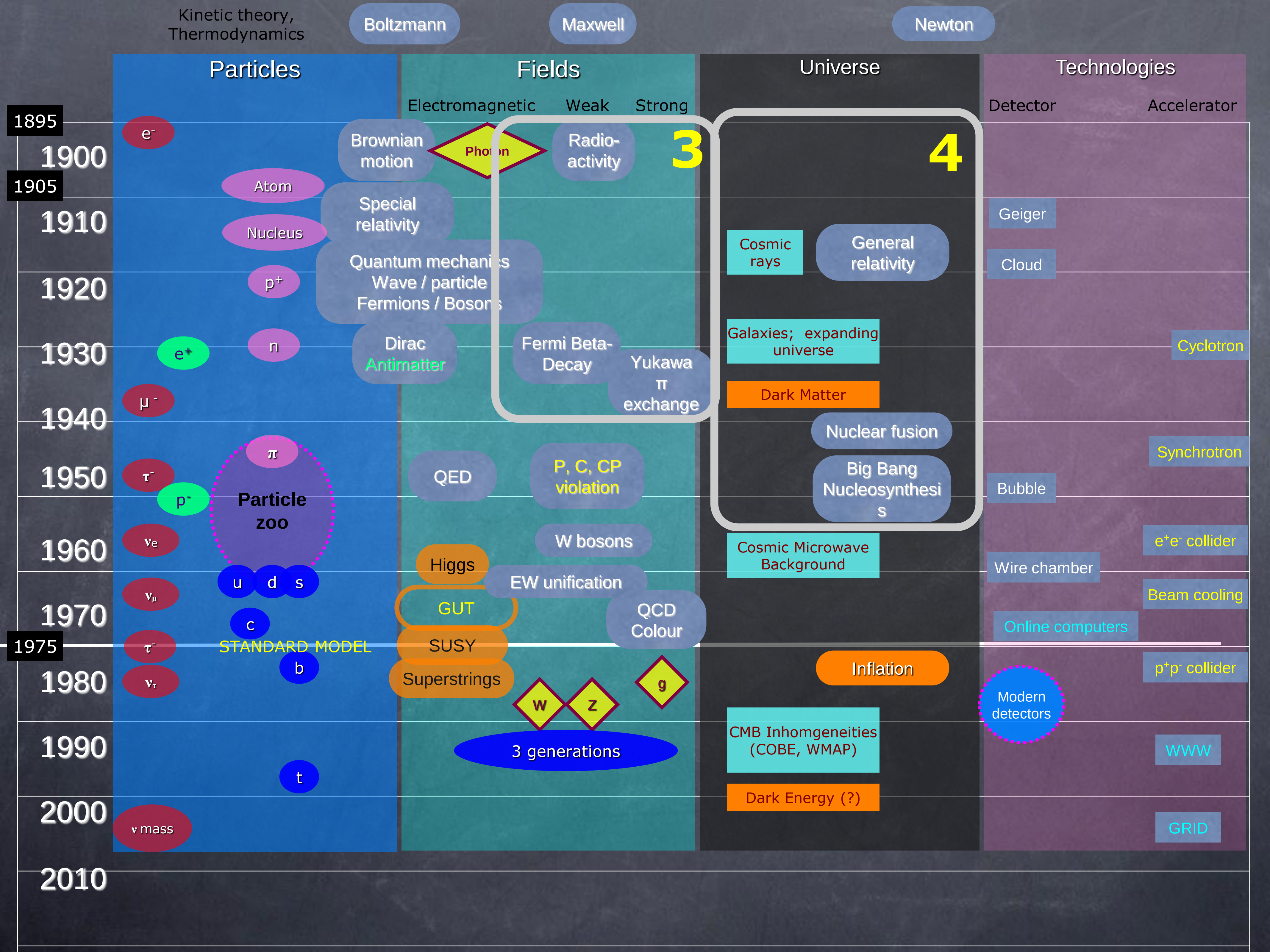
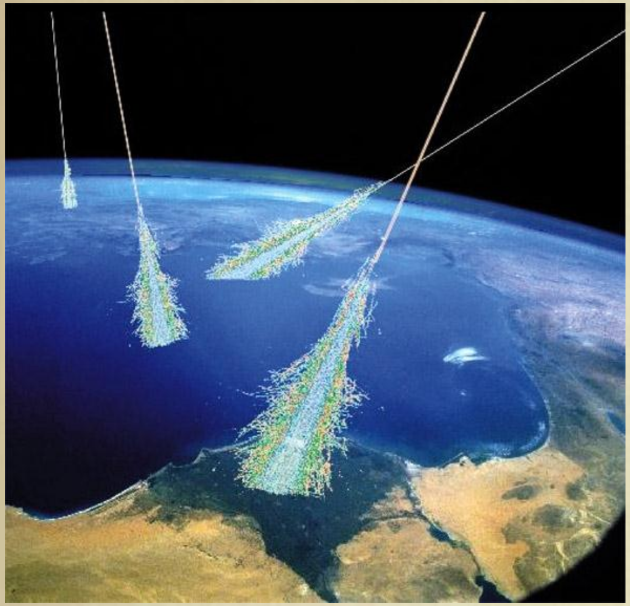
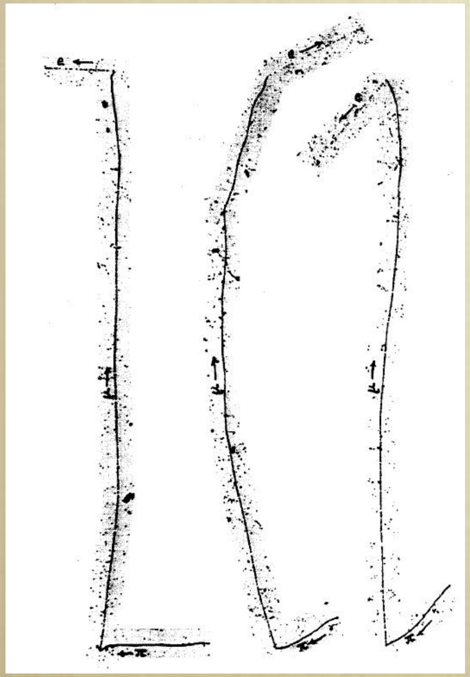


Kinetic theory, Thermodynamics
Boltzmann
Maxwell
Newton
Particles
Fields
Universe
Technologies
Electromagnetic
Weak
Strong
Detector
Accelerator
1895
1900
1905
1910
1920
1930
1940
1950
1960
1970
1975
1980
1990
2000
2010
e^-
Atom
Nucleus
p^+
n
e^+
μ^-
π
τ^-
p^-
Particle zoo
ν_e
u
d
s
ν_μ
c
τ^-
STANDARD MODEL
b
ν_τ
t
ν mass
Brownian motion
Photon
Radio-activity
3
Special relativity
Quantum mechanics
Wave / particle
Fermions / Bosons
Dirac
Antimatter
Fermi Beta-Decay
Yukawa
π
exchange
QED
P, C, CP violation
W bosons
Higgs
EW unification
GUT
QCD
Colour
SUSY
Superstrings
W
Z
g
3 generations
4
Cosmic rays
General relativity
Galaxies; expanding universe
Dark Matter
Nuclear fusion
Big Bang Nucleosynthesis
Cosmic Microwave Background
Inflation
CMB Inhomogeneities (COBE, WMAP)
Dark Energy (?)
Geiger
Cloud
Cyclotron
Synchrotron
Bubble
e^+e^- collider
Wire chamber
Beam cooling
Online computers
p^+p^- collider
Modern detectors
WWW
GRID

PARTICLE SPECTRUM





1913: Cosmic Rays were discovered

Physicists went on mountain tops for experiments!

1937: New particle discovered: negative charge, ~ 200 m_e

Very longe range in matter !? Not Yukawa's "pion" !

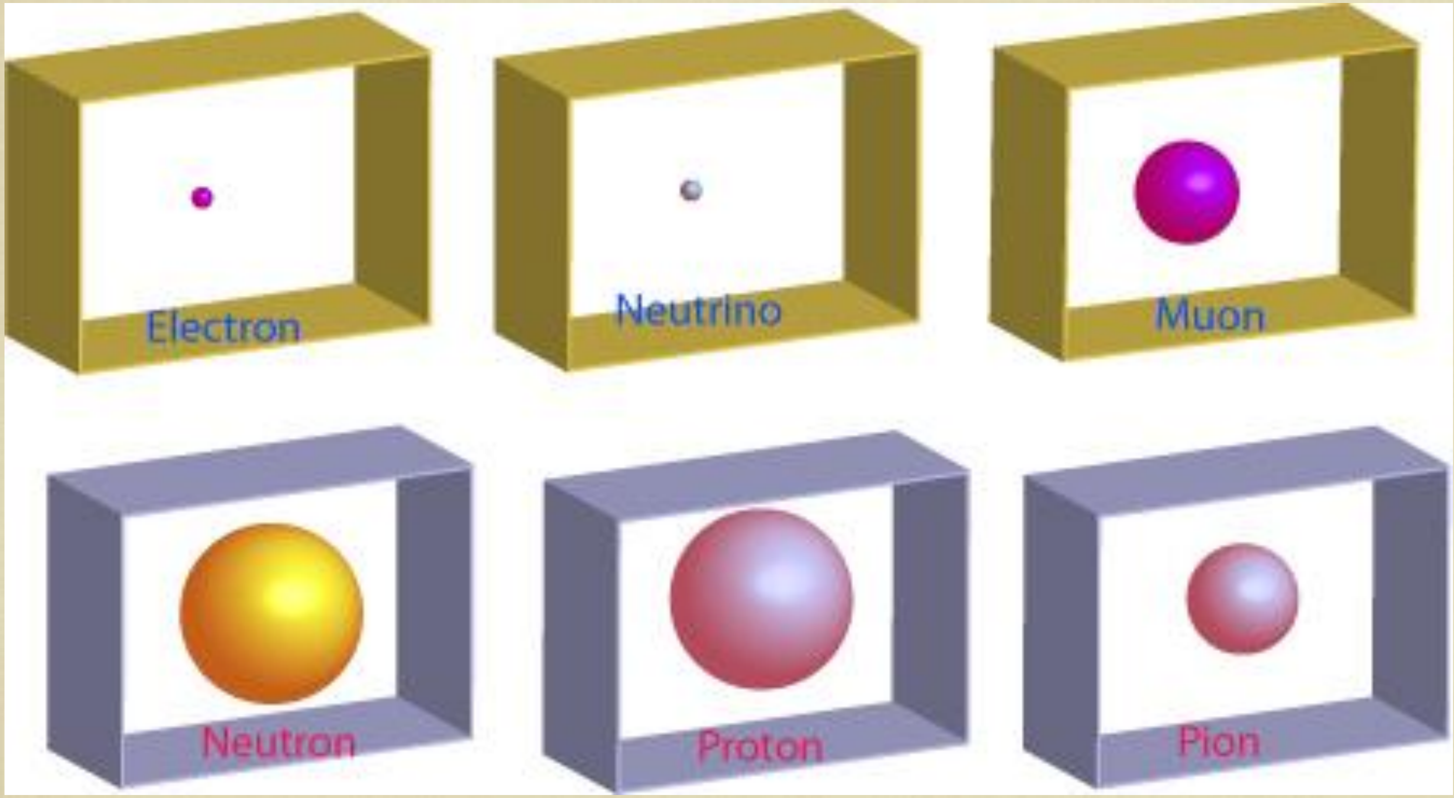
Muon = 'heavy electron'

I. Rabi: "Who ordered that ?"

1948: The "pion" was finally discovered (emulsions)

PARTICLE SPECTRUM

In 1948, the particle spectrum started to look ugly:



PARTICLE SPECTRUM

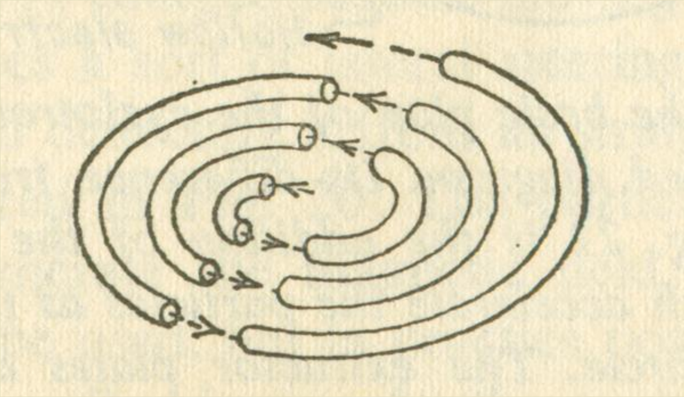
1931 - 1955

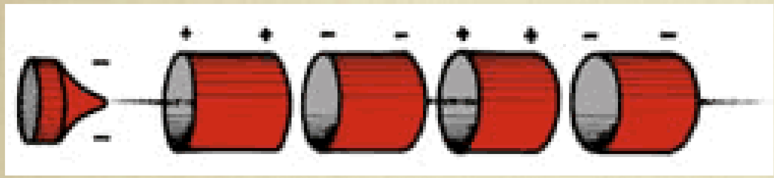
Accelerators

"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

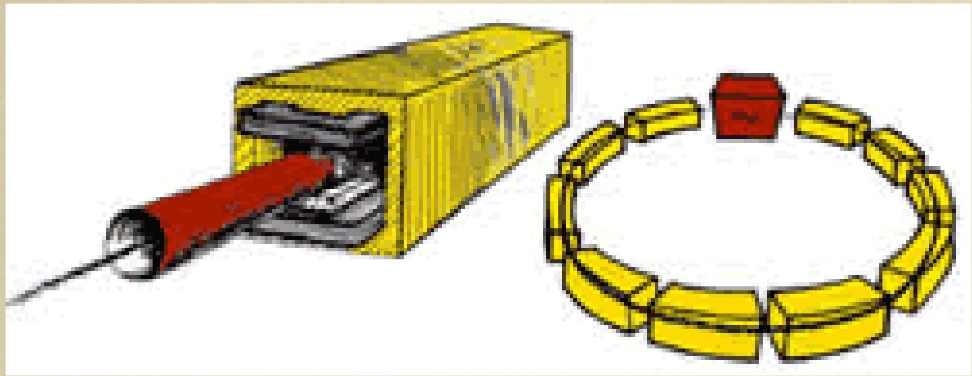
1931: 80 keV
1932: 1000 keV
1939: 19 MeV*
1946: 195 MeV ("synchrocyclotron")

* 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

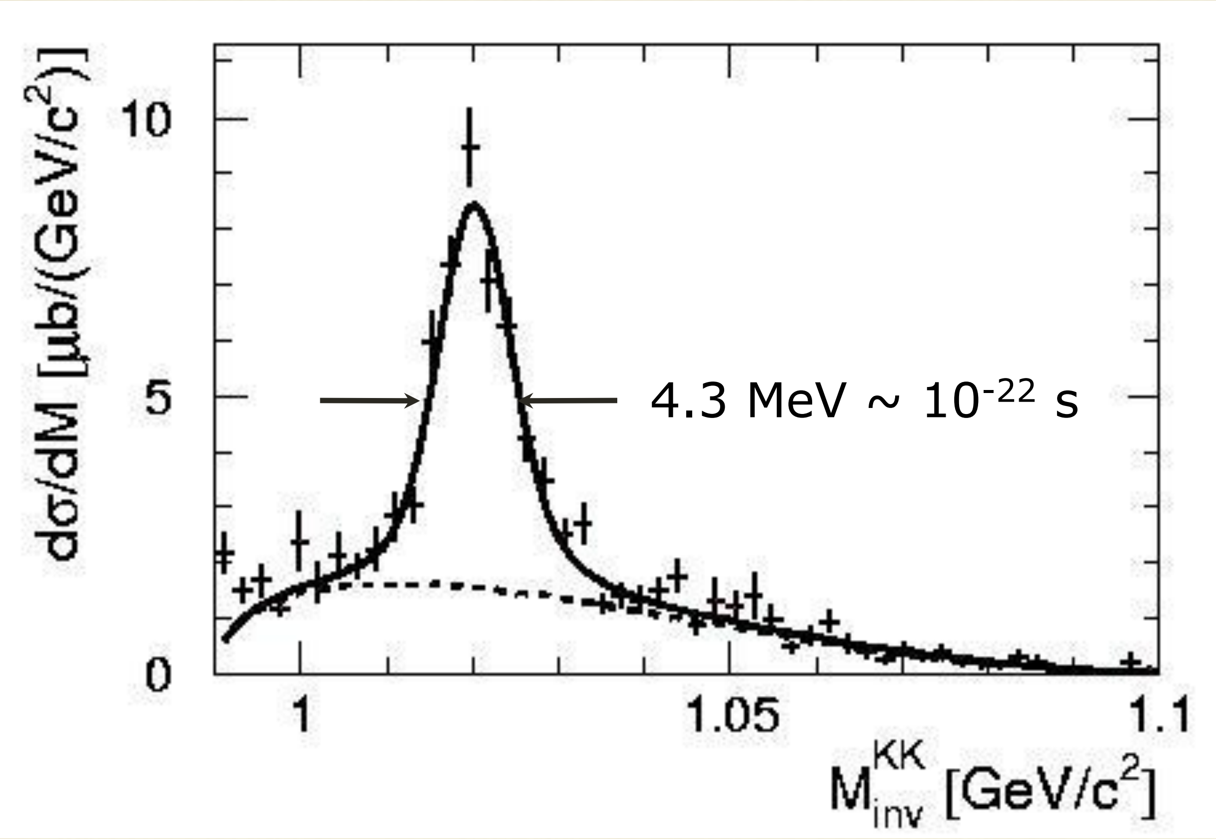
Cerenkov counters
Photomultipliers
Spark chambers

After 1967:

Wire chambers
Drift chambers
Calorimeters

QCD

‘Resonances’ in particle collisions



Resonance = ‘Peak’ in invariant mass spectrum of two or more particles

Lifetime ~ 1 / Width of resonance [~ 10^{-21} .. 10^{-23} s]

PARTICLE SPECTRUM

1950- 1968

Particl e zoo

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

π^{+} π^{-} π^{0}

Pions

K^{+} K^{-} K^{0}

η'

Kaons

Eta-Prime

η

φ

Eta

Phi

ρ^{+} ρ^{-} ρ^{o}

Rho

Mesons

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

Delta

Λ^{0}

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

Lambda (strange!)

Sigma (strange!)

Ξ^{0}, Ξ^{-}

Sigma(very strange!)

BARYONS

What was the underlying structure ?

PARTICLE SPECTRUM

1963

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

Gell-Mann, 1963

(G. Zweig, 1963, CERN)

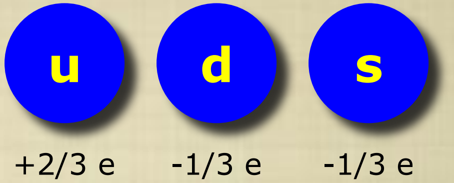
1) 3 types of "quarks" : up, down, strange

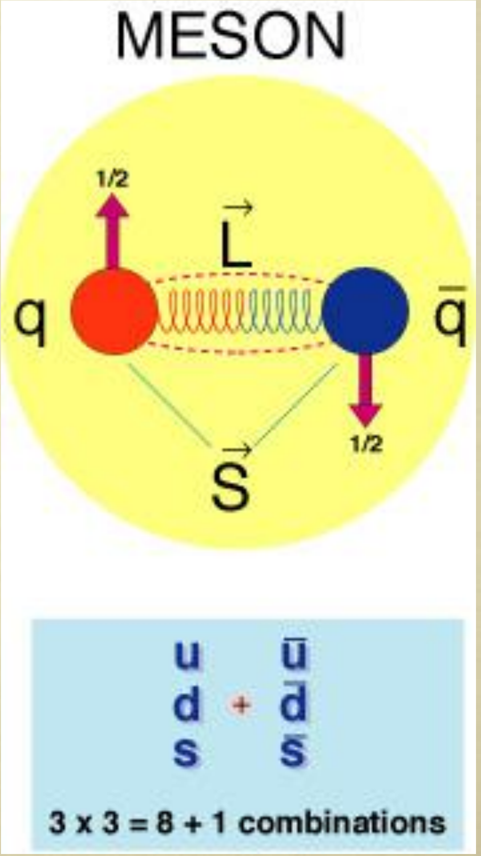
2) Carry electric charges: +2/3, -1/3, -1/3

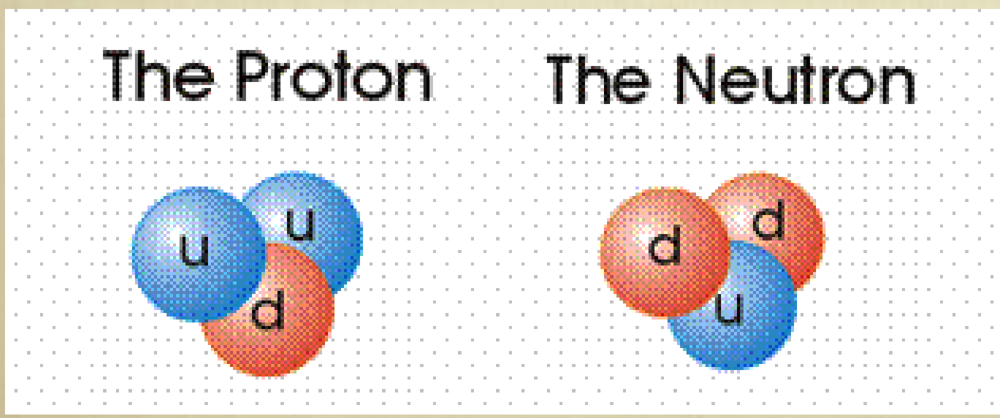
3) Appear in combinations:

Meson = quark+antiquark

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

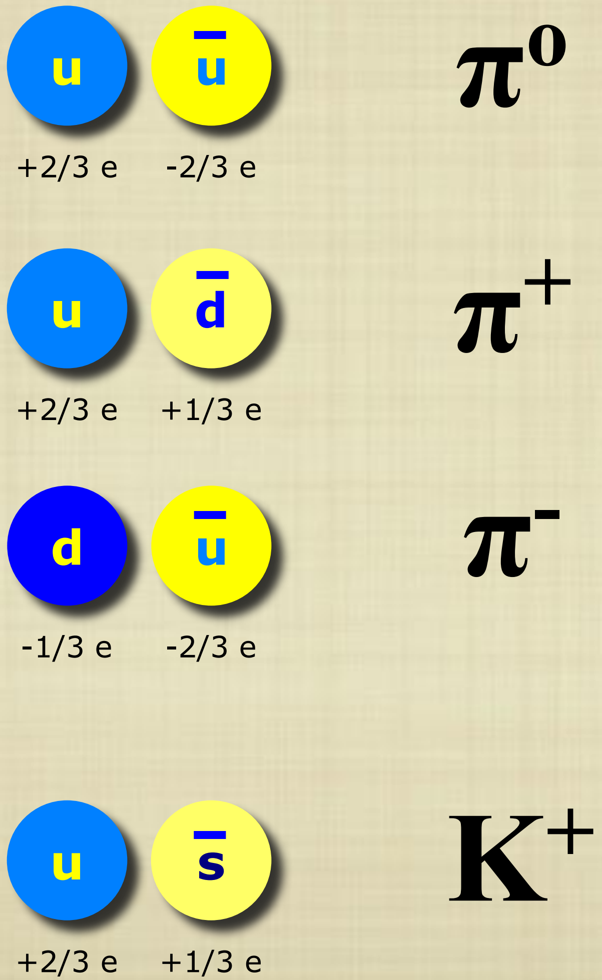


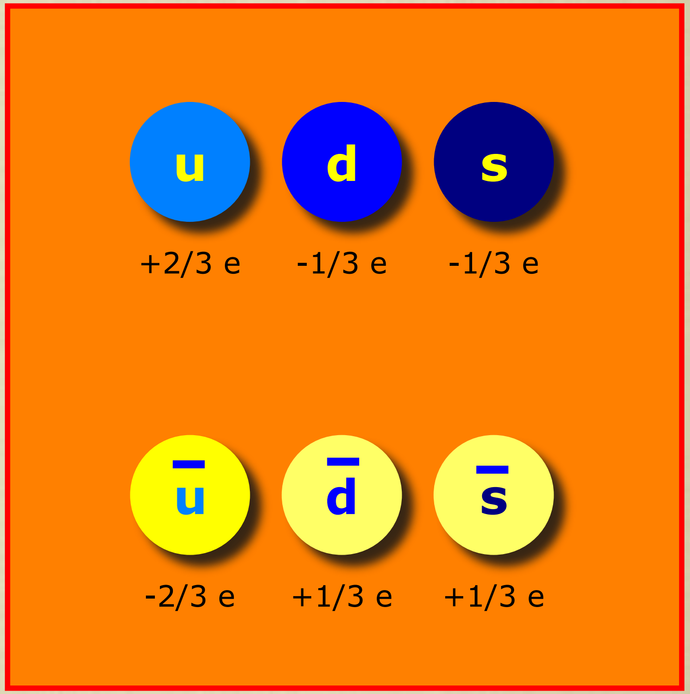




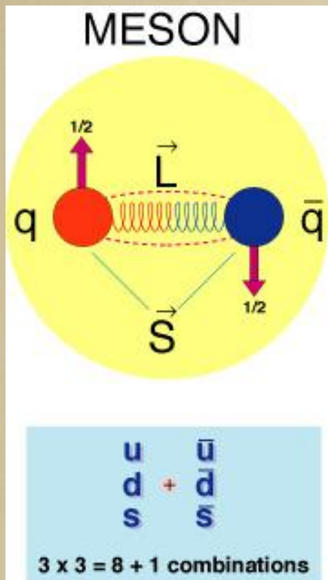
PARTICLE SPECTRUM

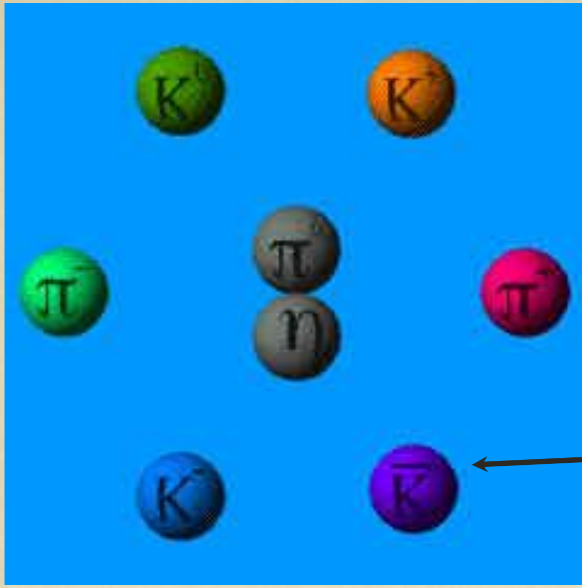
Some mesons (quark+antiquark):





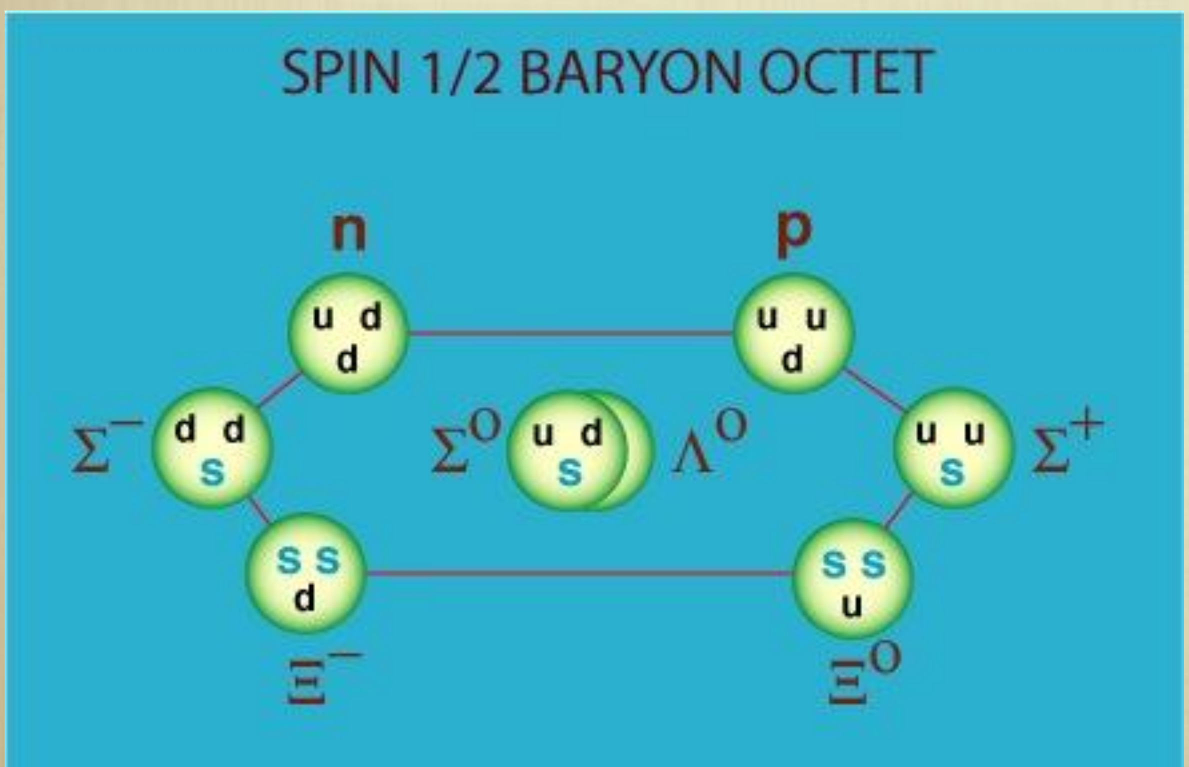
QCD





Pion, Eta-meson

Kaonen besitzen ein ‘strange’ Quark

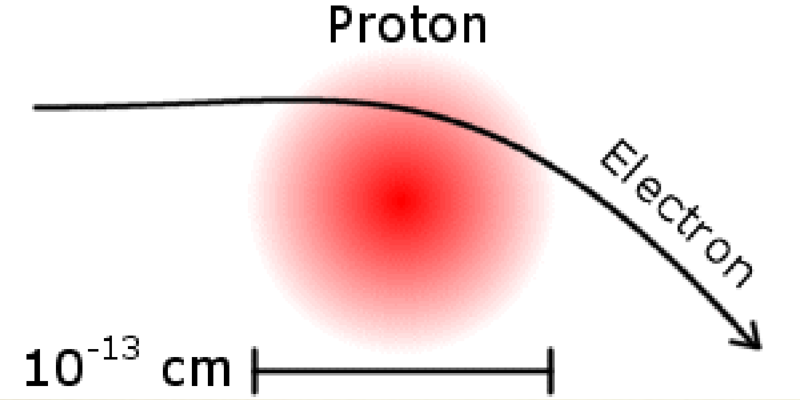


Die leichtesten Baryonen:
Proton, Neutron;
Lambda, Sigma, Xi

PARTICLE SPECTRUM

Discovery of quarks

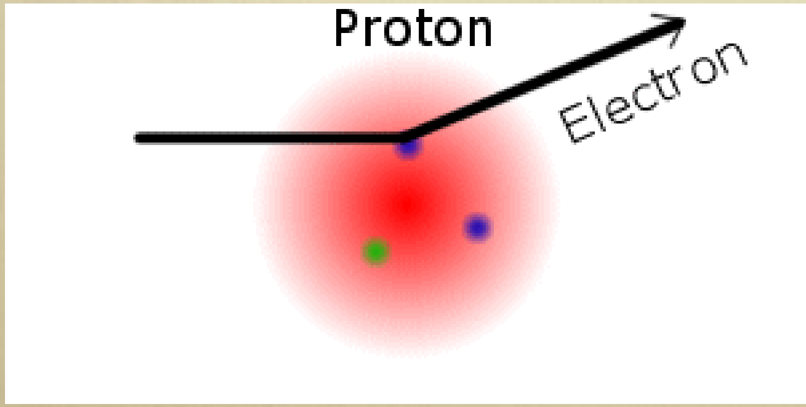
Electron-Proton scattering



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

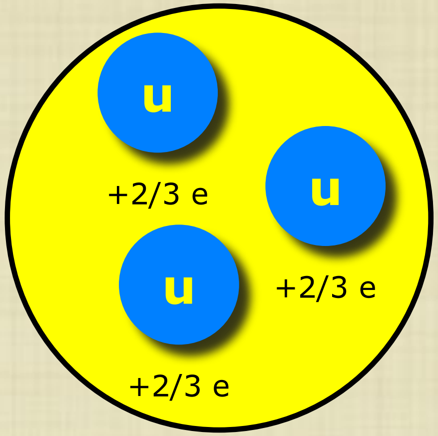
PARTICLE SPECTRUM

1973

The concept of "Colour" charge

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

Δ^{++}



Since the three up-quarks must have parallel spin - there are in a symmetric state

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

(Bardeen, Fritzsch, Gell-Mann)

PARTICLE SPECTRUM

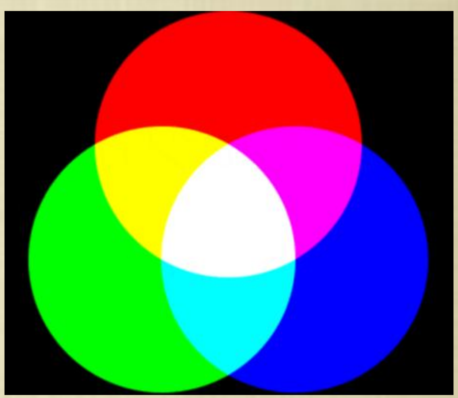
this has nothing to do with our visible colours, just an analogy

Quantum **C**hromo **D**ynamics

Theory constructed in analogy to QED

QCD: 3 different charges (“colour charge”) [red, green, blue]*

‘Strong force’ between quarks is transmitted by (8) gluons



Dogma of QCD: Only colour-neutral bound states are allowed, explains:

MESONS = Quark-Antiquark

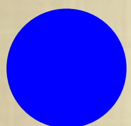
BARYONS = 3-Quark states

QCD

1973

Gluonen

Gluons carry a colour charge !!
Gluon-Gluon interaction



Quark : ‘Colour charge’

Anti-Quark :
‘Anti-Colour’

GLUONS:
Colour+
Anticolour

- Carrier of the strong interaction
- massless
- 3 x 3 - 1 = 8 linear independent combinations (8 gluons)

PARTICLE SPECTRUM

1973

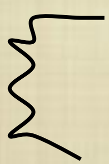
GLUONS CARRY COLOUR CHARGE : SELF-INTERACTION !

At low energies, approximately:

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

For large distances, the force increases:

'slavery' : no free quarks !!

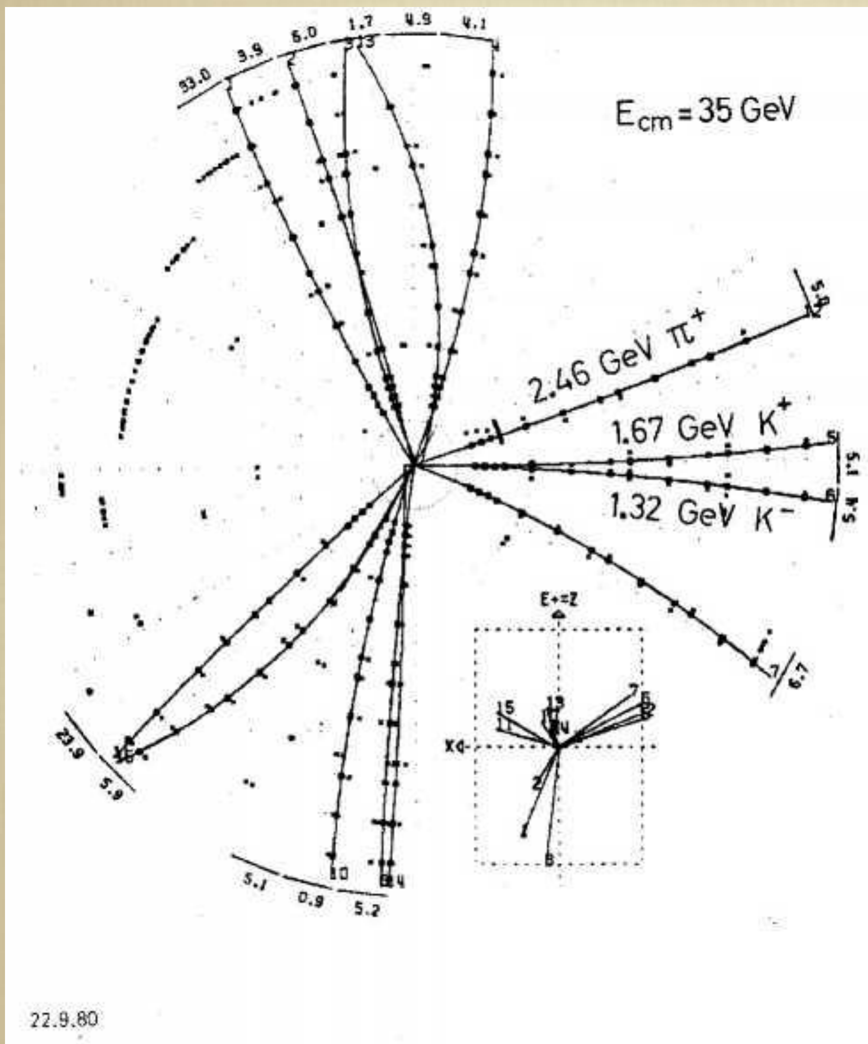


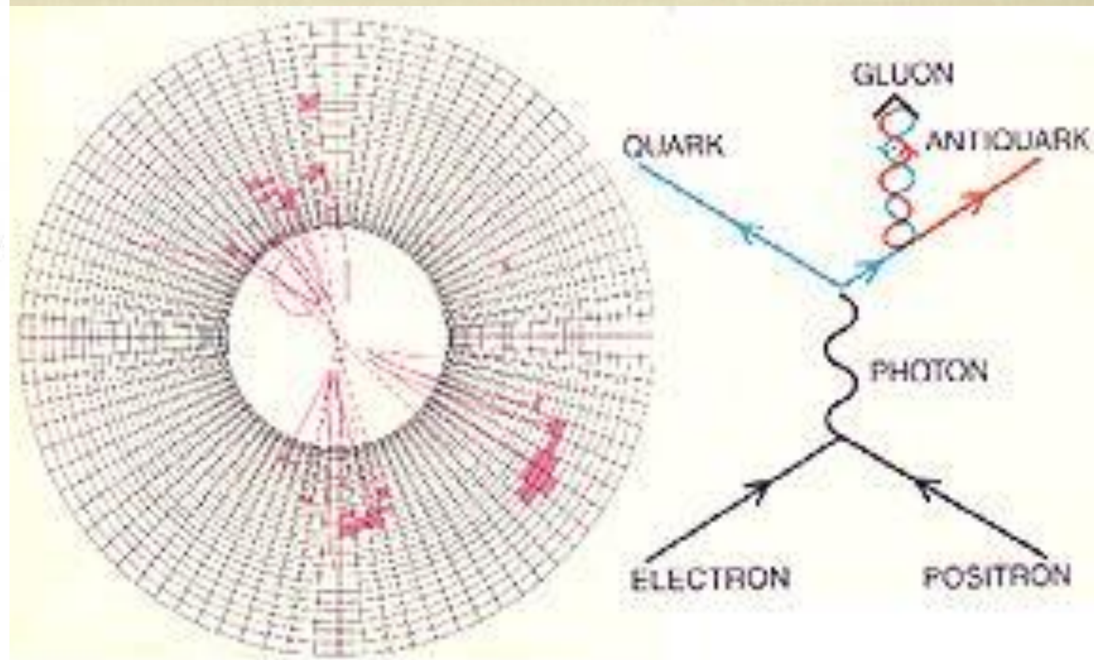
For small distances, the force decreases:

asymptotic freedom

QCD

Gluon discovery in 3-jet events **(DESY, 1979)**





PETRA Storage Ring, 1979, DESY (Hamburg)