hi

Day 24, 04.16.2019

Particle Physics 1

18 days until MSU graduation

Bon Jovi week

April 2019

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
31	1	2 lecture	3	4 lecture	5 HW9 due	6 HW10
7	8	9 lecture	10	11 lecture	12 project day 2 HW10 due	13 HW11
14	15	16 lecture	17	18 lecture	19	20 HW12 MA & paper
21 HW11 due	22	23 lecture	24	25 lecture	26 Honors data upload HW12 MA due	27
28 2nd Midterm (incl early universe)	29	30	1	2	3 FINAL EXAM 07:30 HW12 paper due	4

Week 14, Feynman Diagrams, weak interactions, and exchange forces

TUESDAY, April 16	**Feynman Diagrams, particle zoo, the weak and strong interactions**
Required Readings:	**Chapter 12 in PCC**
	TOE chapter 5 and Appendix C
	Chapter 17 in PCC
	CP Section 4.2
Recommended Readings:	
Additional content:	primitiveDiagrams_0 (13m), primitiveDiagrams_1 (4m), primitiveDiagram_2 (9m) in:
Tasks:	**3 movies on how to make Feynman Diagrams**
Homework available:	
Homework due:	
anything posted?	**slides**
THURSDAY, April 18	**Quarks, W and Z Bosons, and the gluon**
Required Readings:	TOE chapter 5
	Chapter 17 in PCC
	CP Section 4.2
Recommended Readings:	
Additional content:	
Tasks:	
Homework available:	HW12: MasteringPhysics
Homework due:	HW11: Sunday, April 21
anything posted?	**slides**

housekeeping

Poster selection:

reservations were due last Friday from within LON-CAPA

Some tutorial videos to watch

How to draw Feynman Diagrams

you know the drill:

from the mothership:

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: 4/15/2019 - 5/15/2019
ISP 220 002: 4/15/2019 - 5/15/2019

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 5/15/2019 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.

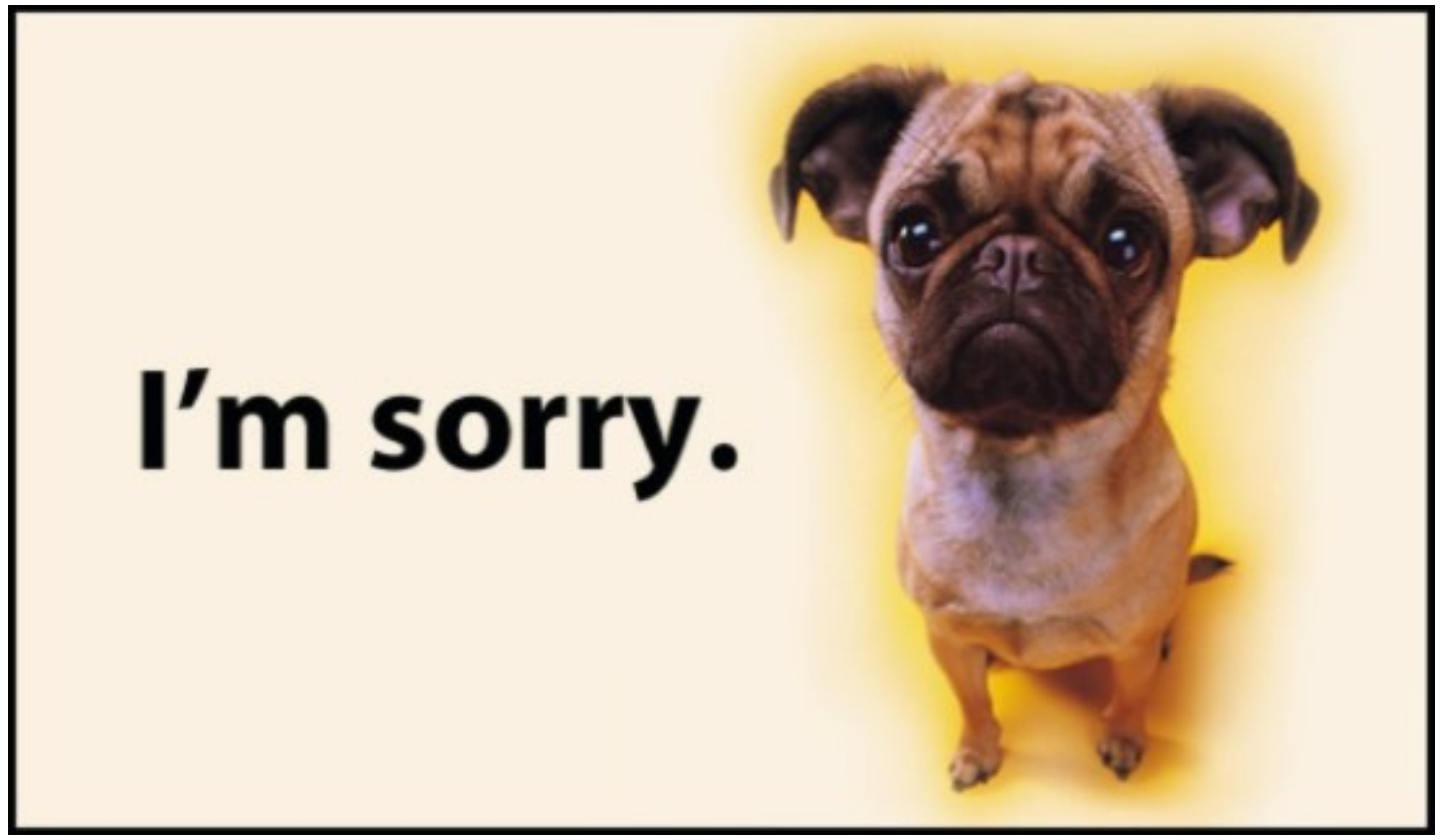
If you have any questions, please contact Michelle Carlson, (mcarlson@msu.edu, (517)432-5936).

Somehow early in the morning last Thursday

...I uploaded a stale version of the project page

It was fixed by afternoon.

and, jeez…



LON-CAPA is misbehaving with formatted additions
so send me your formatted FFB file
BUT:

Put words in the LON-CAPA location to tell me that you sent it!

That way, I'll not lose it
and
I can still use the LON-CAPA grading system

KEEP
CALM
AND
LET'S
REVIEW

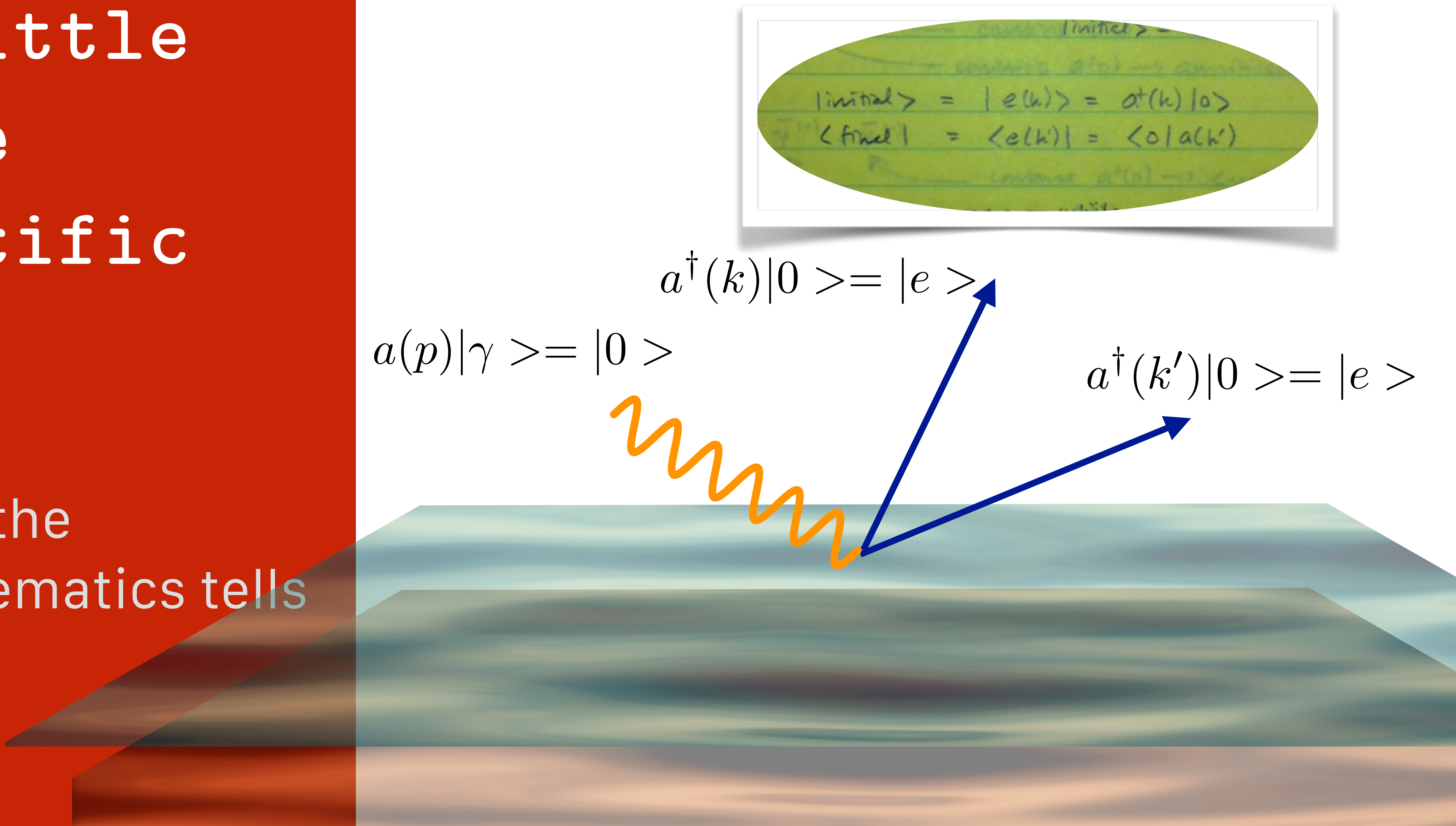
vacuum is full

of fields

one for every “particle”

a little more specific

what the mathematics tells us



it’s not like the photon is now “in” the electron

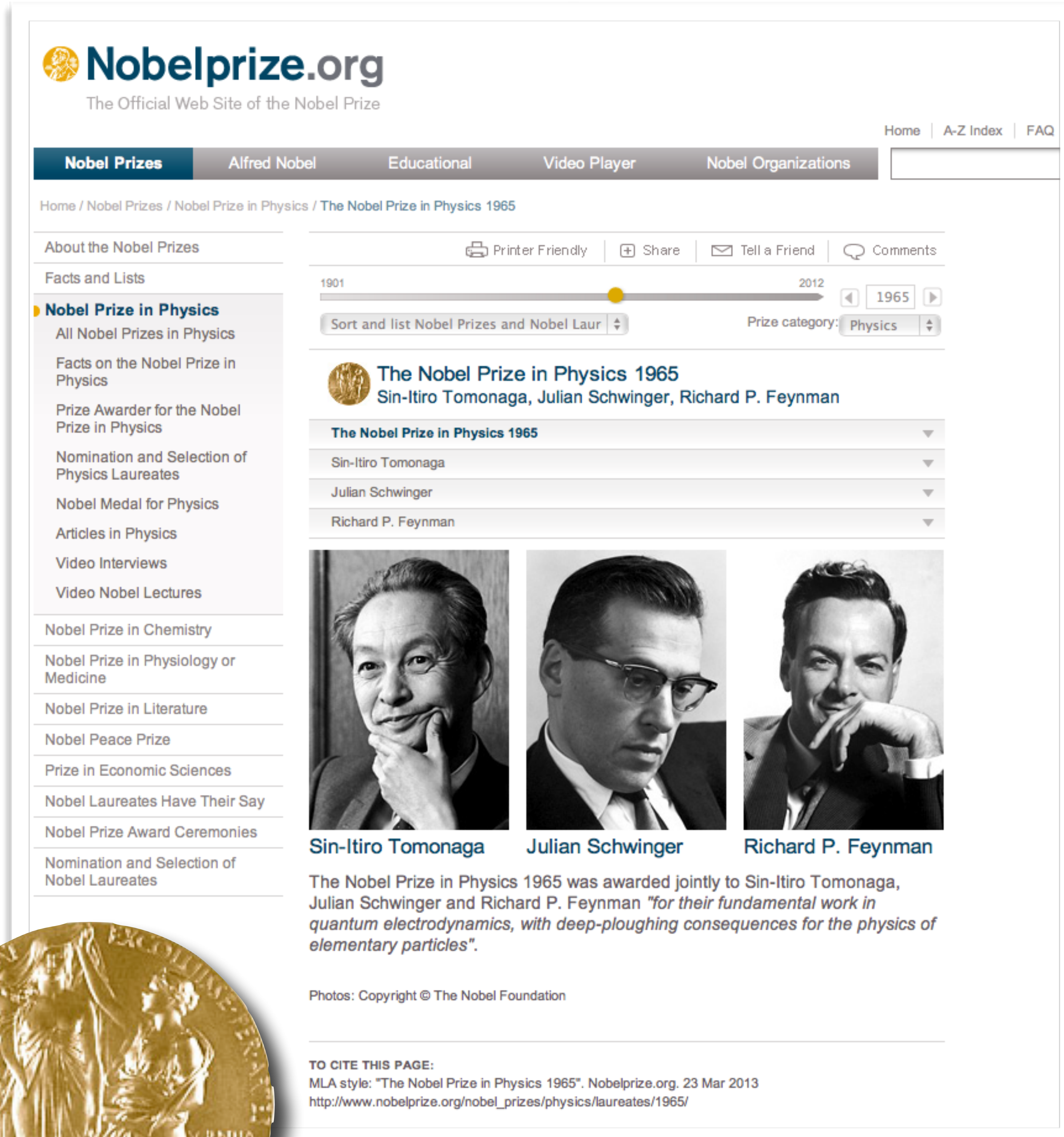
the photon pops the electron- positron pair out of the Ur electron field
and itself disappears back into the Ur photon field.

Feynman Diagrams

now for real.

Richard Feynman, Sin-Itiro Tomonaga, Julian Schwinger

1965 Nobel

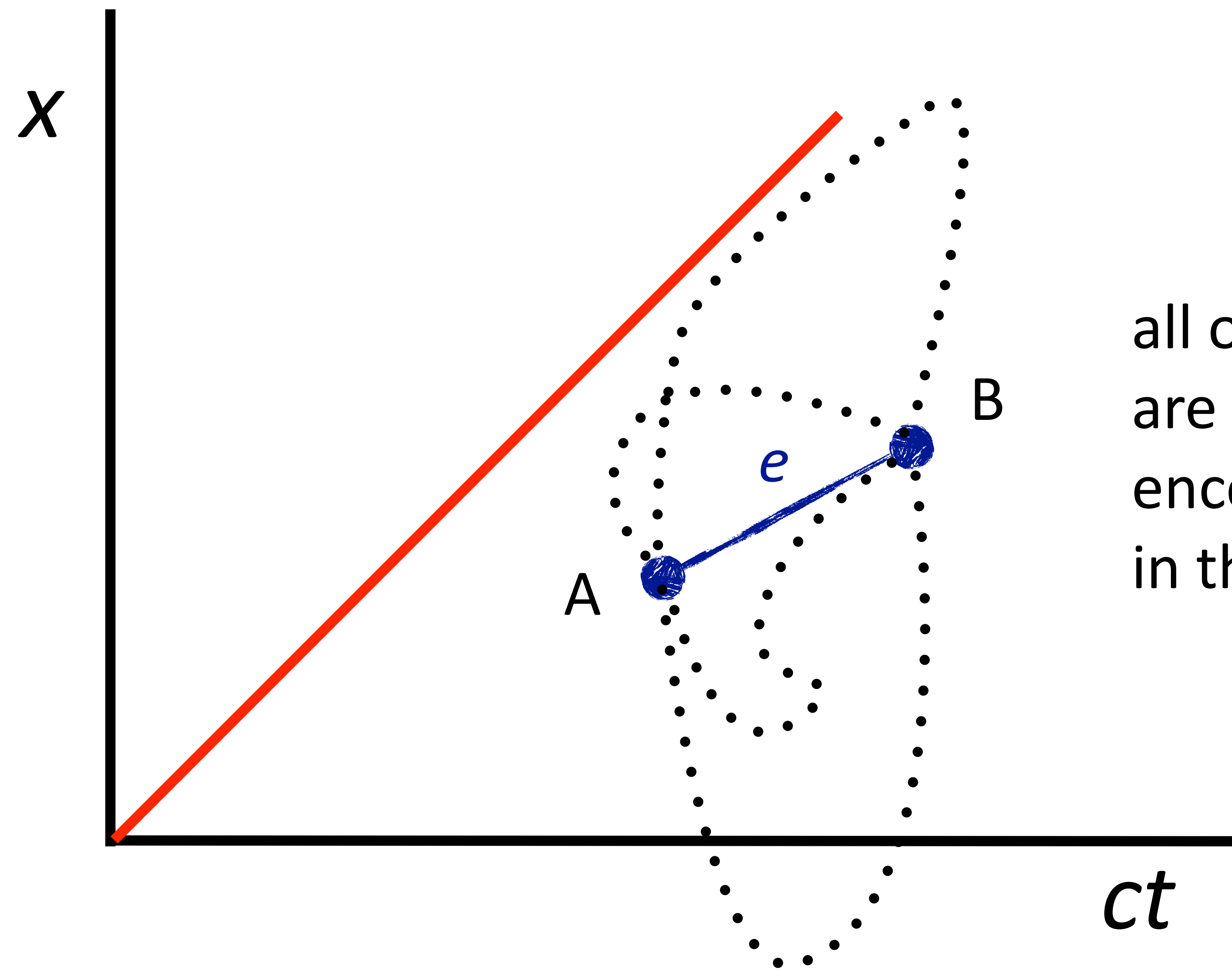


the symbols of Feynman Diagrams

each line represents an entire "history" of trajectories

and "stand in" for many lines of mathematics

to go from A to B, represent all histories with a single line.



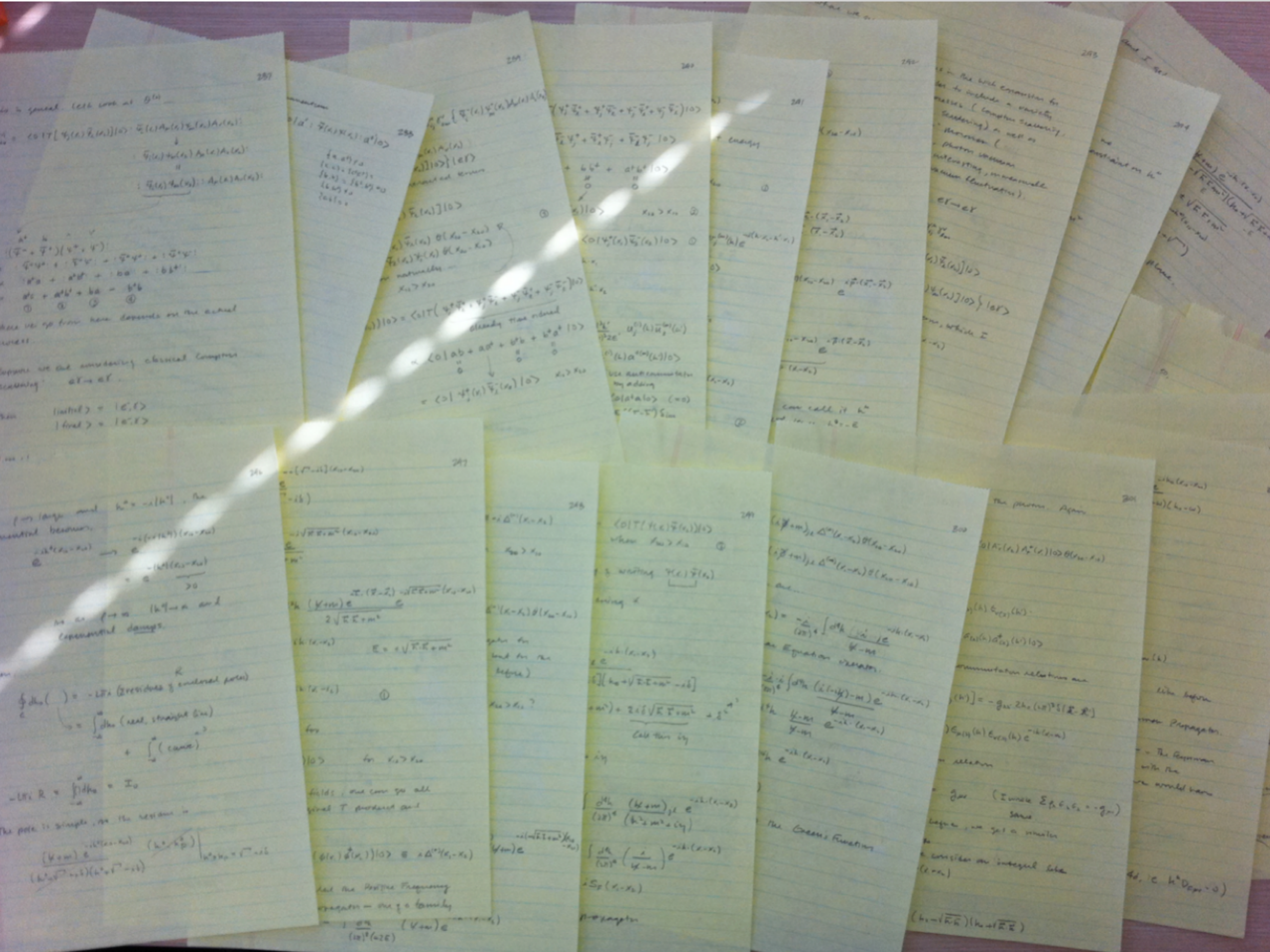
all of the paths are encompassed in the one line

Feynman's lines include rules on how to calculate the possibilities in a relativistically consistent way.

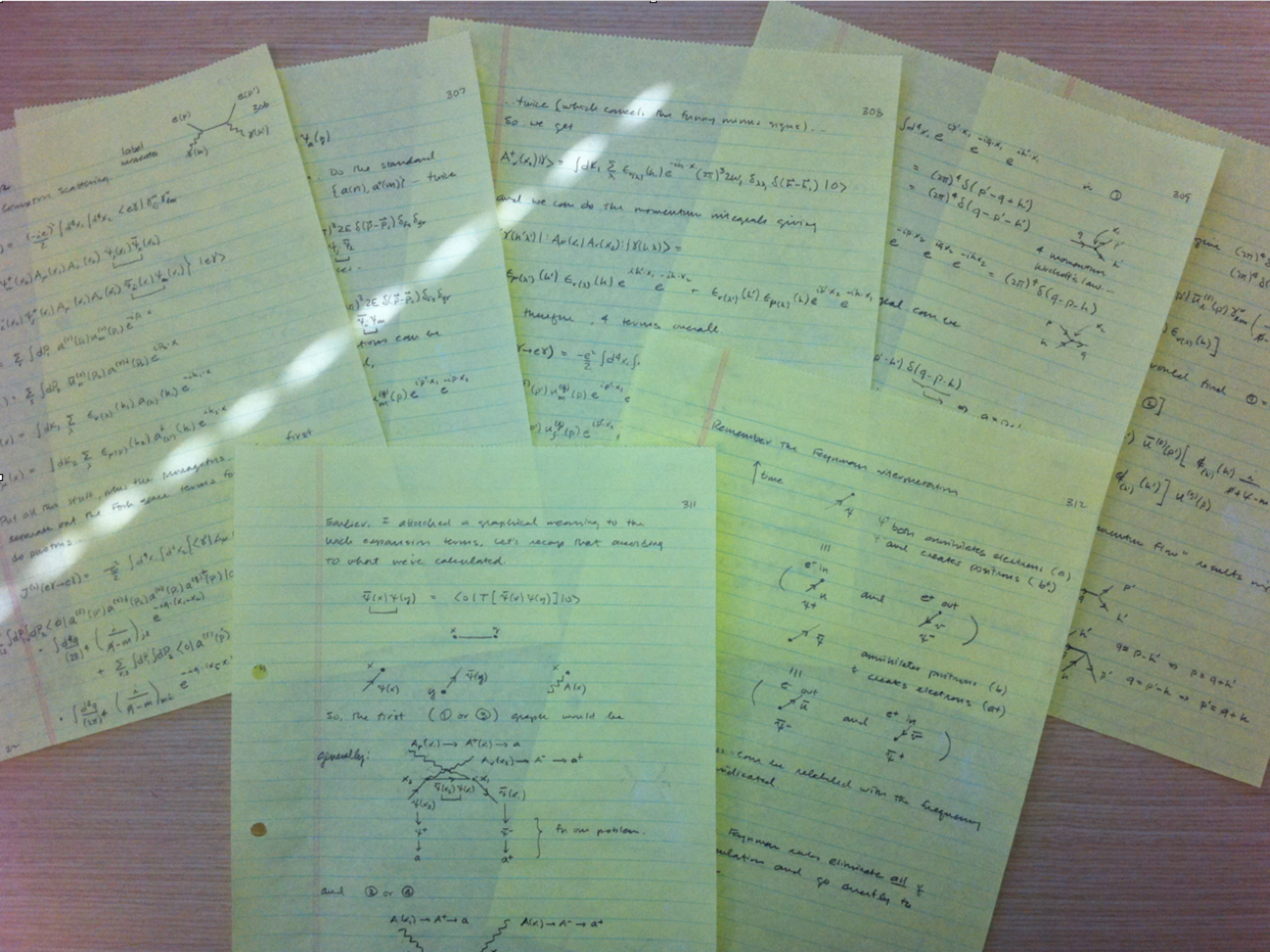
very efficient

avoids lots of technicalities.

When I teach these techniques to second year graduate students, I first do the calculation of Compton Scattering and do it without Feynman's tools.



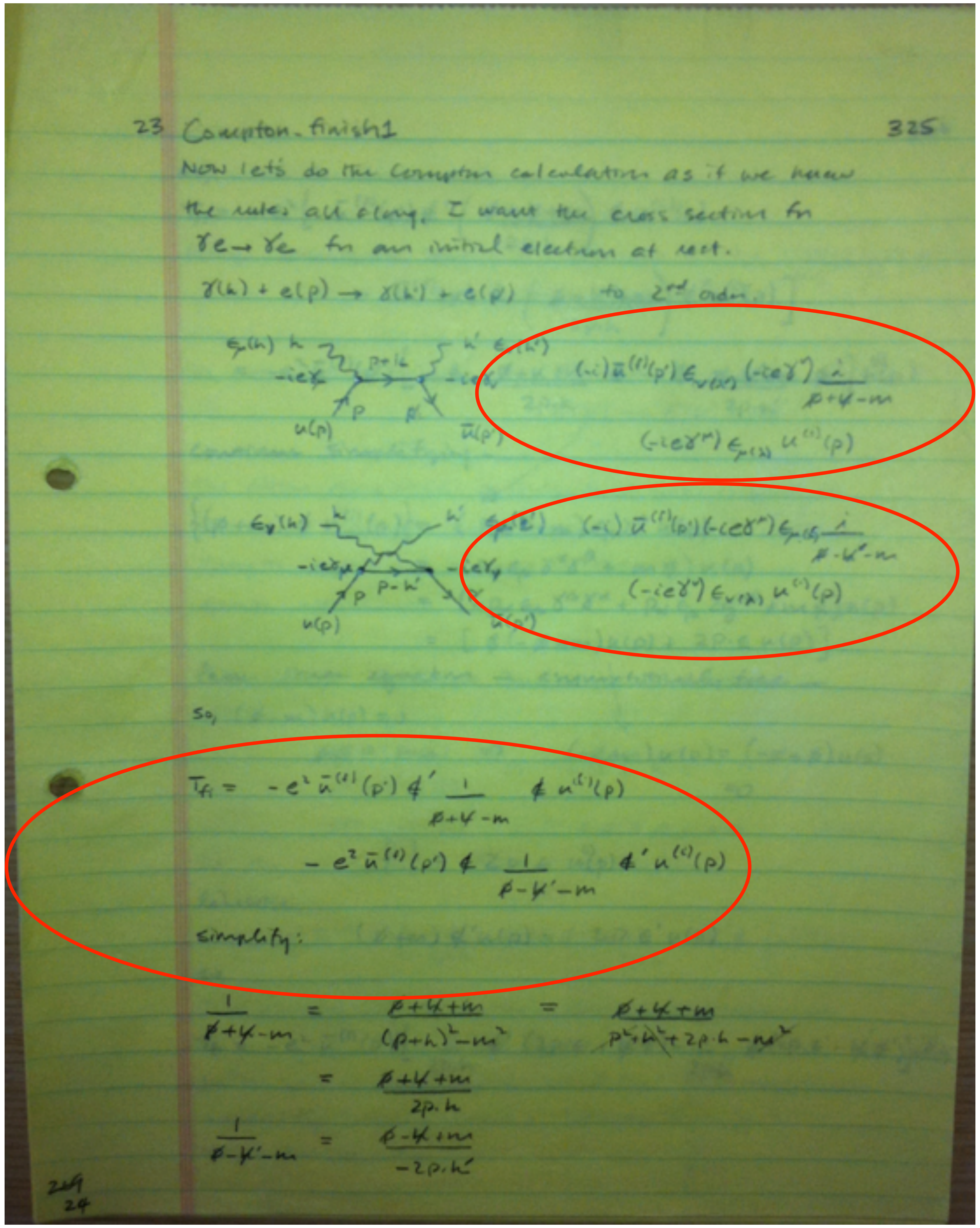
Suppose we are considering classical Compton scattering
exponential damps
call this iε
the Green's Function


311
Earlier, I attached a graphical meaning to the Wick expansion terms. Let's recap that according to what we've calculated.
So, the first (① or ②) graph would be
Generally:
for our problem.
and ③ or ④
312
Remember the Feynman interpretation
time
Ψ both annihilates electrons (a) and creates positrons (b†)
e⁻ in
and
e⁺ out
annihilates positrons (b) & creates electrons (a†)
e⁻ out
and
e⁺ in
307
Do the standard
twice
308
So we get
and we can do the momentum integrals giving
therefore, 4 terms overall.
309
4 momentum conservation laws
Compton Scattering
label momenta
Put all this stuff, plus the Møller-space terms for

his rules eliminate all of that

and I can just write down the "answer"

appropriately labeled, each line tells us what to put into a long equation for further solving



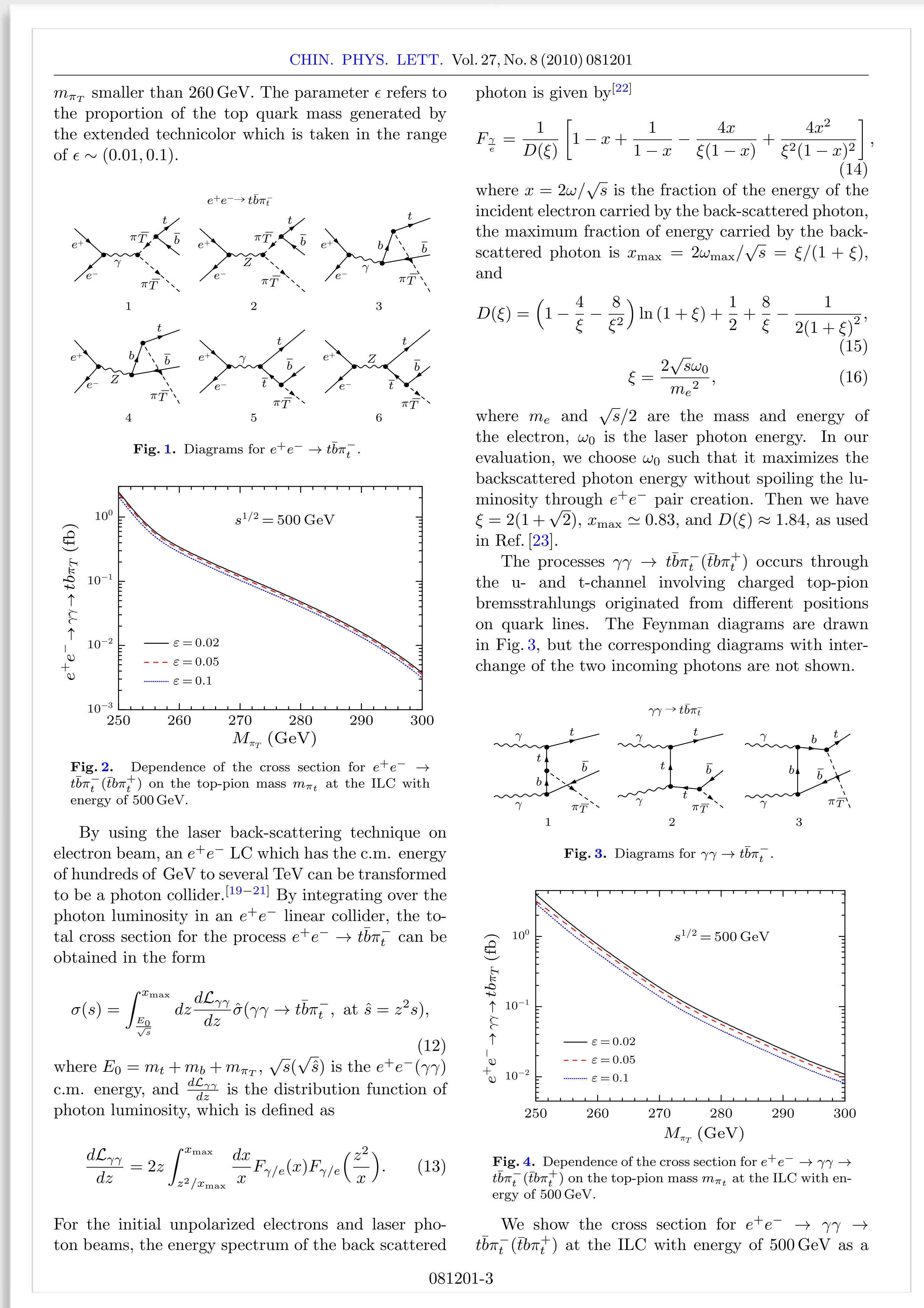
`but the pictures themselves are visually...informative`

and I’m going to try to tell you how to do this

without the geeky mathematics

theoretical papers

each diagram is a complicated calculation



CHIN. PHYS. LETT. Vol. 27, No. 8 (2010) 081201

m_{π_T} smaller than 260 GeV. The parameter ϵ refers to the proportion of the top quark mass generated by the extended technicolor which is taken in the range of $\epsilon \sim (0.01, 0.1)$.

Fig. 1. Diagrams for $e^+e^- \to t\bar{b}\pi_t^-$.

Fig. 2. Dependence of the cross section for $e^+e^- \to t\bar{b}\pi_t^-(\bar{t}b\pi_t^+)$ on the top-pion mass m_{π_t} at the ILC with energy of 500 GeV.

By using the laser back-scattering technique on electron beam, an e^+e^- LC which has the c.m. energy of hundreds of GeV to several TeV can be transformed to be a photon collider.[19–21] By integrating over the photon luminosity in an e^+e^- linear collider, the total cross section for the process $e^+e^- \to t\bar{b}\pi_t^-$ can be obtained in the form

$$\sigma(s) = \int_{\frac{E_0}{\sqrt{s}}}^{x_{\max}} dz \frac{d\mathcal{L}_{\gamma\gamma}}{dz}\hat{\sigma}(\gamma\gamma \to t\bar{b}\pi_t^-, \text{ at } \hat{s} = z^2 s), \quad (12)$$

where $E_0 = m_t + m_b + m_{\pi_T}$, $\sqrt{s}(\sqrt{\hat{s}})$ is the $e^+e^-(\gamma\gamma)$ c.m. energy, and $\frac{d\mathcal{L}_{\gamma\gamma}}{dz}$ is the distribution function of photon luminosity, which is defined as

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dz} = 2z\int_{z^2/x_{\max}}^{x_{\max}} \frac{dx}{x} F_{\gamma/e}(x) F_{\gamma/e}\Big(\frac{z^2}{x}\Big). \quad (13)$$

For the initial unpolarized electrons and laser photon beams, the energy spectrum of the back scattered photon is given by[22]

$$F_{\frac{\gamma}{e}} = \frac{1}{D(\xi)}\Big[1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2}\Big], \quad (14)$$

where $x = 2\omega/\sqrt{s}$ is the fraction of the energy of the incident electron carried by the back-scattered photon, the maximum fraction of energy carried by the back-scattered photon is $x_{\max} = 2\omega_{\max}/\sqrt{s} = \xi/(1+\xi)$, and

$$D(\xi) = \Big(1 - \frac{4}{\xi} - \frac{8}{\xi^2}\Big)\ln(1+\xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1+\xi)^2}, \quad (15)$$

$$\xi = \frac{2\sqrt{s}\omega_0}{m_e{}^2}, \quad (16)$$

where m_e and $\sqrt{s}/2$ are the mass and energy of the electron, ω_0 is the laser photon energy. In our evaluation, we choose ω_0 such that it maximizes the backscattered photon energy without spoiling the luminosity through e^+e^- pair creation. Then we have $\xi = 2(1+\sqrt{2})$, $x_{\max} \simeq 0.83$, and $D(\xi) \approx 1.84$, as used in Ref. [23].

The processes $\gamma\gamma \to t\bar{b}\pi_t^-(\bar{t}b\pi_t^+)$ occurs through the u- and t-channel involving charged top-pion bremsstrahlungs originated from different positions on quark lines. The Feynman diagrams are drawn in Fig. 3, but the corresponding diagrams with interchange of the two incoming photons are not shown.

Fig. 3. Diagrams for $\gamma\gamma \to t\bar{b}\pi_t^-$.

Fig. 4. Dependence of the cross section for $e^+e^- \to \gamma\gamma \to t\bar{b}\pi_t^-(\bar{t}b\pi_t^+)$ on the top-pion mass m_{π_t} at the ILC with energy of 500 GeV.

We show the cross section for $e^+e^- \to \gamma\gamma \to t\bar{b}\pi_t^-(\bar{t}b\pi_t^+)$ at the ILC with energy of 500 GeV as a

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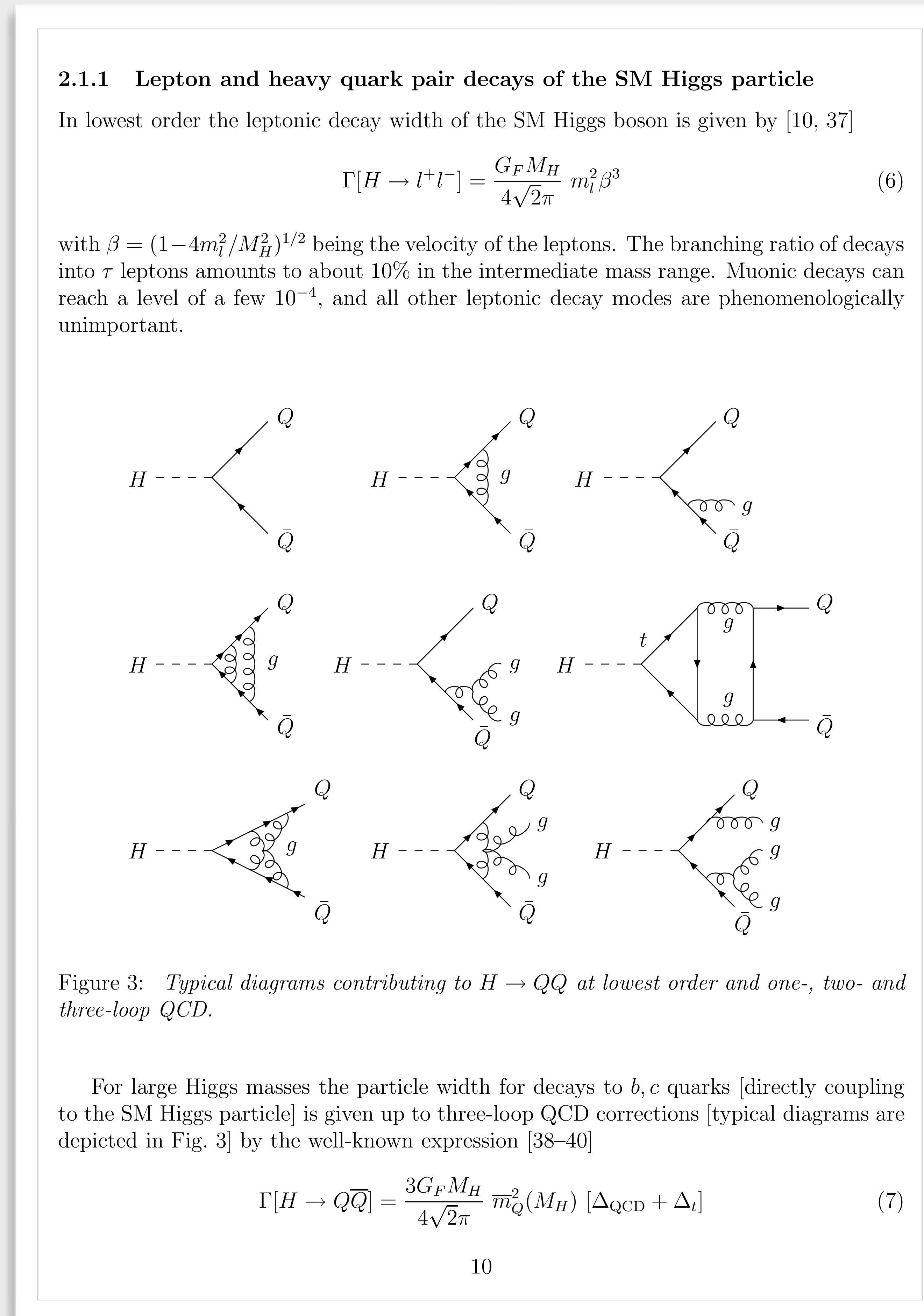


2.1.1 Lepton and heavy quark pair decays of the SM Higgs particle

In lowest order the leptonic decay width of the SM Higgs boson is given by [10, 37]

$$\Gamma[H \to l^+l^-] = \frac{G_F M_H}{4\sqrt{2}\pi}\, m_l^2 \beta^3 \quad (6)$$

with $\beta = (1 - 4m_l^2/M_H^2)^{1/2}$ being the velocity of the leptons. The branching ratio of decays into τ leptons amounts to about 10% in the intermediate mass range. Muonic decays can reach a level of a few 10^{-4}, and all other leptonic decay modes are phenomenologically unimportant.

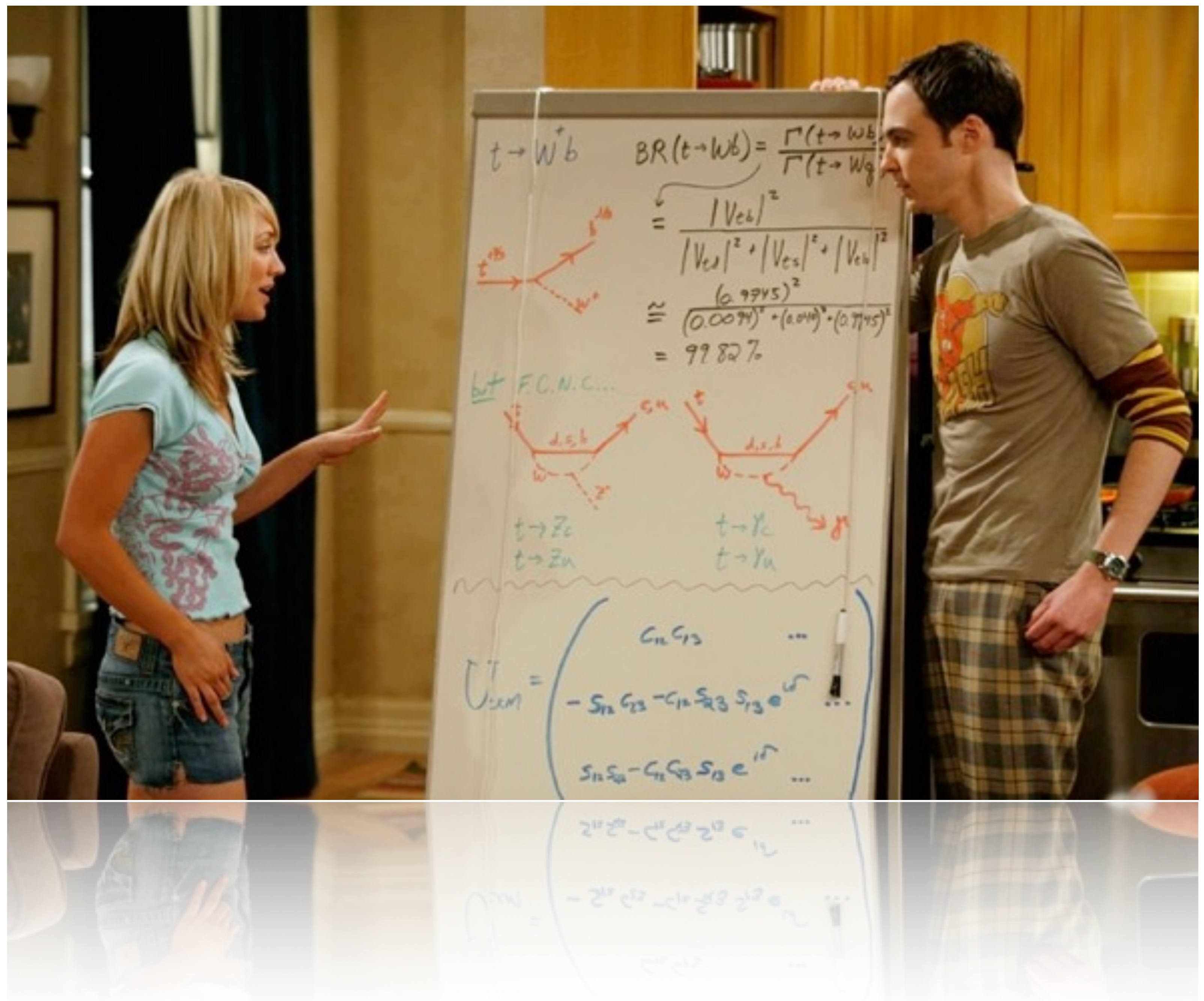
Figure 3: *Typical diagrams contributing to $H \to Q\bar{Q}$ at lowest order and one-, two- and three-loop QCD.*

For large Higgs masses the particle width for decays to b, c quarks [directly coupling to the SM Higgs particle] is given up to three-loop QCD corrections [typical diagrams are depicted in Fig. 3] by the well-known expression [38–40]

$$\Gamma[H \to Q\overline{Q}] = \frac{3G_F M_H}{4\sqrt{2}\pi}\, \overline{m}_Q^2(M_H)\, [\Delta_{\rm QCD} + \Delta_t] \quad (7)$$

10

we really do use Feynman Diagrams



Feynman's approach is really sneaky and really cute

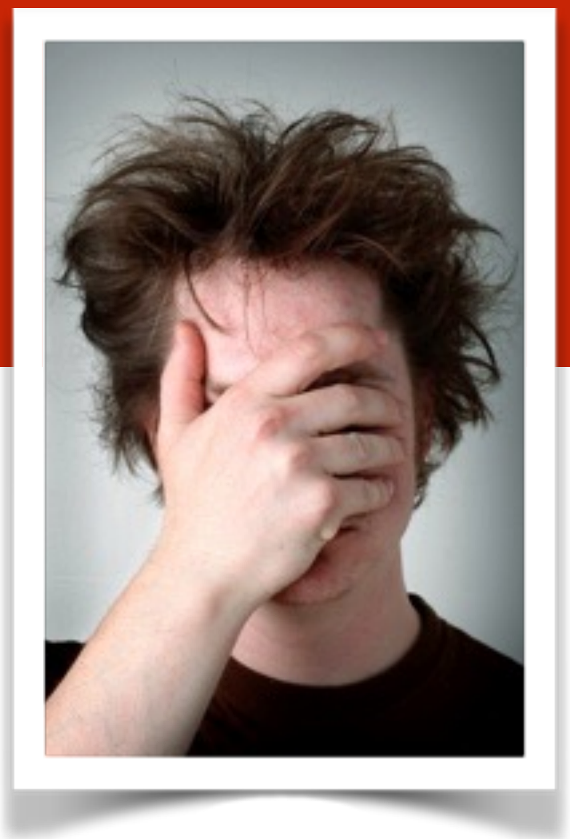
energy and time appear together in the equations:

In essence, this:

either energy solution: $(\pm E)(t)$

just the -E solution: $(-E)(t)$

move the – sign: $(E)(-t)$



Get a whole new interpretation of antimatter

antiparticles

can be intepreted as particles moving backwards in time.

that’s it.

and visa versa

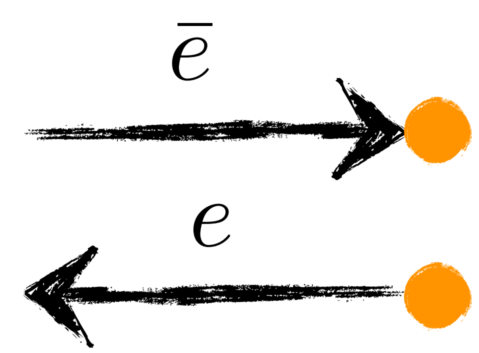
we'll do this in

two steps

1. I'll show you how spacetime can be manipulated to predict new physical processes out of old ones

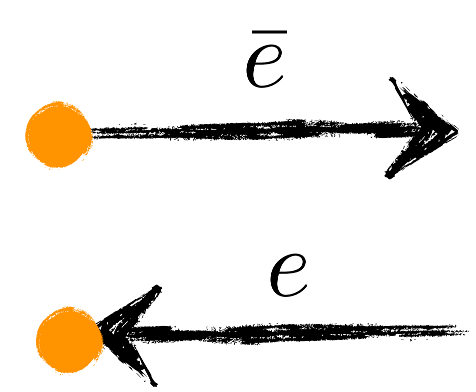
making use of the Feynman idea that antiparticles moving forward in time are the same as particles moving backwards in time

An anti-electron...coming **forwards into** an **initial** state:



is the same thing as
An electron coming
backwards out of an **initial** state

An anti-electron...coming **forwards out** of a **final** state:



is the same thing as
An electron coming
backwards into a **final** state

2. But *the vast majority of our use* will be to develop the handful (11) of "Primitive Diagrams" that we'll put together like a puzzle

to predict all possible physical processes in the "Standard Model" of particle physics jargon alert: **fermion**

refers to:	any particle with half-integer spin
entomology:	from Fermi's theoretical work on the behavior of large numbers of Fermions
example:	electron, proton, neutron

jargon alert: **bosons**

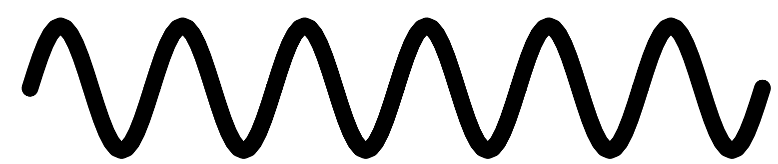
refers to:	any quantum object with integer spin
entomology:	from Satyendra Nath Bose, who worked on the effects of multiple boson aggregates
example:	photon, pion, Higgs Boson

the key

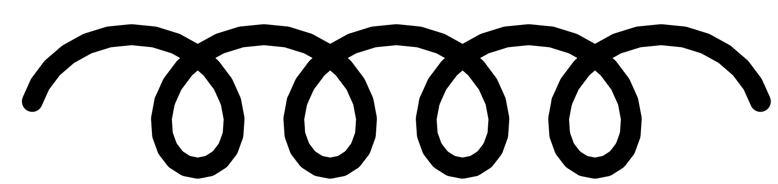
the different kinds of lines

look at your Primitive Diagram Sheet

fermion, spin 1/2, e.g., electron



Vector Boson, spin 1, e.g., photon



gluon, spin 1

scalar Boson, spin 0, e.g., Higgs Boson

the first theory of Feynman's

"Quantum Electrodynamics" or "QED"

the full theory of the physics of photons and electrons

`strap in`

with pencil in hand

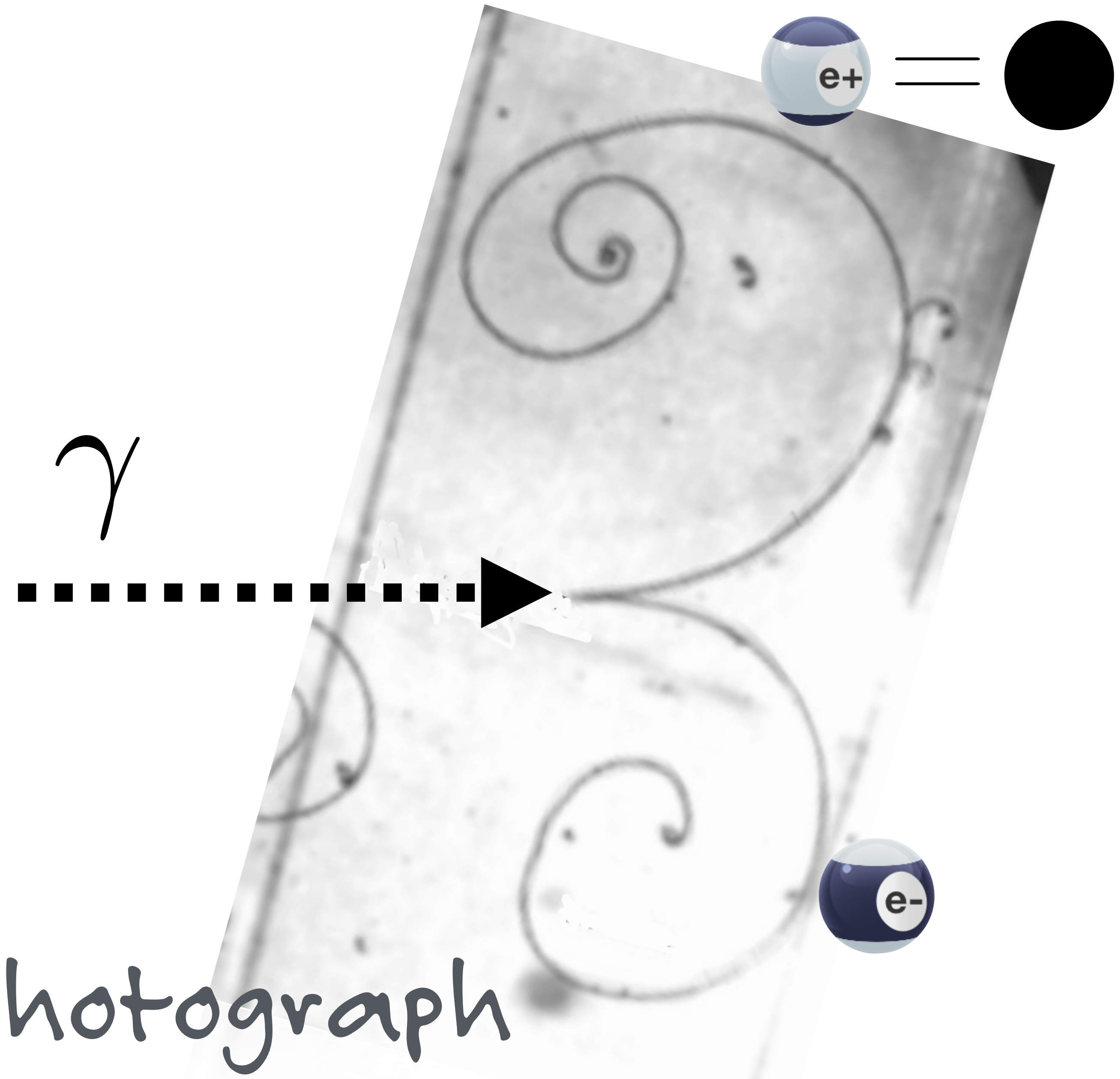
first idea

one can take a single Feynman Diagram that describes a process

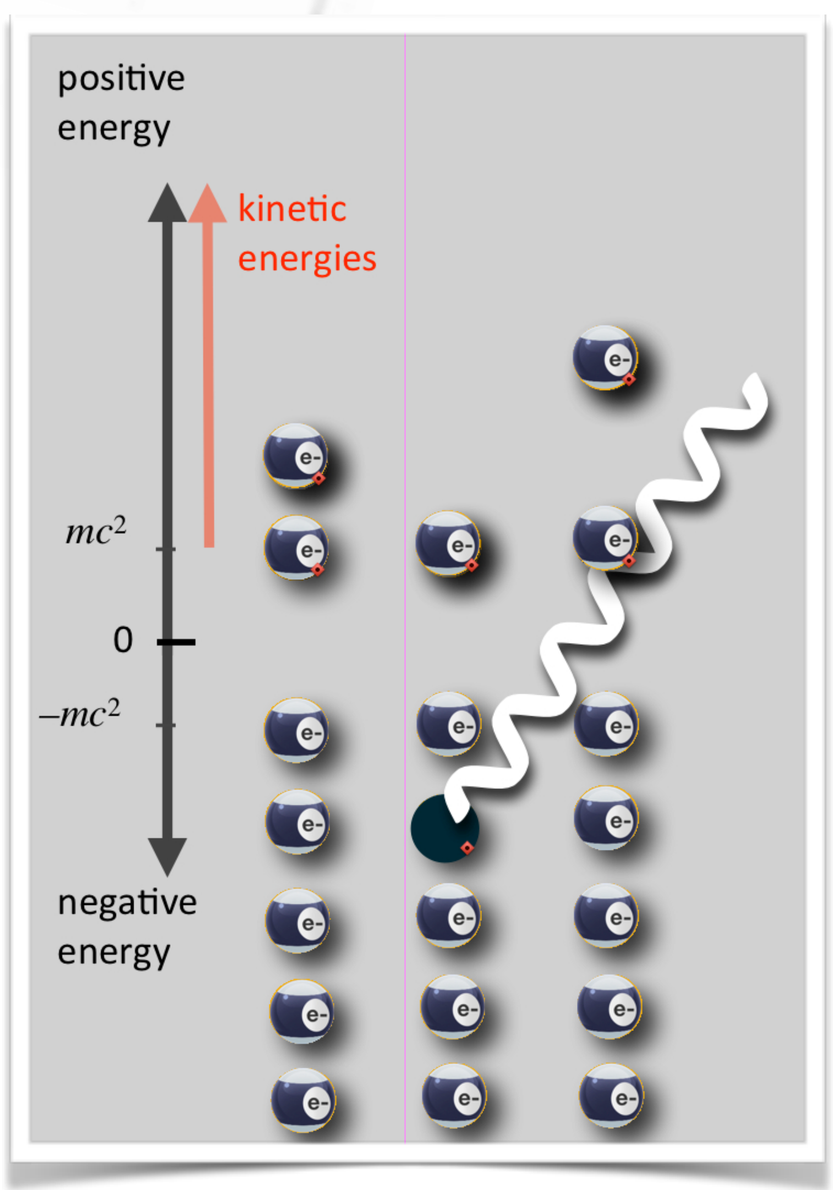
and by rearranging it in spacetime, “predict” additional physical processes

Dirac’s story

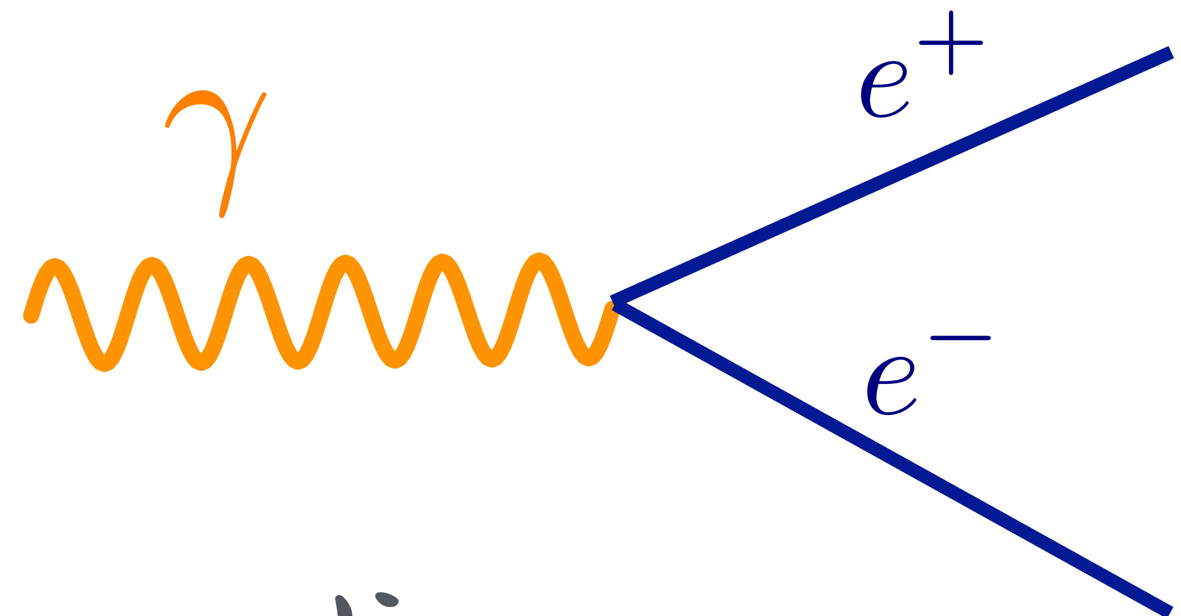
& Feynman’s picture



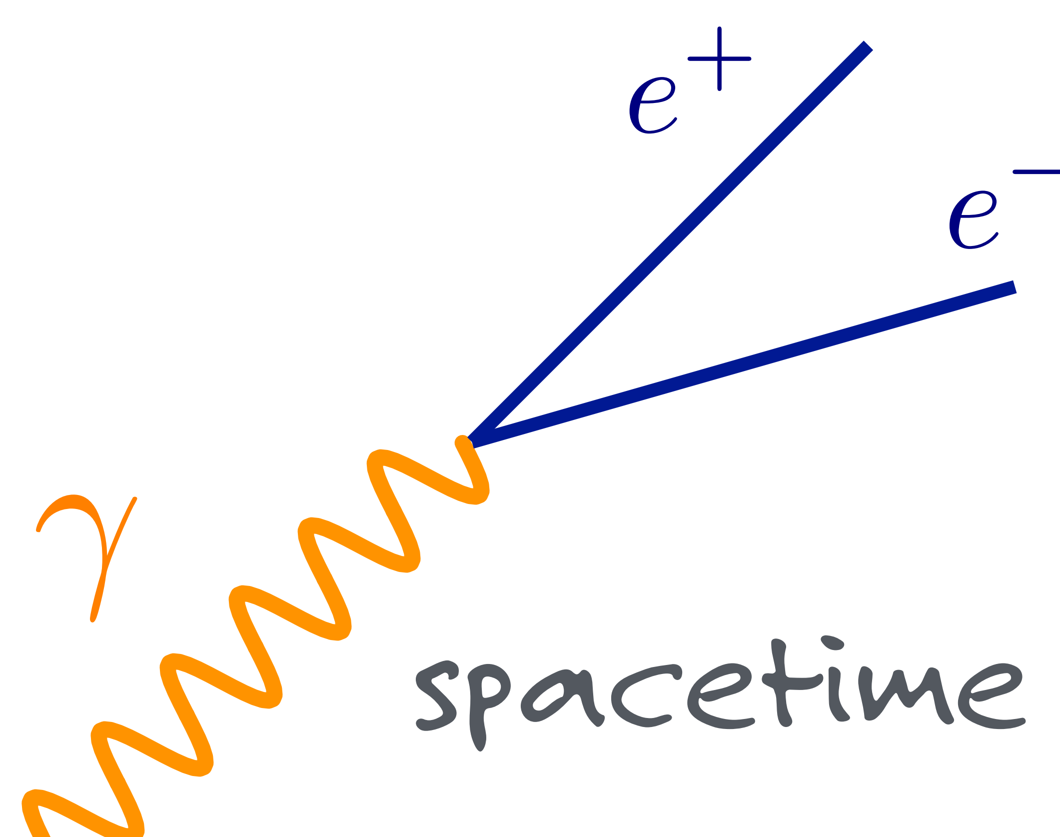
photograph



cartoon



space diagram



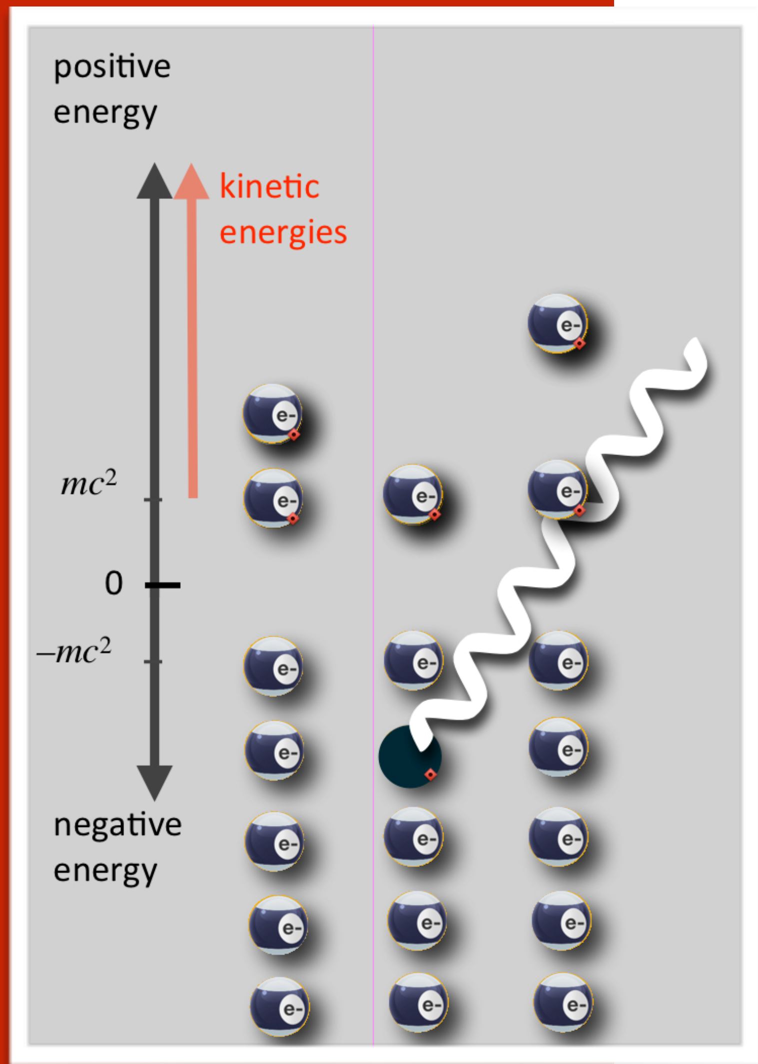
spacetime diagram

Feynman diagram

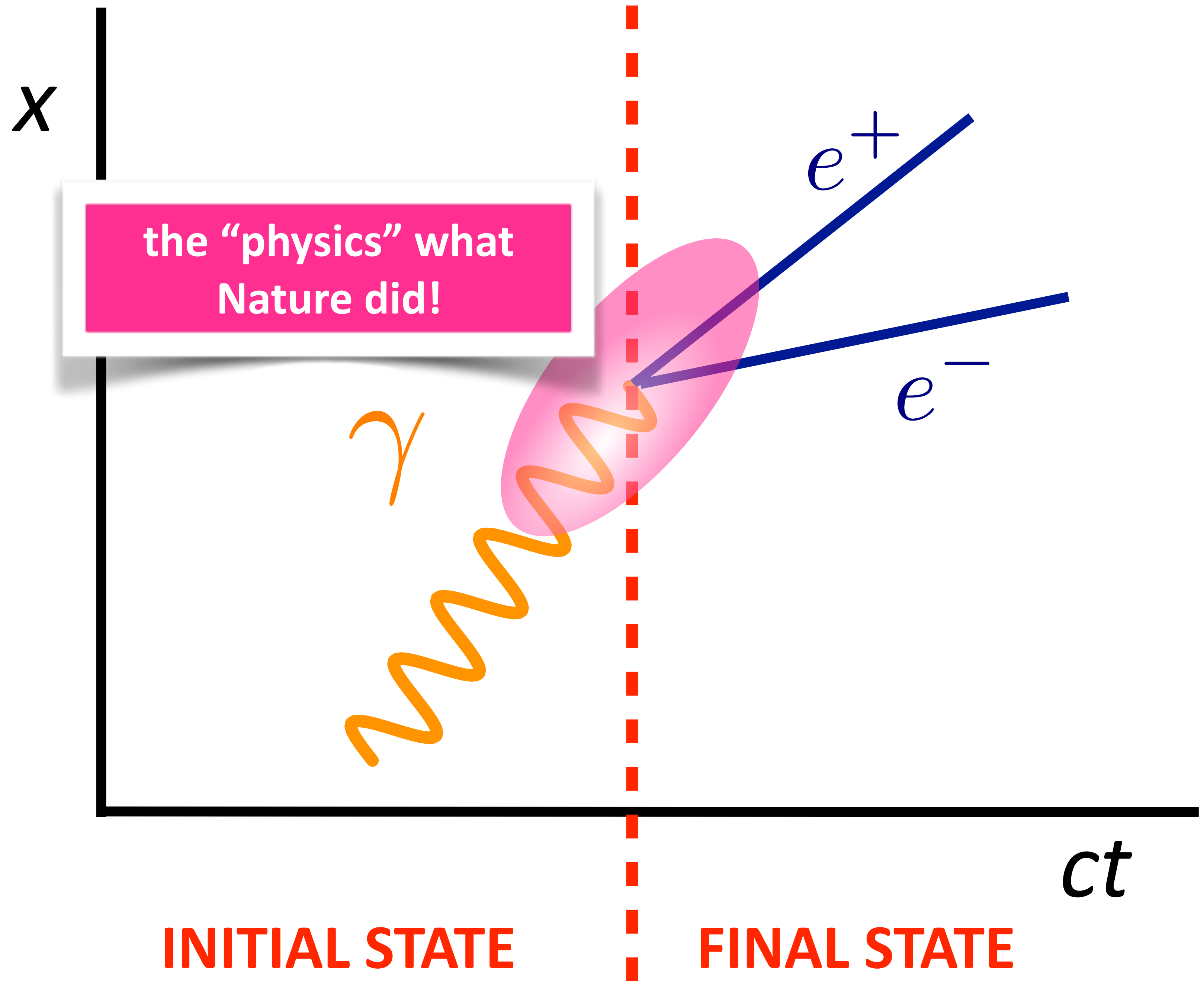
Dirac had photons creating an electron

Feynman's calculus allows that

and more



The Dirac hypothesis is called "Pair Production": photon in, electron & positron out



Now, remember that we treat *ct* and *x* identically...

The physics does not care which orientation is which.

note:

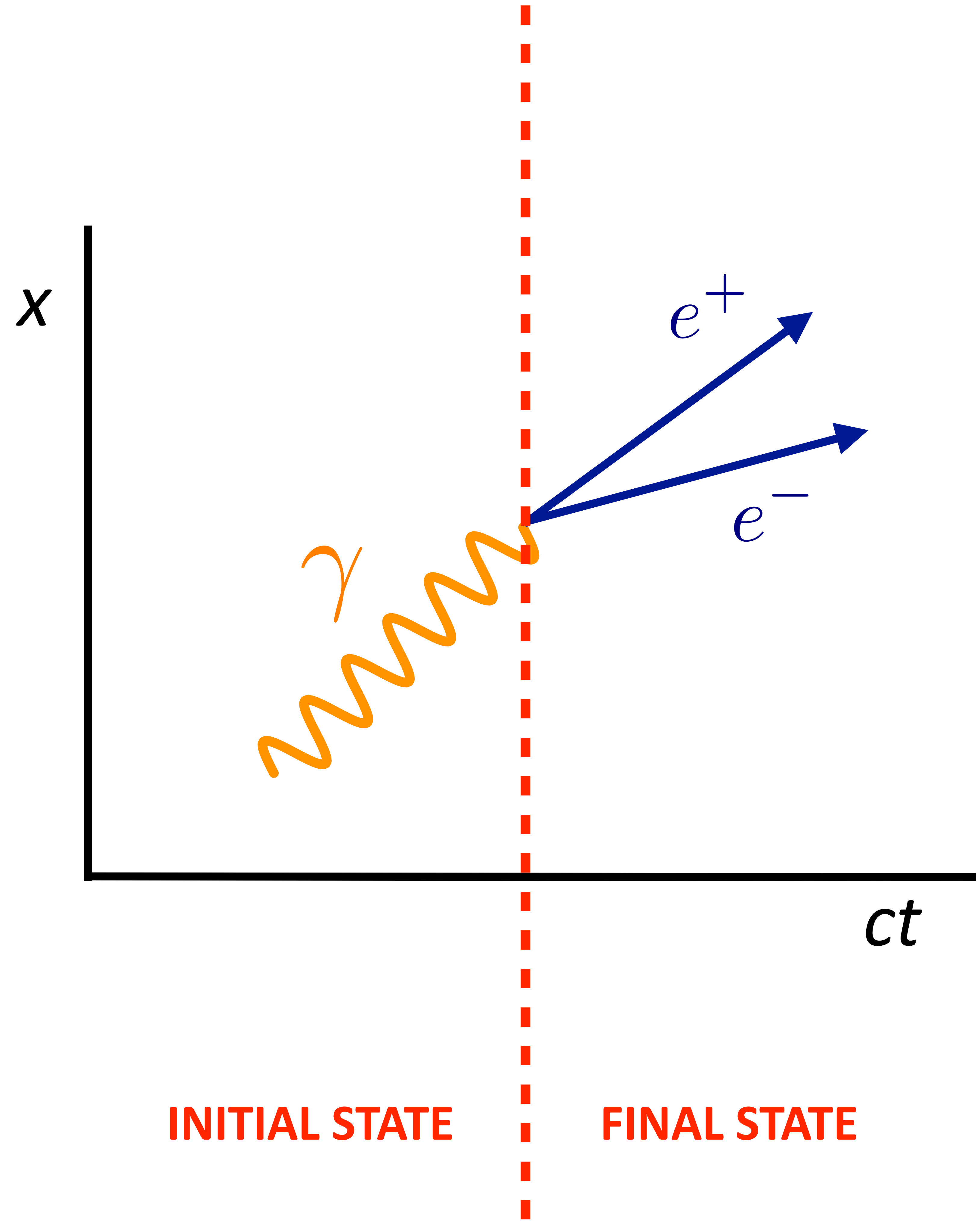
I’ve been banging on you to keep the slopes right

you know, photons have slope associated with c

We’ll relax that now.

can always rotate any Feynman Graph

and get a new one



Feynman’s trick

depends on the in and out states.

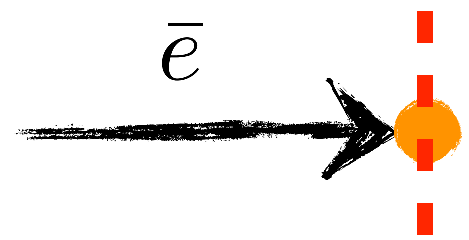
if some manipulation leaves you with particles going the “wrong” direction?

We don’t deal with real particles moving backwards in time

fix it.

particles in time

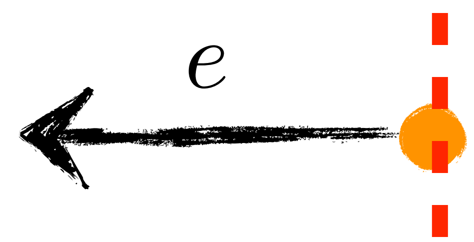
An anti-electron...coming **into** an **initial** state to a node:



Yes, this makes sense

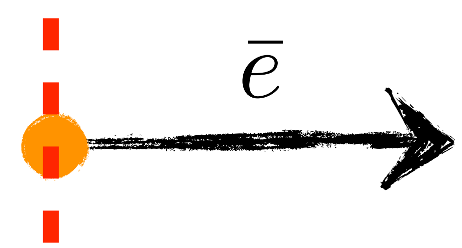
is the same thing as

An electron coming **out** of an **initial** state (?)



Nope, this makes no sense...time-backwards

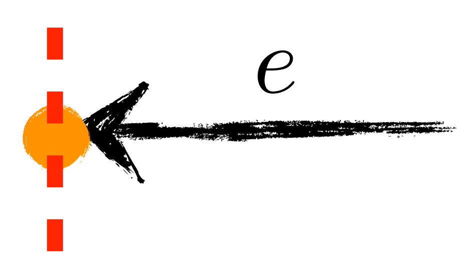
An anti-electron...coming **out** of a **final** state:



Yes, this makes sense

is the same thing as

An electron coming **into** a **final** state (?)



Nope, this makes no sense...time-backwards

Feynman had rules

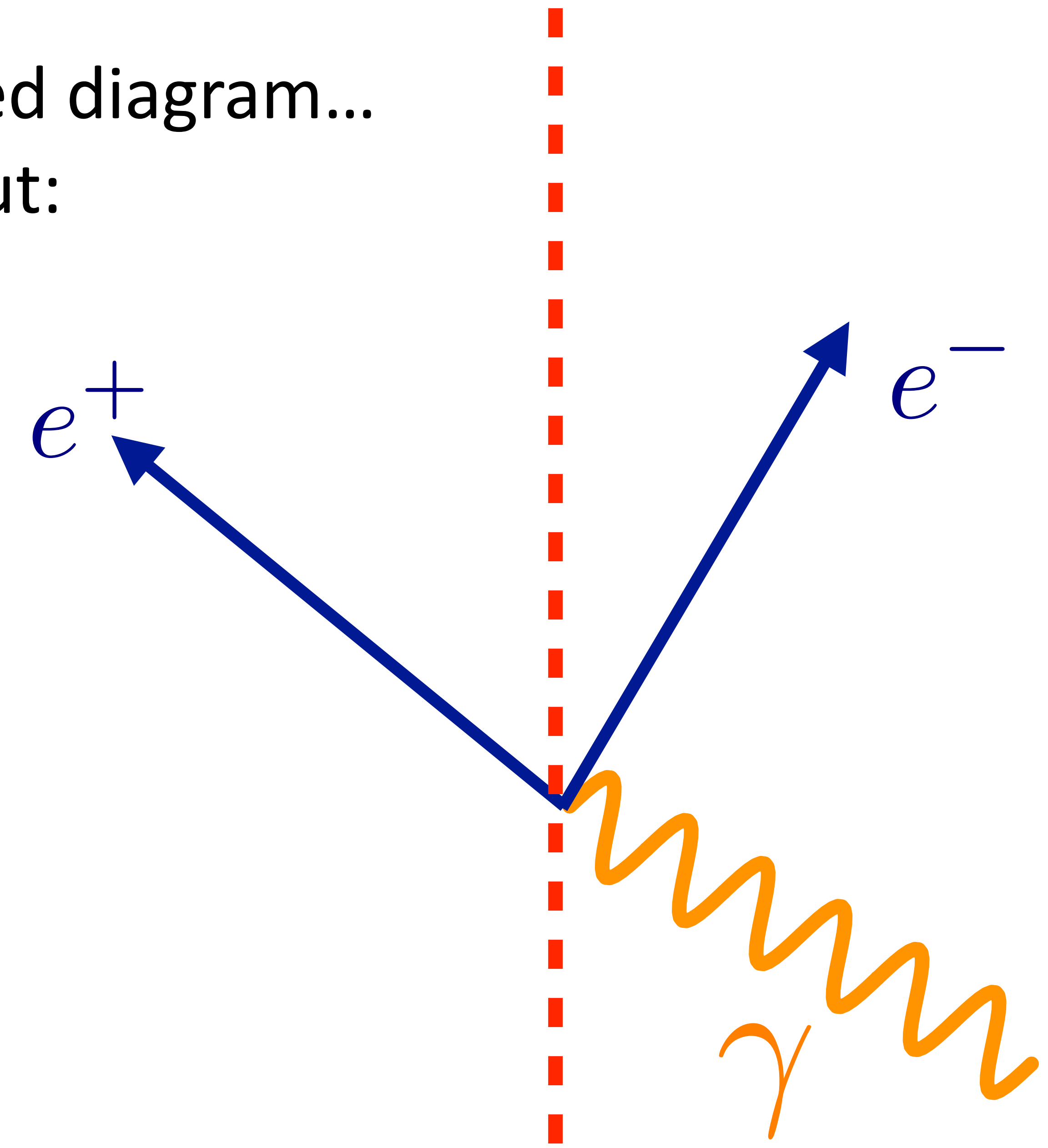
We'll have slightly different rules

but similar in spirit

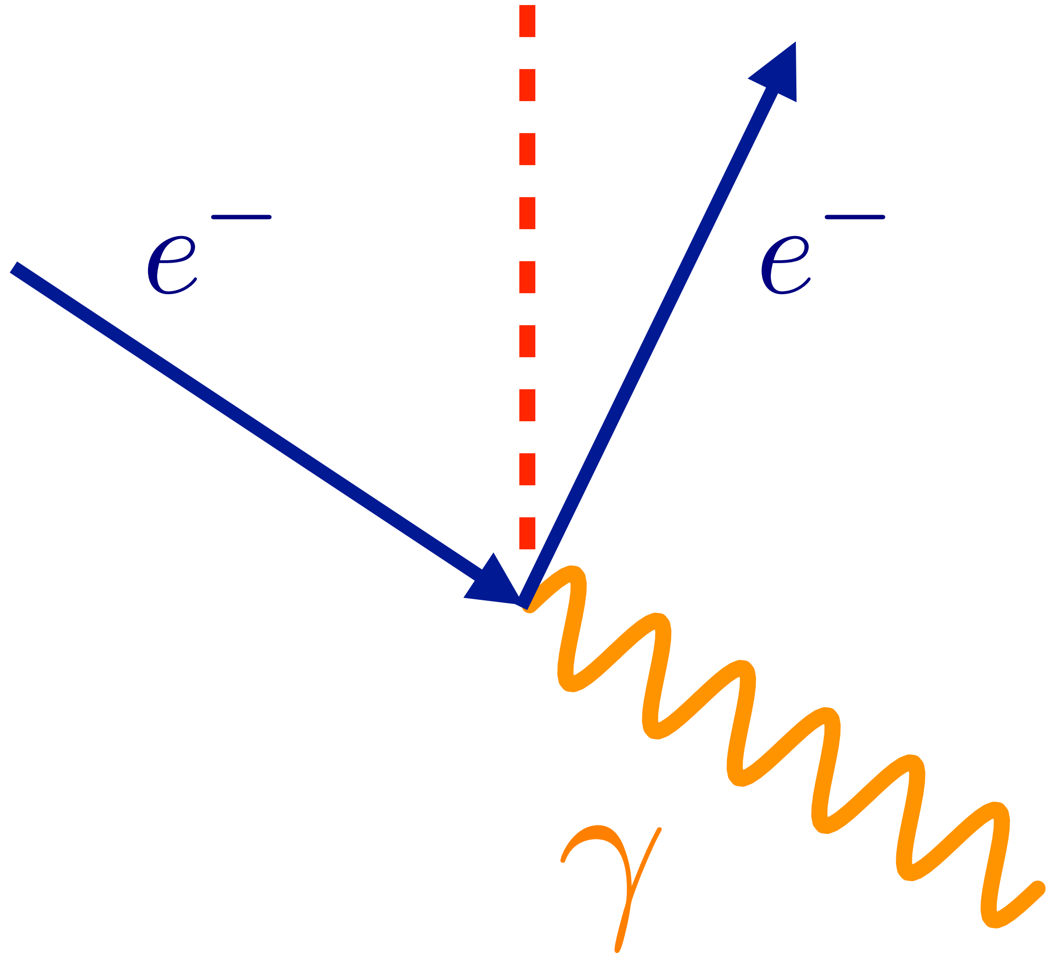
Rule 1.

If you flip a line's arrow forward or backward in time, you change the particle to antiparticle or antiparticle to particle

my rotated diagram… spread out:



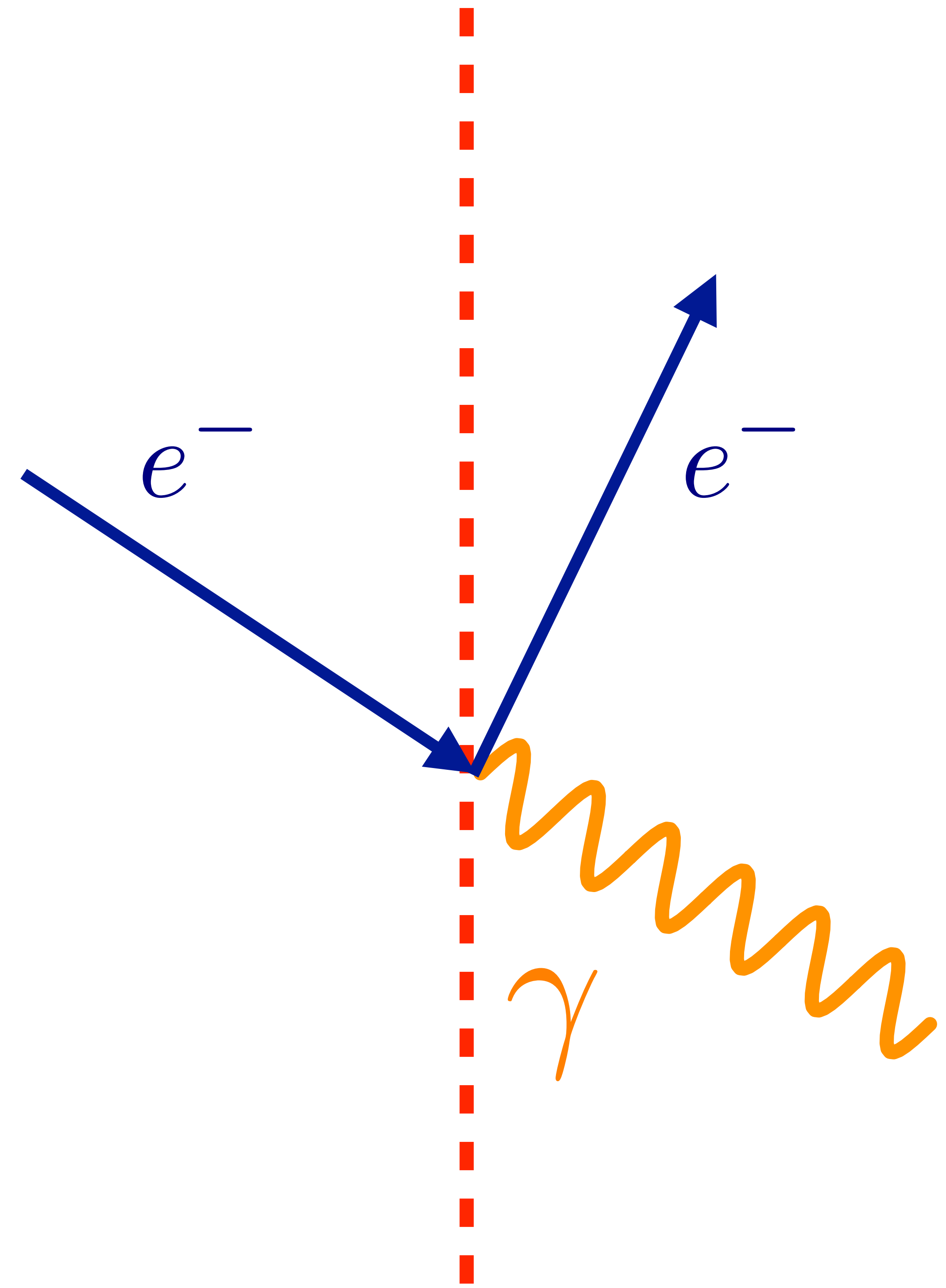
this is the same thing as:



look at this

you know this.

familiar:

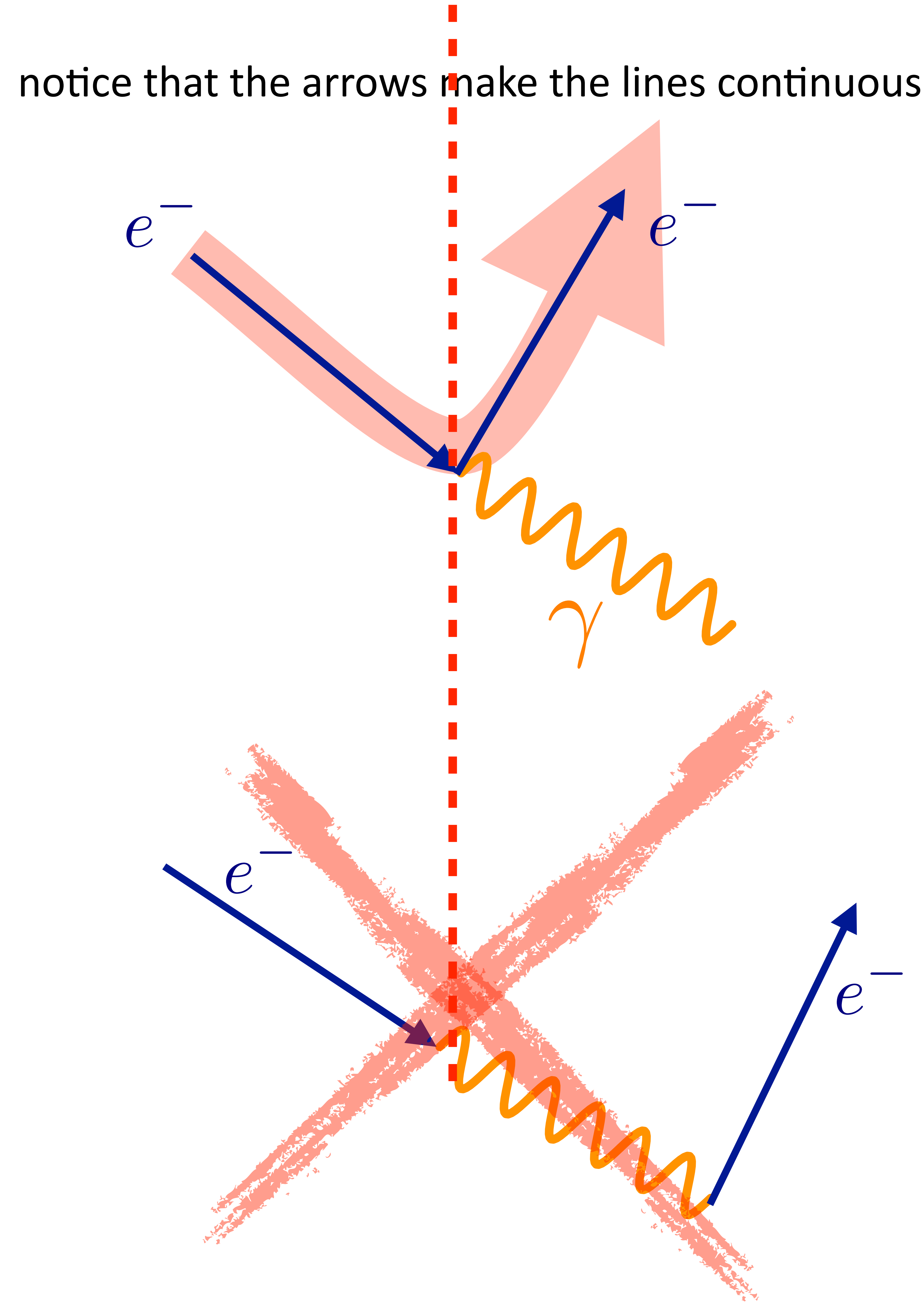


electron comes along and spits out a photon, recoils and goes on its way

regular old radiation

Rule 2.

fermion lines
must be
continuous



This and more is in these 3 movies:

primitiveDiagrams_0 (13m)

primitiveDiagrams_1 (4m)

primitiveDiagram_2 (9m)

full resolution

primitiveDiagrams_0R

primitiveDiagrams_1R

primitiveDiagram_2R

Reduced resolution

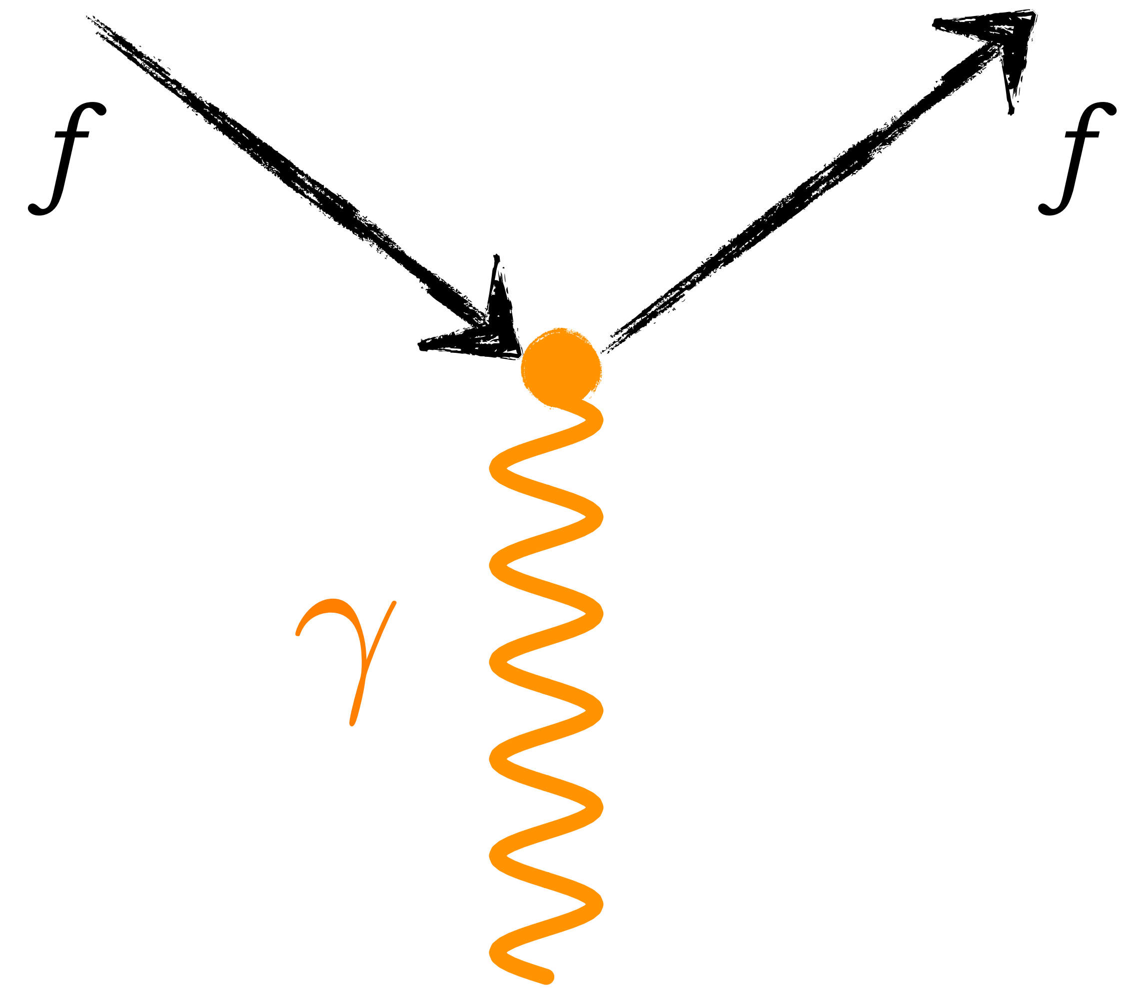
https://qstbb.pa.msu.edu/storage/QS&BB2019/videos_2019/FeynmanDiagrams/

primitive diagrams

are general

a puzzle piece to construct real physical reactions

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

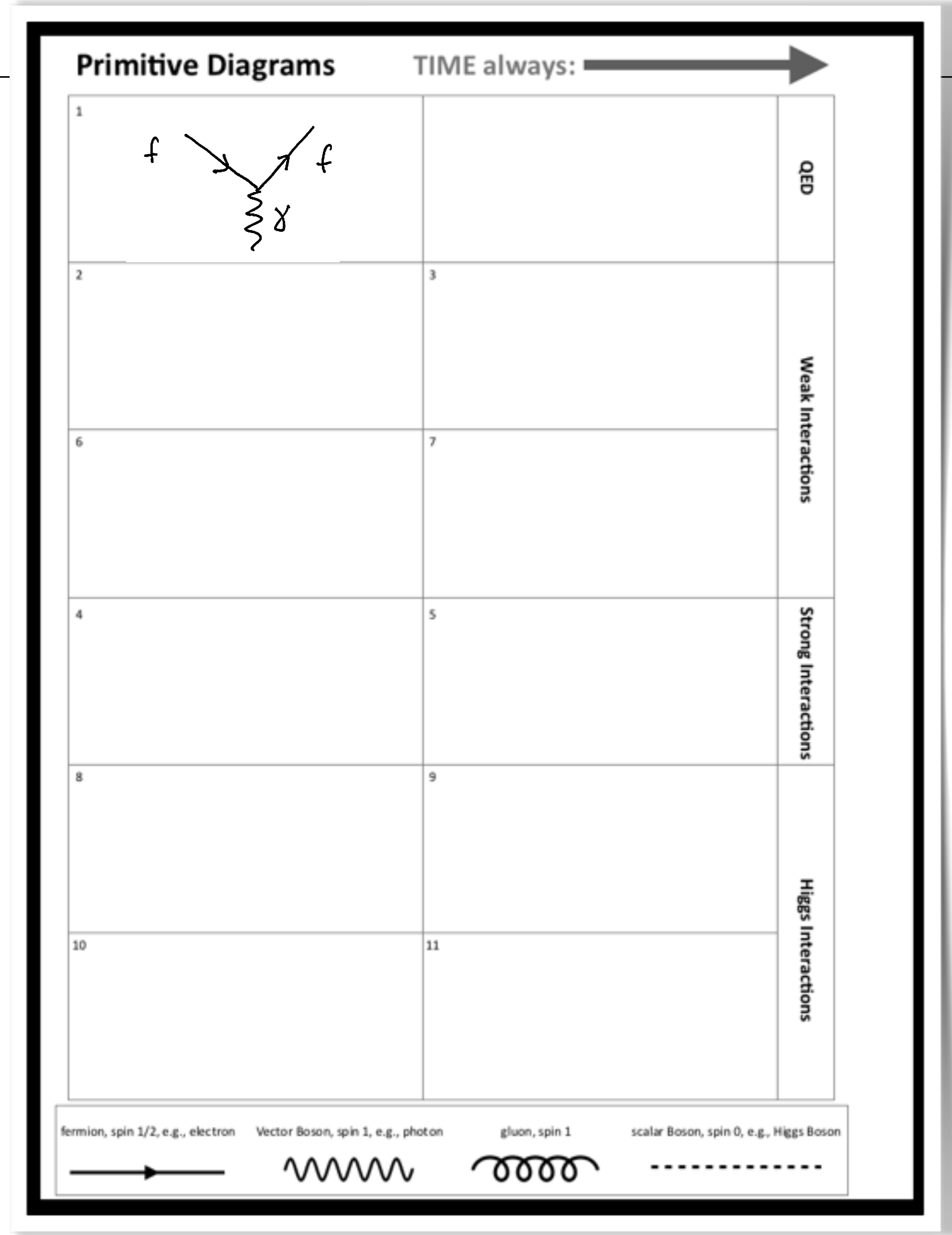


f could be electron, positron, proton, antiproton...and more – any electrically charged **f**ermion.

Their diagrams are identical.

Primitive Diagram Scorecard

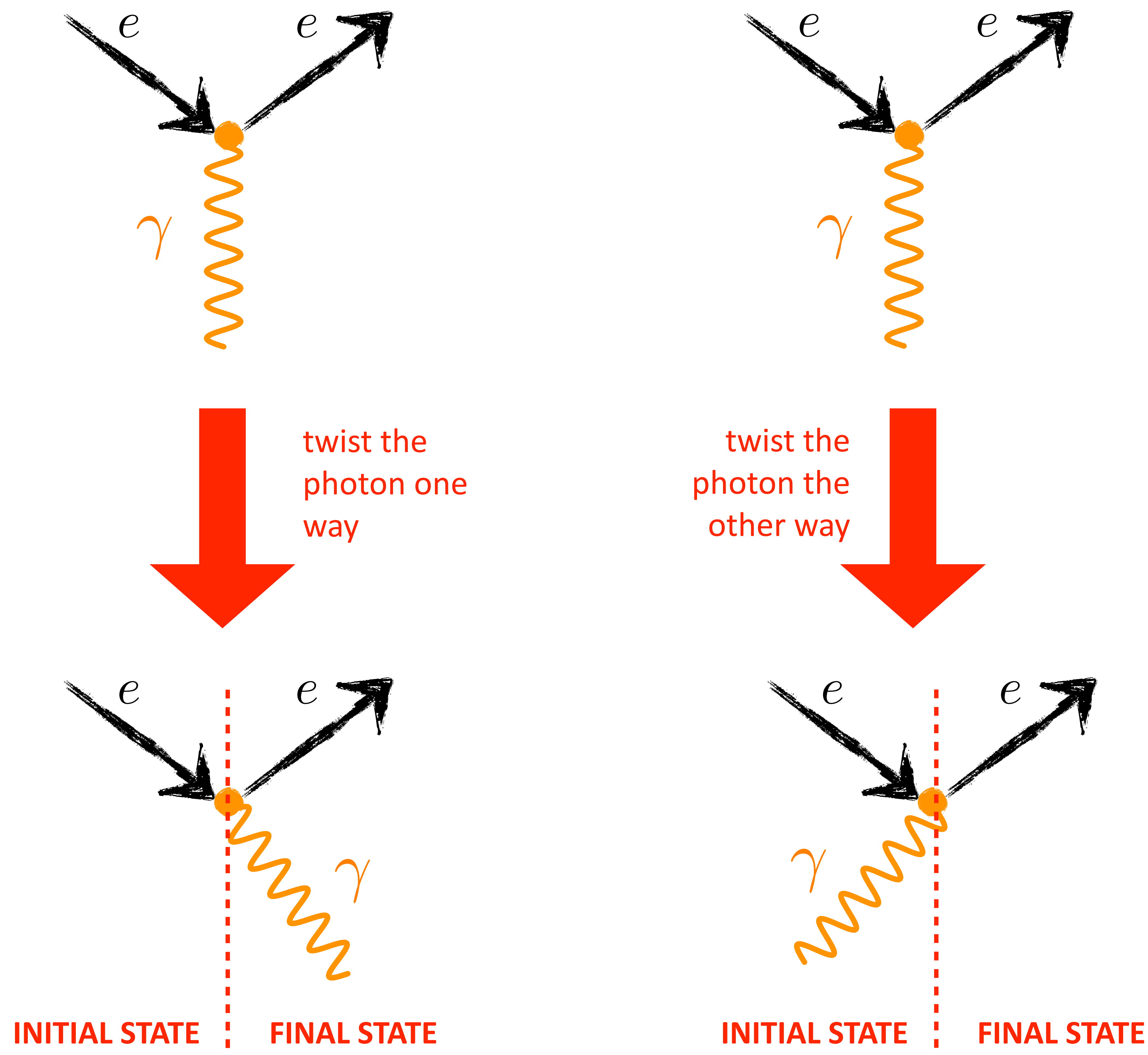
your first entry



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"

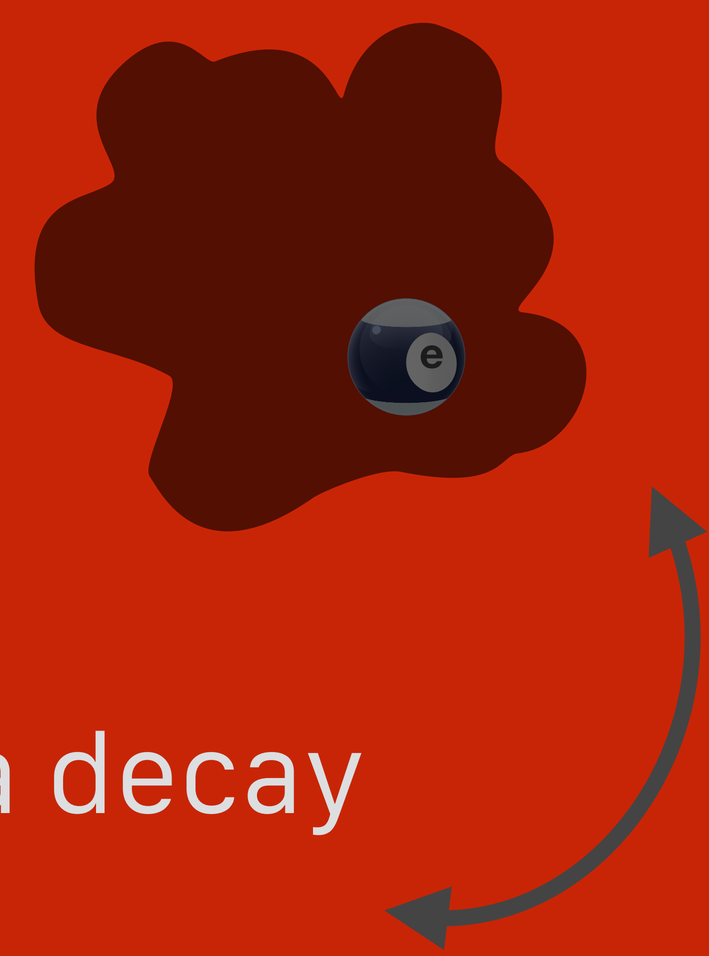
^{13}C: 1.1% & stable
^{14}C: trace & unstable

some isotopes are unstable

they beta-decay

14C: trace amounts & unstable

But there was a problem with beta decay

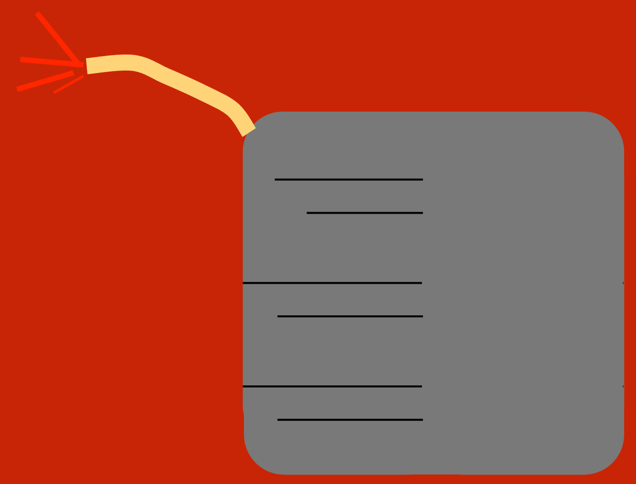


notice the funny recoil?

Suppose we have a firecracker exploding into two pieces:

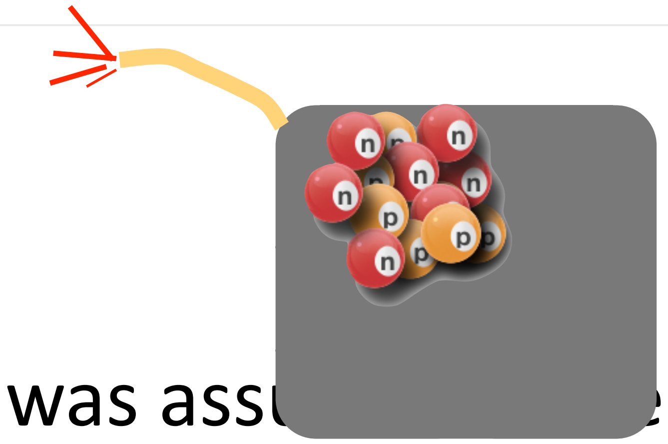
beta decay seemed like this

when you expect this



energies in a “two body decay”

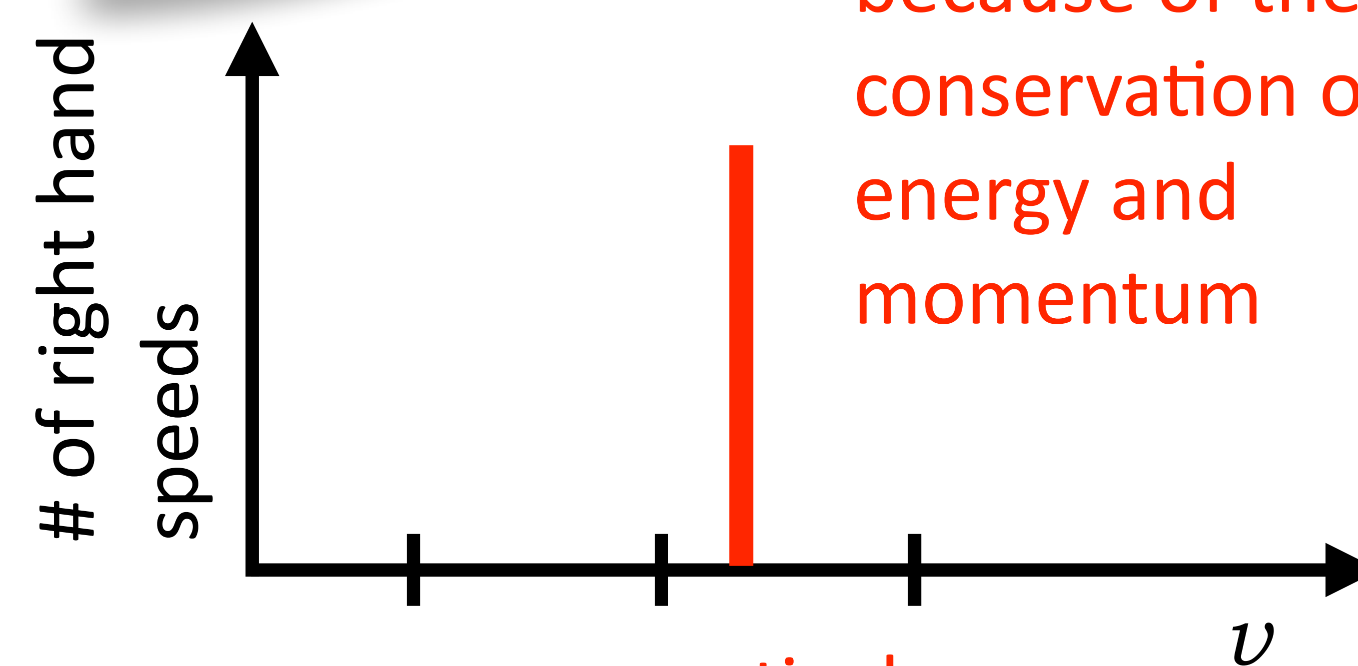
are single-valued



Beta decay was ass[...] 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

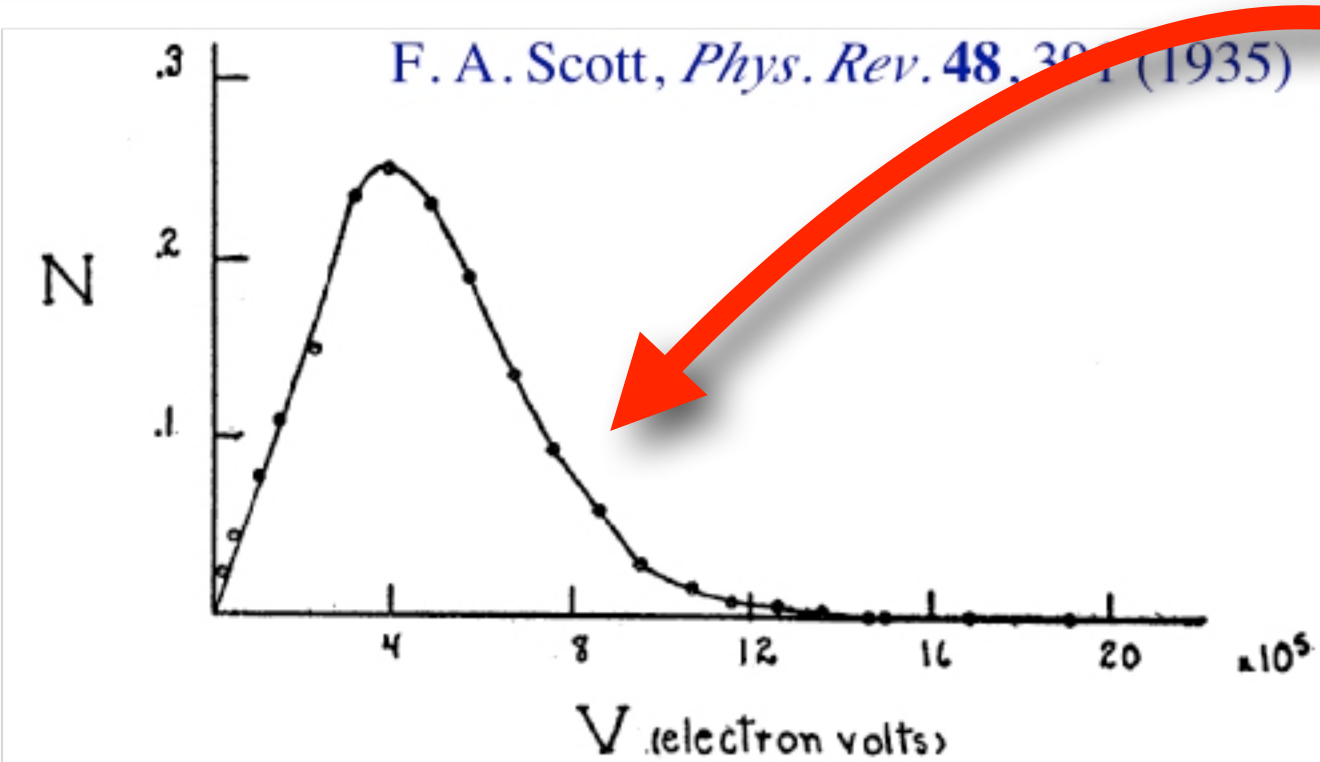
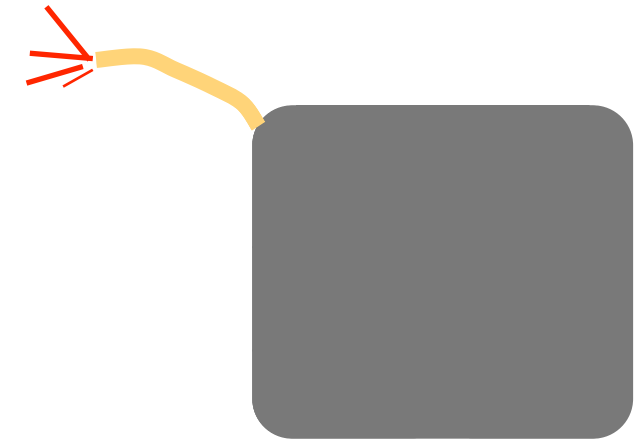


FIG. 5. Energy distribution curve of the beta-rays.

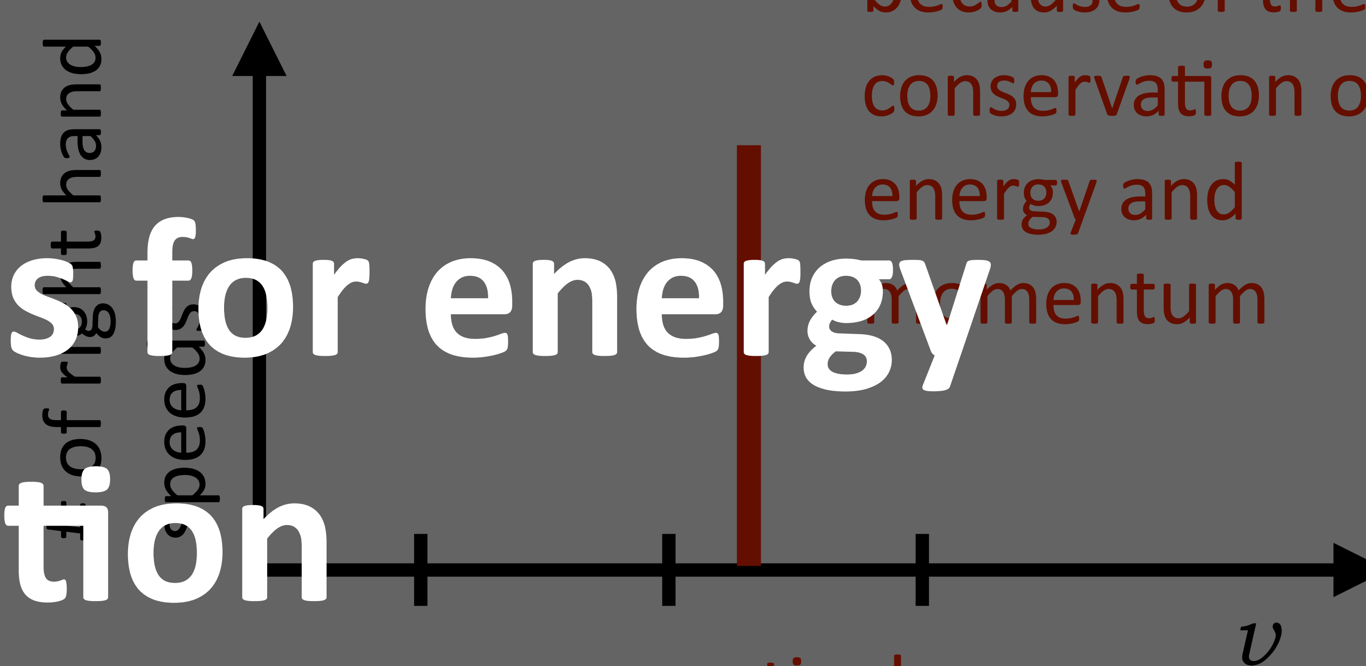
But this is what happened in beta decay. **spread-out values for speed (energy)!**

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

an apparent crisis for energy conservation

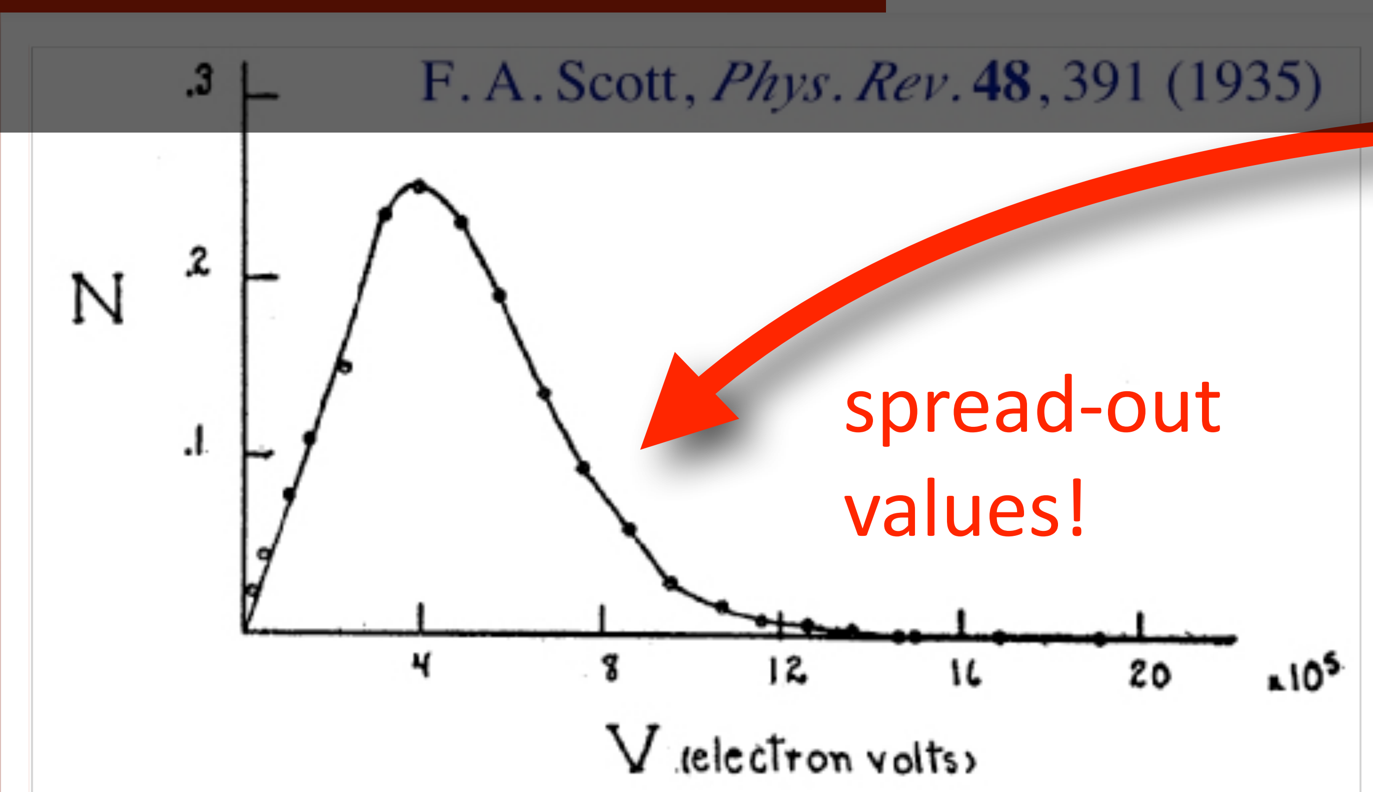
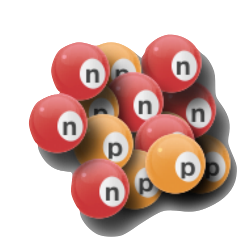


FIG. 5. Energy distribution curve of the beta-rays.

spread-out values!

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



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

“

“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

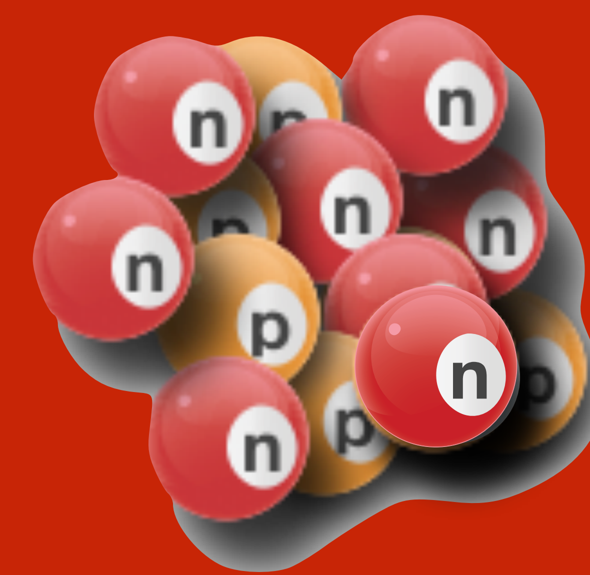
…unfortunately I cannot appear personally in Tubingen since a ball which takes place in Zurich makes my presence here indispensable.”

Oops: James Chadwick called his new particle the “neutron”

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

The prediction of the **Neutrino**
...thought to be undiscoverable!
and massless!

the idea hung around



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

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

cay 1933

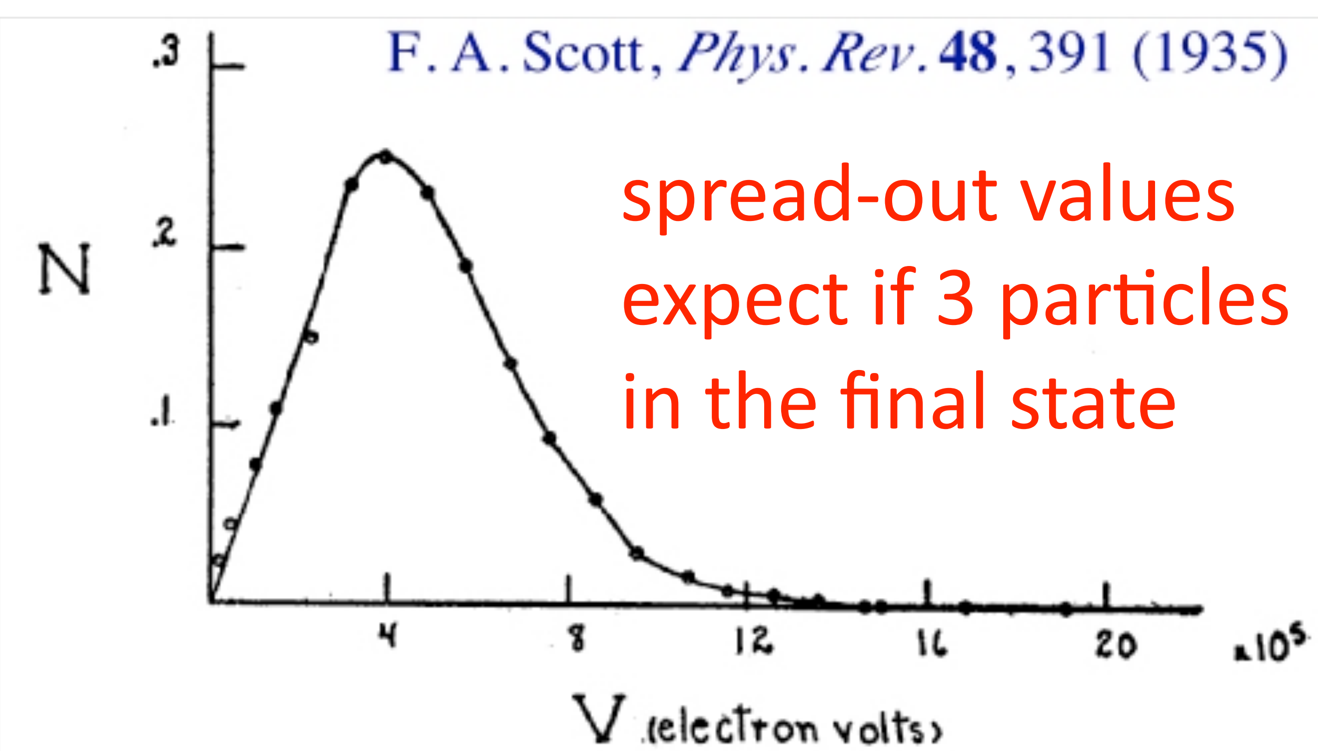
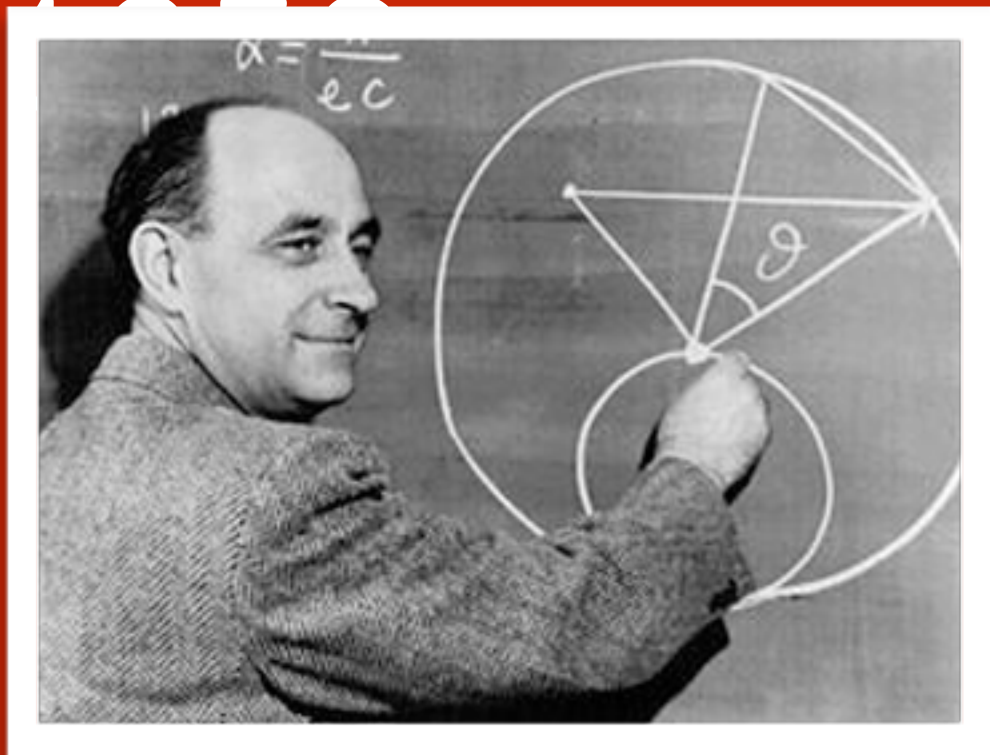


FIG. 5. Energy distribution curve of the beta-rays.

With a decay into 3 objects...the speeds of any of them can vary



Enrico Fermi

1901-1954

experimental &

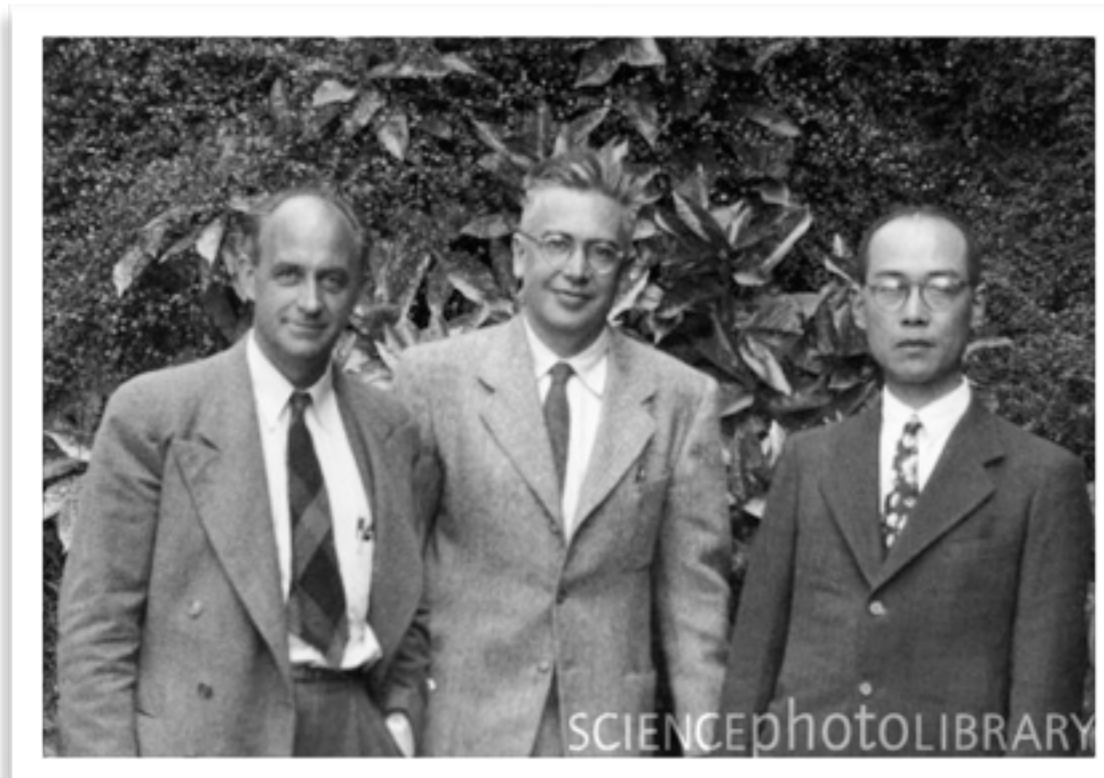
theoretical physicist!

Nobel Laureate 1938

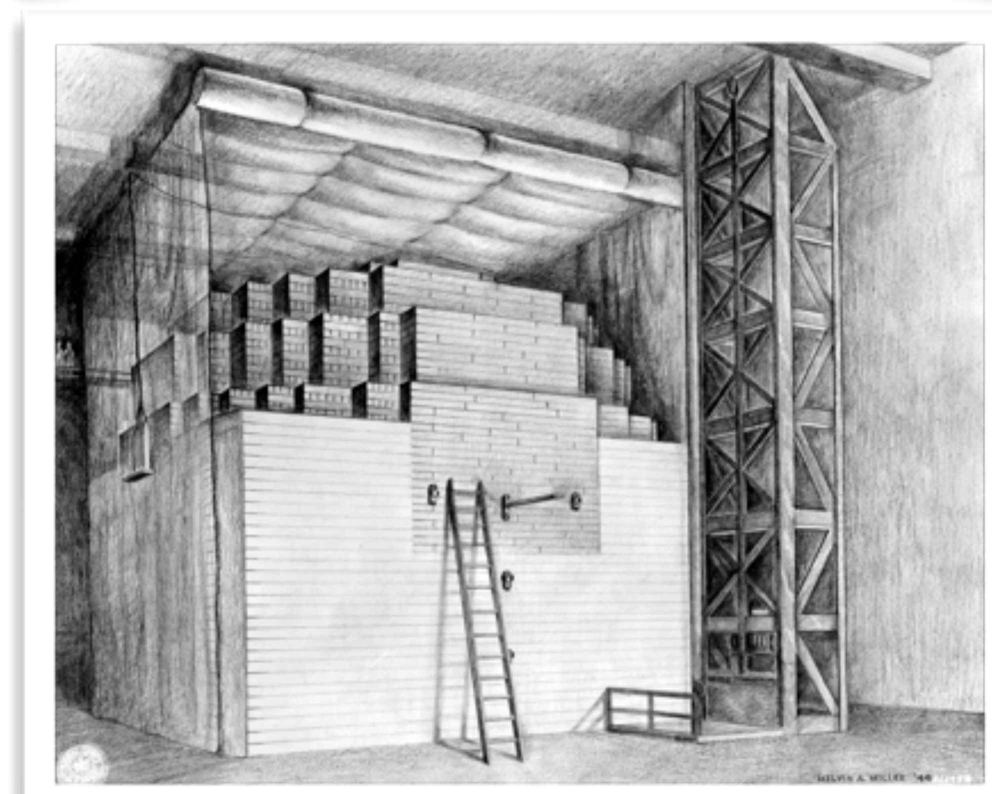
Probably 2, maybe 3 Nobel prize-worthy experiments.

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)



Enrico Fermi

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

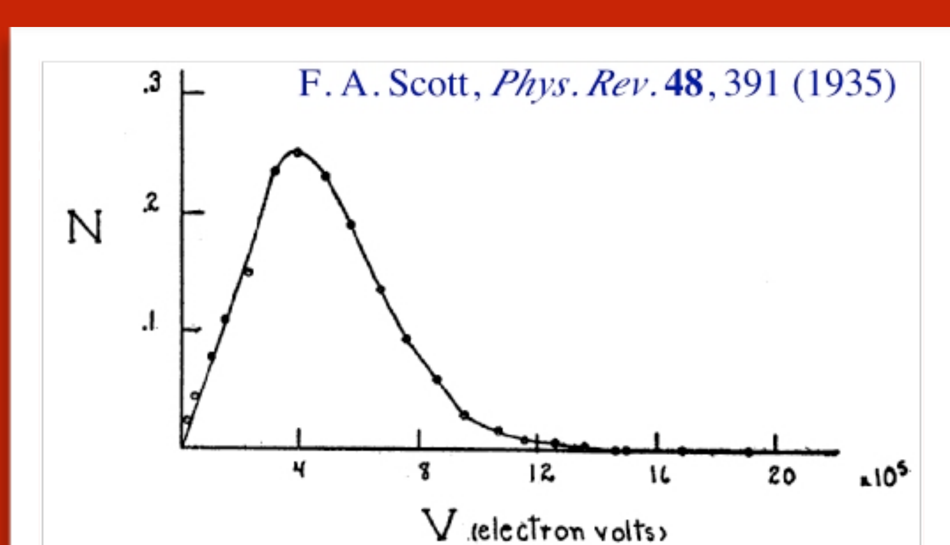
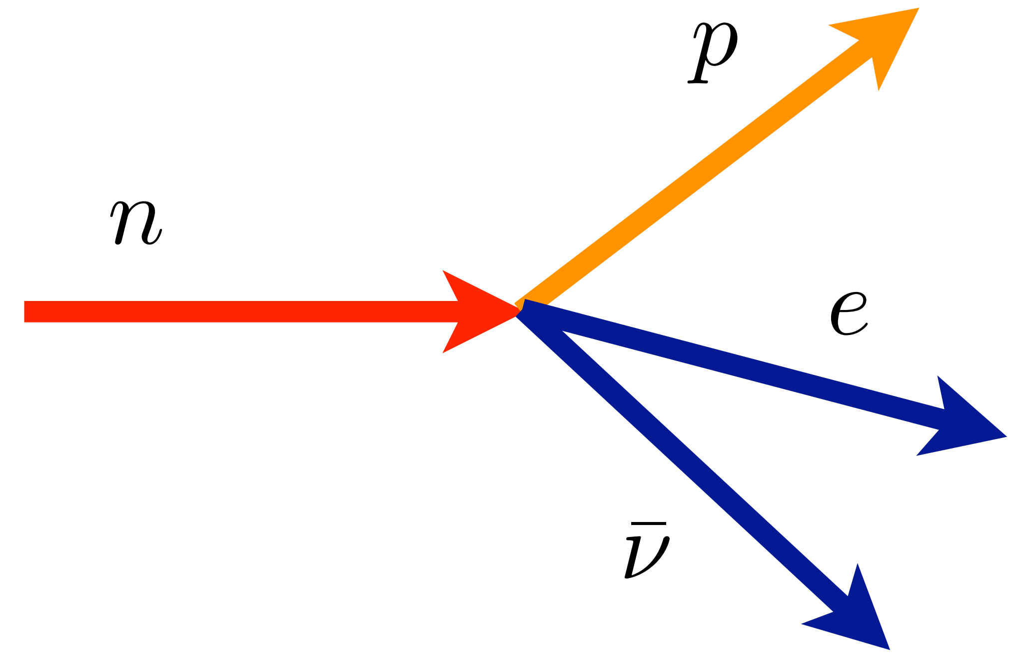


FIG. 5. Energy distribution curve of the beta-rays.

$m_{neutron} > m_{proton}$

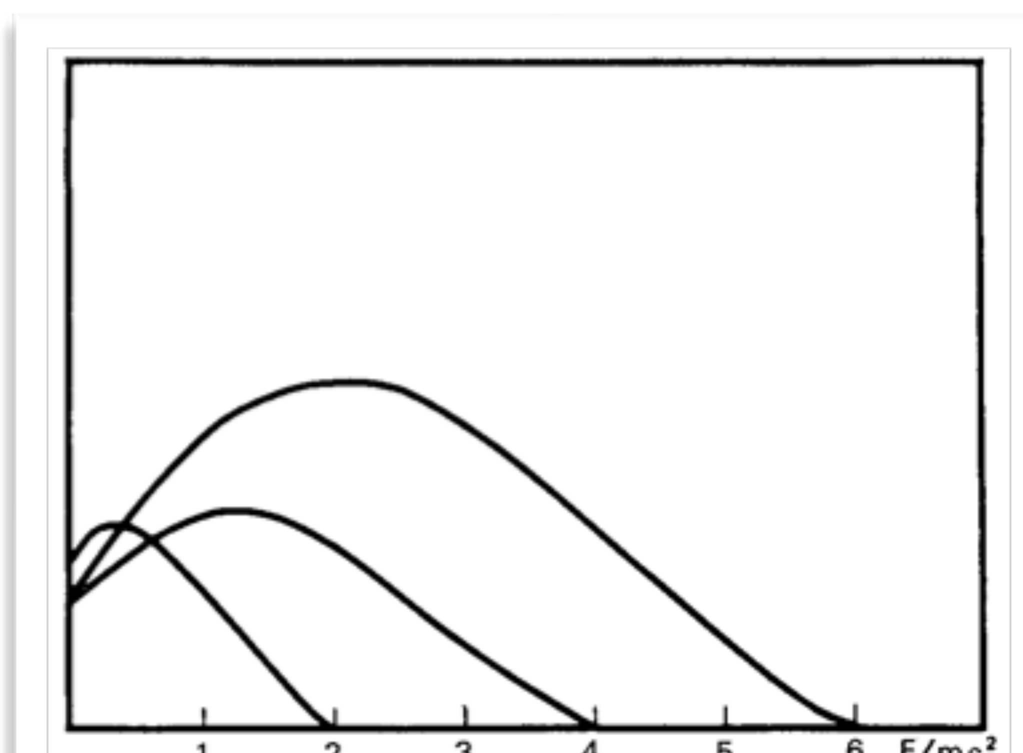
a smidgen.



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:

the notion of an “Exchange Force”

the simplest, but most important modeling suggestion ever

Heisenberg: ‘‘Hmm. Electrons spontaneously appear out of nuclei…’’

maybe they’re in the nucleus all the time?

maybe they’re even holding it together?

Exchange Force

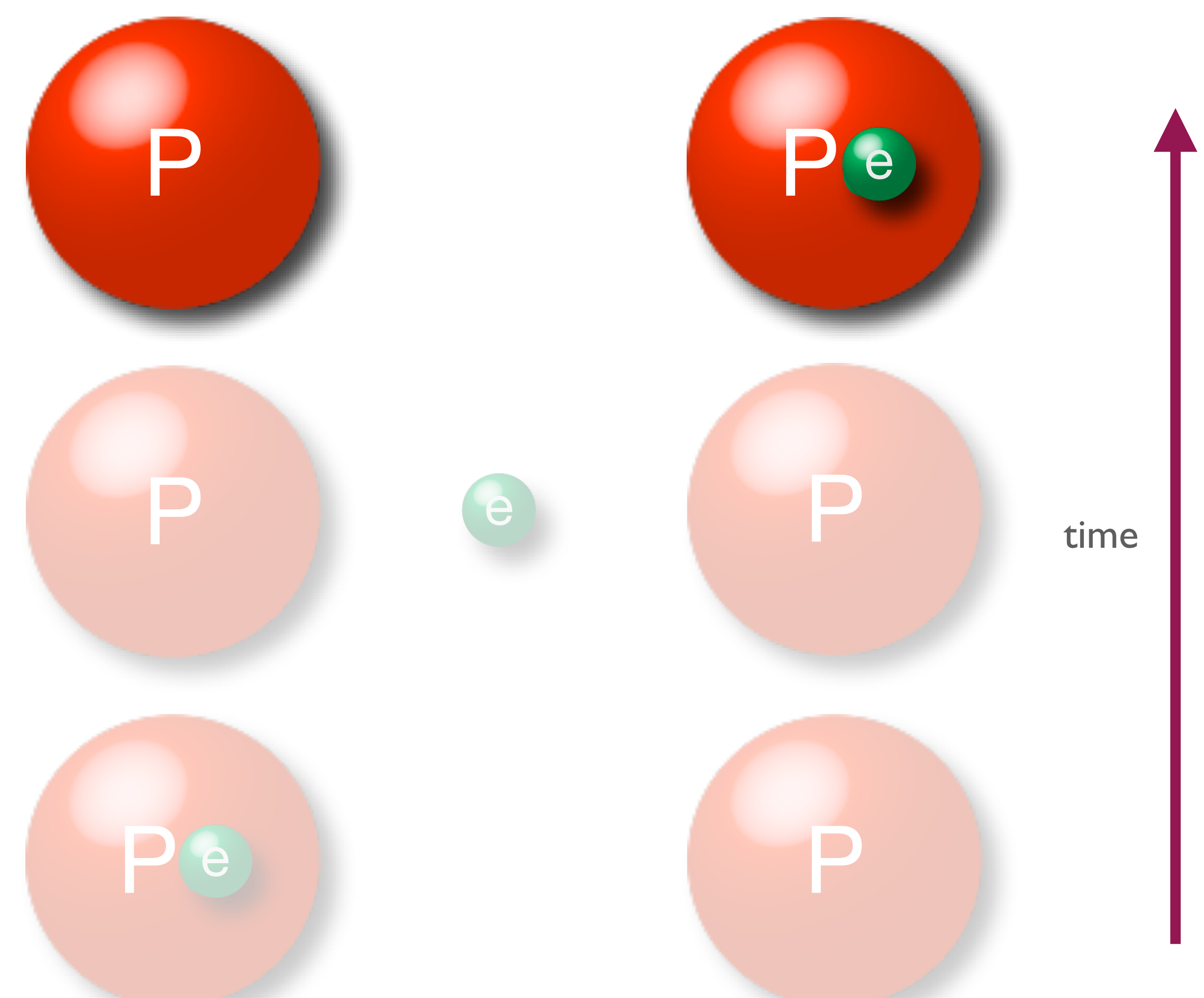
The proton is playing catch with itself

with all he knew about: electrons and protons

maybe beta decay?

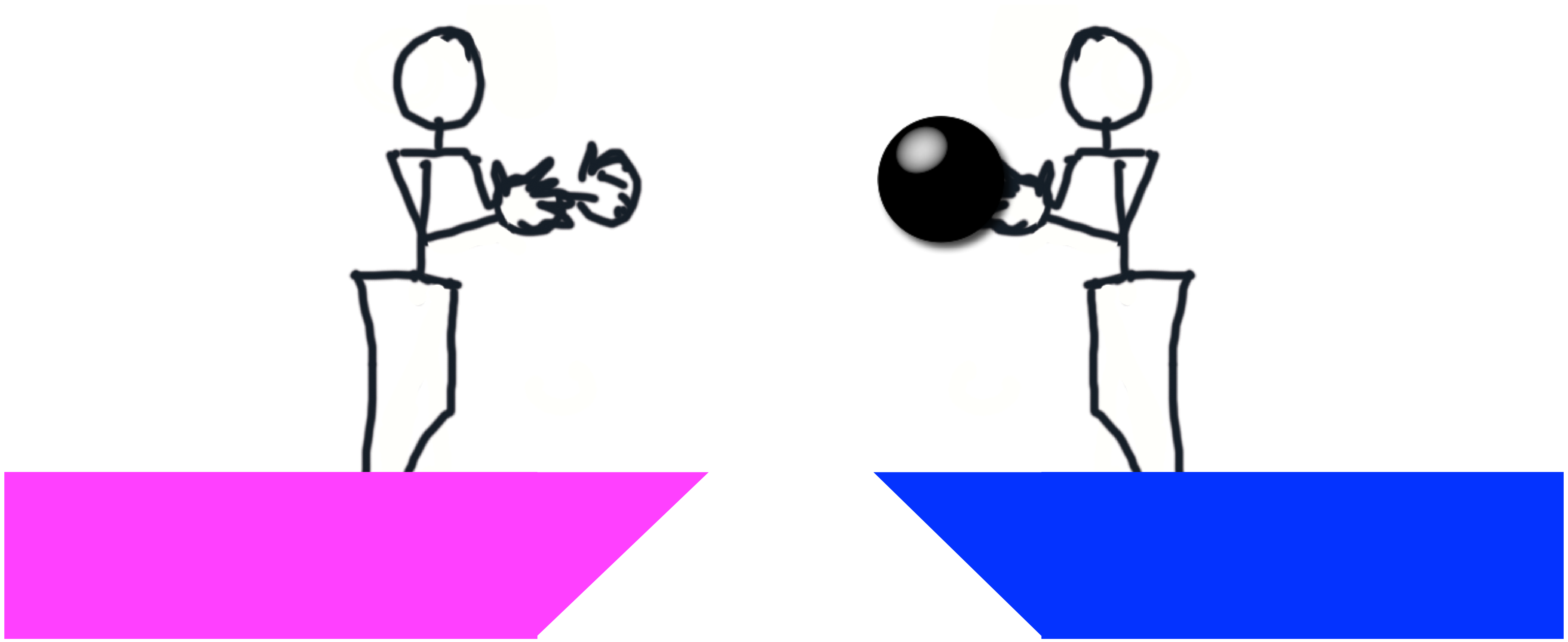
He knew that sometimes nuclei just spit out an electron.

Rutherford's beta decay



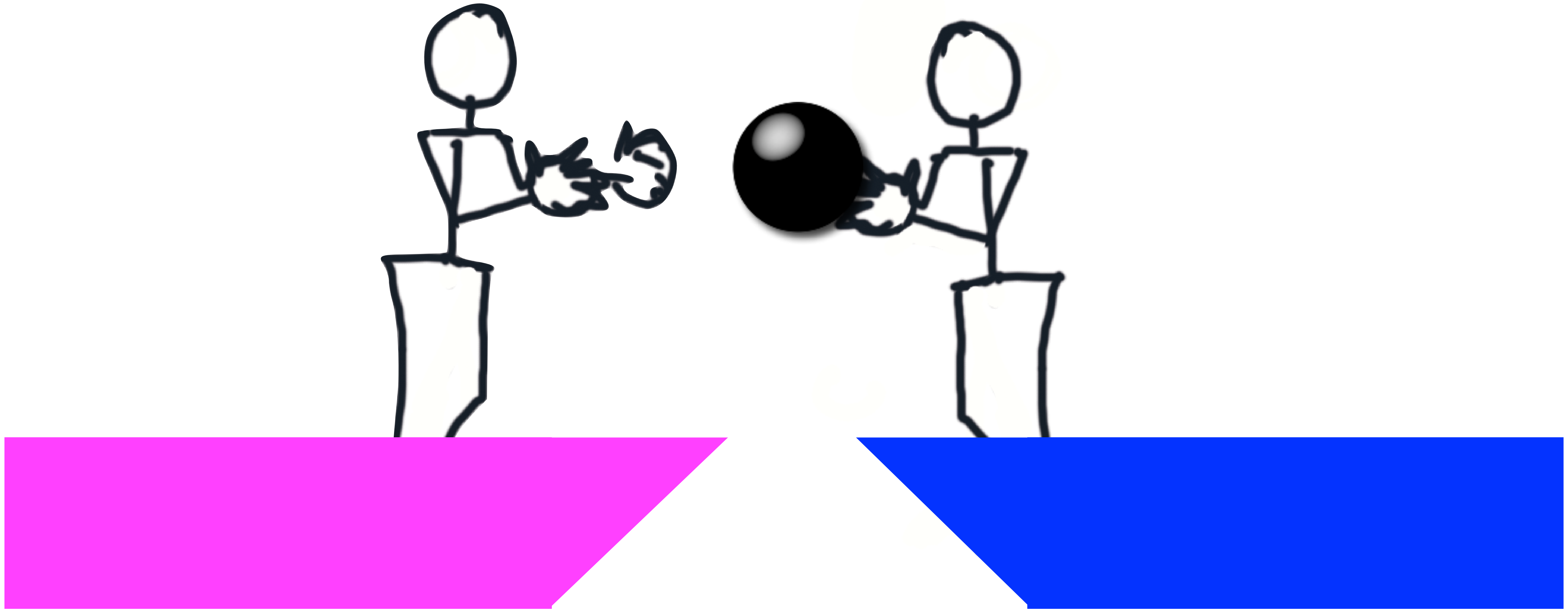
analogy: a repulsive exchange force

a repulsive exchange force



analogy: an attractive exchange force

an attractive exchange force

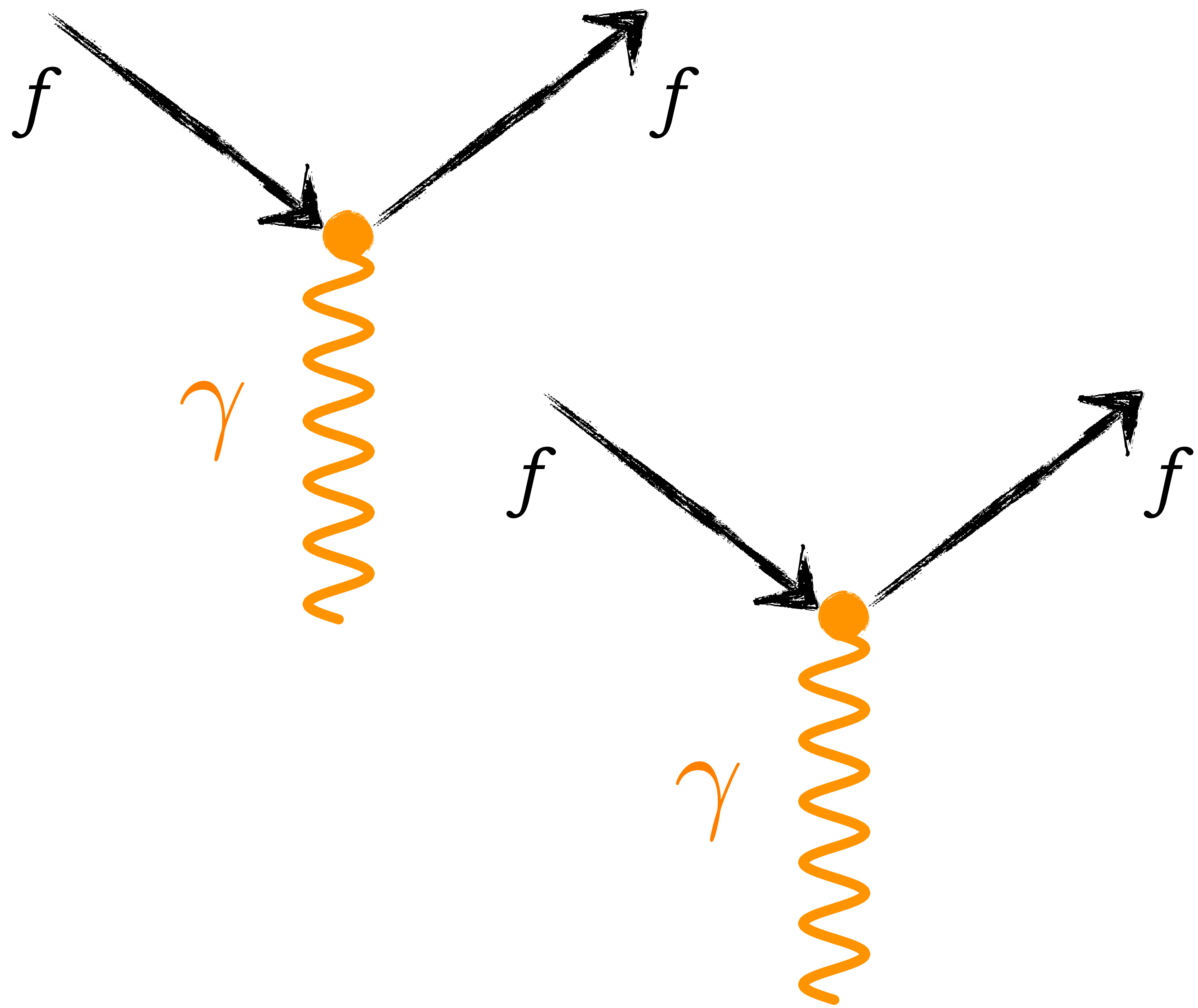


jargon alert: **exchange force**

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

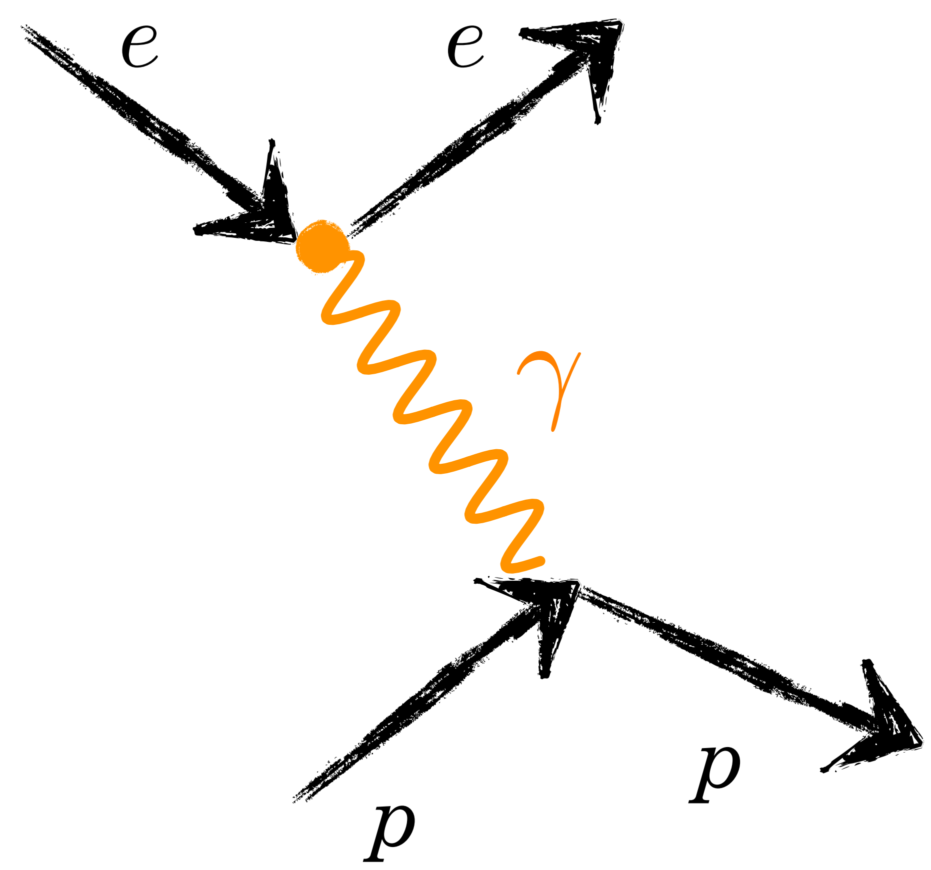
electromagnetism

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.

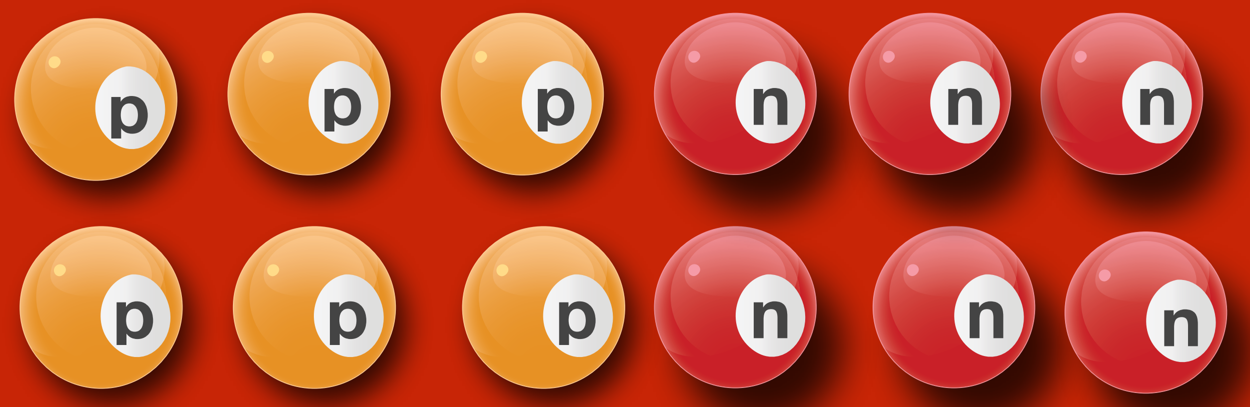
remember:

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

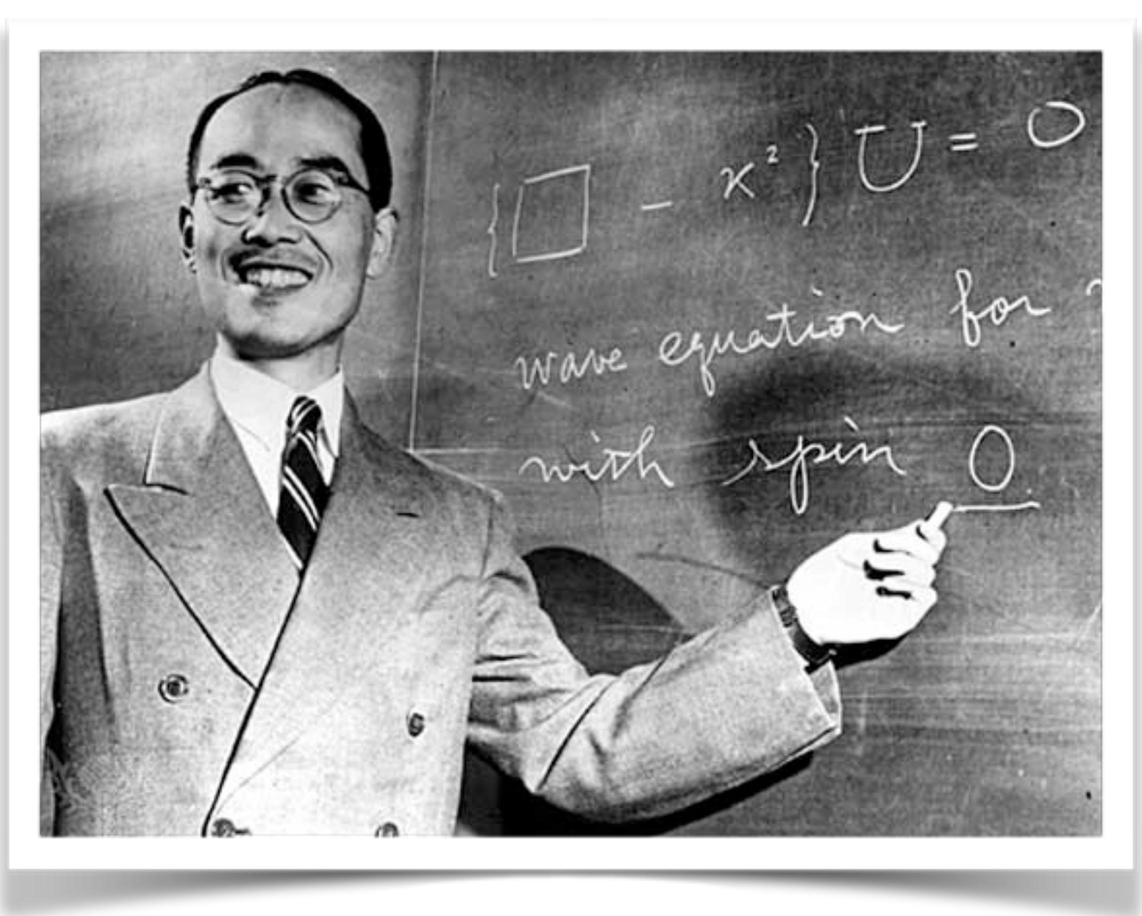
the electrostatic force of repulsion

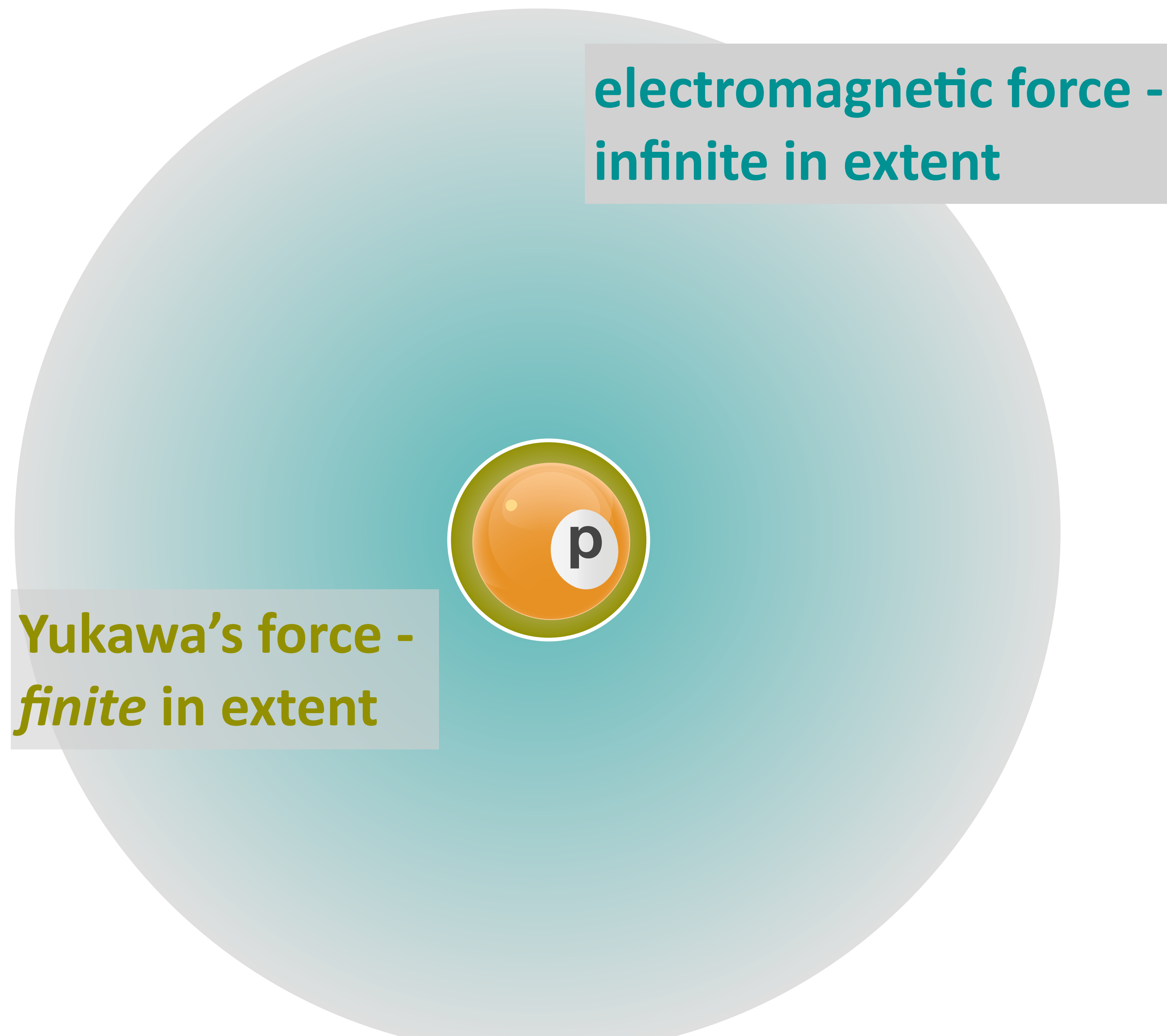
Is countered...by an even stronger force

Strong Force

1934

Hideki Yukawa

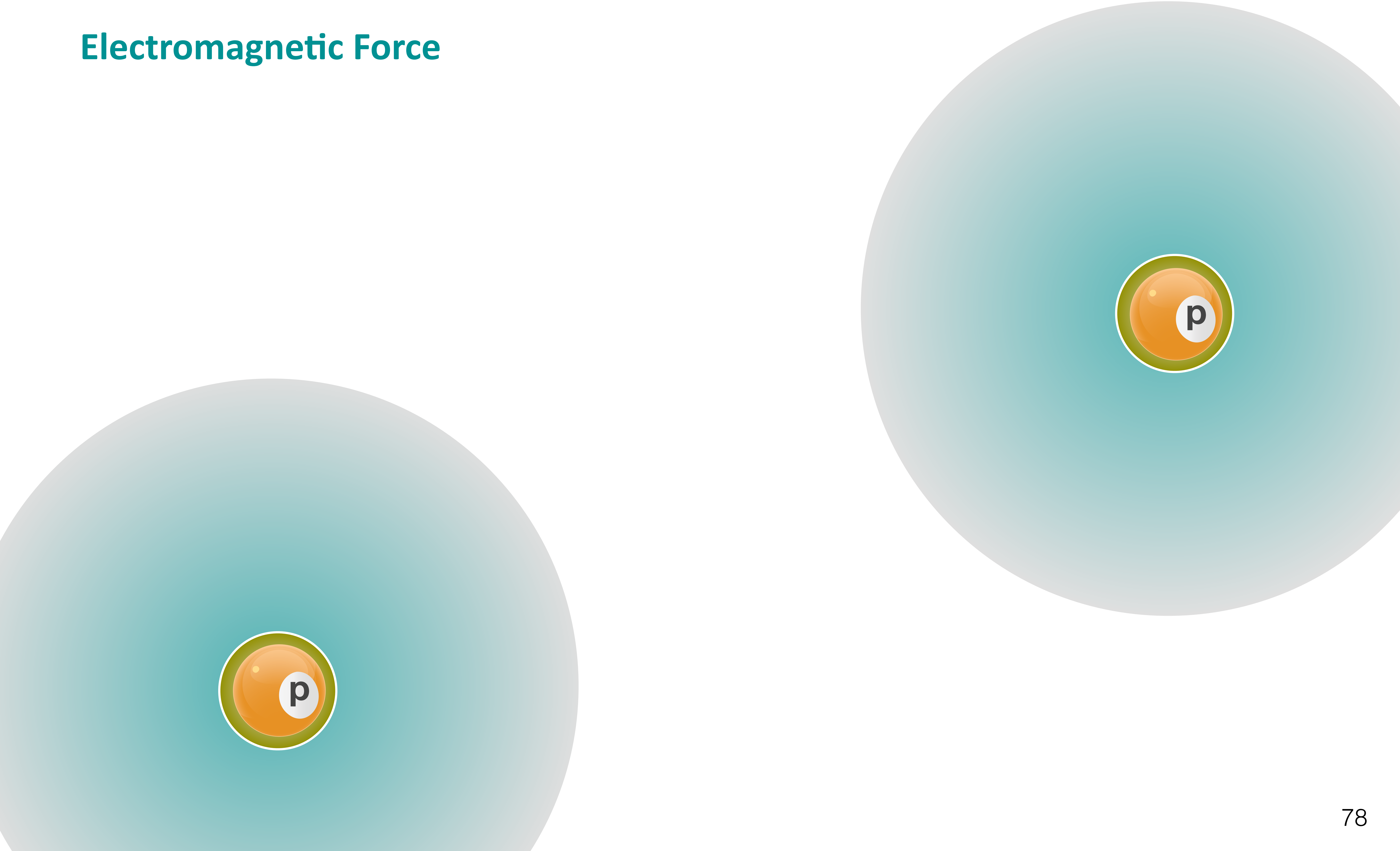




The Strong Force is a stronger than...anything in the universe.

two competing forces:

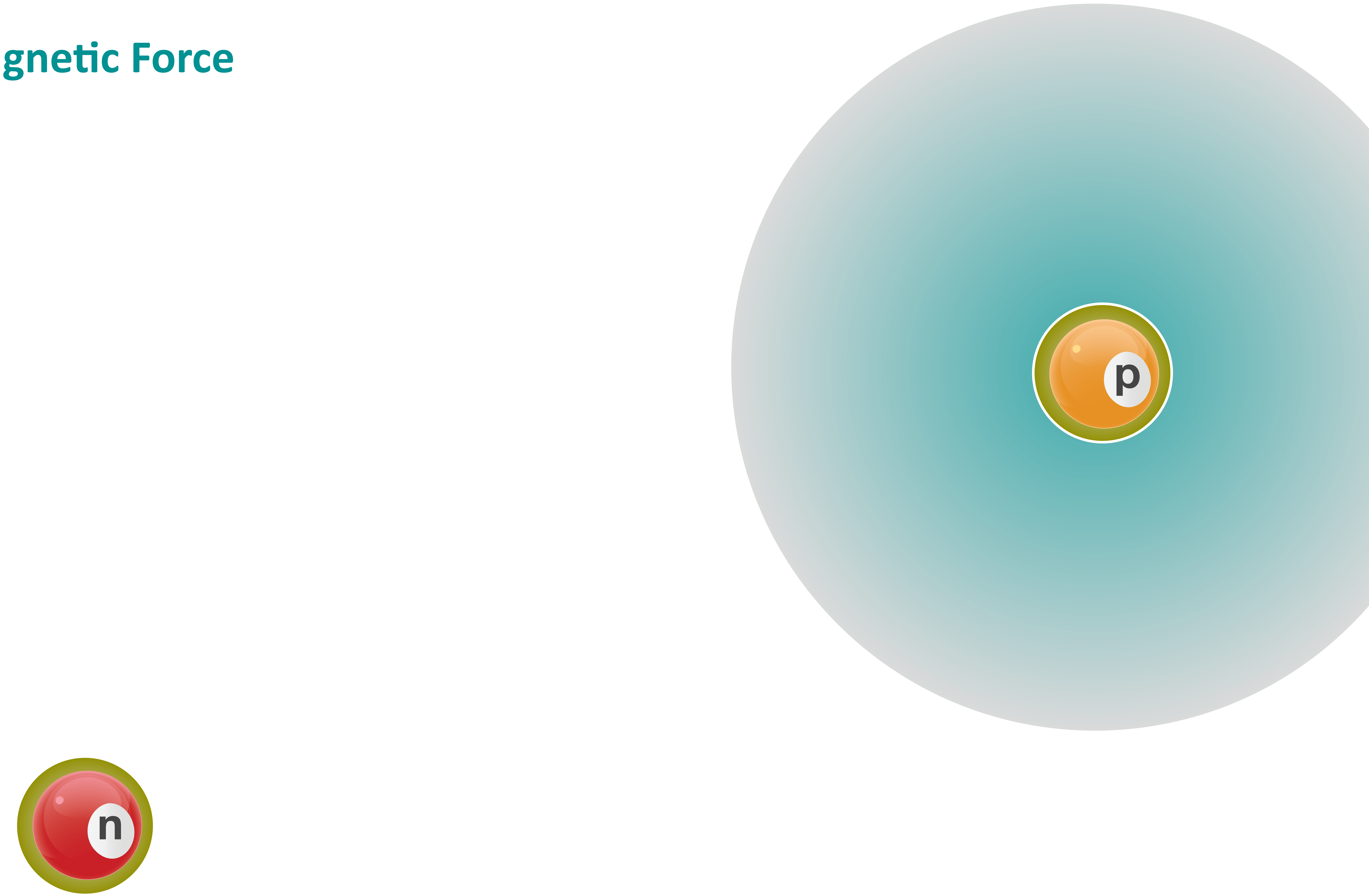
Electromagnetic Force



Strong is stronger than...anything.

two competing forces:

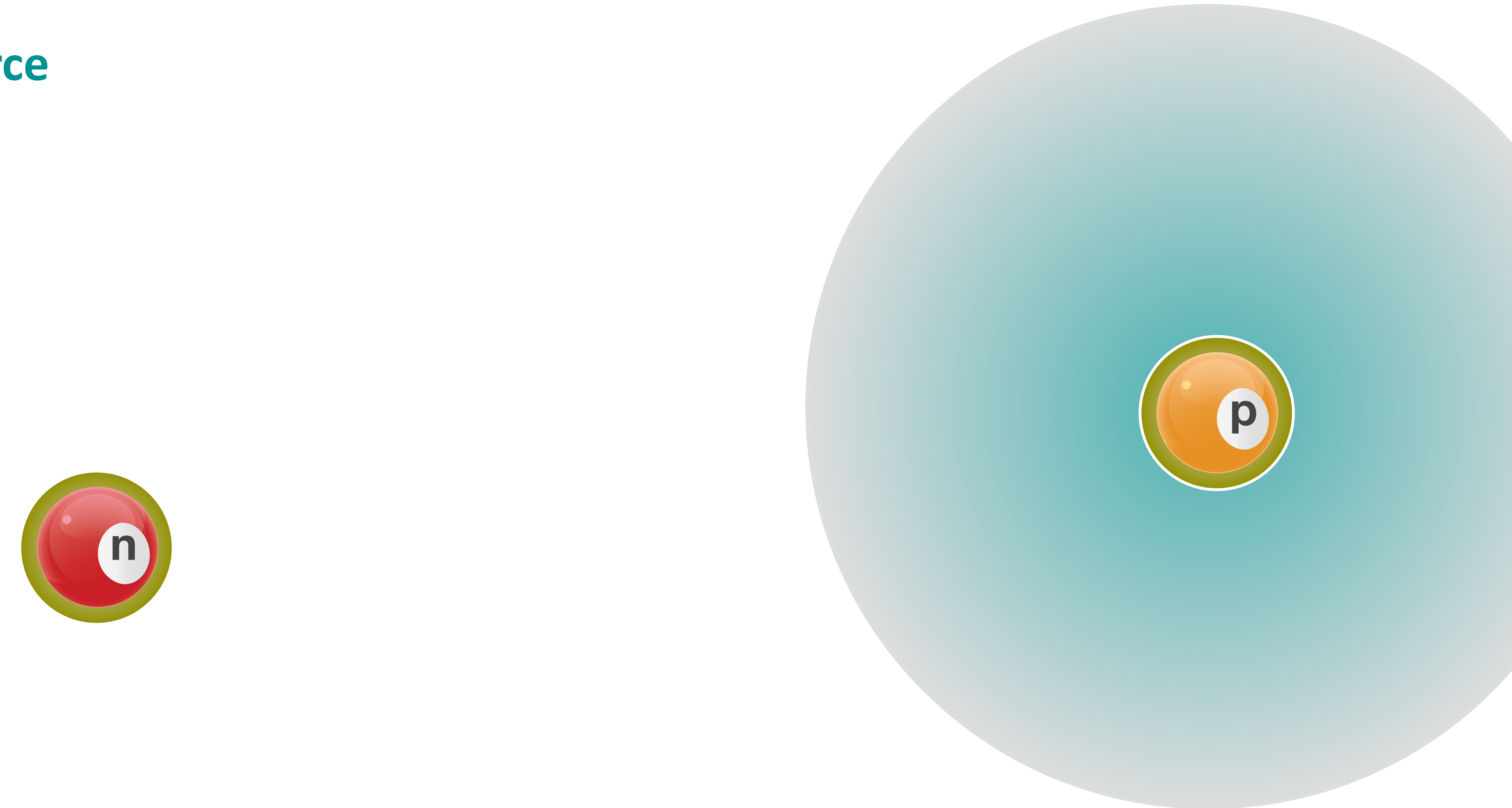
Electromagnetic Force



Strong is stronger than...anything.

two competing forces:

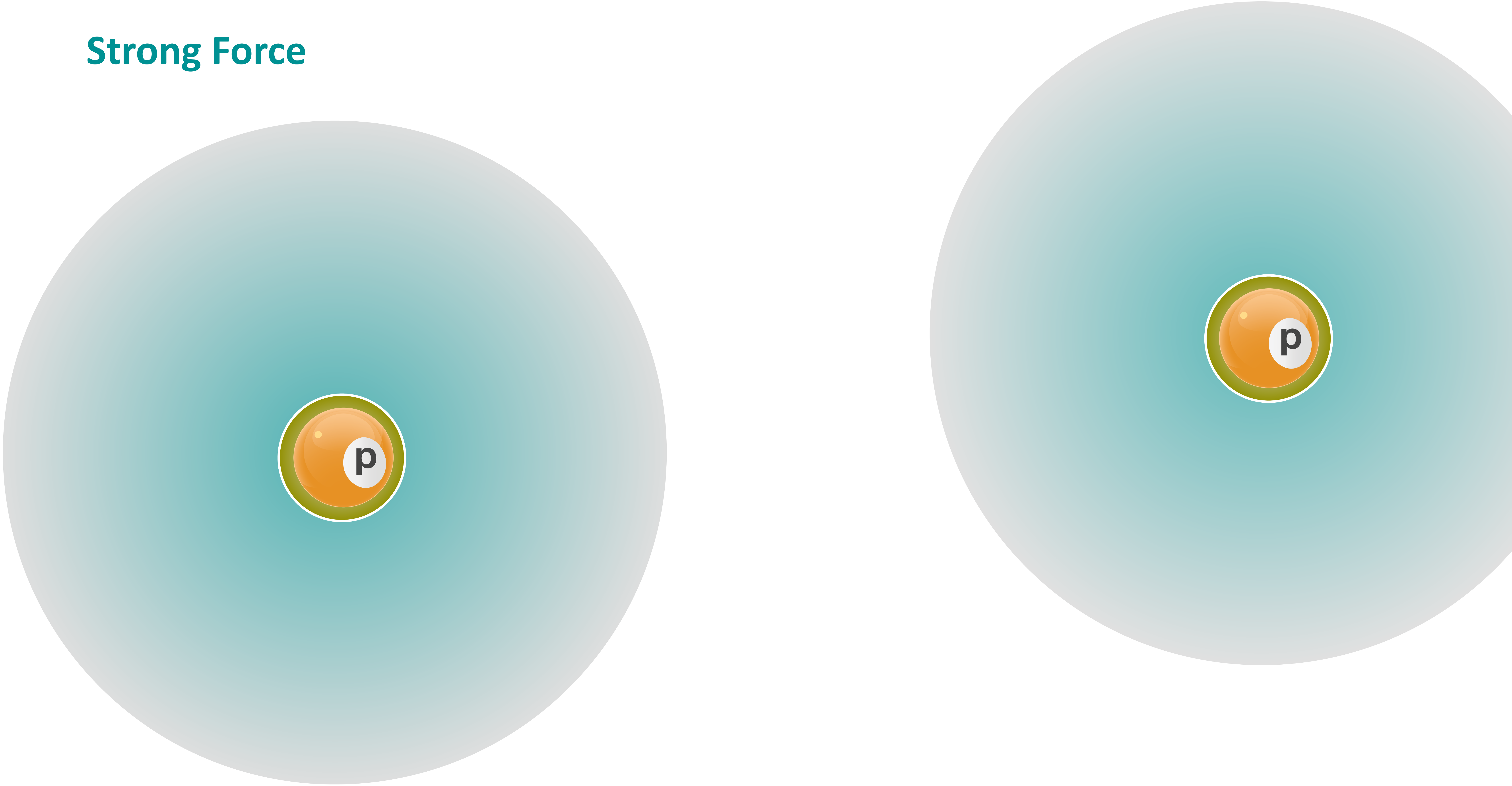
Strong Force



Strong is stronger than...anything.

two competing forces:

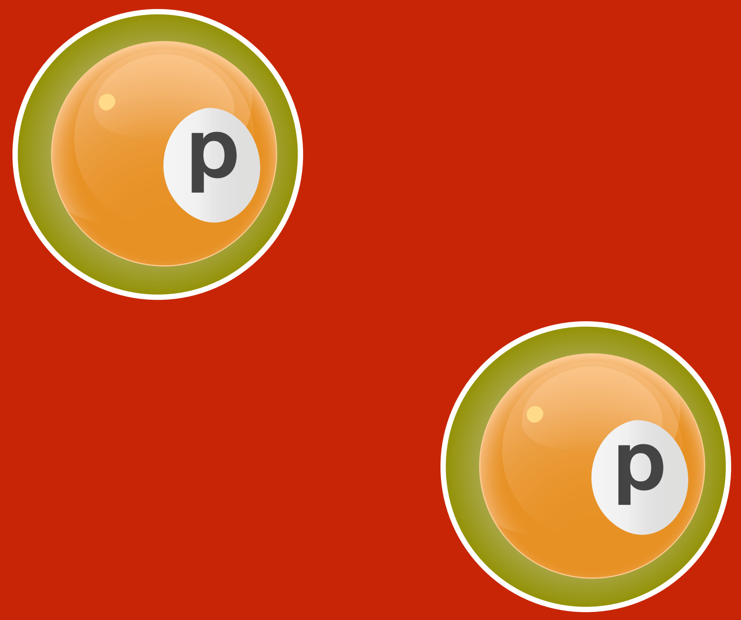
Strong Force



but only over a very short range...

the STRONG force

overwhelms the electromagnetic force



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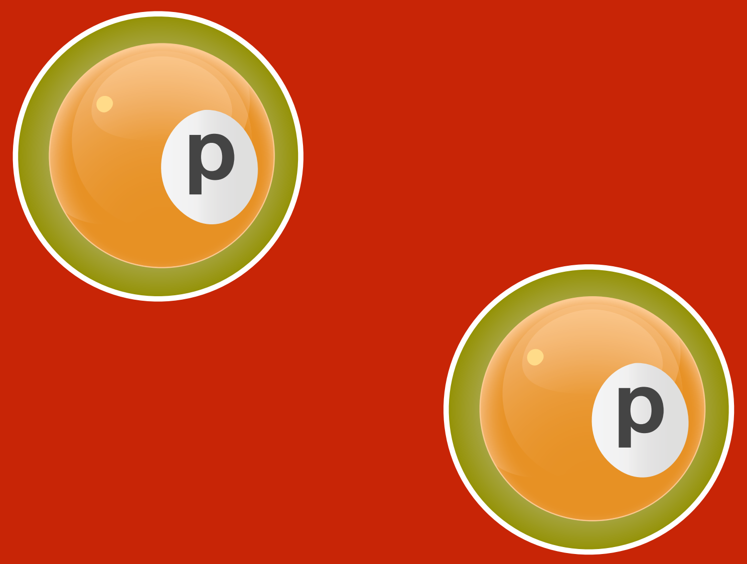
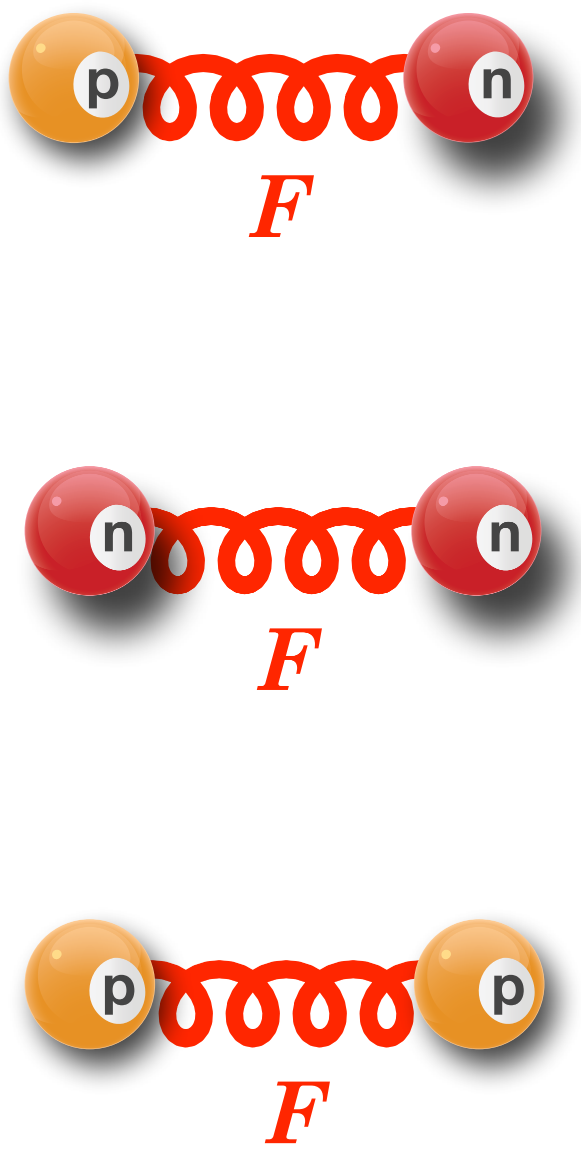


neutrons and protons

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

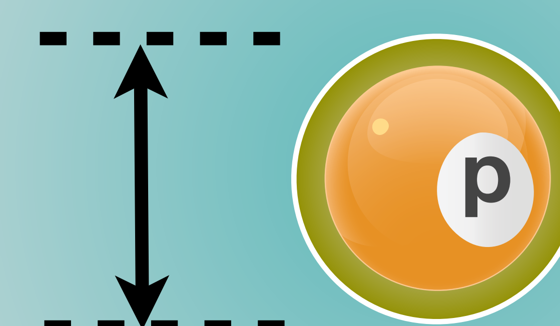
Nature is clumpy

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.

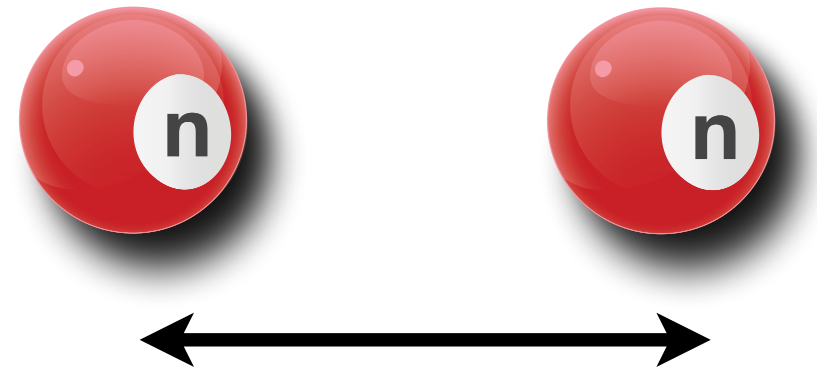
uncertainty certainly to the rescue

brilliant observation by Yukawa

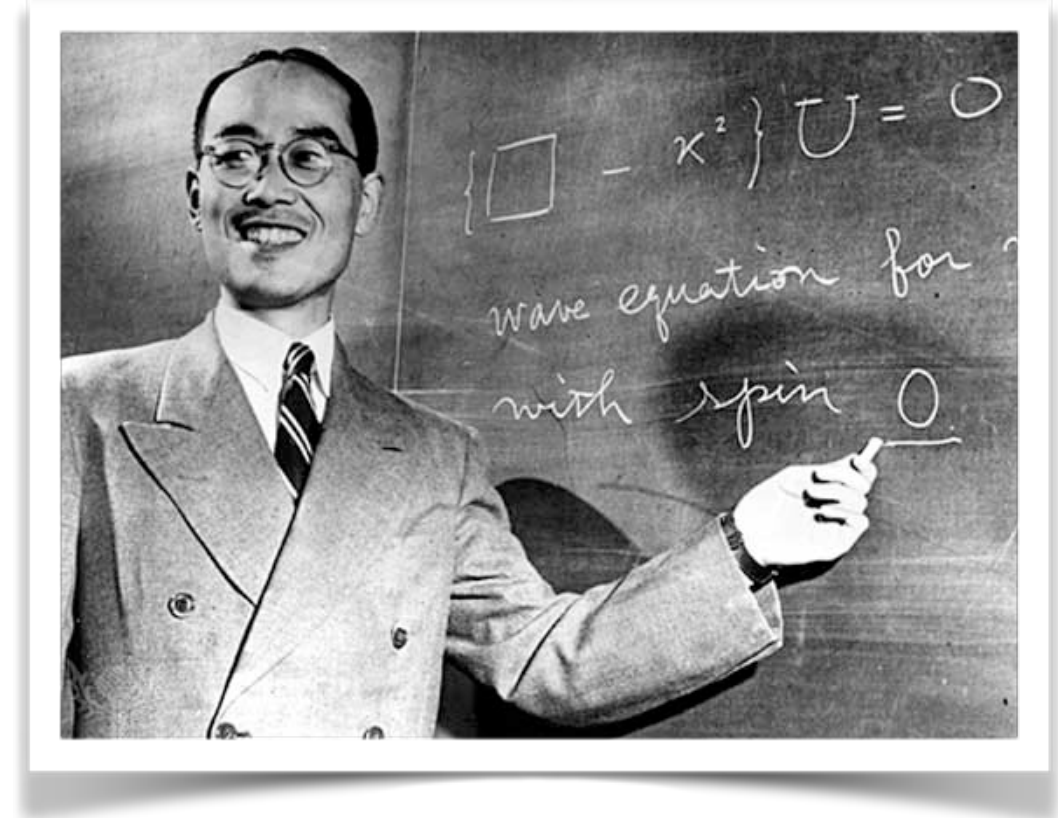
maybe there's a quantum that is active only over the size of a nucleus: "U"

another exchange force/particle?

So: $p \to n + U$?



$$\Delta x = 10^{-15}\ \mathrm{m}$$



Suppose U travels at c within a nucleus... $\Delta t = \Delta x / c$

Then Uncertainty could estimate U's mass... $\Delta E \Delta t = h/4\pi$

$$m_U = \Delta E / c^2$$

$$m_U \overset{?}{\approx} 100 \times 10^6 eV = 100 MeV$$

the most important thing in particle physics?

getting the name right.

the “U-kon”? thankfully, no.

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

medium mass…

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

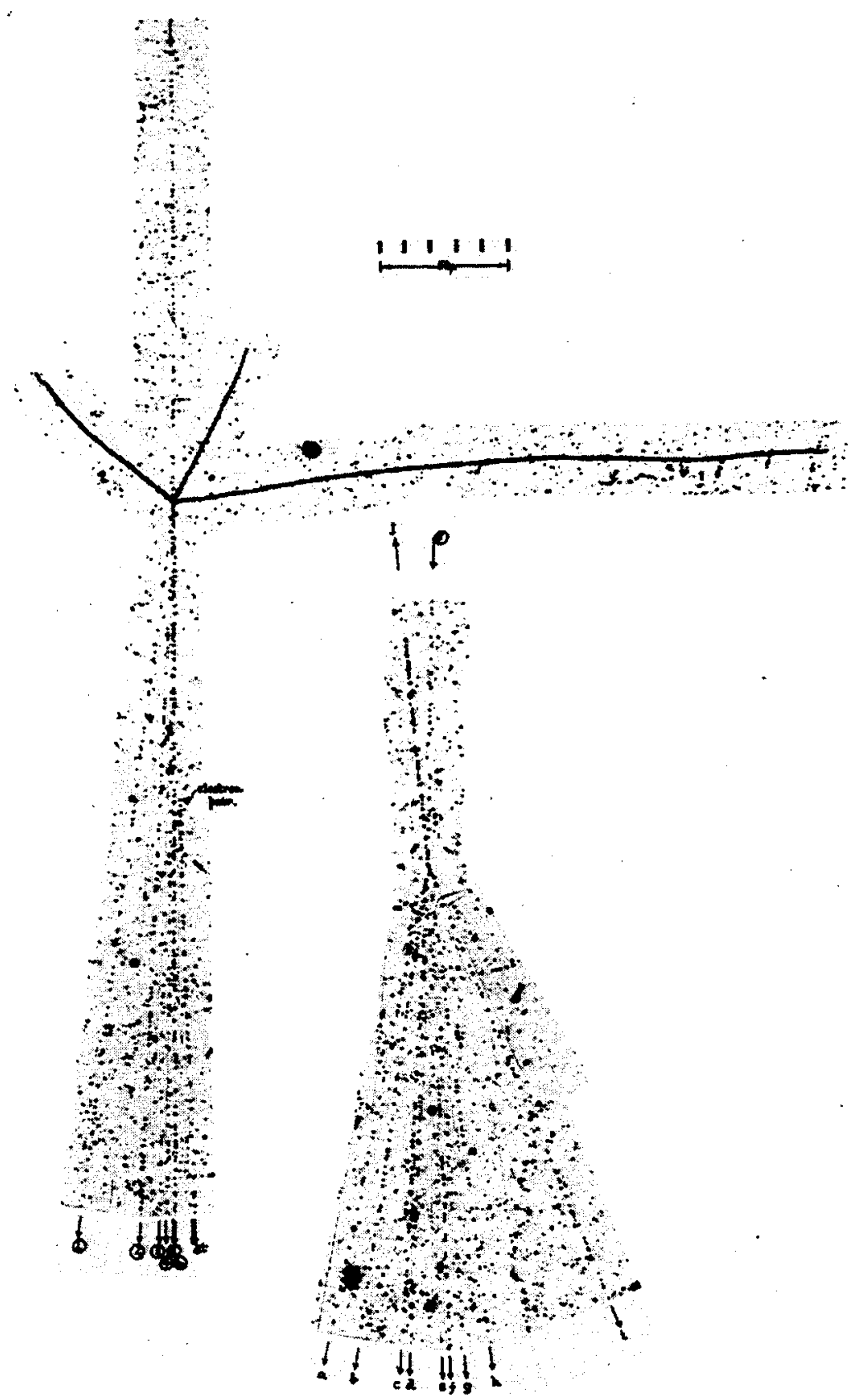
the hunt was on

to find the Yukawa Particle

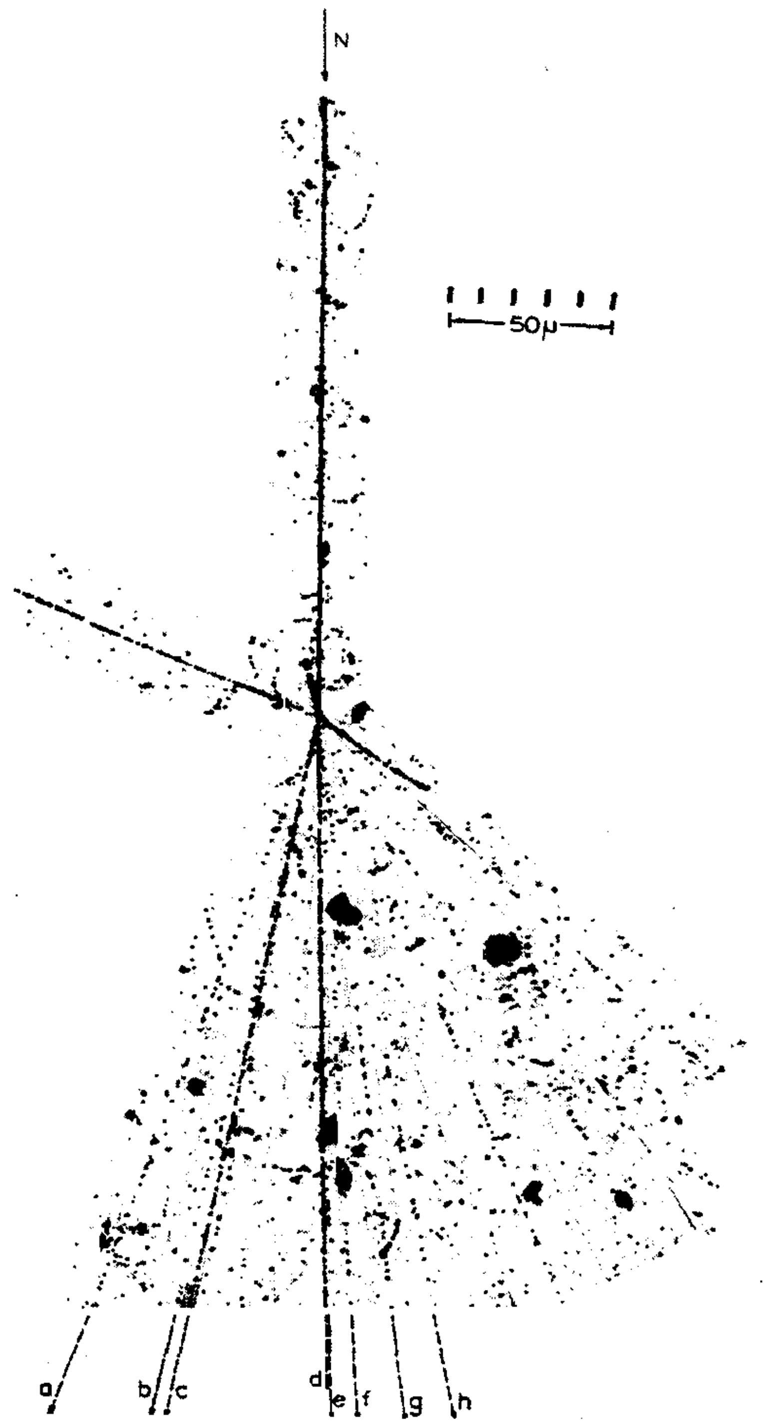
but WWII got in the way

Post-war emulsion exposures were startling

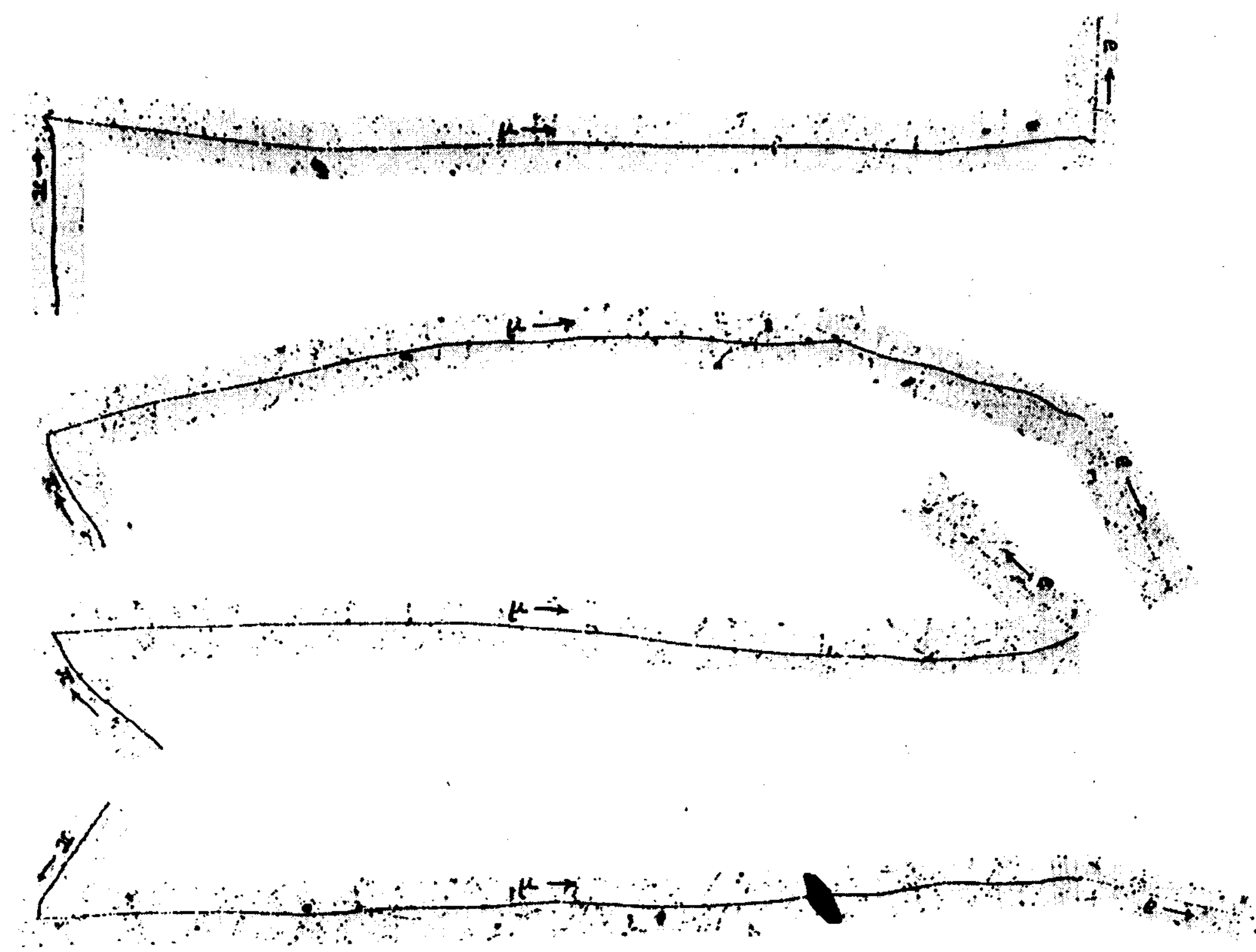
proton in cosmic rays



Nitrogen nucleus in cosmic rays



huh?

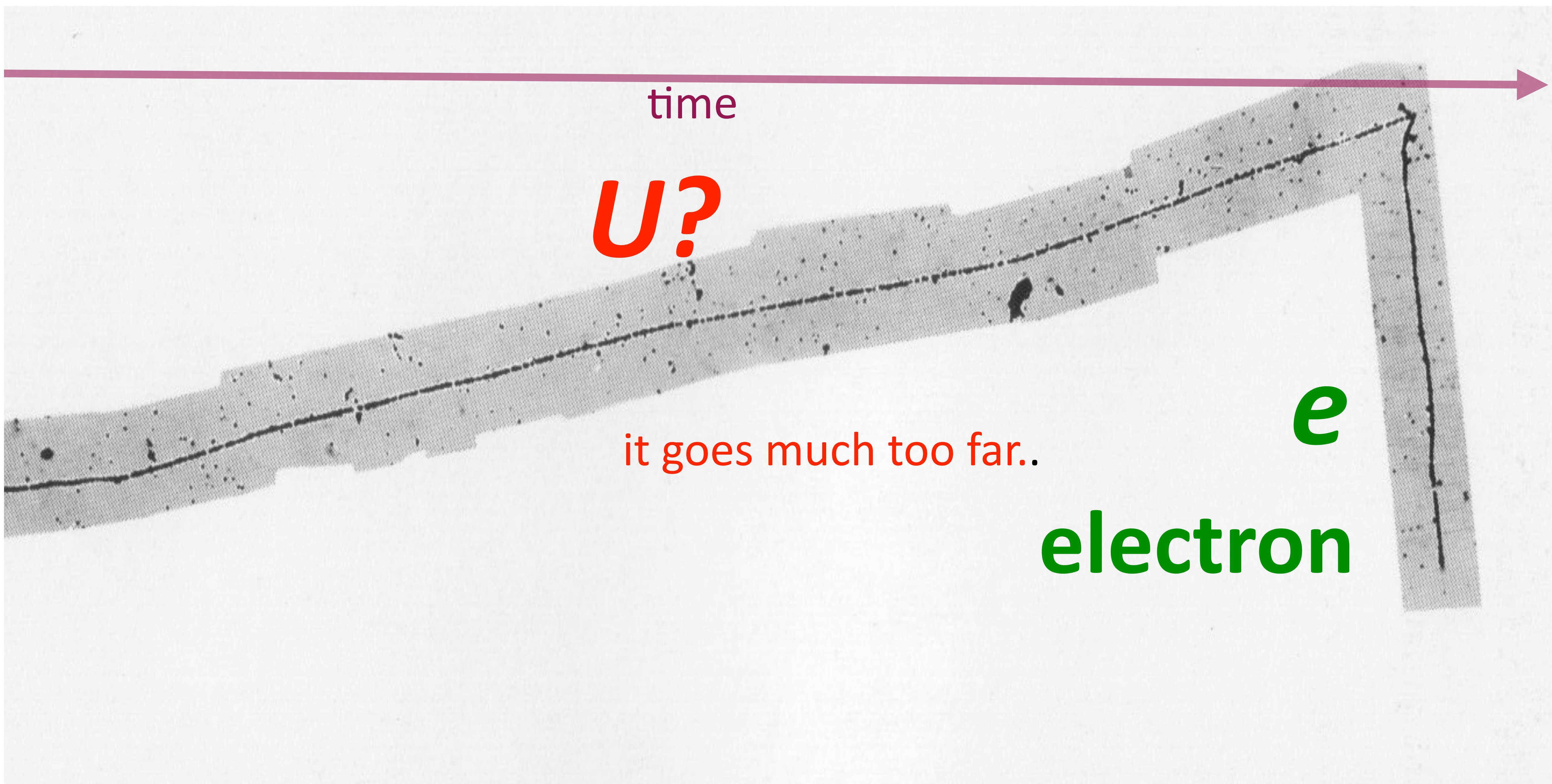


from Cecil Powell's Nobel lecture... a former student of? ...you guessed it.

many of these sort:

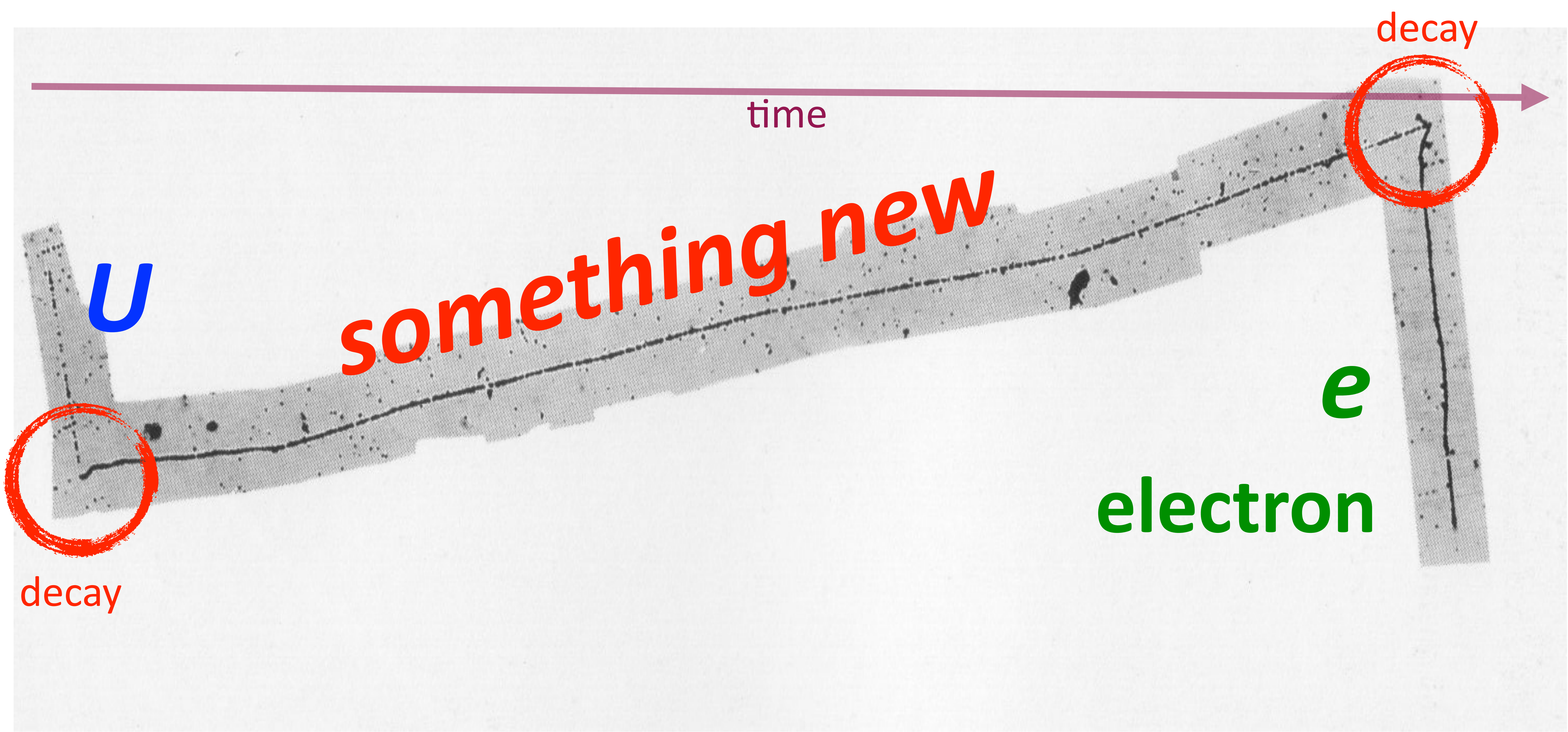
something unknown...

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

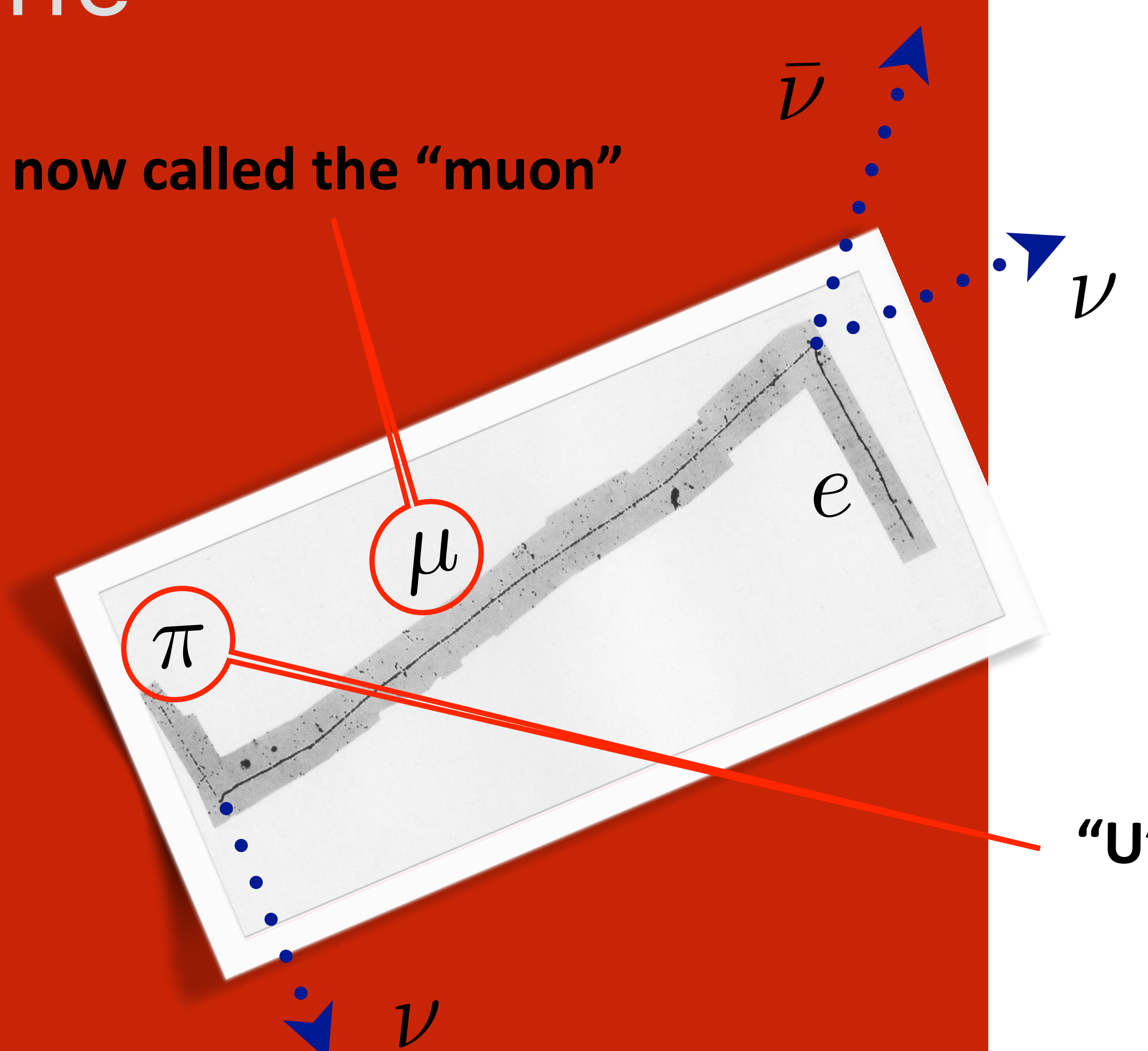
This took some unraveling.

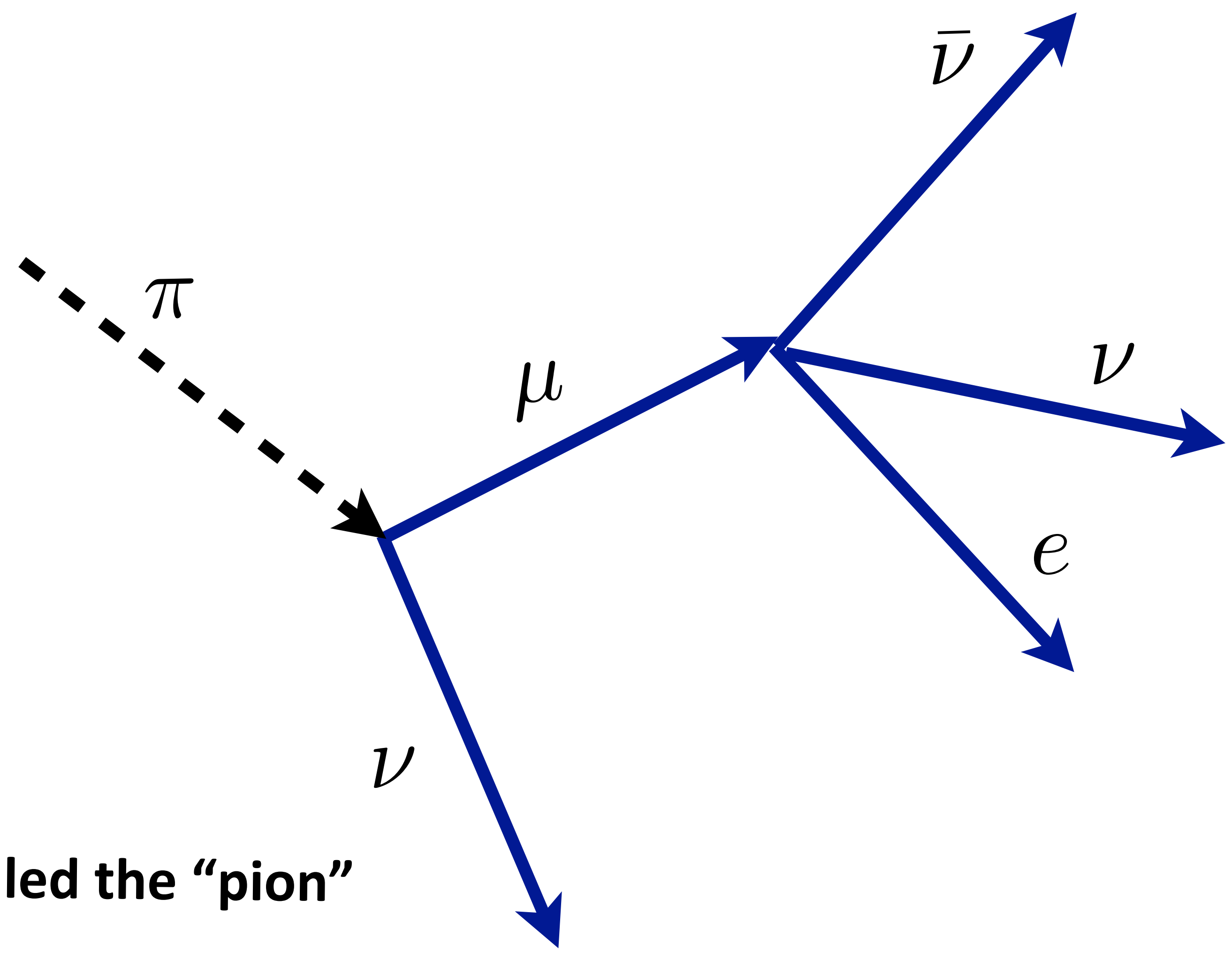
The “meson” appeared in and initiated nuclear collisions

The unknown particle seemed to live about a 6 μsec

too long to be a meson

The winning proposal:



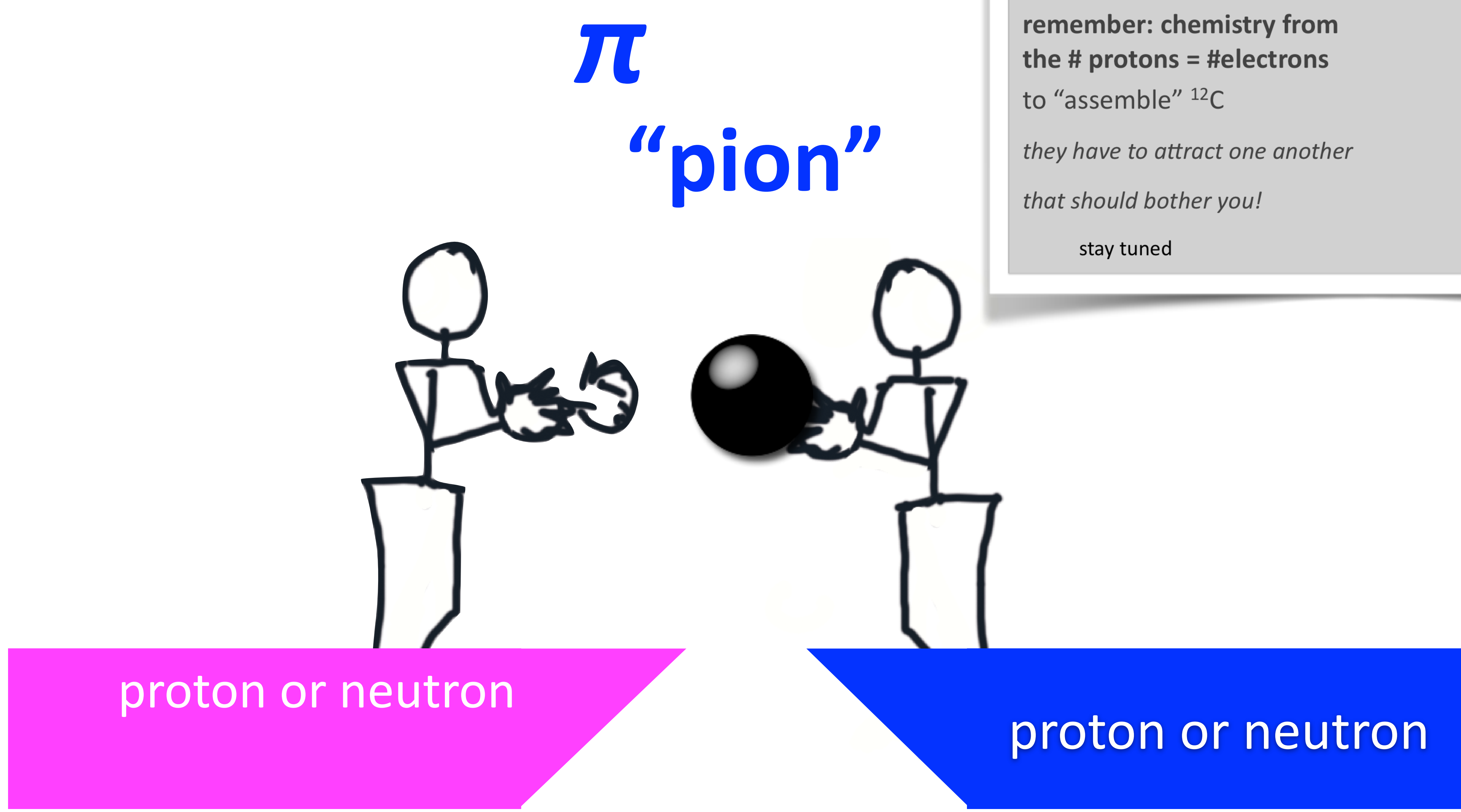


particle: **pion**

symbol:	π
charge:	+, –, 0
mass:	139 MeV/c²,
spin:	0
category:	Boson, hadron, meson

analogy:

an attractive exchange force



remember: chemistry from
the # protons = #electrons

to "assemble" ^{12}C

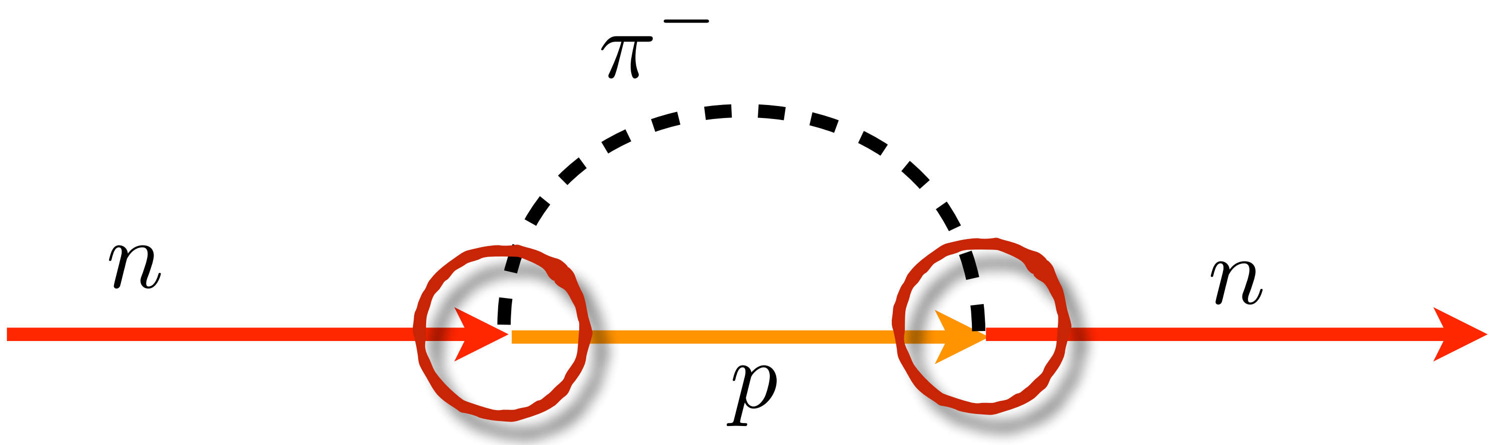
they have to attract one another

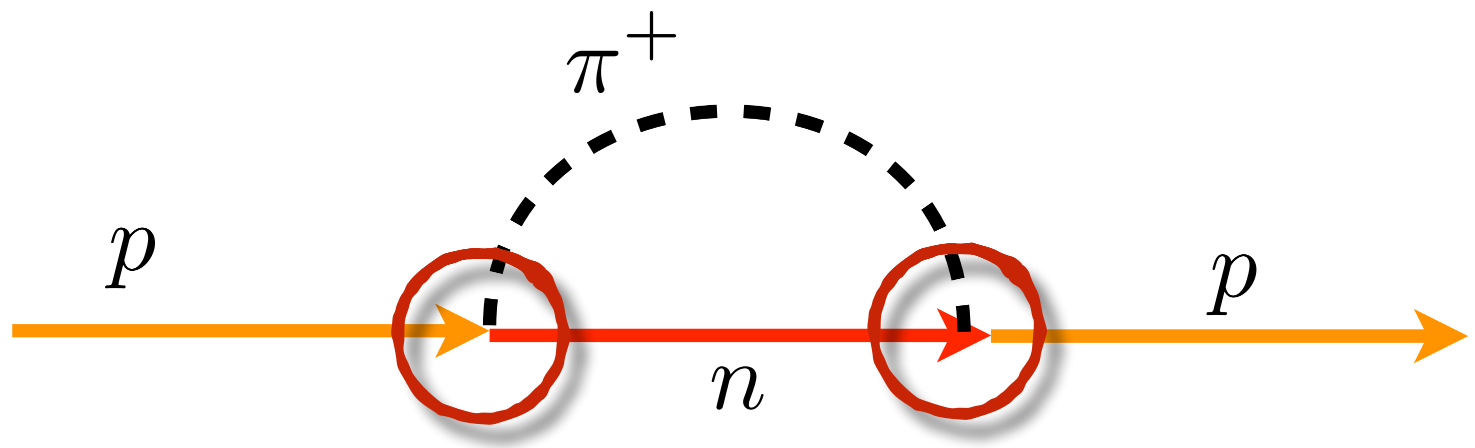
that should bother you!

stay tuned

the Yukawa particle

is the pion



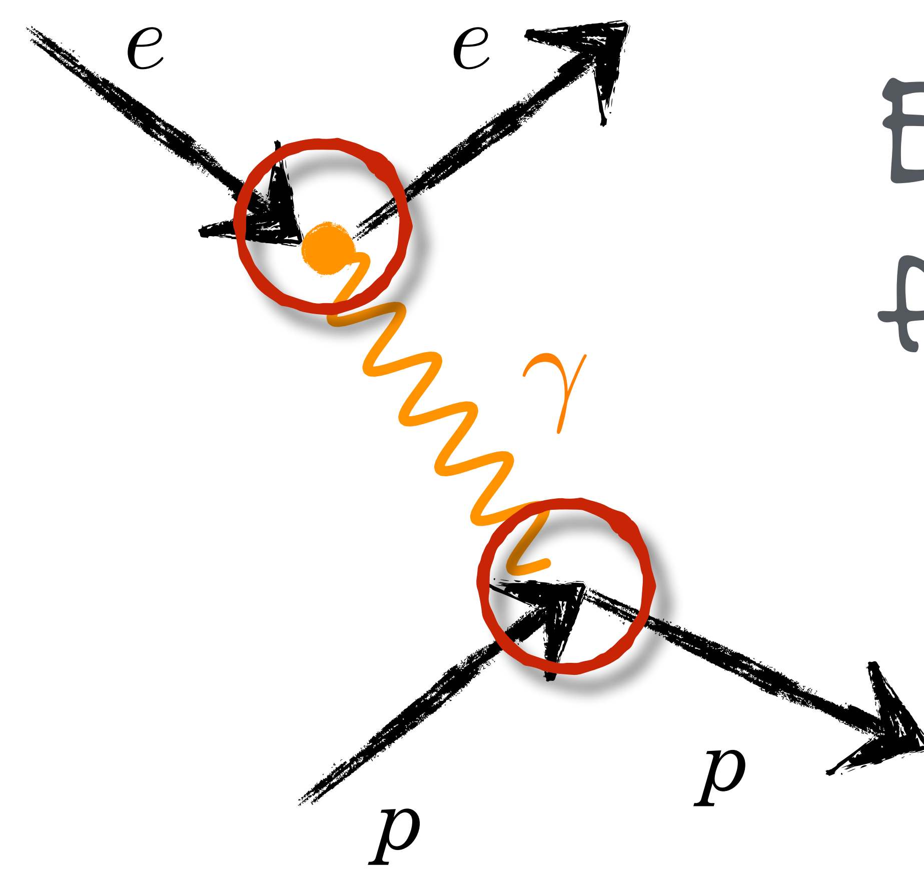


These coupling strengths are large - strong.

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

three forces now

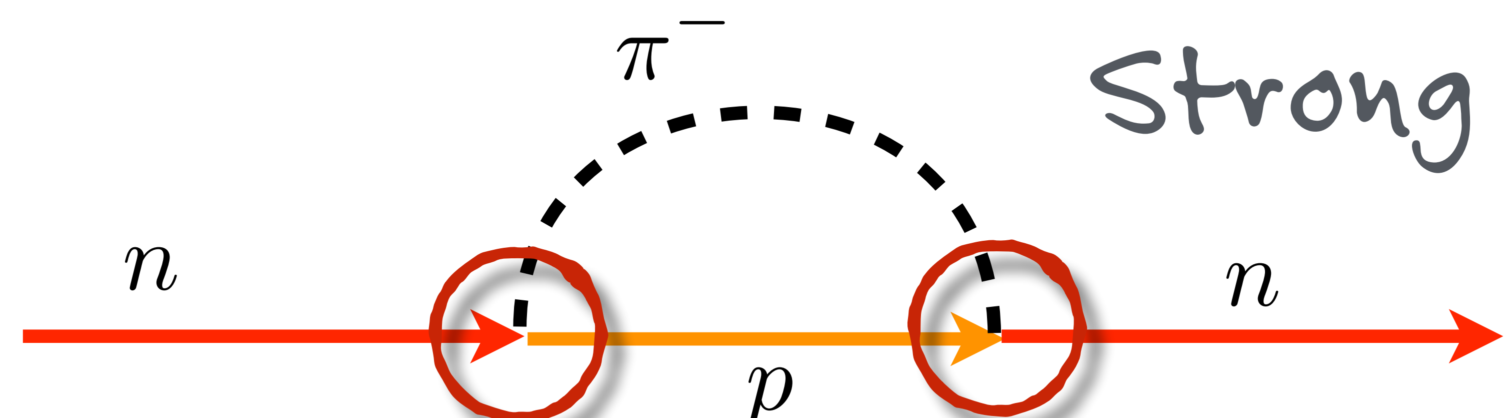
of vastly different strengths



Electromagnetic force 0.007

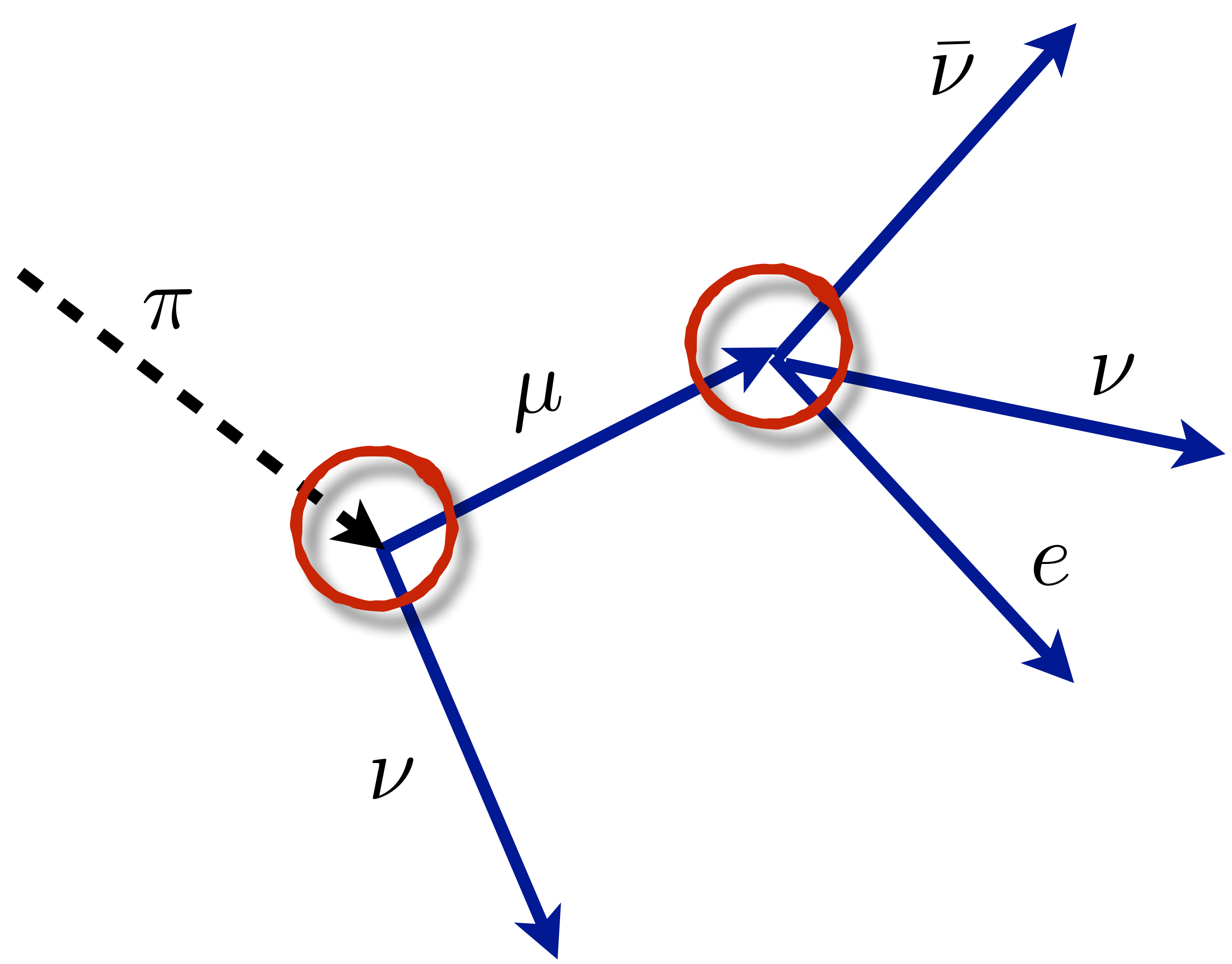
Gravitational force?

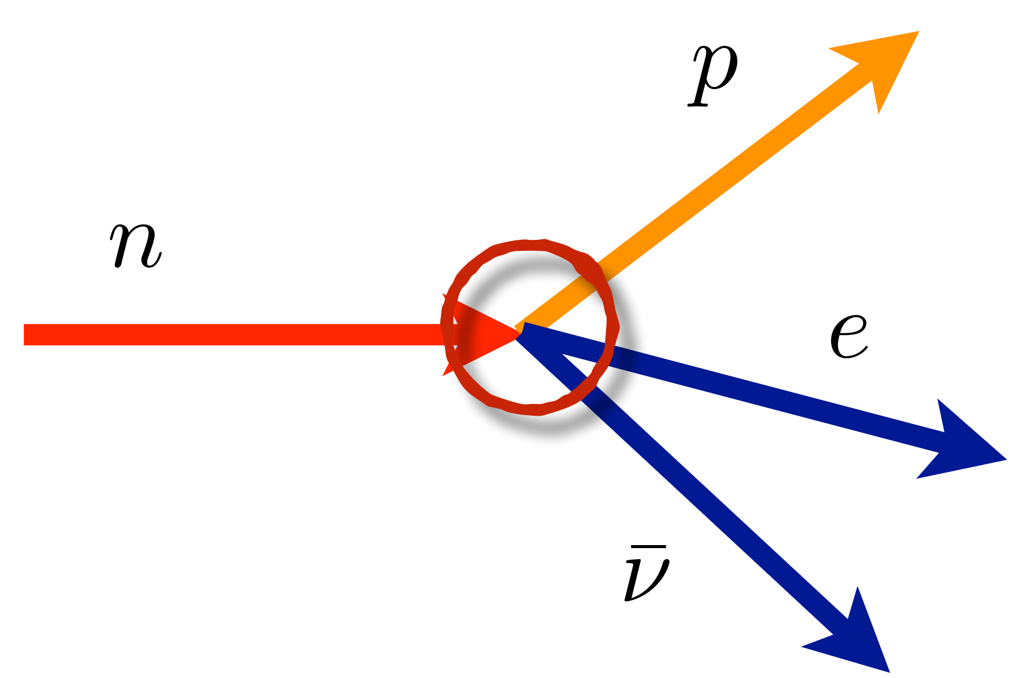
0.0000000000000000
00000000000000001



Strong force 15

Weak force 0.000001





particle:

muon

symbol: μ

charge: +, –

mass: 105.7 MeV/c^2

spin: 1/2

category: Fermion, lepton

particle: **muon**

symbol:

charge:

mass:

spin:

category: Fermion, lepton

The Muo… like an Elec… vier.

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.

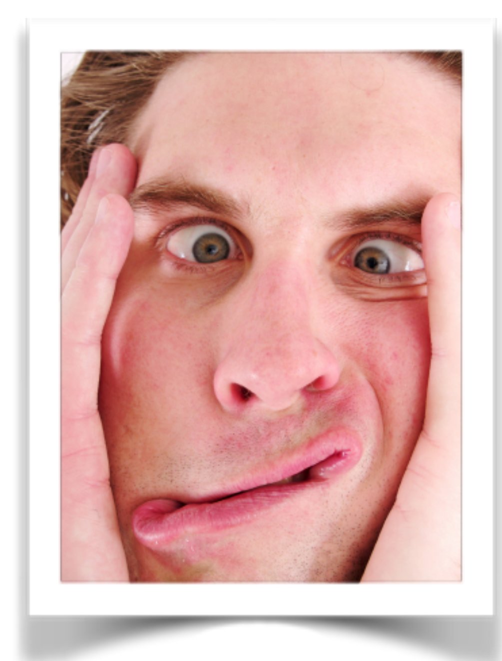
$$\begin{array}{cc} \mathbf{Q} & \\ \begin{array}{c} 0 \\ -1 \end{array} & \begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \end{array}$$

Identical in every way...except mass

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

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

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



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 and 1950s

when all hell broke loose

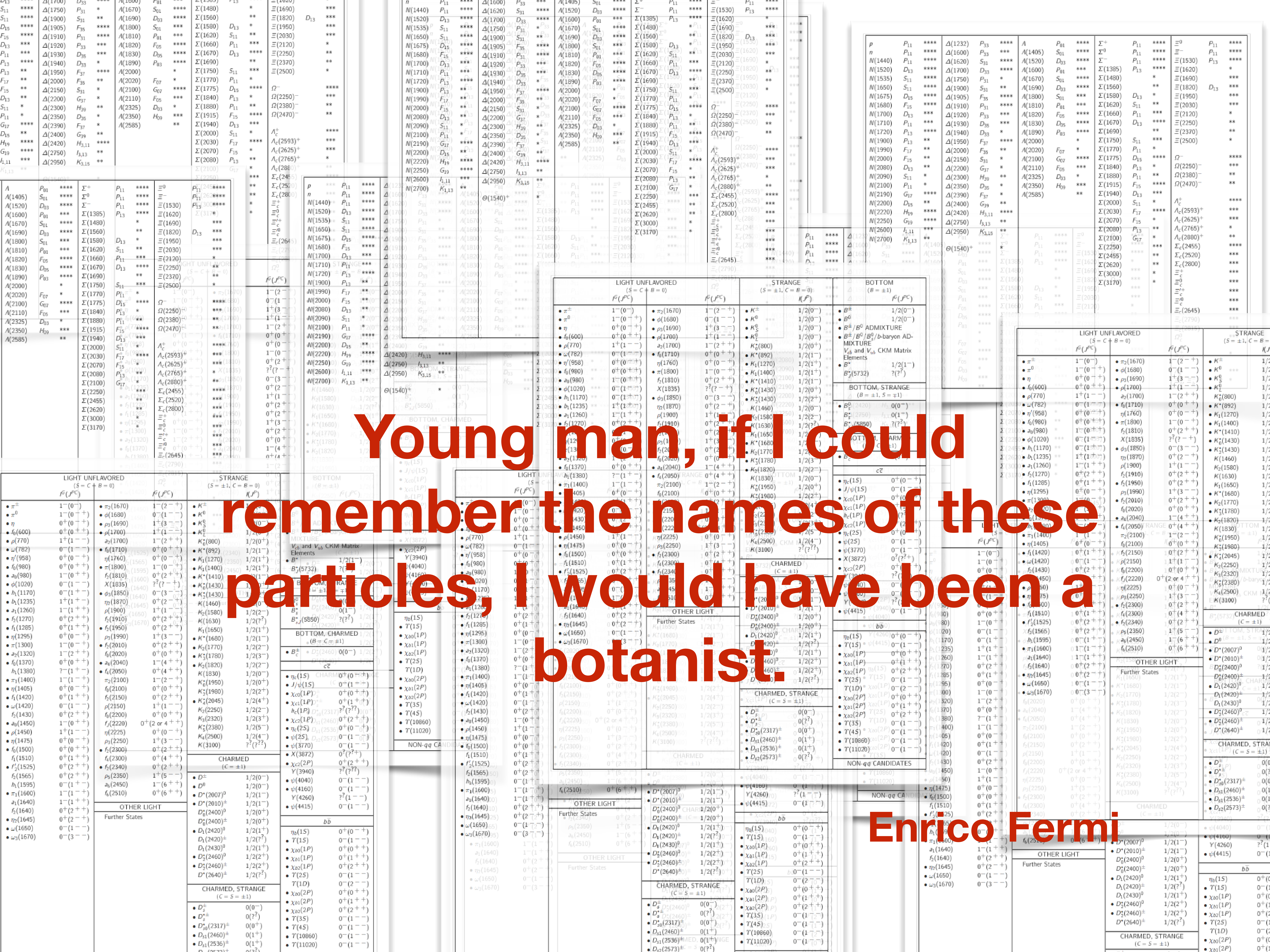
particle:

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

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



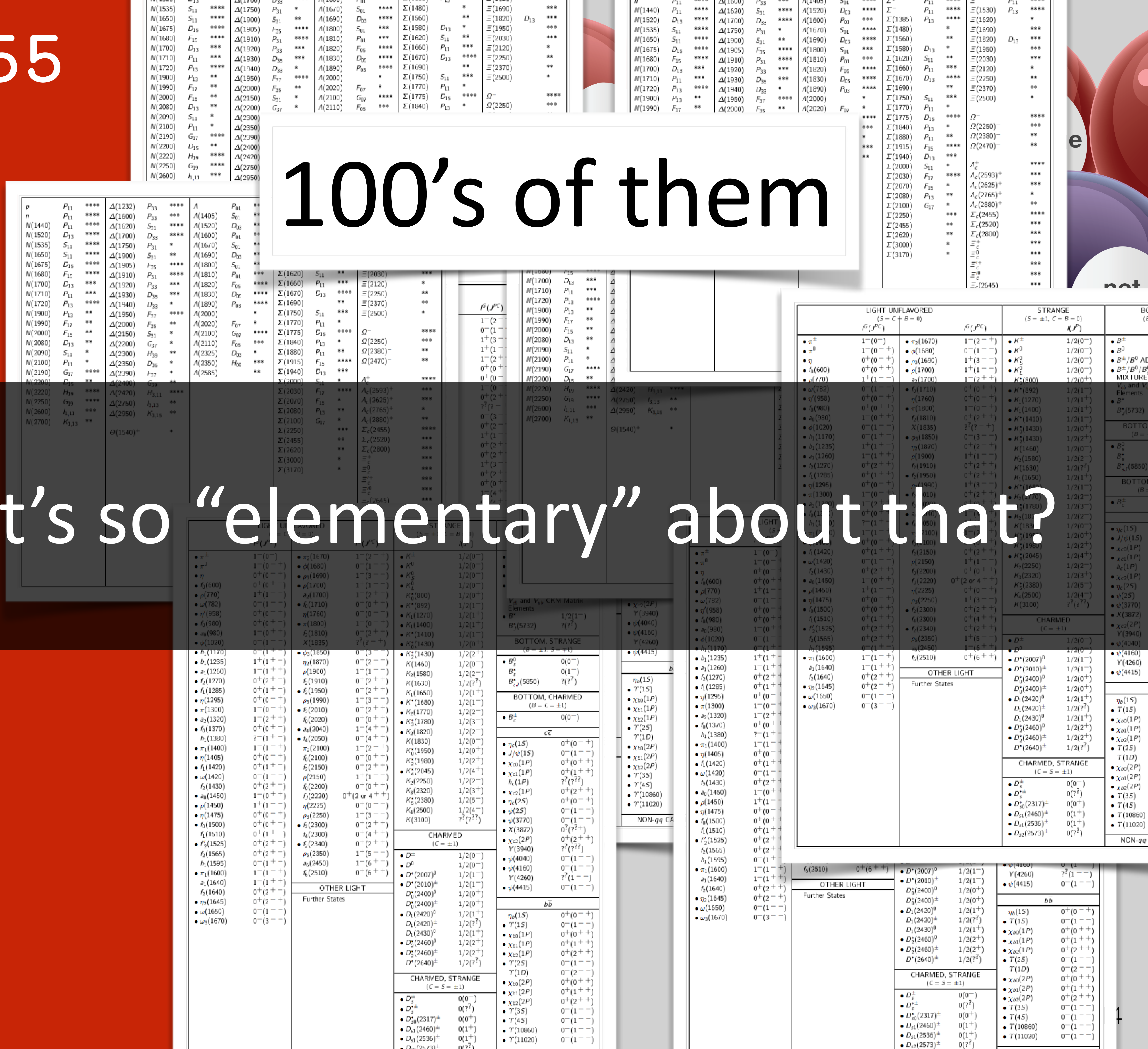
Young man, if I could remember the names of these particles, I would have been a botanist.

Enrico Fermi

By the mid-1950’s

things are officially out of control.

by 1955

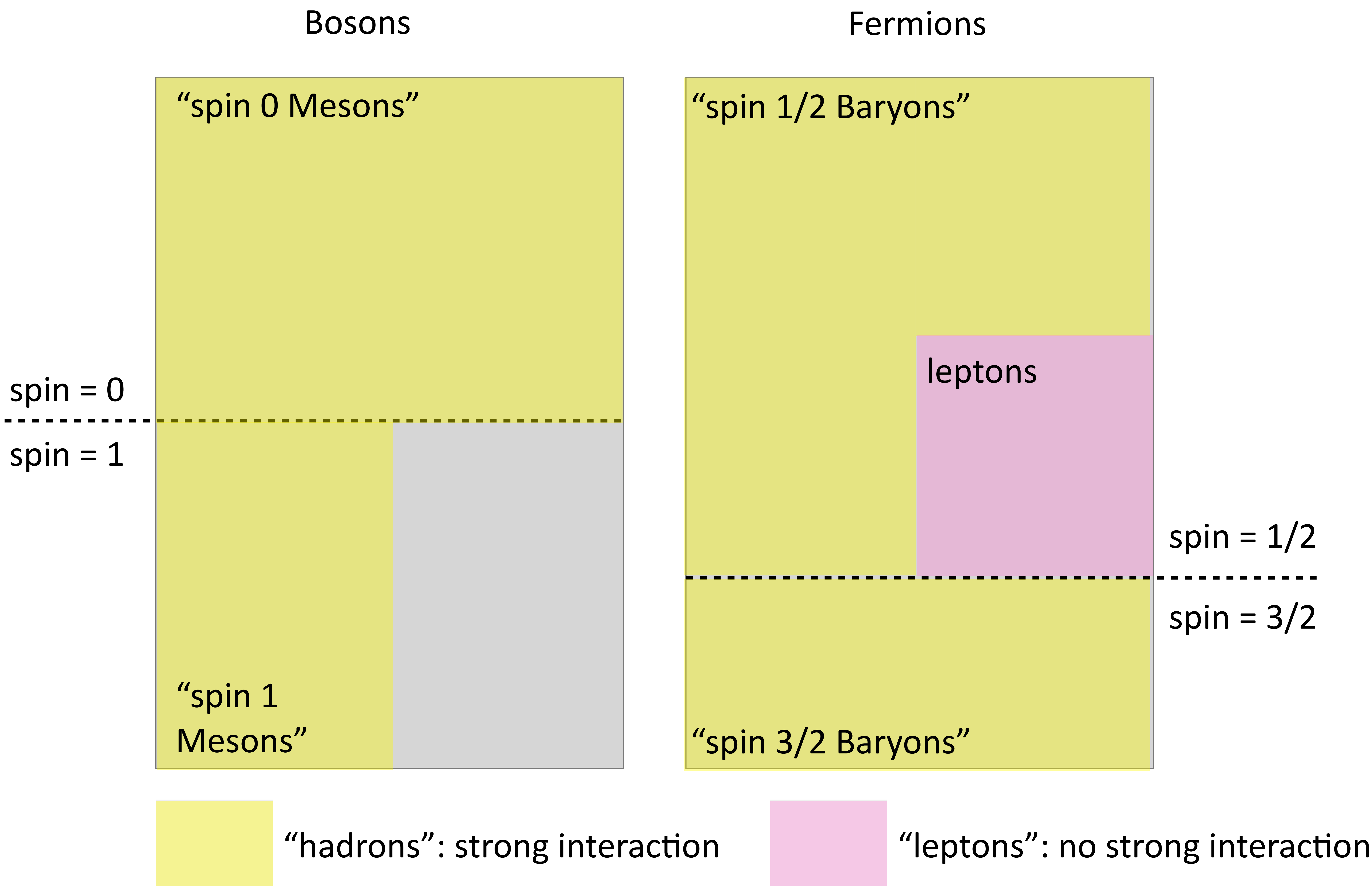


100’s of them

a mess

what’s so “elementary” about that?

The Particle Zoo?



there were clues

patterns and organizing features

began to emerge in the pile of data

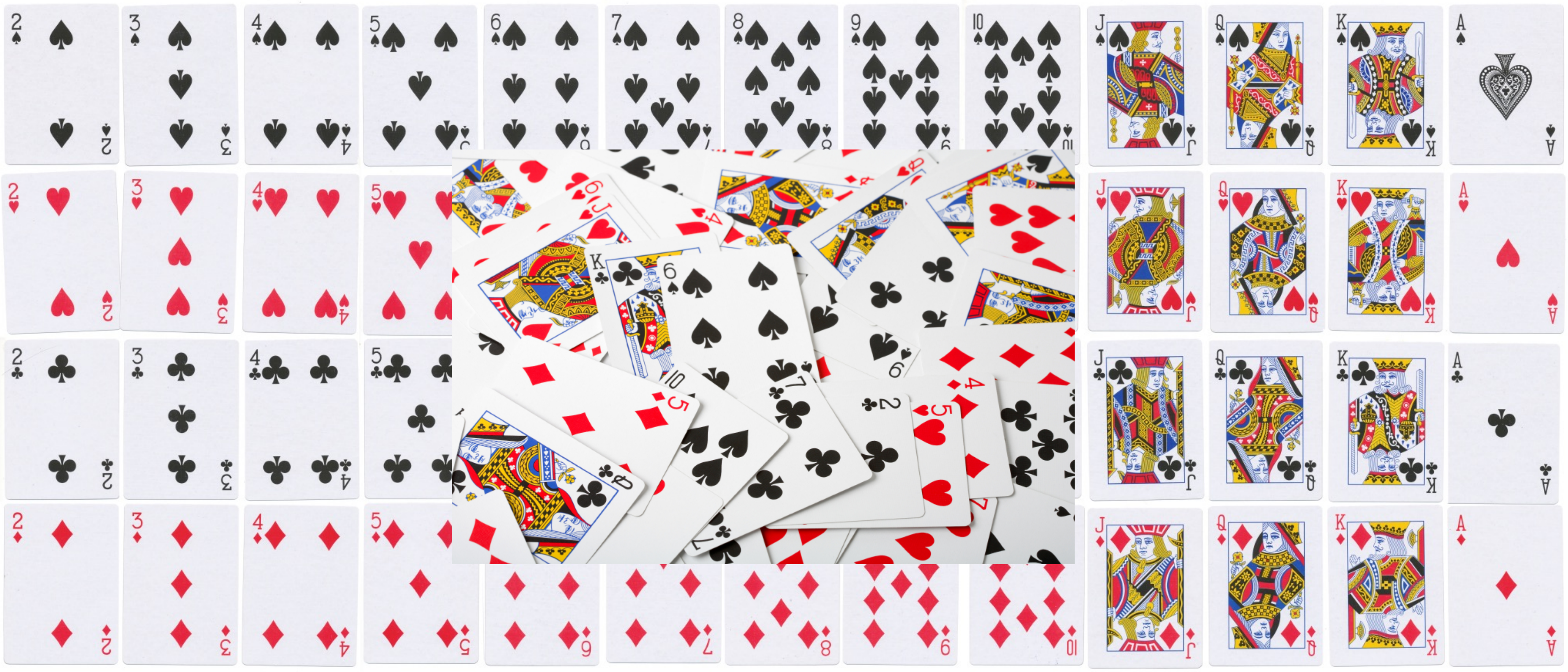
Hundreds of experiments, thousands of physicists measuring lifetimes, probabilities, final state multiplicities...and doing it over and over.

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

so, you'll always see:

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

something like these will never happen:

$$A^+ \longrightarrow B^+ + C^+$$

Q: +1 +1 +1

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

Q: +1 +1 +1 -1

Quantum Number:

"Strangeness" - a conserved quantum number

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 x 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 x 10^{-8}	$\mu^+\nu_\mu, \pi^+\pi^0$
K-short	K_S^0	K_S^0	497.7	0	0	0	+1	0.89 x 10^{-10}	$\pi^+\pi^-, 2\pi^0$
K-long	K_L^0	K_L^0	497.7	0	0	0	+1	5.2 x 10^{-8}	$\pi^\pm\ell^\mp\nu_\ell$
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 x 10^{-23}	$\pi^+\pi^-, 2\pi^0$
Rho-naught	ρ^0	ρ^0	770	1	0	0	0	0.4 x 10^{-23}	$\pi^+\pi^-$
Omega	ω^0	ω^0	782	1	0	0	0	0.8 x 10^{-22}	$\pi^+\pi^-\pi^0$
Phi	ϕ	ϕ	1020	1	0	0	0	20 x 10^{-23}	$K^+K^-, K^0\bar{K}^0$

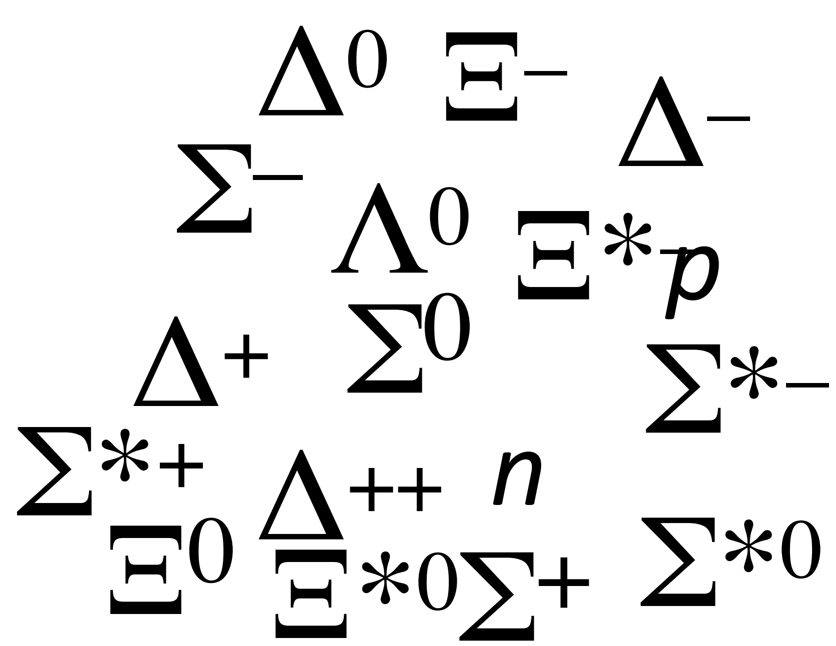
anyhow...back to the Zoo problem

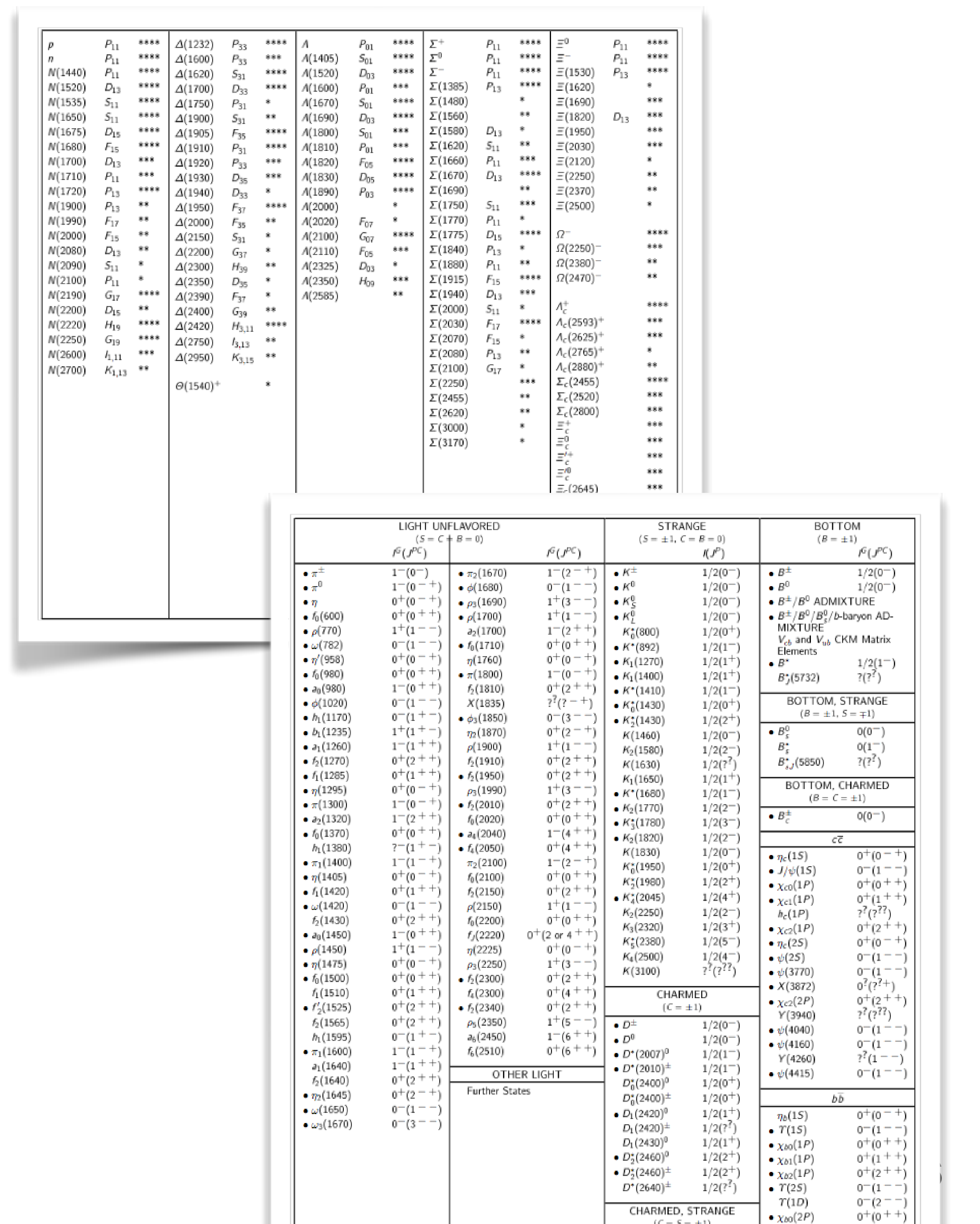
all those particles.

There were some hints

patterns emerged

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



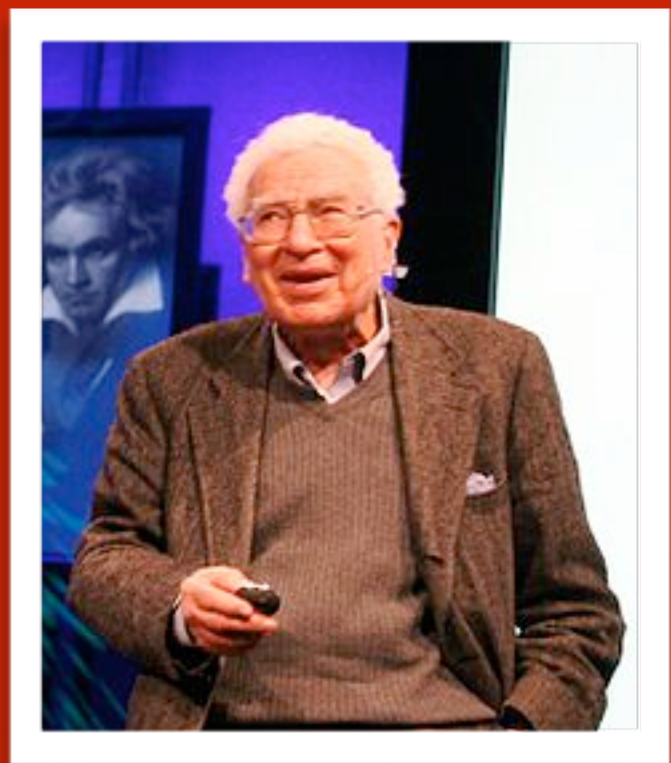


family arrangements

quarks

the mathematical description of such patterns

1964



Murray Gell-Mann

1929 -

theoretician

Nobel Laureate 1969

genius...ask him

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.

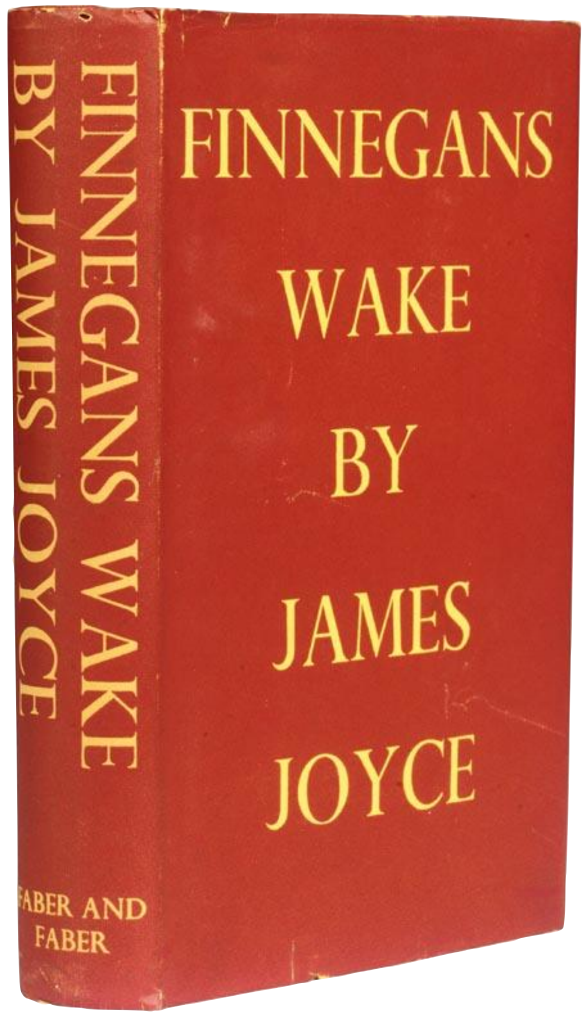
Not known for his humility.

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

$$\begin{array}{r} \text{up} \\ \text{down} \\ \text{strange} \end{array} \begin{pmatrix} u \\ d \\ s \end{pmatrix} \text{“Quarks”}$$



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

fundamental particles, circa…now

quarks and leptons

hadrons are composite: made of quarks

electrons and cousins are fundamental on their own

Baryons & Mesons differ by quark-content

Baryons are made of 3 quarks

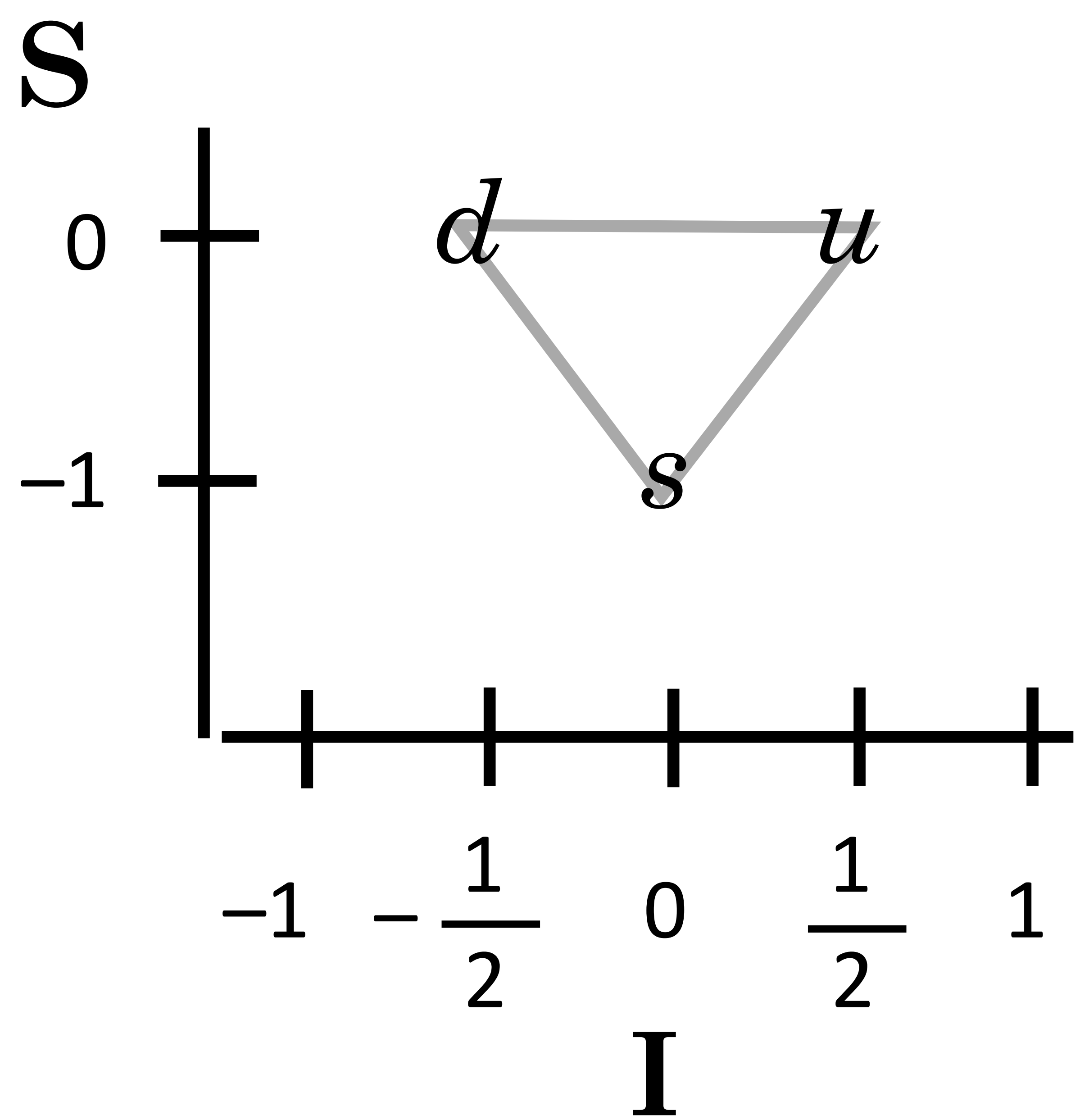
Mesons are made of 1 quark and 1 antiquark

Quarks

1964 version

fundamental fermions

in same league as electrons and neutrinos

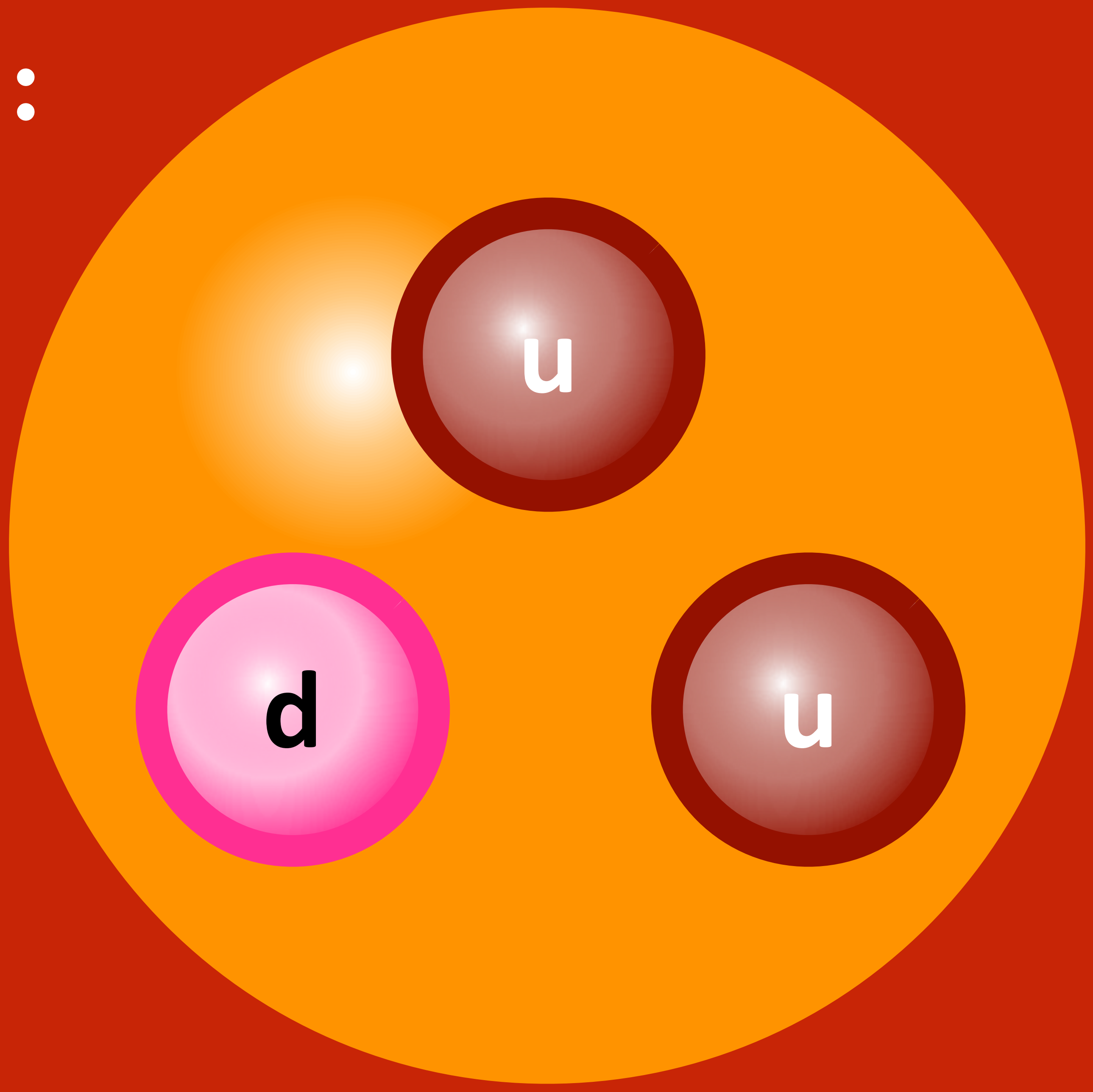


Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece ‘em together:

proton

electric charge = +1

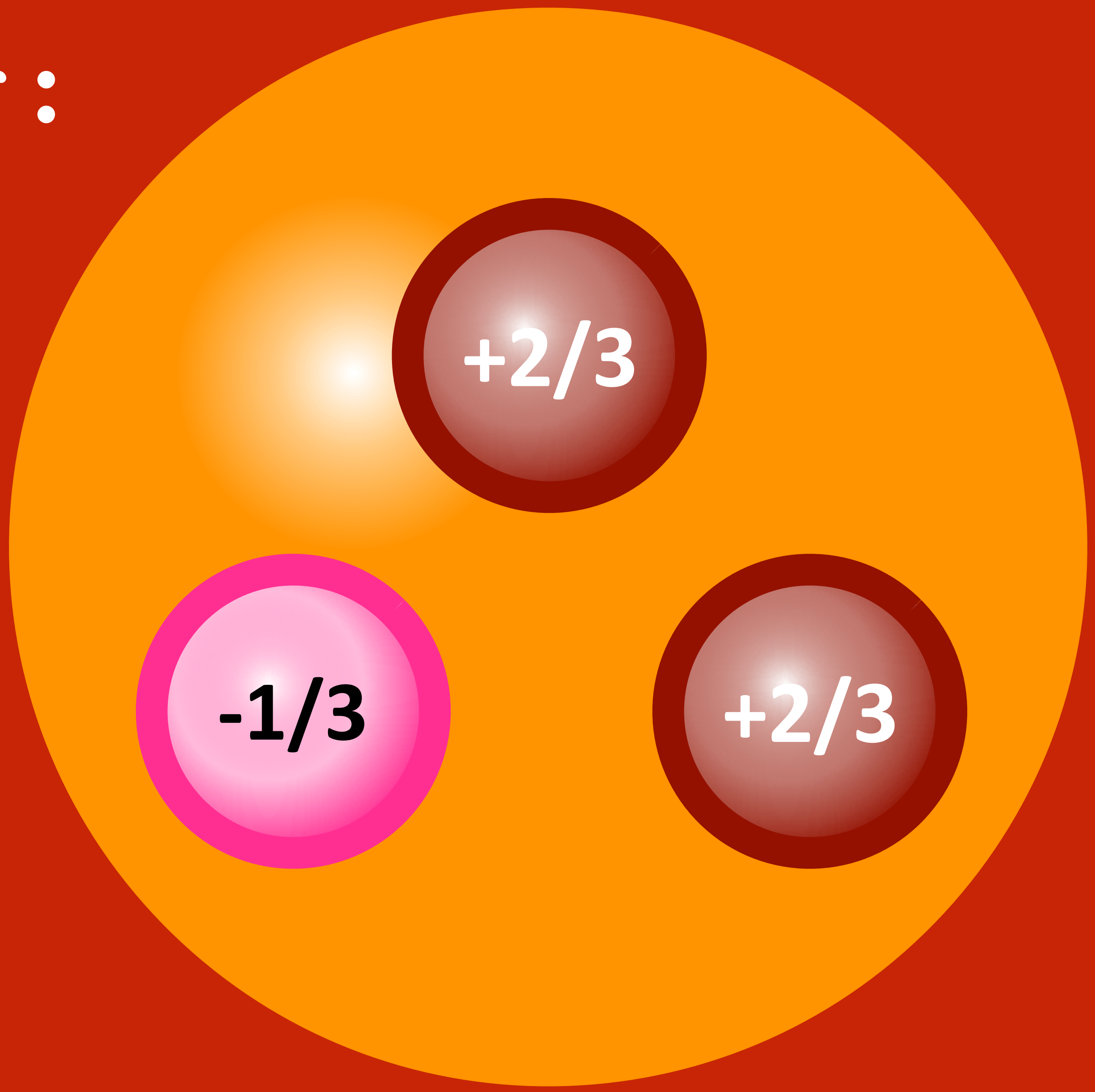


Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece 'em together:

proton

electric charge = +1

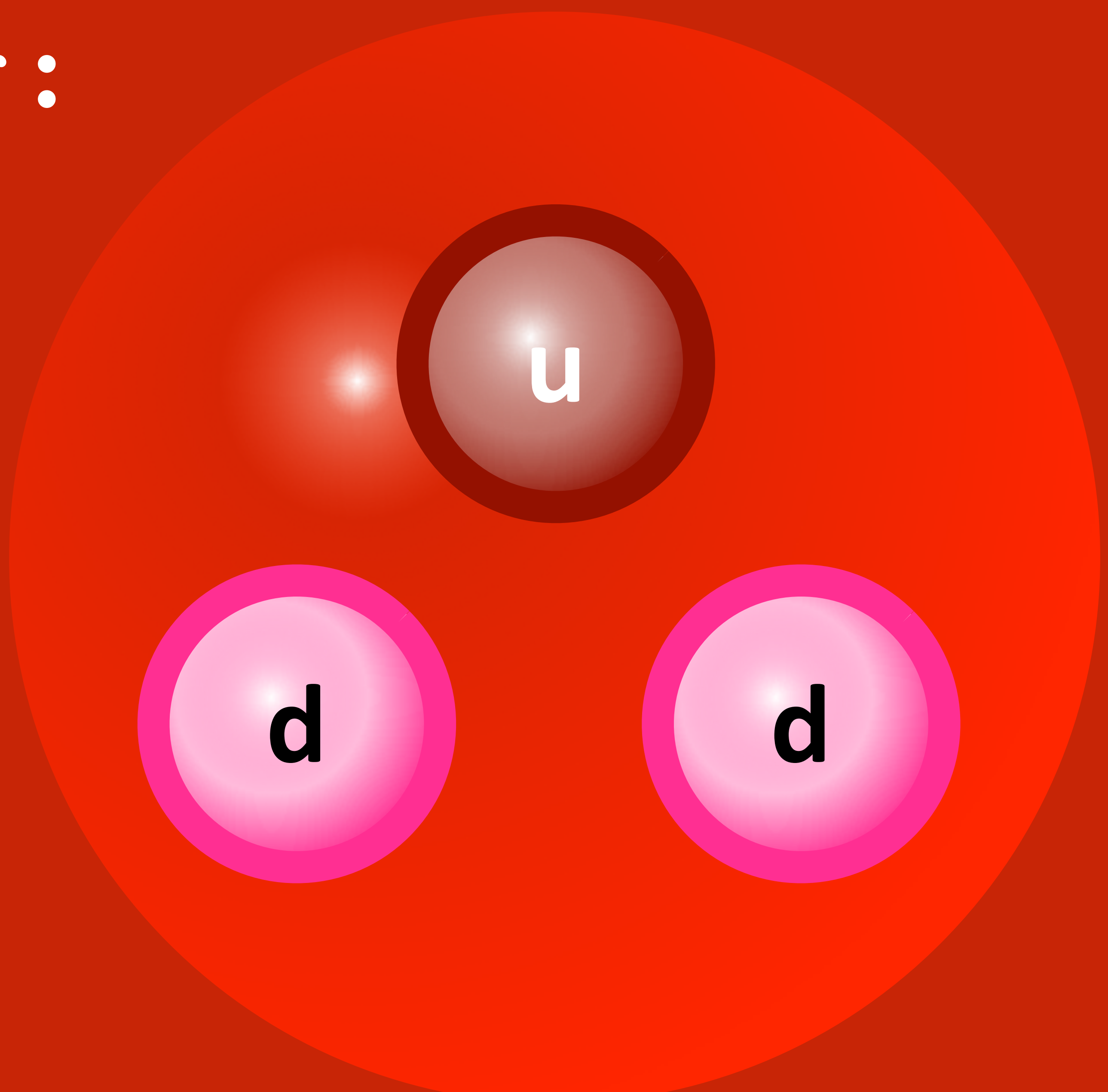


Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece 'em together:

neutron

electric charge = 0

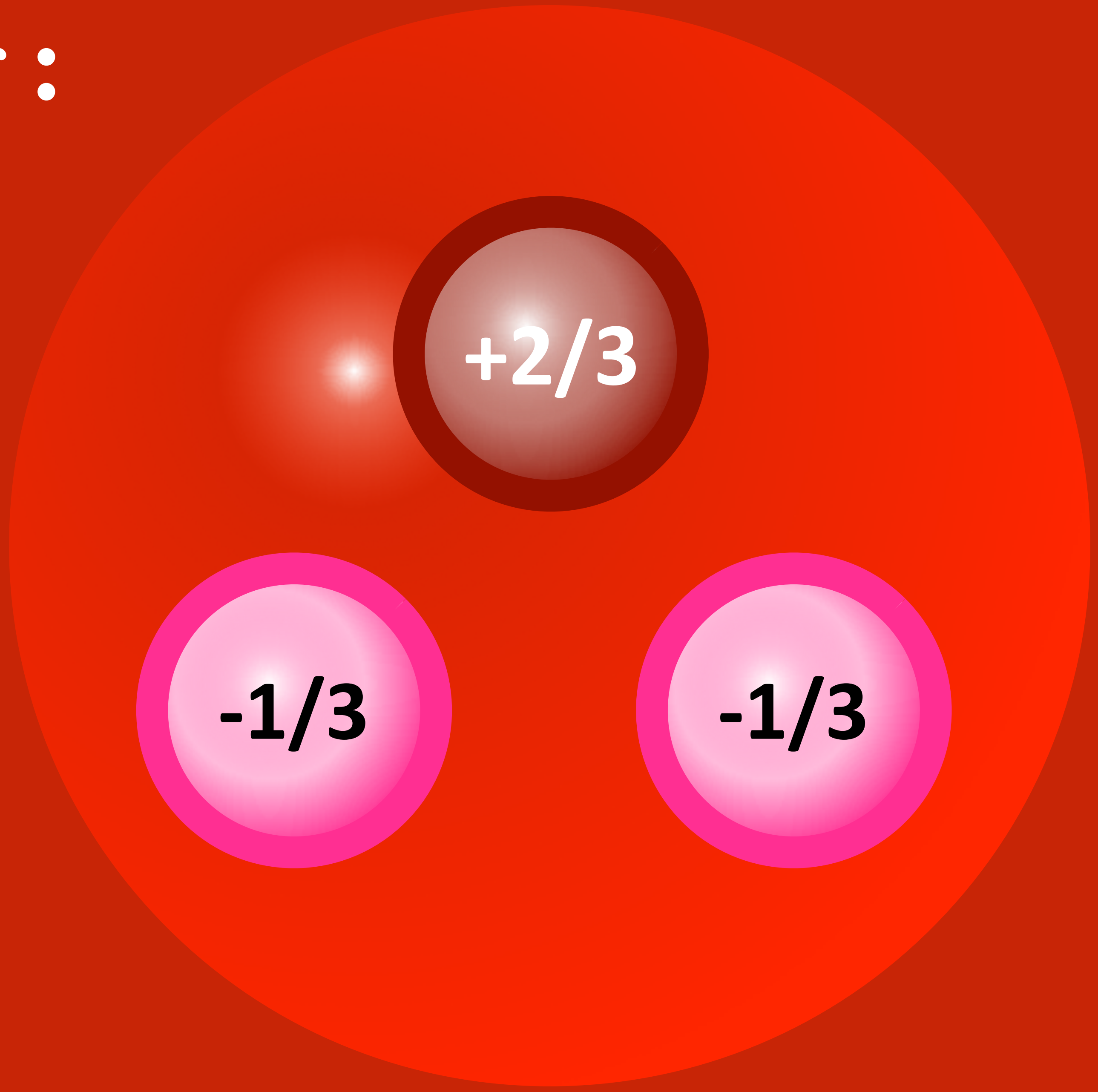


Quark	Symbol	Rest Mass MeV/c^2	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece ‘em together:

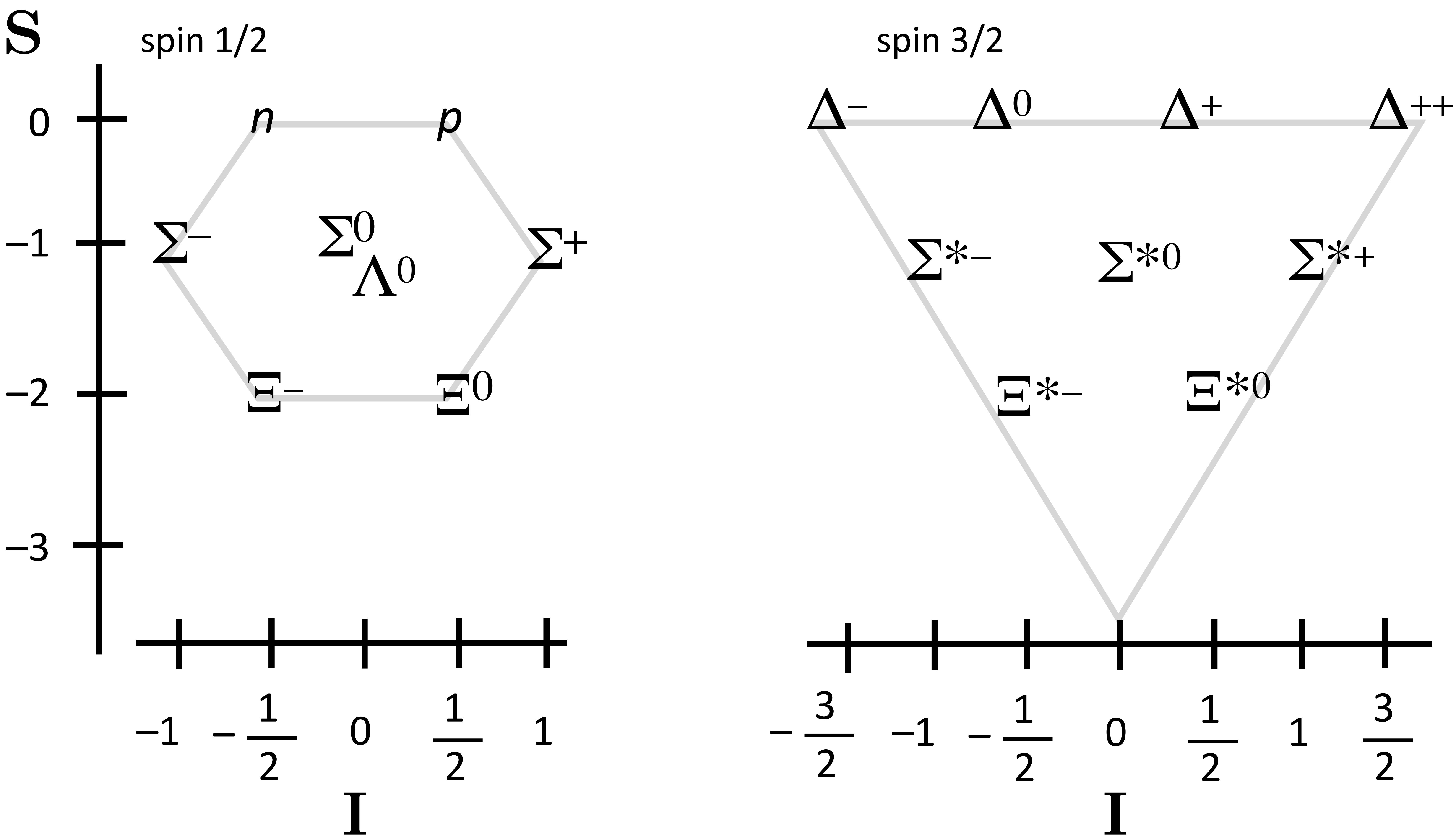
neutron

electric charge = 0

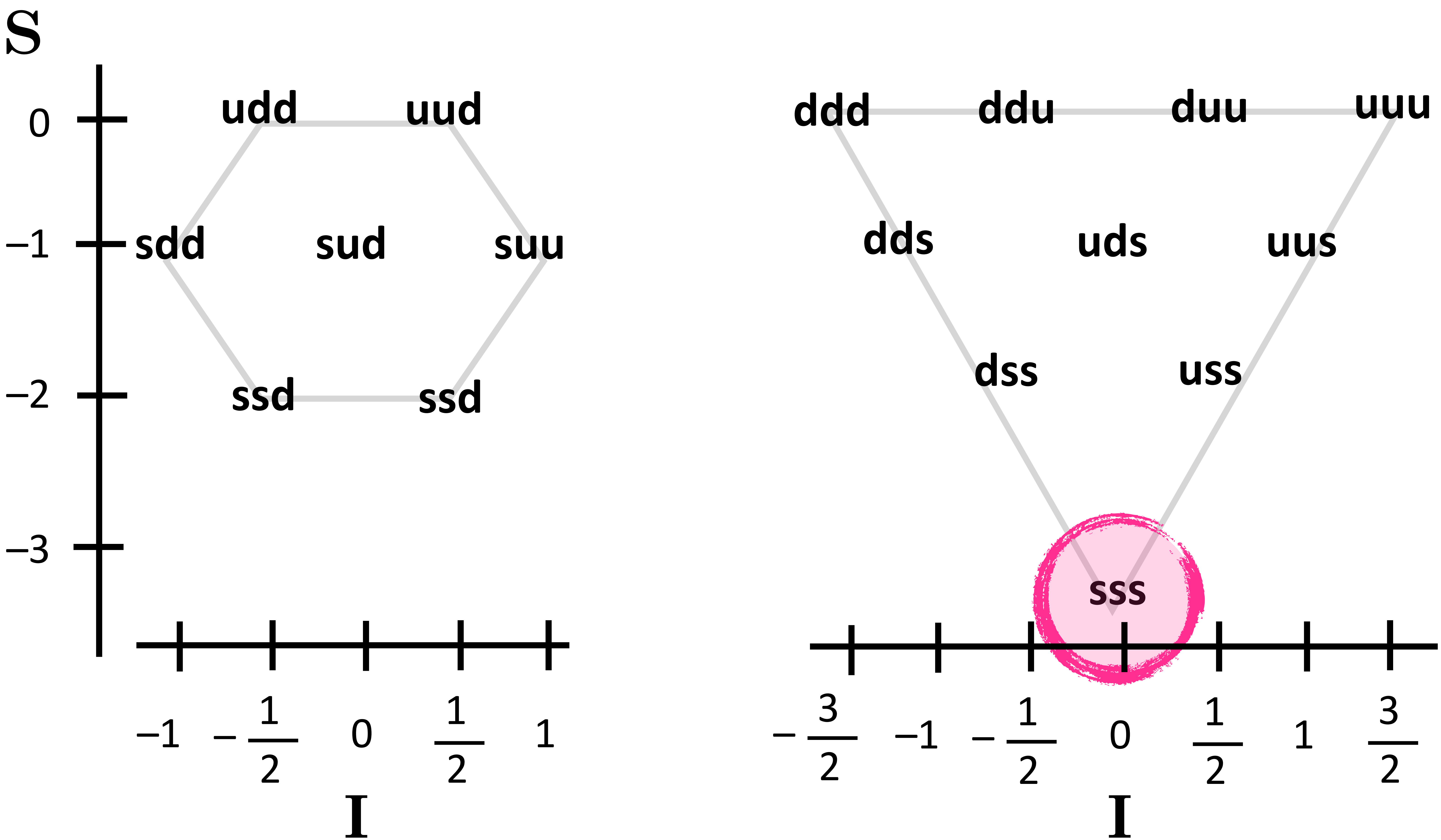


Quark	Symbol	Rest Mass MeV/c^2	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

they all fit

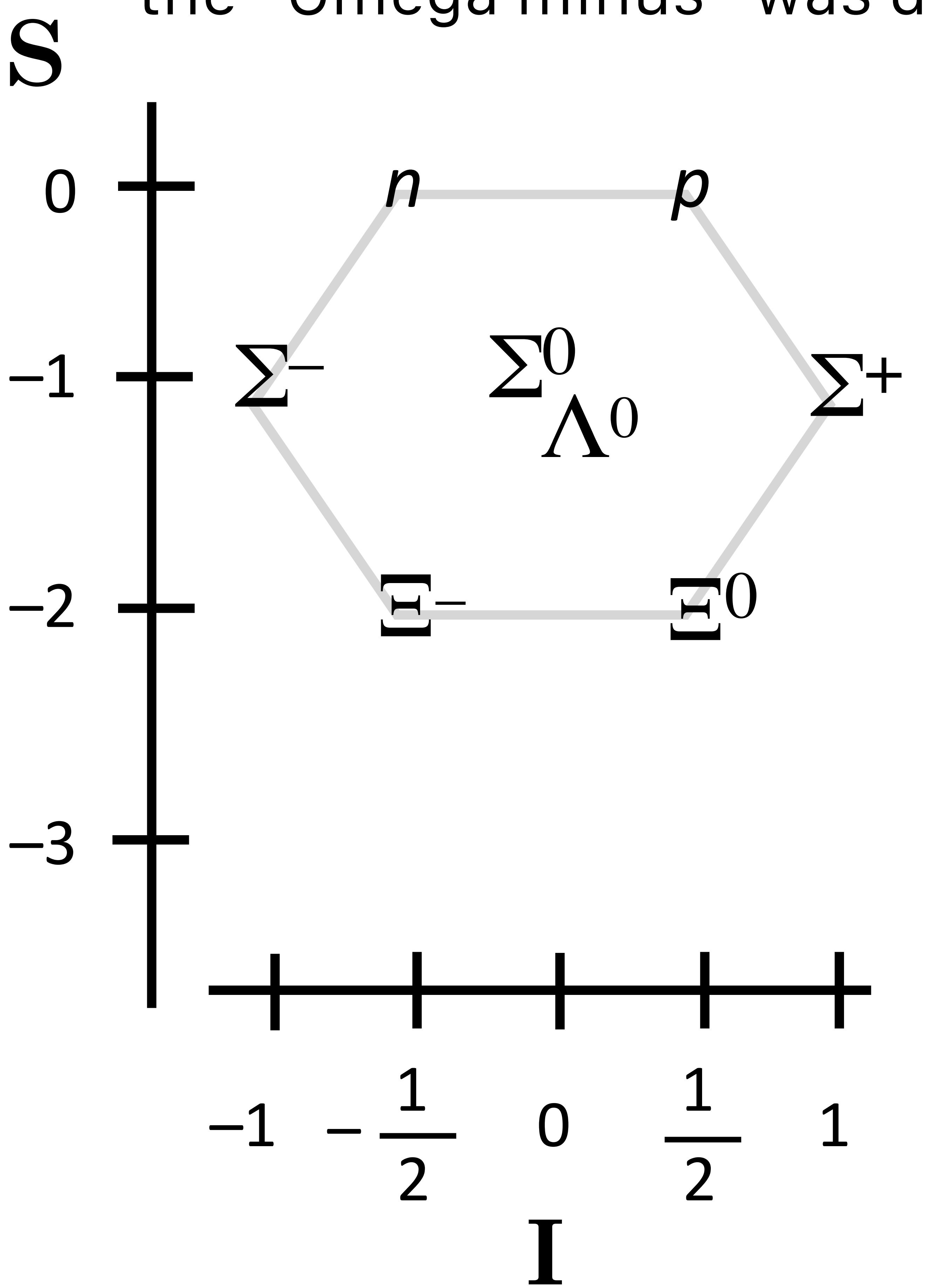

S
spin 1/2
0
−1
−2
−3
n
p
Σ−
Σ0
Λ0
Σ+
Ξ−
Ξ0
−1
− 1/2
0
1/2
1
I
spin 3/2
Δ−
Δ0
Δ+
Δ++
Σ*−
Σ*0
Σ*+
Ξ*−
Ξ*0
− 3/2
−1
− 1/2
0
1/2
1
3/2
I

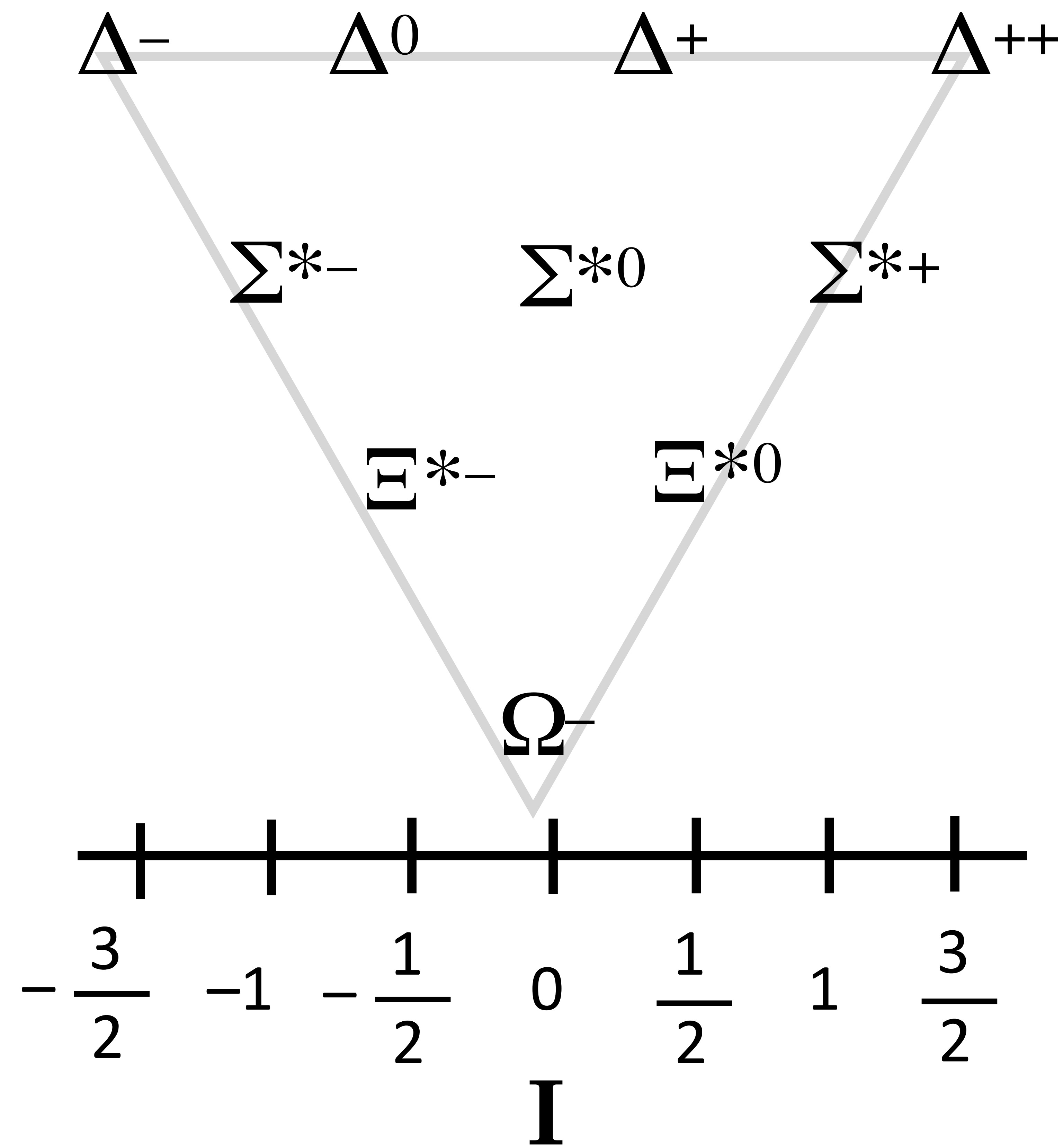
like a glove


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

VOLUME 12, NUMBER 8 PHYSICAL REVIEW LETTERS 24 FEBRUARY 1964

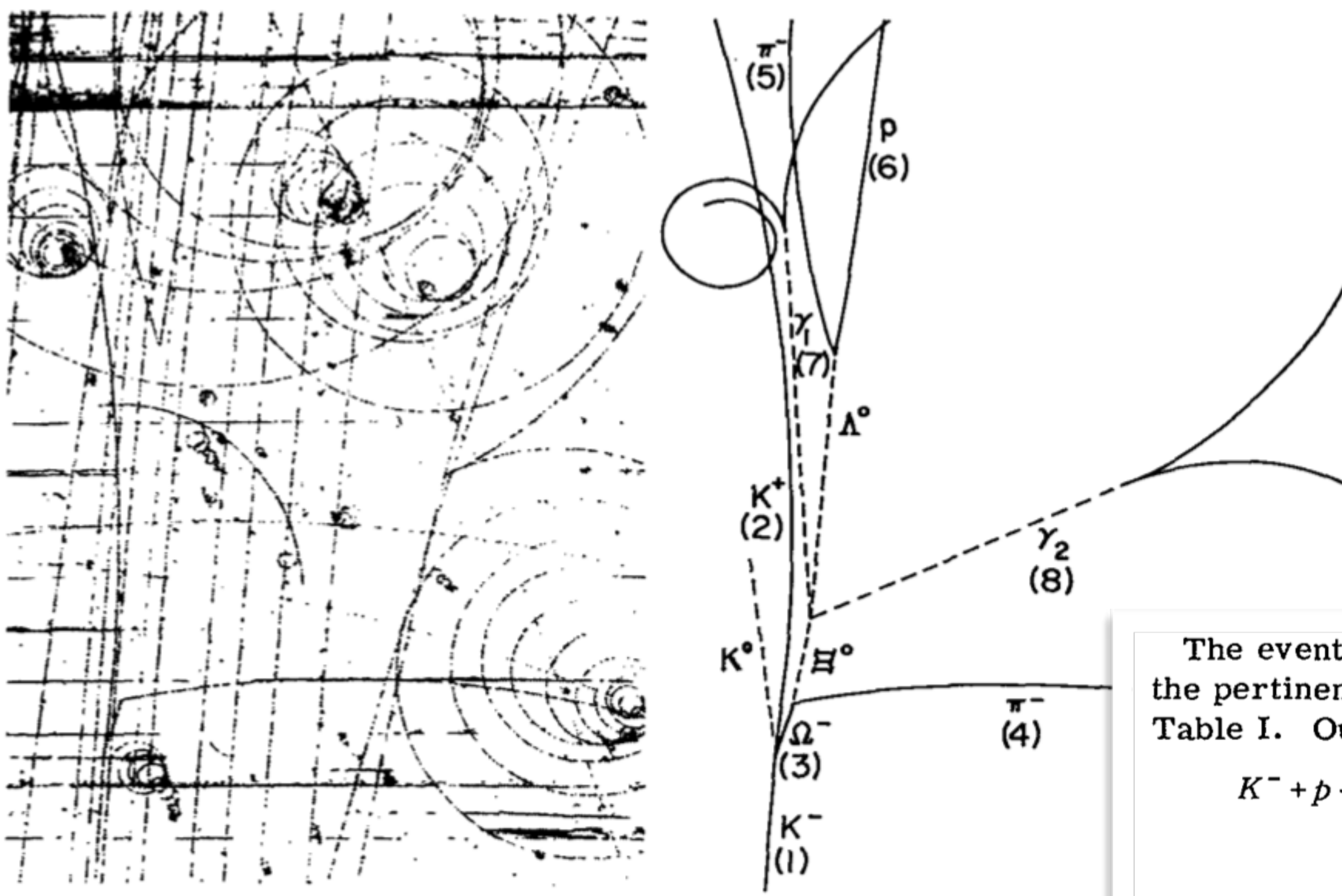


FIG. 2. Photograph and line diagram of event showing dec

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

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

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:

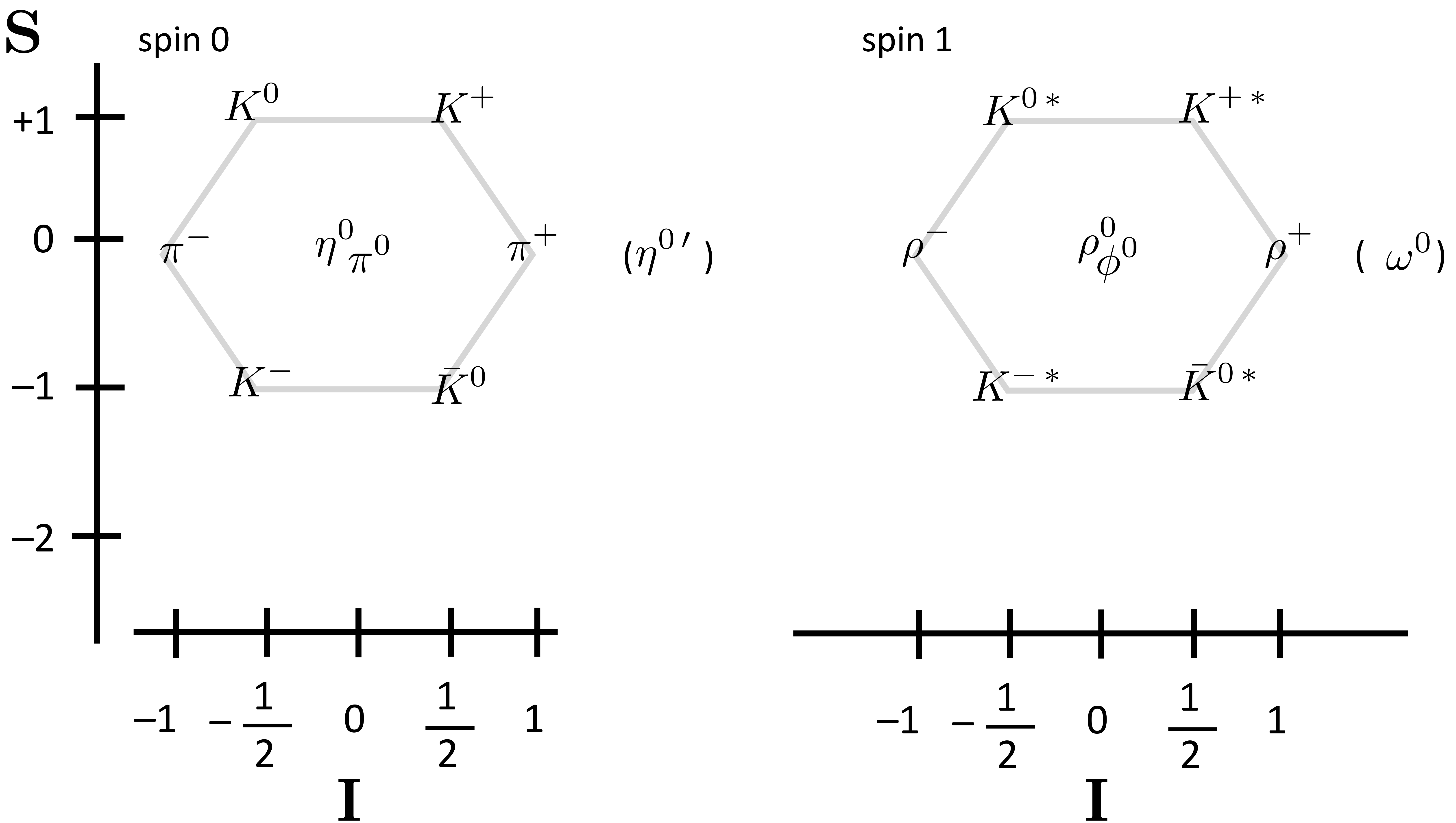
Particle	Symbol	anti-particle	Rest Mass MeV/c²	spin	Q	B	S
Pion	π^+	π^-	139.6	0	+1	0	0

$$\pi^+ = (u \quad \& \quad \bar{d})$$ has the right stuff.

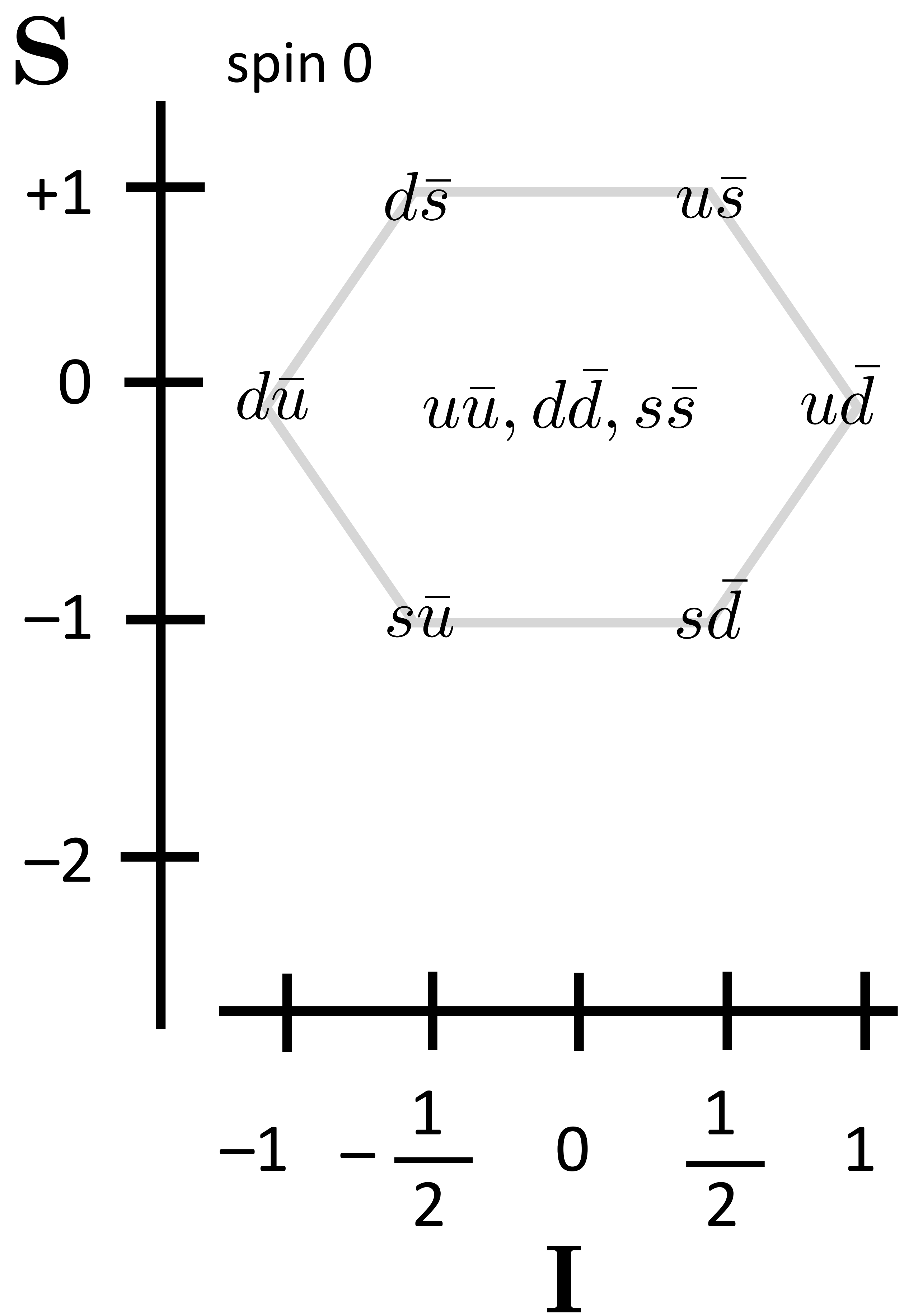
Q:	+1	+2/3 +	−(−1/3)
B:	0	1/3 +	−(1/3)
S:	0	0	0

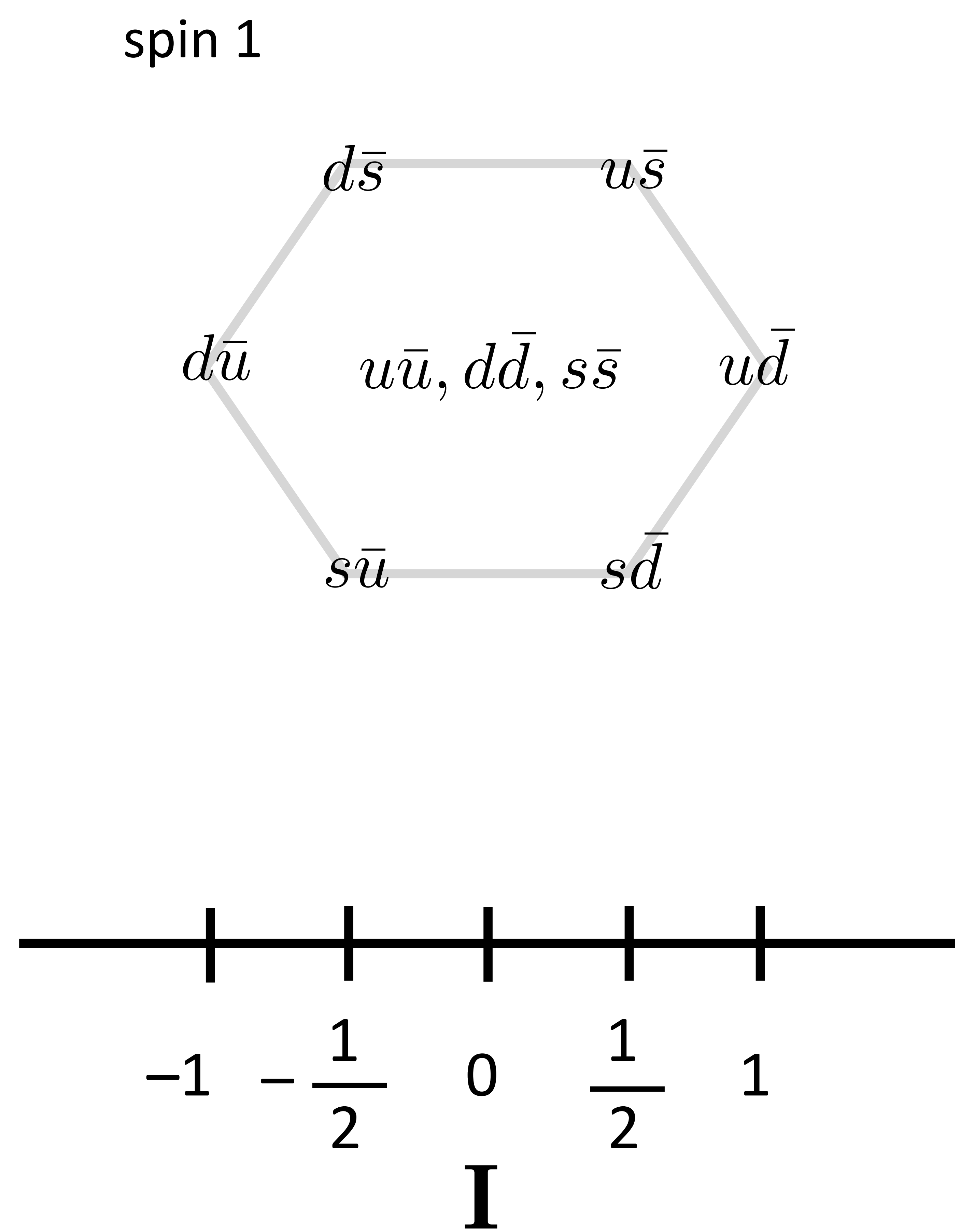
$$\pi^+ = u\bar{d}$$

a similar thing happens for the mesons



meson quark content





the dominant Mesons

Particle	Symbol	anti-particle	Rest Mass MeV/c²	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^0_S	K^0_S	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^0_L	K^0_L	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..

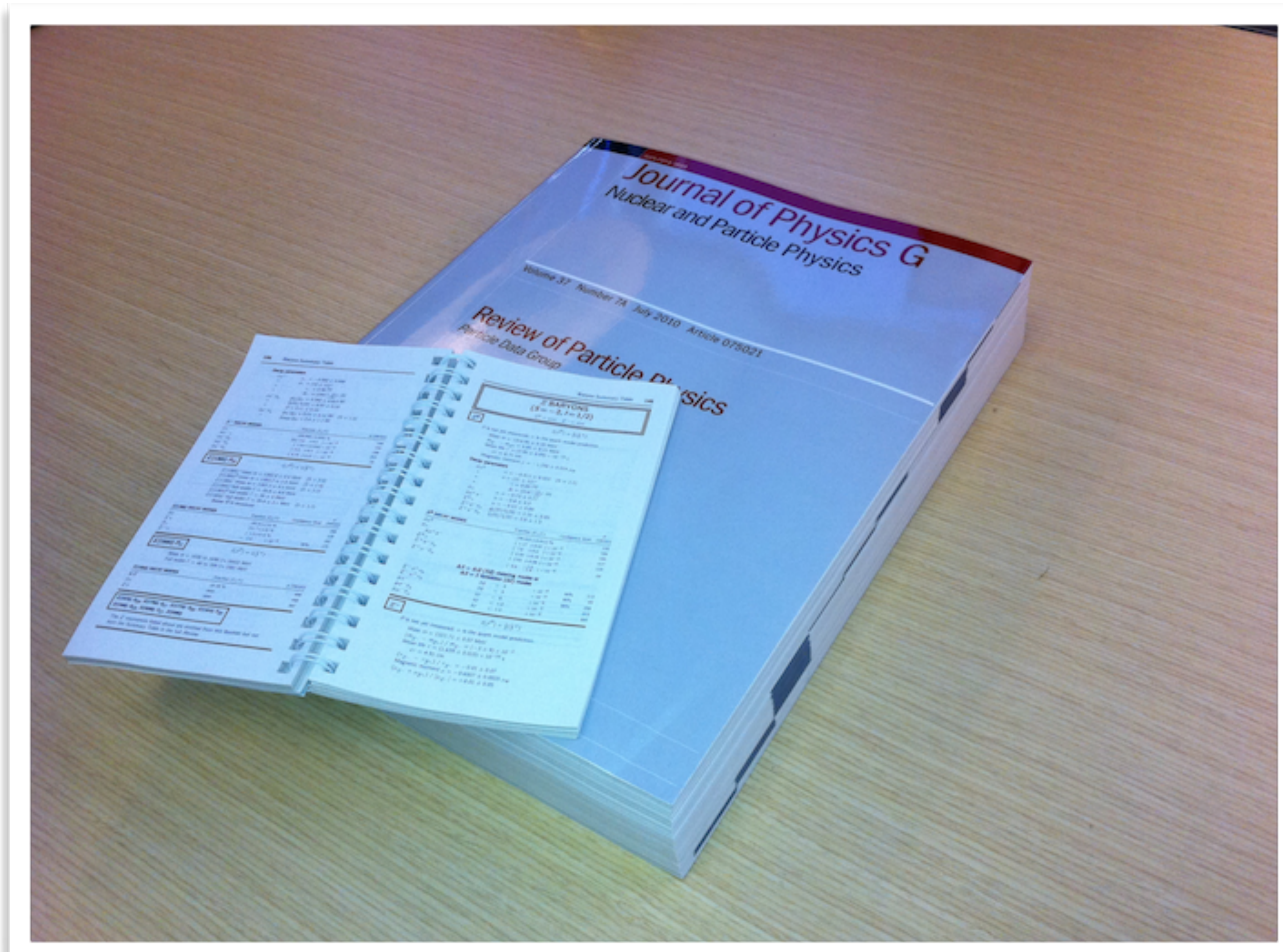
d

u u

you can tell a particle physicist

by the books that we carry

"I laughed, I cried"



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

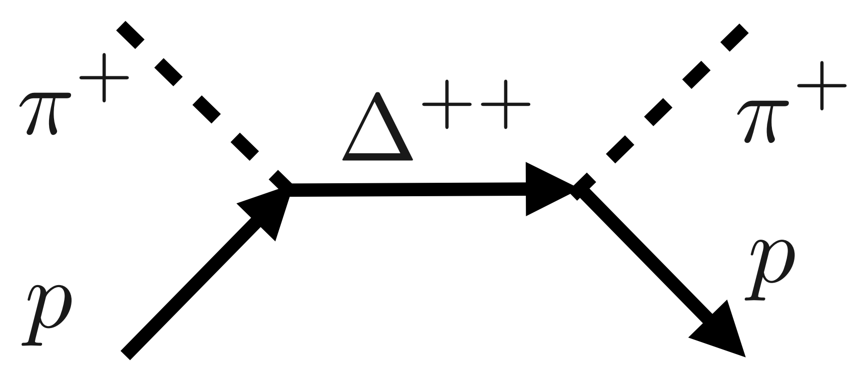
became apparent

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

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



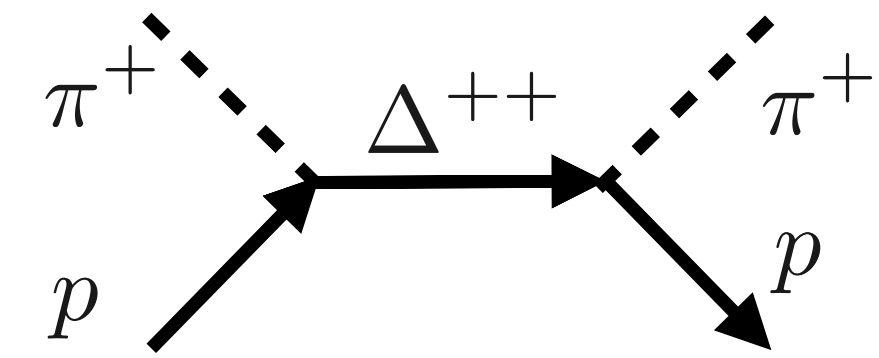
* I call them “pseudo” as doing real calculations with them are kind of ad-hoc

scatterings now are thought of diferently

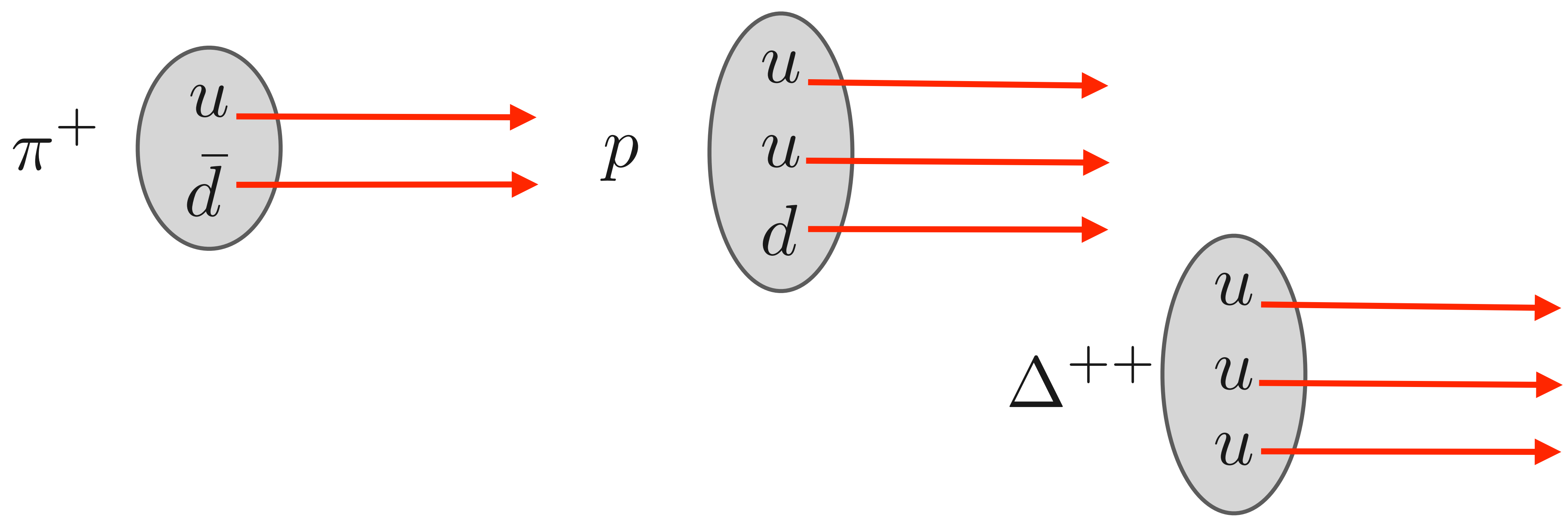
by following the lines...

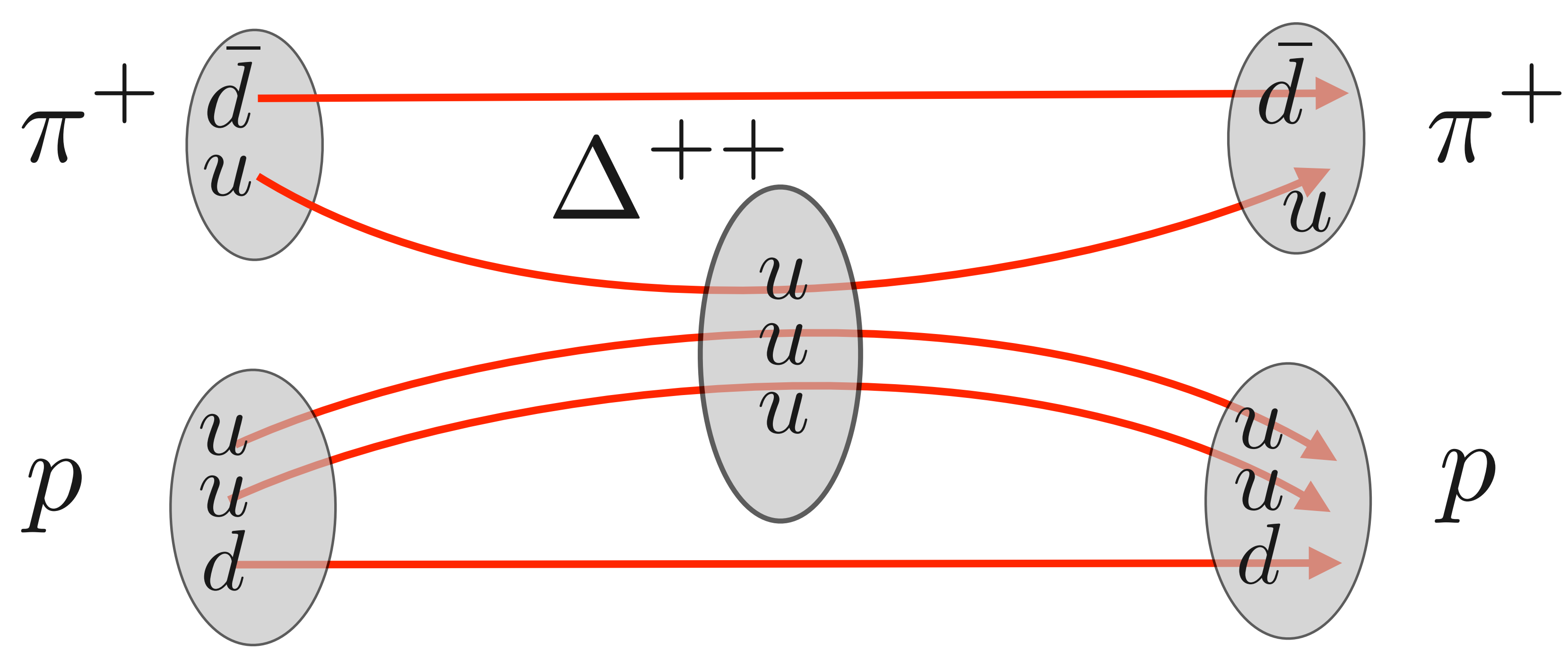
$$\pi^+ + p \to \Delta^{++} \to \pi^+ + p$$

Feynman Diagram, pre-1964:



in quark language:



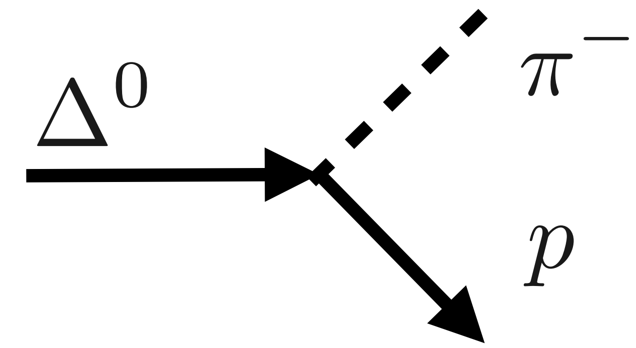


how about a strong interaction decay?

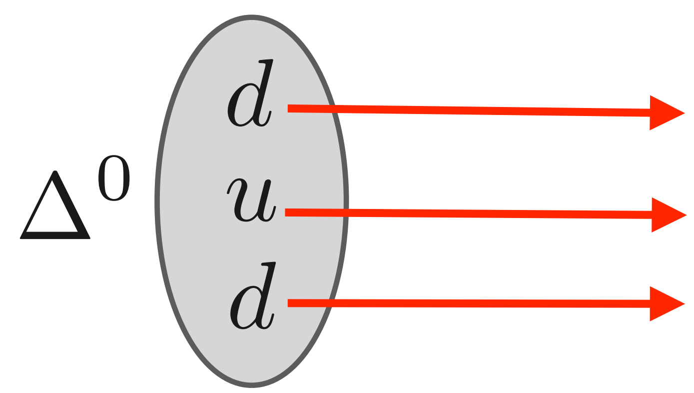
a little non-intuitive.

$$\Delta^0 \to \pi^- + p$$

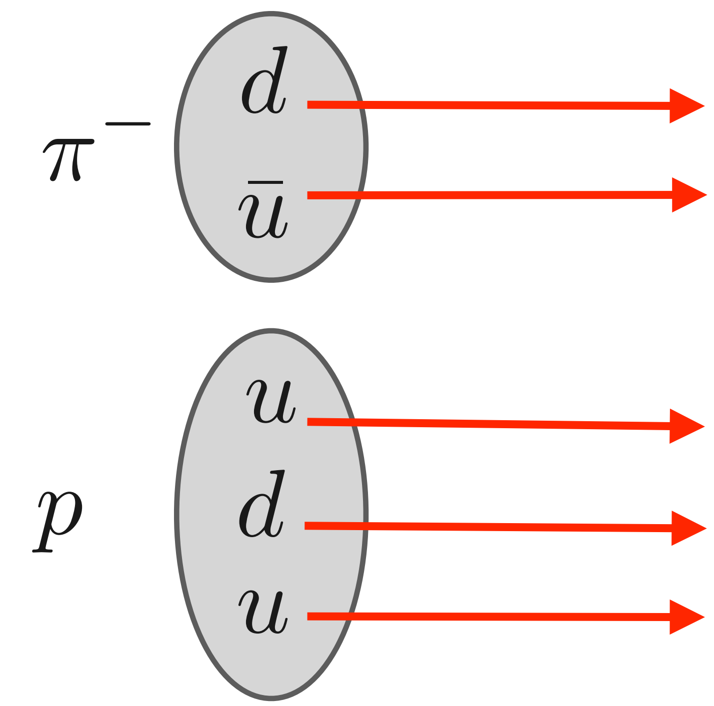
the old way:



the quark way:

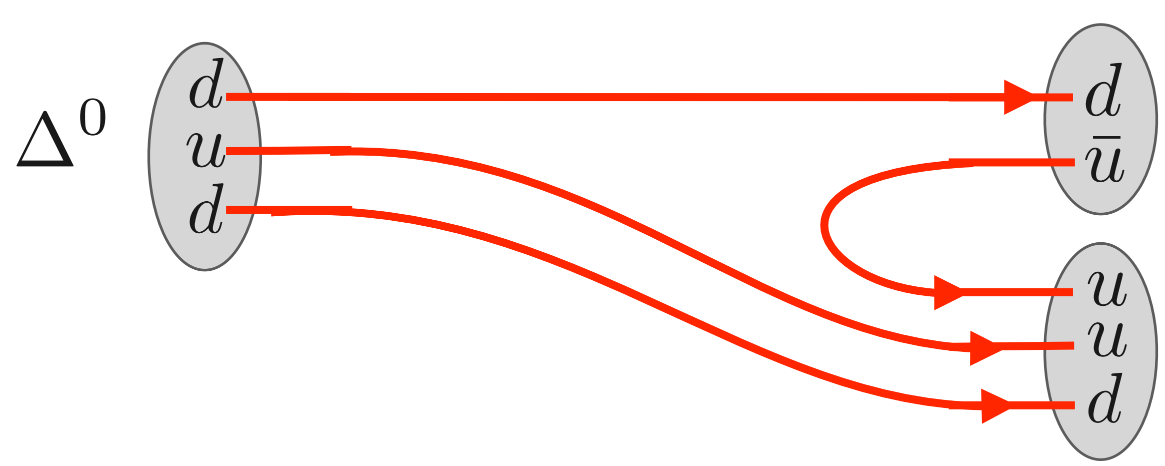


3 quarks



5 quarks

some quark-creation required!



stay tuned.