

STRUCTURE OF MATTER

Discoveries and Mysteries

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PREFACE

**This is a lecture about 100 years of particle physics.
It covers about 100 years of ideas, theories and experiments.**

More than 50 Nobel prize winners on particle physics
This is a broad overview about the main discoveries.

In the early 1900s, most physicists believed that physics was complete, described by classical mechanics, thermodynamics, and the Maxwell theory.



Lord Kelvin

“There is nothing new to be discovered in physics now. All that remains is more and more precise measurement. “ (Lord Kelvin,

DARK CLOUDS:
1900)

- 1) Blackbody radiation - Quantum Physics
- 2) Michelson-Morley experiment - Special Relativity

1895
1900
1905
1910
1920
1930
1940
1950
1960
1970
1975
1980
1990
2000
2010



MATTER IS MADE OF PARTICLES



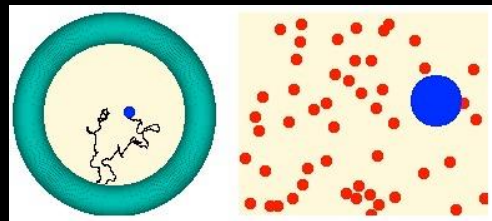
J.J. Thomson

1897: ELECTRON - the first 'discrete' building block of matter



A. Einstein

1905: ATOMS ARE REAL - Explanation of Brownian Motion (Perrin)



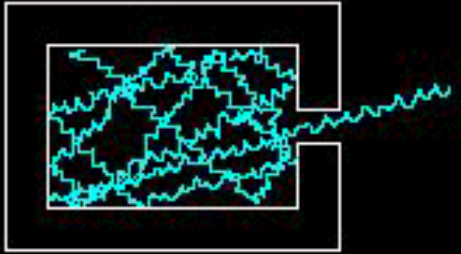
$$\langle x^2 \rangle = \frac{2kTt}{\alpha} = \frac{kTt}{3\pi\eta a}$$

ENERGY COMES IN QUANTA



M. Planck

1900: ELECTROMAGNETIC RADIATION IS EMITTED IN QUANTA



$$\varepsilon = h \nu$$

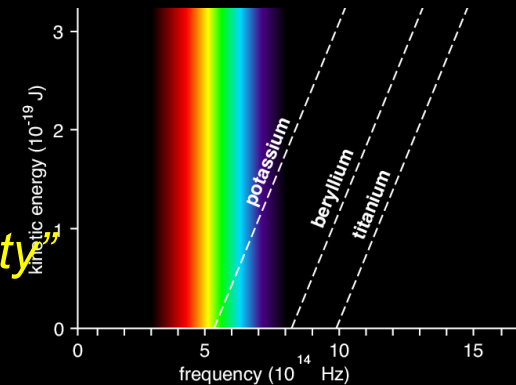
$$I(\nu) \sim \nu^2 \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$$



P. von Lenard

1902: PHOTOELECTRIC EFFECT

“The electron energy does not show the slightest dependence on the light intensity”



A. Einstein

1905: LIGHT IS EMITTED AND ABSORBED IN QUANTA

$$E_{\max} = h\nu - W$$

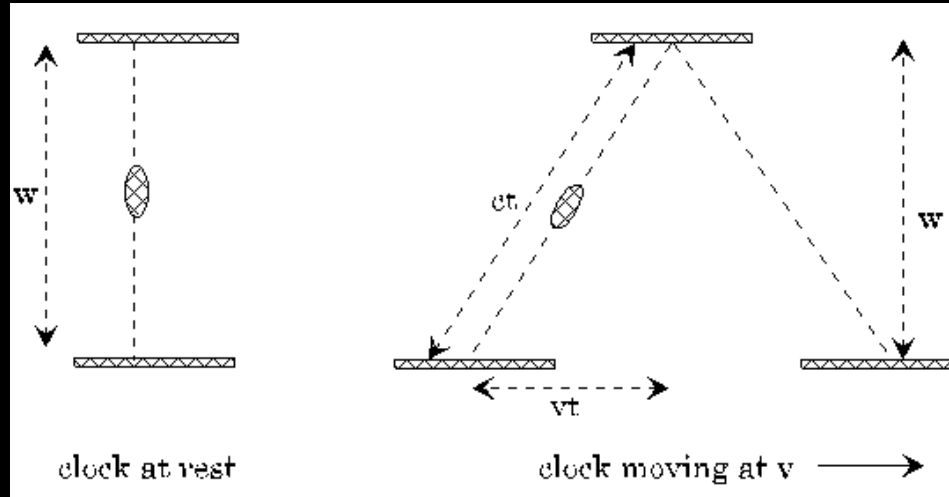
“My only revolutionary contribution to physics”

SPECIAL RELATIVITY



A. Einstein

1905: SPEED OF LIGHT IS ALWAYS CONSTANT



$$c^2 t^2 = v^2 t^2 + w^2$$

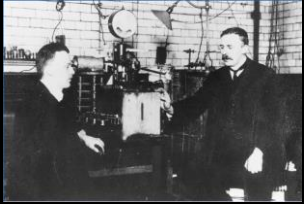
$$t = \frac{w/c}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma \cdot \tau$$

1) Time dilation, space contraction

2) Modification of Newton's laws, relativistic mass increase.

$$E=mc^2$$

THE BEGINNING OF ATOMIC PHYSICS



Rutherford

1909: NUCLEI: very small + heavy within (almost) empty atom



Hydrogen

1913: BOHR MODEL- (empirical) explanation of discrete spectral lines

(using Planck's constant h) to quantize angular momentum

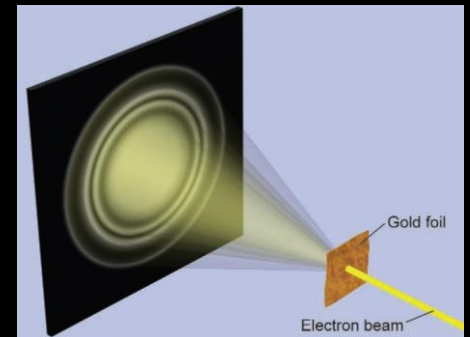


L. de Broglie

1923: DE BROGLIE

Particles are waves

$$\lambda = \frac{h}{p}$$



QUANTUM MECHANICS

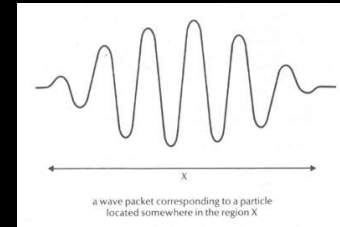


Heisenberg

1923: UNCERTAINTY RELATION

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$\Delta E \Delta t \geq \hbar$$



Schrödinger

1926: SCHRÖDINGER EQUATION

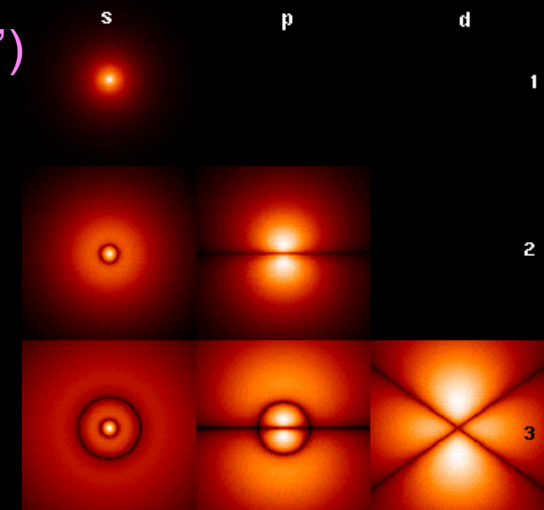
$$H\psi(\mathbf{r}, t) = (T + V)\psi(\mathbf{r}, t) = \left[-\frac{\hbar^2}{2m} \nabla^2 + V(\mathbf{r}) \right] \psi(\mathbf{r}, t) = i\hbar \frac{\partial \psi}{\partial t}(\mathbf{r}, t)$$

(electrons in atoms form 'standing waves')

Interpretation (Born, 1927):

ψ = probability amplitude

$|\psi|^2$ = probability



RELATIVISTIC QUANTUM MECHANICS



Paul A.M. Dirac
(1928)

$$E^2 = p^2 + m^2 \rightarrow$$
$$E = \pm(\alpha \cdot p) + \beta m$$

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

$$\Psi = \begin{pmatrix} e^- \uparrow \\ e^- \downarrow \\ e^+ \uparrow \\ e^+ \downarrow \end{pmatrix}$$

Spin

Antimatter

ELECTRON **SPIN 1/2** EXPLAINED

ANTIPARTICLES MUST EXIST !

SPIN 1/2 PARTICLES (FERMIONS) MUST OBEY EXCLUSION PRINCIPLE

ANTIPARTICLES



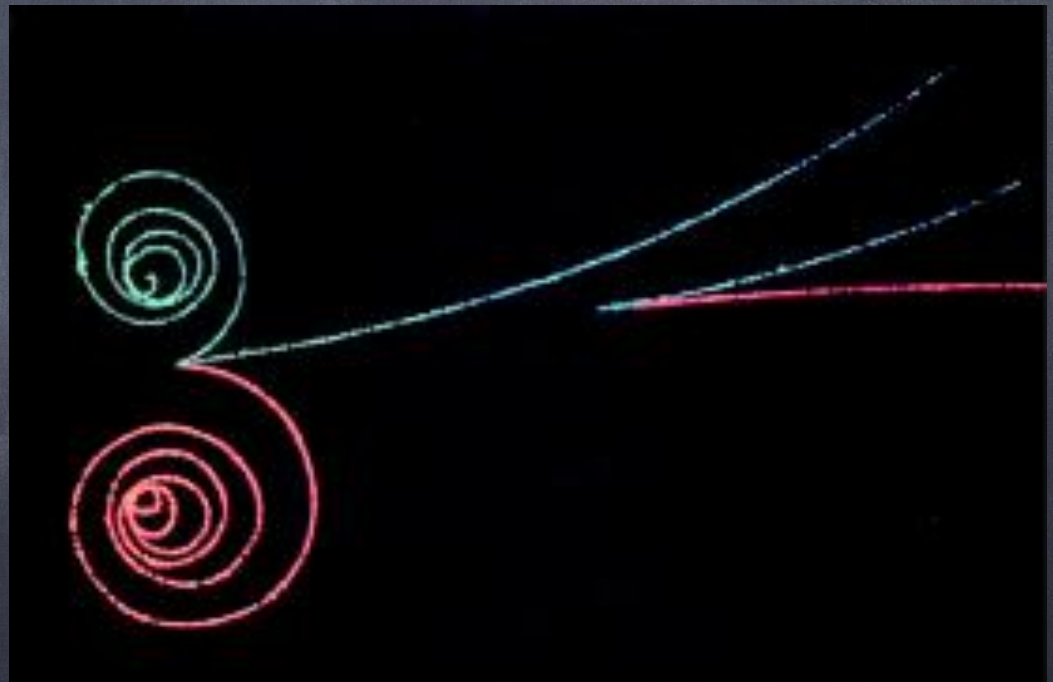
Anderson

1932: POSITRON DISCOVERY



EVERY PARTICLE HAS AN ANTIPARTICLE

$$E=mc^2$$



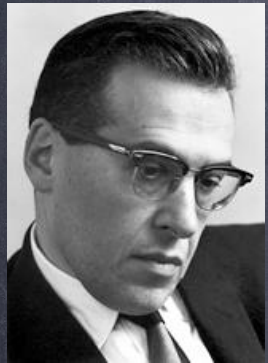
WHEN ENERGY CONVERTS TO MASS,
PARTICLES AND ANTIPARTICLES ARE PRODUCED

QUANTUM FIELD THEORY (1927 - 1948)



S.I. Tomonaga

It was known that the **electromagnetic field consists of photons**



J. Schwinger

How could the interaction between electrons and photons be correctly described, respecting quantum mechanics and special relativity?



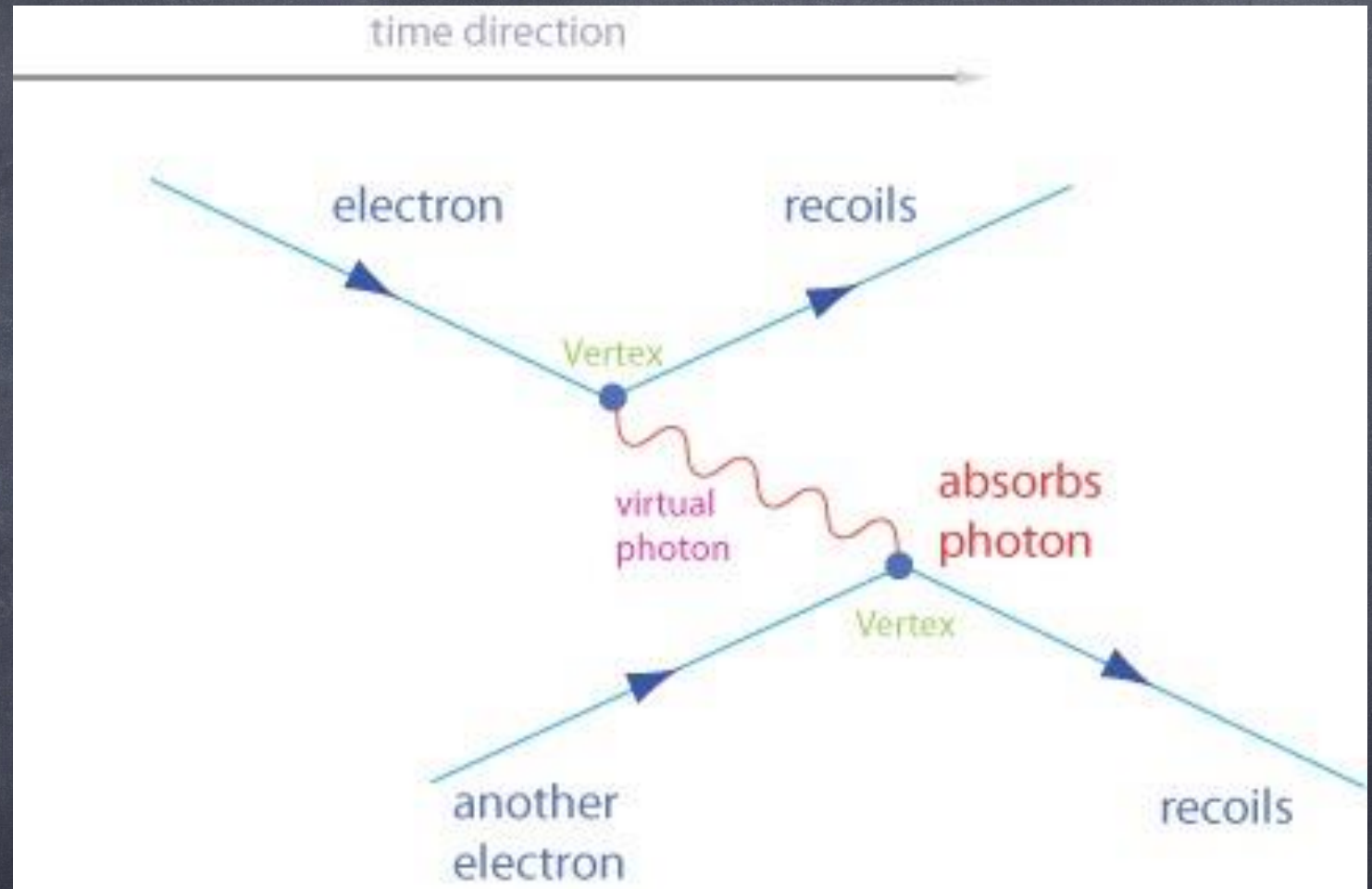
F. Dyson

Many people worked on this problem ...

Quantum Electrodynamics (QED)



R.P. Feynman

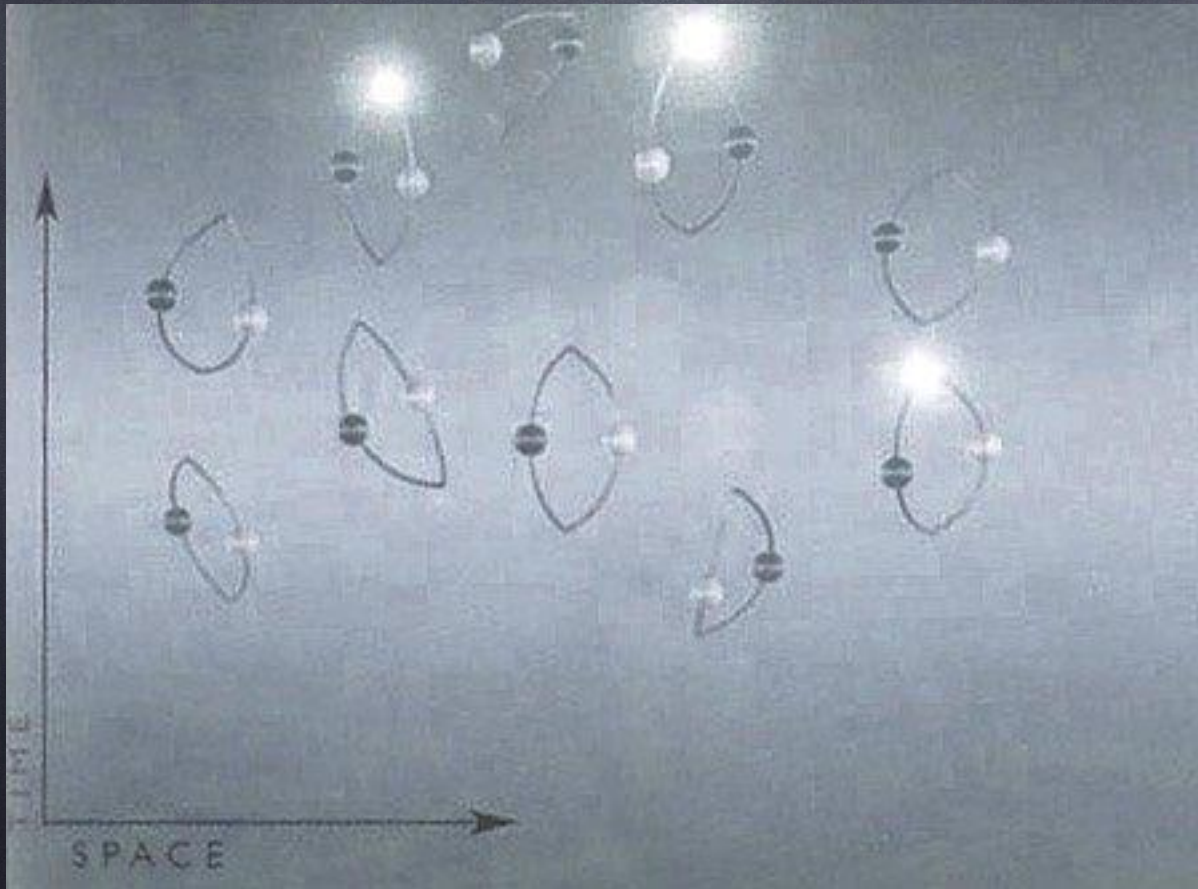


VACUUM FLUCTUATIONS

Quantized fields: Ground state energy is $\neq 0$

Photons and particle-antiparticle-pairs populate empty space !

[Remark: should give rise to (lots of) “vacuum energy”]



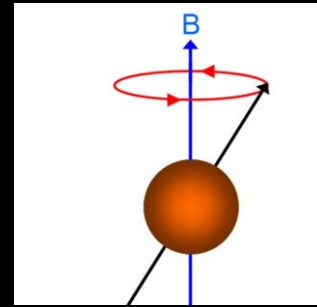
UNCERTAINTY RELATION:

$$\Delta E \times \Delta t \geq h/2\pi$$

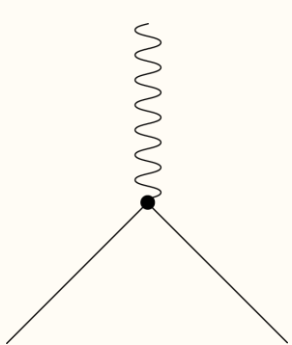
Vacuum fluctuations have observable effects

The world record for the most precise calculation in physics goes to:

Electron anomalous magnetic moment “g”

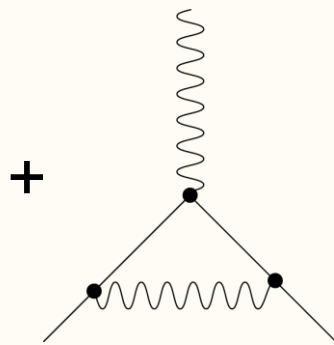


$$\mu = g \frac{e}{2m} S$$



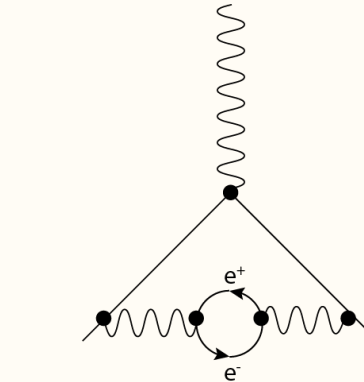
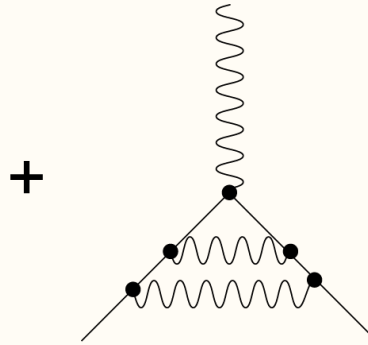
“Leading order”

$$g = 2$$



Second order

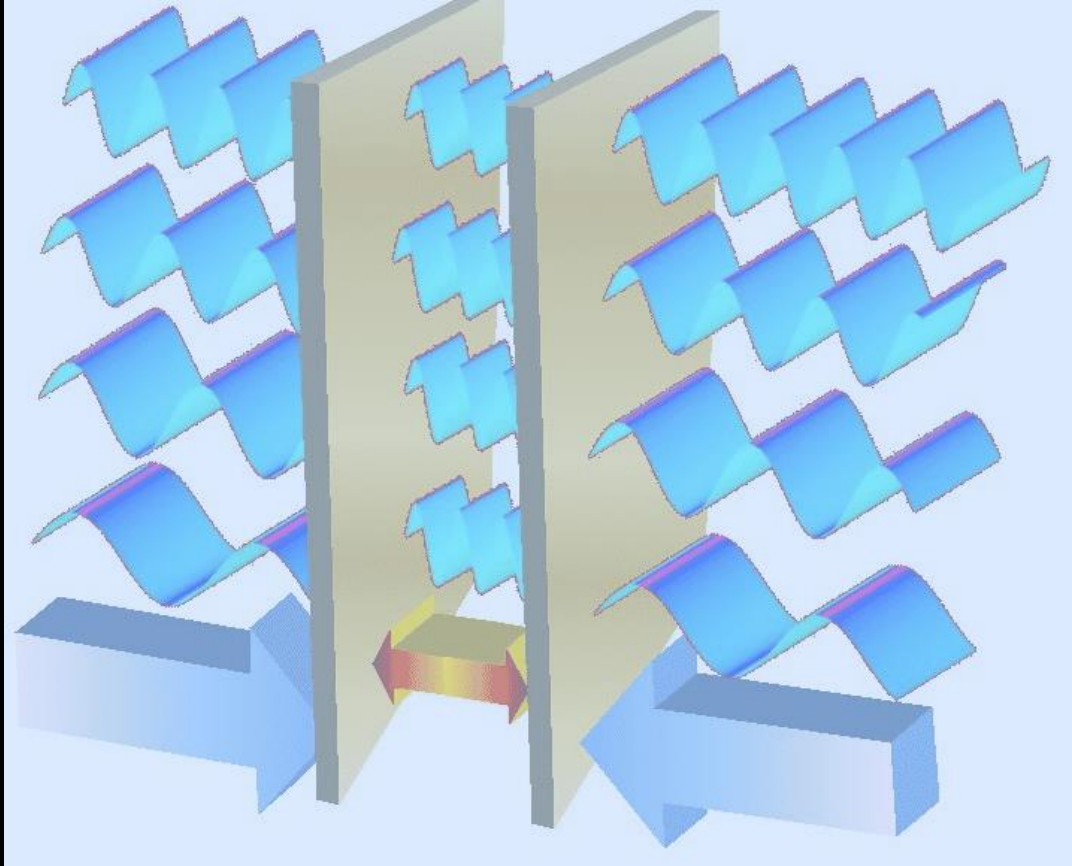
$$a = (g-2)/2 = 1/2\pi * 1/137$$
$$\sim 0.0011614$$



Fourth order corrections

Current precision (theory and experiment agree.)
 $a = 0.00115965218073(28)$

CASIMIR EFFECT



$$p_c = \frac{F_c}{A} = \frac{\hbar c \pi^2}{240 \cdot d^4}$$

$$p = 100 \text{ kPa (d=11 nm)}$$

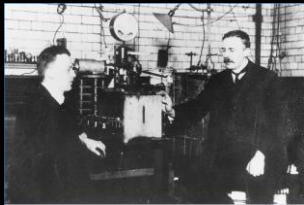
SPOOKY: at 11 nm distance, the pressure is 1 atm.

NUCLEAR PHYSICS



M. Curie

1895-1900: RADIOACTIVITY - strange radiation phenomena



E. Rutherford

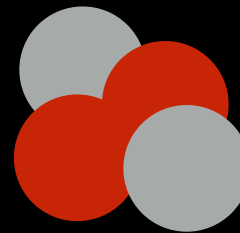
1903: Alpha-, Beta-, Gamma-Radiation known
(different penetration depth)



J. Chadwick

1911: Nucleus positive, small - surrounded by electrons

1932: DISCOVERY OF THE NEUTRON



Alpha particle = He nucleus

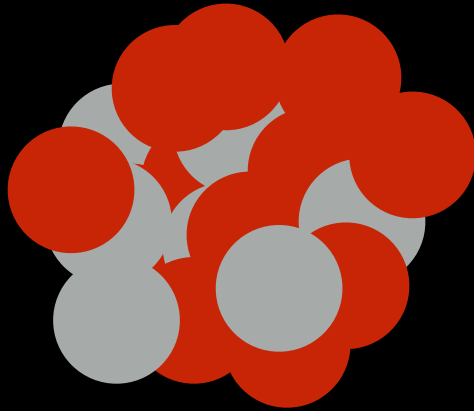
NUCLEAR PHYSICS - 1934



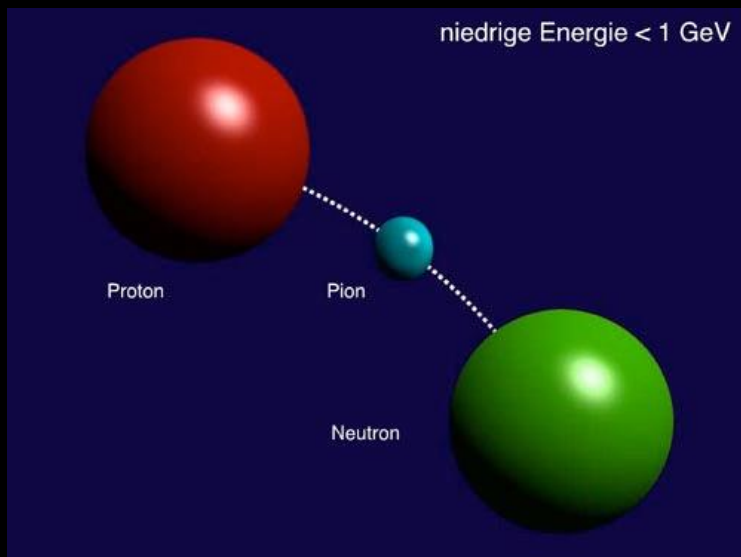
Yukawa (1934)



What keeps protons and neutrons together ?

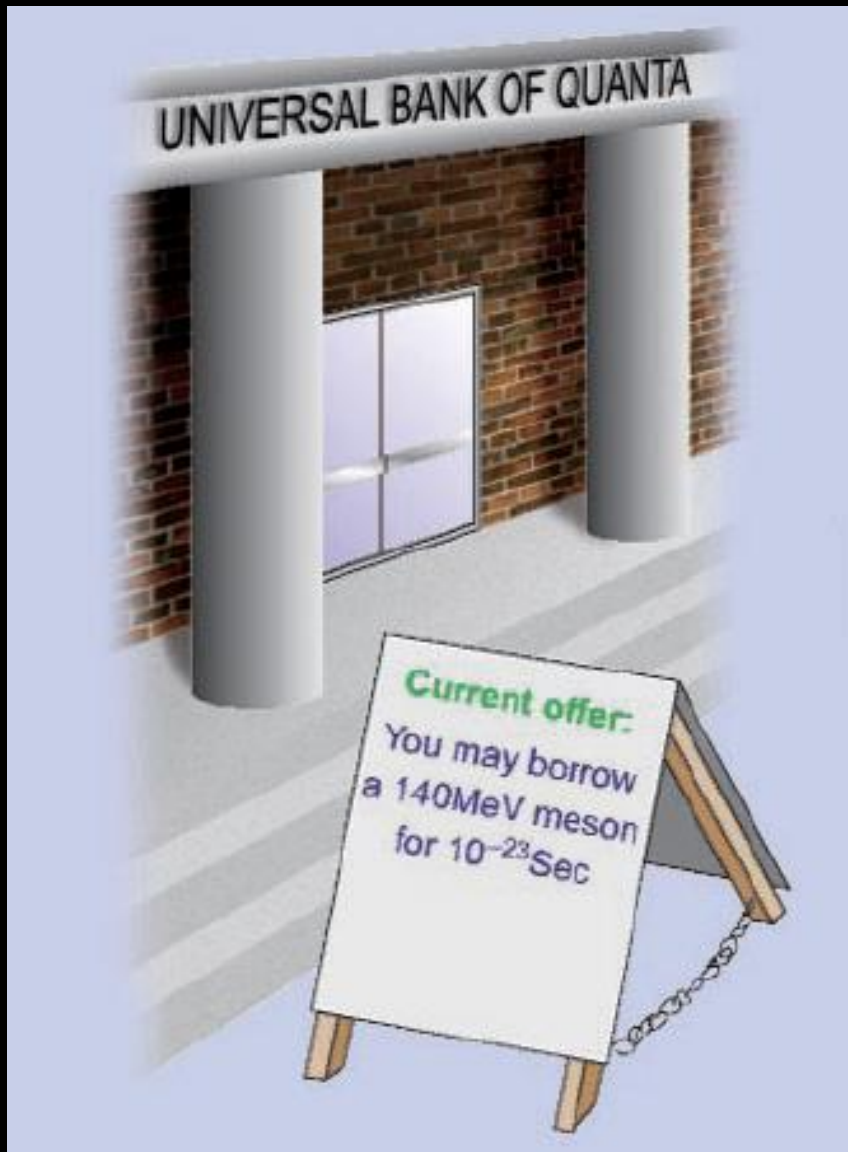


Why is the range of nuclear forces finite?
(maximum size of nuclei ~ 5 fm)



Yukawa model:

- New “strong” interaction
- Exchange of “pion”
- Pion has mass: finite range of 1-2 fm



Toy model:

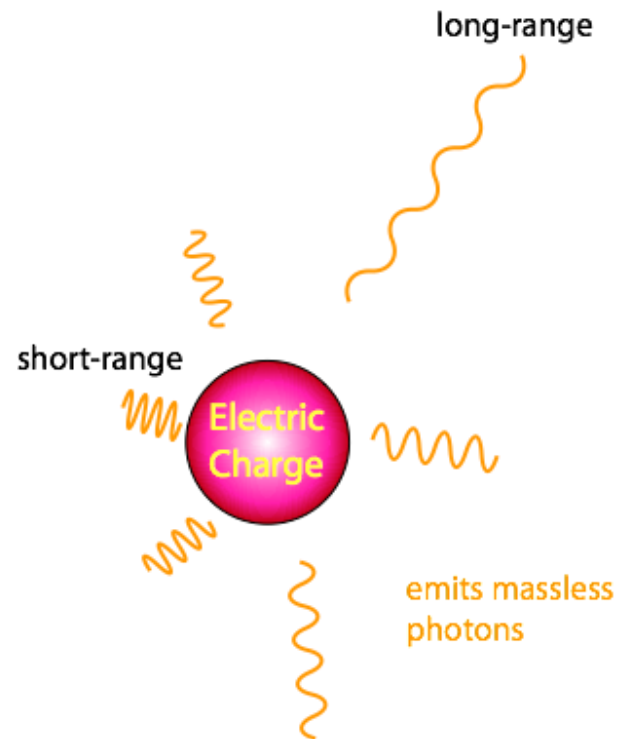
UBS offers you a loan of

1000 Euro x Seconds

UNCERTAINTY RELATION:

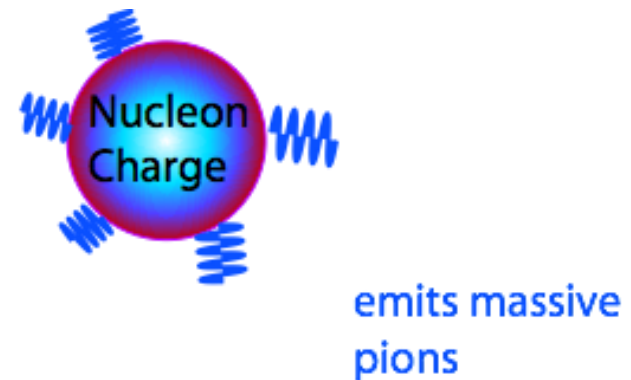
$$\Delta E \times \Delta t \geq h/2\pi$$

Electromagnetic vs Nuclear Exchange Forces



$$V(r) = -e^2 \frac{1}{r}$$

Coulomb law



$$\Delta E \Delta t \geq \hbar \quad (\Delta E \sim m)$$

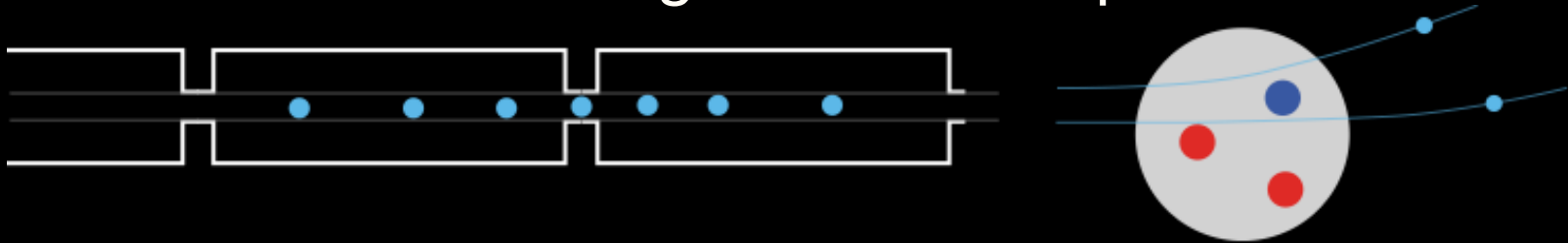
$$r = c \Delta t = \frac{\hbar c}{m} \sim \frac{200 \text{ MeV fm}}{m}$$

$$V(r) = -g^2 \frac{e^{-mr}}{r}$$

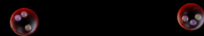
Yukawa potential \sim Modified "Coulomb" law

QUARKS AND QCD

An accelerator is a giant microscope



... and can also produce new particles:



$$E = mc^2$$

1948 - 1960s: New accelerators and detectors

PARTICLE ZOO contains ~ 200 'elementary particles'

π^+ π^- π^0

Pions

K^+ K^- K^0

Kaons

η'

Eta-Prime

η

Eta

ϕ

Phi

ρ^+ ρ^- ρ^0

Rho

Mesons

Δ^{++} , Δ^+ , Δ^0 , Δ^-

Delta

Λ^0

Lambda (strange!)

Σ^+ , Σ^0 , Σ^-

Sigma (strange!)

Ξ^0 , Ξ^-

Sigma(very strange!)

BARYONS

Underlying structure ?

Classification scheme based on 'quarks'

1963



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

Gell-Mann, 1963
(G. Zweig, 1963)

3 types of "quarks" : up, down, strange (and their anti-particles)



$+2/3$

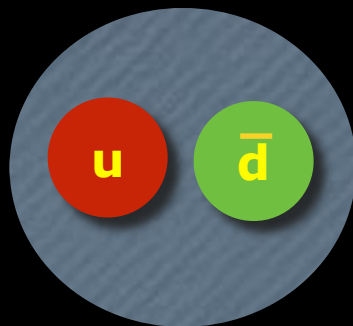


$-1/3$



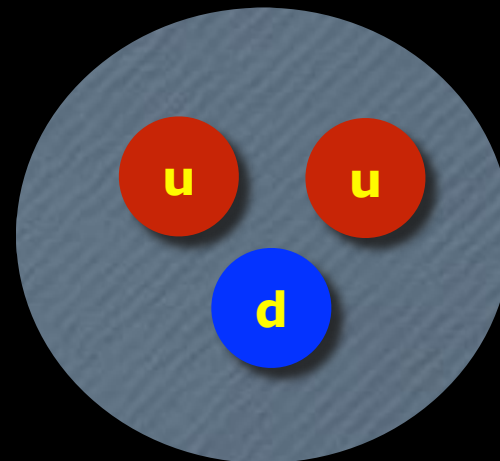
$-1/3$

electric charge



π^+

Meson



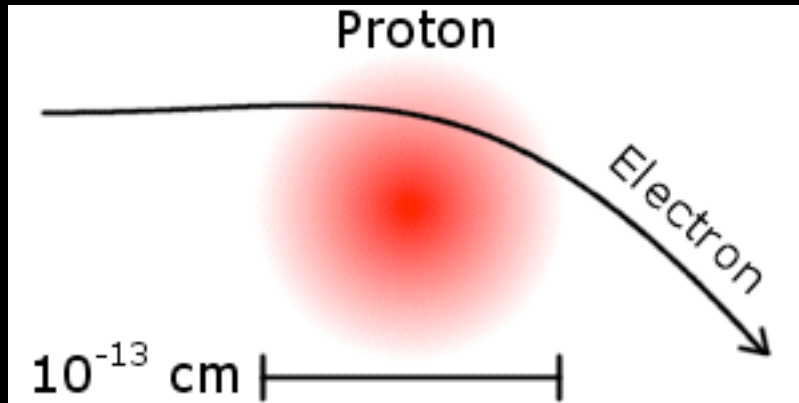
p

Baryon

Discovery of quarks

Electron-Proton scattering at Stanford

1956 Hofstadter: proton radius ~ 1 fm

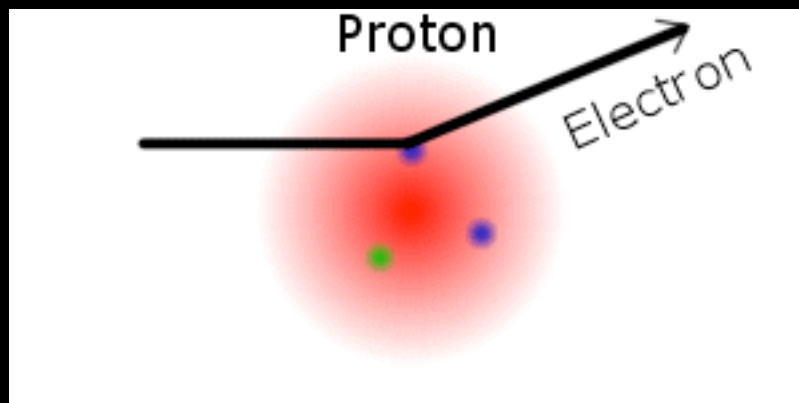


$E = 0.2$ GeV



Stanford Linear Accelerator Centre

1967 Friedmann, Kendall, Taylor: three 'point-like particles' inside a proton



$E = 20$ GeV

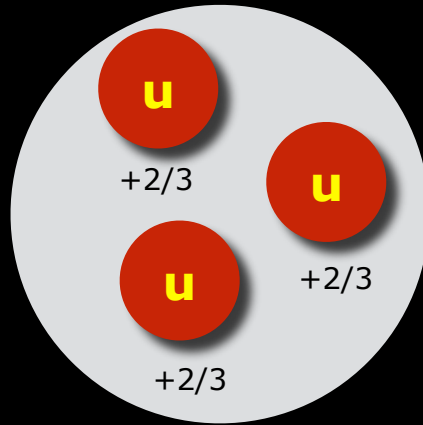
Measured cross-sections perfectly compatible with presence of 2 up- and 1 down-quark in proton

The concept of "Colour" charge

How can you explain this particle ?

Δ^{++}

Spin = 3/2



*three fermions are **not allowed** to be in the **same** quantum state (Pauli exclusion principle)*

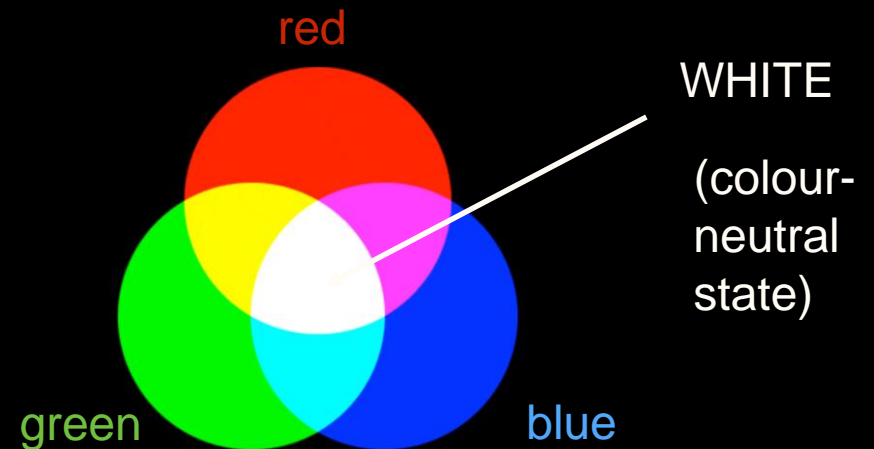
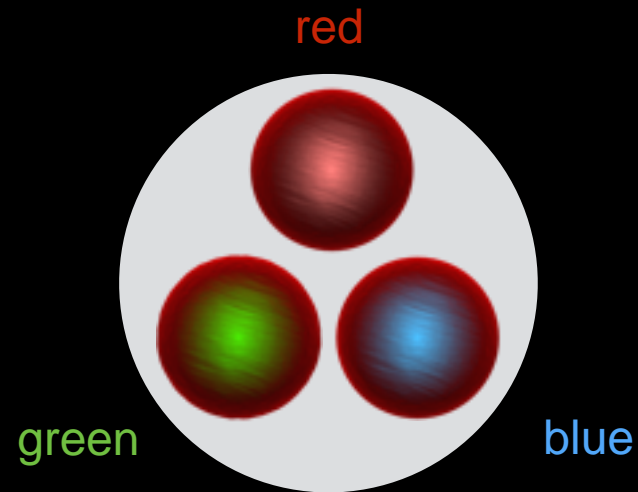
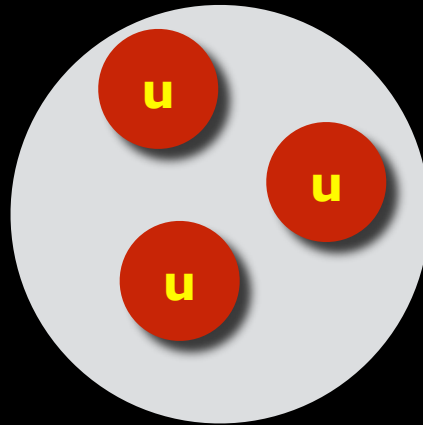
A new concept: "colour charge"

- 1) Colour charge is source of 'strong force'***
- 2) There are three types of colour (e.g. "red", "green", "blue")***
- 3) Only colour-neutral states can exist***

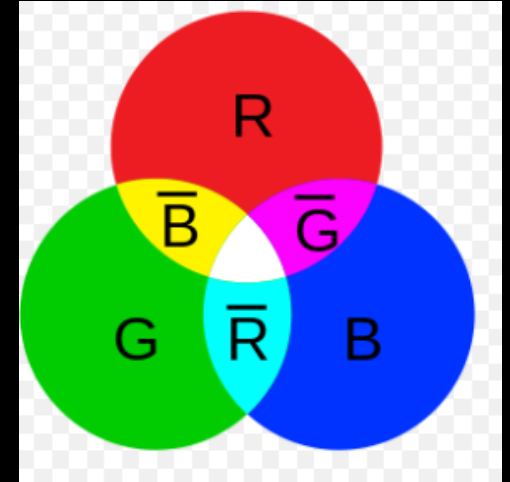
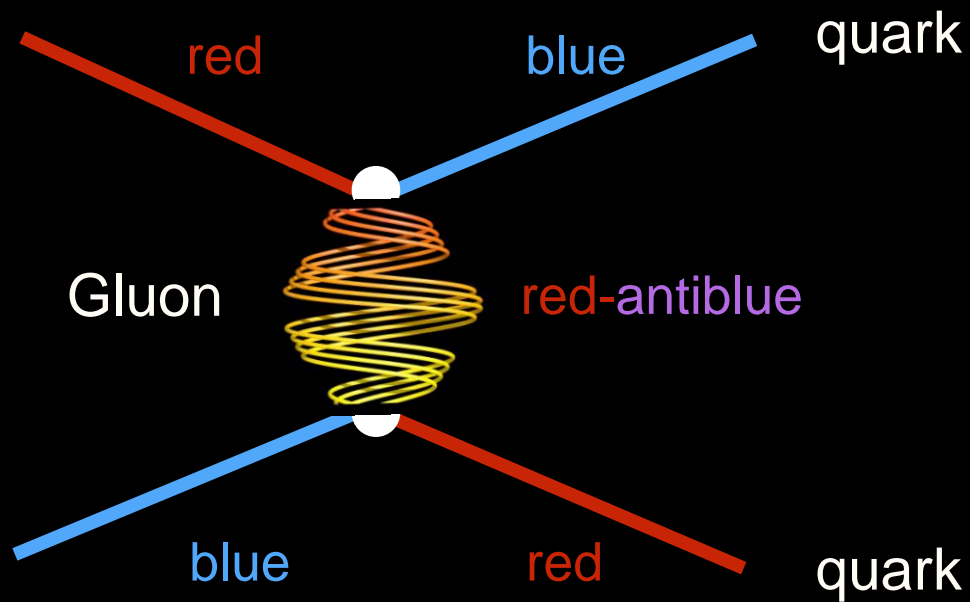
(Bardeen, Fritzsch, Gell-Mann)

Quarks carry a “colour” charge - in addition to their electric charge
(that makes them different and hence exclusion principle does not apply)

Δ^{++}



Quarks interact by exchanging 'gluons' that carry colour (and anti-colour)

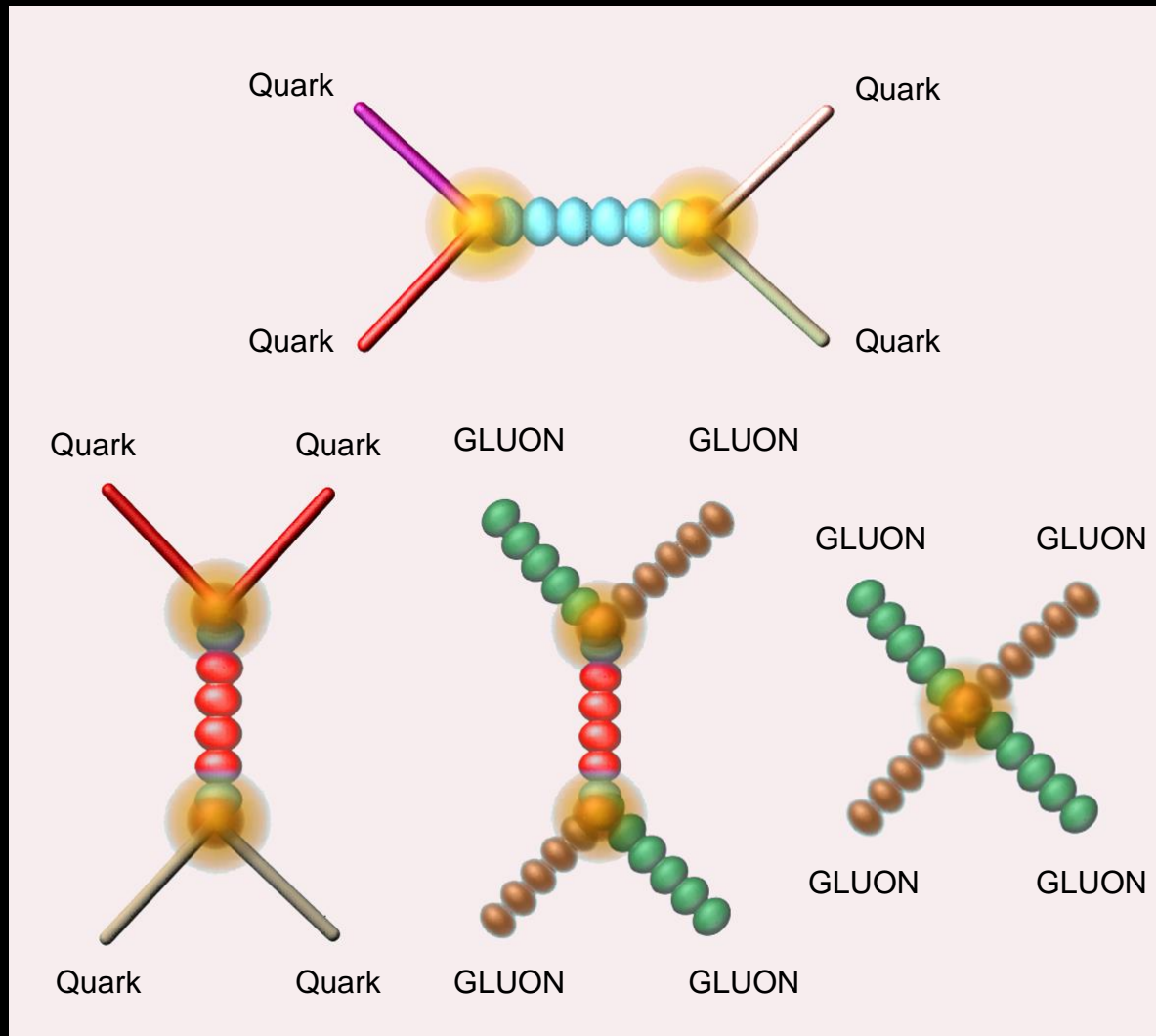


Total number of gluons: $3 \times 3 - 1 = 8$

(1 combination is a 'colour-singlet', i.e. neutral)

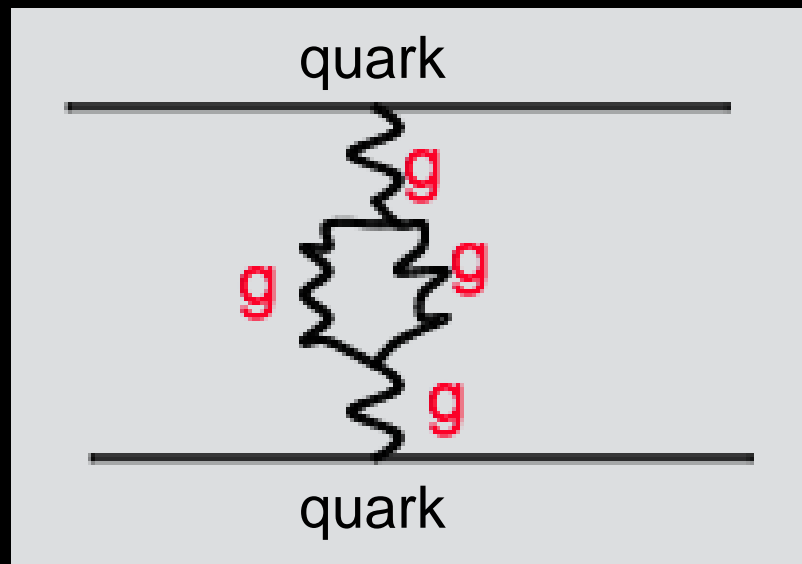
Since gluons carry a (colour) charge:

Gluons can interact with other gluons

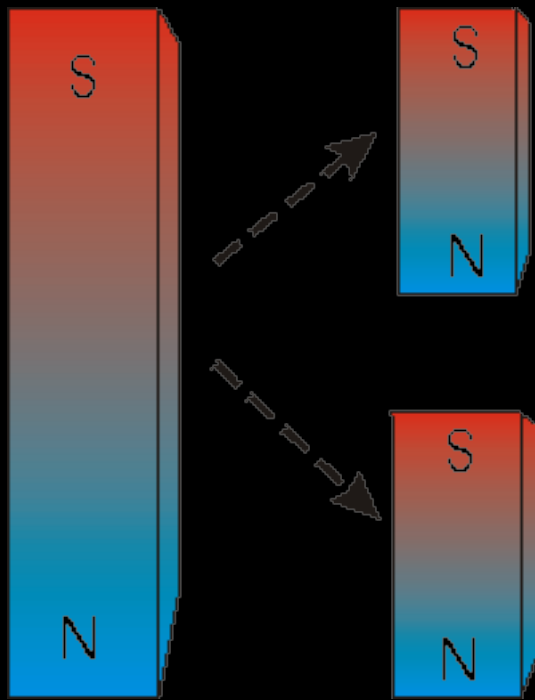


The self-interaction of the gluons results in the energy of the gluon string increasing with distance between quarks.

This produces a force that keeps the quarks as 'prisoners'.



Gluon 'strings' break : new quark-antiquark pairs



Analogy to breaking a magnet into two halves: does not produce a magnetic monopole

