

Let's Smash The Proton!

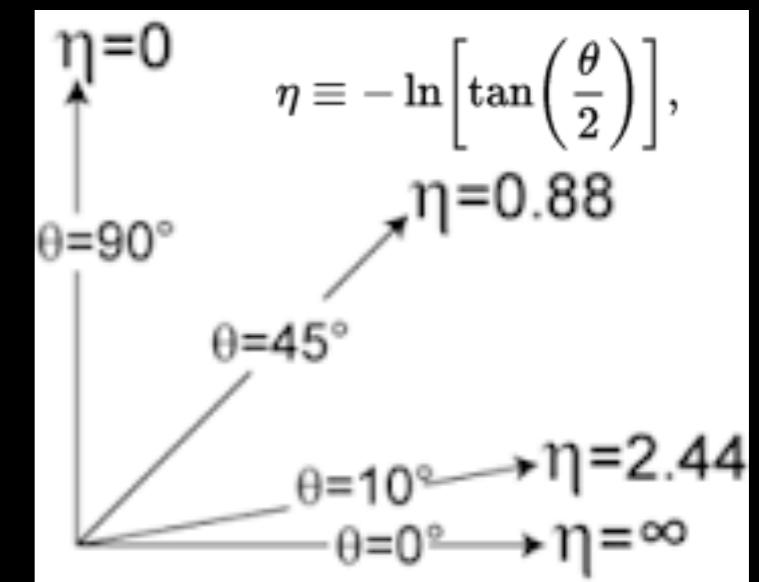
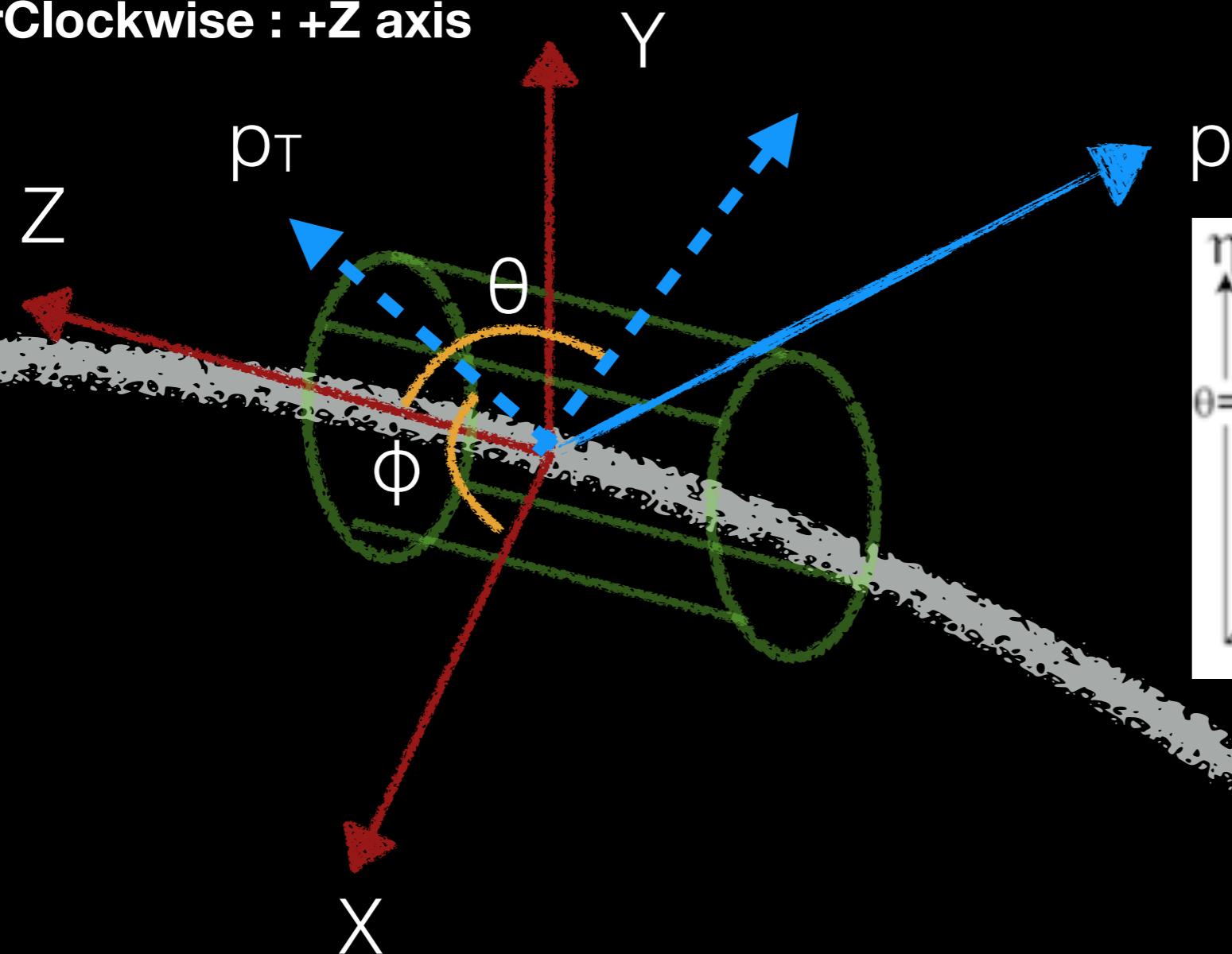
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(they/them)

School of Science and Math at Vanderbilt
Summer 2023

Day 3 - Studying the particles produced in the collisions

Axis and Variables

CounterClockwise : +Z axis



X-Y : Transverse Plane

Y-Z : Longitudinal Plane

UNITS

Lets introduce the electron volt (eV):

Energy of e- after accelerating through 1V potential field.

Energy = (mass)(length)²/(time)²

Energy/velocity = (mass)(length)/(time) - units of
momentum

Momentum/velocity = mass

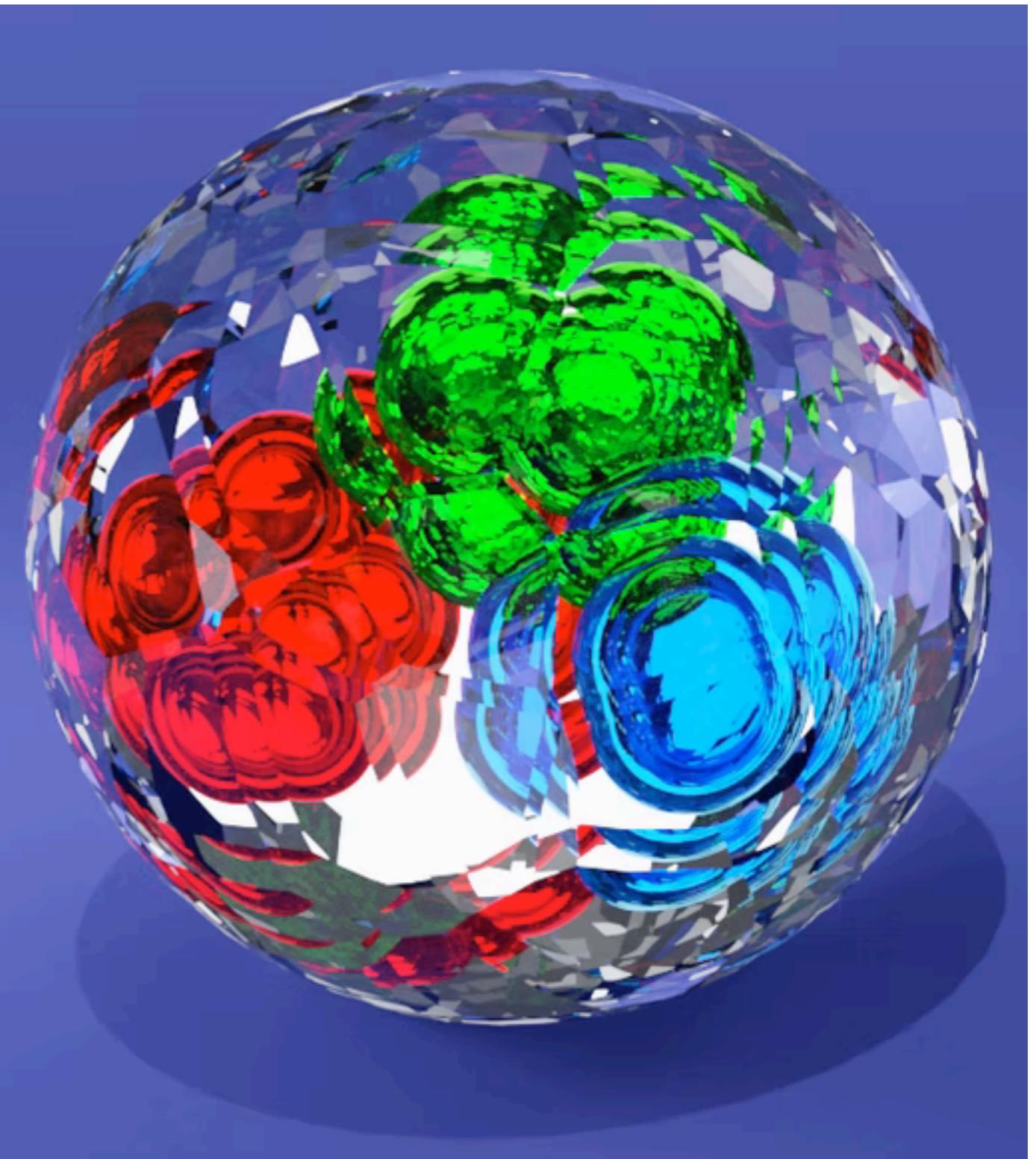
Energy: 1 eV = $1.602176487 \times 10^{-19}$ J

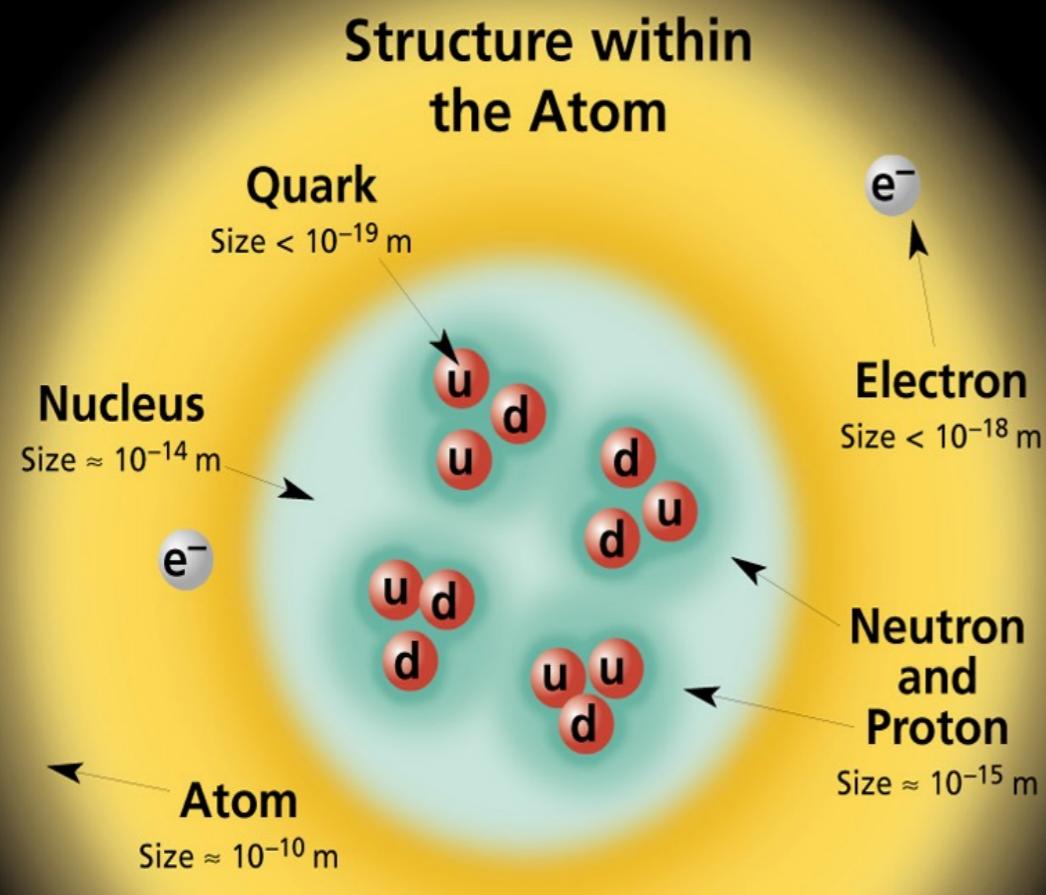
Momentum: 1 eV/c = 5.36×10^{-28} kgm/s

Mass: 1 eV/c² = 1.783×10^{-36} kg (e- 511 keV/c² ~ 10^{-30} kg)

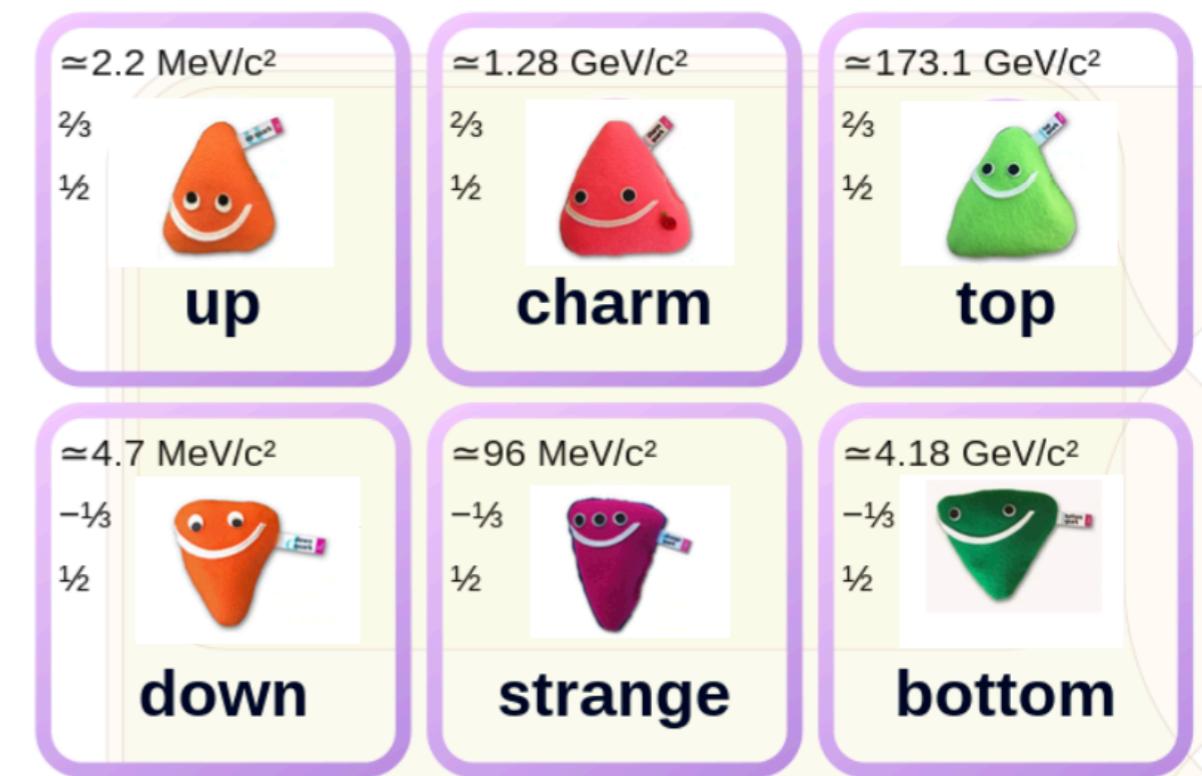
Topic of the day!

What is more fundamental than the proton?





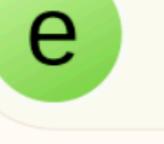
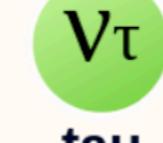
Ordinary matter made of **up** and **down** quarks



Family of quarks!

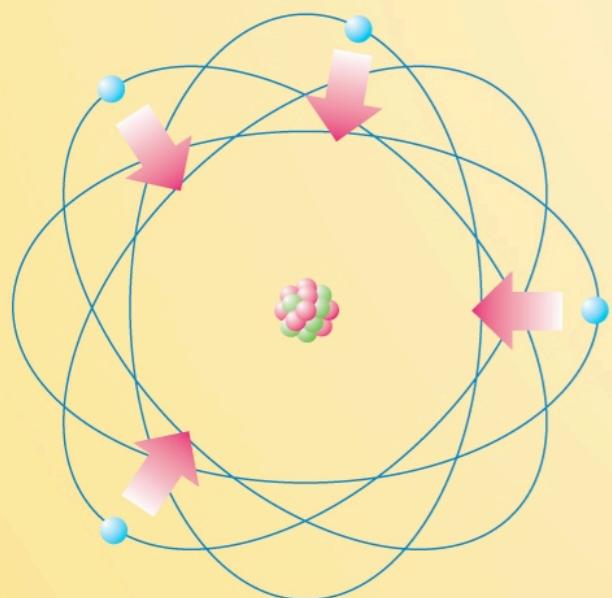
Quarks, held together by gluons, make up the proton/neutron

Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III	
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	
charge	$2/3$	$2/3$	$2/3$	
spin	$1/2$	$1/2$	$1/2$	
QUARKS	 up	 charm	 top	 gluon
	 down	 strange	 bottom	 photon
	 electron	 muon	 tau	 Z boson
	 electron neutrino	 muon neutrino	 tau neutrino	 W boson
				 higgs
				
				
				
				
LEPTONS			GAUGE BOSONS VECTOR BOSONS	

The Four Fundamental Forces of Nature

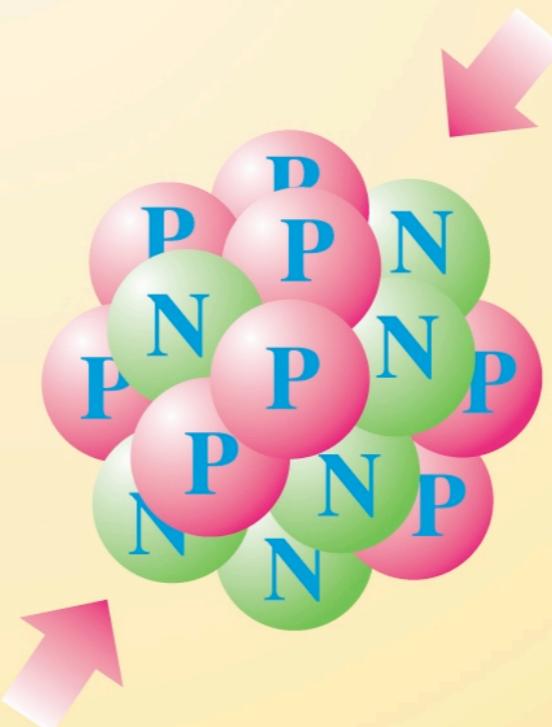
Electro-magnetism



Weak Interaction



Strong Interaction

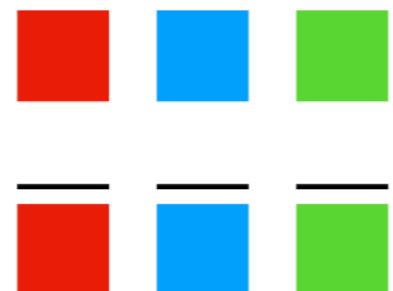


Gravitation



Quantum ChromoDynamics (QCD)

Interactions with color



- Quarks carry color charge - red/blue/green
- Anti-quarks also carry color charge - anti-red/anti-blue/anti-green

Comparing with Electromagnetism



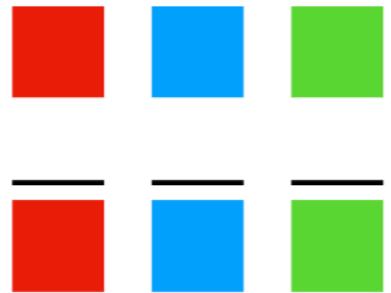
Electron
Negative
Charge



Positron
Positive
Charge

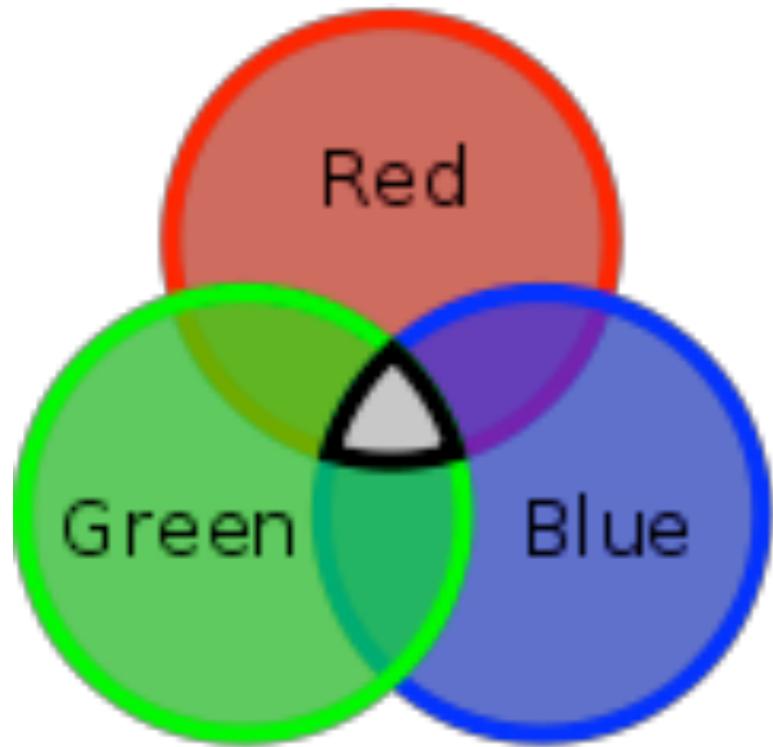
Quantum ChromoDynamics (QCD)

Interactions with color

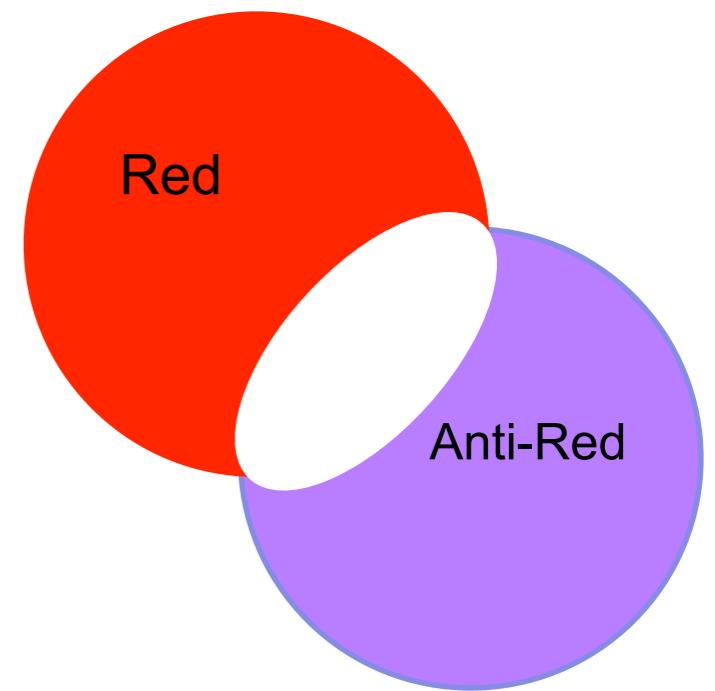


- Quarks carry color charge - red/blue/green
- Anti-quarks also carry color charge - anti-red/anti-blue/anti-green

Color is an abstract quantity



(Anti-)Quarks
must combine
to make
colorless (white)
objects

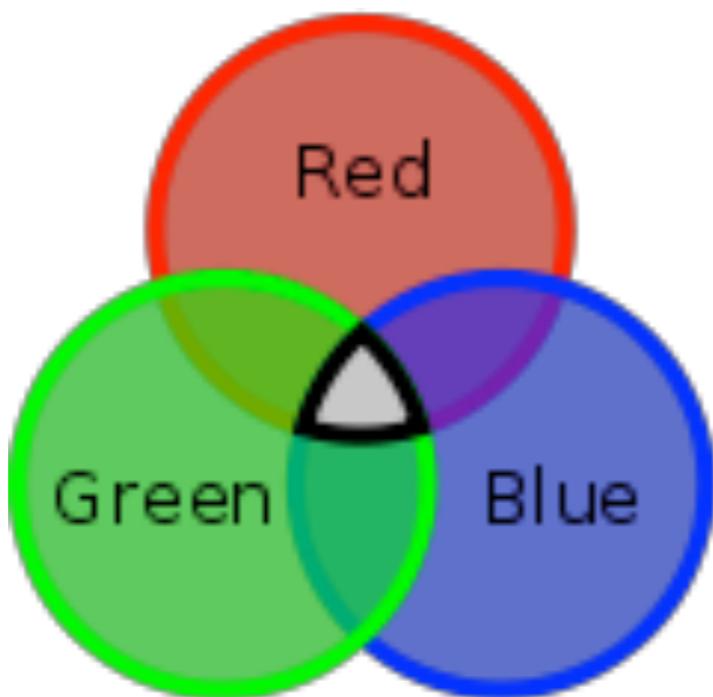


Question - 3

**What possible color-less
combinations of quarks/
anti-quarks can you make?**

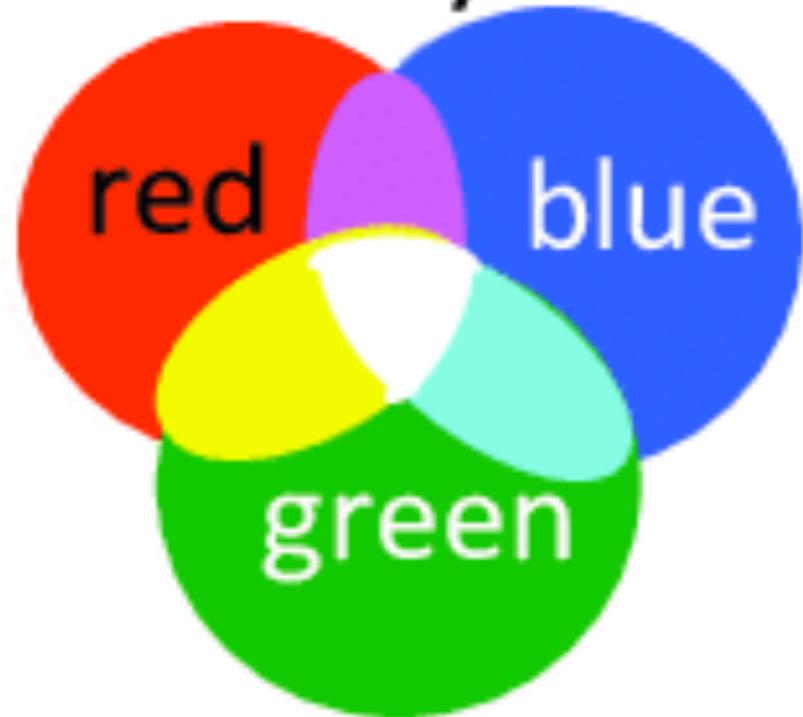
Question - 3

What possible color-less combinations of quarks/anti-quarks can you make?



Red + Green + Blue = White
Red + anti-Red = White

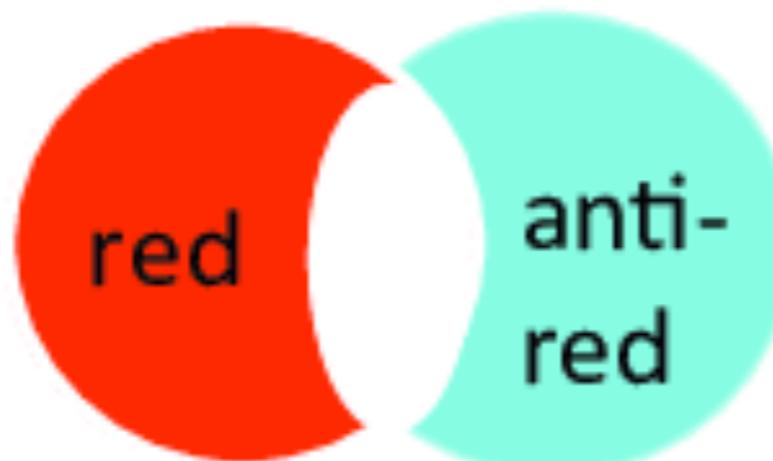
baryon



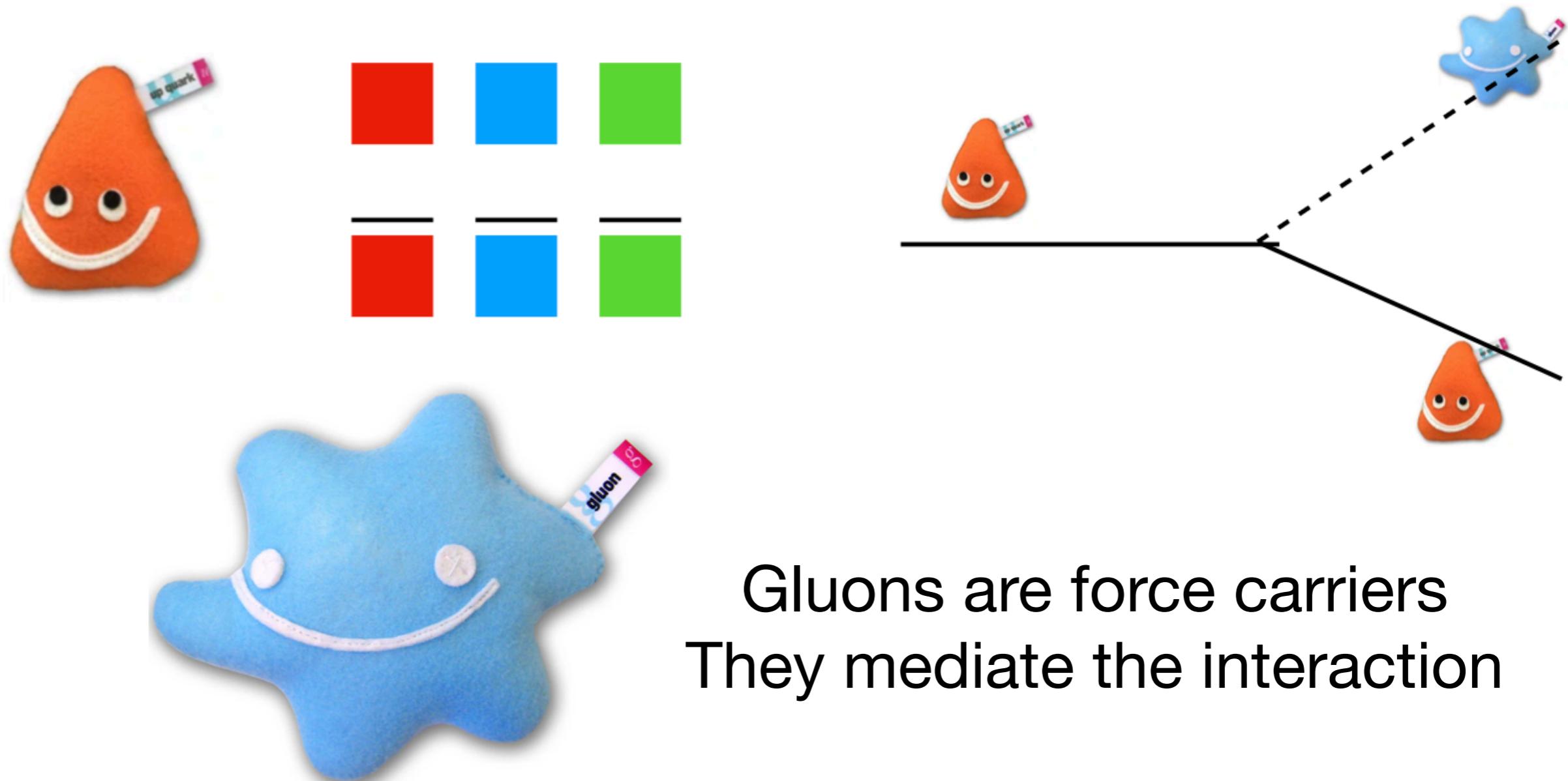
antibaryon



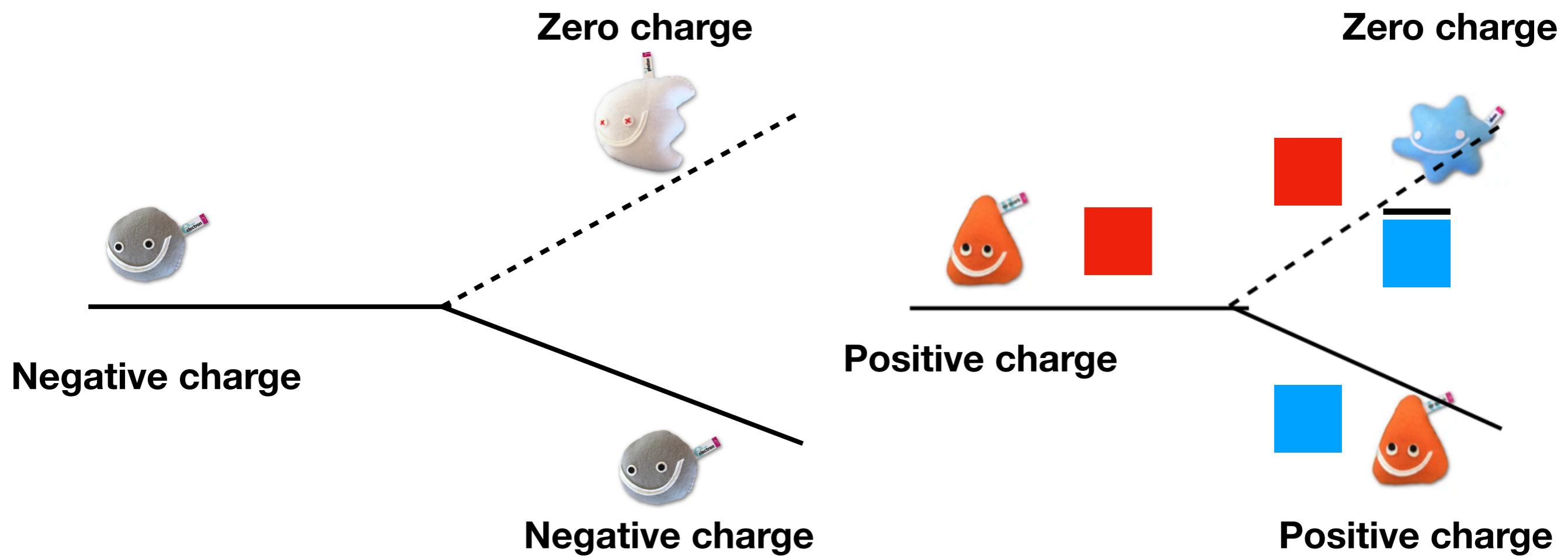
meson



Where do gluons come into the picture?

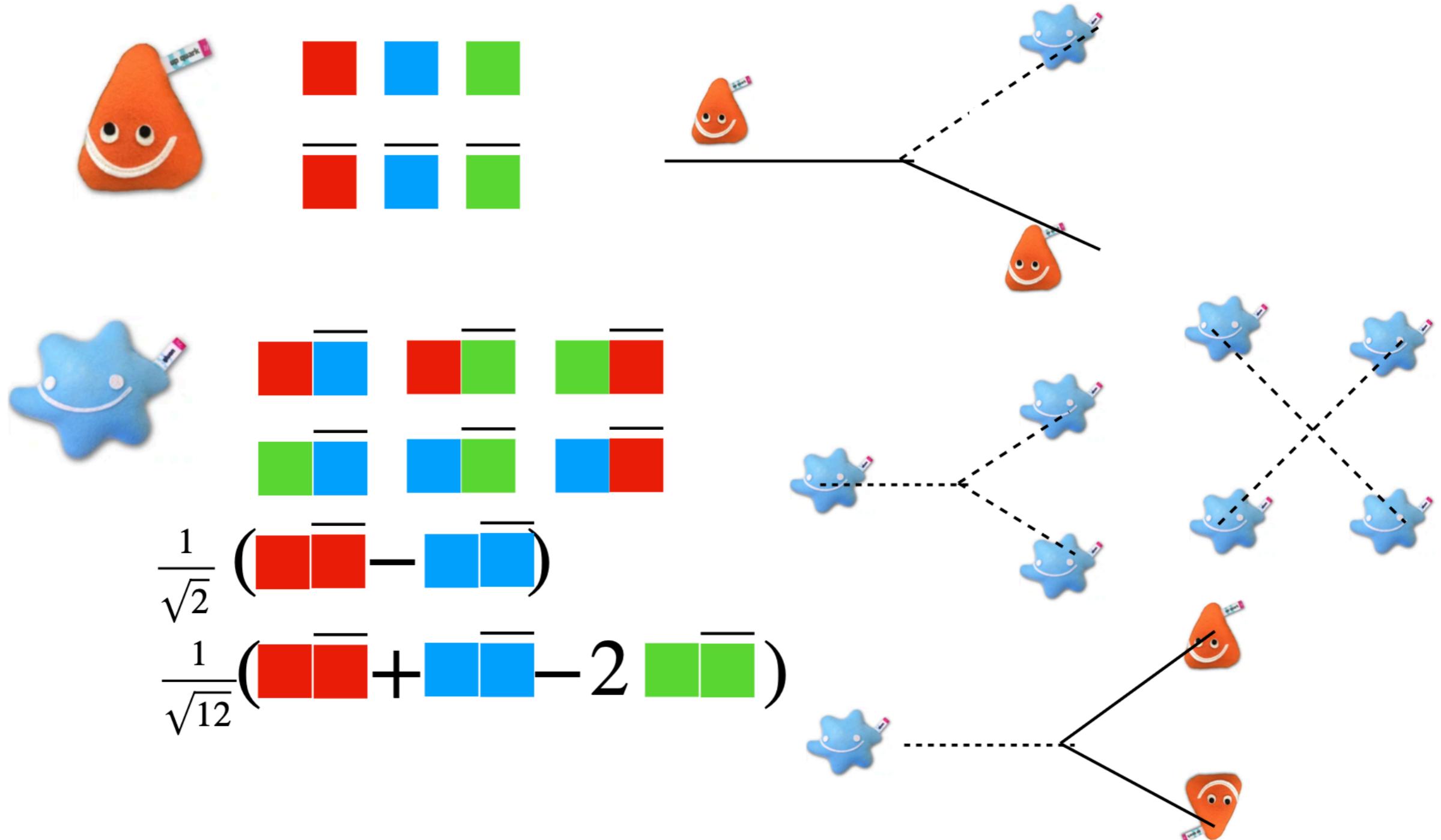


One essential difference with electro-magnetism



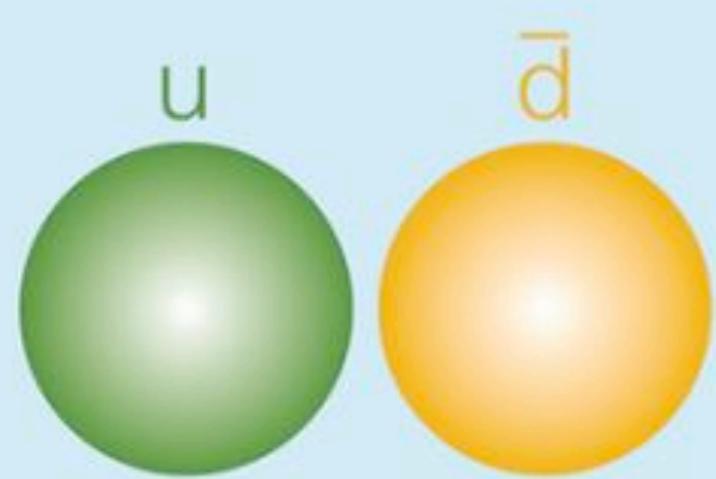
- Gluons carry color charge! Meaning that they can interact via the

Where do gluons come into the picture?



Types of matter particles made with quarks

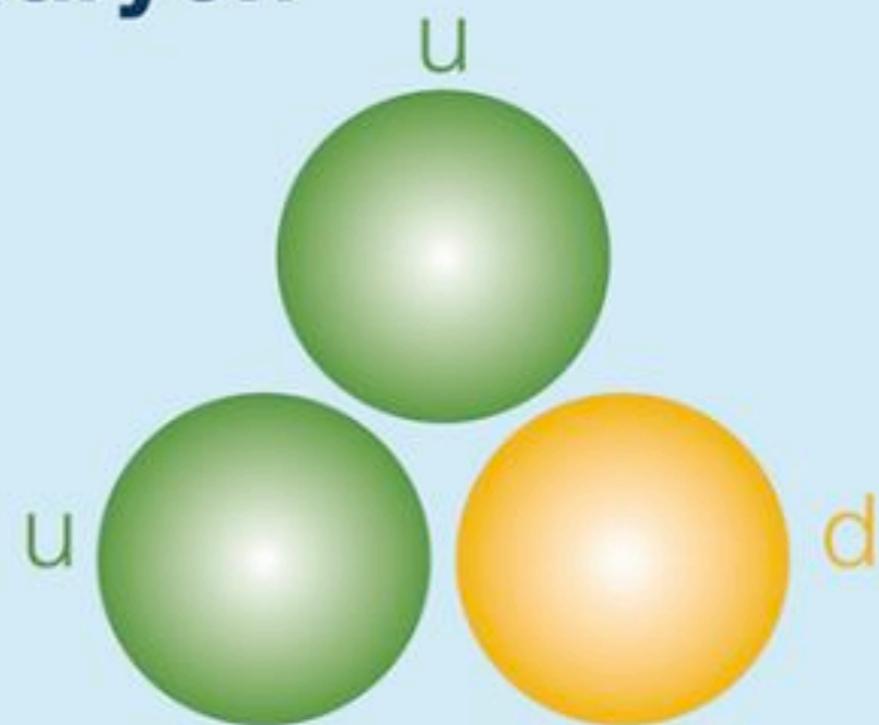
meson



Mesons are made of a quark and anti-quark

Shown here is a pion, made of an up and a down quark.

baryon



Baryons are made of three quarks

Shown here is a proton, made of two ups and a down.

Matter

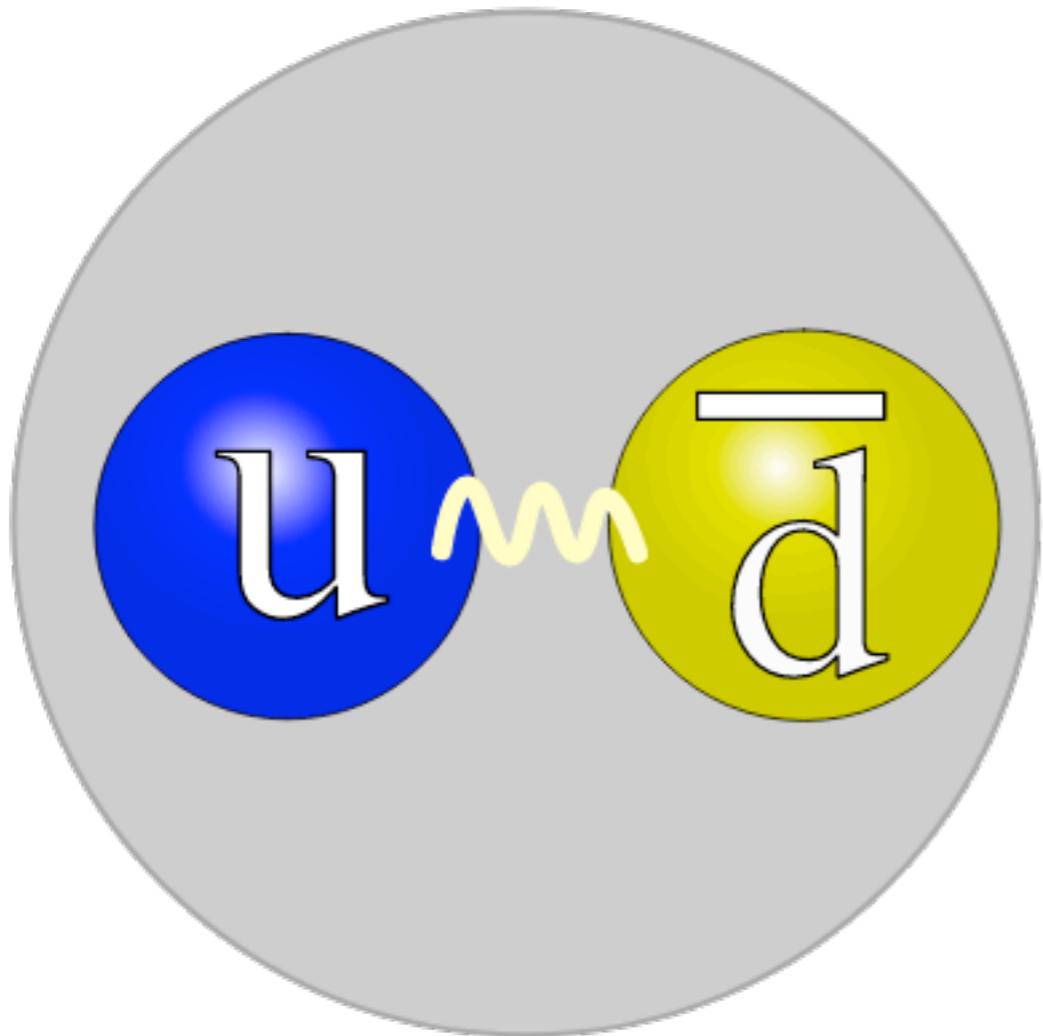


Anti-Matter



Collision of matter and anti-matter creates energy!

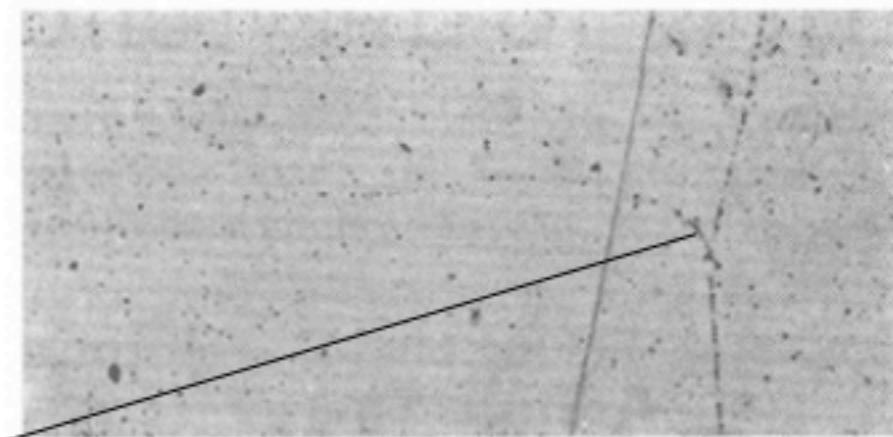
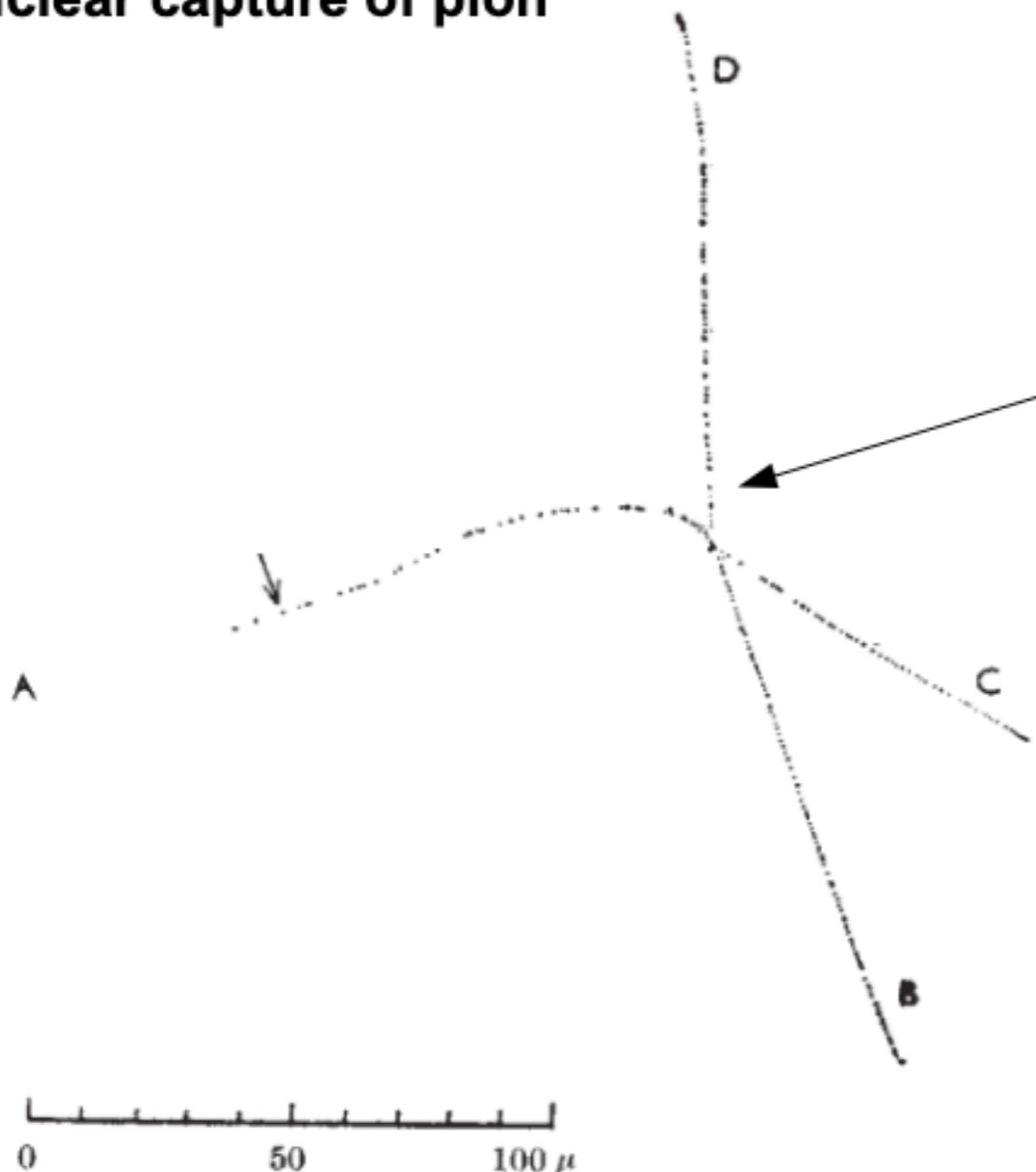
The simplest meson



- Positively charged pion
- Combination of up quark and anti down quark
- If I tell you the color of the up quark, what is the color of the anti-down quark?

First observation of the pion

Nuclear capture of pion



g. 1 a. PHOTOMICROGRAPH OF CENTRE OF STAR, SHOWING TRACK OF MESON PRODUCING DISINTEGRATION. (LEITZ 2 MM. OIL-IMMERSION OBJECTIVE. $\times 500$)

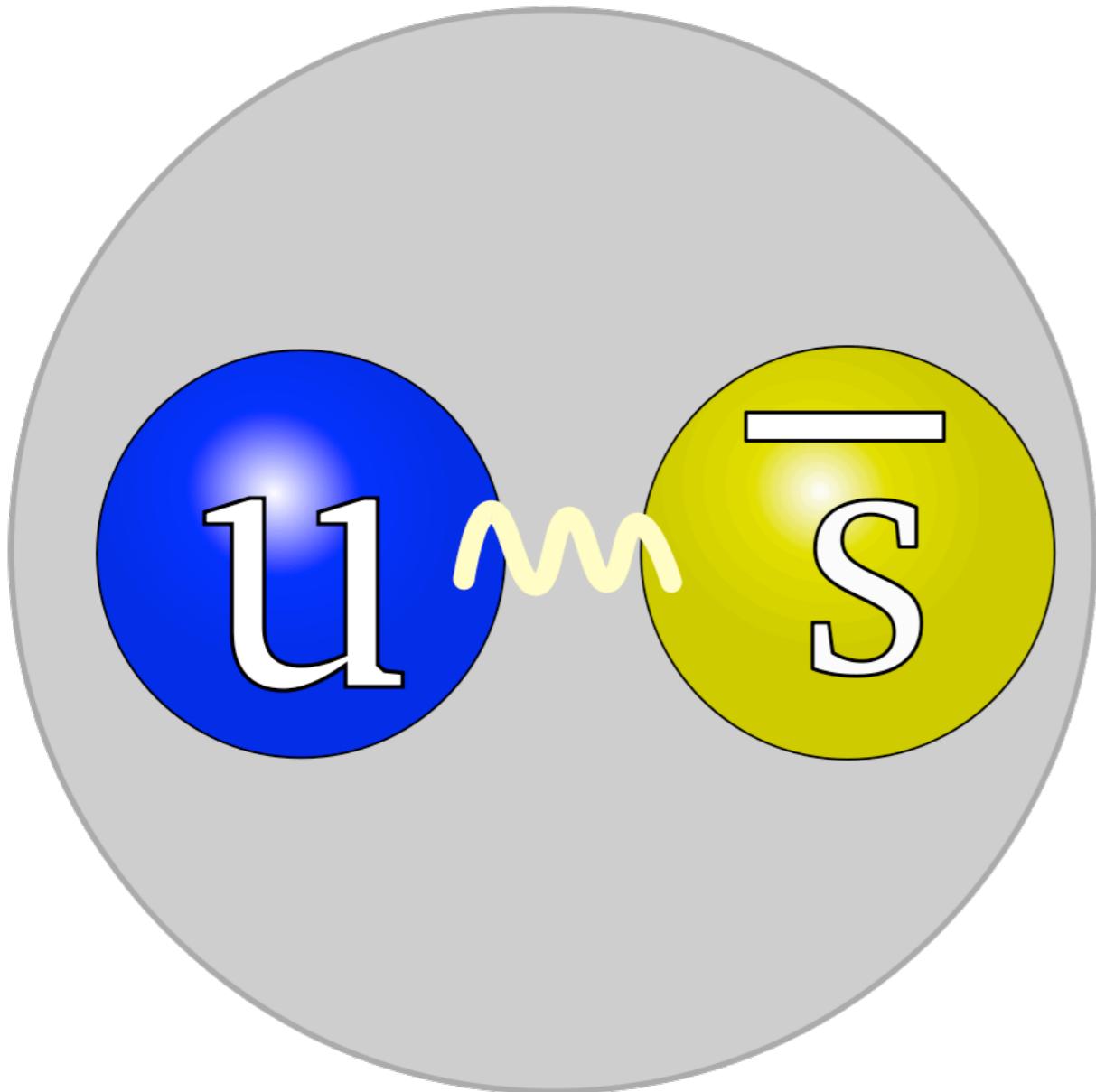
- A is the new meson
- B,D,C are likely protons
- Track C goes into the page

Why A is a new meson:
electron: range too large
proton: scattering too large
muon: frequent nuclear interaction

Fig. 1 b. TRACE OF COMPLETE STAR ON SCREEN OF PROJECTION MICROSCOPE, SHOWING PROJECTION OF THE TRACKS IN THE PLANE OF THE EMULSION. TRACK A CANNOT BE TRACED WITH CERTAINTY BEYOND THE ARROW

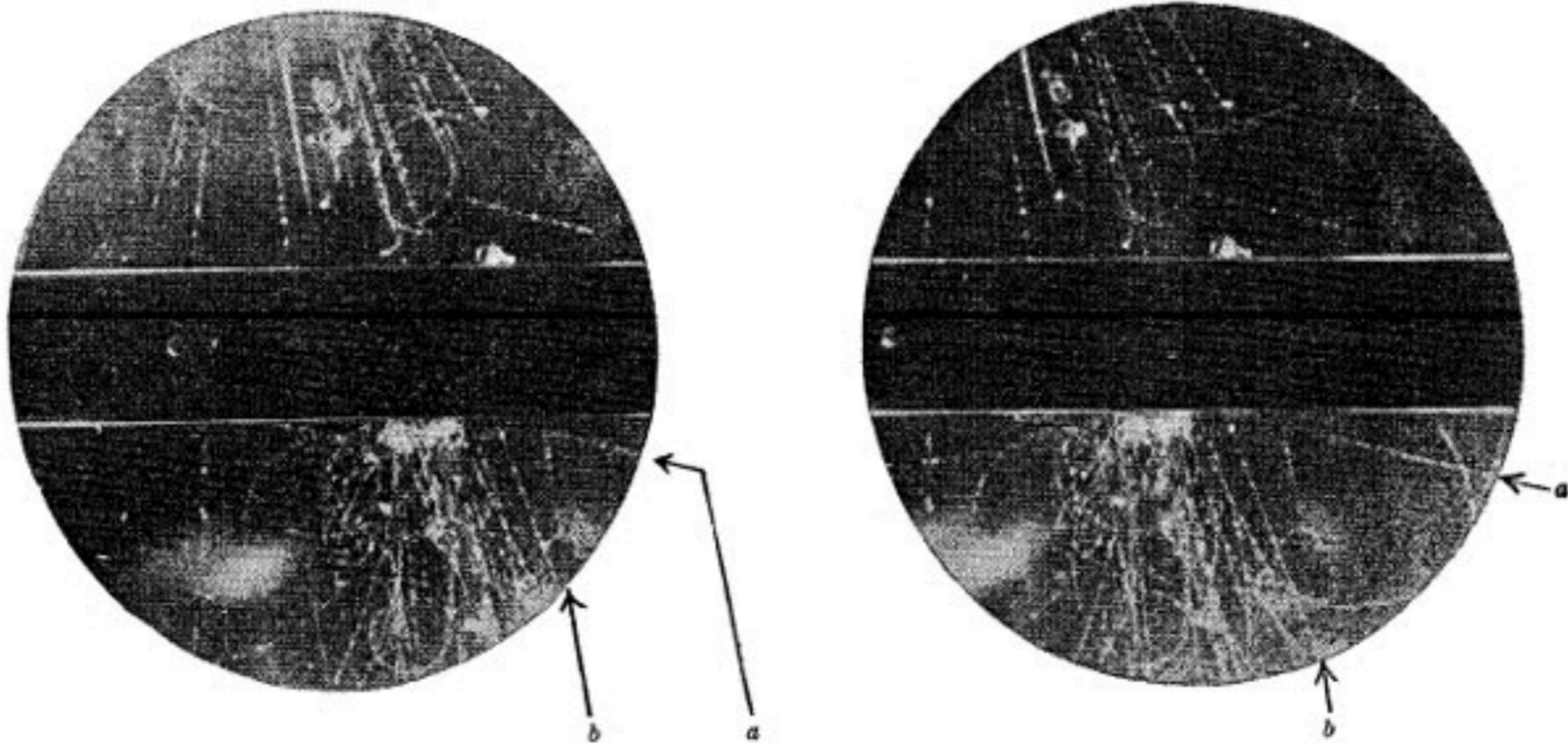
(Jan 1947, observed by D. Perkins)

A bit strange meson



- Kaon!
- What is its charge?
- Does the proton originally have anti-strange quark?

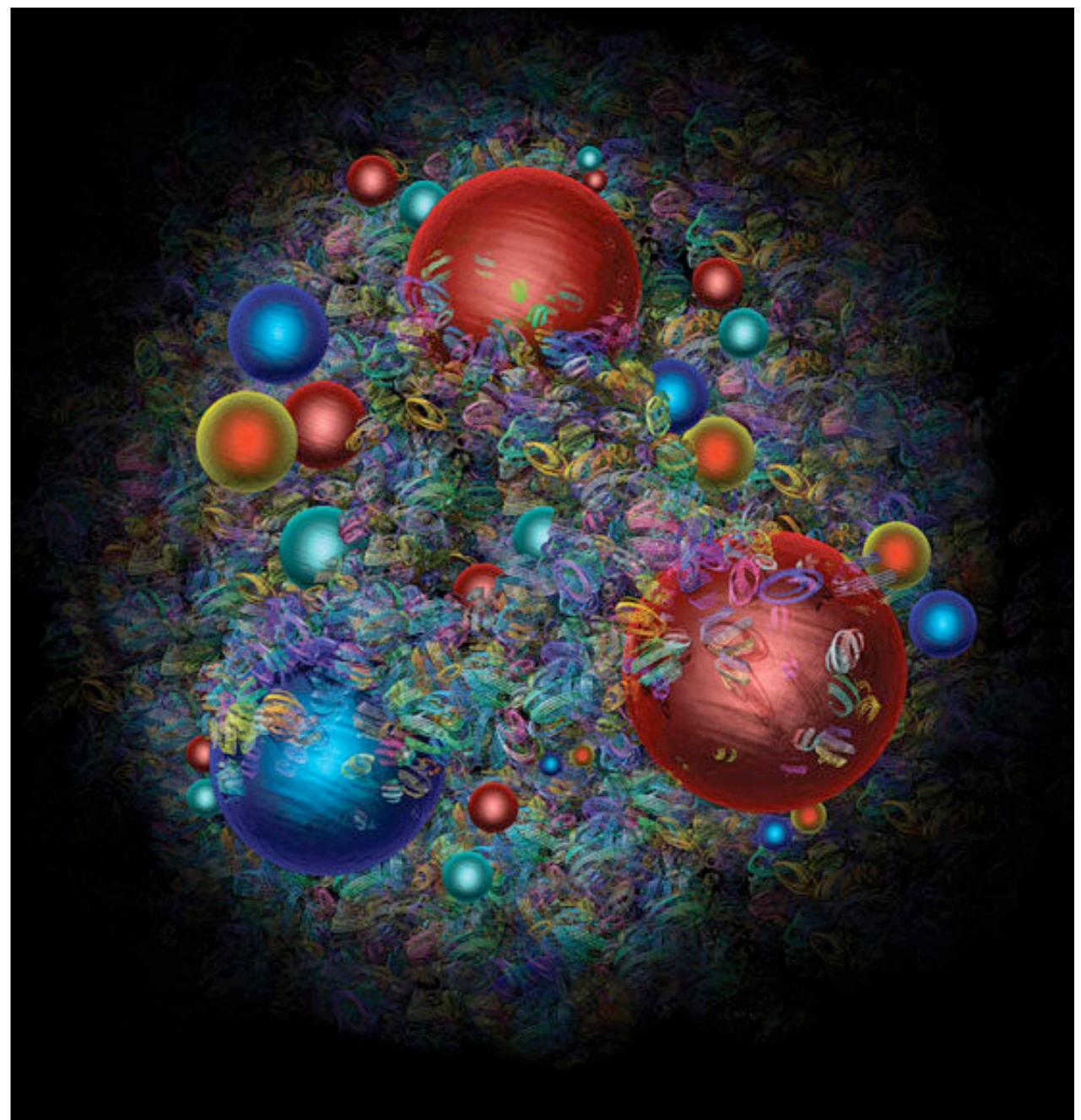
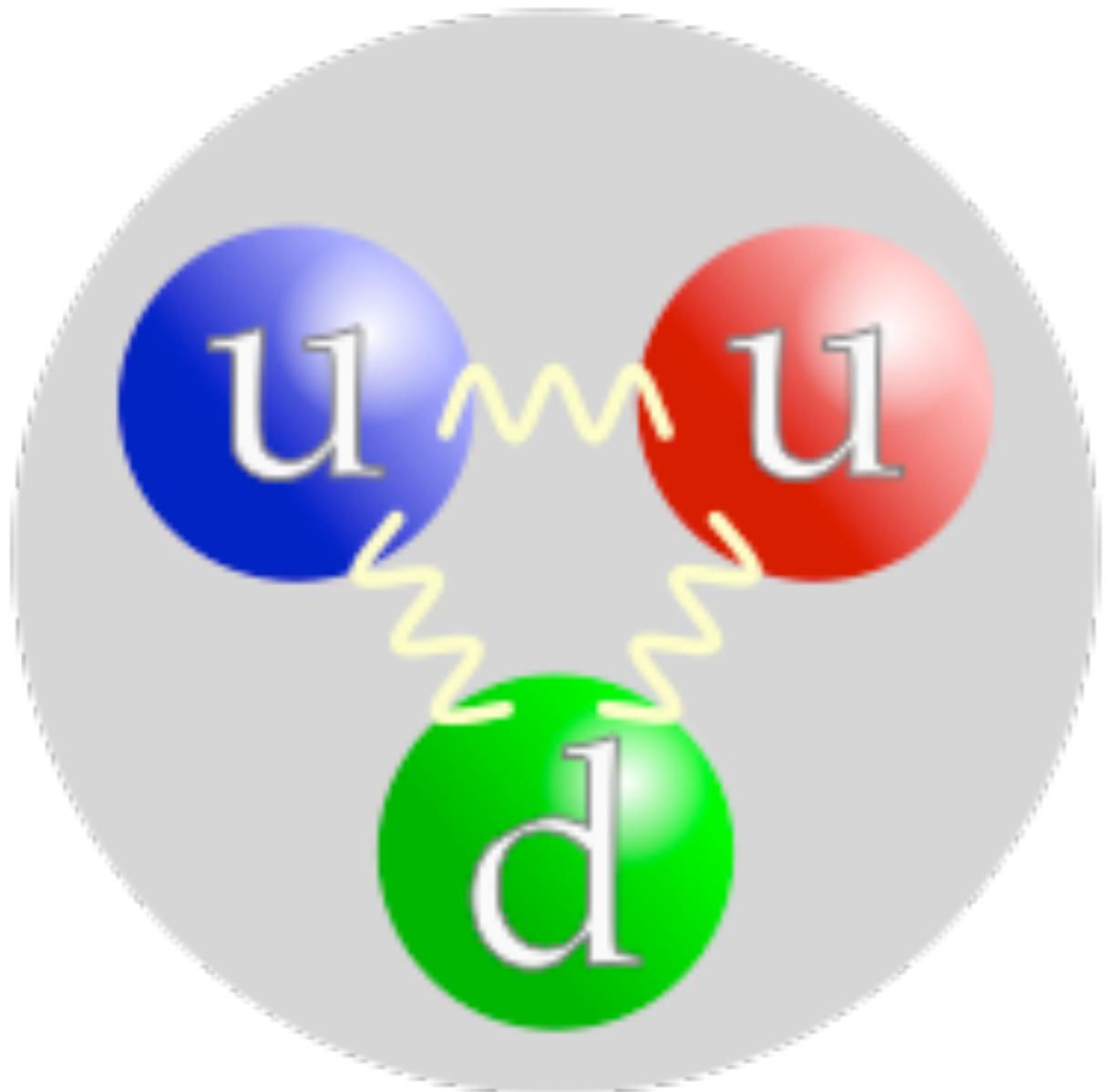
Observation of Kaon



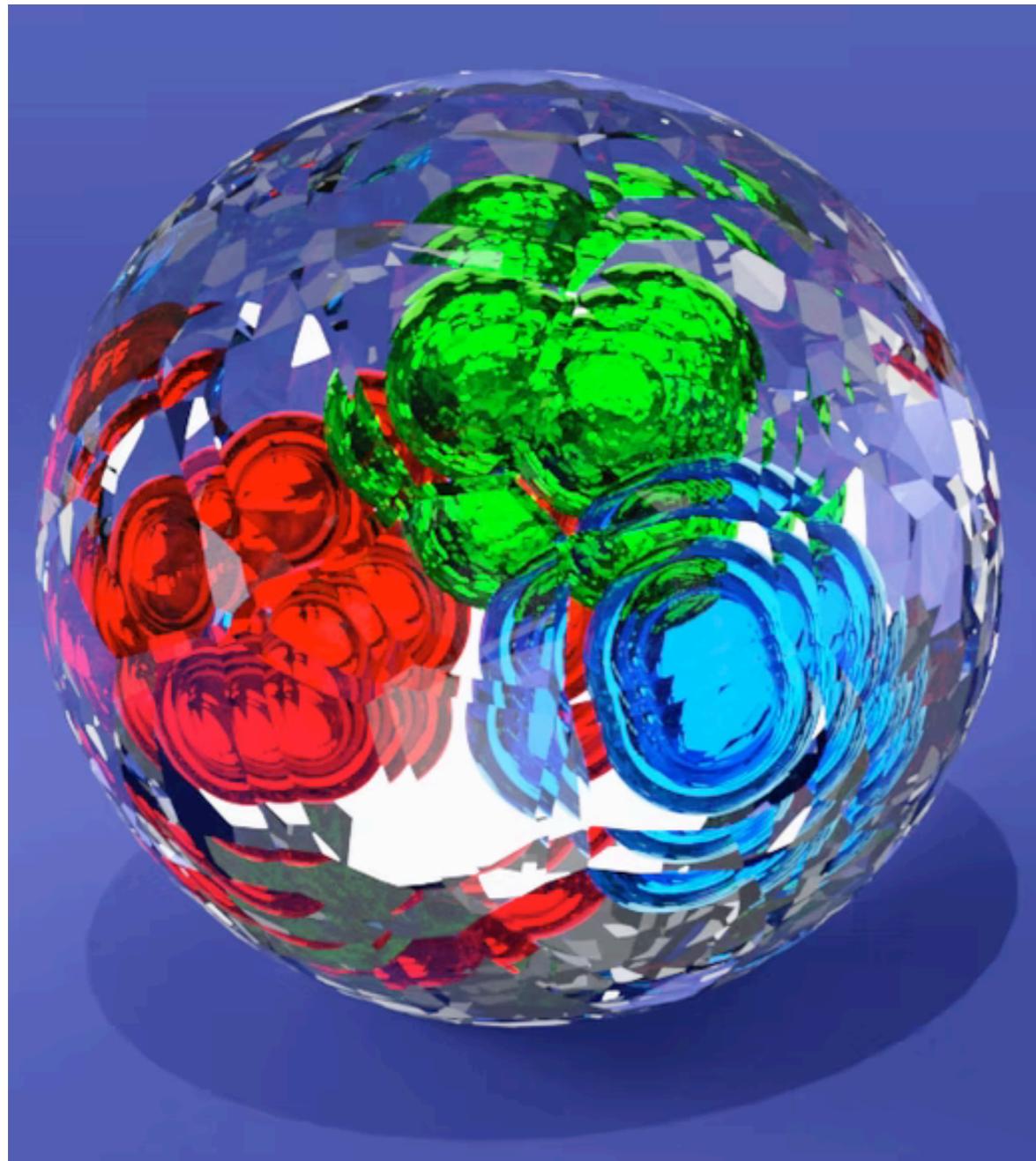
Stereoscopic photographs showing an unusual fork (a b) in the gas. The direction of the magnetic field is such that a positive particle coming downwards is deviated in an anticlockwise direction (Image: Nature)

Published December 1947

Baryons

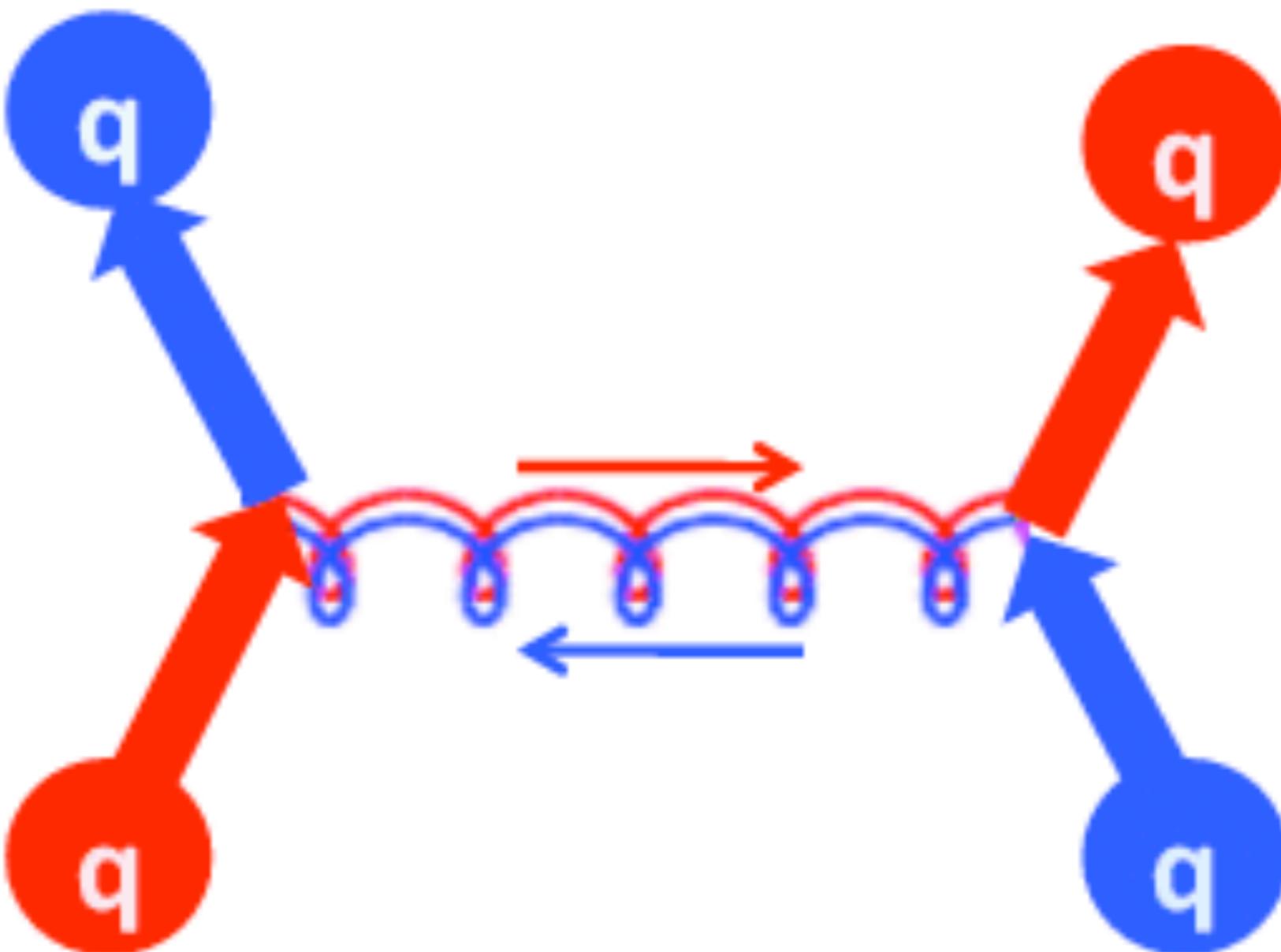


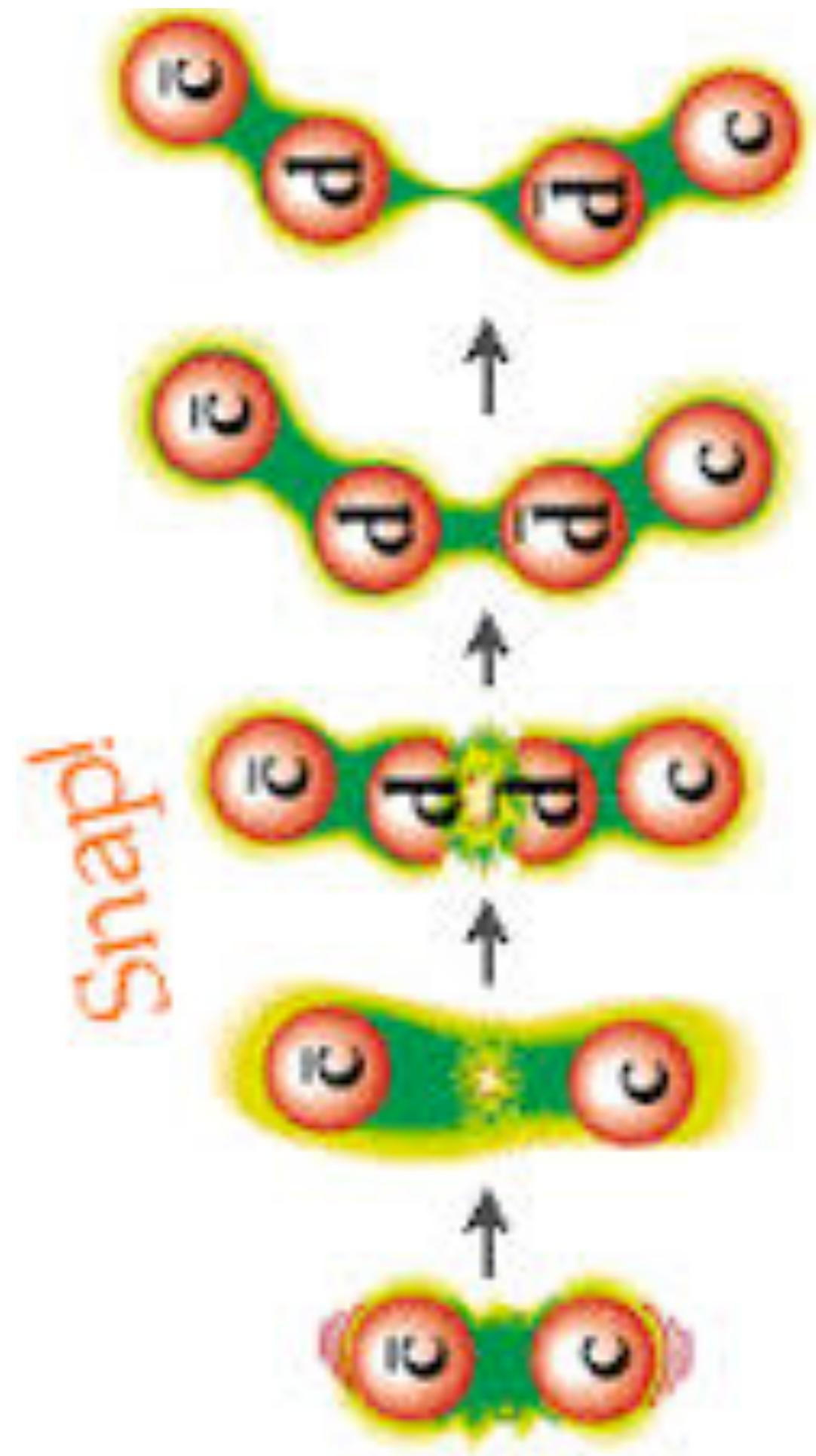
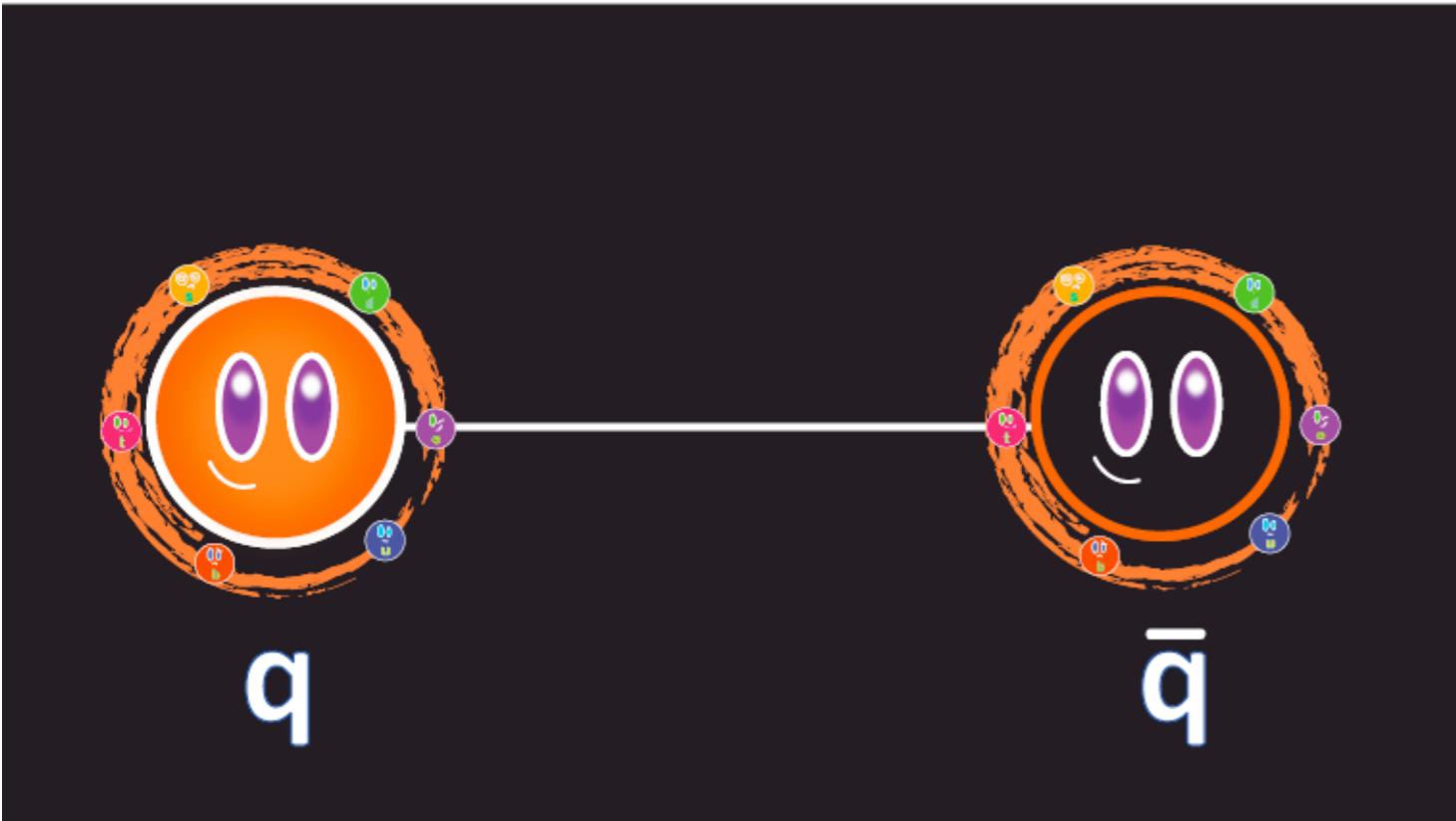
Where does the mass come from?

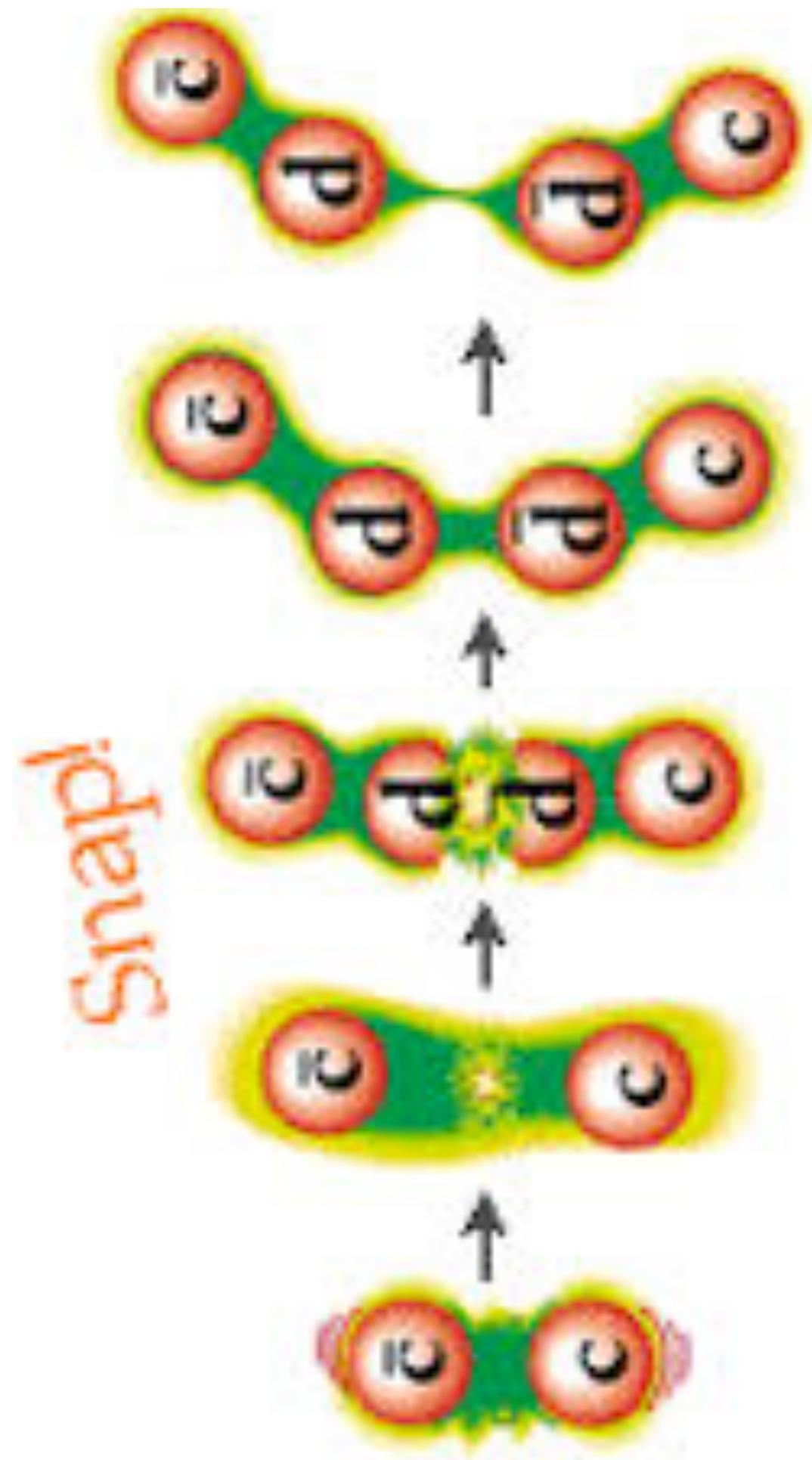
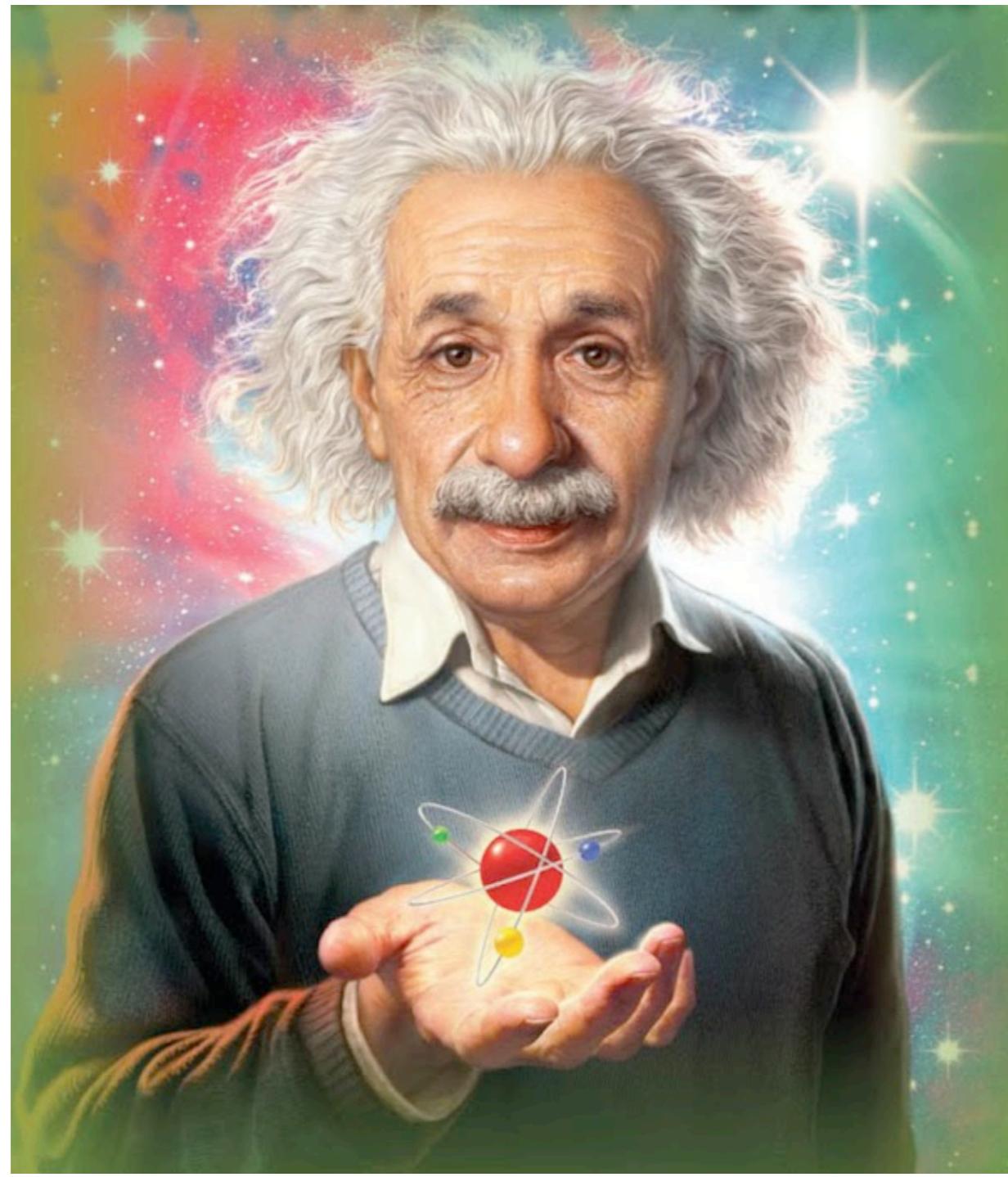


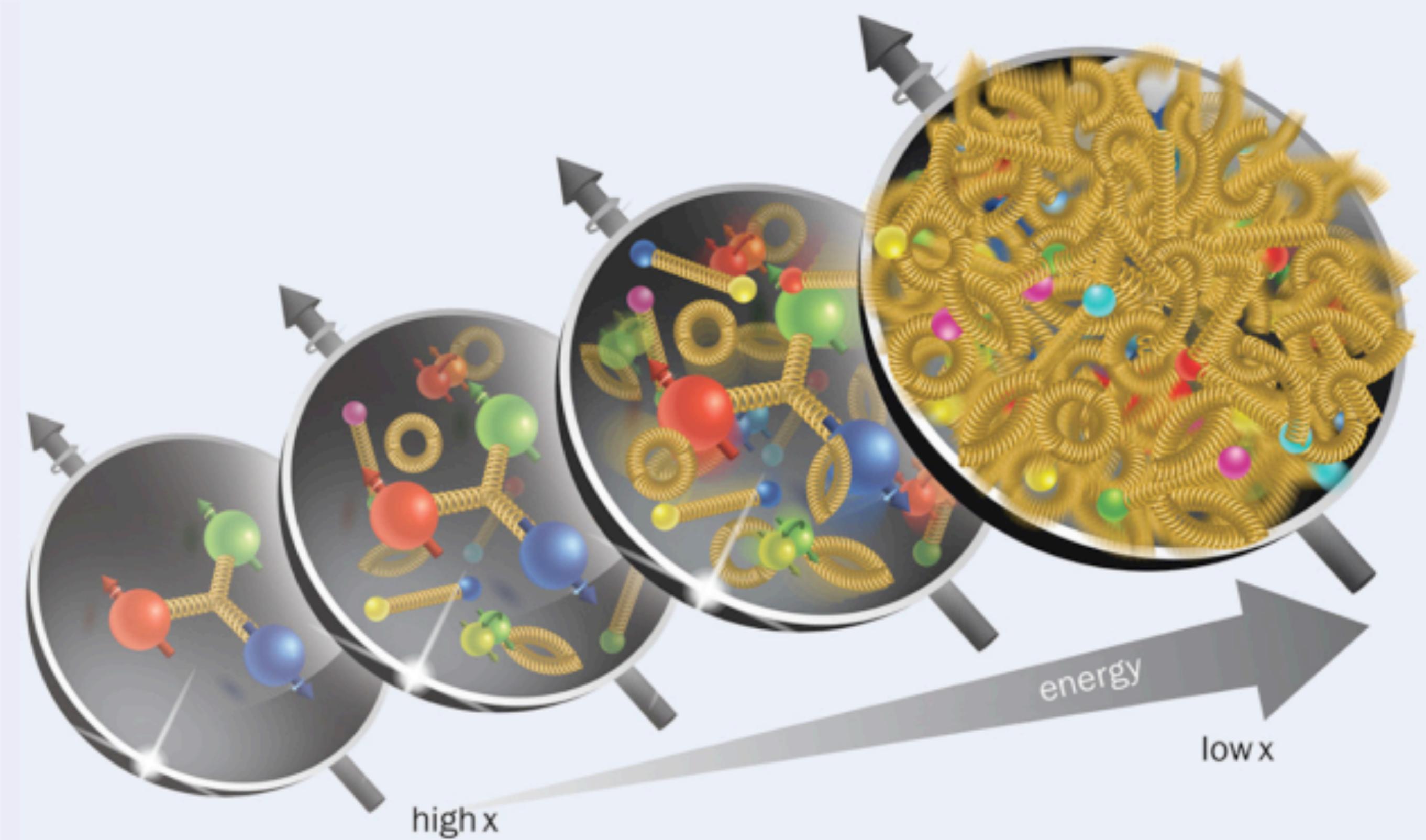
- Up quark mass ~ 2 MeV
- Down quark mass ~ 4.7 MeV
- Proton mass ~ 1000 MeV
- Where is the rest??

Gluons are crucial!







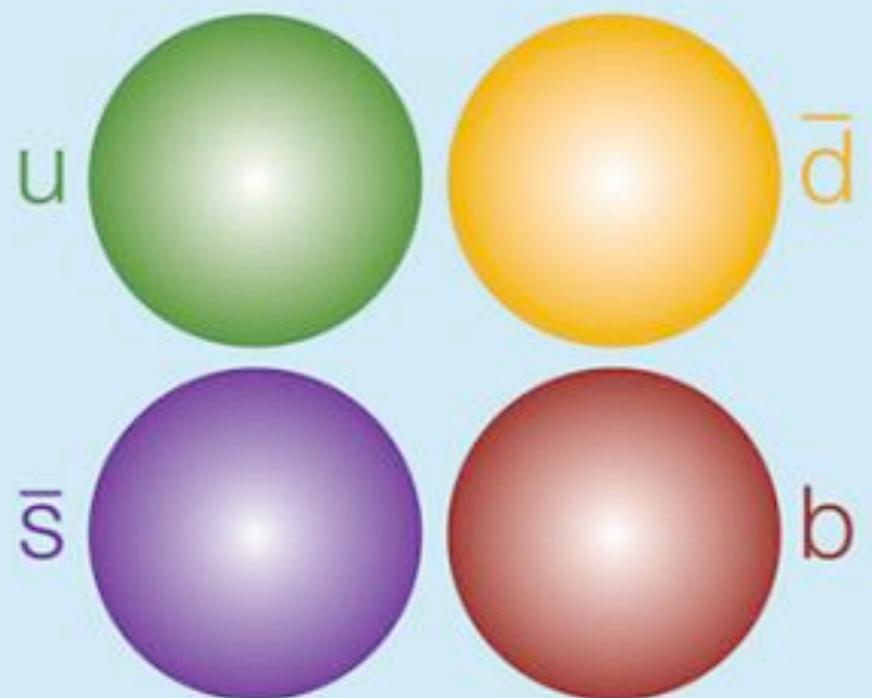


Ok so there are baryons and mesons.

Any more color neutral combinations you can think of?

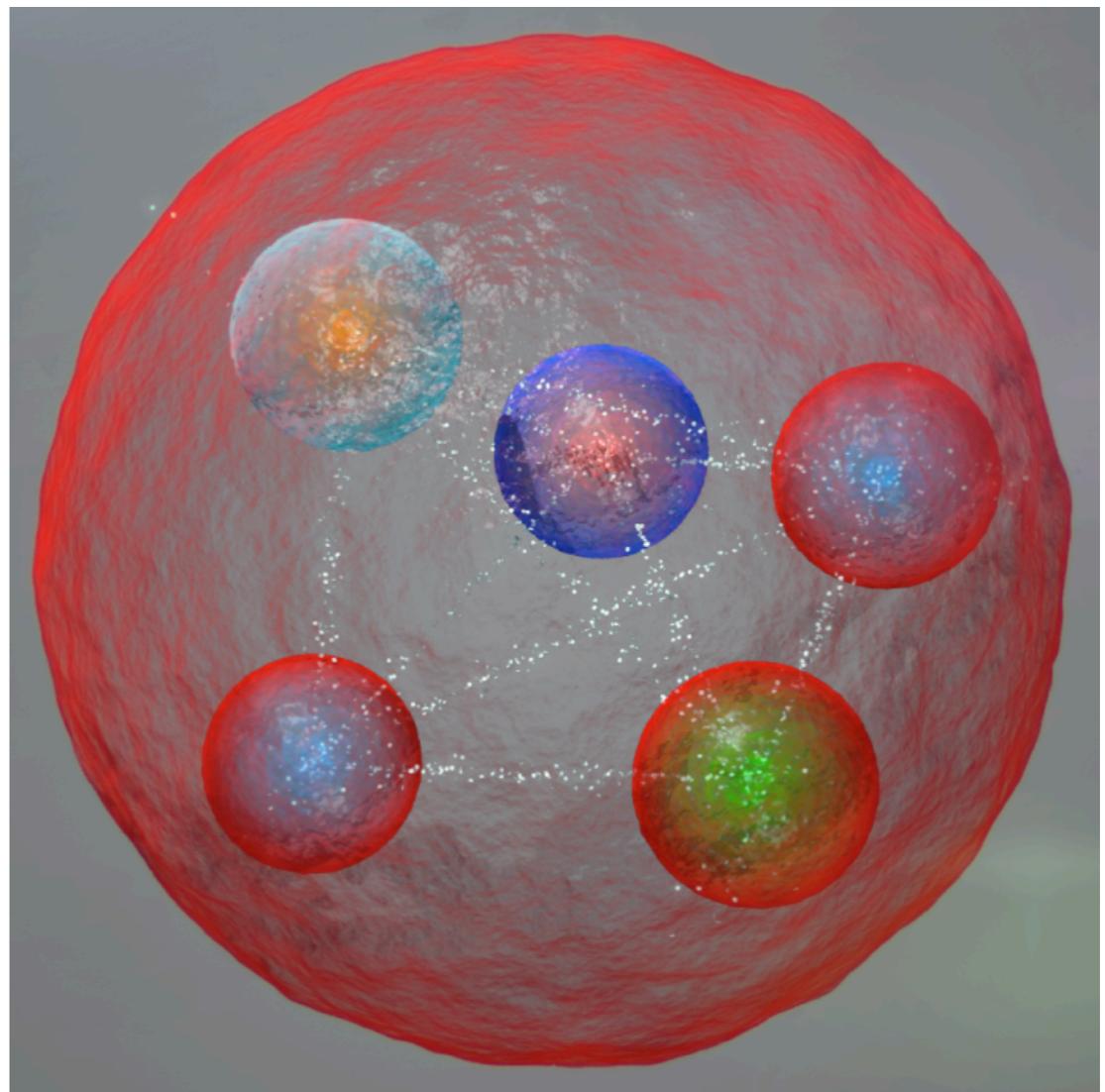
Potential new particles!

tetraquark



Tetraquarks are
made of four quarks

Pentaquark!



This is $X(5568)$, which is made of an up, down, strange and bottom quark.

Collisions products

- Fundamental Particles
- Scattered Electron
- Photons
- Positrons
- Composite Particles
- Mesons (Pions/Kaons/..)
- Baryons (protons/neutrons)
- Any more?



Lets run our own simulations! - to the jupyter notebooks