hi

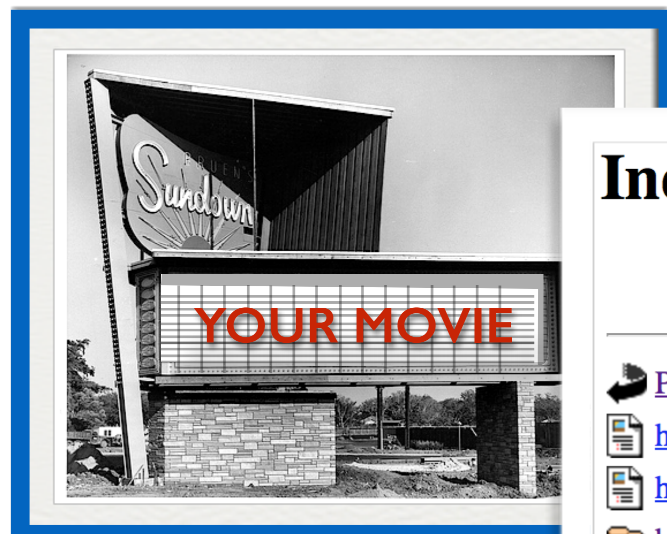
Lecture 27, 04.18.2017

Particle Physics 2

housekeeping

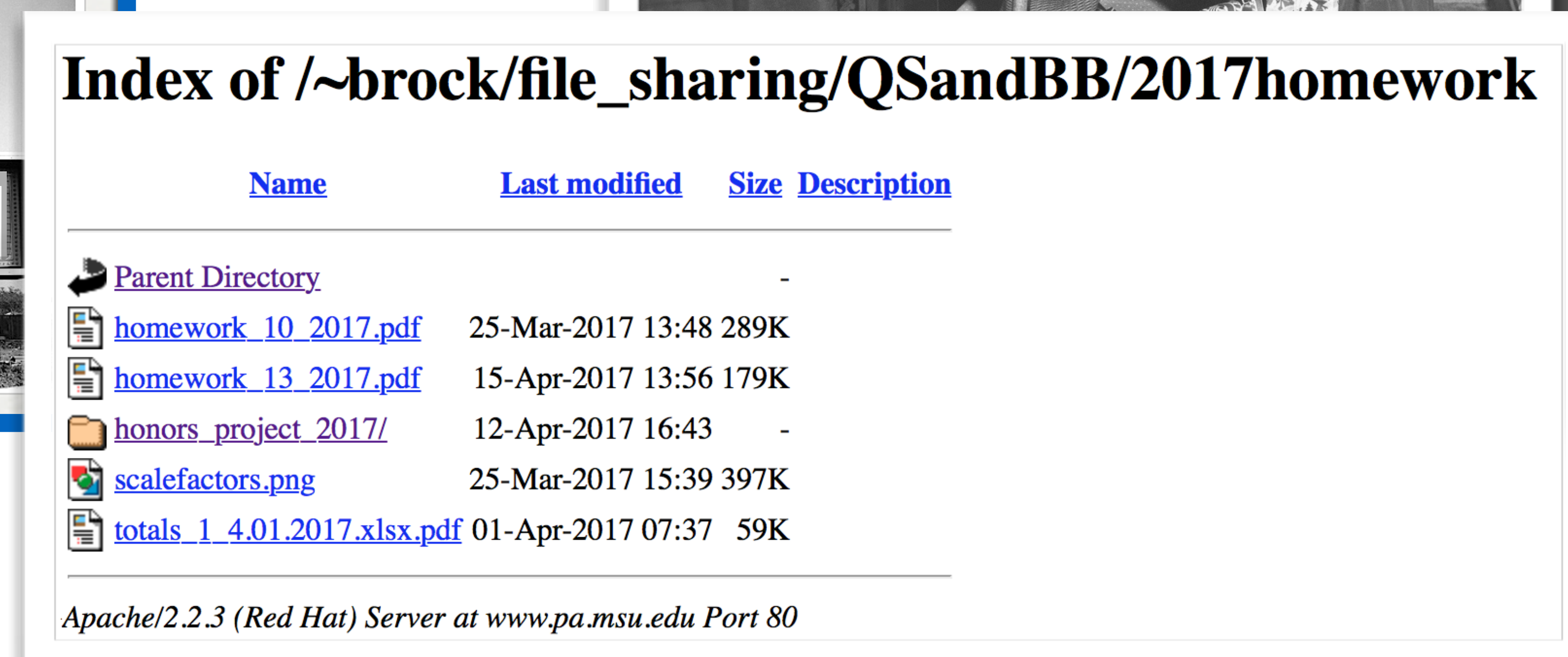
Question about anything?

I'll make a movie for you:



Poster selection:

outline due April 20...read the instructions.



Index of /~brock/file_sharing/QSandBB/2017homework

Name	Last modified	Size	Description
Parent Directory		-	
homework_10_2017.pdf	25-Mar-2017 13:48	289K	
homework_13_2017.pdf	15-Apr-2017 13:56	179K	
honors_project_2017/	12-Apr-2017 16:43	-	
scalefactors.png	25-Mar-2017 15:39	397K	
totals_1_4.01.2017.xlsx.pdf	01-Apr-2017 07:37	59K	

Apache/2.2.3 (Red Hat) Server at www.pa.msu.edu Port 80

Final:

There is a second midterm (think "final") next week. It will happen over the last weekend before Finals Week

One of the homeworks will walk you through some of the Feynman Diagram parts of the actual Finals-day FD part

Homework:

13 points-worth in MasteringPhysics + 17 points-worth on paper

http://www.pa.msu.edu/~brock/file_sharing/QSandBB/2017homework/

now hear this

To: RAYMOND L BROCK

From: sirs@msu.edu

Student Instruction Rating System (SIRS Online) collects student feedback on courses and instruction at MSU. Student Instructional Rating System (SIRS Online) forms will be available for your students to submit feedback during the dates indicated:

ISP 220 001: 4/17/2017 - 5/17/2017
ISP 220 002: 4/17/2017 - 5/17/2017

Direct students to https://sirsonline.msu.edu.

Students are required to complete the SIRS Online form OR indicate within that form that they decline to participate. Otherwise, final grades (for courses using SIRS Online) will be sequestered for seven days following the course grade submission deadline for this semester.

SIRS Online rating summaries are available to instructors and department chairs after 5/17/2017 at https://sirsonline.msu.edu. Instructors should provide copies of the rating summaries to graduate assistants who assisted in teaching their course(s). Rating information collected by SIRS Online is reported in summary form only and cannot be linked to individual student responses. Student anonymity is carefully protected.

If you have any questions, please contact Michelle Carlson, (mcarlson@msu.edu, (517)432-5936).

also:

I'll have an optional anonymous course review with points

Honors Project

Data due April 22. Paper due on May 4 (final day).

the dropbox instructions? Forget them. We'll be uploading files to a site in Norway. I'll let you know.

Read the Second of two sets of instructions:

`MinervaInstructions2_2017.pdf` in

www.pa.msu.edu/~brock/file_sharing/QSandBB/2017homework/

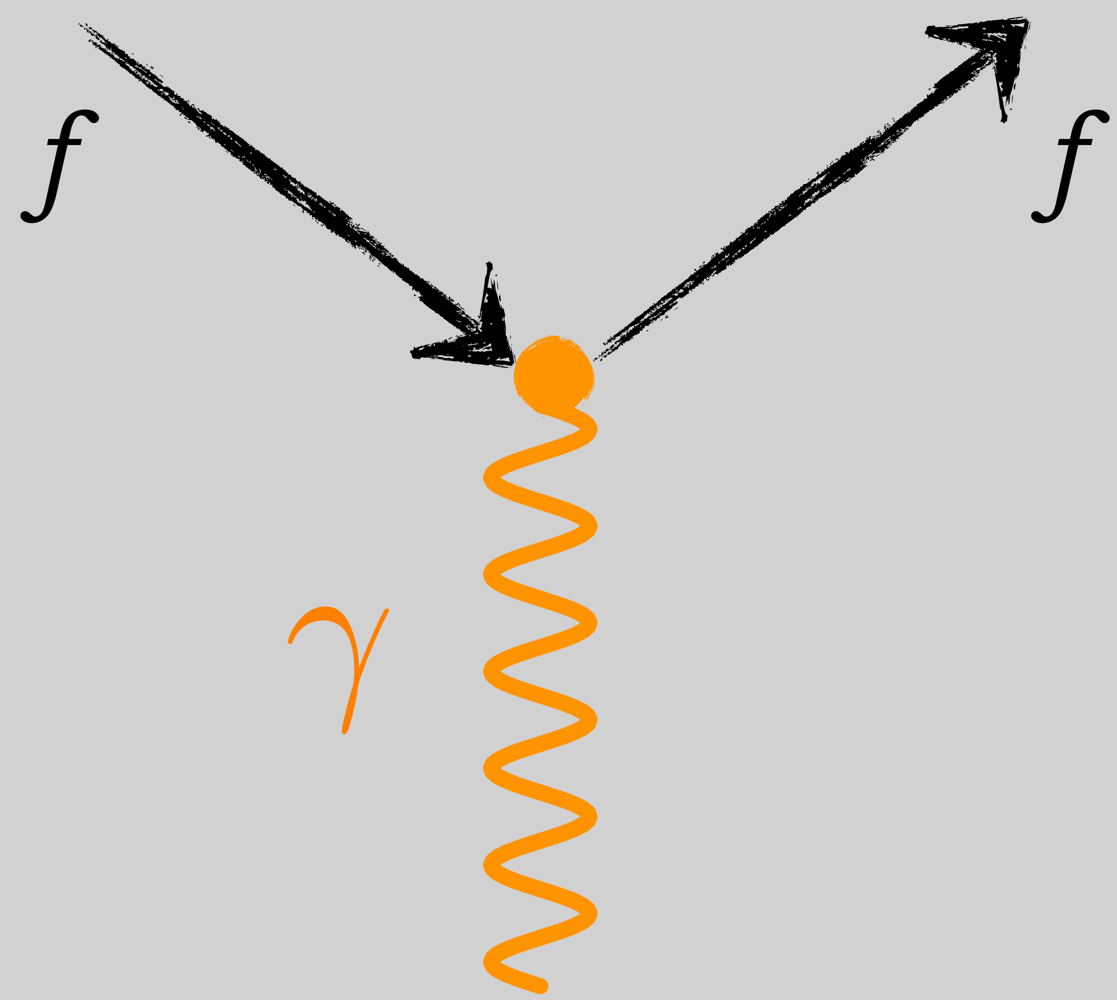
I need a 

to test the Z-path uploading machinery and instructions

primitive diagrams

are general

but this is completely general...for any charged fermion:

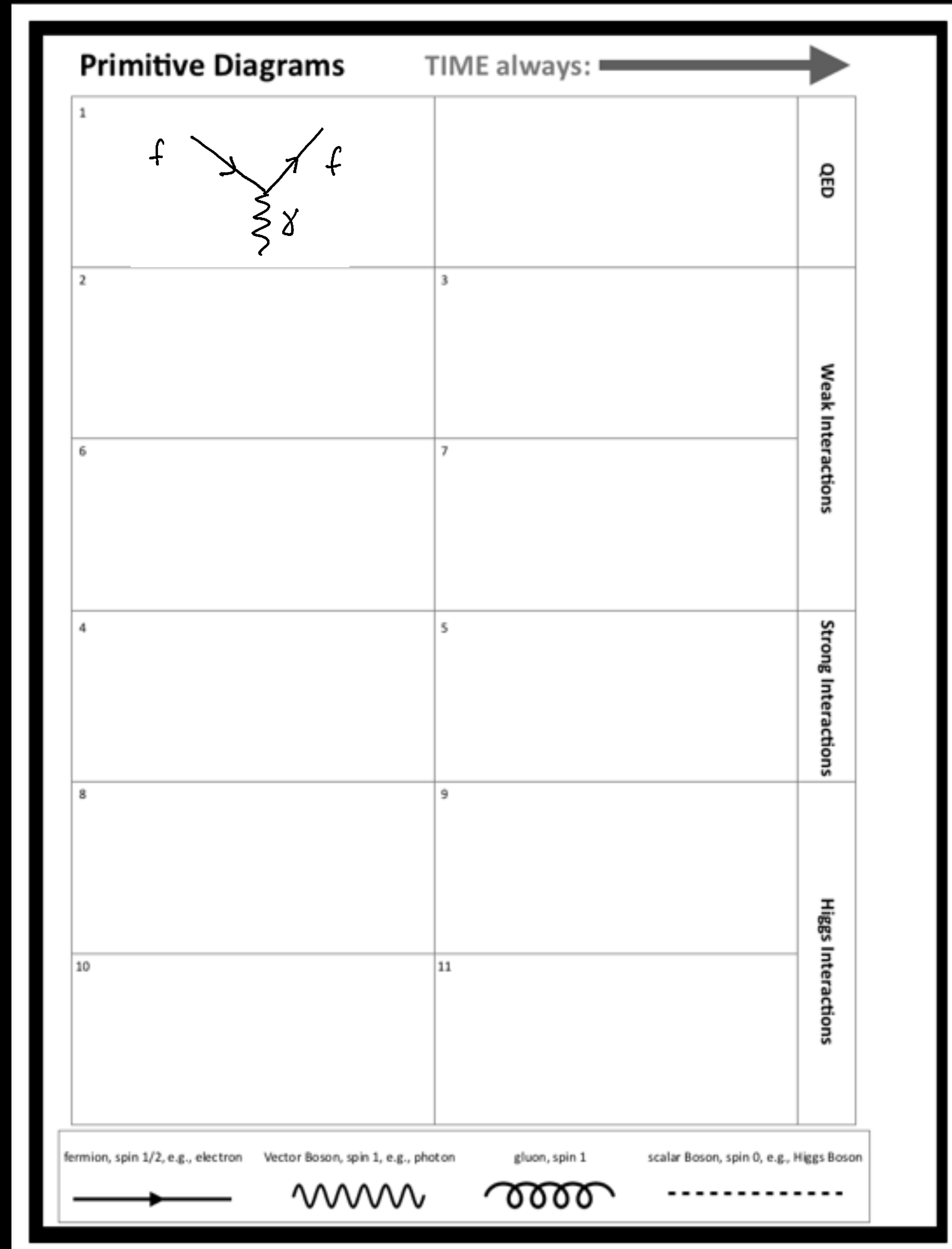


f could be electron, positron, proton, antiproton...and more – any electrically charged **f**ermion.

Their diagrams are identical.

Primitive Diagram Scorecard

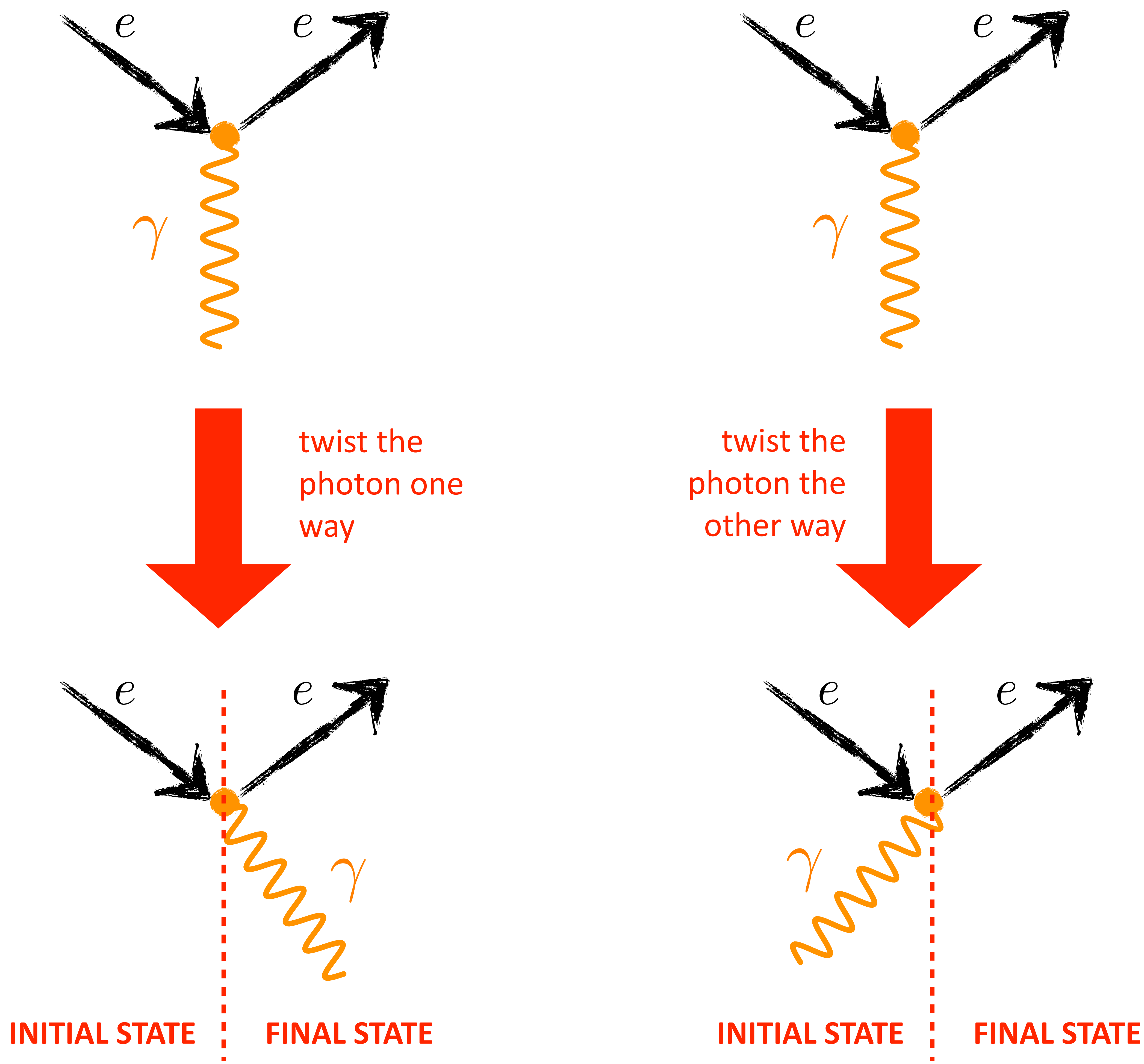
your first entry



for example

from my primitive, I can make two standard processes

the photon is its own antiparticle



electron radiating, as I noted

electron reacting to a electric Coulomb force or a magnetic Lorentz force

particle physics

particle: **neutron**

symbol:	n
charge:	0
mass:	1.6749×10^{-27} kg, 939.6 MeV/c^2
spin:	1/2
category:	fermion, baryon, I = –1/2, B = 1

particle: **proton**

symbol:	p
charge:	$+1e$
mass:	1.6726×10^{-27} kg, 938.2 MeV/c^2
spin:	1/2
category:	fermion, baryon, I = 1/2, B = 1

important realizations

weak force: neutrinos

exchange force

nuclear force

beta decay

the "weak force"

beta decay

something seriously wrong

remember: #neutrons doesn't affect the Chemistry

can add neutrons

as long as the nucleus is energetically stable

"isotopes"

^{13}C: 1.1% & stable

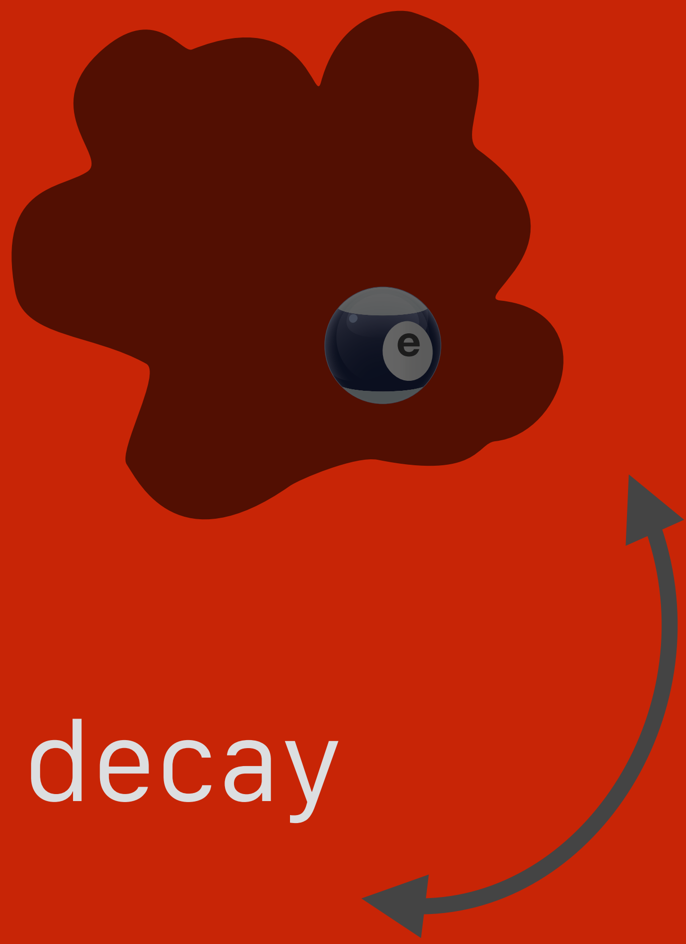
^{14}C: trace & unstable

some isotopes are unstable

they beta-decay

14C: trace amounts & unstable

But there was a problem with beta decay

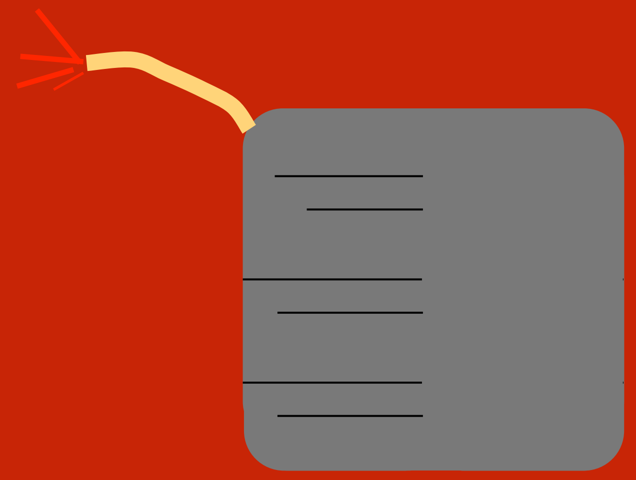


notice the funny recoil?

Suppose we have a firecracker exploding into two pieces:

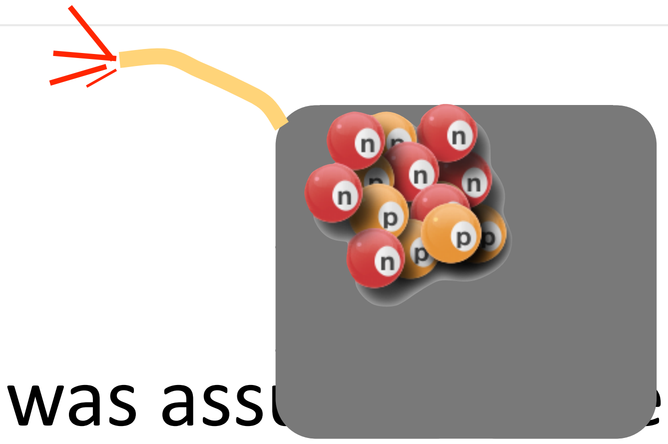
beta decay seemed like this

when you expect this



energies in a “two body decay”

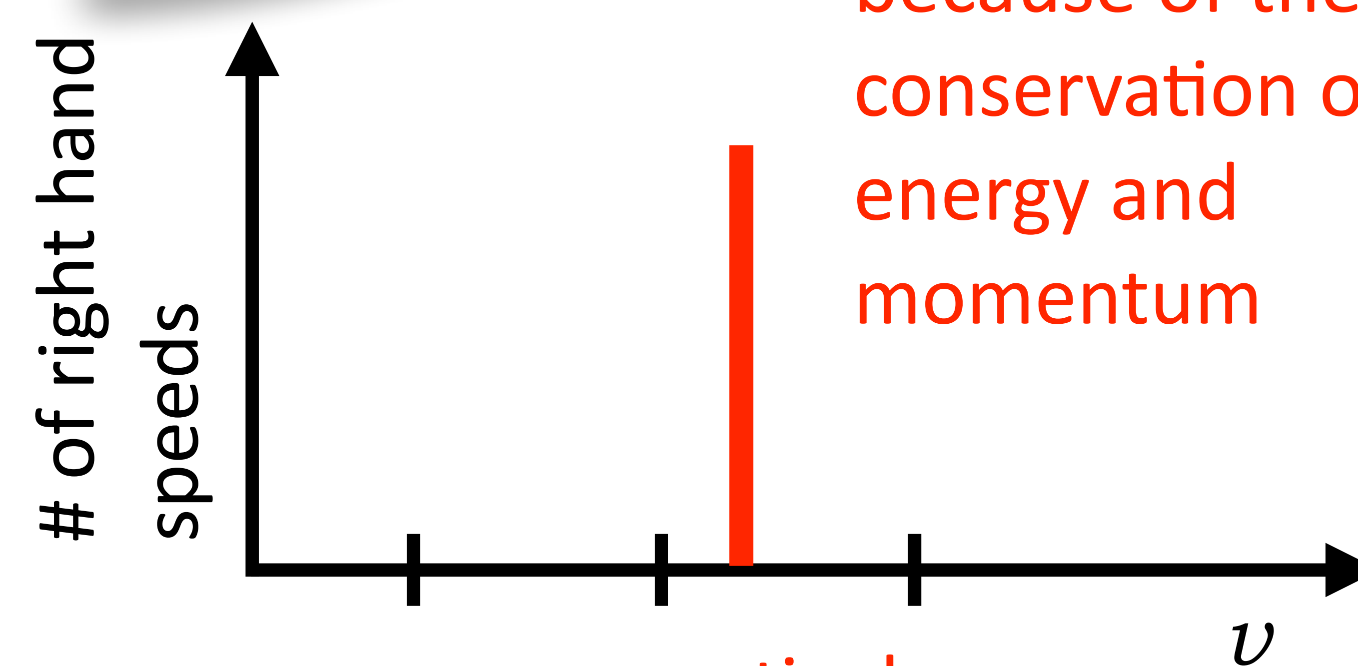
are single-valued



Beta decay was assu[...] 2-body decay:
Nucleus ---> e and Nucleus’

Do 100 decays and measure the energy of either object...

Should get a particular speed for the electron



because of the conservation of energy and momentum

a particular value

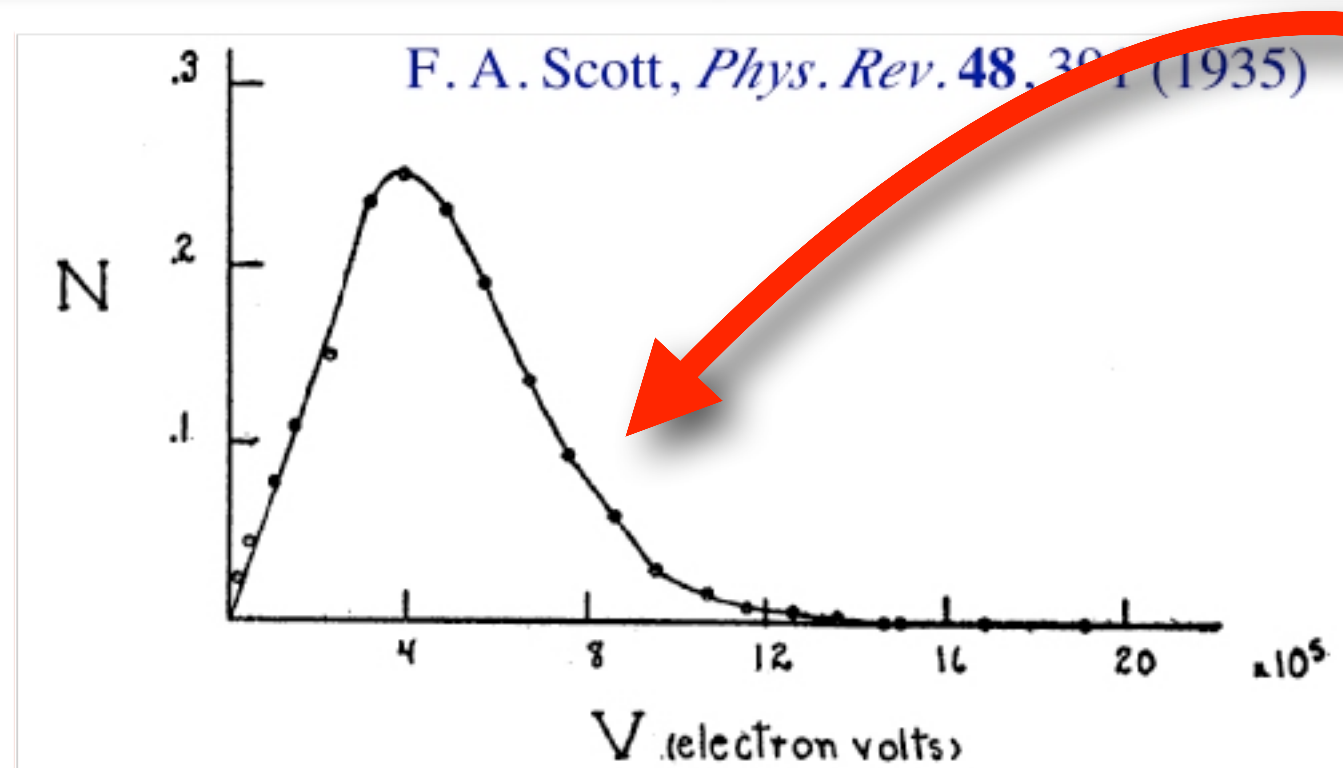


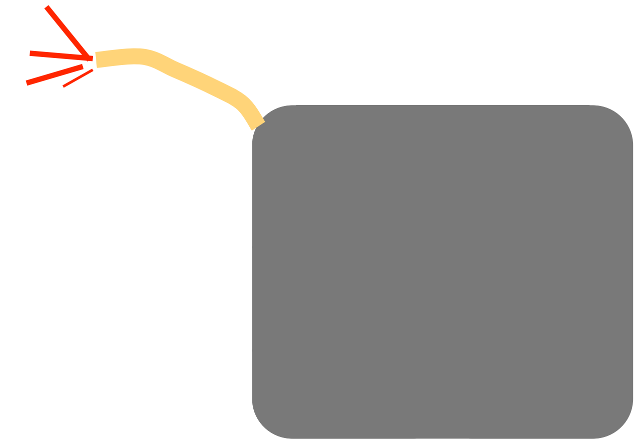
FIG. 5. Energy distribution curve of the beta-rays.

But this is what happened in beta decay. **spread-out values for speed (energy)!**

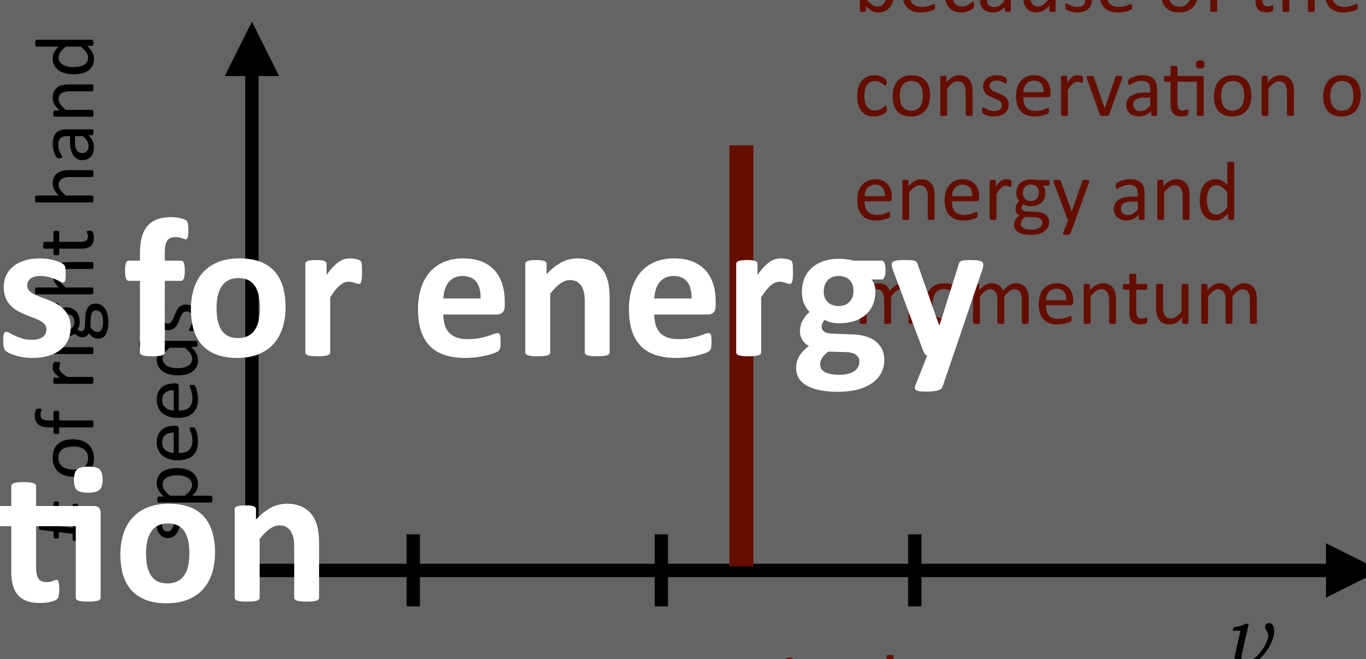
an apparent crisis for energy conservation

suppose you have a "two body"

a single object decays into two objects



Do 100 explosions and measure the energy of either object...



because of the conservation of energy and momentum

a particular value

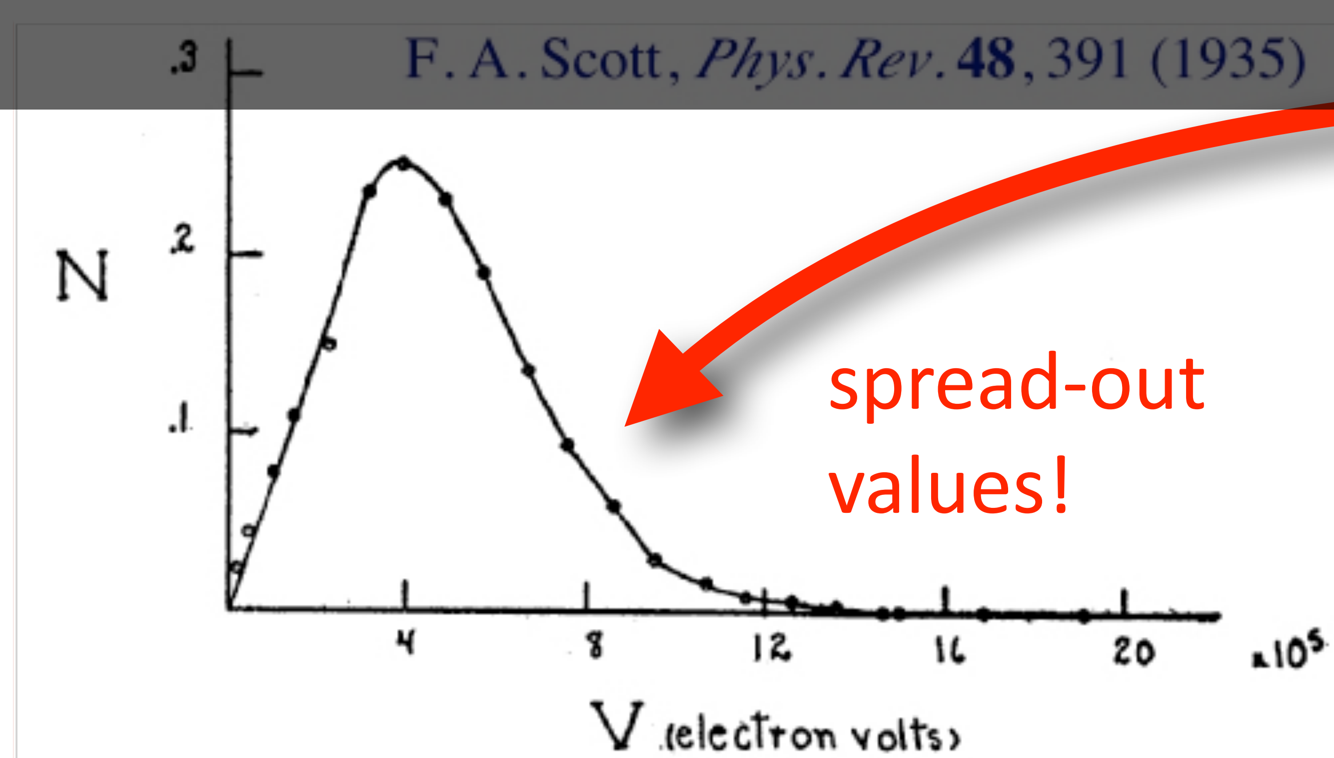
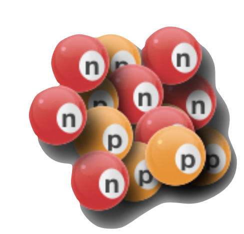


FIG. 5. Energy distribution curve of the beta-rays.

spread-out values!

But this is what happened in beta decay.
Assumed to be 2 bodies:
Nucleus ---> e and Nucleus'



“I have come upon a desperate way out. To wit, the possibility that there could exist in the nucleus electrically neutral particles which I shall call neutrons…the mass…should not be larger than 0.01 times the proton…the … beta [energy] would then be understandable from the assumption that…a [neutron] is emitted along with the electron…I admit that my way out may not seem very probable…But only he who dares wins

…unfortunately I cannot appear personally in Tubingen since a ball which takes place in Zurich makes my presence here indispensable.”

Wolfgang Pauli, distressed at the crisis and unwilling to part with energy conservation–like Bohr suggested!–in 1930 made a bold proposal, in an off-hand way

Naming problem: Chadwick called his particle “neutron”

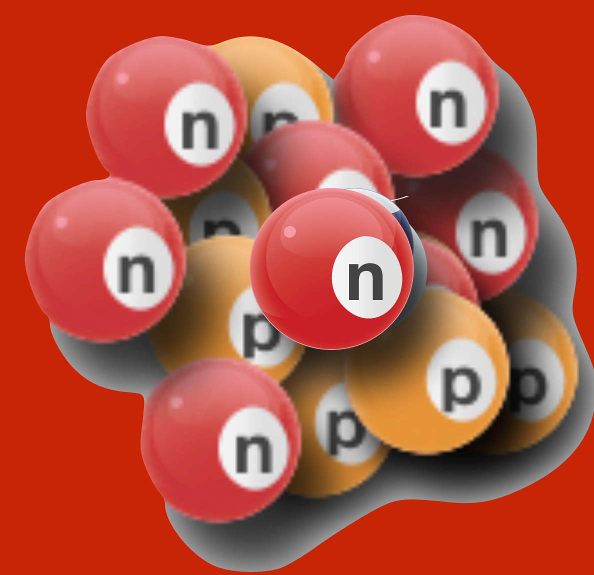
Fermi called Pauli’s the *neutrino*…little neutron

The prediction of the **Neutrino**

...thought to be undiscoverable!

and massless!

the idea hung around



the discovery of the neutron in 1932 gave Enrico Fermi an idea

cay 1933

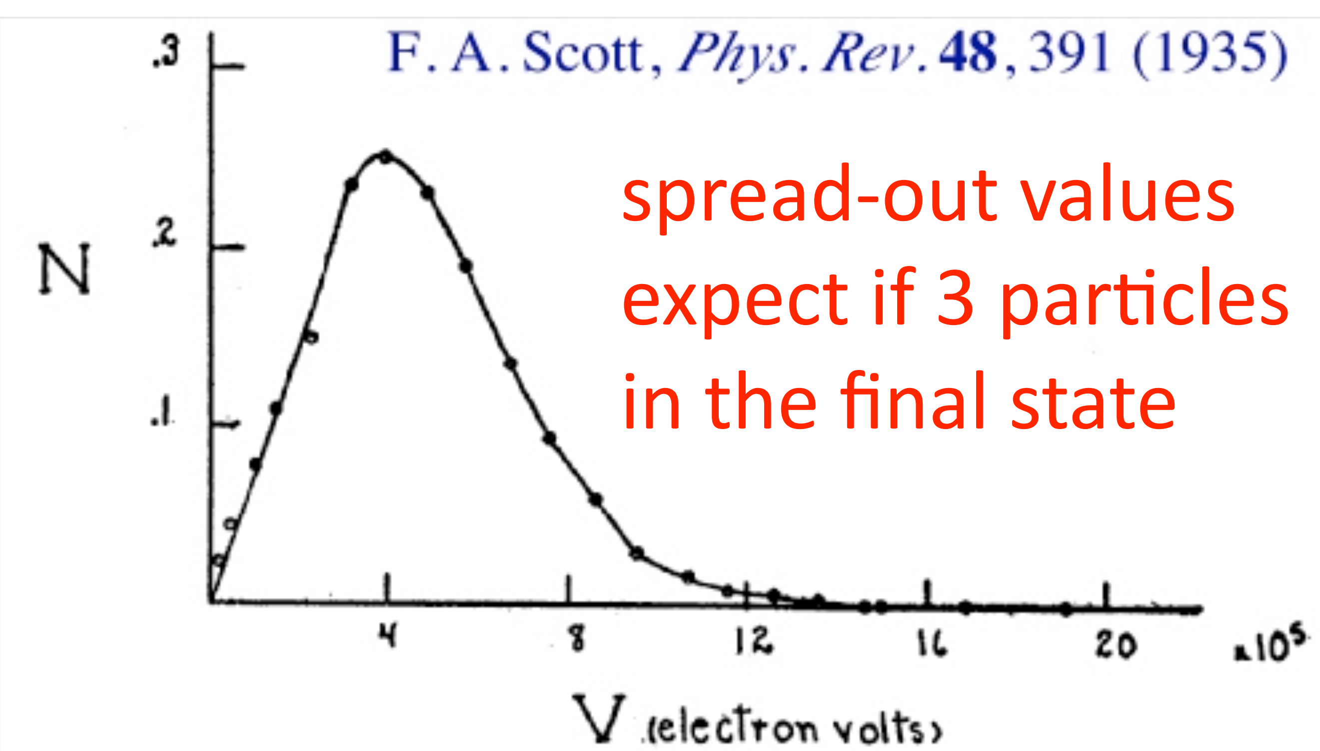
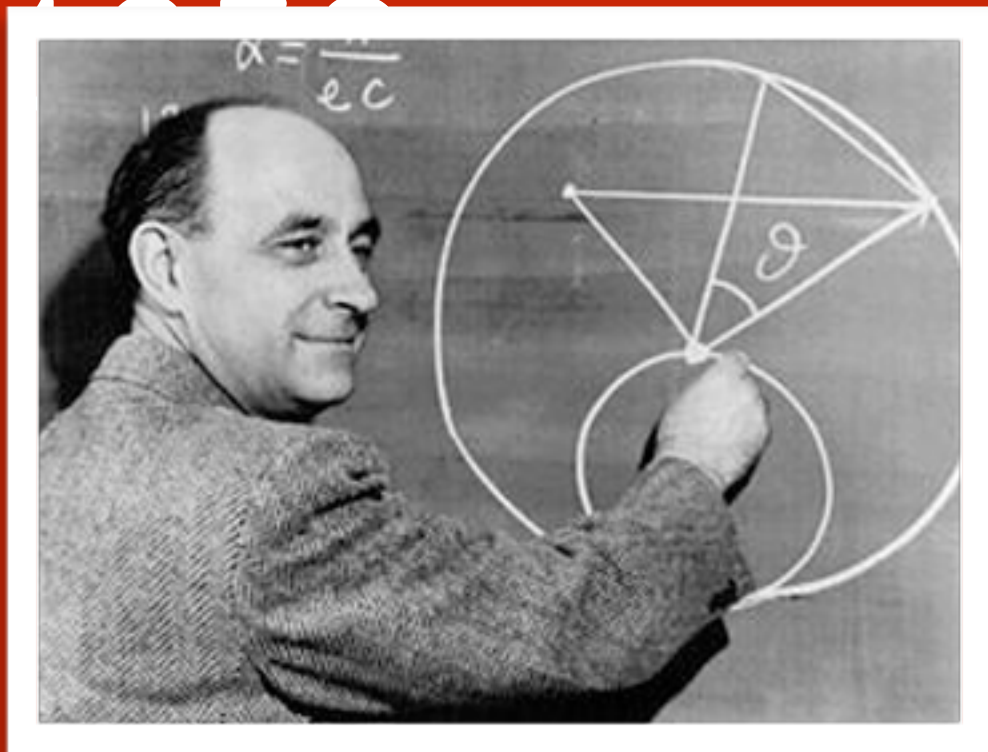


FIG. 5. Energy distribution curve of the beta-rays.

He suggested that a neutron turns into a proton during beta decay



Enrico Fermi

1901-1954

experimental &

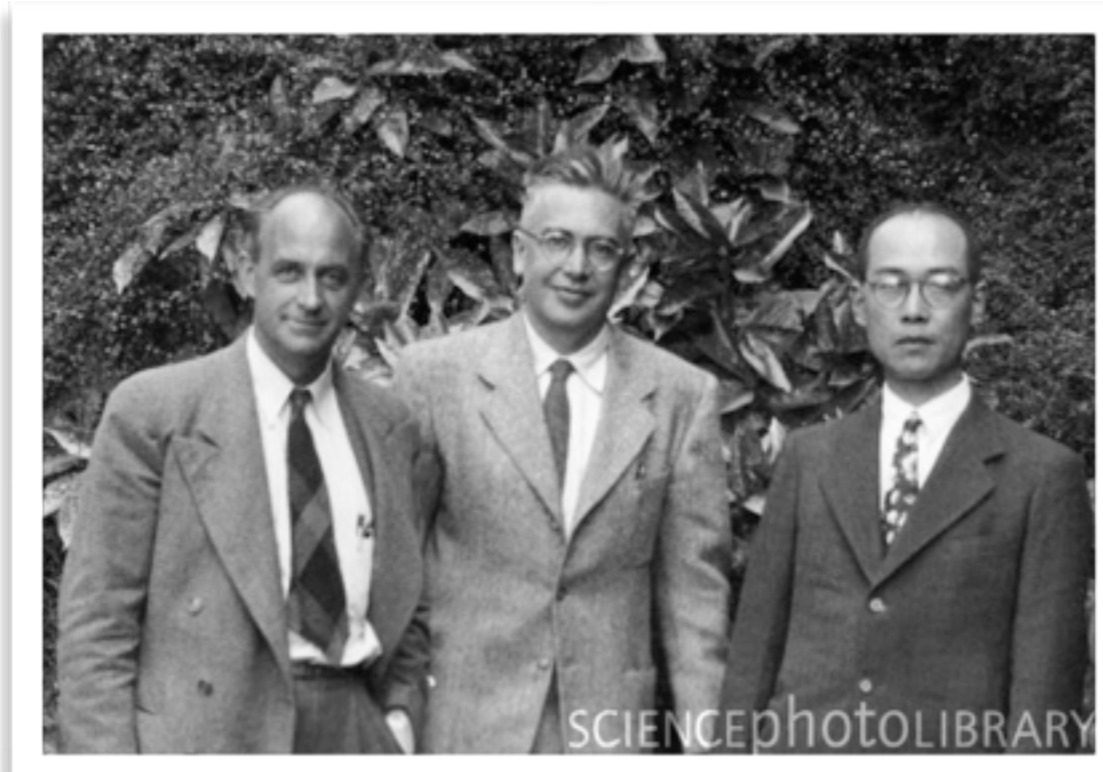
theoretical physicist!

Nobel Laureate 1938

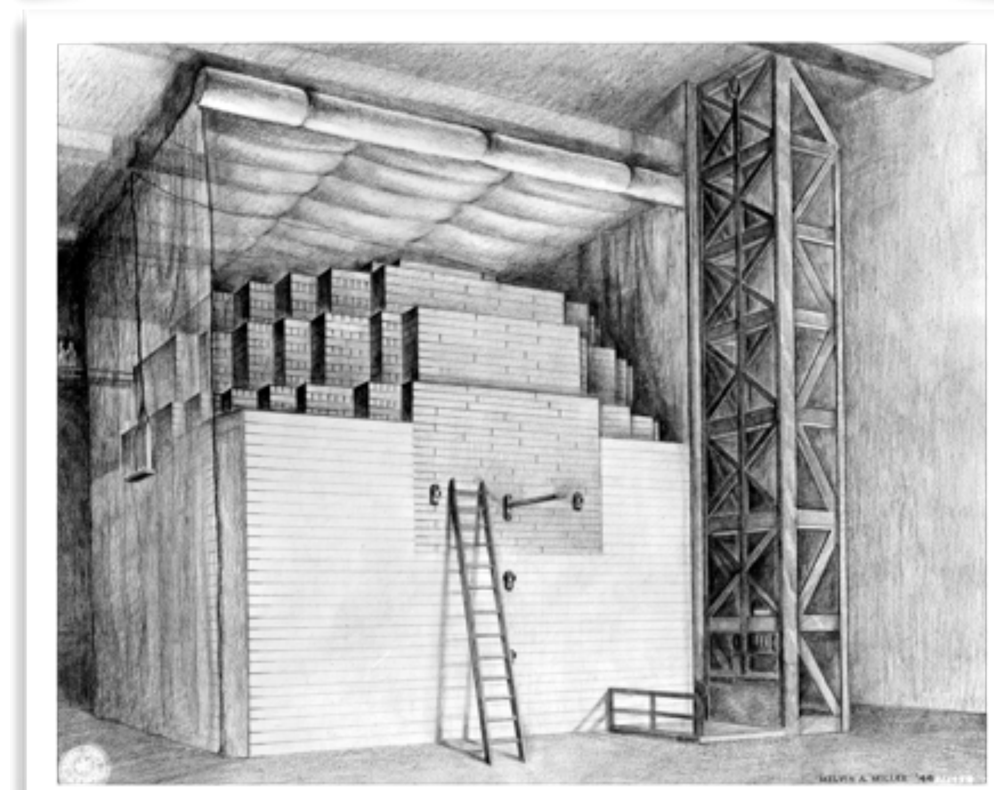
Probably 2, maybe 3 Nobel prize-worthy experiments.

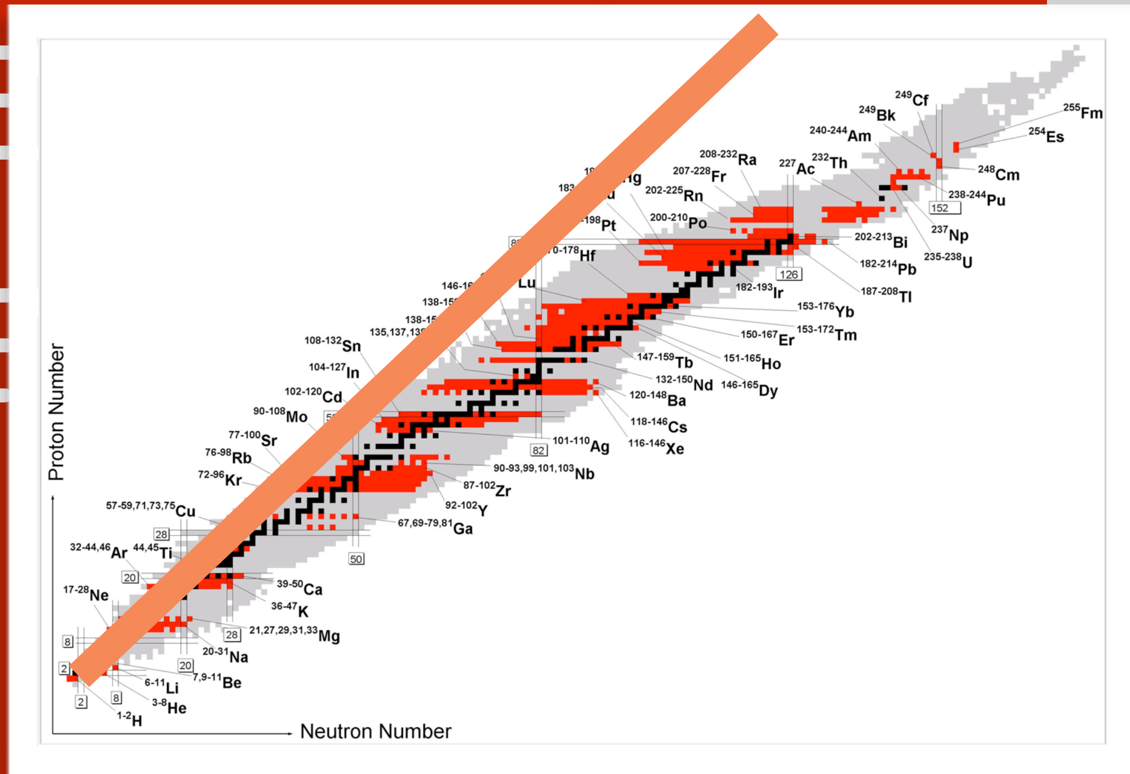
Probably 2, maybe 3 Nobel prize-worthy theoretical products.

There will never be anyone like Enrico Fermi again.



Enrico Fermi
1901-1954
(actually in a cafeteria in Ann Arbor, 1935)

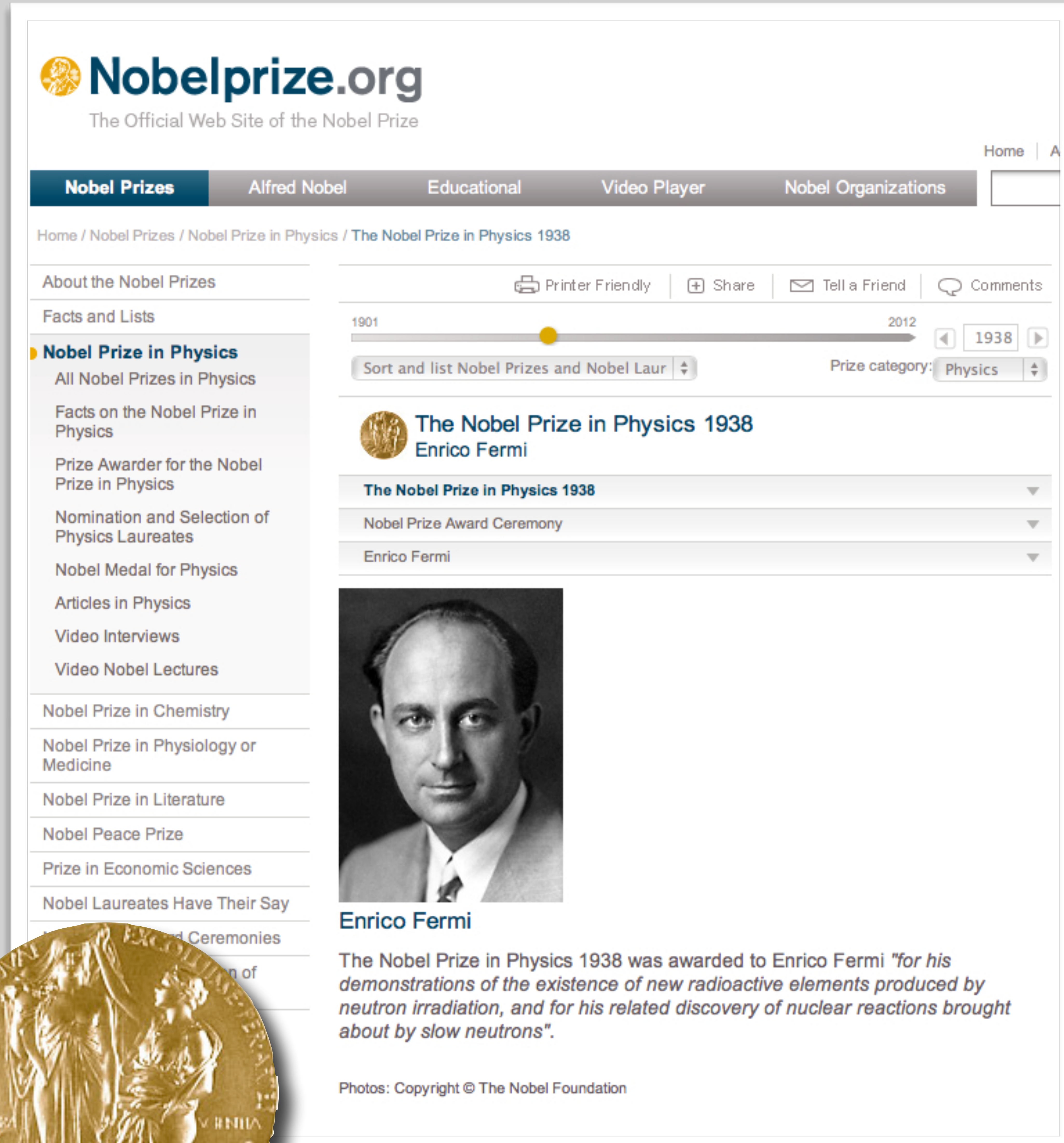




Nobel 1938

not for beta decay

for bombarding nuclei with neutrons and causing fission



Fermi Theory of Beta Decay

uses the Dirac ideas of quantum electrodynamics

particle creation and annihilation

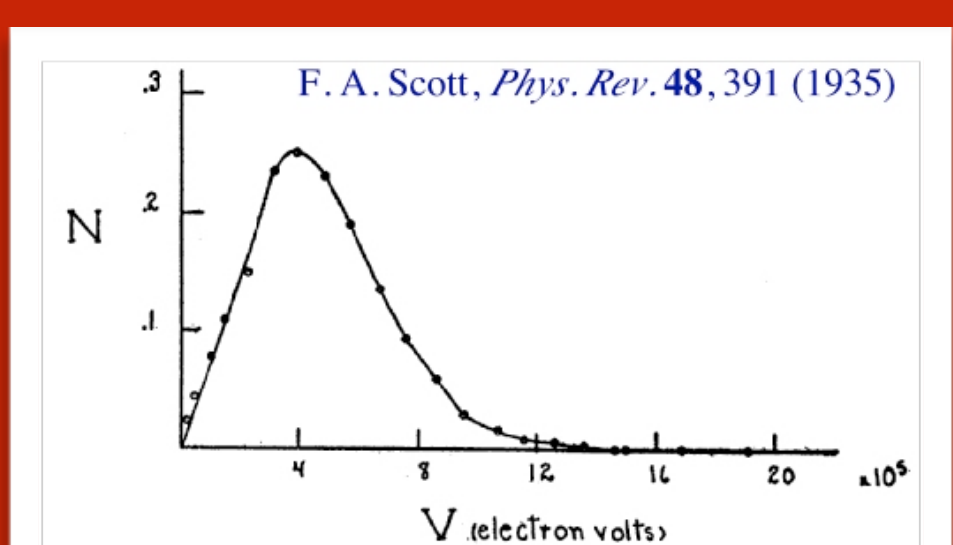
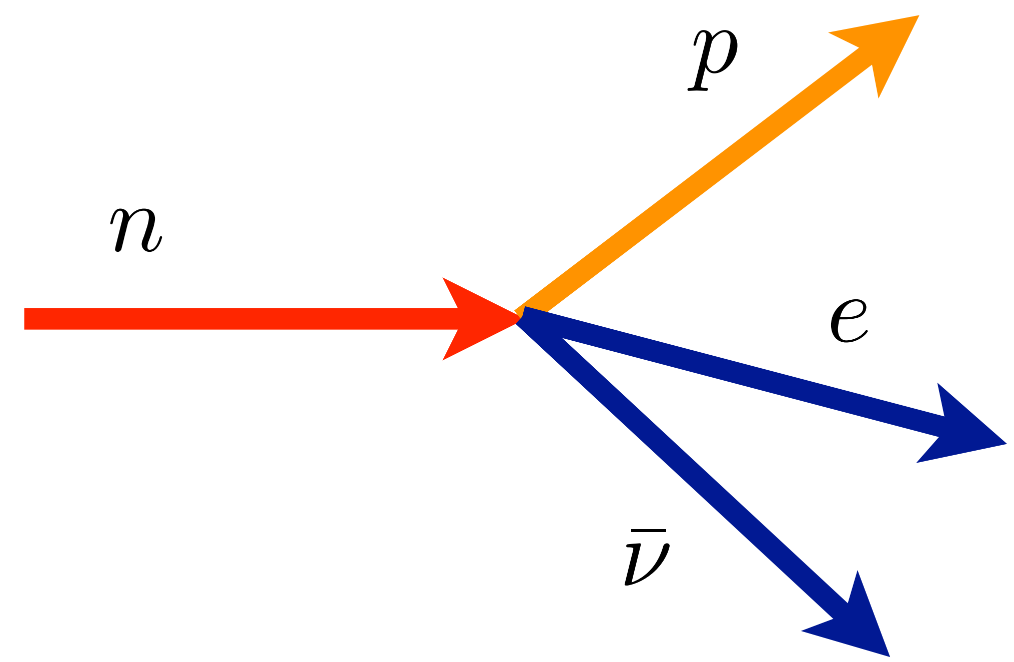


FIG. 5. Energy distribution curve of the beta-rays.

$m_{neutron} > m_{proton}$

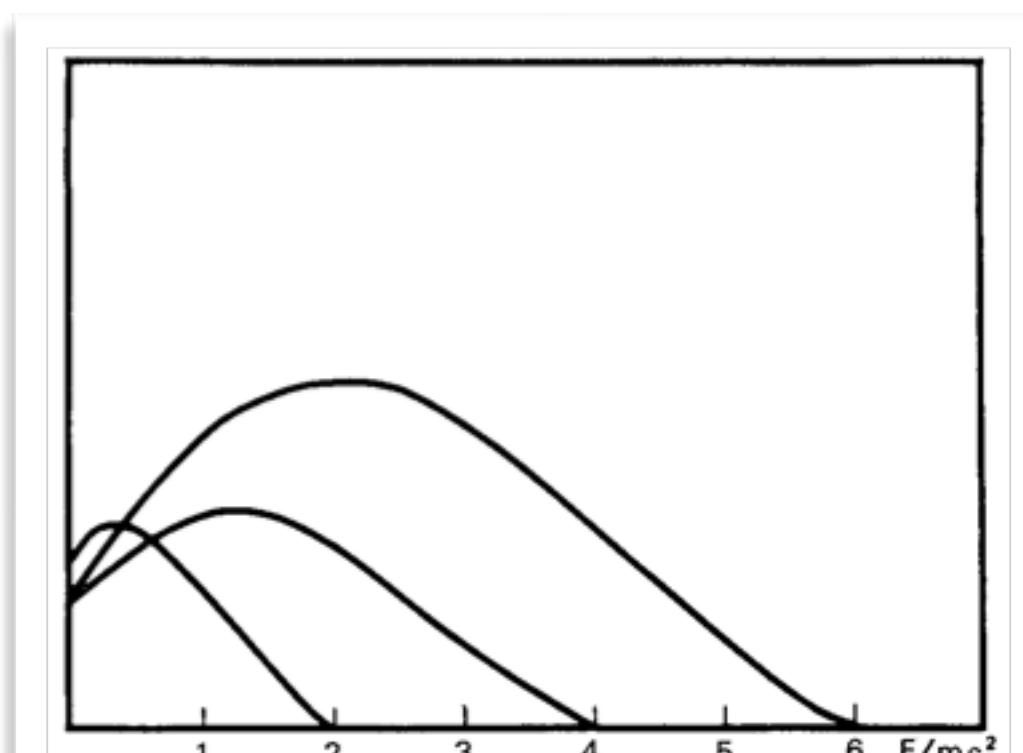
a smidgen.



a free neutron has a lifetime of about 11 minutes.

He sent the paper to *Nature*, but it was rejected:

"it contained speculations which were too remote from reality"



energy of the electron

from his original paper for different nuclear species parameters

discovery of the neutrino

took 25 years

experimental tour de-force

Neutrinos very weakly interact in matter
lightyears of lead to stop one!

exchange force

the modern view:

if there’s a force…there’s a field

if there’s a field…there’s a particle

in 1932 Heisenberg had good idea:

“Exchange Force” the simplest, but most important notion yet

Heisenberg: hmm. electrons appear out of nuclei

maybe they’re in the nucleus?

maybe they’re even holding it together?

Exchange Force

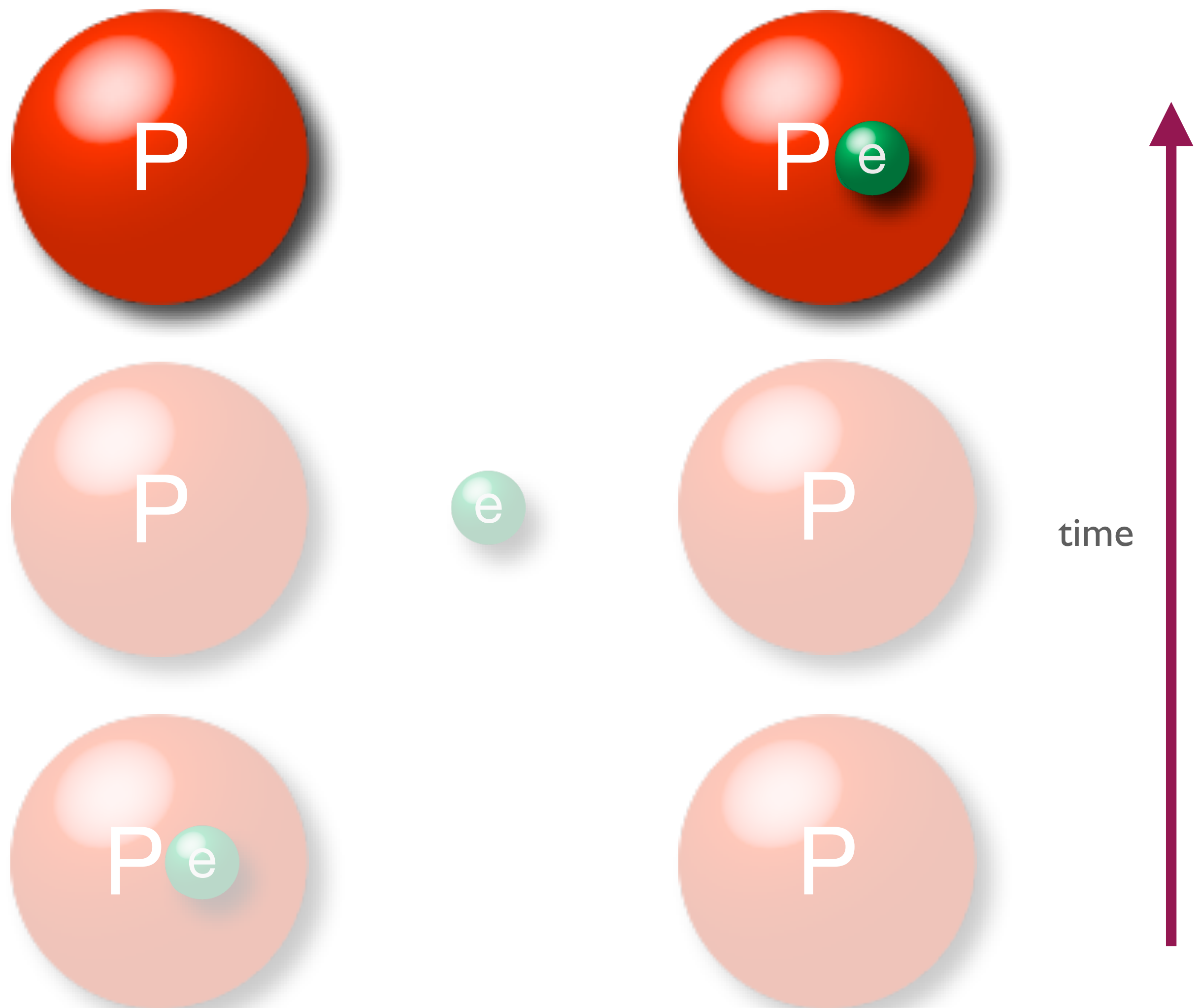
The proton is playing catch with itself

with all he knew about: electrons and protons

maybe beta decay?

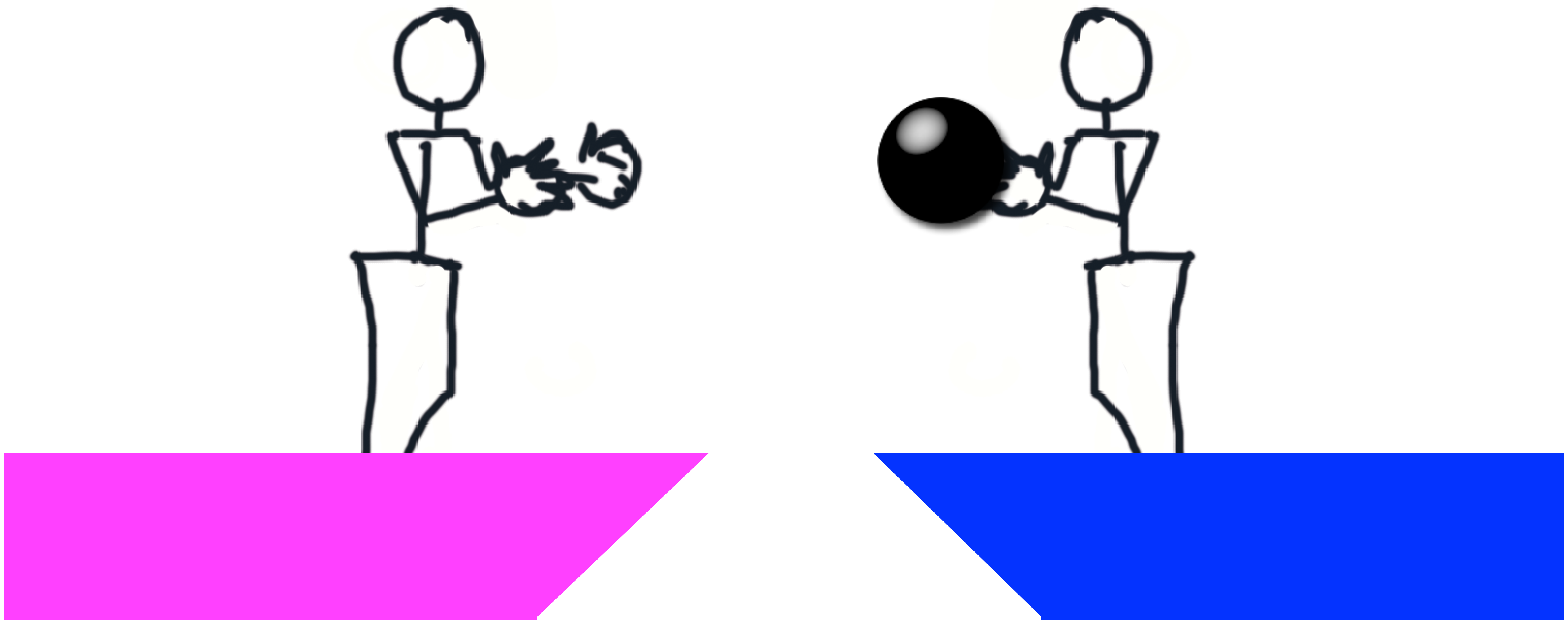
He knew that sometimes nuclei just spit out an electron.

Rutherford's beta decay



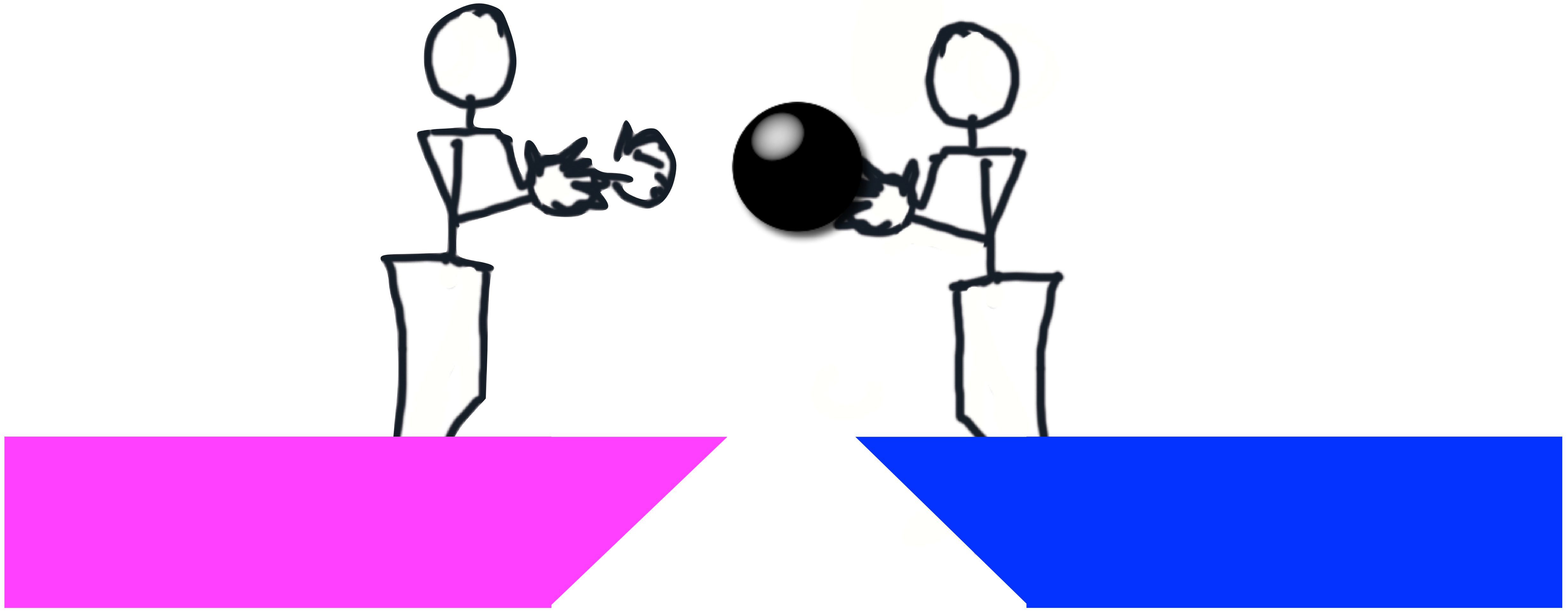
analogy: a repulsive exchange force

a repulsive exchange force



analogy: an attractive exchange force

an attractive exchange force

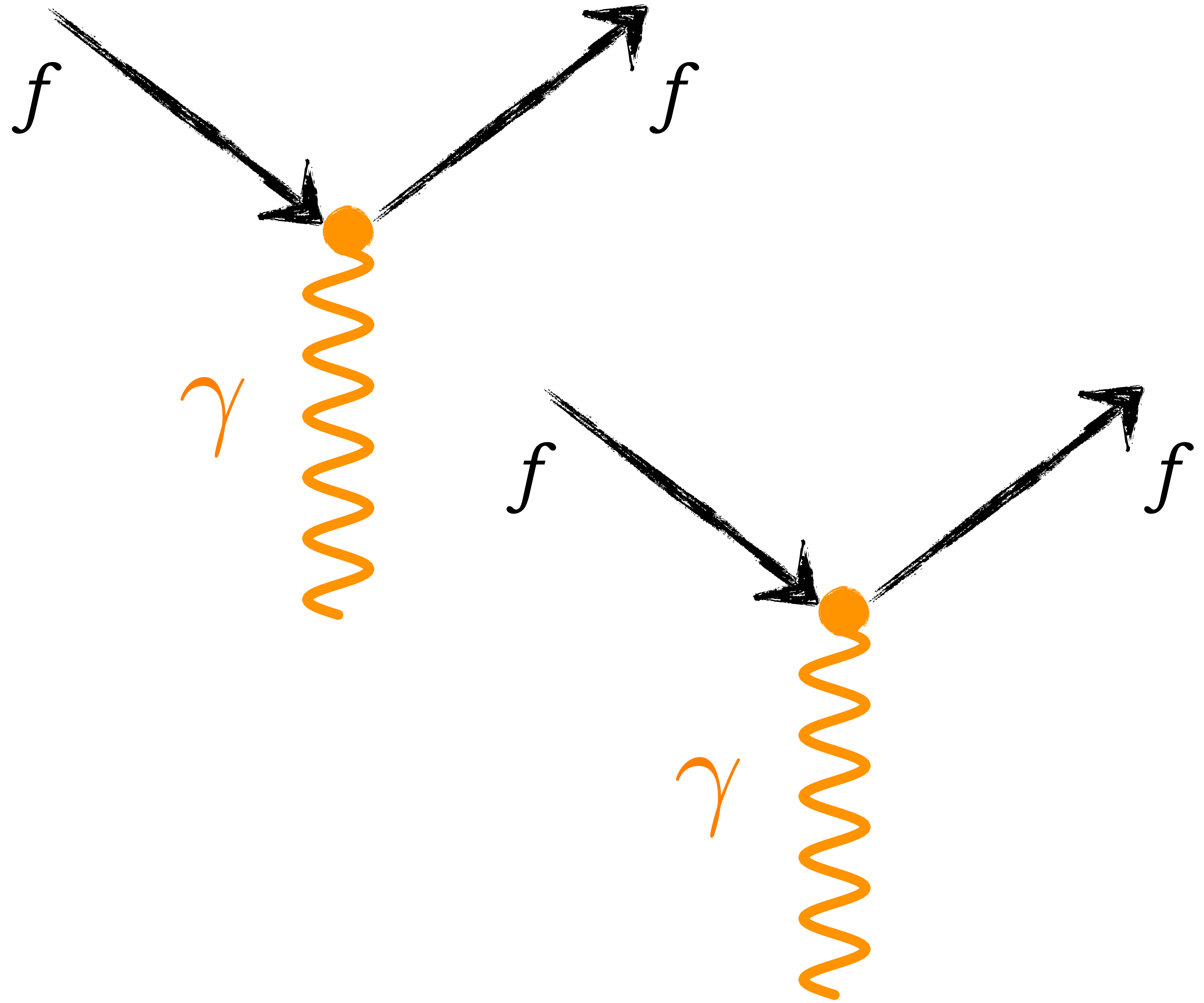


jargon alert: **exchange force**

refers to:	the idea that the forces of nature are propagated by quanta
entomology:	Heisenberg's picture of exchanging them
example:	the photon!

piece the primitives together

sharing a leg



we know one force

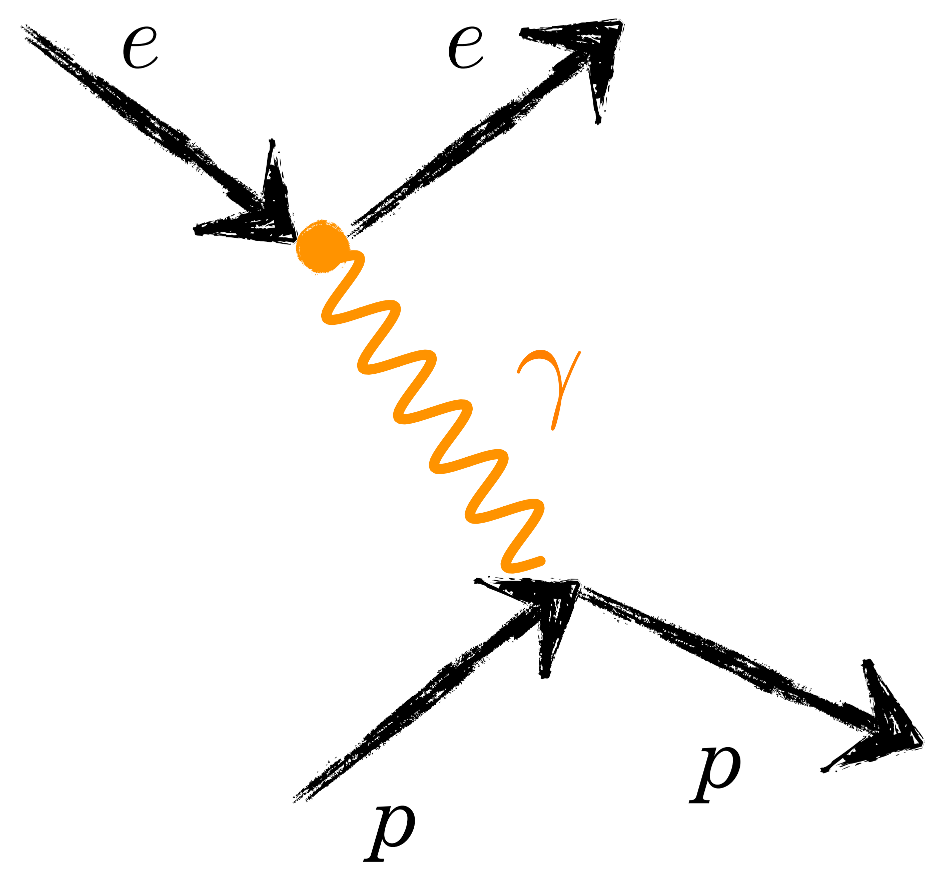
electromagnetism

electricity

magnetism

united by Relativity

remember?



The modern idea:

The force of electromagnetism is "propagated" by the photon.

Multiple names: "propogator"
"Intermediate Vector Boson"

I'll call the photon: the "Messenger Field for Electromagnetism"

`There's something funny about the nucleus`

that it **is**.

charge independence

Heisenberg's original idea was before the neutron

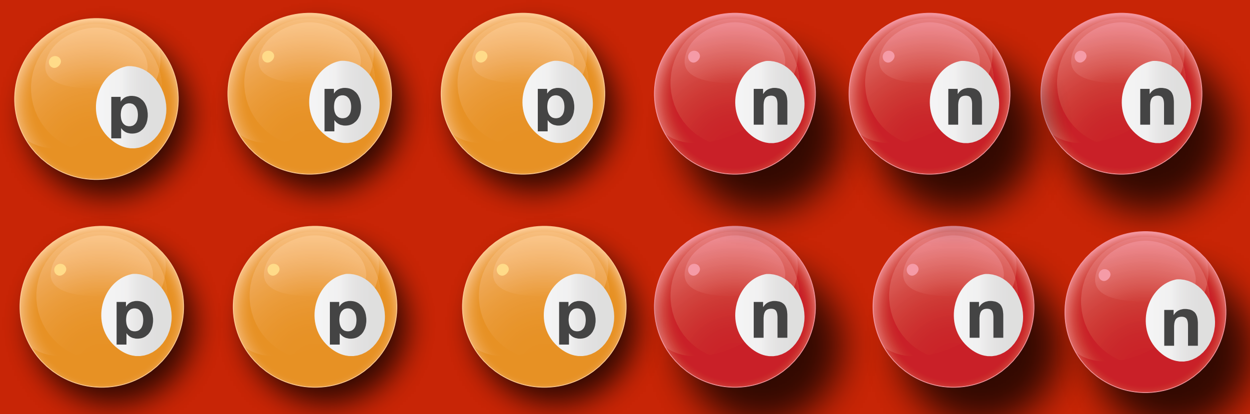
his protons playing catch with electrons?

nope.

remember:

chemistry from # protons = #electrons

to “assemble” ^{12}C



they have to attract one another

NOT electromagnetism

remember:

chemistry from # protons = #electrons

to "assemble" ^{12}C

they have to attract one another

But *how* does it hold together?

why does any nucleus beyond Hydrogen hang together?

those protons want to get away from one another

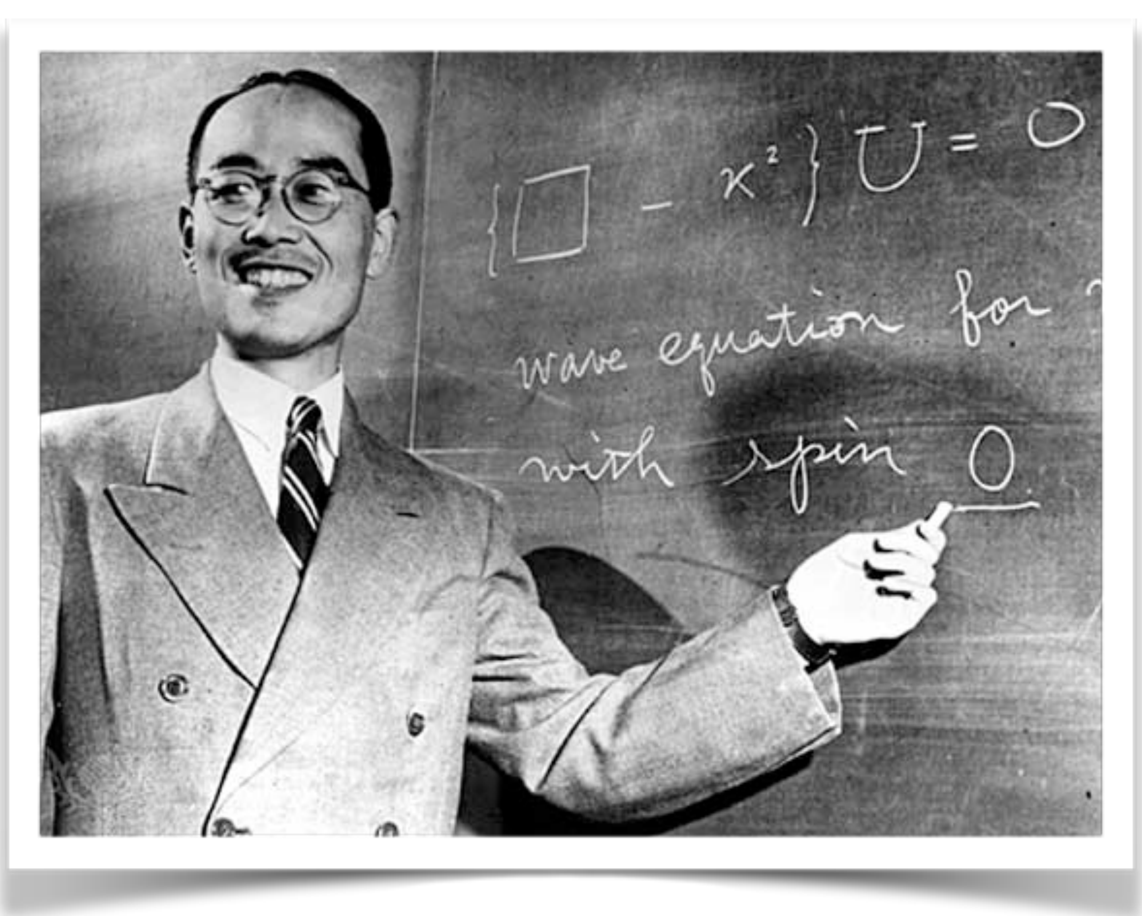
the electrostatic force of repulsion: about 2 N per proton, so enormous accelerations should be happening!

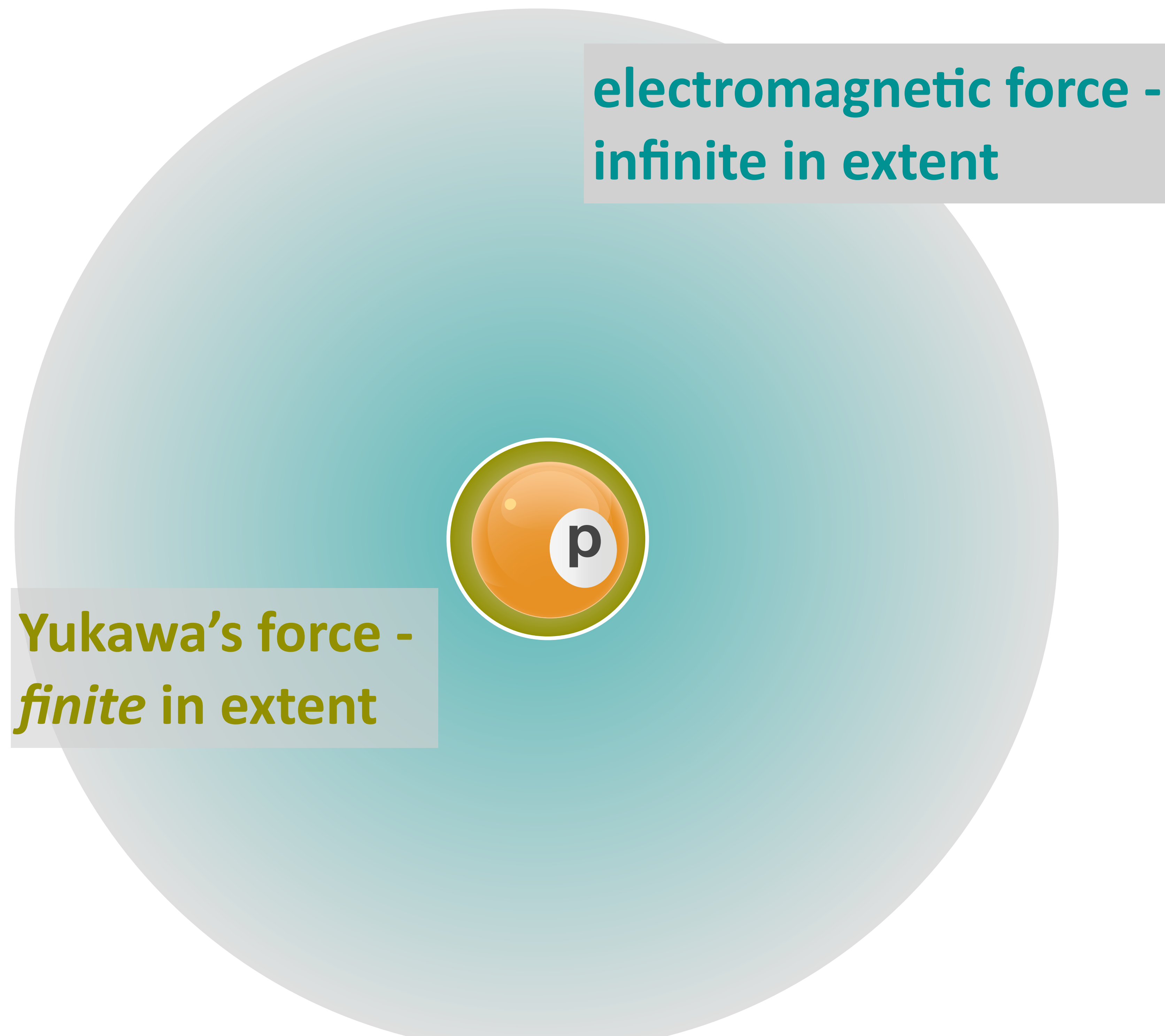
This must be countered...by an even stronger force 

Strong Force

1934

Hideki Yukawa

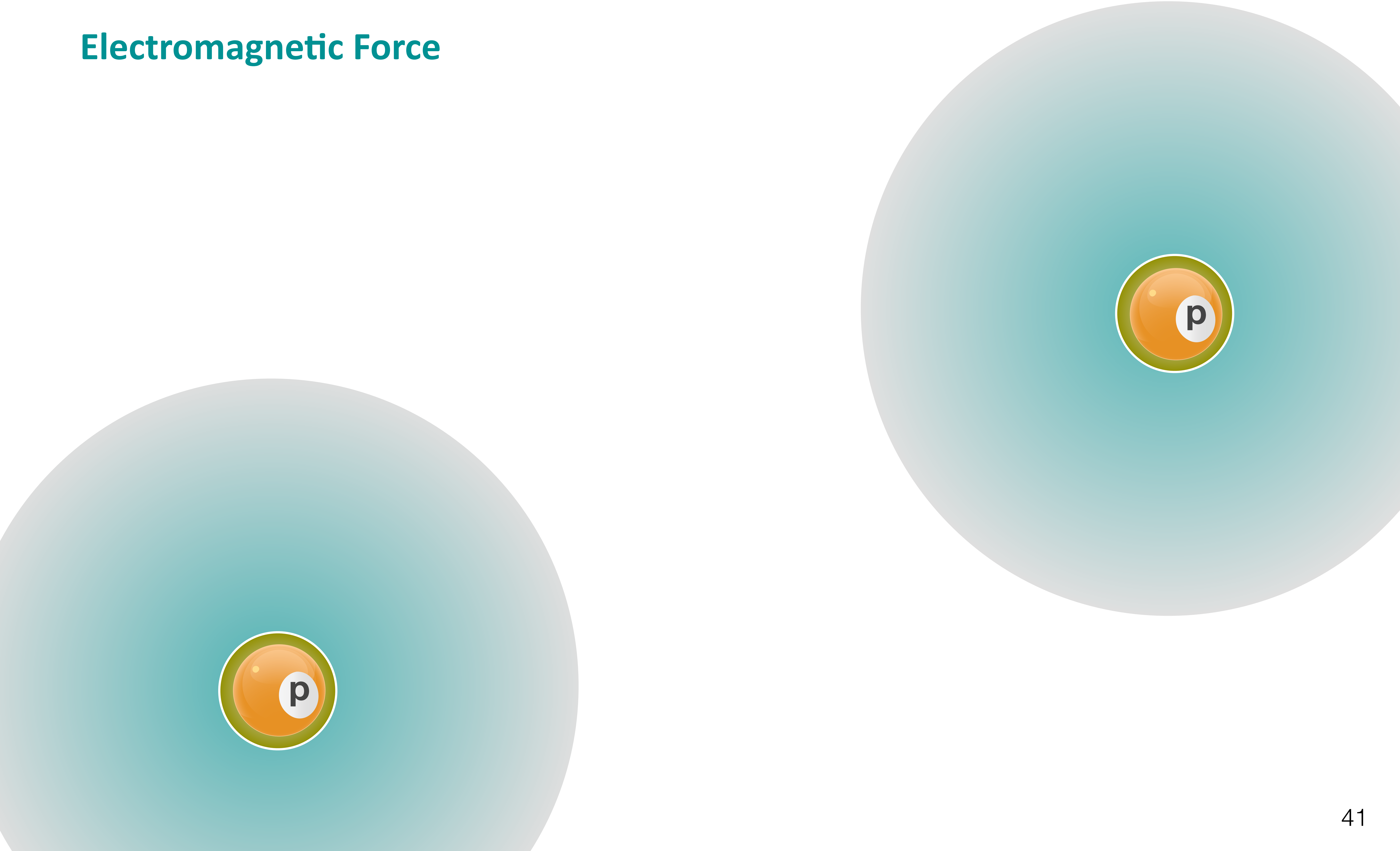




The Strong Force is a stronger than...anything in the universe.

two competing forces:

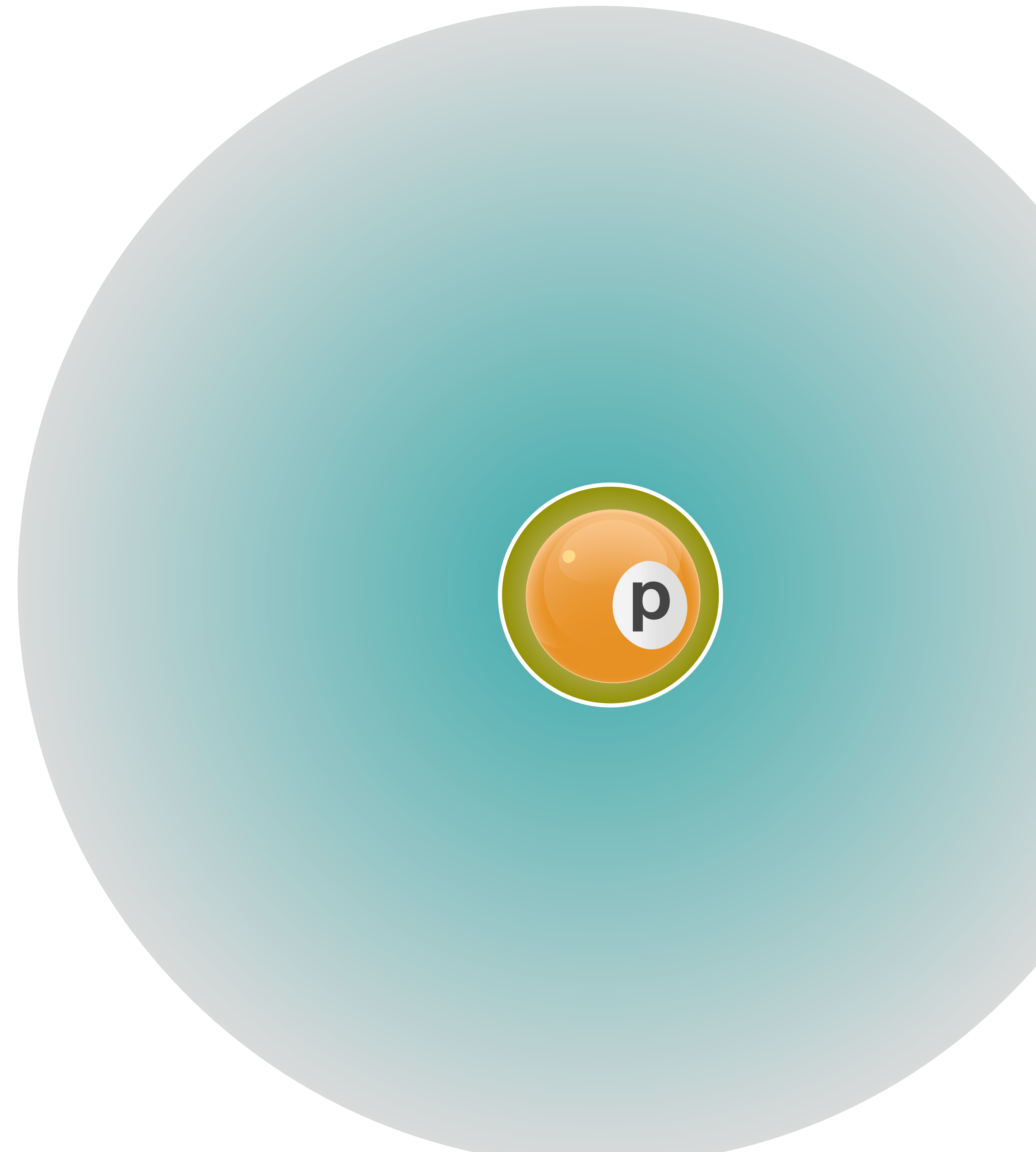
Electromagnetic Force



Strong is stronger than...anything.

two competing forces:

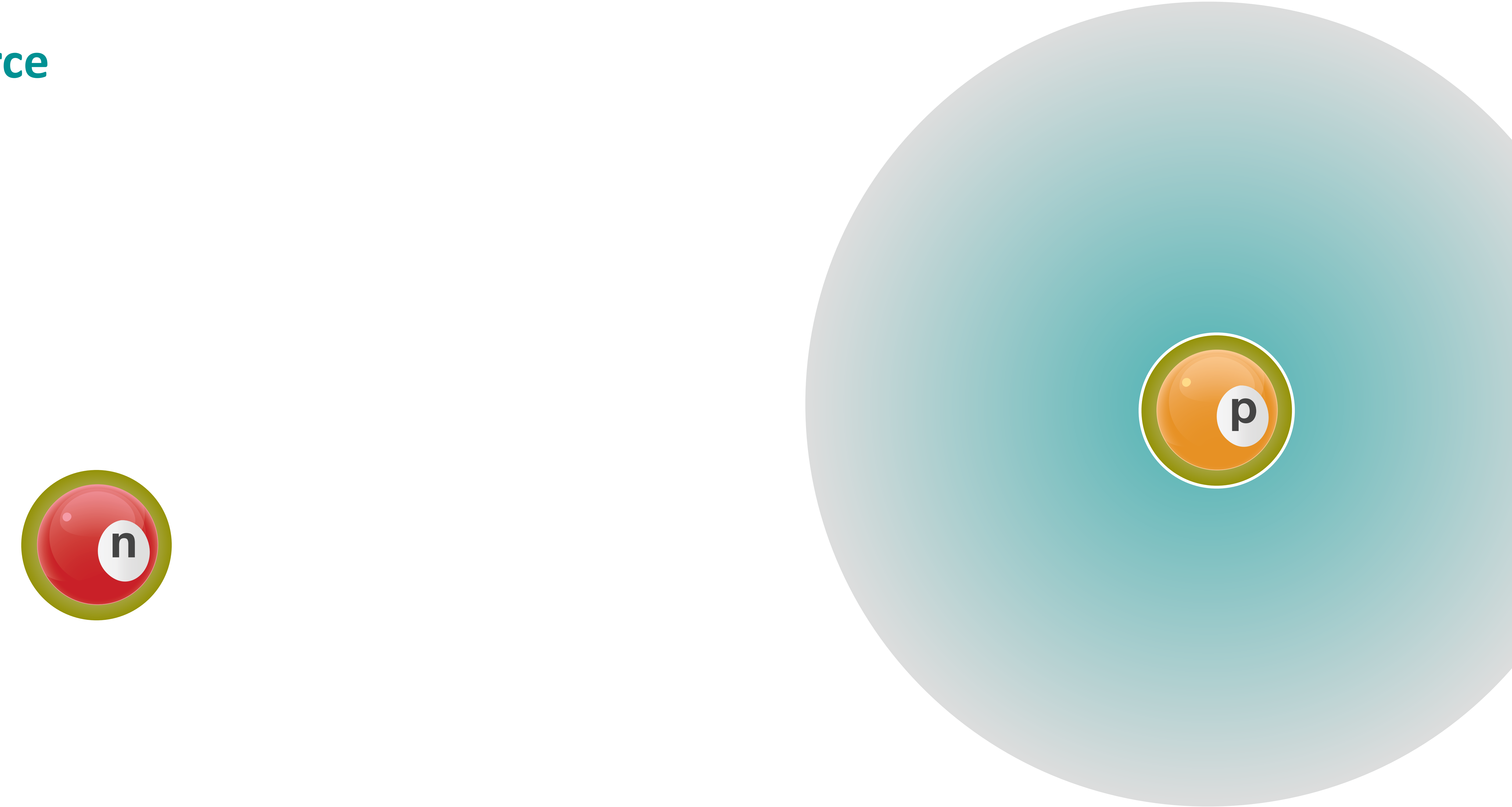
Electromagnetic Force



Strong is stronger than...<u>anything</u>.

two competing forces:

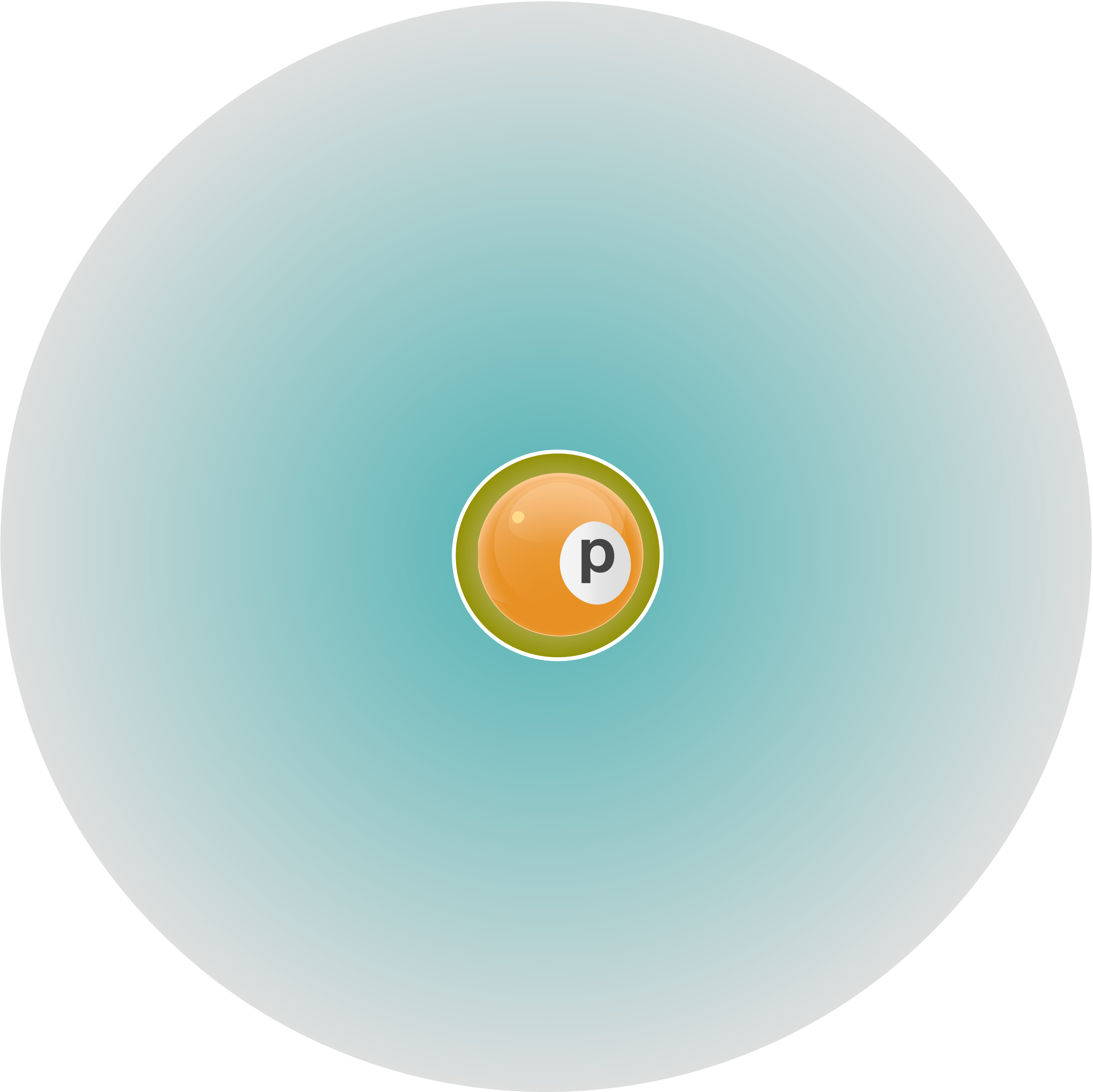
Strong Force

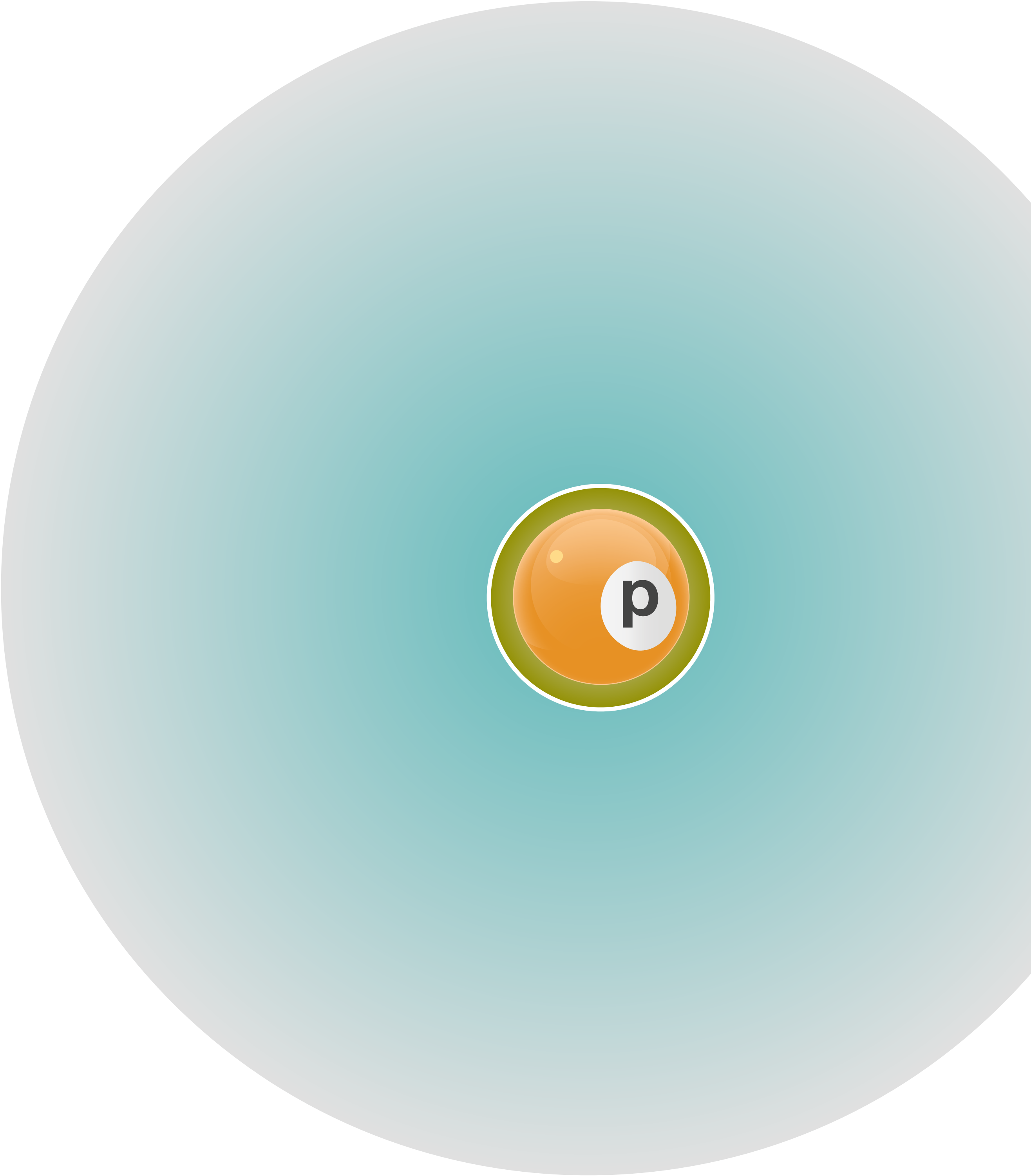


Strong is stronger than...anything.

two competing forces:

Strong Force

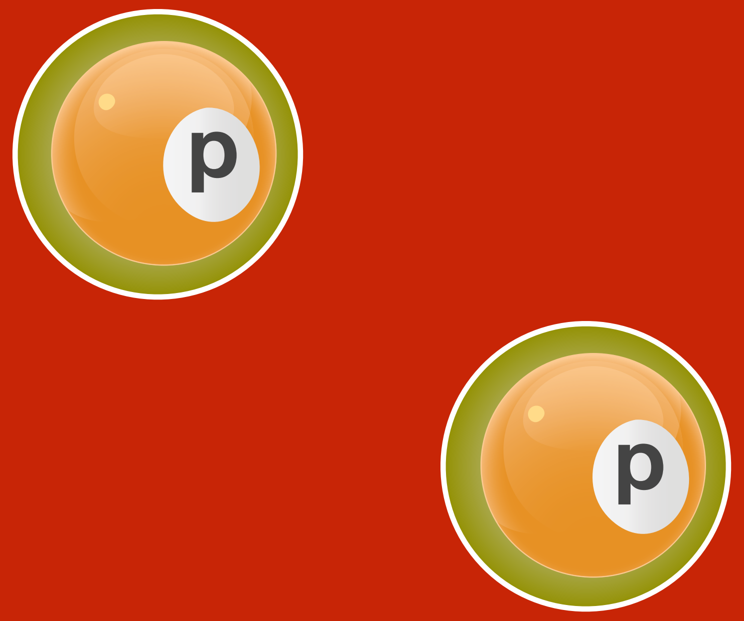




but only over a very short range...

the STRONG force

overwhelms the electromagnetic force



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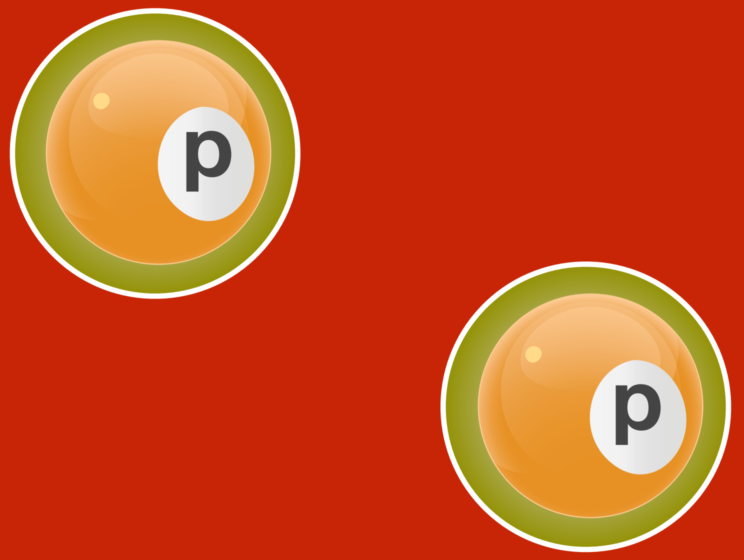
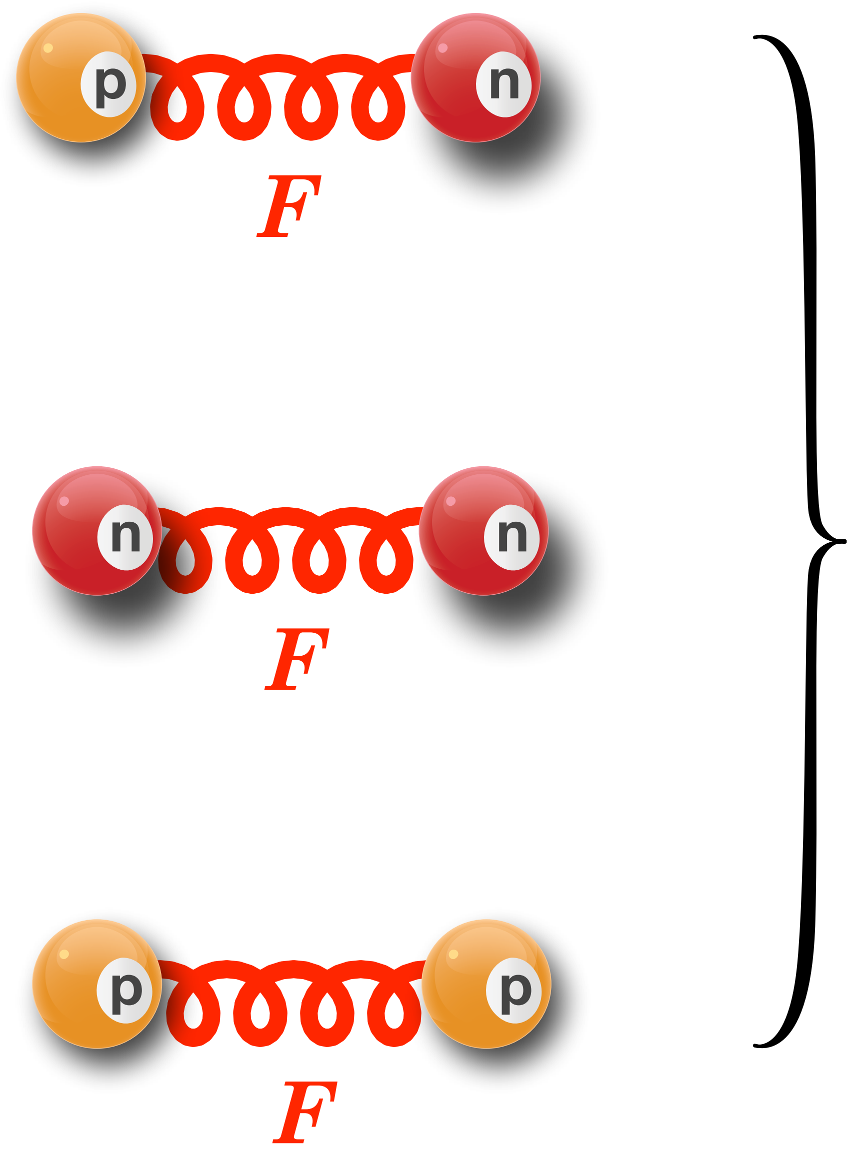


neutrons and protons

in the nucleus, the proton and neutron

are two manifestations of the same particle

whatever it is that holds the nucleus together:
it's symmetric between the proton and the neutron



same force, same strength

For all practical purposes – in holding the nucleus together – the neutron and proton are the same particle – the "**Nucleon**."

If we ignore electromagnetism...the proton & the neutron are very much alike - we can treat them as being the same particle

neutrons and protons

act like they are identical particles

the electric charge?

as a force...Yukawa's force is 100 times the electromagnetic

For nuclear forces: treat p and n as identical and differing only by a "quantum number" called "**Isospin**"

$$N = \begin{pmatrix} p \\ n \end{pmatrix} \qquad \begin{matrix} I \\ +1/2 \\ -1/2 \end{matrix}$$

"nucleon"

A neutron... is a "nucleon" with "isospin down"
A proton... is a "nucleon" with "isospin up"

They go together...within the strong, nuclear force.

How?

jargon alert: **nucleon**

refers to:	either a proton or a neutron
entomology:	from “nucleus”...the “-on” tends to be a particle name
example:	“nucleon force”

jargon alert: **hadron**

refers to:	any particle that interacts via the Strong Force
entomology:	*αδρόσ* “hadros” "large", "massive"
example:	proton and neutron *not electron, not photon*

remember

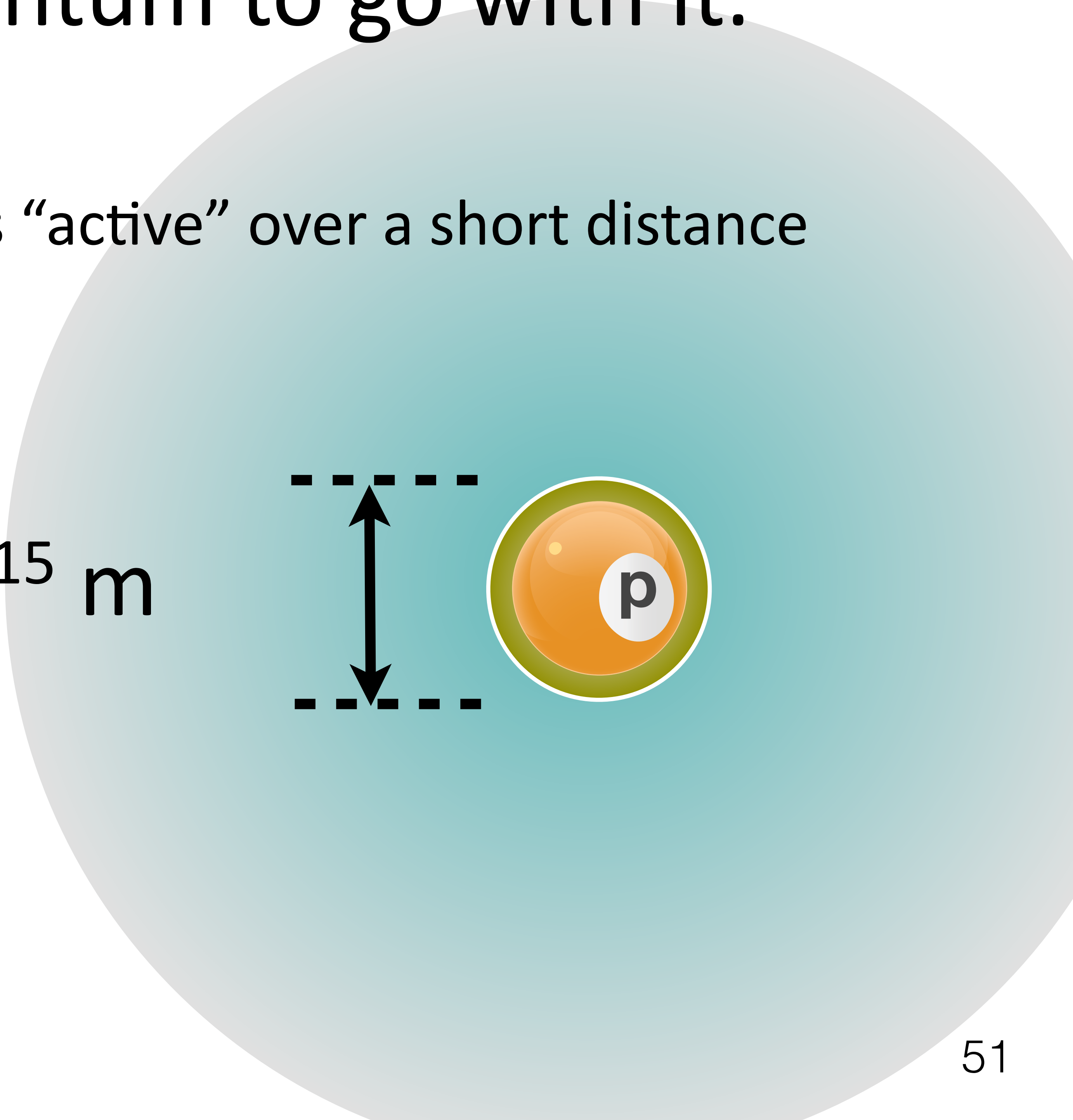
Nature is clumpy

If there is a force...there's a field

If there's a field, there's a quantum to go with it.

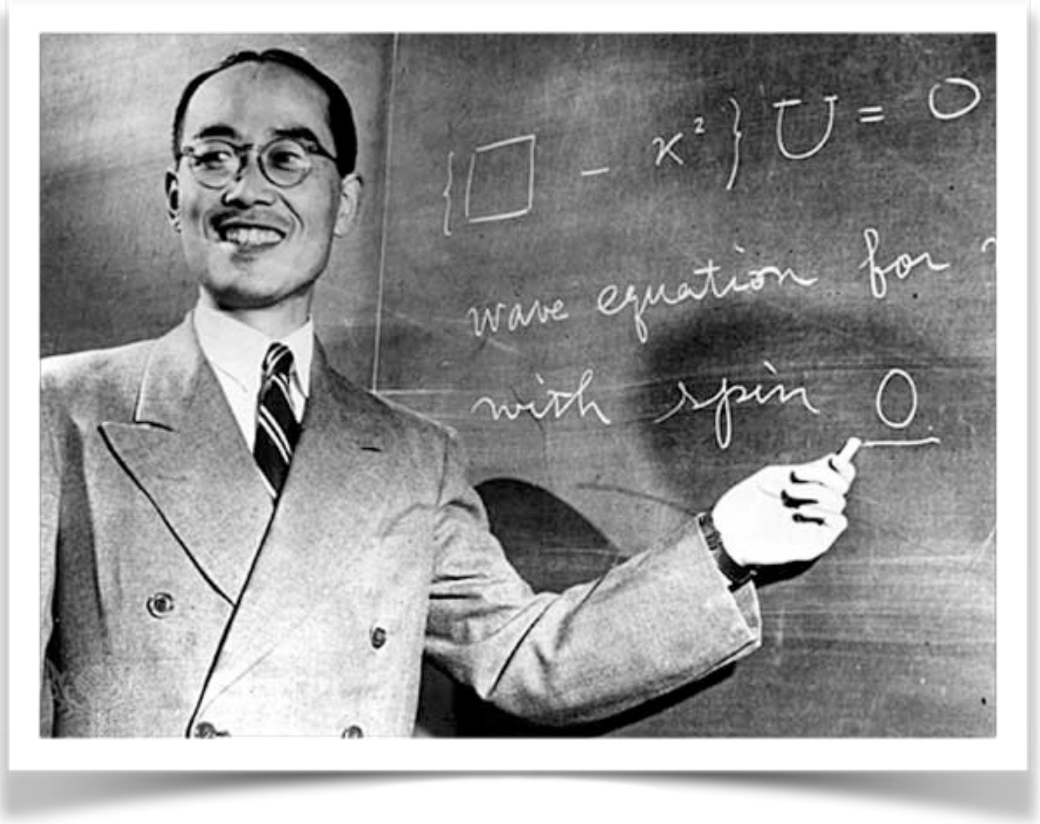
The nuclear force is "active" over a short distance

~10^{-15} m



Yukawa knew that.

uncertainty certainly to the rescue



brilliant observation by Yukawa

maybe there’s a quantum that is active only over the size of a nucleus: “U”

another exchange force/particle?

the most important thing in particle physics?

getting the name right.

the “Yukon”? thankfully, no.

the “meson?” Why yes, I think I like it.

medium mass…

not too big (proton) not too small (electron): just right.

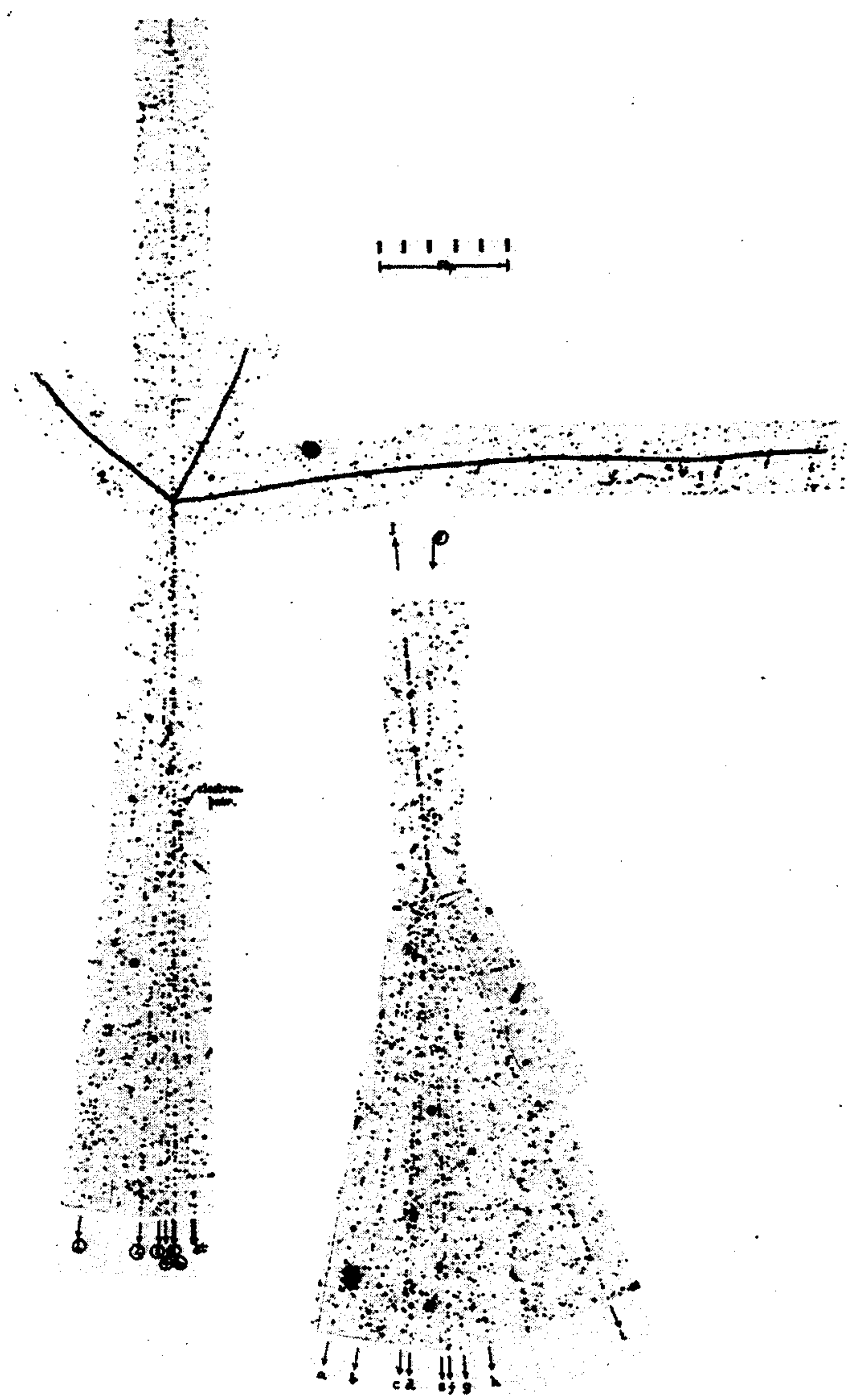
the hunt was on

to find the Yukawa Particle

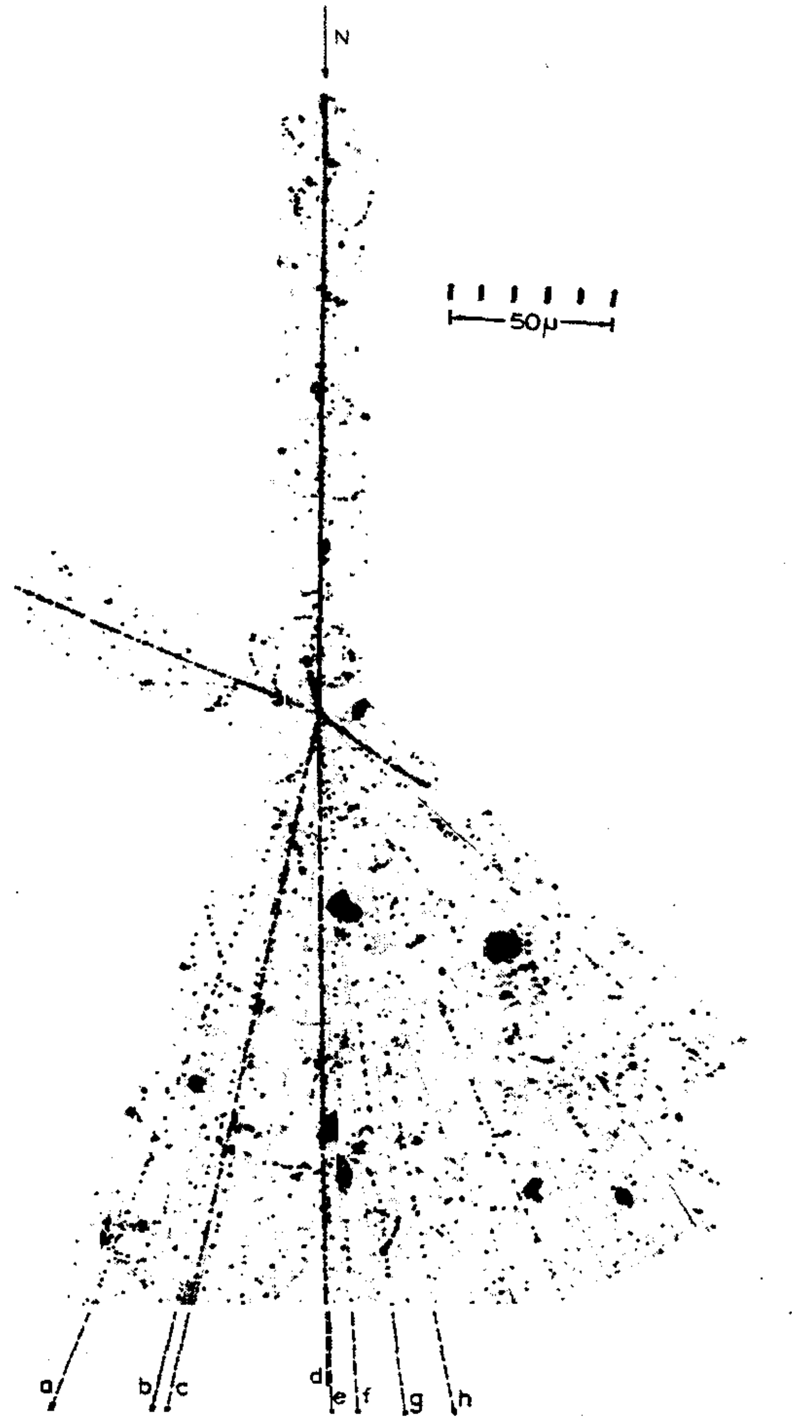
but WWII got in the way

Post-war emulsion exposures were startling

proton in cosmic rays



Nitrogen nucleus in cosmic rays



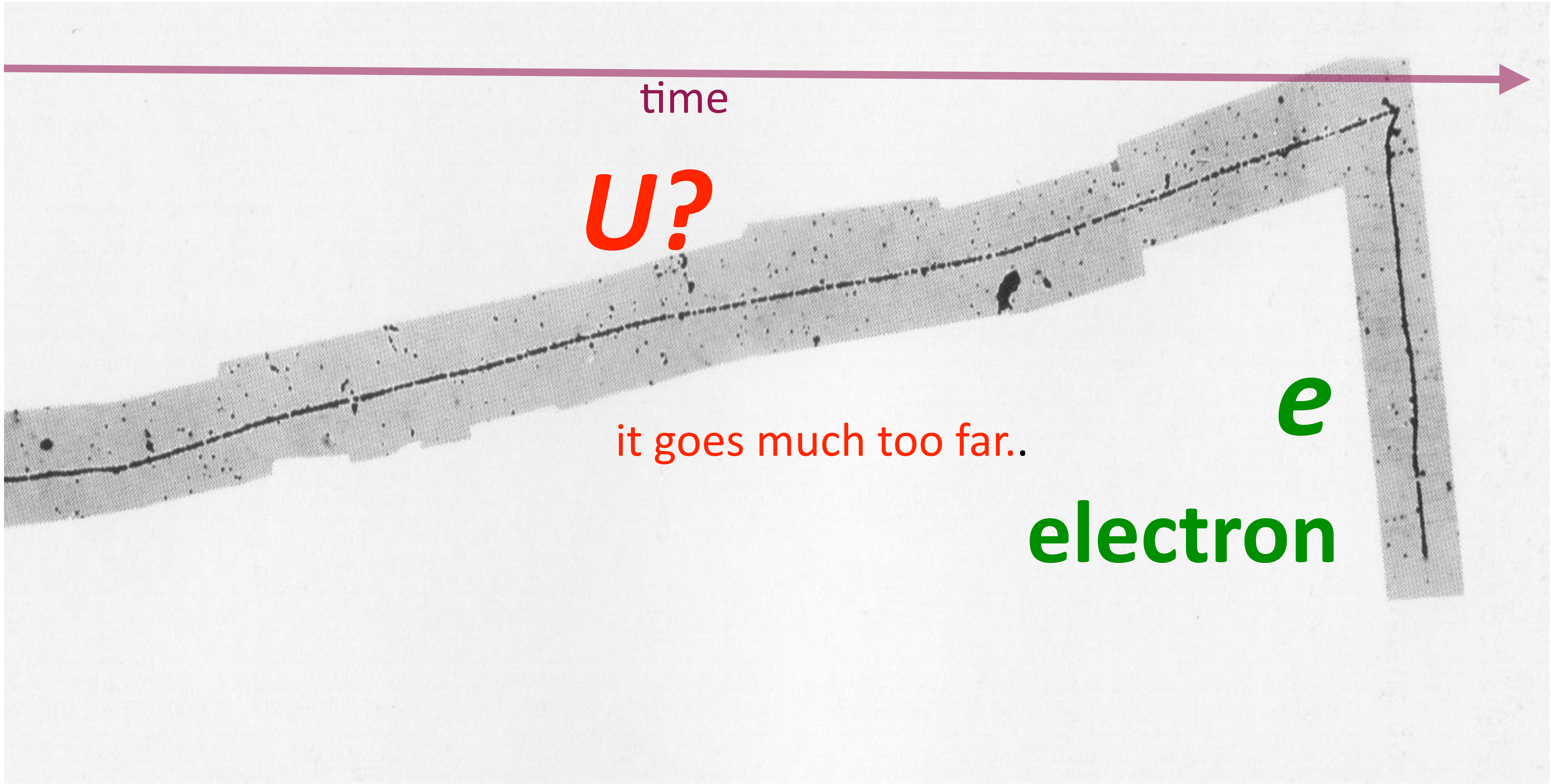
huh?

from Cecil Powell's Nobel lecture... a former student of? ...you guessed it.

many of these sort:

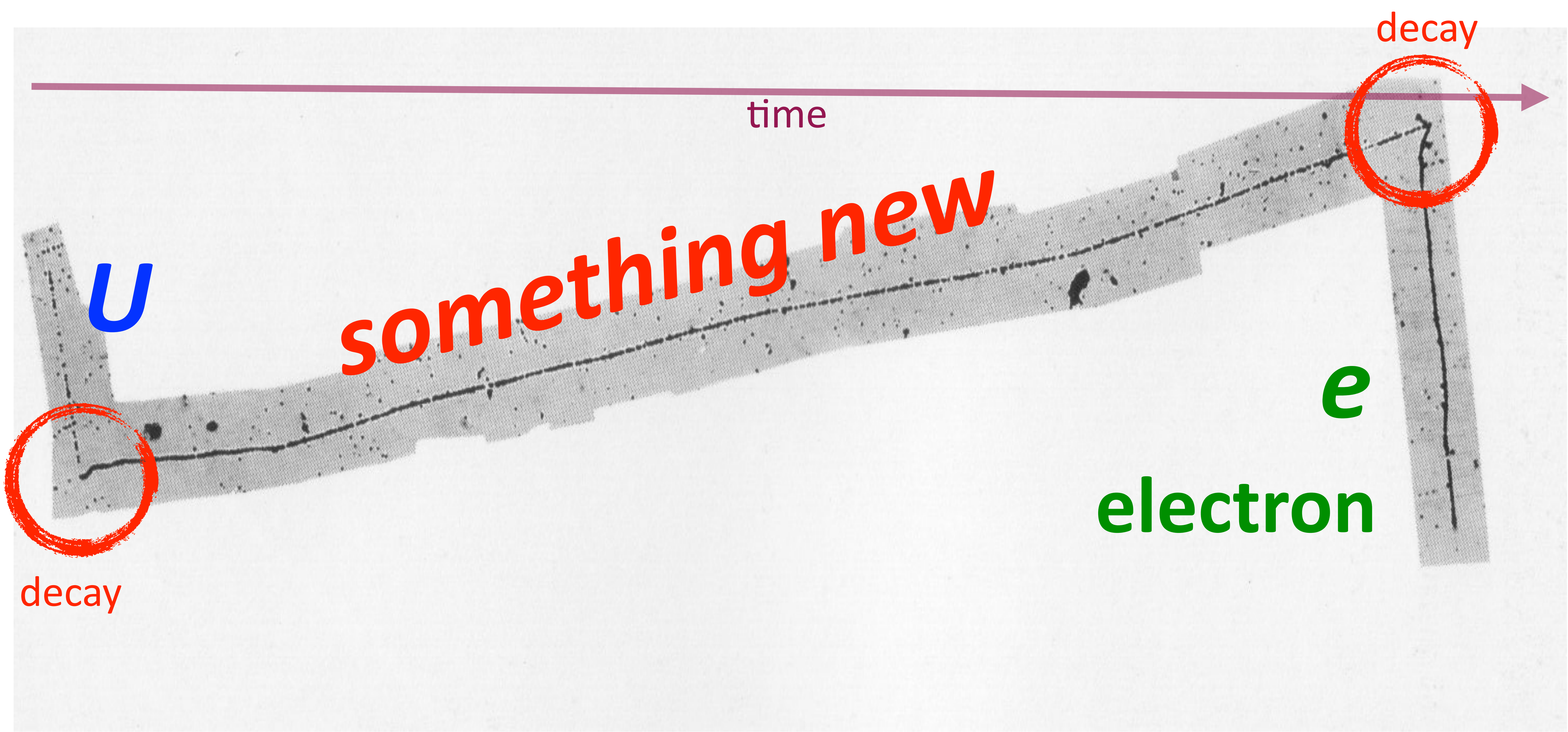
something unknown...

20,000 stereo photos --> 1600 usable tracks in 3 cm^2 plate



strange things in cosmic rays

thick photographic substrates



two discoveries

for the price of one

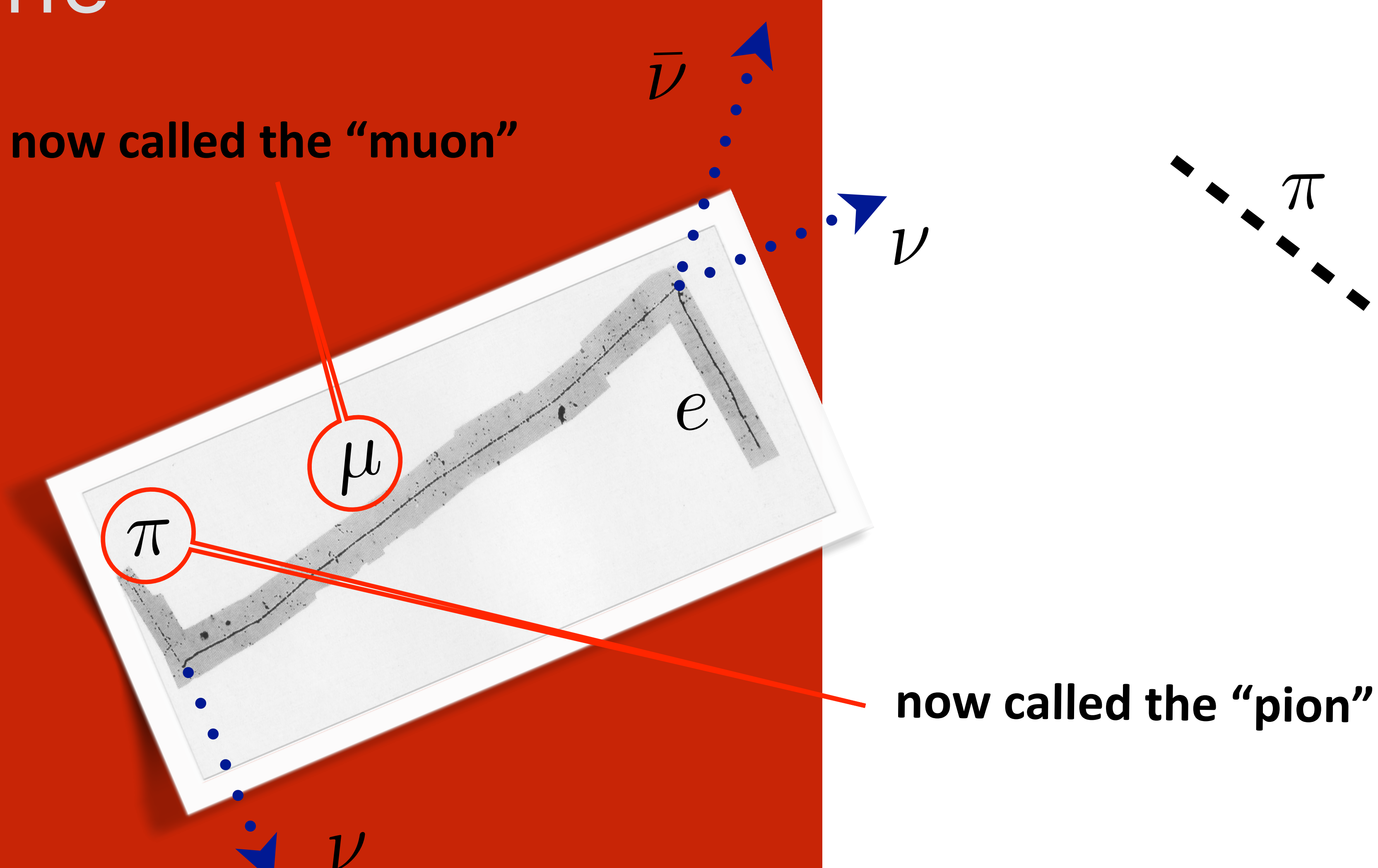
This took some unraveling.

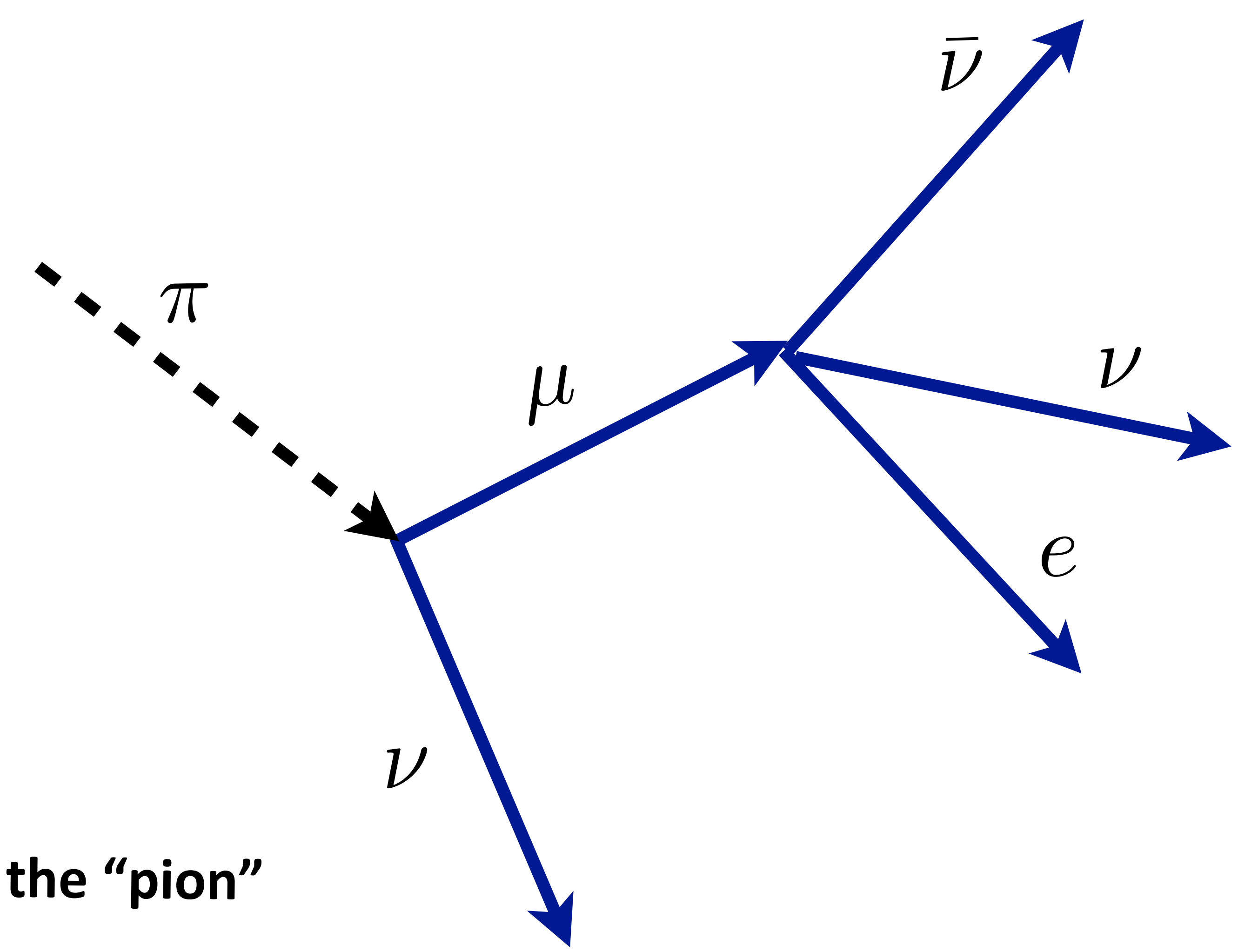
The “meson” appeared in and initiated nuclear collisions

The unknown particle seemed to live about a 6 μsec

too long to be a meson

The winning proposal:



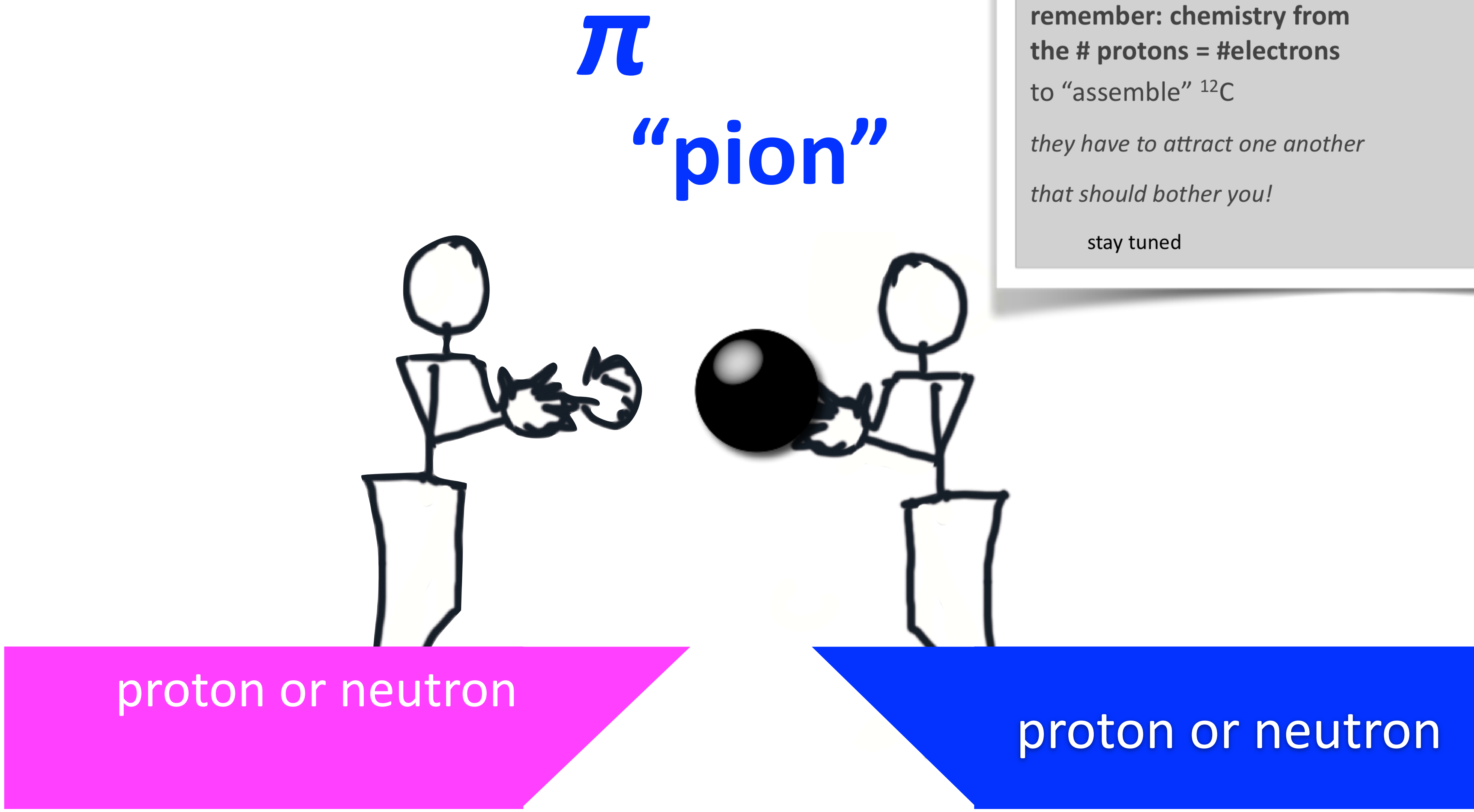


particle: **pion**

symbol:	π
charge:	+, –, 0
mass:	139 MeV/c^2,
spin:	0
category:	Boson, hadron, meson

analogy:

an attractive exchange force



remember: chemistry from
the # protons = #electrons

to "assemble" ^{12}C

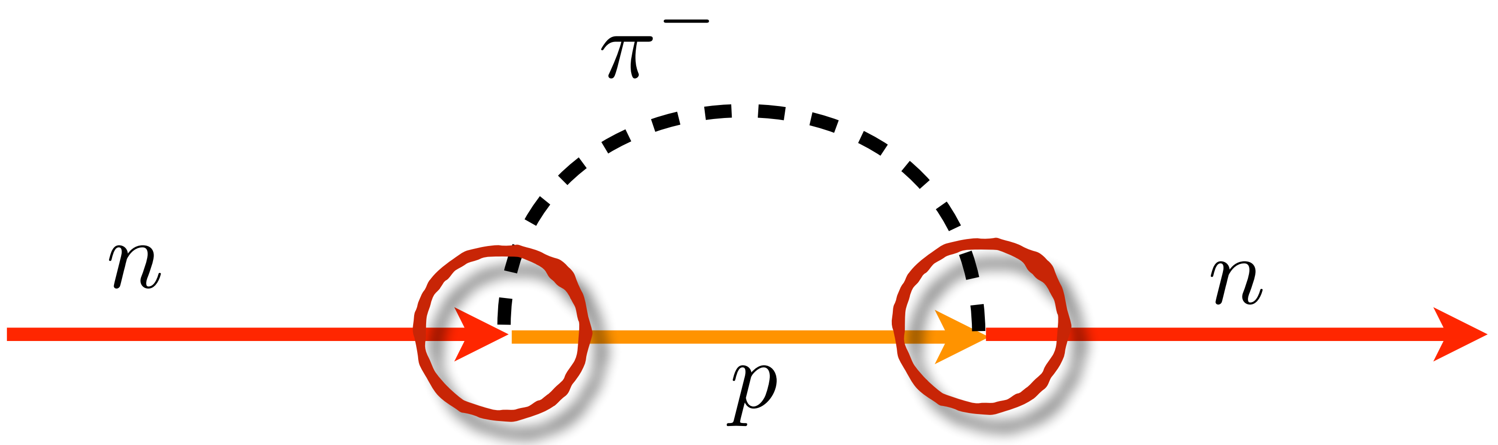
they have to attract one another

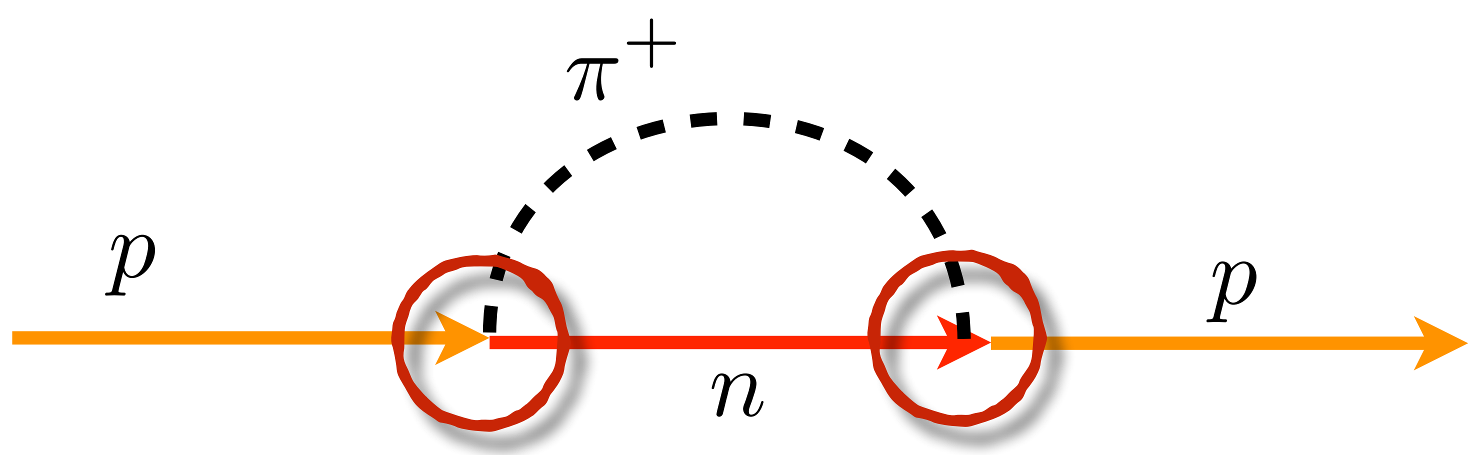
that should bother you!

stay tuned

the Yukawa particle

is the pion



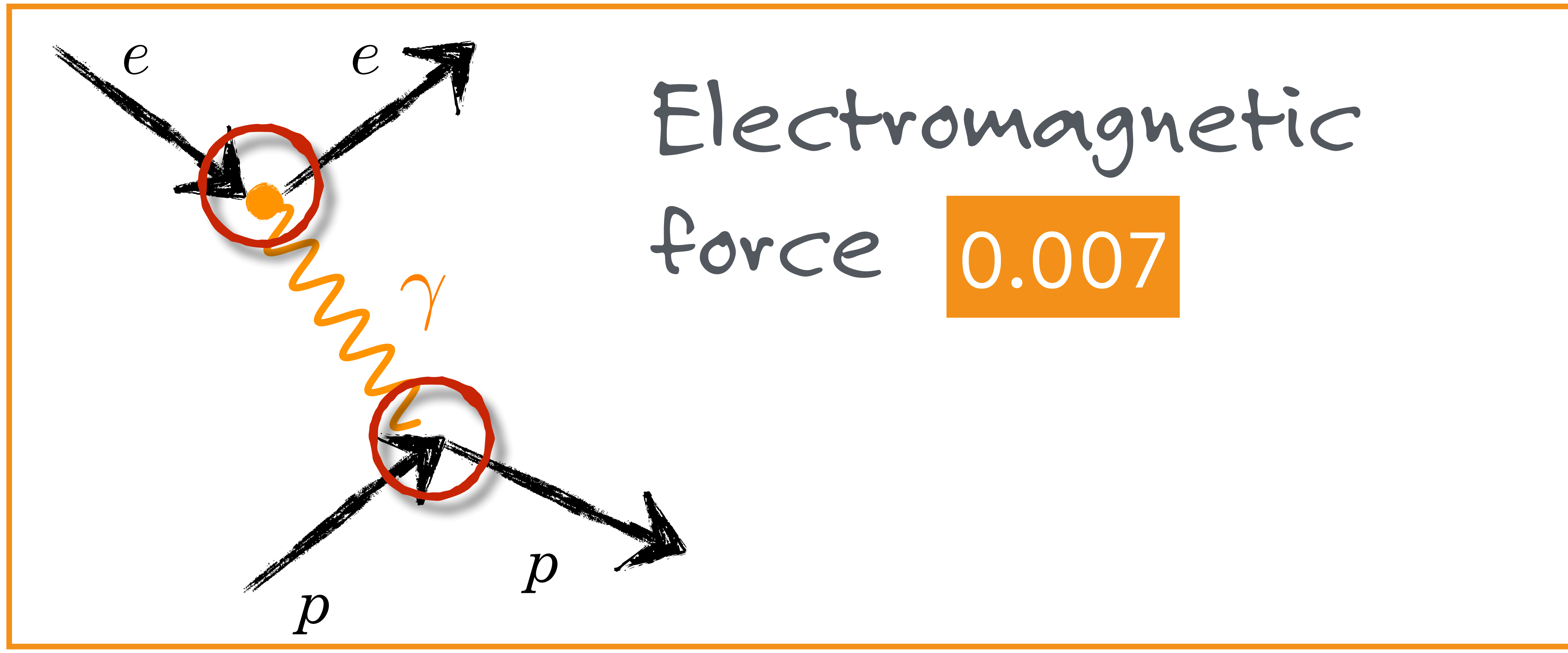


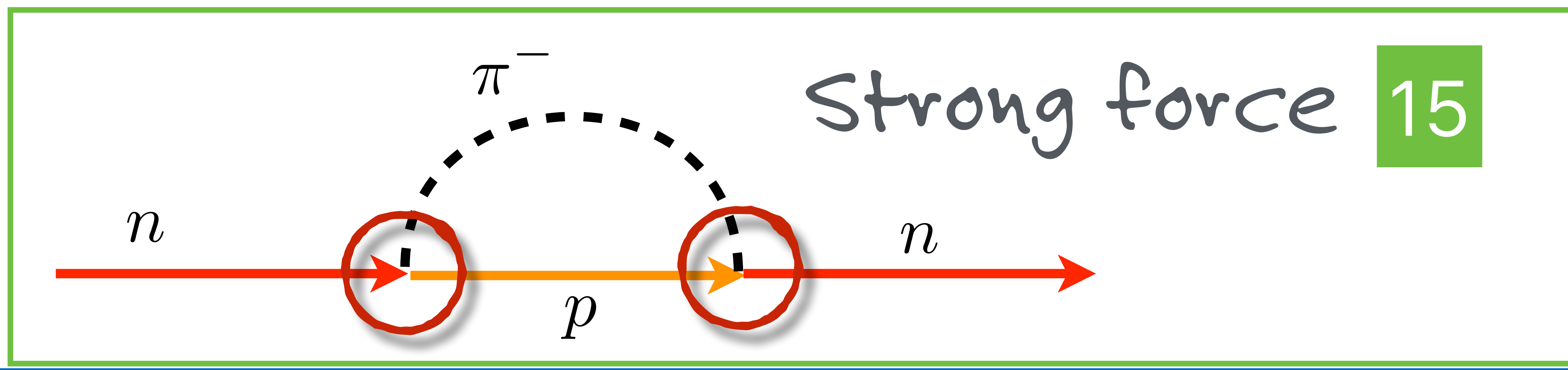
These coupling strengths are large - strong.

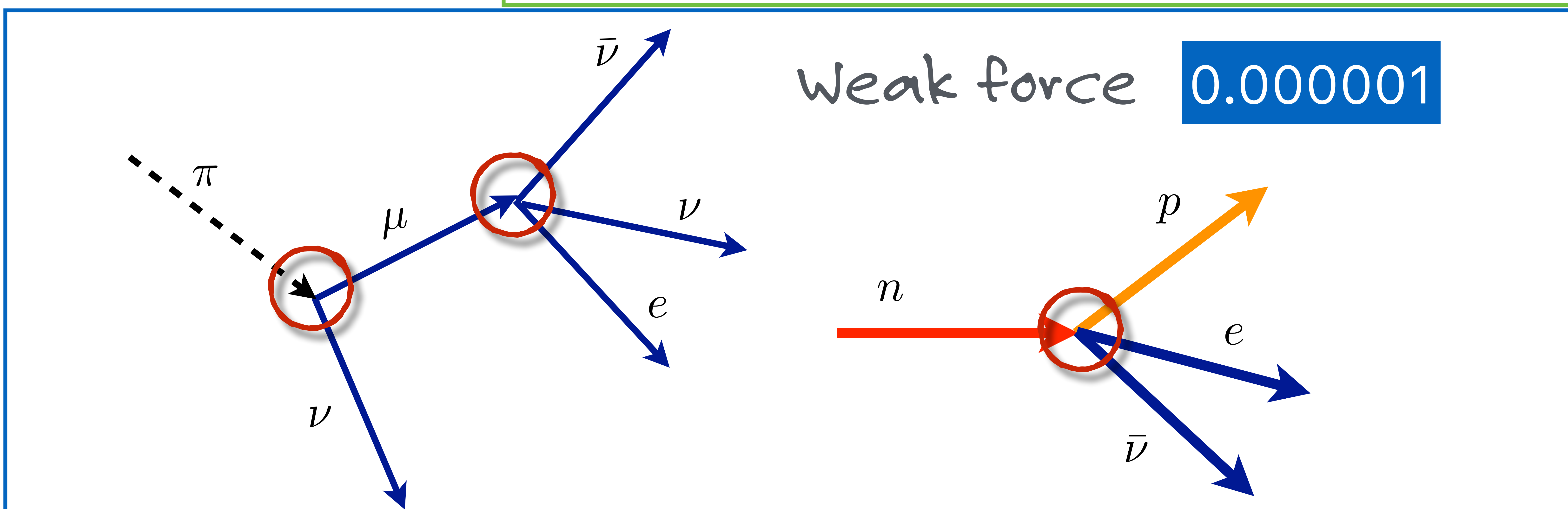
In technical terms we call this...the strong interaction.

three forces now

of vastly different strengths







particle: **muon**

symbol: μ

charge: +, –

mass: 105.7 MeV/c^2

spin: 1/2

category: Fermion, lepton

The Muo ... like an Ele ... vier.

particle: **muon**

symbol:

charge:

mass:

sp

category: Fermion, lepton

The Tau is exactly like an Electron just more um…heavier.

particle: tau

symbol: τ

charge: +, –

mass: 1776.82 ± 0.16 MeV/c^2

spin: 1/2

category: Fermion, lepton

BTW

there are as many neutrinos

as there are "electrons"

we got the original electron, we got an electron-neutrino

the muon, a muon neutrino

aaaand. another one: the tau and its neutrino particle:

muon-neutrino

symbol: ν_μ

charge: 0

mass: 0 or 0.4-ish to 1-ish eV/c^2

spin: 1/2

category: Fermion, lepton

particle: **tau-neutrino**

symbol:	ν_τ
charge:	0
mass:	0 or 0.4-ish to 1-ish eV/c^2
spin:	1/2
category:	Fermion, lepton

FAMILIES

Nature prefers

like-particles

Lepton Families

electrons and a neutrino

muons and a neutrino

taus and a neutrino

These sorts of patterns are a huge deal.

Q			
0	ν_e	ν_μ	ν_τ
−1	e	μ	τ

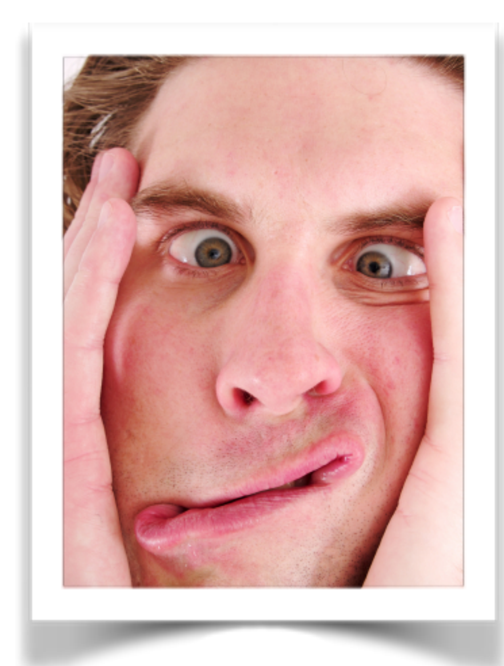
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Identical in every way...except mass

$$m_e \sim \frac{1}{1835} \times m_p$$

$$m_\mu \sim 10\% \times m_p$$

$$m_\tau \sim 1.8 \times m_p \text{ !!}$$



jargon alert: **lepton**

refers to:	originally, an electron, muon, neutrino
entomology:	"λεπτός" (leptos), "fine, small, thin"
example:	electron, muon, neutrino, tau!

back to the 1940s

cosmic rays continue to surprise

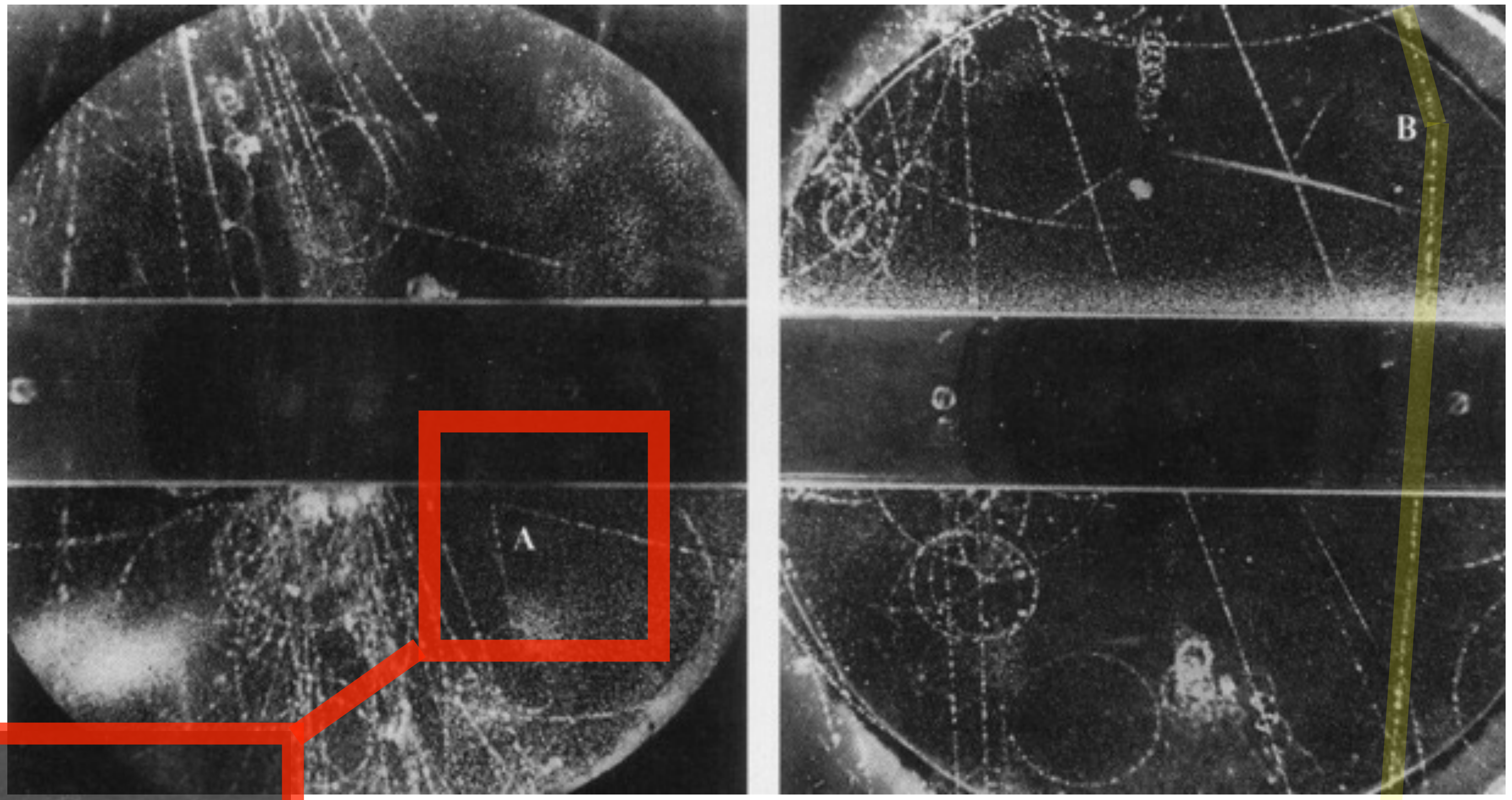
1946

Manchester University

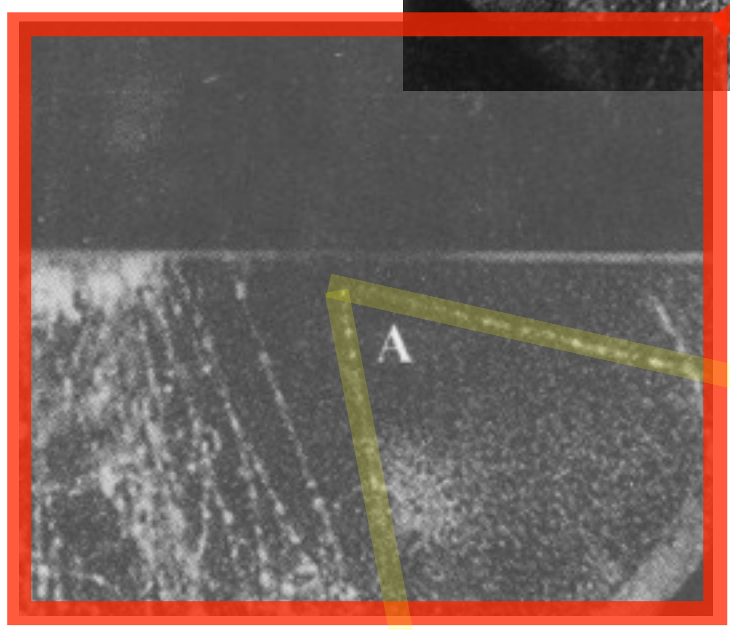
academic home for many years of...? who else.

Mysterious “Vees” began to crop up...

“Vee” $\rightarrow \pi^+ + \pi^-$ “Vee” $\rightarrow \mu + \nu$?



Cloud chamber...with Pb sheet



π

π

$K^0 \rightarrow \pi^+ + \pi^-$

μ

$K^\pm \rightarrow \mu^\pm + \nu$

dubbed “Kaons”...they were

“strange”

particle: **Kaon**

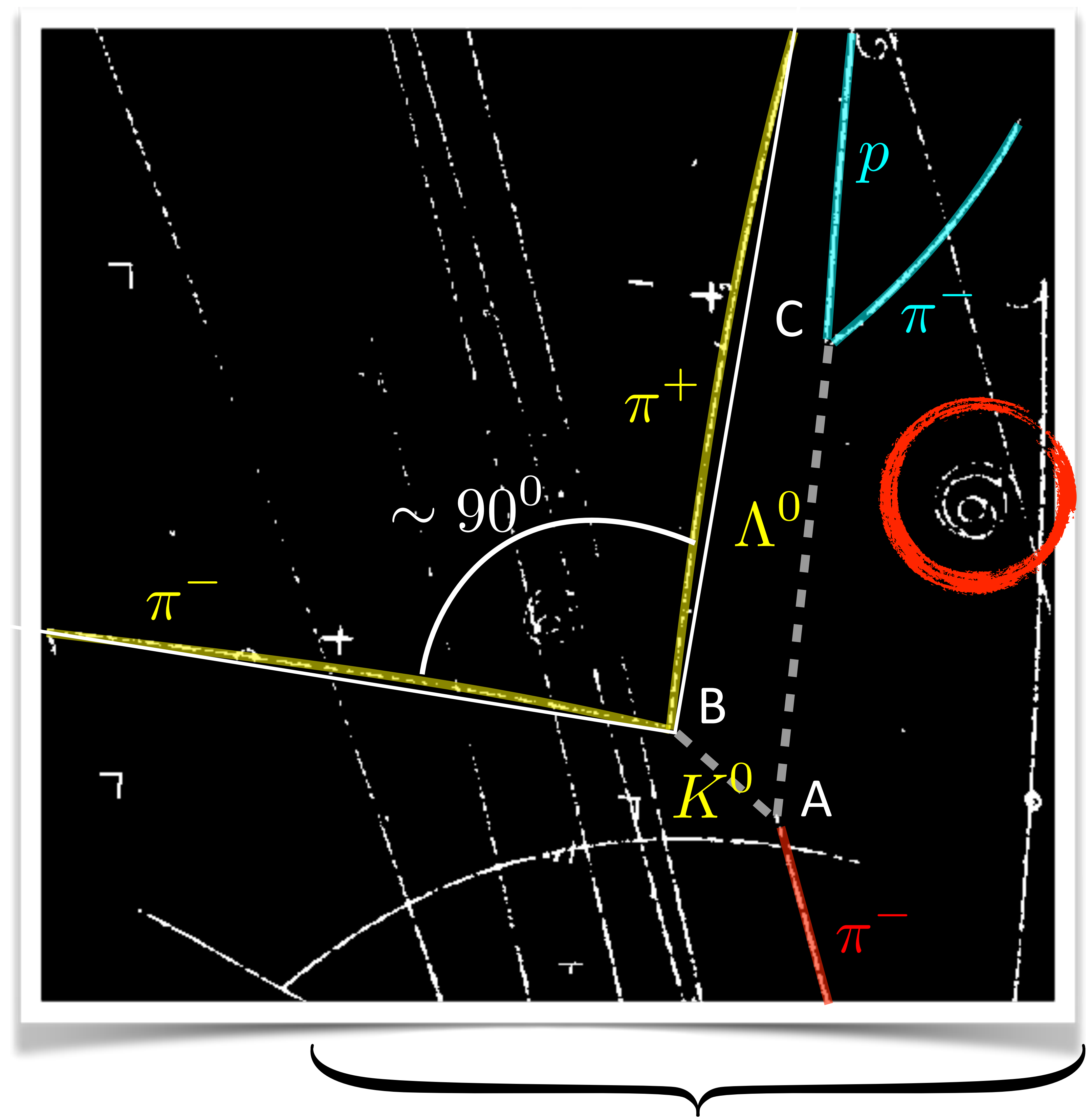
symbol:	K
charge:	±1, 0
mass:	493.677 (charged state) MeV/c^2
spin:	0
category:	Fermion, baryon, I = ±1/2, B=1, S=-3

at the Bevatron

"cosmic ray" events could be manufactured on earth

at will.

Without knowing details, we can decipher a lot:



a little atomic electron kicked out of liquid – tells us the magnetic field direction

π^-

a beam of negative pions at the Bevatron

1. the direction of the field is such that negatives curve left
2. there are two neutral particles produced at A...which decay at B and C
3. @B: the almost 90 degree opening angle – decay products are the same mass
3. @A: the positive track is a proton (bubble density at end), other a pion

yes, more strange particles

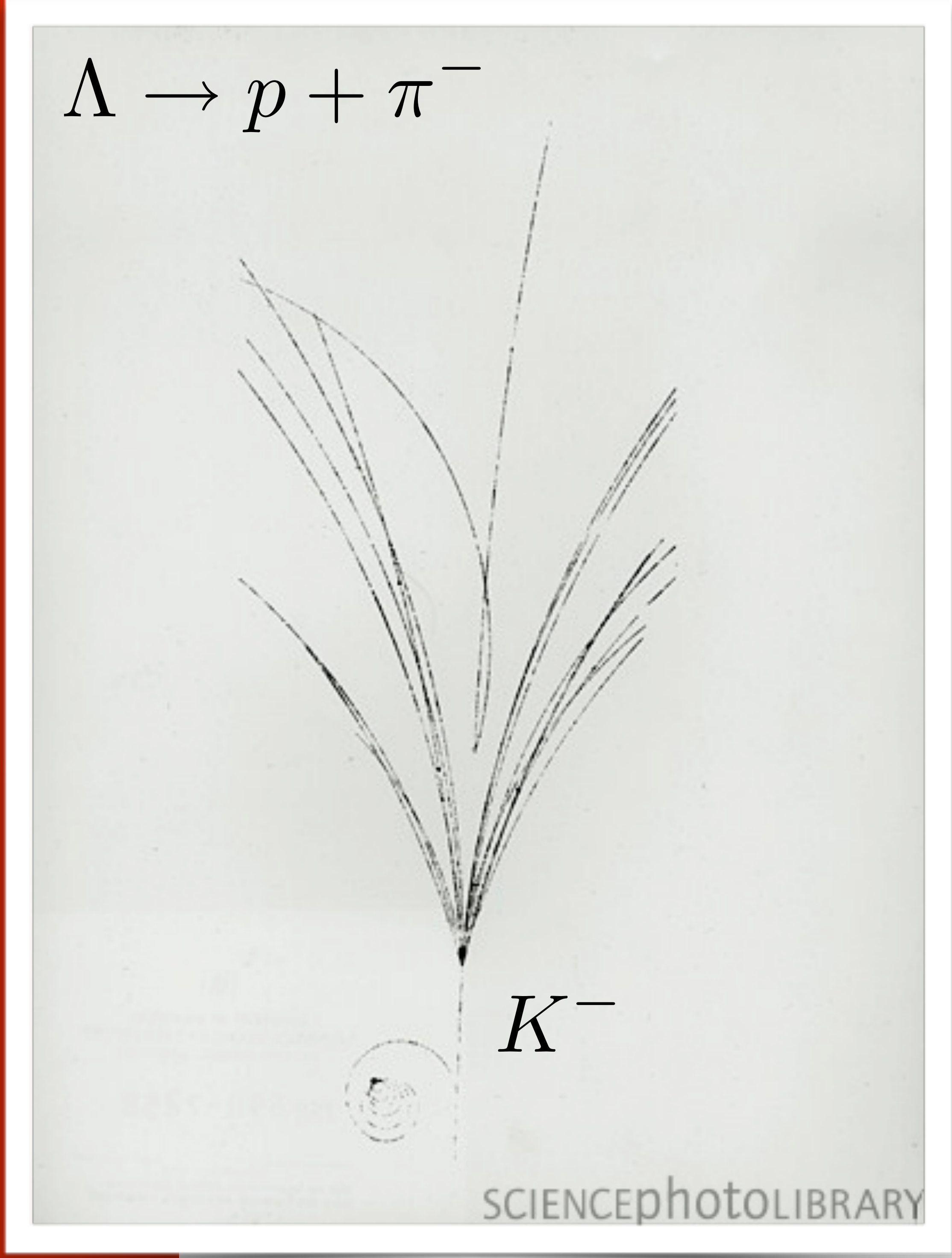
$$\Lambda \rightarrow p + \pi^- \quad 64\%$$

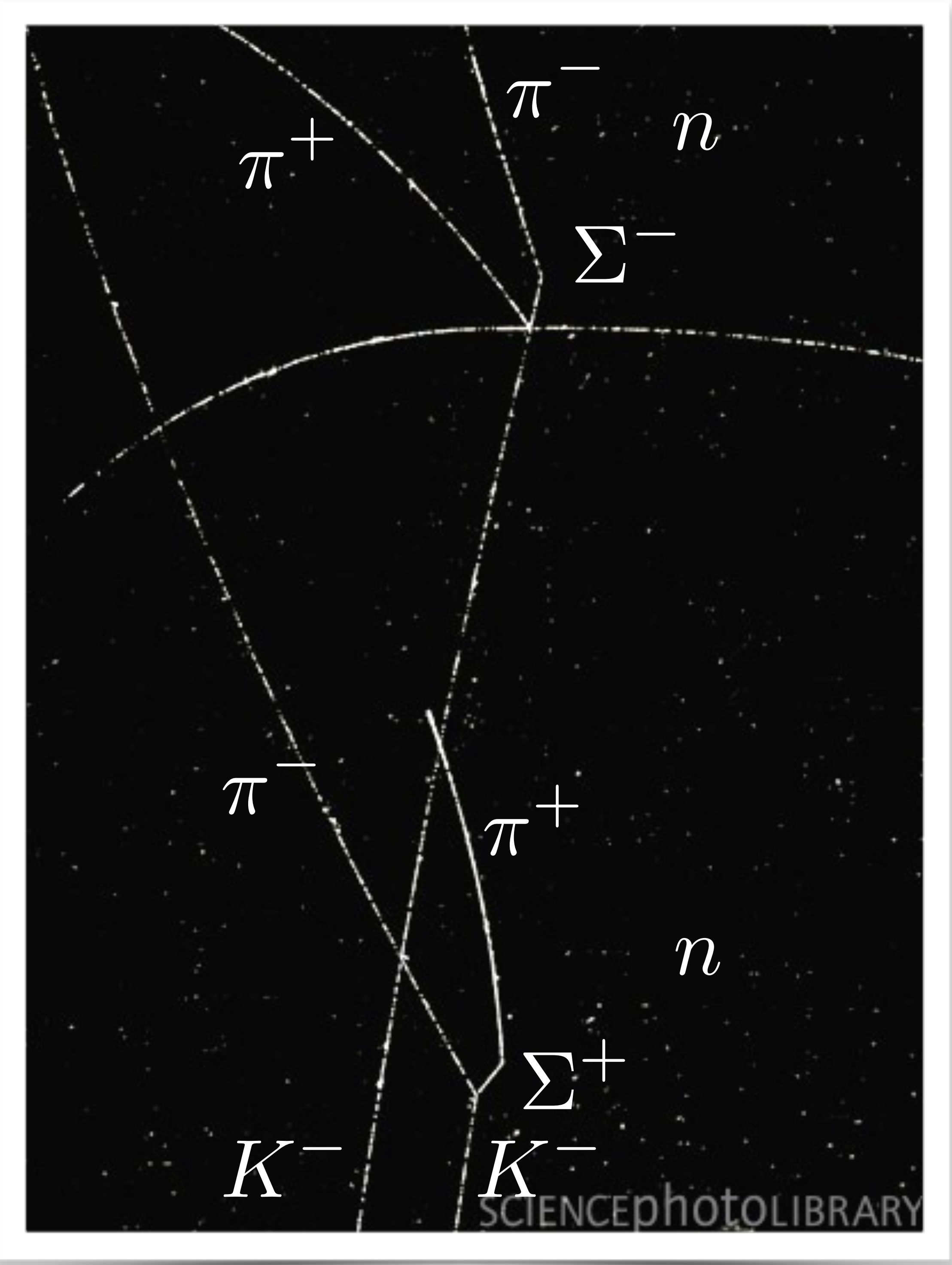
$$\Lambda \rightarrow n + \pi^0 \quad 36\%$$

$$\Sigma^+ \rightarrow n + \pi^+ \quad 51.6\%$$

$$\Sigma^+ \rightarrow p + \pi^0 \quad 48.4\%$$

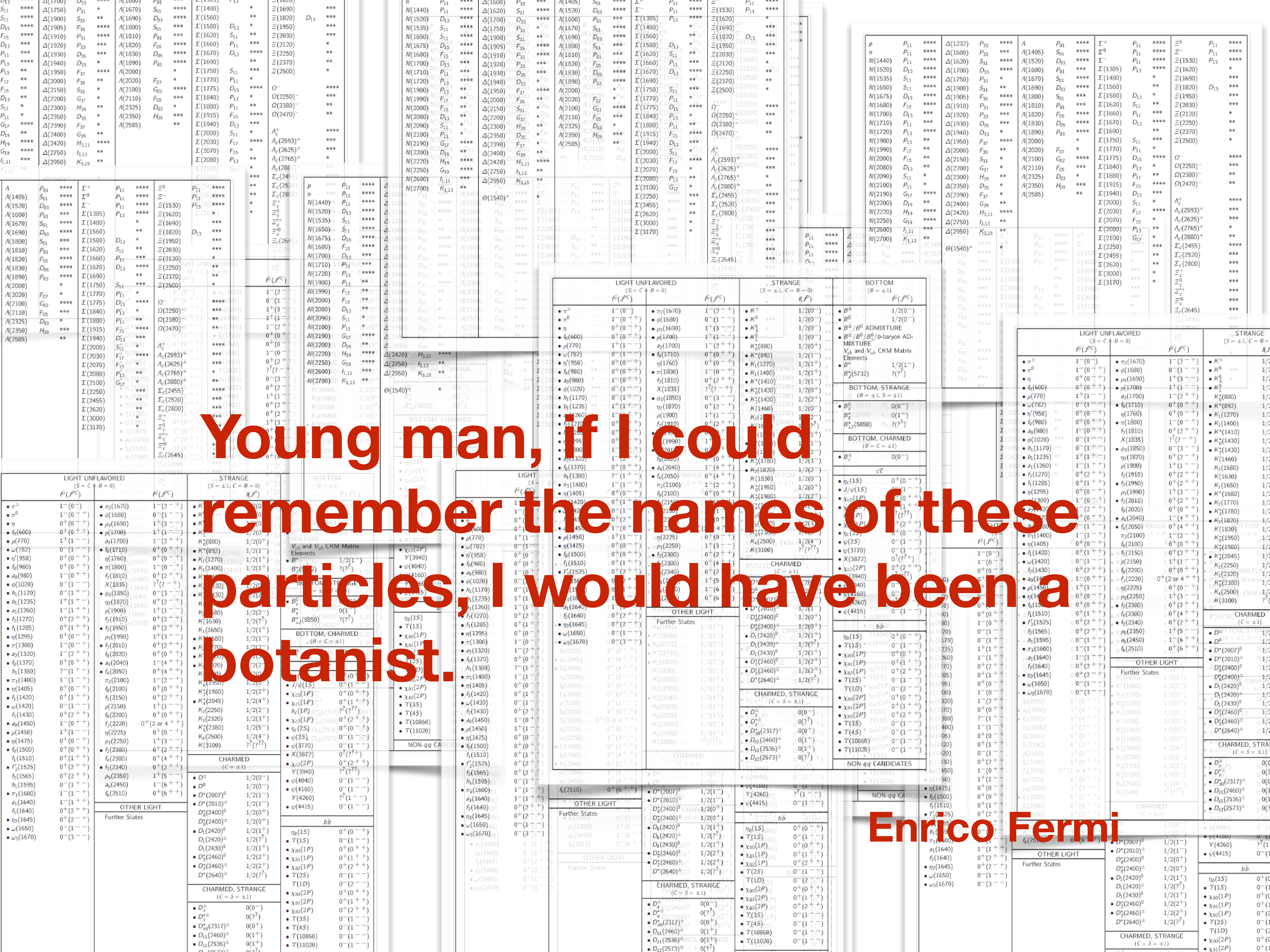
- "Lambdas"
- "Sigmas"
- "Cascades"
- "K-stars"





particle: **Lambda**

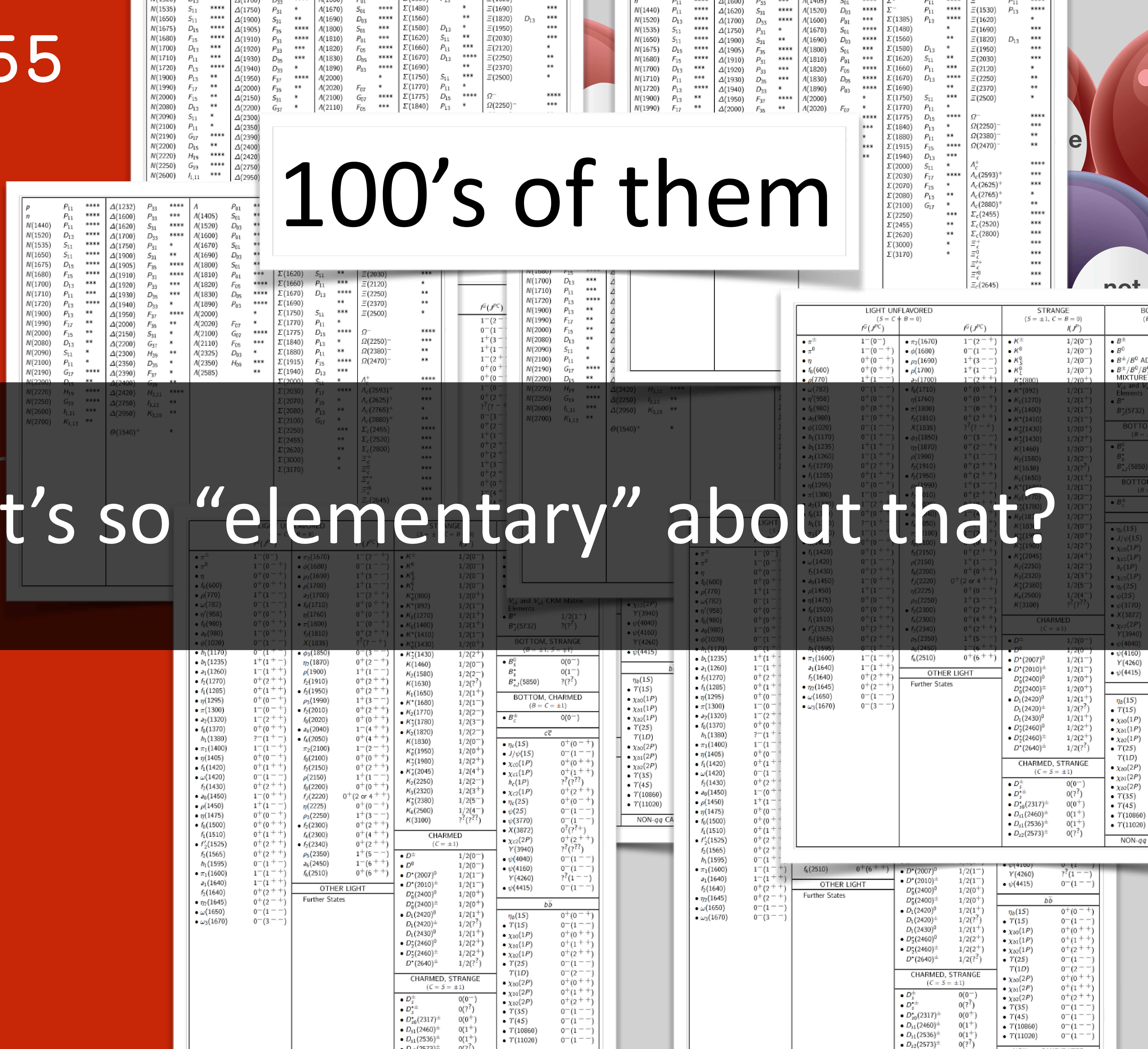
symbol:	Λ
charge:	0
mass:	1,115.683 MeV/c^2
spin:	1/2
category:	Fermion, baryon, I = 0, B=1, S=-1


Young man, if I could remember the names of these particles, I would have been a botanist.
Enrico Fermi

By the mid-1950's

things are officially out of control.

by 1955

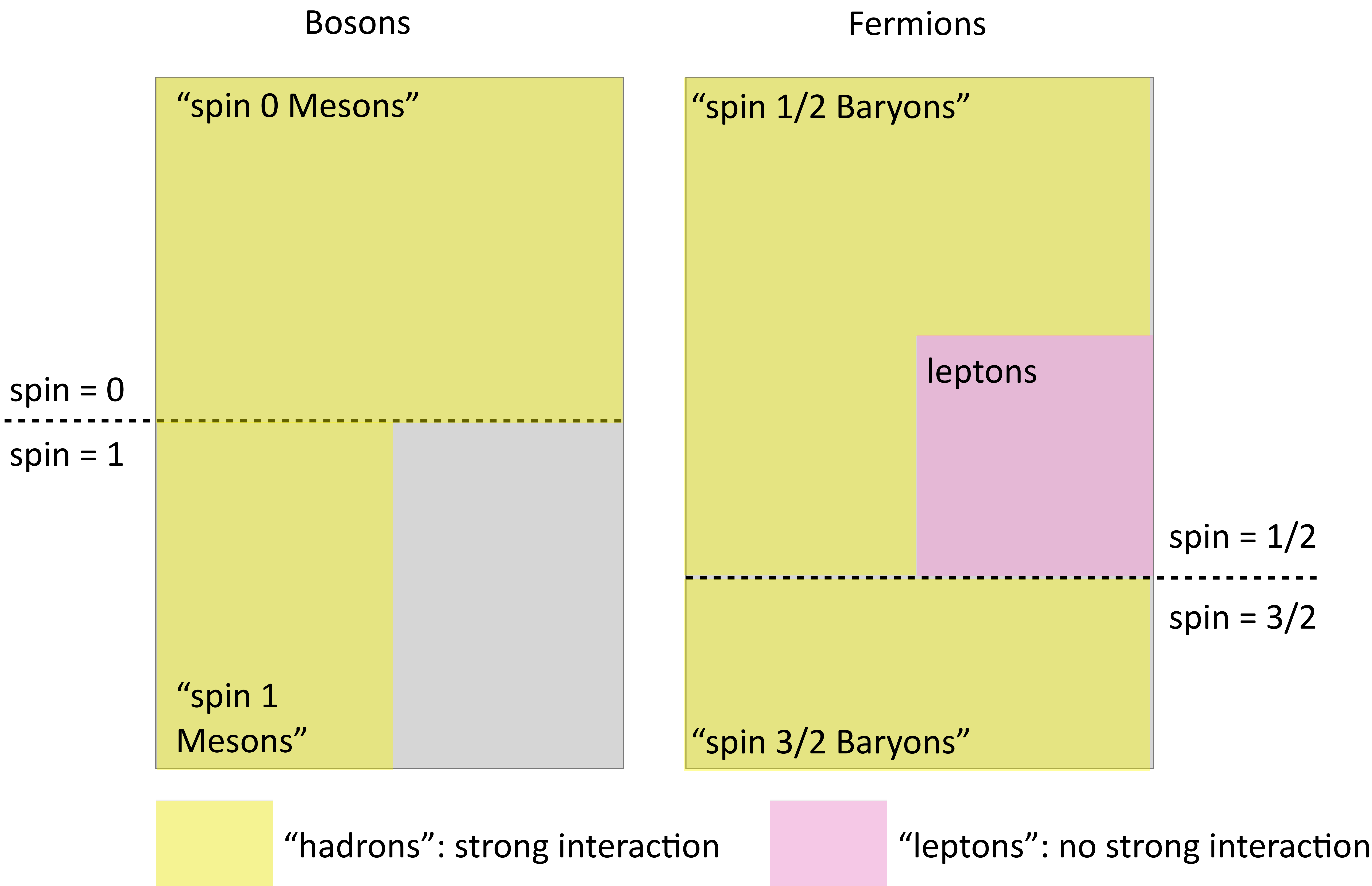


100's of them

things were messy

what's so "elementary" about that?

The Particle Zoo?



there were clues

patterns and organizing features

began to emerge in the pile of data

Hundreds of experiments, thousands of physicists measuring lifetimes, probabilities, final state multiplicities...and doing it over and over.

organizing

with many different patterns at a time

Strictly Empirical:

From a 20 year-long accumulation of thousands of different results on production, decay, mass, spin properties of 100's of particles...whole careers. *No clue why the patterns.*

Various "Quantum Numbers" – all reflecting an underlying "internal symmetry"

Electric Charge
Lepton Numbers
Baryon Number
Strangeness

jargon alert:

particle quantum numbers

refers to: quantities that are inherently a part of particles, which are conserved in interactions or decays

entomology: historical to Bohr and Schroedinger

example: electric charge, baryon number, lepton number, isospin

this is empirical - it’s what Nature seems to do

we have some ideas about how/why

but understanding quantum number rules is work in progress!

Quantum Number:

Electric Charge

something like these will never happen:

so, you'll always see:

$$A^+ \rightarrow B^+ + C^+$$

Q: +1 +1 +1

$$A^+ + B^+ \rightarrow C^+ + D^-$$

Q: +1 +1 +1 -1

total electric charge at the beginning equals total charges at the end

Quantum Number:

Strangeness

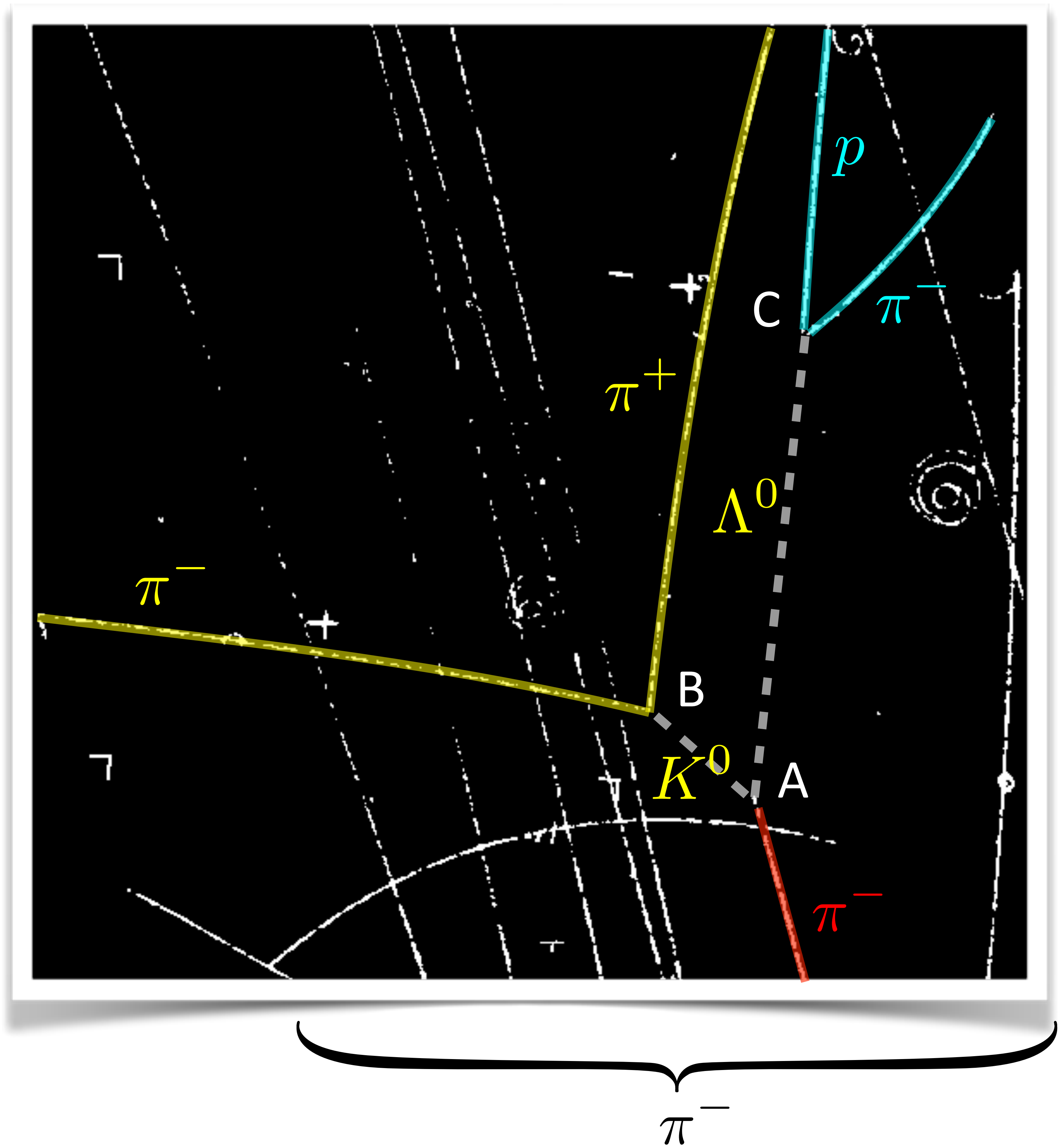
a clue

of another kind of "number"

$$\pi^- + p \rightarrow \Lambda^0 + K^0$$

some particles are easily produced...but **only in pairs**

and they, in turn, are reluctant to decay



Strangeness, S

strangeness seems to come in pairs

assign "strangeness" empirically.

$$\pi^- + p \rightarrow \Lambda^0 + K^0$$

S:	0	0	–1	+1

Strong interaction

~~$\pi^- + p \rightarrow \Lambda^0 + n$~~ ?

S:	0	0	–1	0

and yet you *do* see:

$$\Lambda \rightarrow p + \pi^-$$

S:	–1	0	0

Weak interaction

Production of a subset of all baryons seems to require them to come in pairs.
Strong interactions conserve Strangeness

Decay of those same baryons...notsomuch
Weak interactions change Strangeness by 1 unit

the dominant Baryons

Particle	Symbol	Rest Mass MeV/c²	spin	Q	B	S	Lifetime	dominant decay modes
proton	p	938.3	1/2	+1	+1	0	> 10^{31} y	
neutron	n	939.6	1/2	0	+1	0	920	$pe^-\bar{\nu}_e$
Lambda	Λ^0	1115.6	1/2	0	+1	–1	2.6 x 10^{-10}	$p\pi^-,\ n\pi^0$
Sigma	Σ^+	1189.4	1/2	+1	+1	–1	0.8 x 10^{-10}	$p\pi^0,\ n\pi^+$
Sigma	Σ^0	1192.5	1/2	0	+1	–1	6 x 10^{-20}	$\Lambda^0\gamma$
Sigma	Σ^-	1197.3	1/2	–1	+1	–1	1.5 x 10^{-10}	$n\pi^-$
Delta	Δ^{++}	1232	3/2	+2	+1	0	0.6 x 10^{-23}	$p\pi^+$
Delta	Δ^+	1232	3/2	+1	+1	0	0.6 x 10^{-23}	$n\pi^+,\ p\pi^0$
Delta	Δ^0	1232	3/2	0	+1	0	0.6 x 10^{-23}	$n\pi^0$
Delta	Δ^-	1232	3/2	–1	+1	0	0.6 x 10^{-23}	$n\pi^-$
Xi	Ξ^0	1315	1/2	0	+1	–2	2.9 x 10^{-10}	$\Lambda^0\pi^0$
Xi	Ξ^-	1321	1/2	–1	+1	–2	1.64 x 10^{-10}	$\Lambda^0\pi^-$
Omega	Ω^-	1672	3/2	–1	+1	–3	0.82 x 10^{-10}	$\Xi^0\pi^-,\ \Lambda^0K^-$

the dominant Mesons

Particle	Symbol	anti-particle	Rest Mass MeV/c²	spin	Q	B	S	Lifetime	dominant decay modes
Pion	π^+	π^-	139.6	0	+1	0	0	2.6×10^{-8}	$\mu^+\nu_\mu$
Pi-zero	π^0	π^0	135	0	0	0	0	920	2γ
Kaon	K^+	K^-	493.7	0	+1	0	+1	1.24×10^{-8}	$\mu^+\nu_\mu, \pi^+\pi^0$
K-short	K_S^0	K_S^0	497.7	0	0	0	+1	0.89×10^{-10}	$\pi^+\pi^-, 2\pi^0$
K-long	K_L^0	K_L^0	497.7	0	0	0	+1	5.2×10^{-8}	$\pi^\pm\ell^\mp\nu_\ell$
Eta	η^0	η^0	548.8	0	0	0	0	$< 10^{-18}$	$2\gamma, \pi^+\pi^-\pi^0$
Eta-prime	$\eta^{0\prime}$	$\eta^{0\prime}$	958	1	0	0	0	…	$\pi^+\pi^-\eta$
Rho	ρ^+	ρ^-	770	1	+1	0	0	0.4×10^{-23}	$\pi^+\pi^-, 2\pi^0$
Rho-naught	ρ^0	ρ^0	770	1	0	0	0	0.4×10^{-23}	$\pi^+\pi^-$
Omega	ω^0	ω^0	782	1	0	0	0	0.8×10^{-22}	$\pi^+\pi^-\pi^0$
Phi	ϕ	ϕ	1020	1	0	0	0	20×10^{-23}	$K^+K^-, K^0\bar{K}^0$

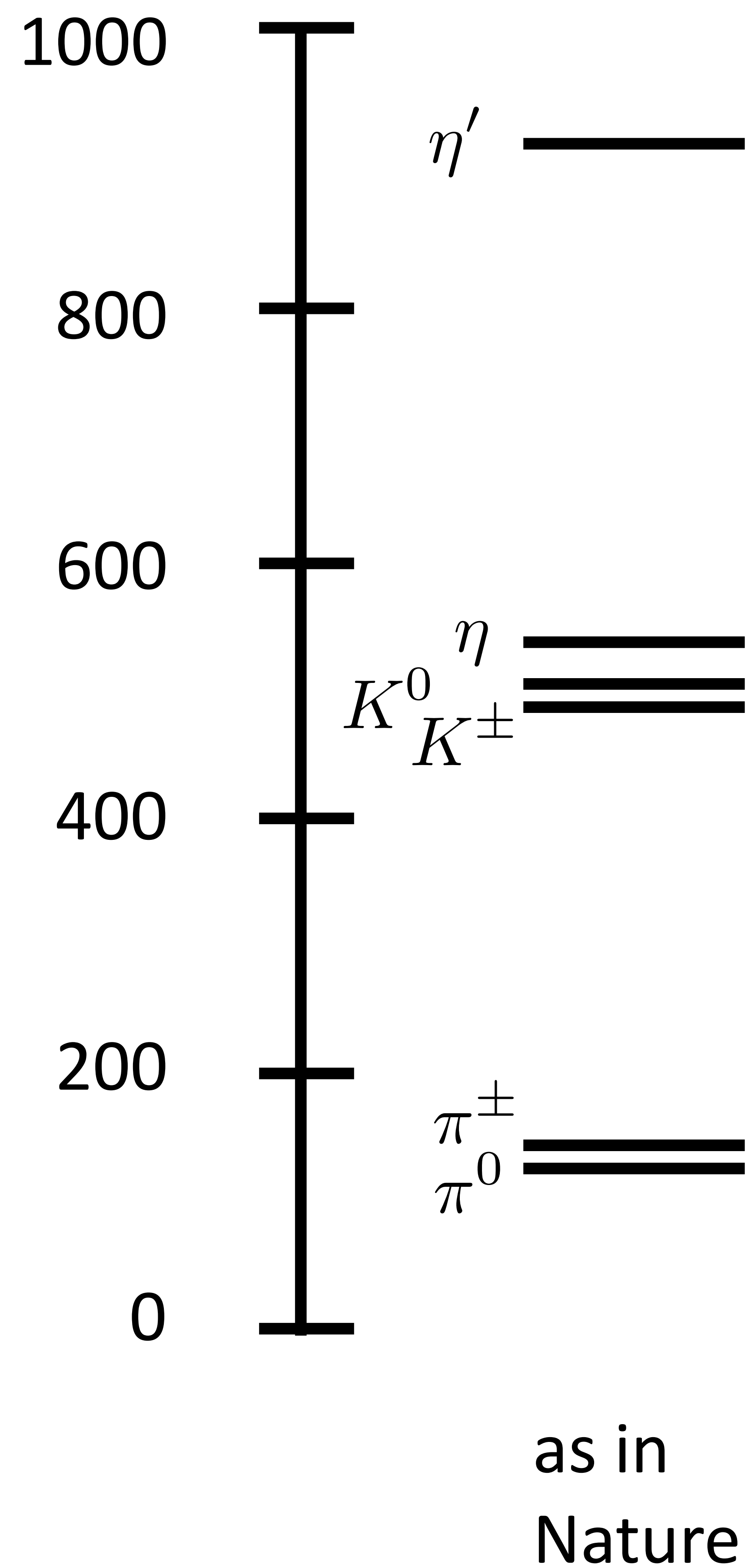
anyhow...back to the Zoo problem

all those particles.

There were some hints:

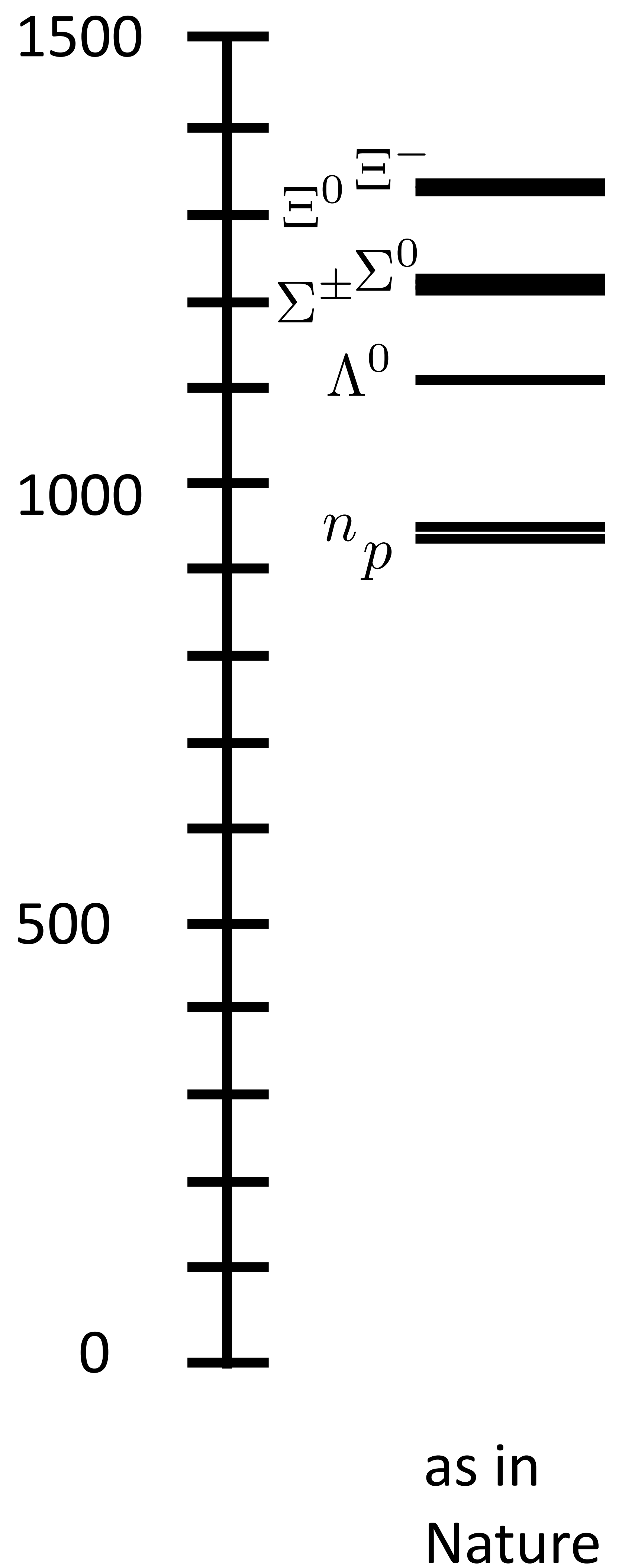
masses seem to clump

look at a set of the mesons



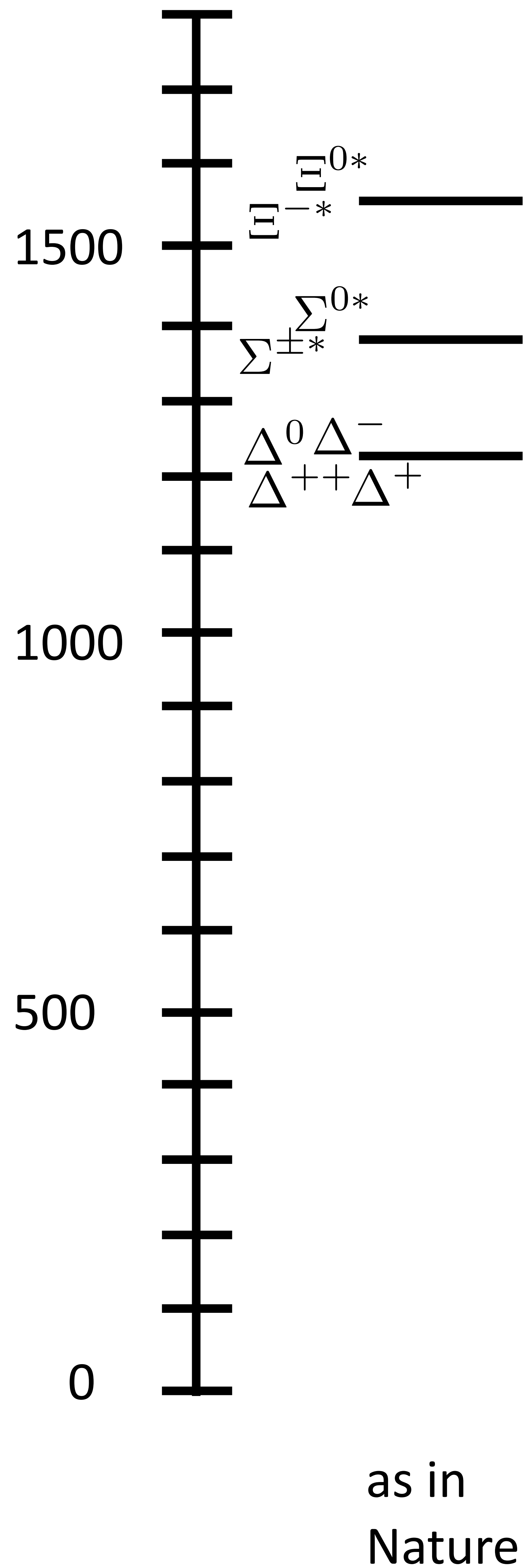
masses seem to clump

look at the baryons



masses seem to clump

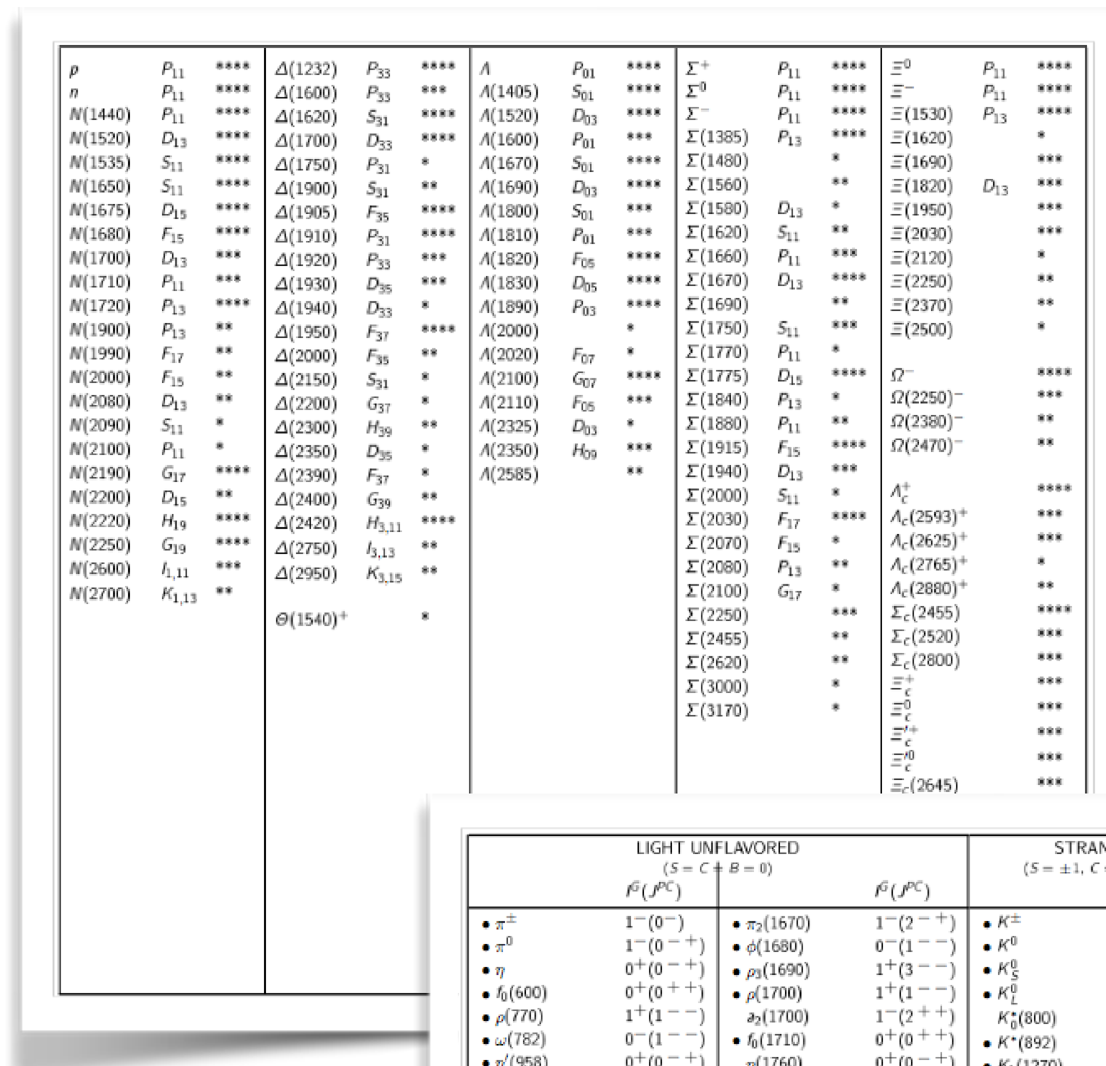
look at a different set of the baryons

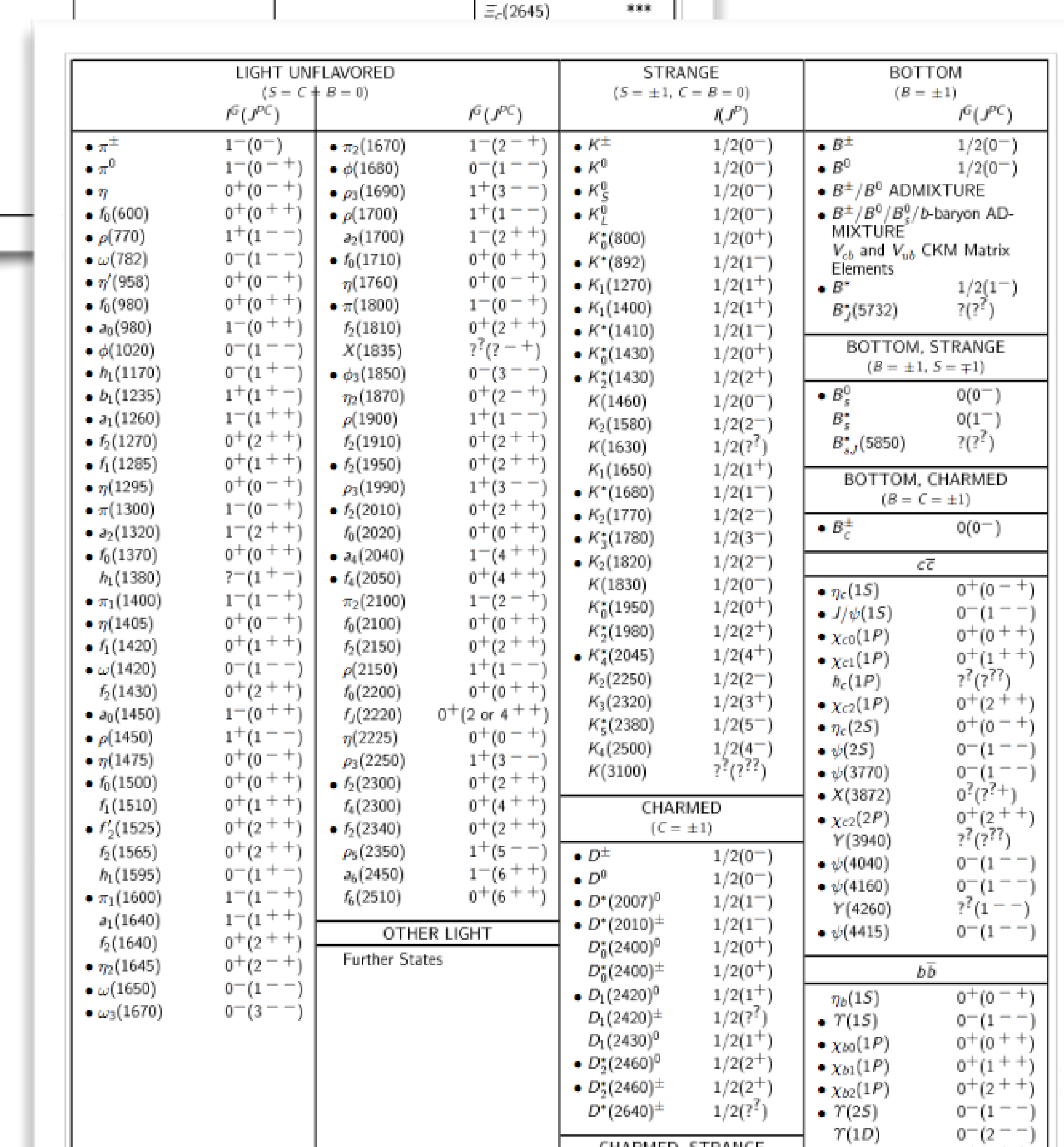


patterns emerged

to Murray Gell-Mann & (independently) Yuval Ne’eman in 1964

Δ^0 Ξ^- Δ^- Σ^- Λ^0 Ξ^* p Δ^+ Σ^0 Σ^{*-} Σ^{*+} Δ^{++} n Ξ^0 Ξ^{*0} Σ^+ Σ^{*0}



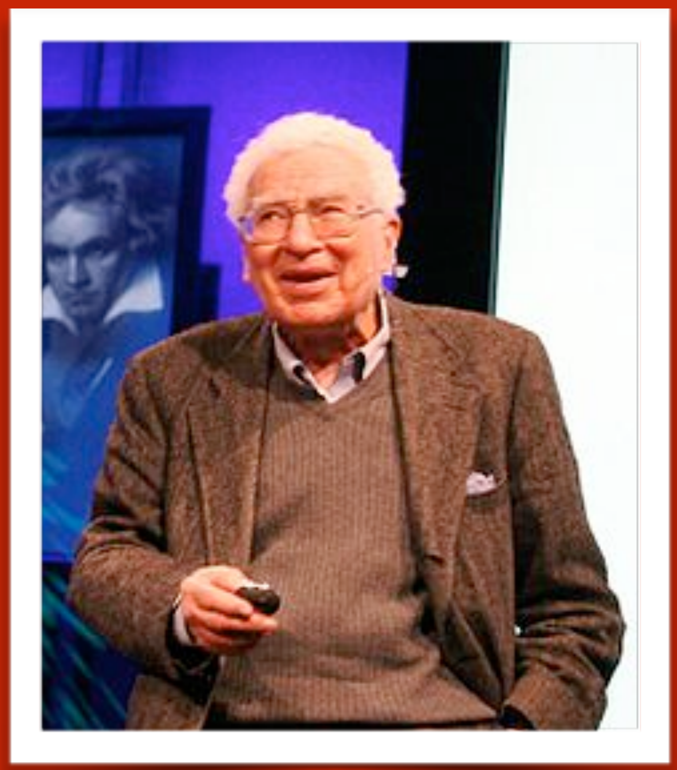


family arrangements

quarks

the mathematical description of such patterns

1964



Murray Gell-Mann

1929 -

theoretician

Nobel Laureate 1969

genius

Yale at age of 15. PhD from MIT at age of 22.

Speaks at least 13 languages fluently. Studies linguistics now, among other things.

Unraveled many of the organization puzzles of the particle zoo:

- strangeness
- an empirical mass formula relating them

Worries a lot now about the nature of physical law.

A not-so-good TED lecture on mathematical Beauty in physics...link below.

Not known for his humility.

http://www.ted.com/talks/murray_gell_mann_on_beauty_and_truth_in_physics.html

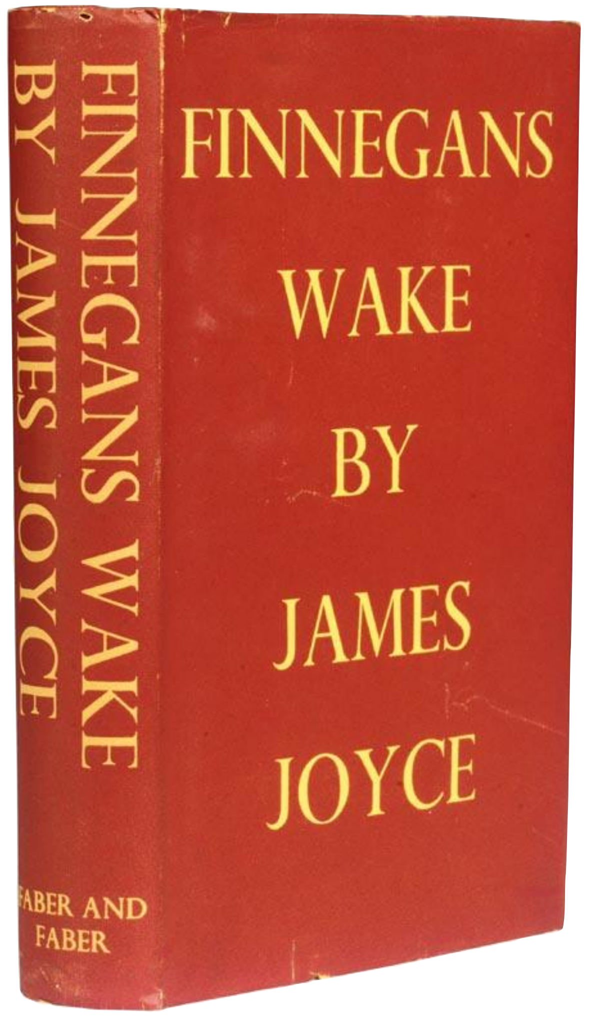
Gell-Mann found that the patterns work

if every particle is composed of smaller bits

up
down
strange

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

"Quarks"



Gell-Mann's original pattern for quarks. Changed...

with fractional electric charge:

charge of up quark:	+2/3 e
charge of down quark:	–1/3 e
charge of strange quark:	–1/3 e

Baryons & Mesons differ by quark-content

Baryons are made of 3 quarks

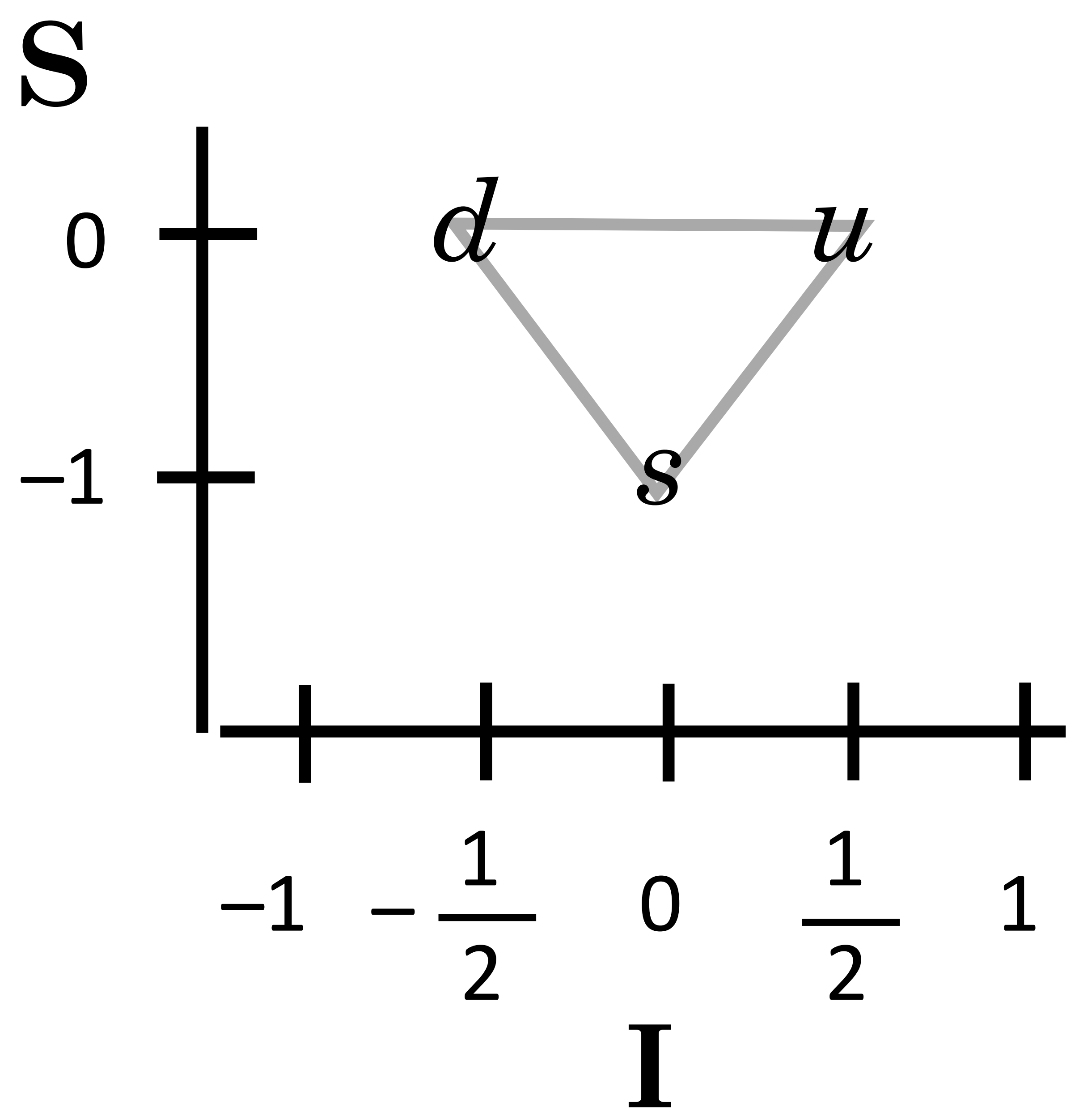
Mesons are made of 1 quark and 1 antiquark

Quarks

1964 version

fundamental fermions

in same league as electrons and neutrinos

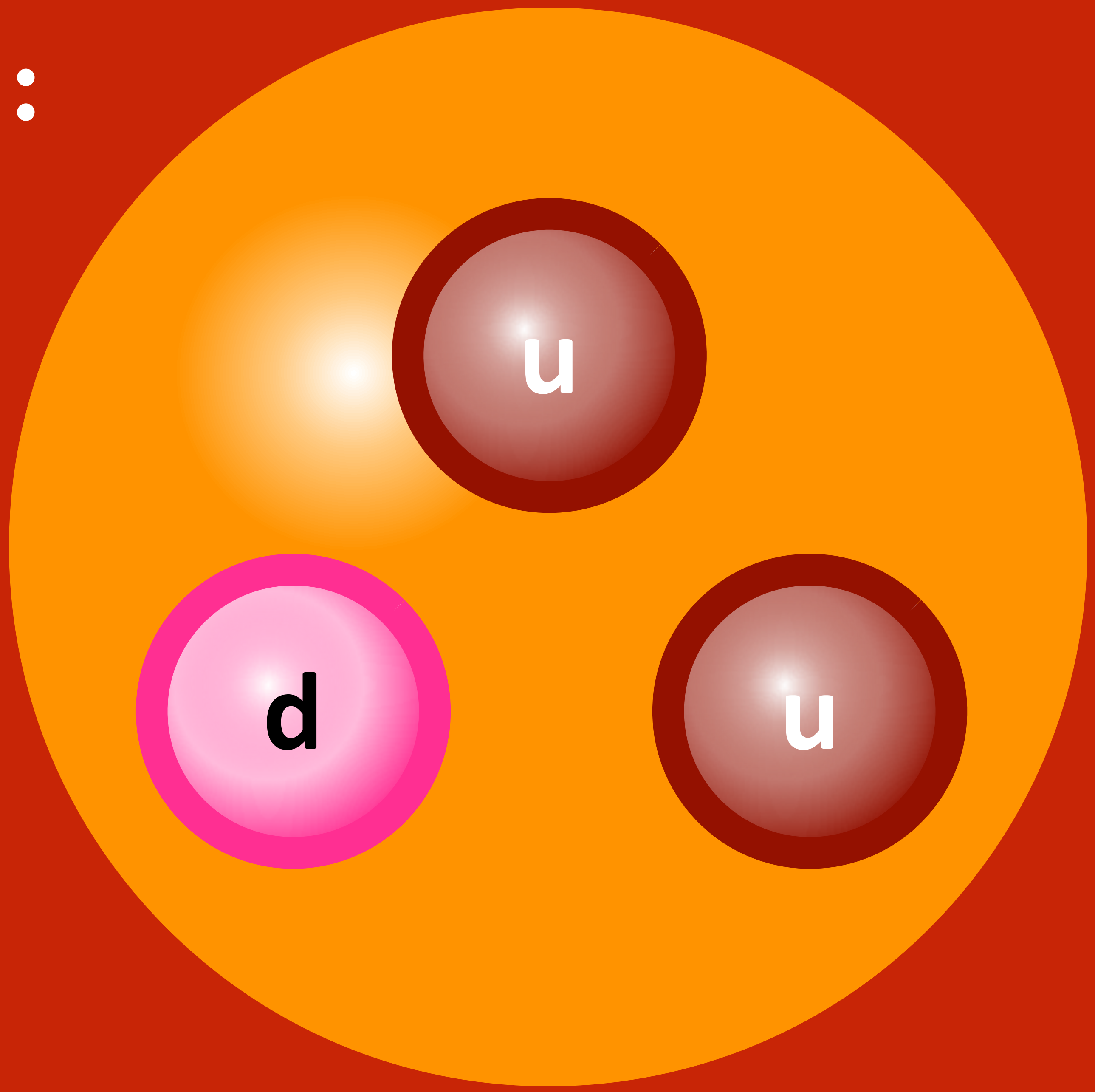


Quark	Symbol	Rest Mass MeV/c^2	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece 'em together:

proton

electric charge = +1

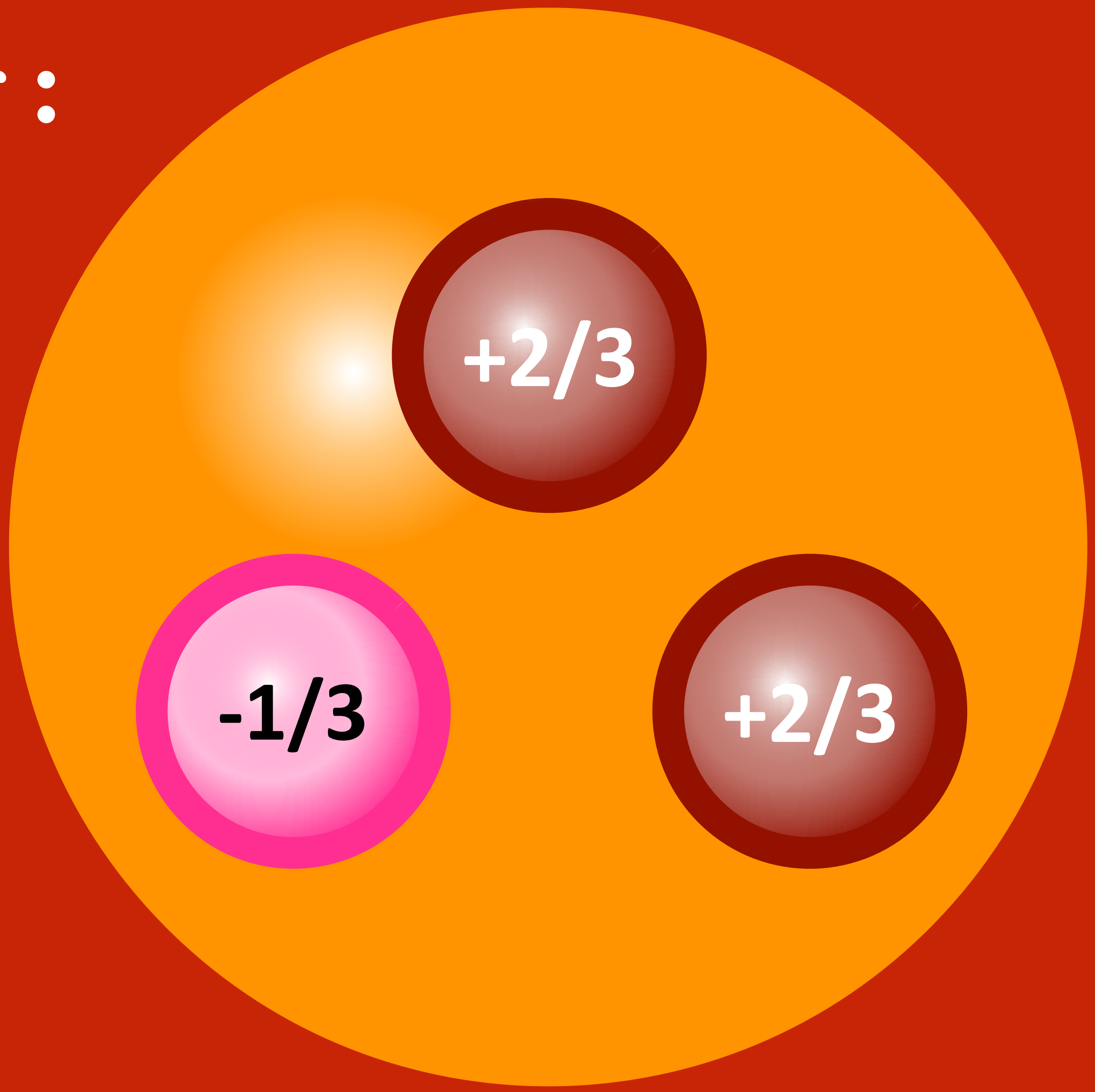


Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece ‘em together:

proton

electric charge = +1

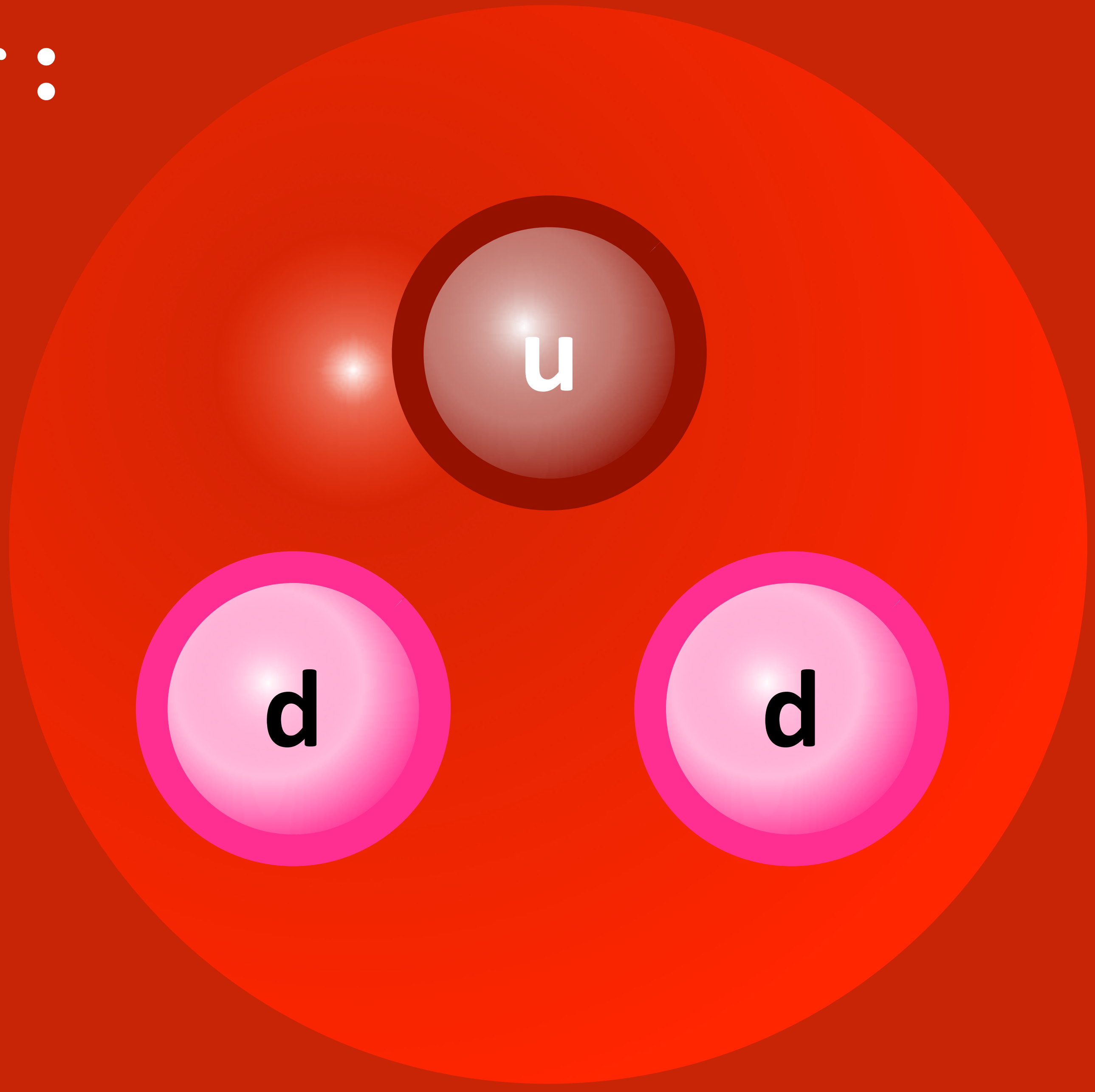


Quark	Symbol	Rest Mass MeV/c^2	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece 'em together:

neutron

electric charge = 0

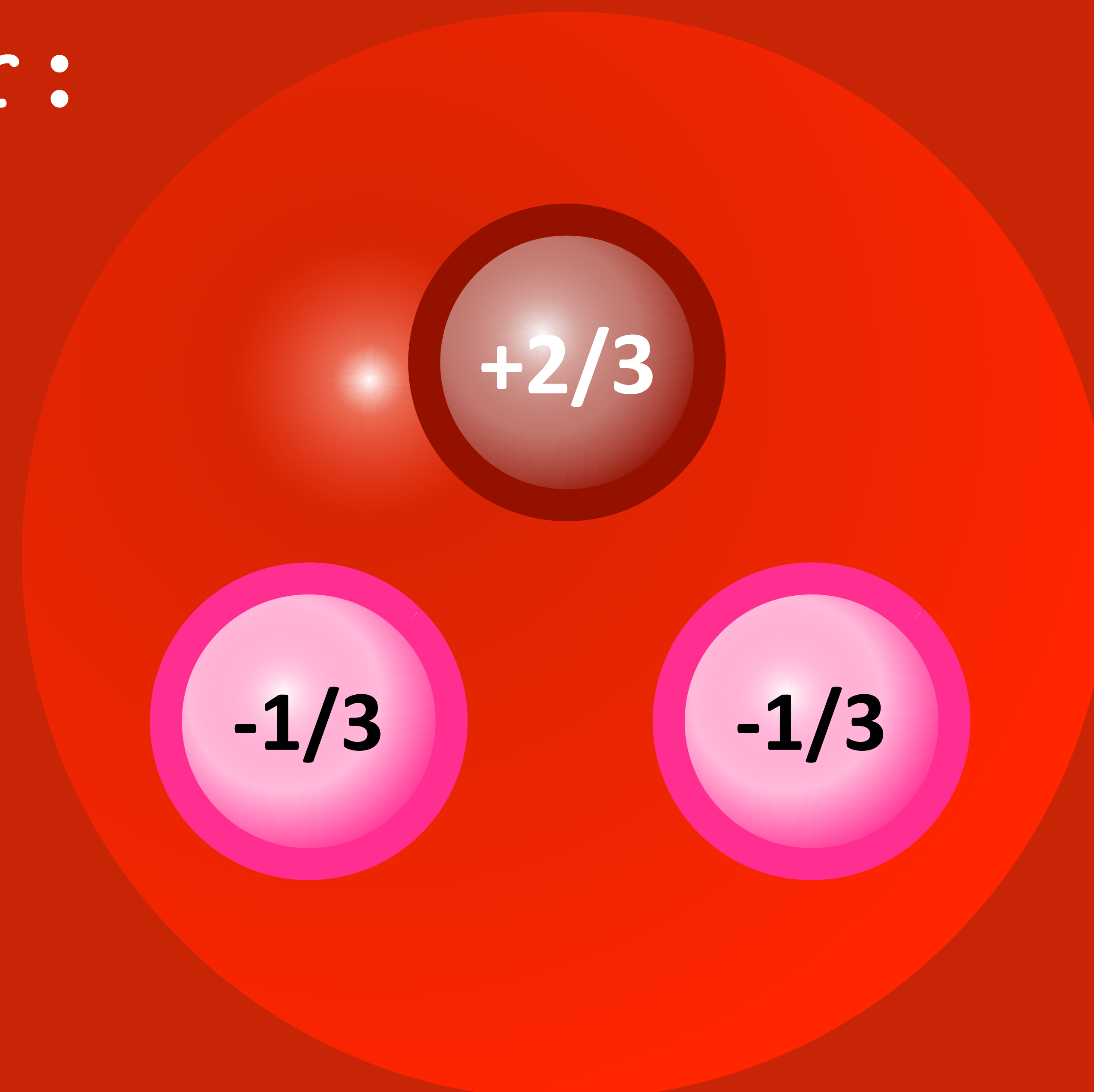


Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece 'em together:

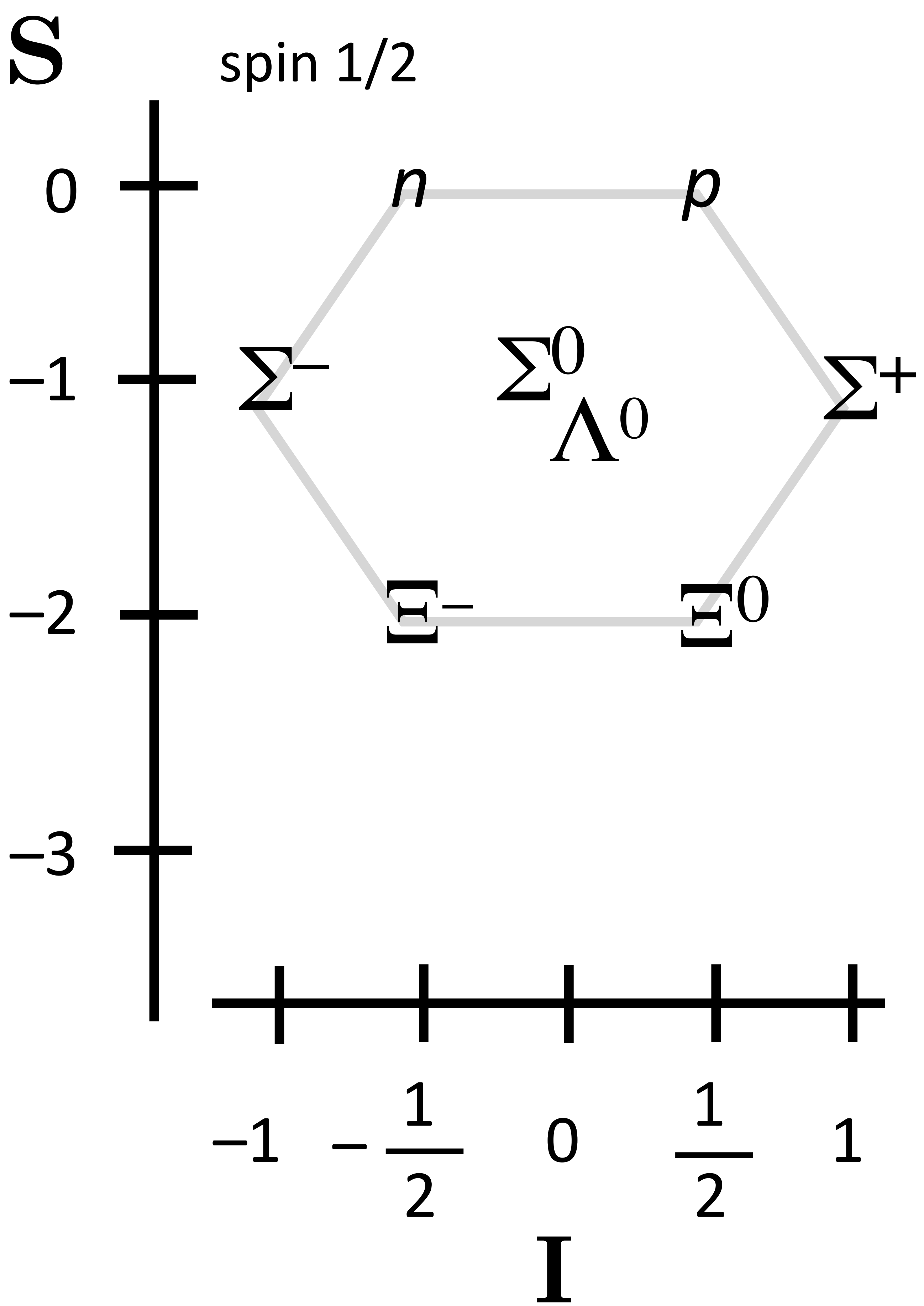
neutron

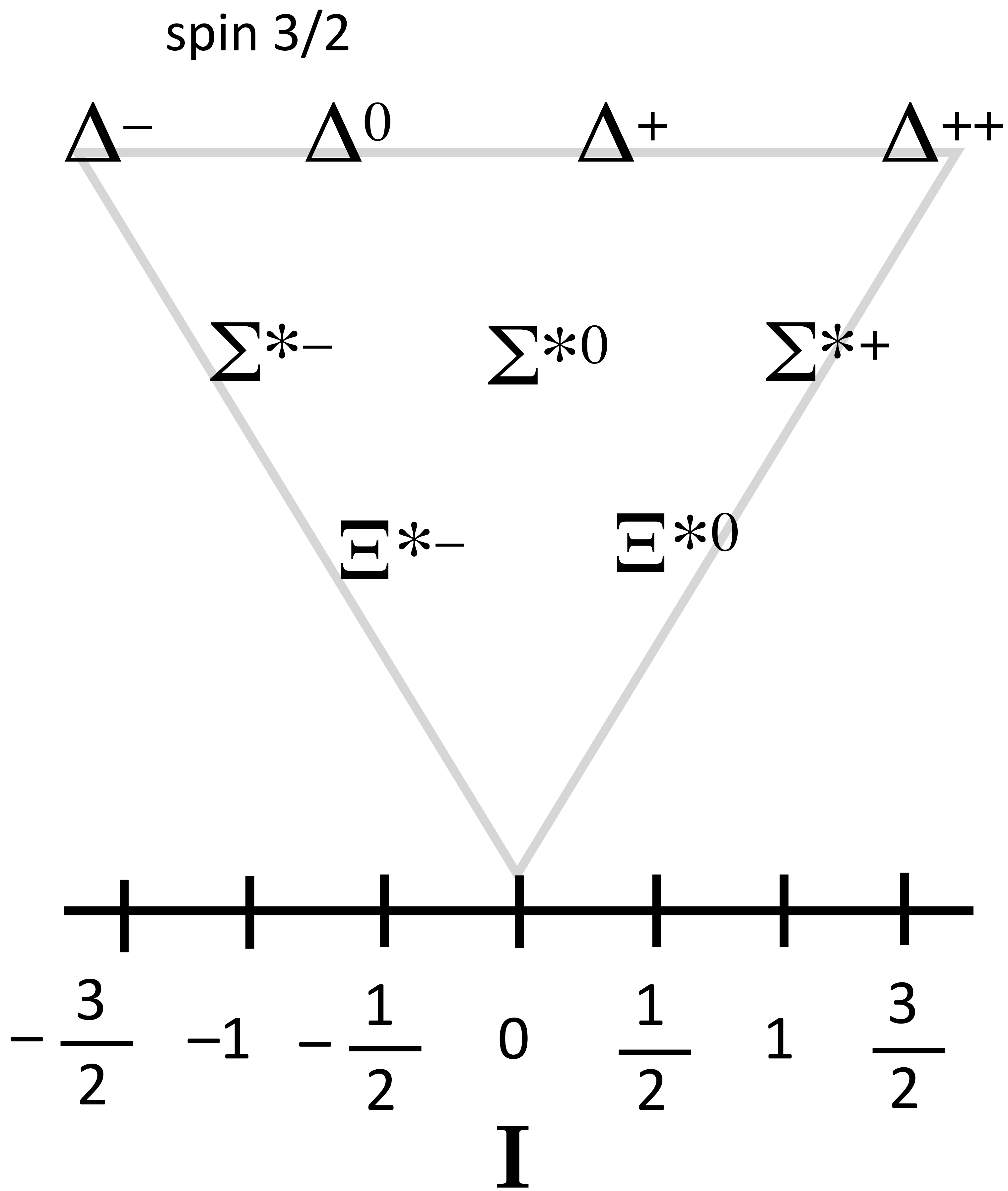
electric charge = 0



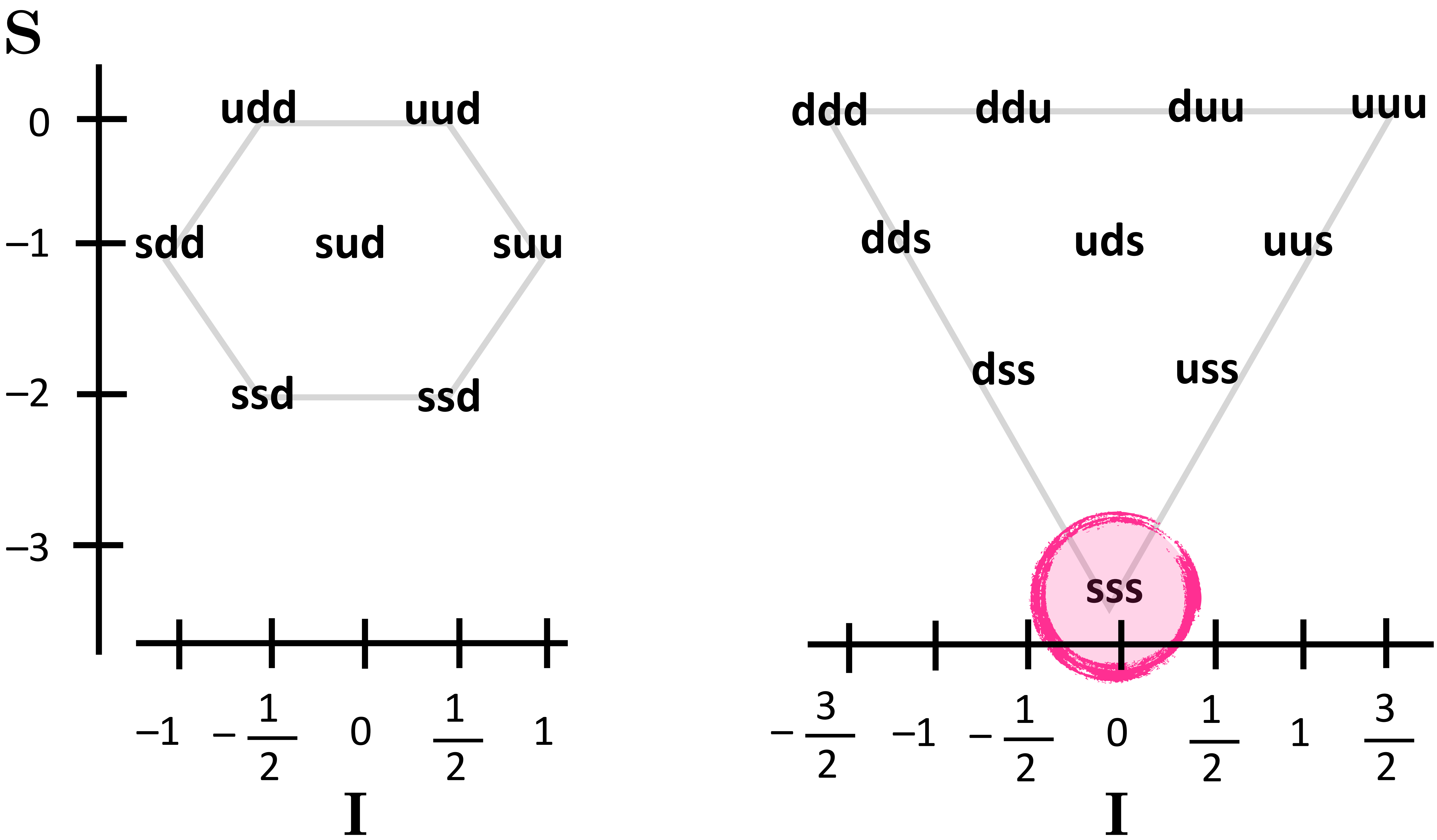
Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

they all fit


S
spin 1/2
0
−1
−2
−3
n
p
Σ−
Σ0
Λ0
Σ+
Ξ−
Ξ0
−1
− 1/2
0
1/2
1
I

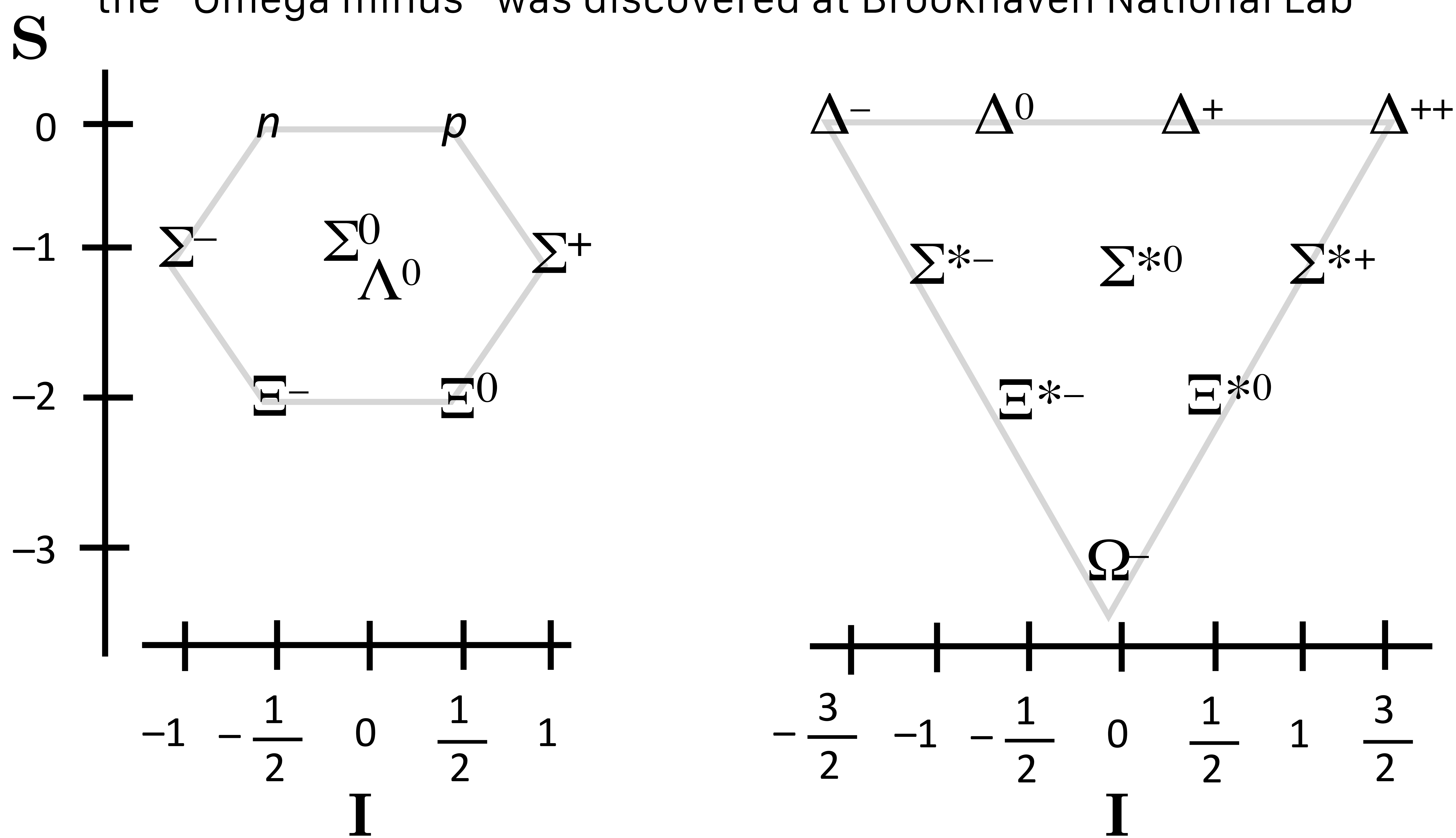

spin 3/2
Δ−
Δ0
Δ+
Δ++
Σ*−
Σ*0
Σ*+
Ξ*−
Ξ*0
− 3/2
−1
− 1/2
0
1/2
1
3/2
I

like a glove


S
0
−1
−2
−3
udd
uud
sdd
sud
suu
ssd
ssd
−1
− 1/2
0
1/2
1
I
ddd
ddu
duu
uuu
dds
uds
uus
dss
uss
sss
− 3/2
−1
− 1/2
0
1/2
1
3/2
I

discovered at Brookhaven within a year

the “Omega minus” was discovered at Brookhaven National Lab



most famous bubble chamber picture in history, 1964

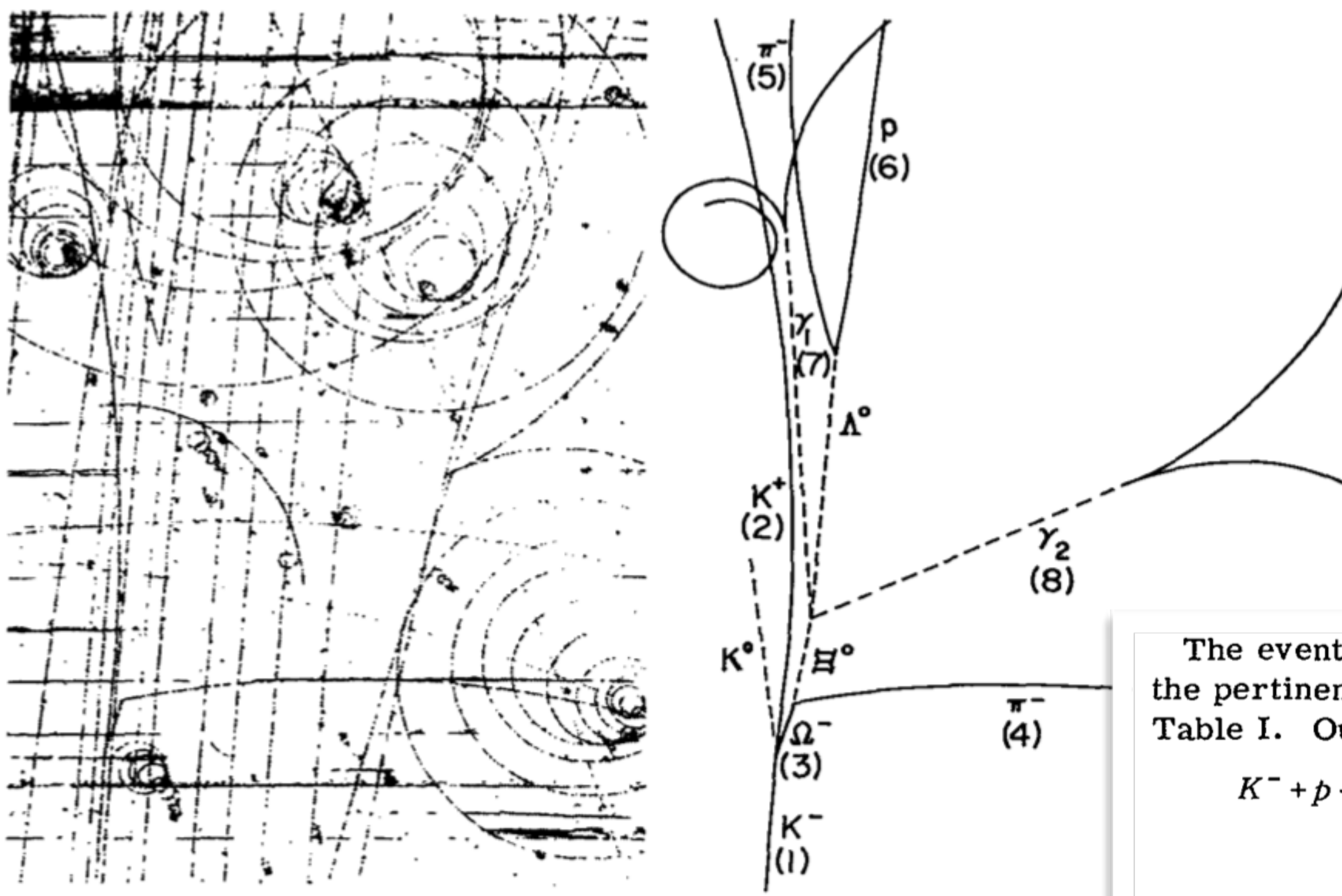


FIG. 2. Photograph and line diagram of event showing dec

The event in question is shown in Fig. 2, and the pertinent measured quantities are given in Table I. Our interpretation of this event is

$$K^- + p \to \Omega^- + K^+ + K^0$$
$$\Omega^- \to \Xi^0 + \pi^-$$
$$\Xi^0 \to \Lambda^0 + \pi^0$$
$$\pi^0 \to \gamma_1 + \gamma_2$$
$$\gamma_2 \to e^+ + e^-$$
$$\gamma_1 \to e^+ + e^-$$
$$\Lambda^0 \to \pi^- + p. \qquad (1)$$

particle: **Omega minus**

symbol:	Ω^-
charge:	–1
mass:	1672.45 MeV/c^2
spin:	3/2
category:	Fermion, baryon, I = 0, B=1, S=-3

the dominant Baryons

Particle	Symbol	Rest Mass MeV/c²	spin	Q	B	S	Lifetime	dominant decay modes	quark content
proton	p	938.3	1/2	+1	+1	0	> 10^{31} y		uud
neutron	n	939.6	1/2	0	+1	0	920	$pe^-\bar{\nu}_e$	ddu
Lambda	Λ^0	1115.6	1/2	0	+1	−1	2.6 x 10^{-10}	$p\pi^-,\ n\pi^0$	uds
Sigma	Σ^+	1189.4	1/2	+1	+1	−1	0.8 x 10^{-10}	$p\pi^0,\ n\pi^+$	uus
Sigma	Σ^0	1192.5	1/2	0	+1	−1	6 x 10^{-20}	$\Lambda^0\gamma$	uds
Sigma	Σ^-	1197.3	1/2	−1	+1	−1	1.5 x 10^{-10}	$n\pi^-$	dds
Delta	Δ^{++}	1232	3/2	+2	+1	0	0.6 x 10^{-23}	$p\pi^+$	uuu
Delta	Δ^+	1232	3/2	+1	+1	0	0.6 x 10^{-23}	$n\pi^+,\ p\pi^0$	uud
Delta	Δ^0	1232	3/2	0	+1	0	0.6 x 10^{-23}	$n\pi^0$	udd
Delta	Δ^-	1232	3/2	−1	+1	0	0.6 x 10^{-23}	$n\pi^-$	ddd
Xi	Ξ^0	1315	1/2	0	+1	−2	2.9 x 10^{-10}	$\Lambda^0\pi^0$	uss
Xi	Ξ^-	1321	1/2	−1	+1	−2	1.64 x 10^{-10}	$\Lambda^0\pi^-$	dss
Omega	Ω^-	1672	3/2	−1	+1	−3	0.82 x 10^{-10}	$\Xi^0\pi^-,\ \Lambda^0K^-$	sss

mesons

a little different

Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

The pion:

Particle	Symbol	anti-particle	Rest Mass MeV/c²	spin	Q	B	S
Pion	π^+	π^-	139.6	0	+1	0	0

$$\pi^+ = (u \quad \& \quad \bar{d})$$

has the right stuff.

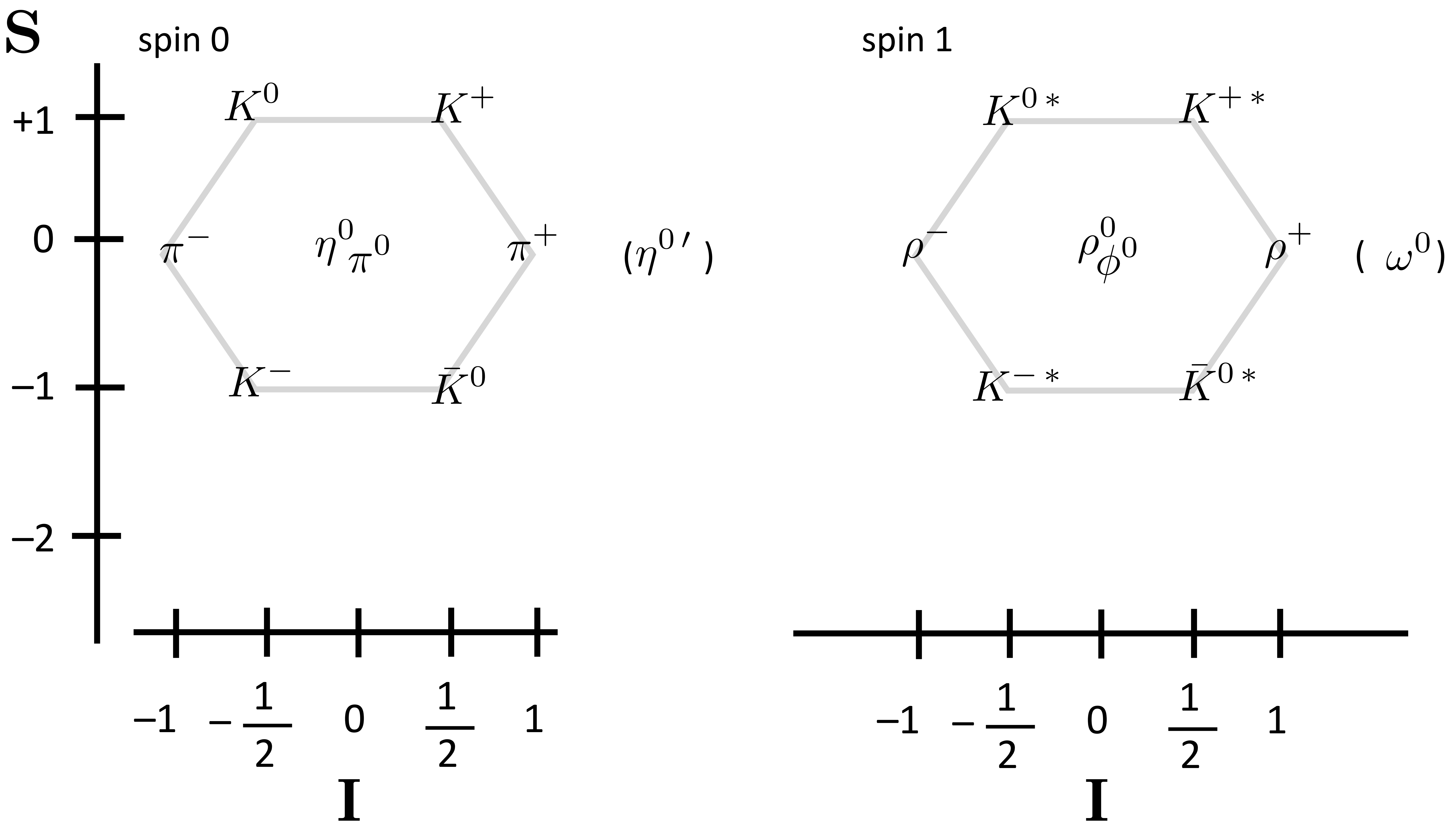
Q: +1 +2/3 + −(−1/3)

B: 0 1/3 + −(1/3)

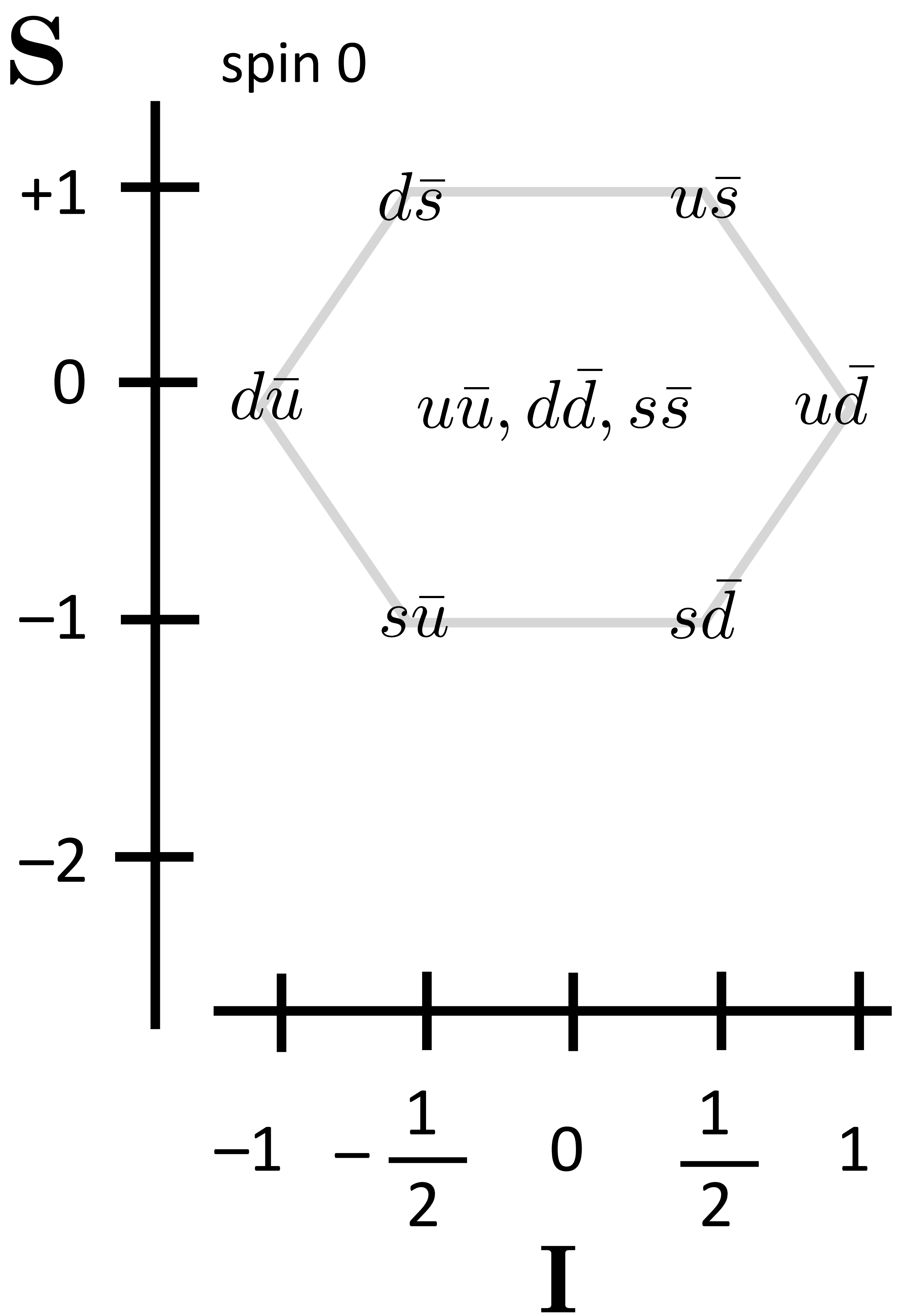
S: 0 0 0

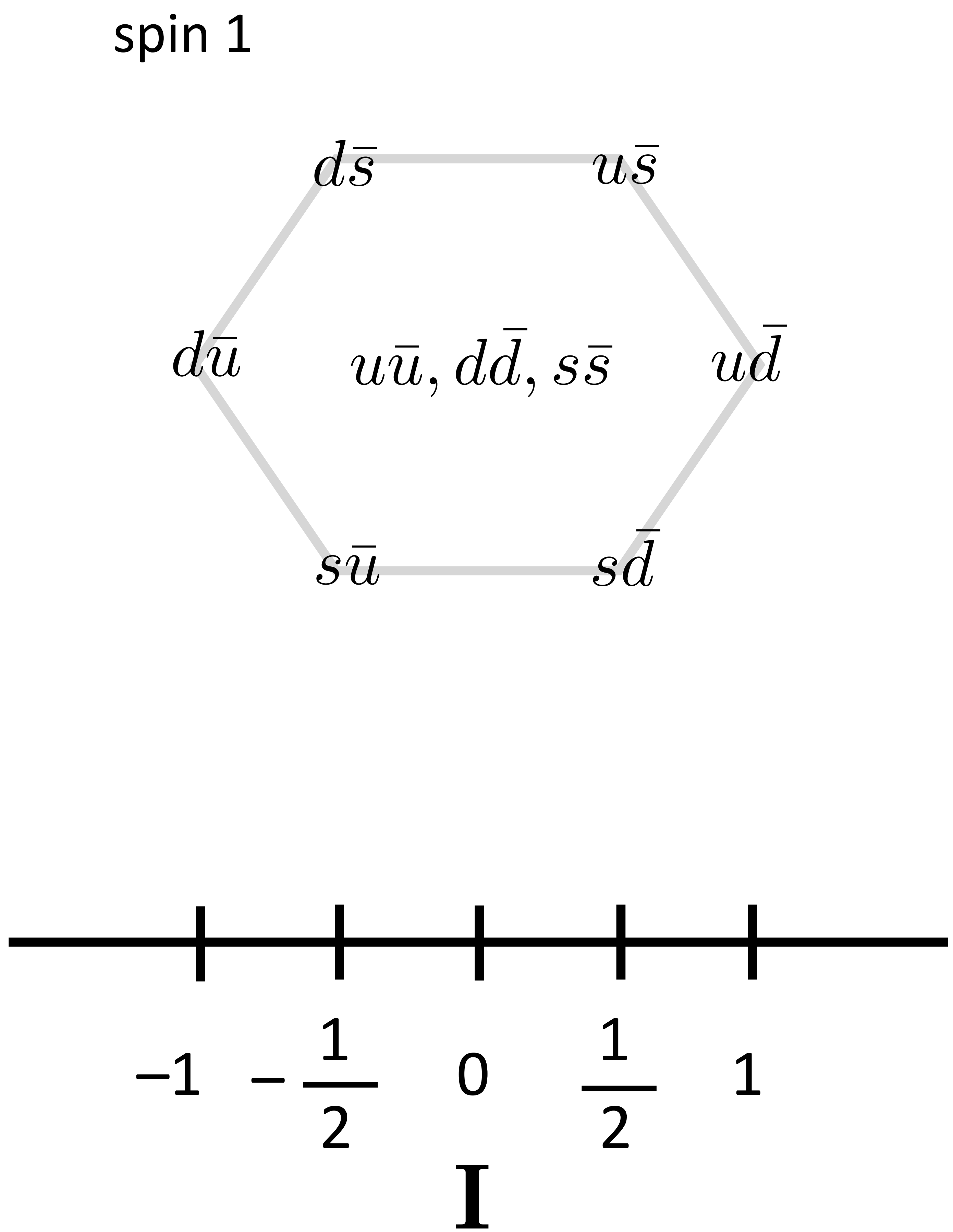
$$\pi^+ = u\bar{d}$$

a similar thing happens for the mesons



meson quark content





the dominant Mesons

Particle	Symbol	anti-particle	Rest Mass MeV/c^2	spin	Q	B	S	Lifetime	dominant decay modes	quark content
Pion	π^+	π^-	139.6	0	+1	0	0	2.6 x 10^{-8}	$\mu^+\nu_\mu$	$u\bar{d}$
Pi-zero	π^0	π^0	135	0	0	0	0	920	2γ	$\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$
Kaon	K^+	K^-	493.7	0	+1	0	+1	1.24 x 10^{-8}	$\mu^+\nu_\mu, \pi^+\pi^0$	$u\bar{s}$
K-short	K_S^0	K_S^0	497.7	0	0	0	+1	0.89 x 10^{-10}	$\pi^+\pi^-, 2\pi^0$	$d\bar{s}, s\bar{d}$
K-long	K_L^0	K_L^0	497.7	0	0	0	+1	5.2 x 10^{-8}	$\pi^\pm\ell^\mp\nu_\ell$	$d\bar{s}, s\bar{d}$
Eta	η^0	η^0	548.8	0	0	0	0	< 10^{-18}	$2\gamma, \pi^+\pi^-\pi^0$	$u\bar{u}, d\bar{d}, s\bar{s}$
Eta-prime	$\eta^{0\prime}$	$\eta^{0\prime}$	958	1	0	0	0	...	$\pi^+\pi^-\eta$	$u\bar{u}, d\bar{d}, s\bar{s}$
Rho	ρ^+	ρ^-	770	1	+1	0	0	0.4 x 10^{--23}	$\pi^+\pi^-, 2\pi^0$	$u\bar{d}$
Rho-naught	ρ^0	ρ^0	770	1	0	0	0	0.4 x 10^{--23}	$\pi^+\pi^-$	$u\bar{u}, d\bar{d}$
Omega	ω^0	ω^0	782	1	0	0	0	0.8 x 10^{--22}	$\pi^+\pi^-\pi^0$	$u\bar{u}, d\bar{d}$
Phi	ϕ	ϕ	1020	1	0	0	0	20 x 10^{-23}	$K^+K^-, K^0\bar{K}^0$	$s\bar{s}$

spins work out

add up the spins

Keep track of quark spins: spin +1/2 $q\uparrow$

spin –1/2 $q\downarrow$

for example, a couple of baryons:

p $u\uparrow u\downarrow d\uparrow$ total spin: 1/2

Δ^+ $u\uparrow u\uparrow d\uparrow$ total spin: 3/2

for example, a couple of mesons:

π^+ $u\uparrow \bar{d}\downarrow$ total spin: 0

ρ^+ $u\uparrow \bar{d}\uparrow$ total spin: 1

there are still

100's more baryons and mesons

what's up with that? you're asking

A model of "quark molecules"...

Molecules can have vibrational and rotational excited states...

So can quarks.

N^* is a state with the same quark content as a proton but which has a high orbital angular momentum

d u u

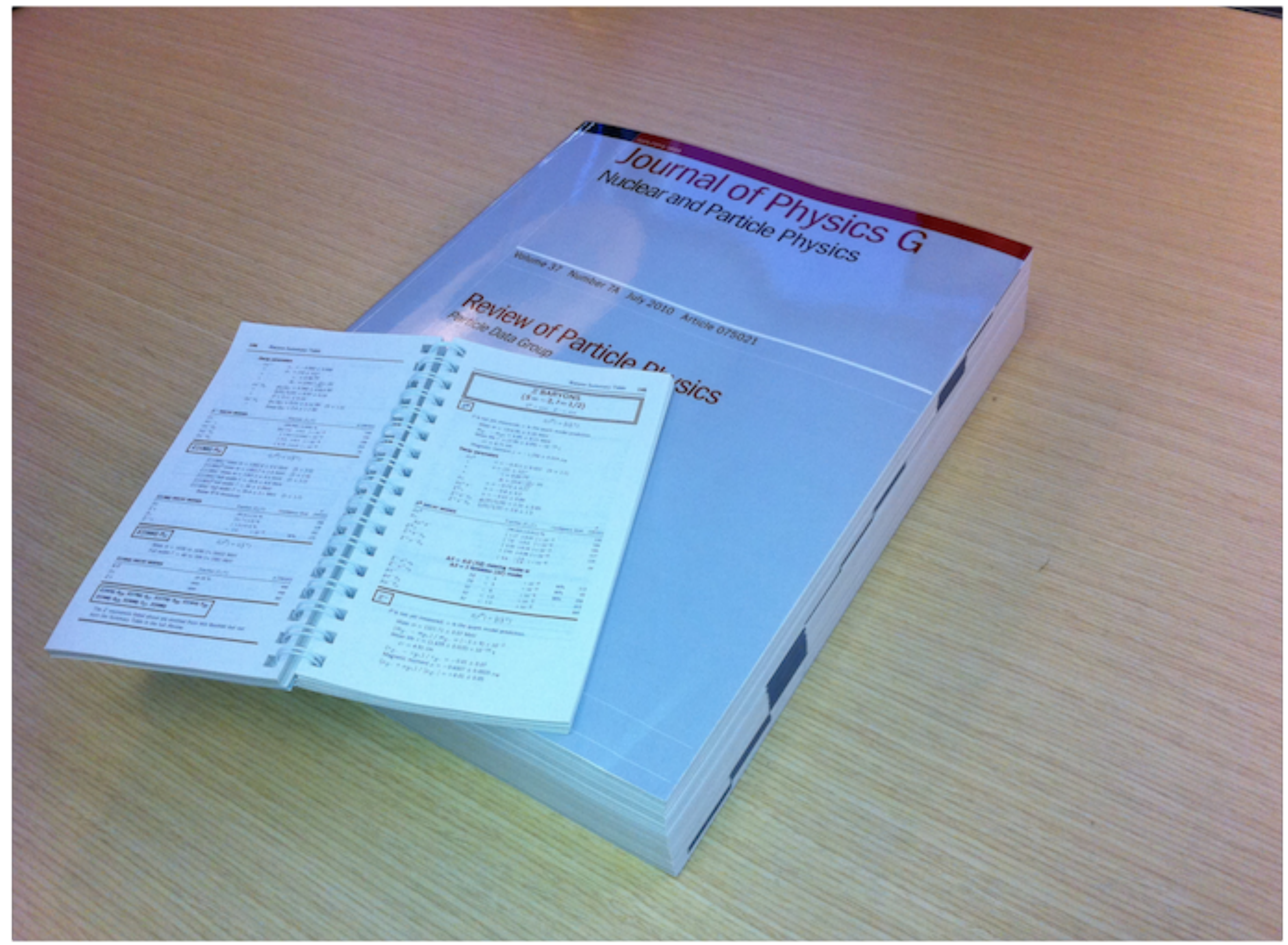
Other states can be well-modeled by assuming relative vibrational modes..

d

u u

you can tell a particle physicist

by the book that they carry



now the jargon

gets a little more straightforward

now defined:

Hadrons: particles made of quarks.

now defined:

Baryons: particles made of 3 quarks.

now defined:

Mesons: particles made of 1 quark and 1 antiquark.

a variety of consequences

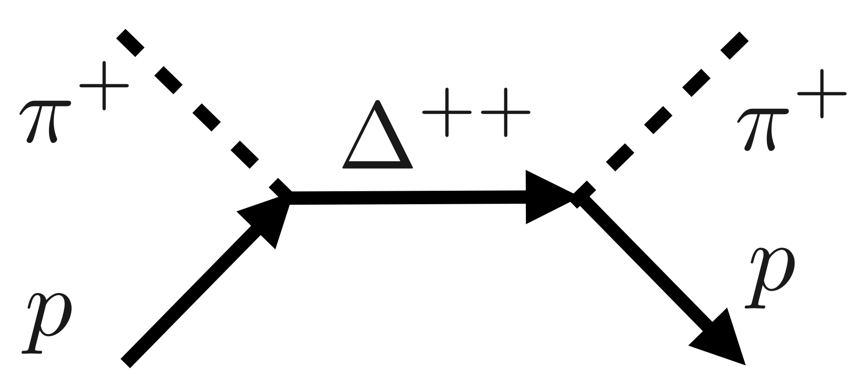
became apparent

One could begin to understand particle decays and reactions in terms of pseudo-Feynman diagrams* like this:

$$\pi^+ + p \rightarrow \pi^+ + p$$

Fermi had produced “resonances” that suggested that something was “in between” the initial and final states

$$\pi^+ + p \rightarrow \Delta^{++} \rightarrow \pi^+ + p$$



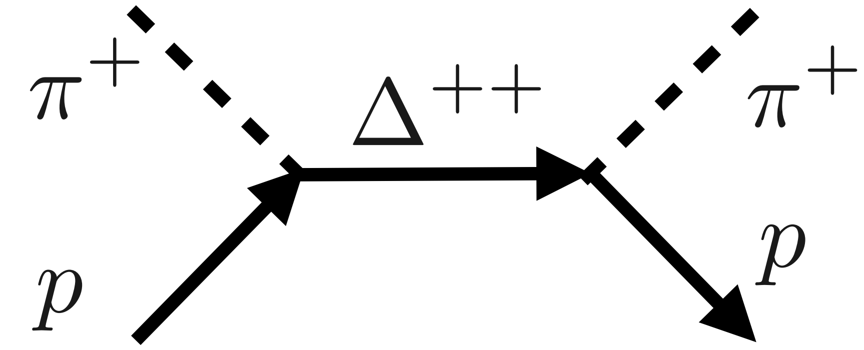
* I call them “pseudo” as doing real calculations with them are kind of ad-hoc

scatterings now are thought of diferently

by following the lines...

$$\pi^+ + p \to \Delta^{++} \to \pi^+ + p$$

Feynman Diagram, pre-1964:



in quark language: