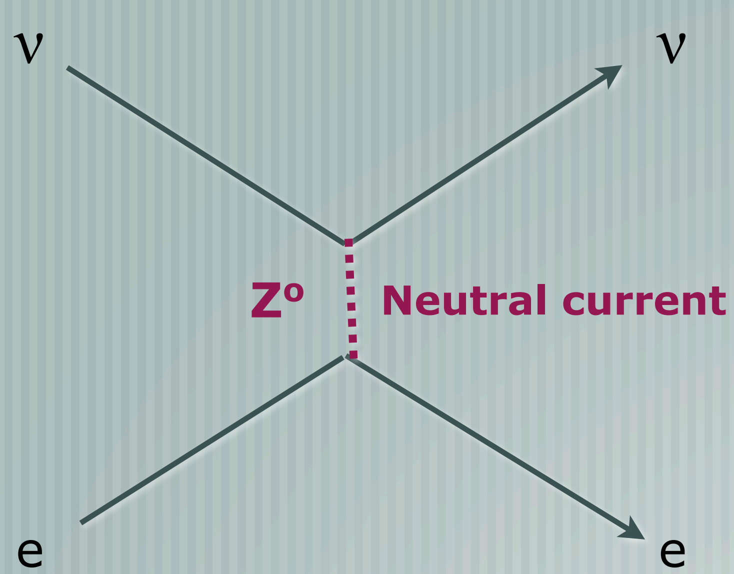


Glashow, Salam, Weinberg (1968) - Electroweak Force

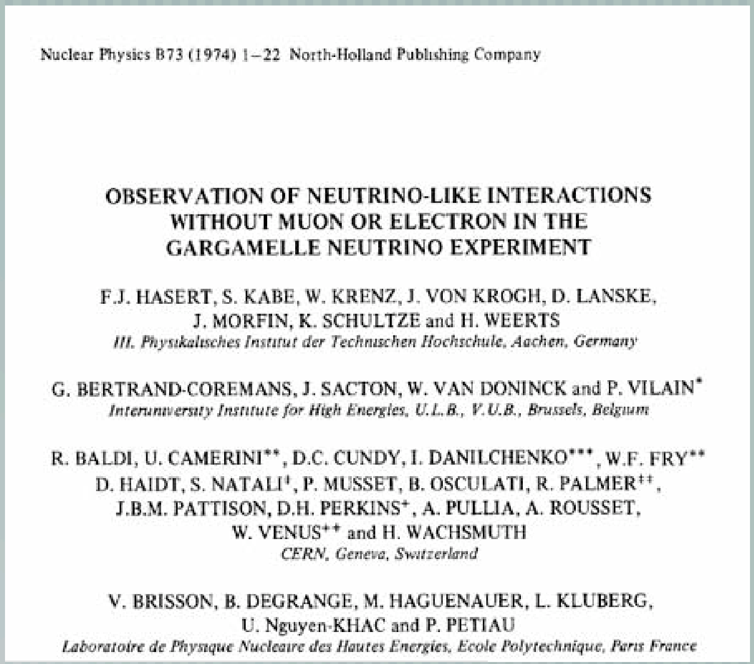
- The electromagnetic and weak interaction are different aspects of the same 'electroweak' force
- All quarks and leptons have a 'weak' charge
- There should be a 'heavy photon' (Z^o) and two charged vector boson ($W^{\pm}$) of mass ~ 50-100 GeV
- They acquire their mass by the interaction with the (new) "Higgs field" H.
- There are only 'left-handed' interactions

Fields

Discovery of neutral currents at CERN (1973)



- Neutrino beam directed on a bubble chamber
  - An electron track emerges out of 'nowhere'



Nuclear Physics B73 (1974) 1–22 North-Holland Publishing Company

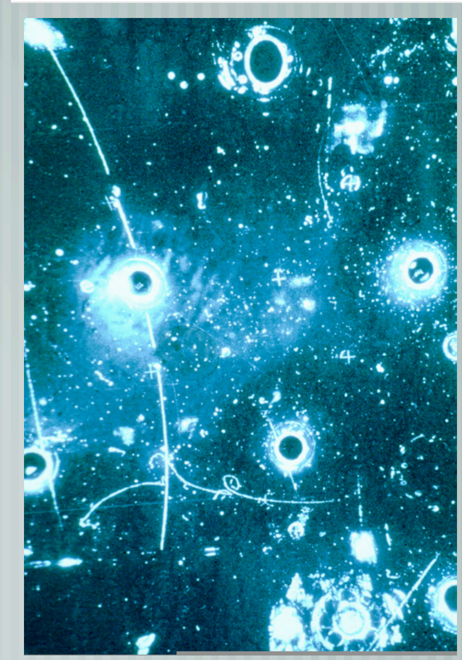
OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

F.J. HASERT, S. KABE, W. KRENZ, J. VON KROGH, D. LANSKE, J. MORFIN, K. SCHULTZE and H. WEERTS
III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

G. BERTRAND-COREMANS, J. SACTON, W. VAN DONINCK and P. VILAIN*
Interuniversity Institute for High Energies, U.L.B., V.U.B., Brussels, Belgium

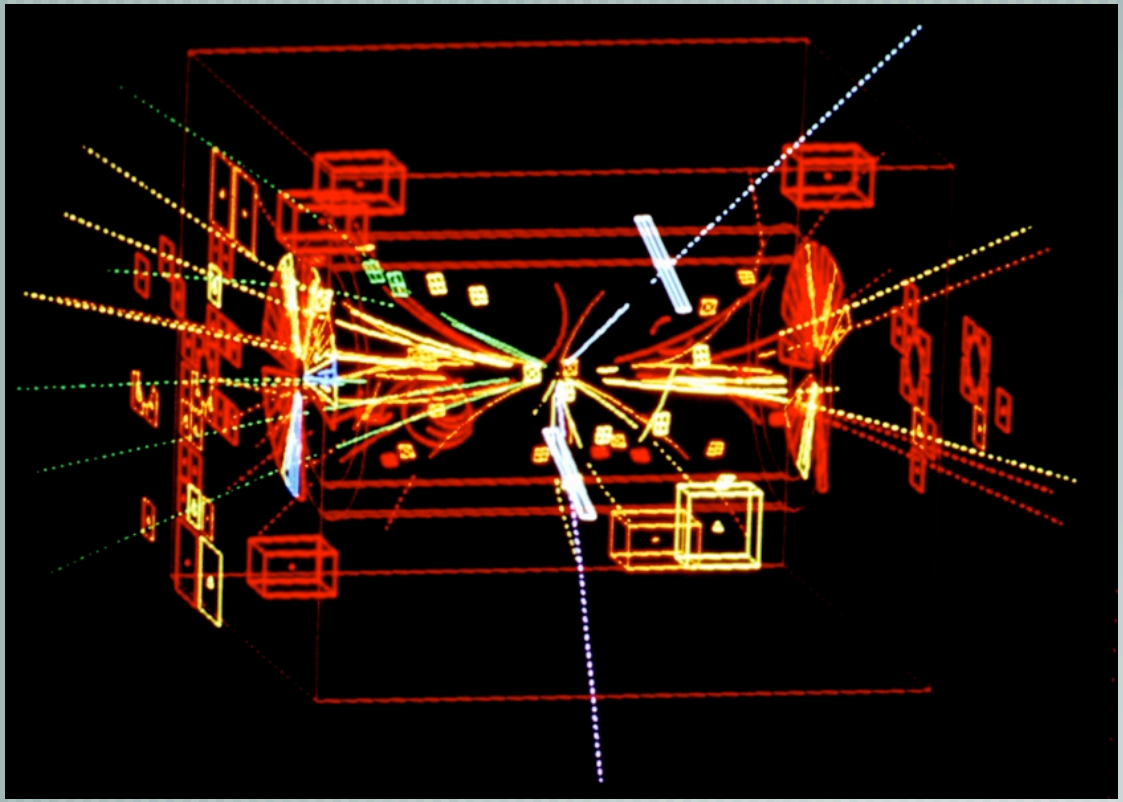
R. BALDI, U. CAMERINI**, D.C. CUNDY, I. DANILCHENKO***, W.F. FRY**
D. HAIDT, S. NATALI†, P. MUSSET, B. OSCULATI, R. PALMER††,
J.B.M. PATTISON, D.H. PERKINS+, A. PULLIA, A. ROUSSET,
W. VENUS++ and H. WACHSMUTH
CERN, Geneva, Switzerland

V. BRISSON, B. DEGRANGE, M. HAGUENAUER, L. KLUBERG,
U. Nguyen-KHAC and P. PETIAU
Laboratoire de Physique Nucleaire des Hautes Energies, Ecole Polytechnique, Paris France



Discovery of the W, Z bosons at CERN (1983)

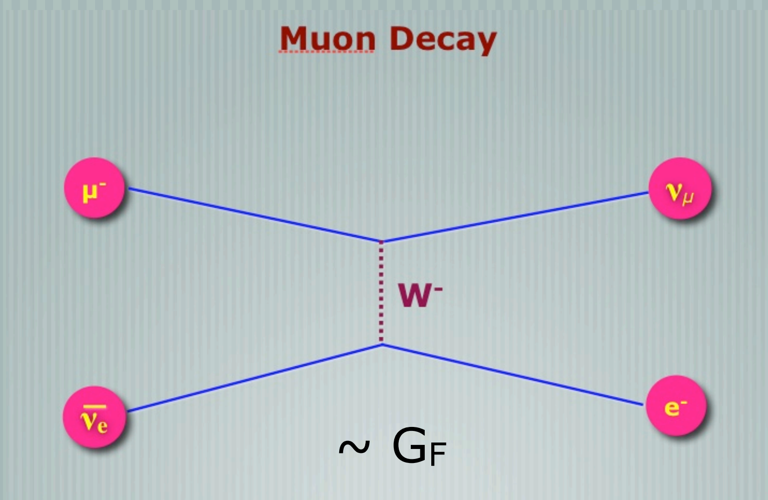
(Carlo Rubbia - leader of UA1 collaboration, and proponent of proton-antiproton collider in SpS)
(Simon van der Meer - inventor of stochastic beam cooling)

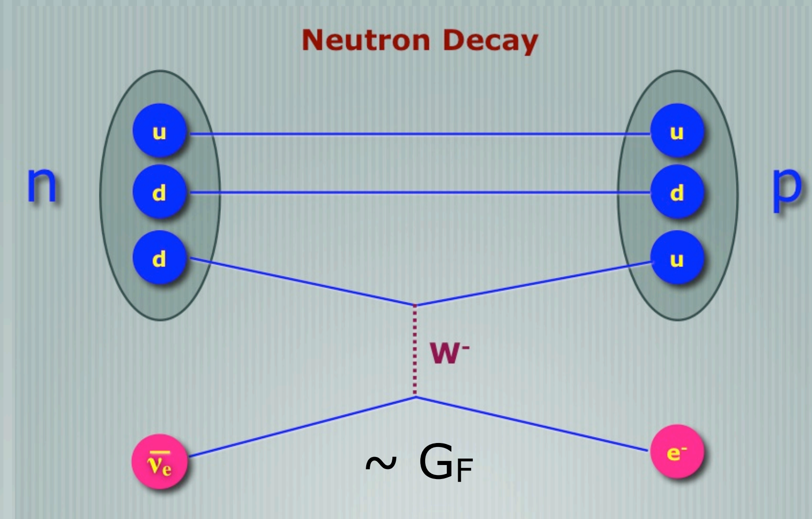


Fields

'Electroweak' interaction

Universality of the weak interaction:
same interaction strength for leptons and quarks





Concept of 'weak' charge ("flavour") of quarks and leptons
Transmitted by exchange of W particles

Universality: the transition ($\mu \rightarrow e$) and ($d \rightarrow u$) have approx. same probability!

'Perfect' universality if one assumes that different quark states 'mix':

$$d' = d \cos\theta_c + s \sin\theta_c$$
$$s' = -d \sin\theta_c + s \cos\theta_c$$

θ_c = Cabbibo angle ~ 20°

Fields

Electroweak Interaction

1970

The prediction of the charm quark helped to understand a rare kaon decay

This was now called the 'Standard Model' (with two families)

Fields

Electroweak Interaction

1970

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

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Milestone paper (Glashow, Iliopoulos, Maiani)

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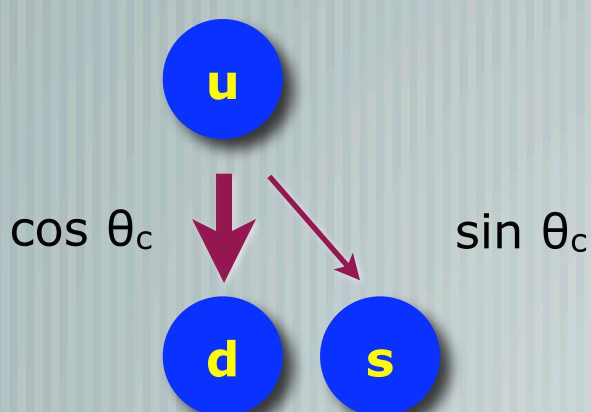

Quarks

The prediction of the charm quark helped to understand a rare kaon decay

This was now called the 'Standard Model' (with two families)

Fields

Electroweak Interaction

1970

Milestone paper (Glashow, Iliopoulos, Maiani)

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
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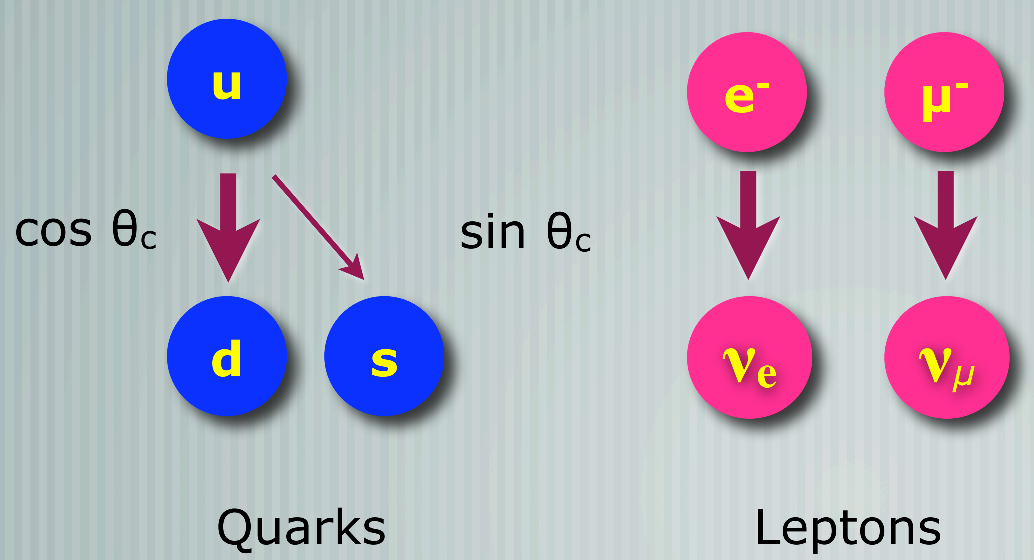

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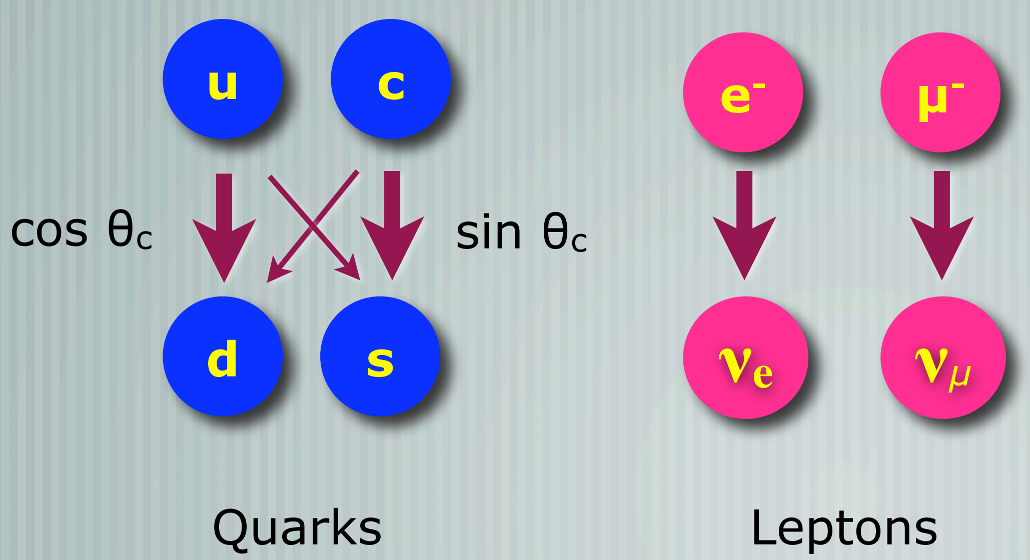

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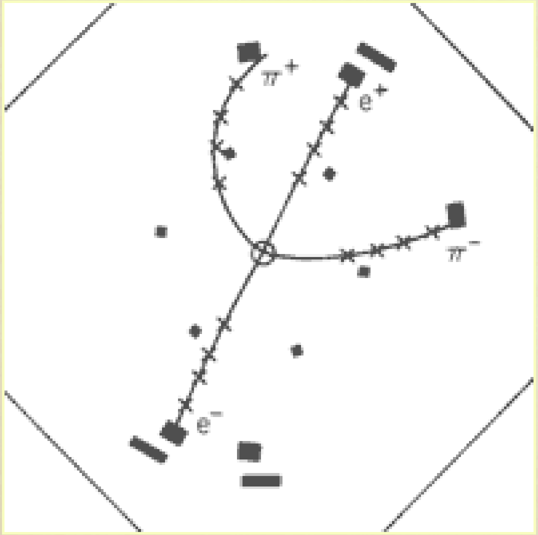
PARTICLE SPECTRUM

1974

And the charm quark was to be discovered soon afterwards :

The NOVEMBER REVOLUTION (11 November 1974)

Two groups discovered ~ simultaneously a new particle, which they called **'Psi'** at SLAC (Burt Richter) and '**J**' at Brookhaven (Sam Ting).



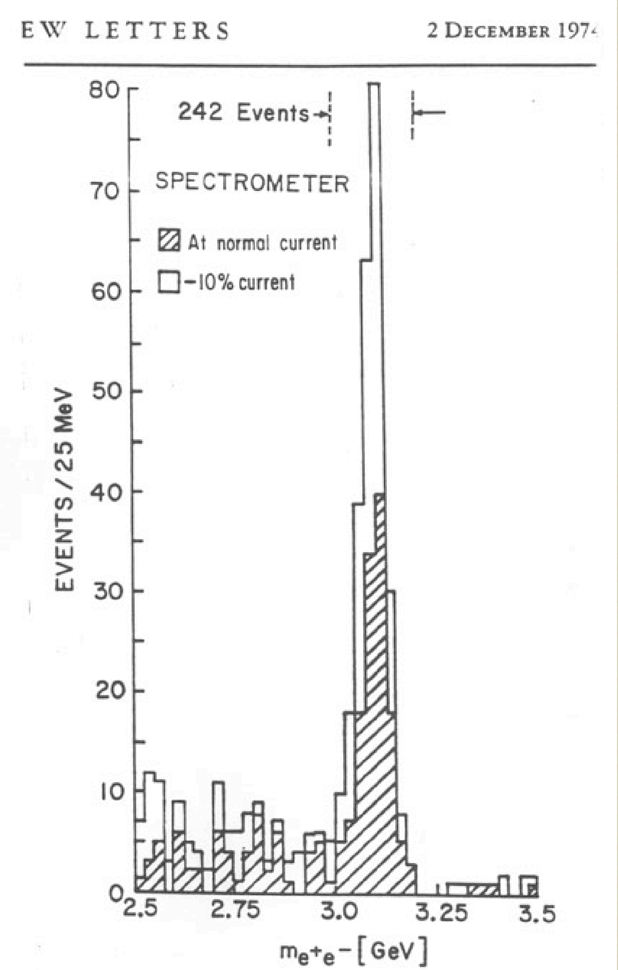


FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted wing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

The J/psi resonance was 'long-lived' (~10^{-20} sec). It could only decay by weak interactions, preferably into an s-quark. This explains the narrow peak.

PARTICLE SPECTRUM

But a third family of particles was going to be discovered

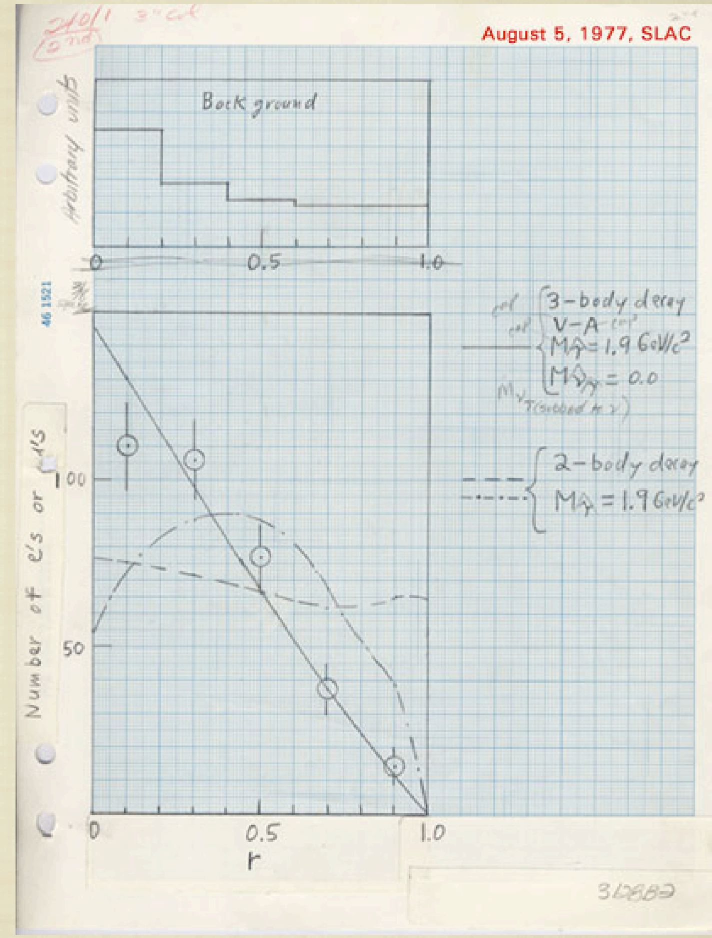
SLAC (Marty Perl)

A new 'heavy electron' with 3500 x m_e

… who ordered that?

THERE MUST BE A WHOLE NEW FAMILY

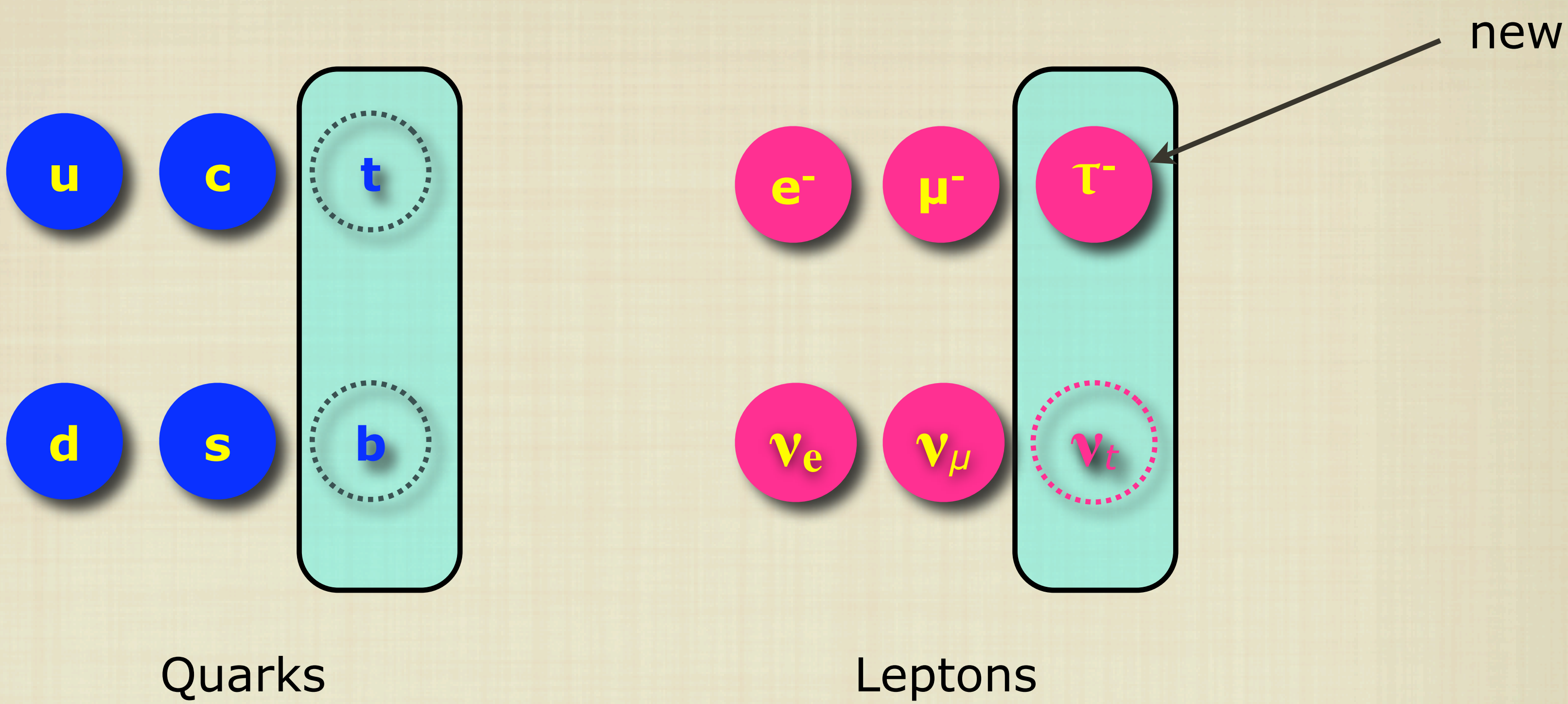
another neutrino (the 'tau neutrino'),
and two more quarks ('top' and 'bottom')



Marty Perl's logbook page

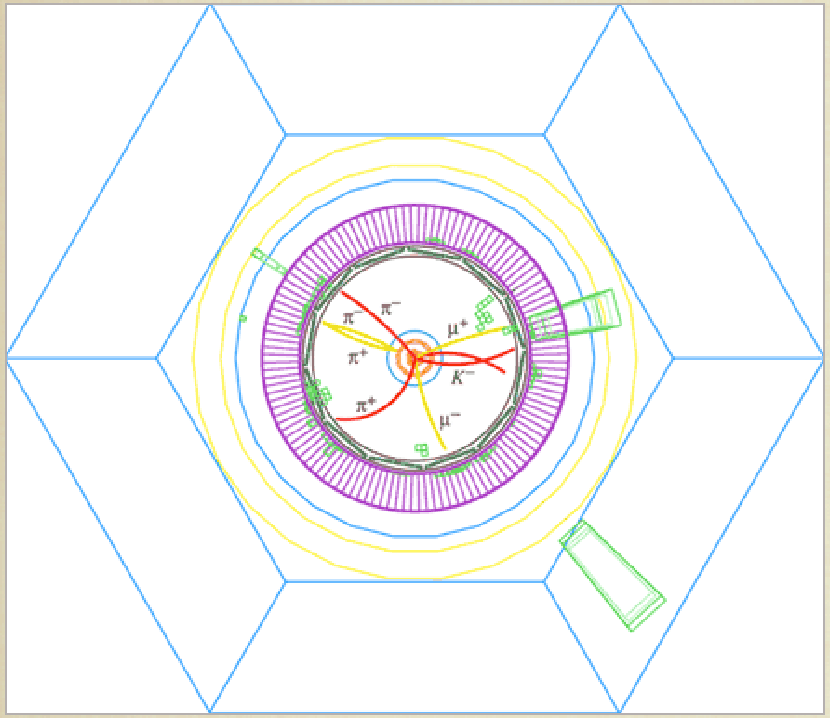
PARTICLE SPECTRUM

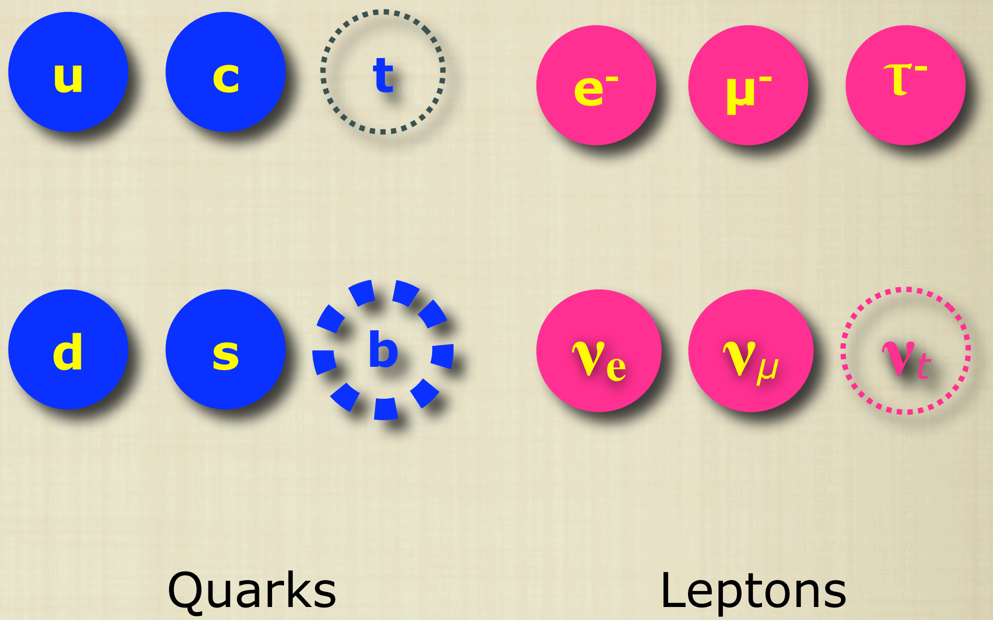
The search for the other family members started



PARTICLE SPECTRUM

Discovery of the **'Bottom' Quark (Fermilab)**





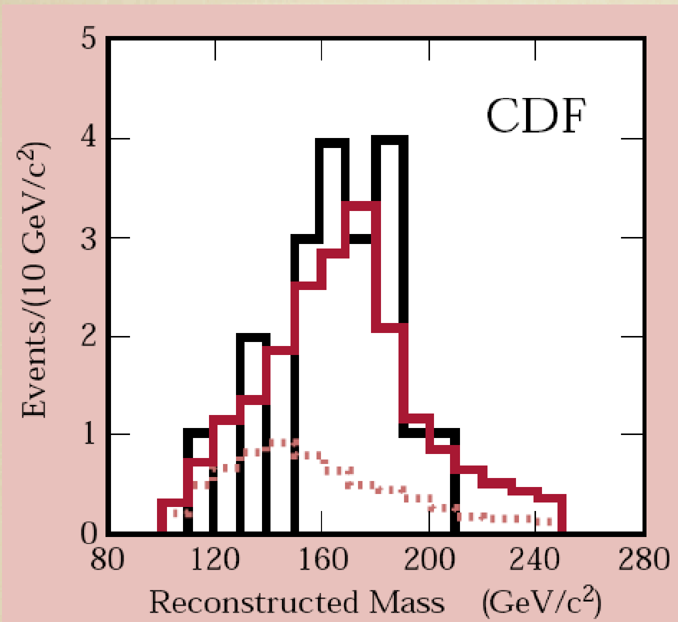
In 1977 physicists discovered a new meson called the Upsilon at the Fermi National Accelerator Laboratory.

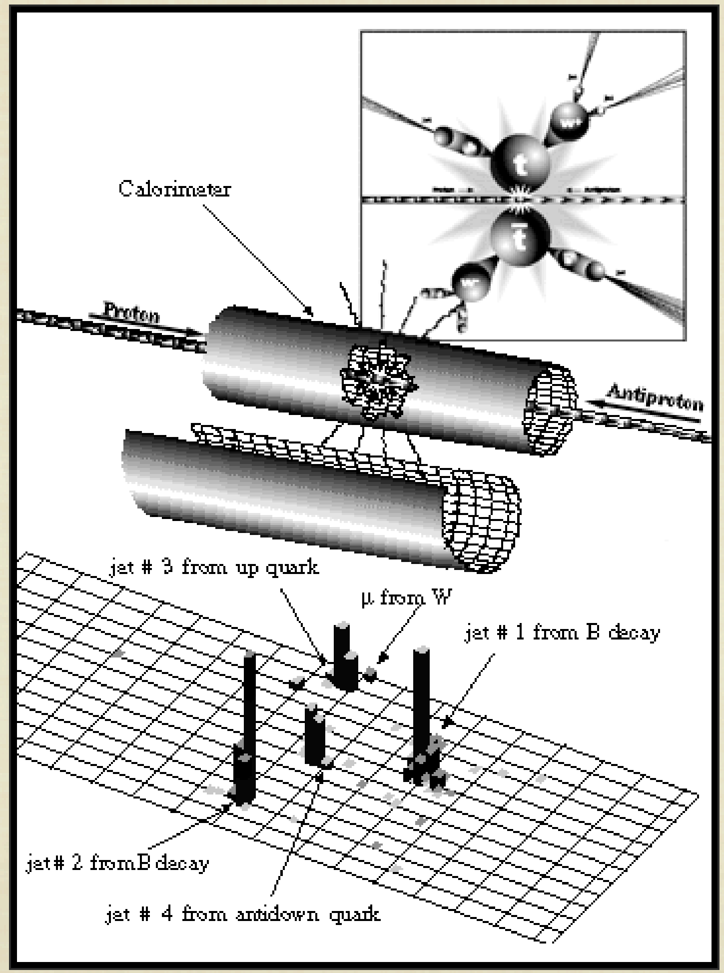
This meson was immediately recognized as being composed of a bottom/anti-bottom quark pair.

The bottom quark had charge -1/3 and a mass of roughly 5 GeV.

PARTICLE SPECTRUM

Discovery of the **'Top' Quark (Fermilab)**



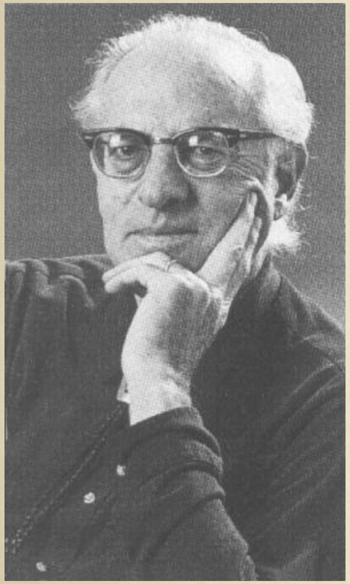


u c t

d s b

Quarks

The story of the neutrinos



Fred Reines

Discovery of the (electron) neutrino

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

Nuclear reactors (n decay) are a strong source of (anti) neutrinos

Coincident signal from n capture and positron annihilation

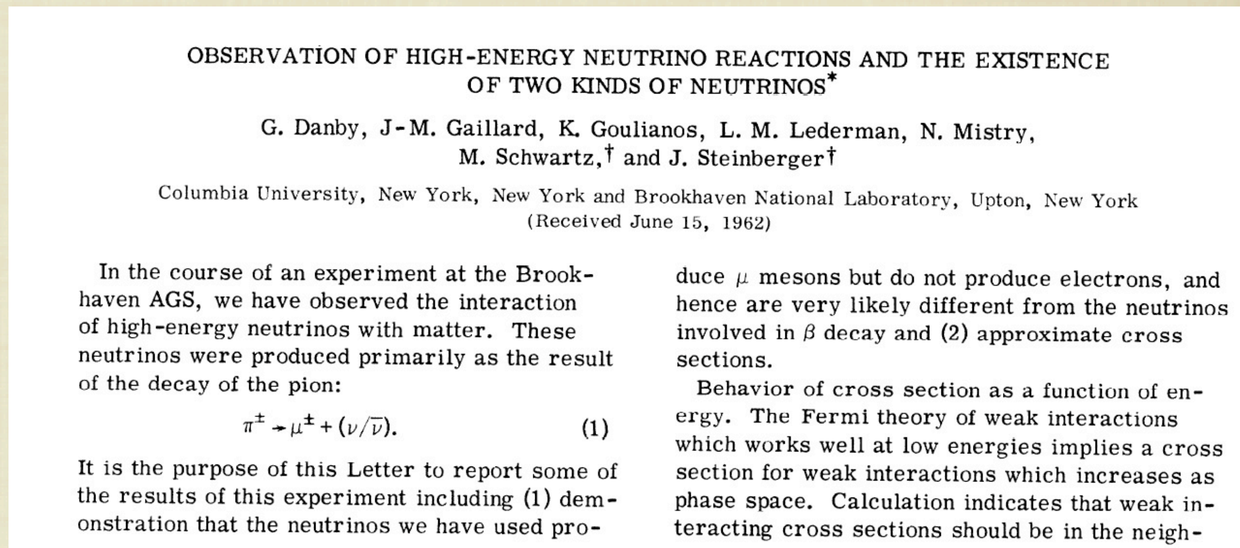
PARTICLE SPECTRUM

"Muon" neutrino

Two different kinds of neutrinos exist: electron- and muon-neutrino

Jack Steinberger, 1962

Jack Steinberger, HST 2002



OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)

In the course of an experiment at the Brookhaven AGS, we have observed the interaction of high-energy neutrinos with matter. These neutrinos were produced primarily as the result of the decay of the pion:

$$\pi^{\pm} \rightarrow \mu^{\pm} + (\nu/\bar{\nu}). \quad (1)$$

It is the purpose of this Letter to report some of the results of this experiment including (1) demonstration that the neutrinos we have used produce μ mesons but do not produce electrons, and hence are very likely different from the neutrinos involved in β decay and (2) approximate cross sections.

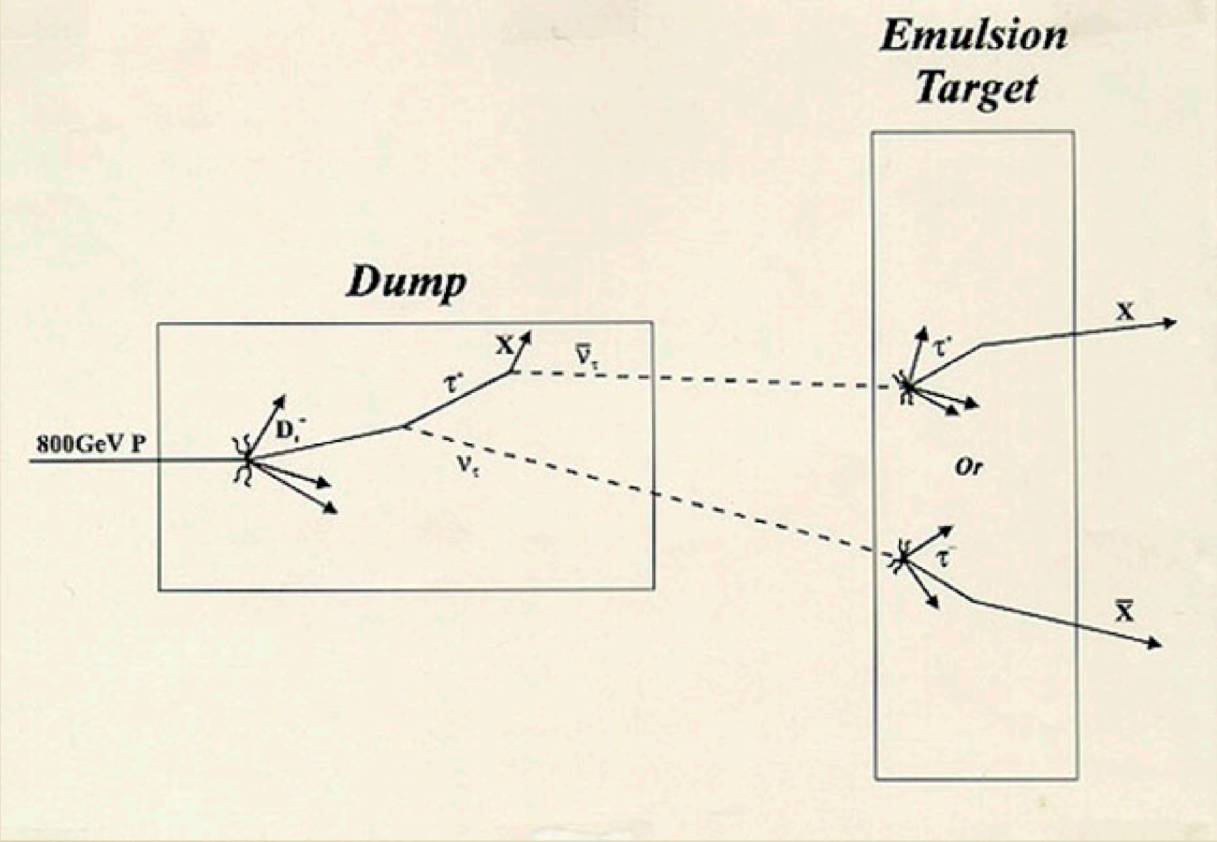
Behavior of cross section as a function of energy. The Fermi theory of weak interactions which works well at low energies implies a cross section for weak interactions which increases as phase space. Calculation indicates that weak interacting cross sections should be in the neigh-

Do neutrinos have a mass? Can they transform into each other ('oscillations') ?

PARTICLE SPECTRUM

Discovery of the tau neutrino

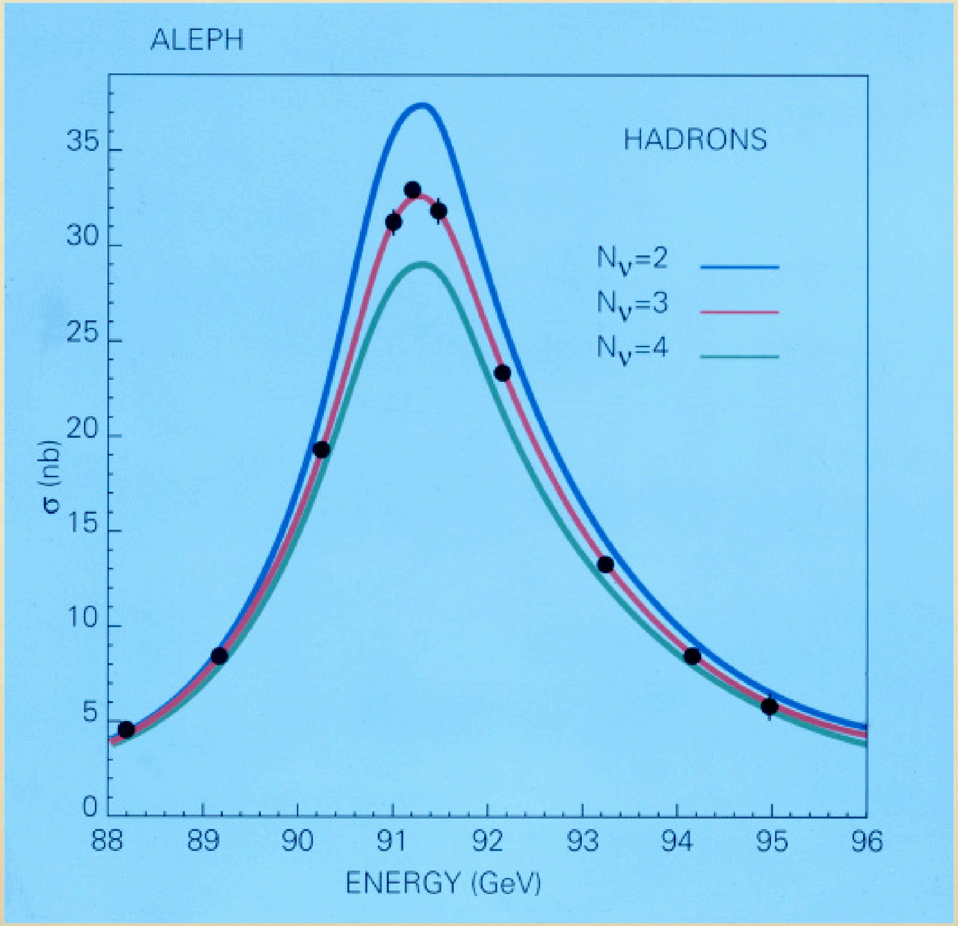
DONUT collaboration (Fermilab)



PARTICLE SPECTRUM

3 generations of neutrinos

LEP measures the decay width of the Z^o particle

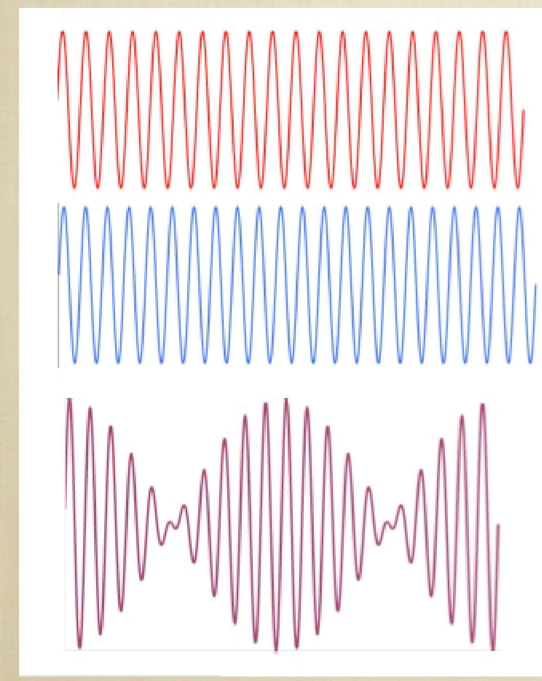


PARTICLE SPECTRUM

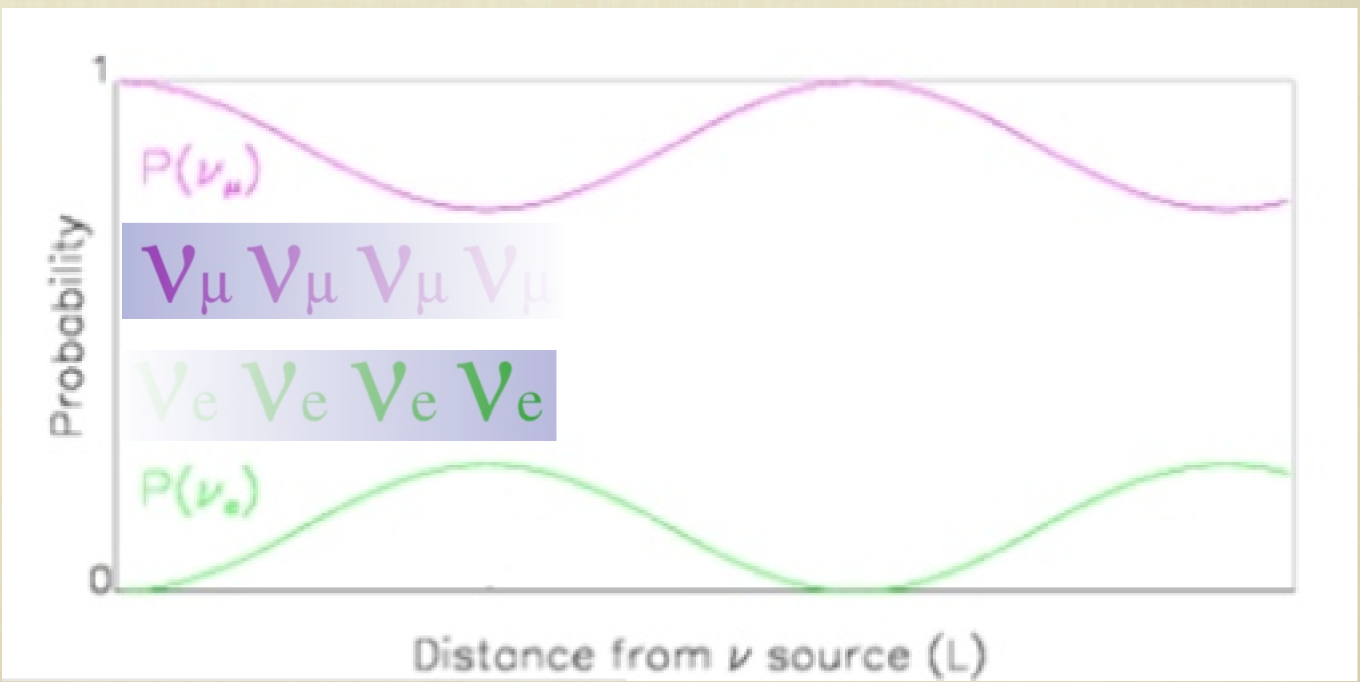
Do neutrinos have a rest mass ?

Neutrino oscillations

... like musical beats



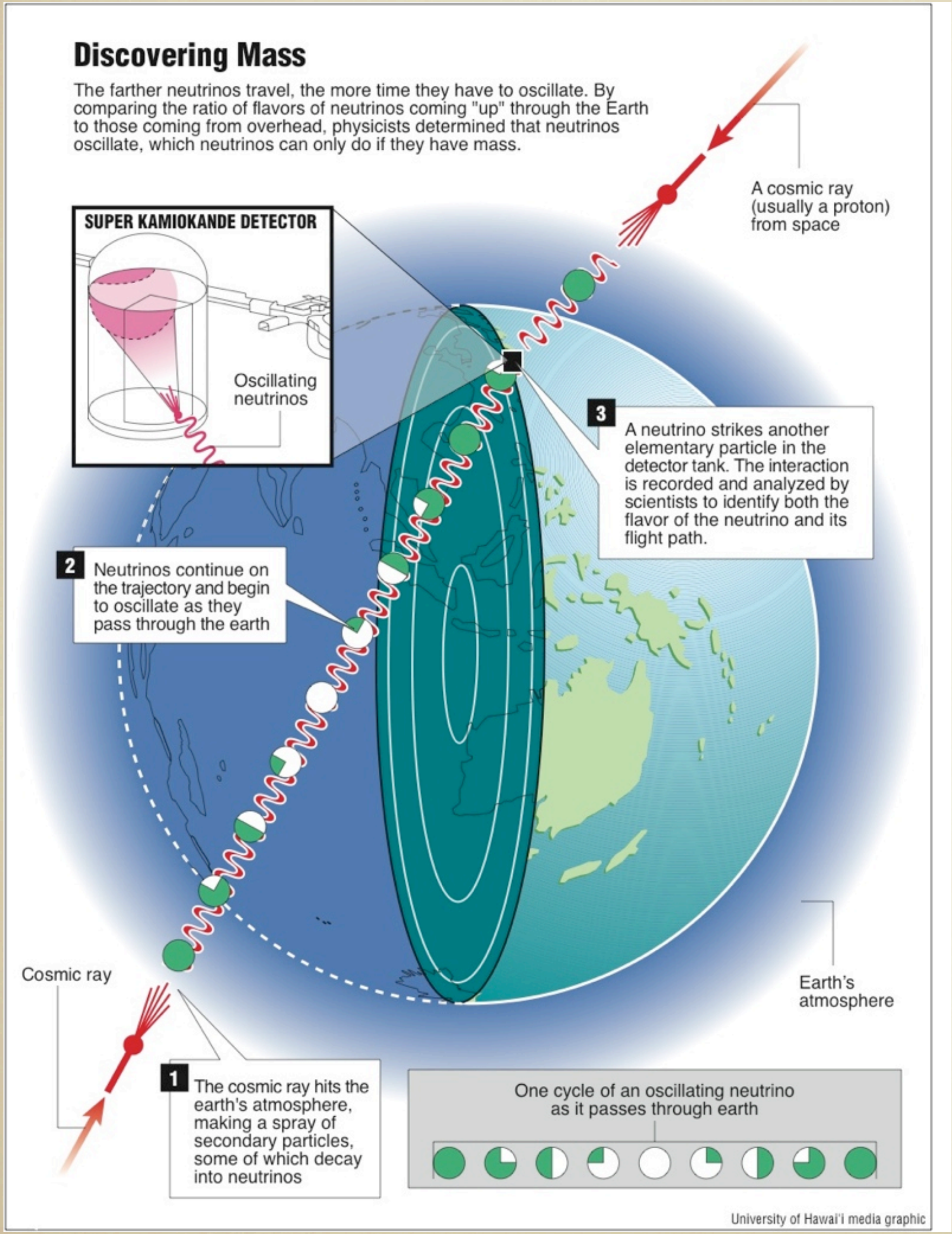
If masses are not too different, frequencies are quite similar



PARTICLE SPECTRUM

1998

Neutrino oscillations discovery



Muon neutrinos are produced by cosmic rays in the upper atmosphere

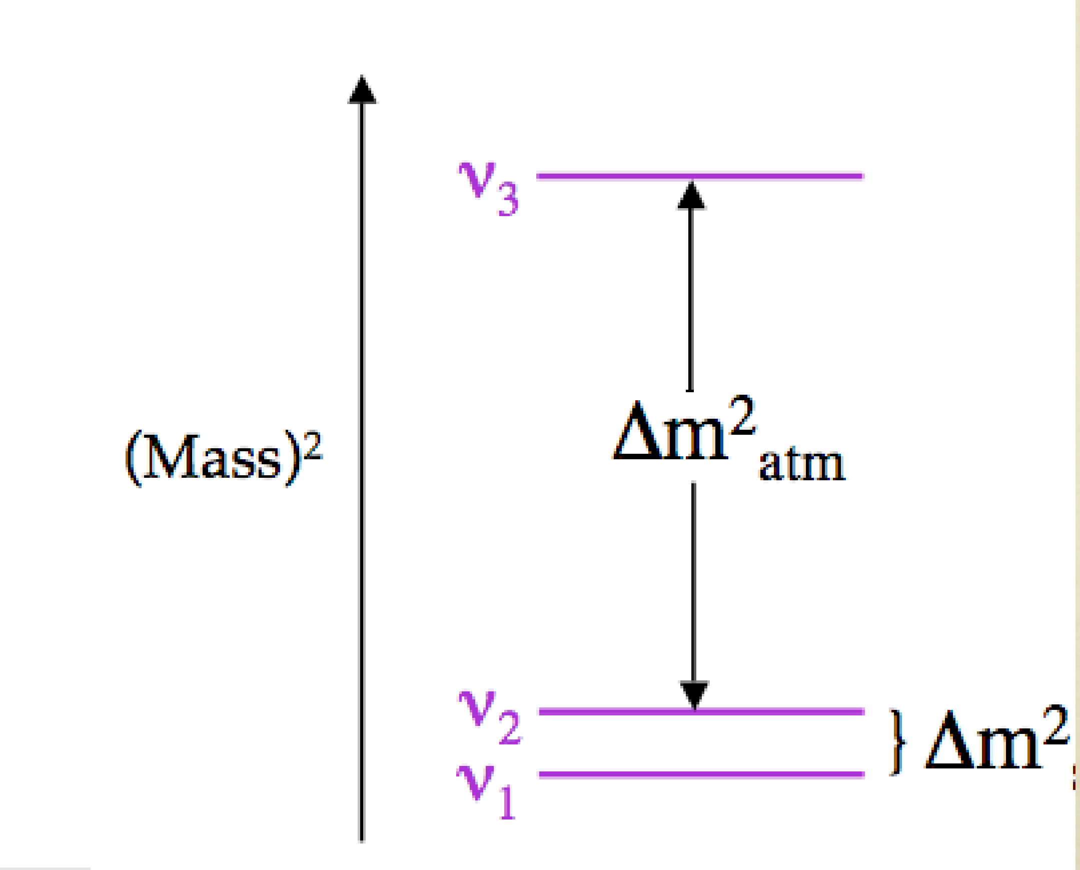
Deficit of muon neutrinos:

from 'below' - only about 1/2 expected
(and seen from 'above')

PARTICLE SPECTRUM

Neutrinos have mass !

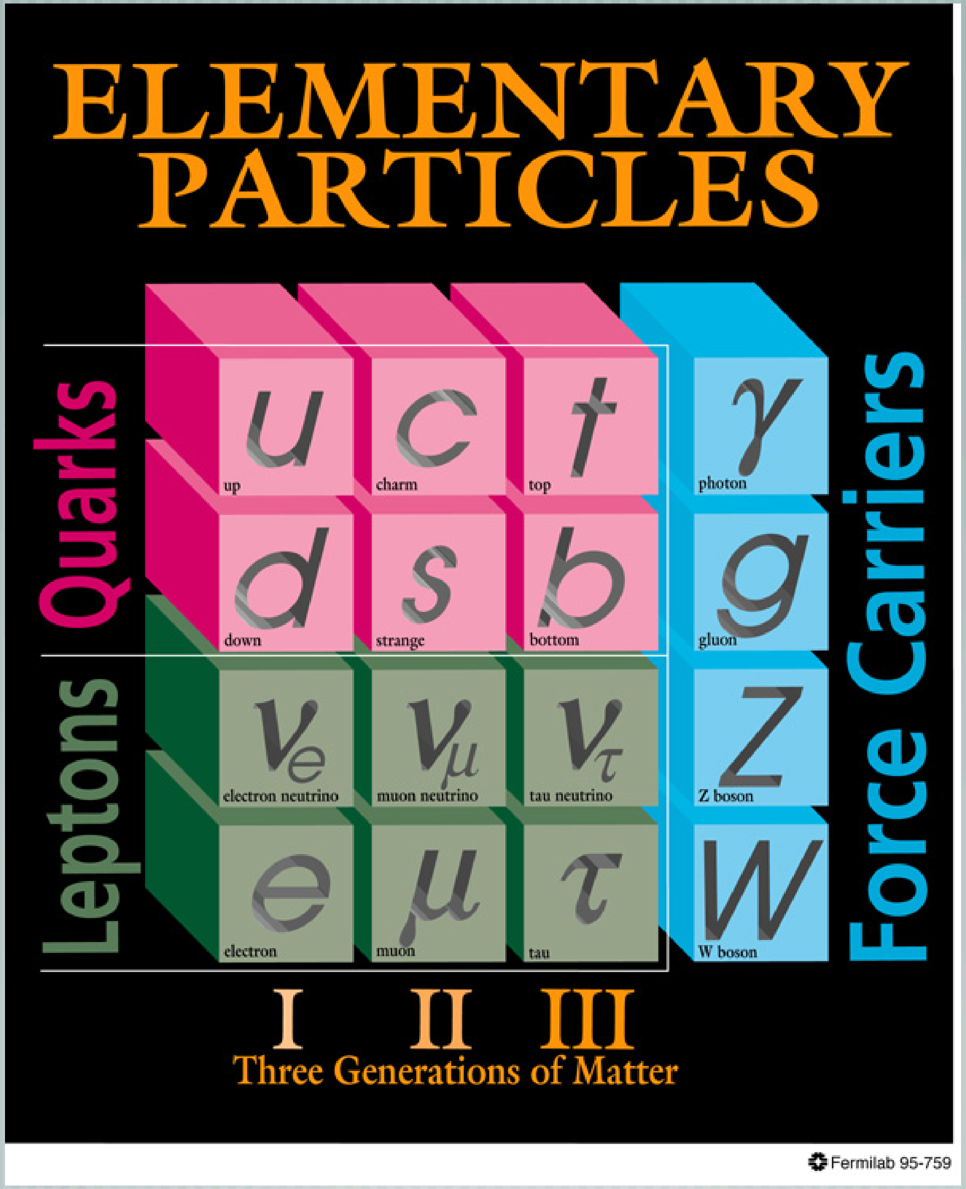
Today, only mass differences are known, but most models assume that the absolute masses are between ~ 0.01 - 0.1 eV



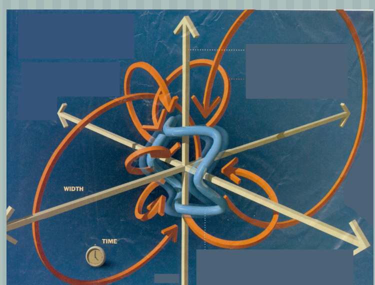
$\sim 2.5 \cdot 10^{-3}$ eV^2

$\sim 8 \cdot 10^{-5}$ eV^2

THE STANDARD MODEL

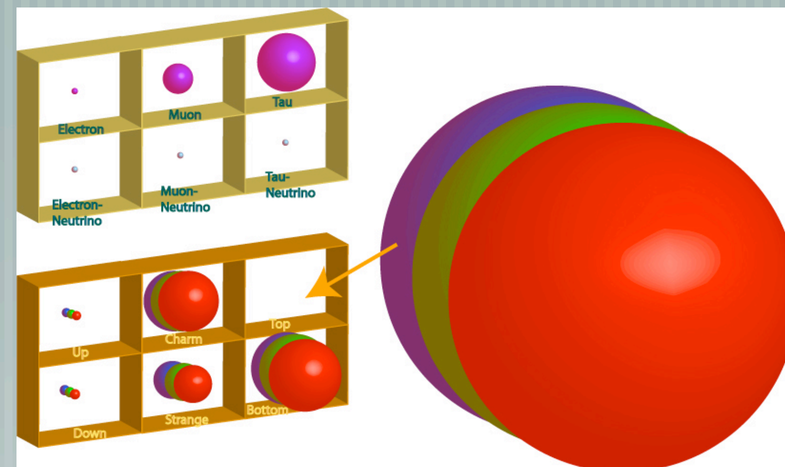


BEYOND THE STANDARD MODEL



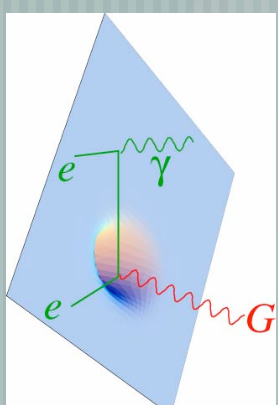
What are particles?

Superstrings in 10 dimensions?



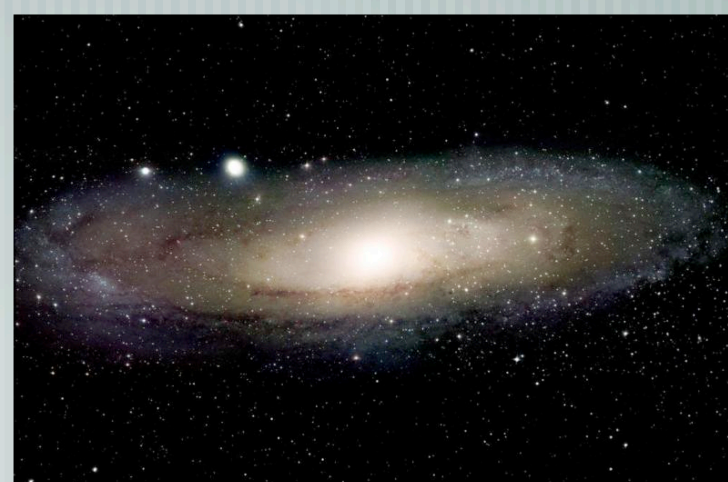
Why are the masses of leptons and quarks so different ?

Higgs field(s) ?



Quantum Gravity

Does gravity act in more than 3 spatial dimensions?
Newton's law?
Is there a connection between gravity and the other forces?

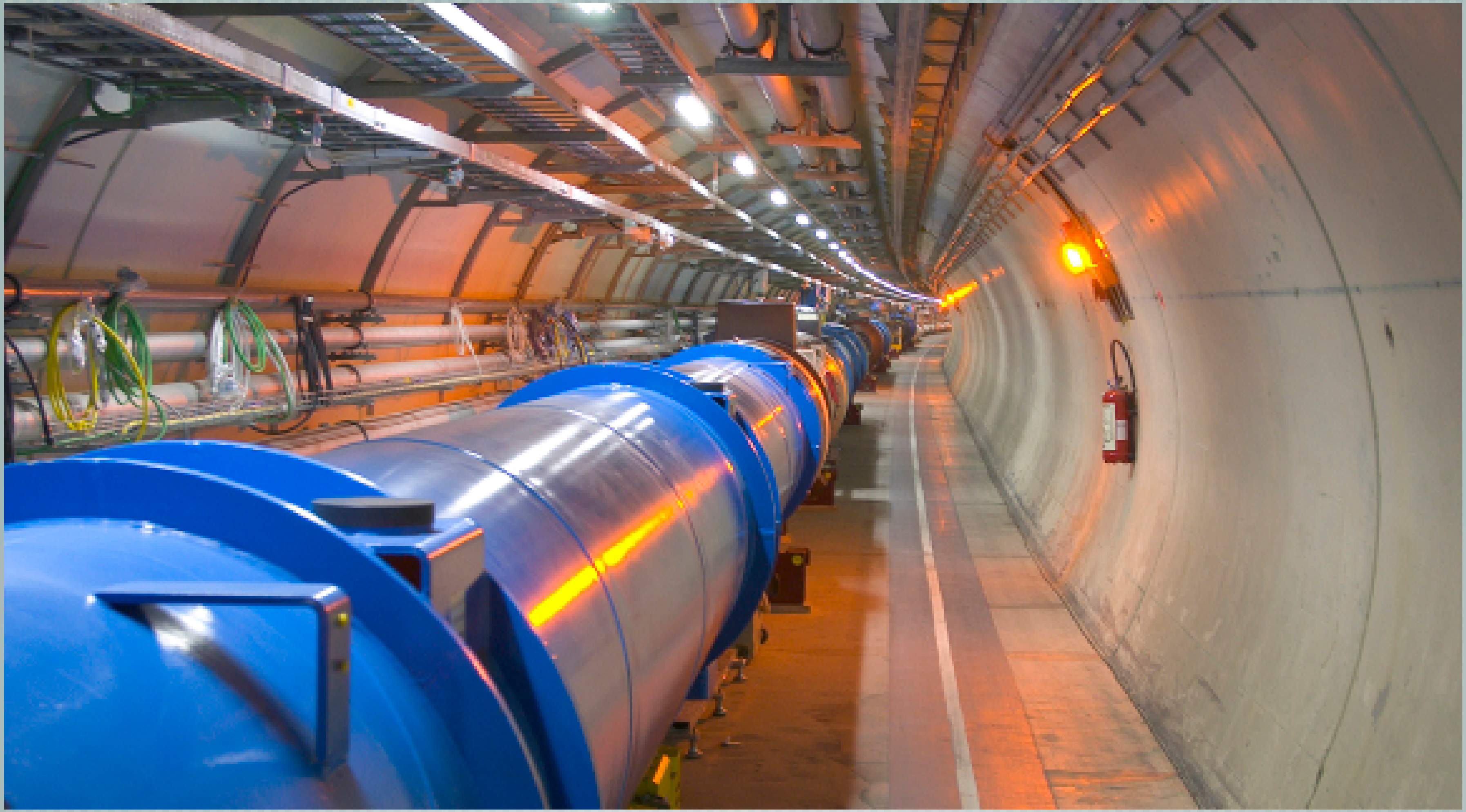


Dark Matter ?

Supersymmetry ?

BEYOND THE STANDARD MODEL

LHC STARTUP IN 2008



new answers !