# hi

Day 26, 17.04.2018

Particle Physics 1

# housekeeping

The end game: next slide

Particle Physics:

**Readings**: Oerter and Hobson

***Hobson_PP.pdf is chapter 17 out of Hobson***

Homework #12 is all from MasteringPhysics - normal due date

Feynman Diagram rules

3 movies in the lecture slide directory - you'll need them for homework and the final

they are: primitiveDiagrams_X. mp4 where X = 0,1,2

# last 2 weeks & final

Homework #13 will be assigned 4/21 and due 4/28 - normal rotation

On-line final exam will be assigned Sunday, 4/29 and due Tuesday night, May 1

will cover material since midterm plus the last week of class

There is 1 more 10 point quiz (stay tuned)…

only the shadow knows when

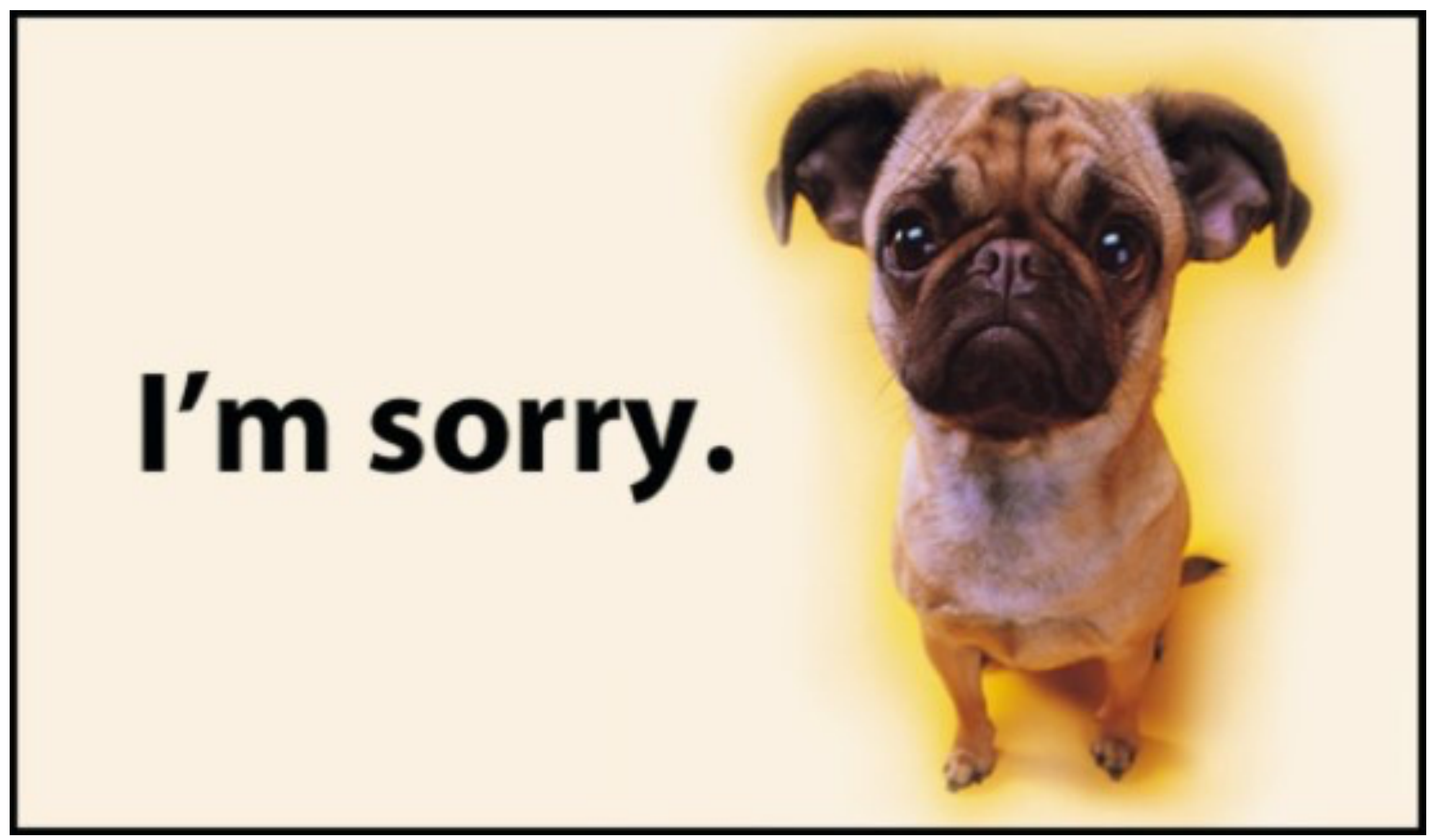
Remember when I was sick?

been trying to catch up, but not going to make it. Hence:

Final Exam day:

1. You'll arrive at 0745 on May 4, here. I know.
2. I'll provide bagels. You supply liquids.
3. We'll have a quiz.
4. I'll finish with about a 1 hour grand finale, lalapalooza, mind-bending lecture
5. You'll do your Feynman Diagram Project
6. There will be no poster project this year


SORRY!®
The Game of Sweet Revenge
START
Plan a Family Game Night®
Family
AGE 6+ EDAD
PARKER BROTHERS


I'm sorry.

# honors project began

https://qstbb.pa.msu.edu/storage/Homework_Projects/honors_project_2018/

contains:

- the first instructions: the plan & tutorial
- the second instructions – v2 uploaded, added a missing student
- the data, assigned by name in the second instructions - see next

dates:

- complete first part, March 16
- analyze data by April 24 and hand in complete writeup at the final exam

# the data

should have been in zipped format

rather, somehow they were unzipped in some process

*fixed: now*

*https://qstbb.pa.msu.edu/storage/Homework_Projects/honors_project_2018/*

**Index of /storage/Homework_Projects/honors_project_2018**

| Name | Last modified | Size | Description |
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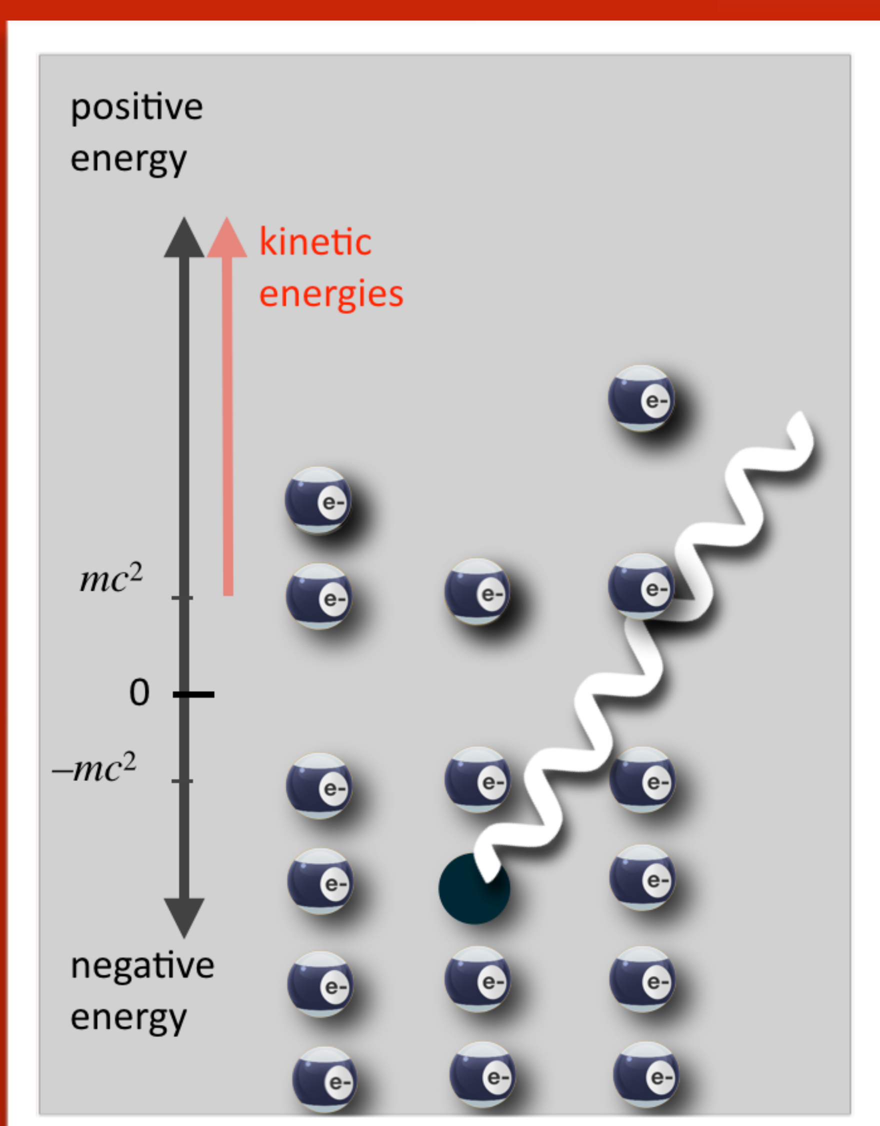
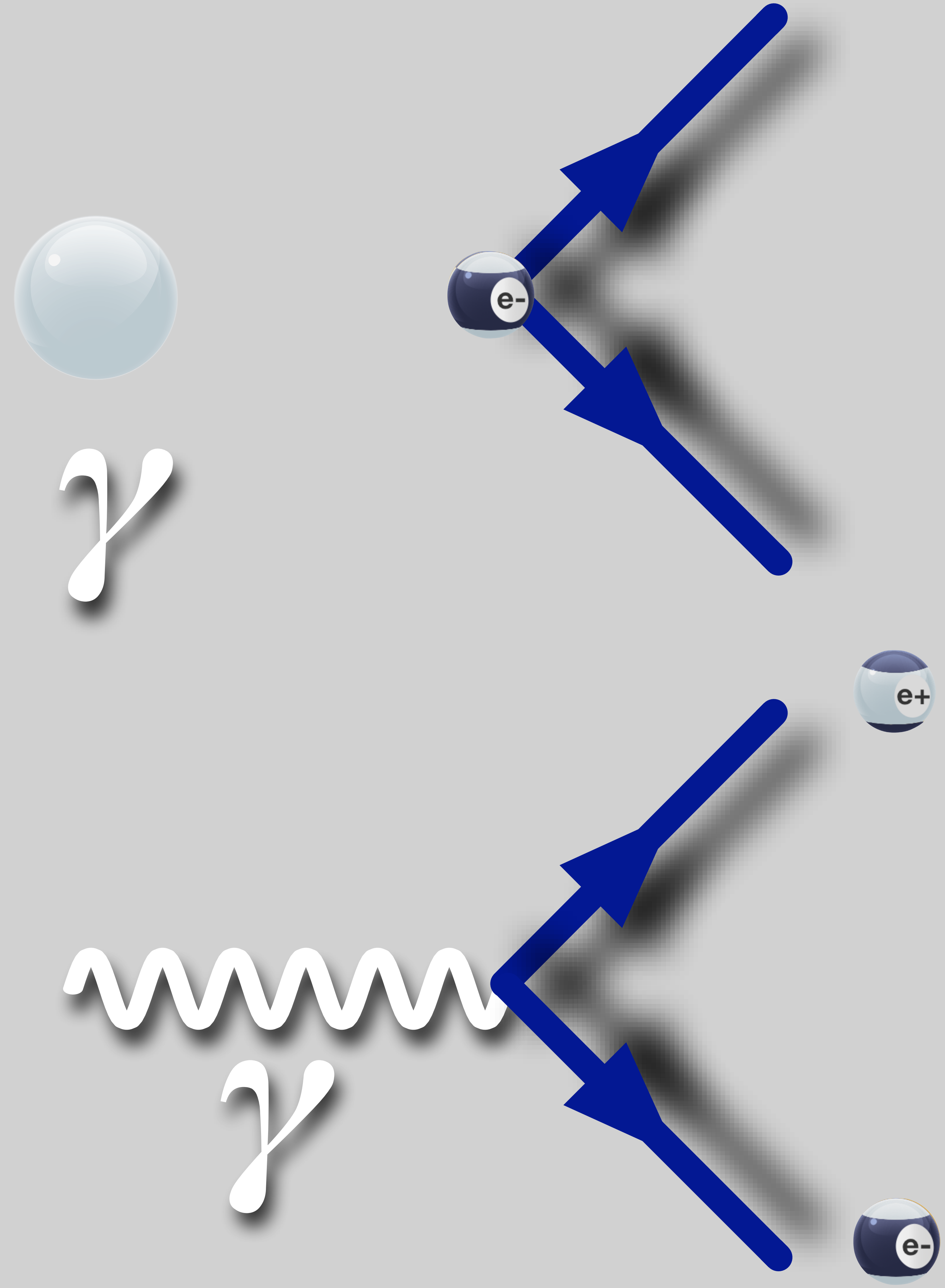
# I need a Section 2

to test the Z-path uploading machinery and instructions

# modern intepretat

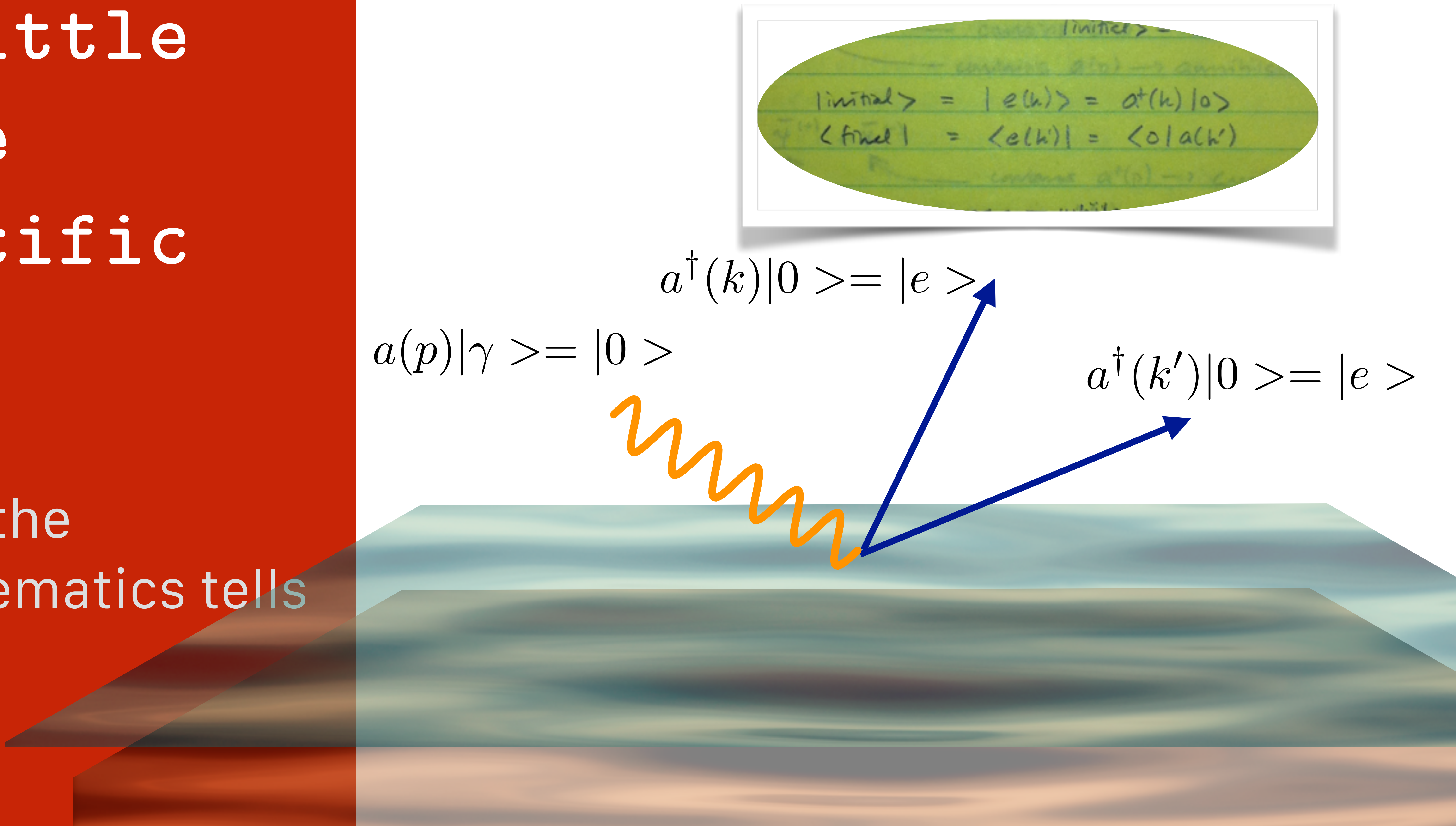
a photon poof-disappears



# a little more specific

what the mathematics tells us




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

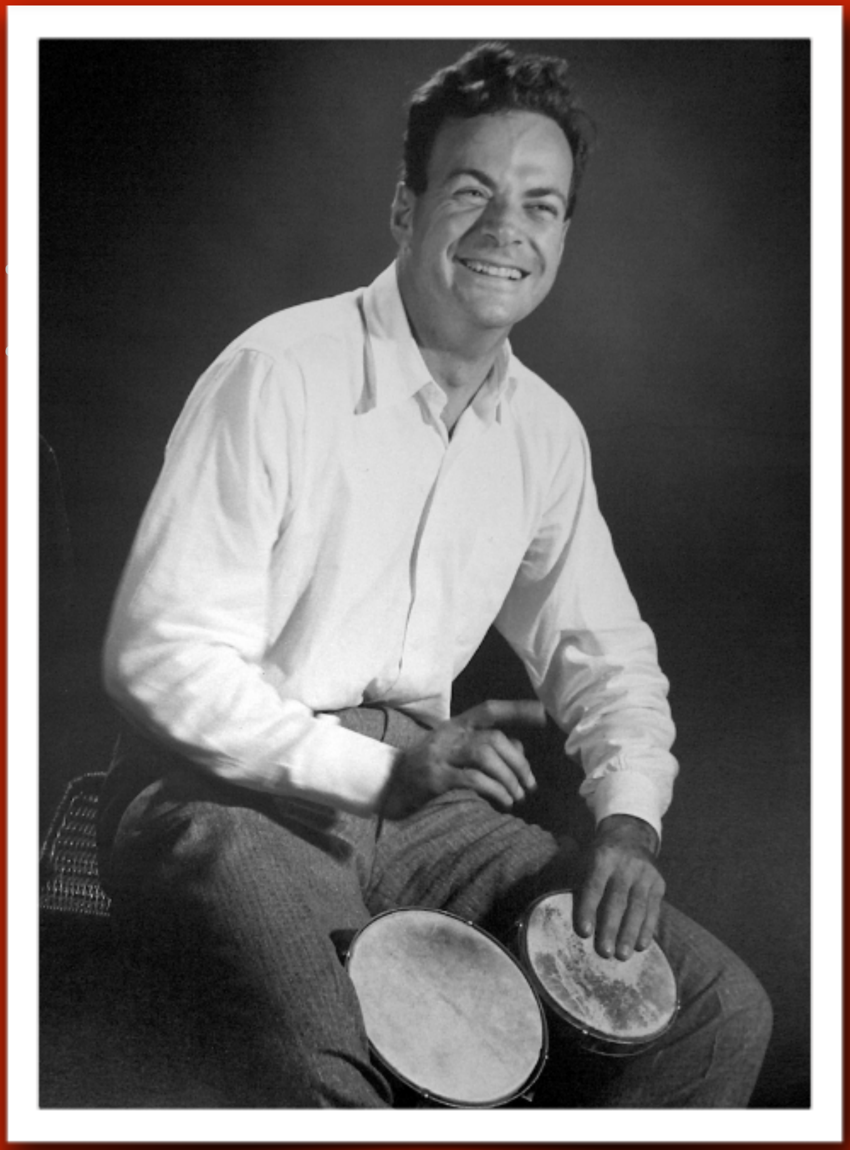
the photon pops the electron- positron pair out of the Ur electron field
and itself disappears back into the Ur photon field.

# Feynman Diagrams

now for real.

**creation and annihilation of**

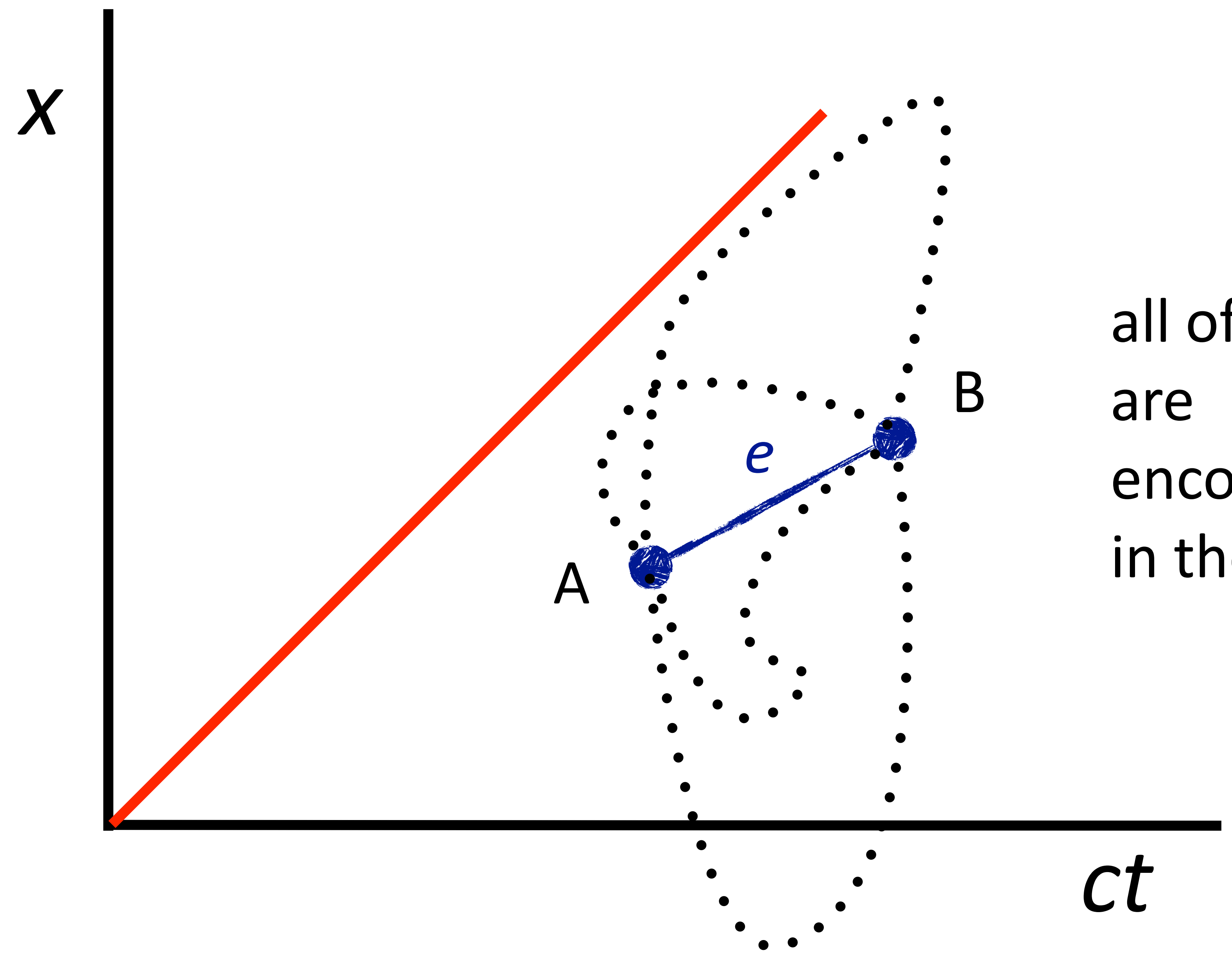
can be embodied in Feynman Diagrams



# the symbols of Feynman Diagrams

each line represents an entire “history” of trajectories

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.

# 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

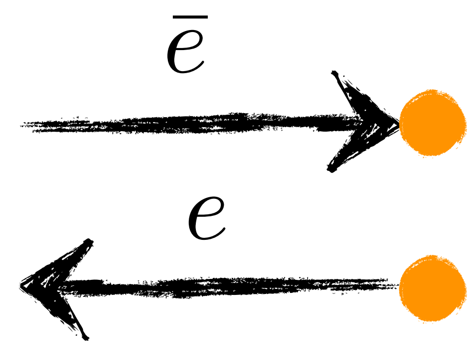
# we'll do this in

two steps

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

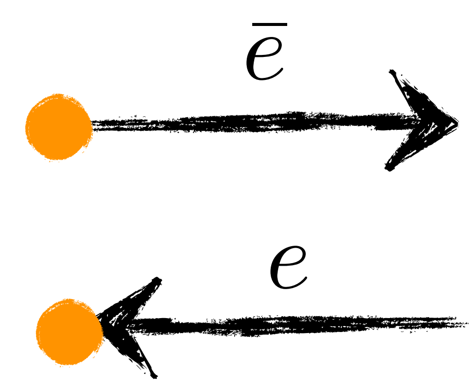
making use of the Feynman idea that antiparticles moving forward in time are the same as particles moving backwards in time

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 |

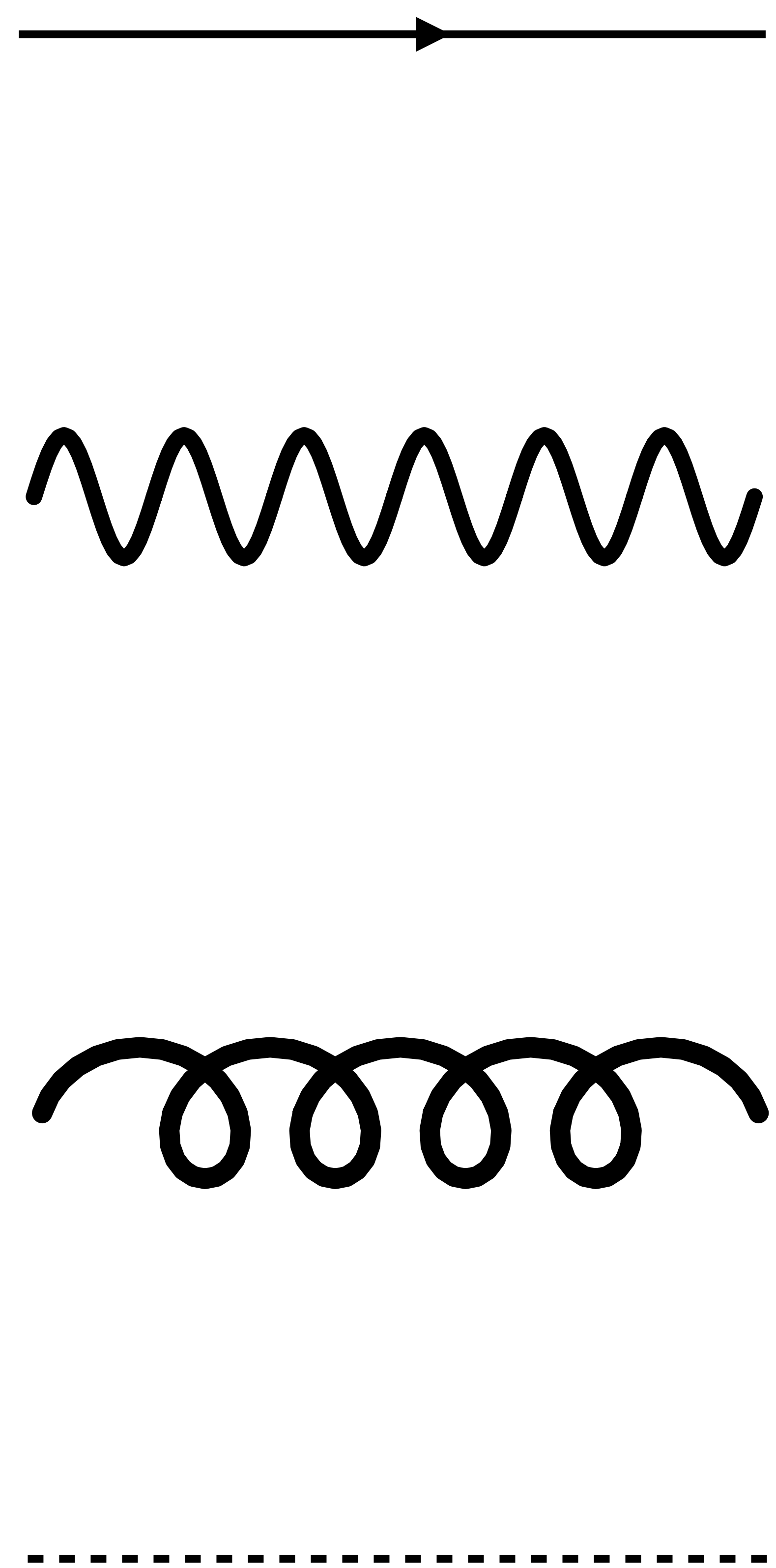
jargon alert: **bosons**

| | |
|---|---|
| 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

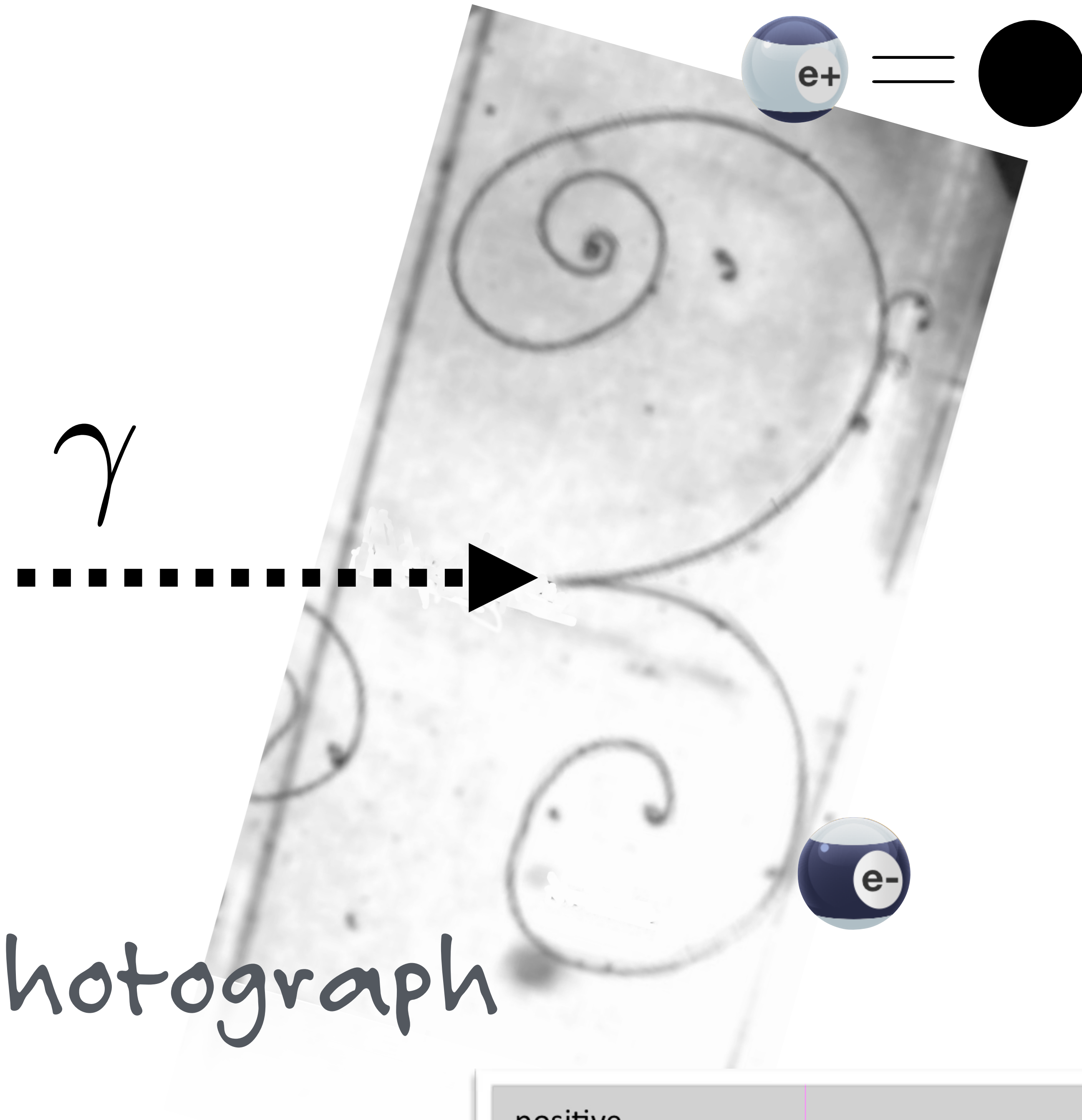
# first idea

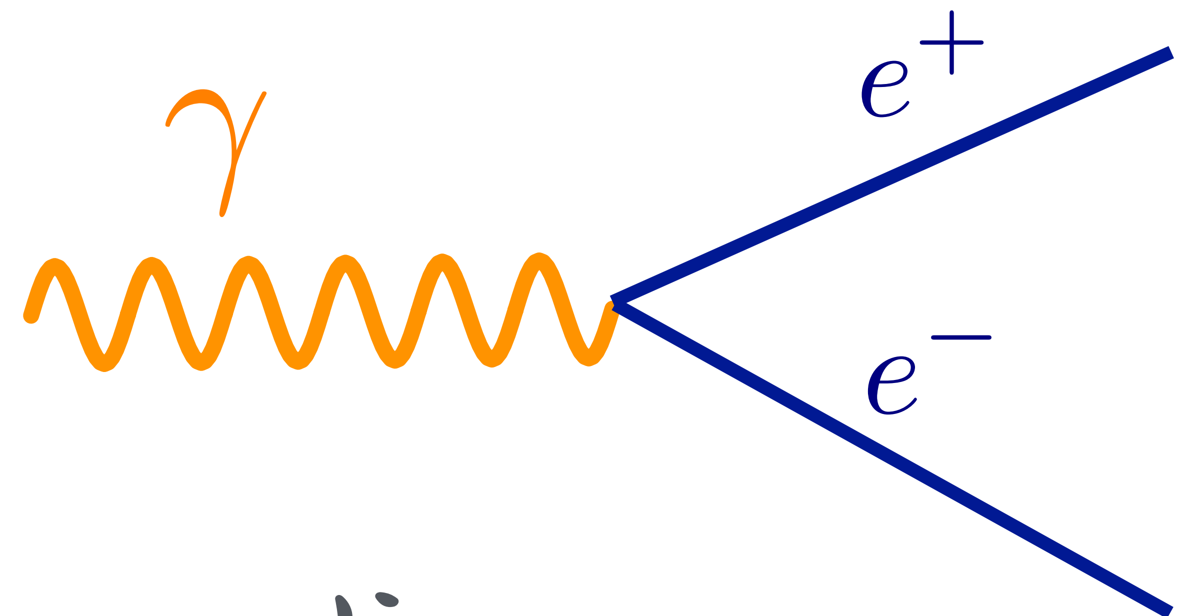
one can take a single Feynman Diagram that describes a process

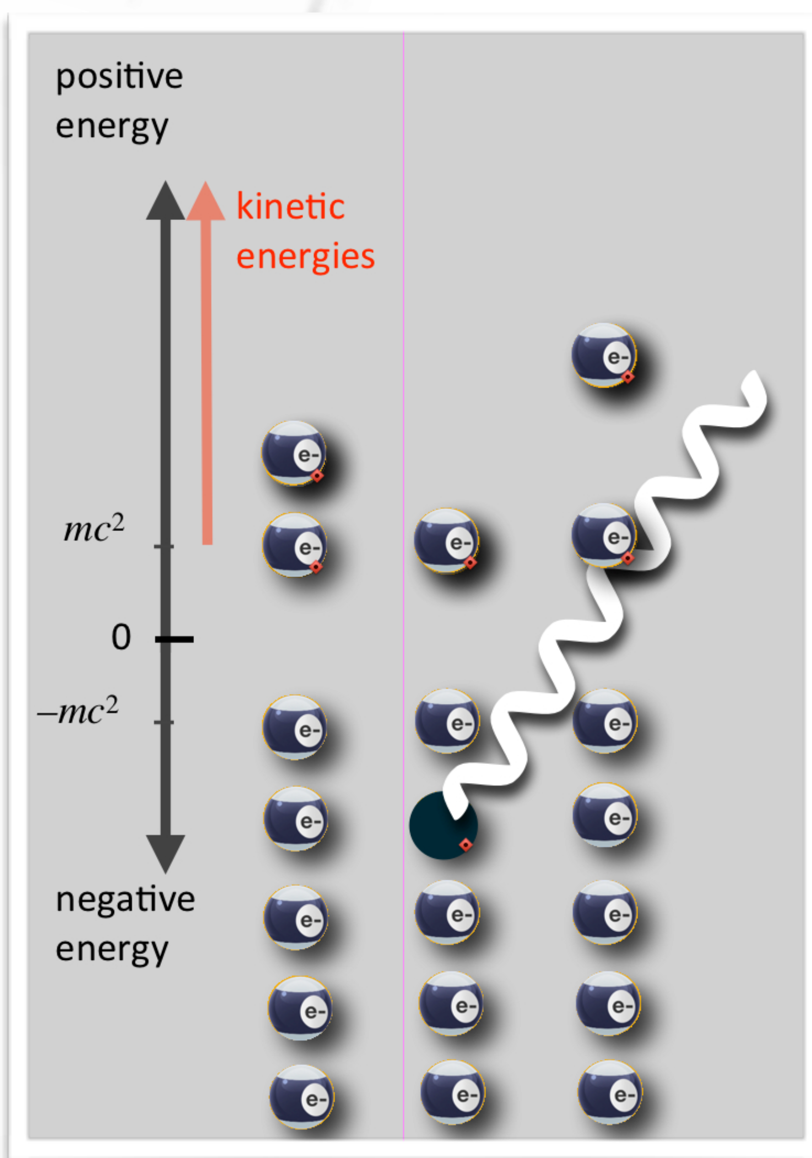
and by rearranging it in spacetime, “predict” additional physical processes

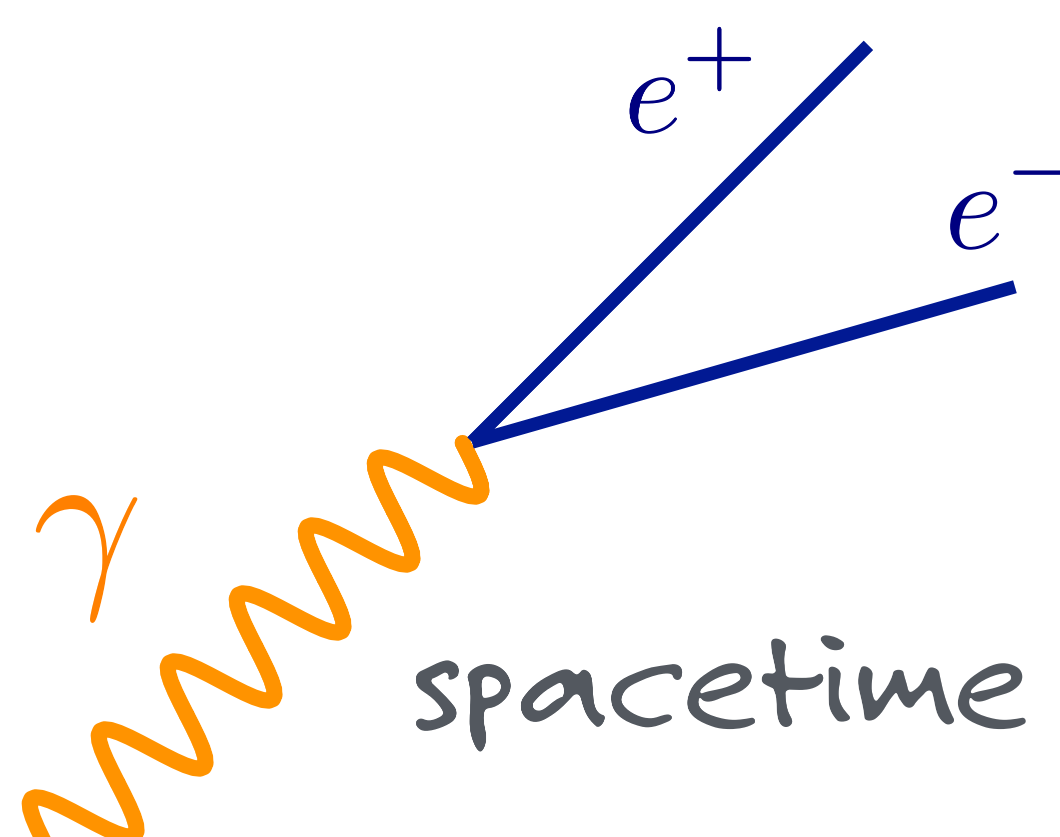
# Dirac's story

## & Feynman's picture



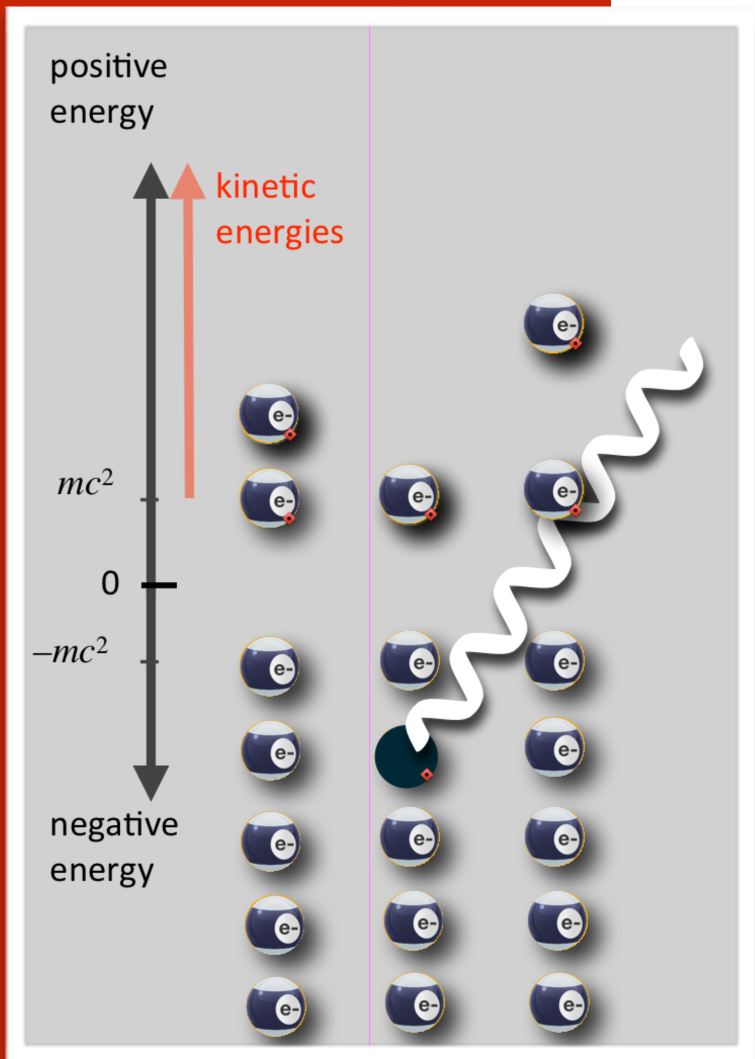



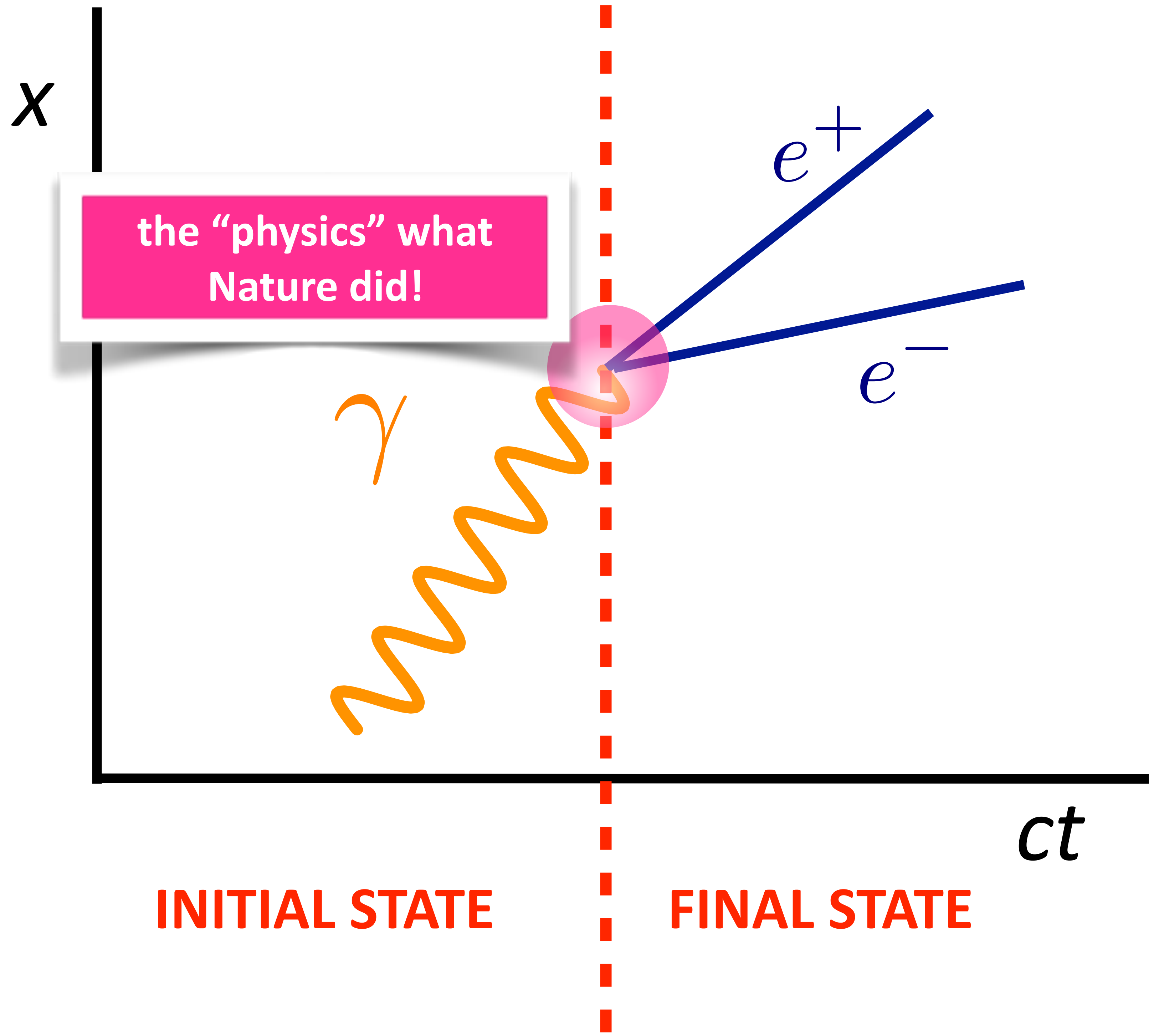
# Dirac had photons creating an electron

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:

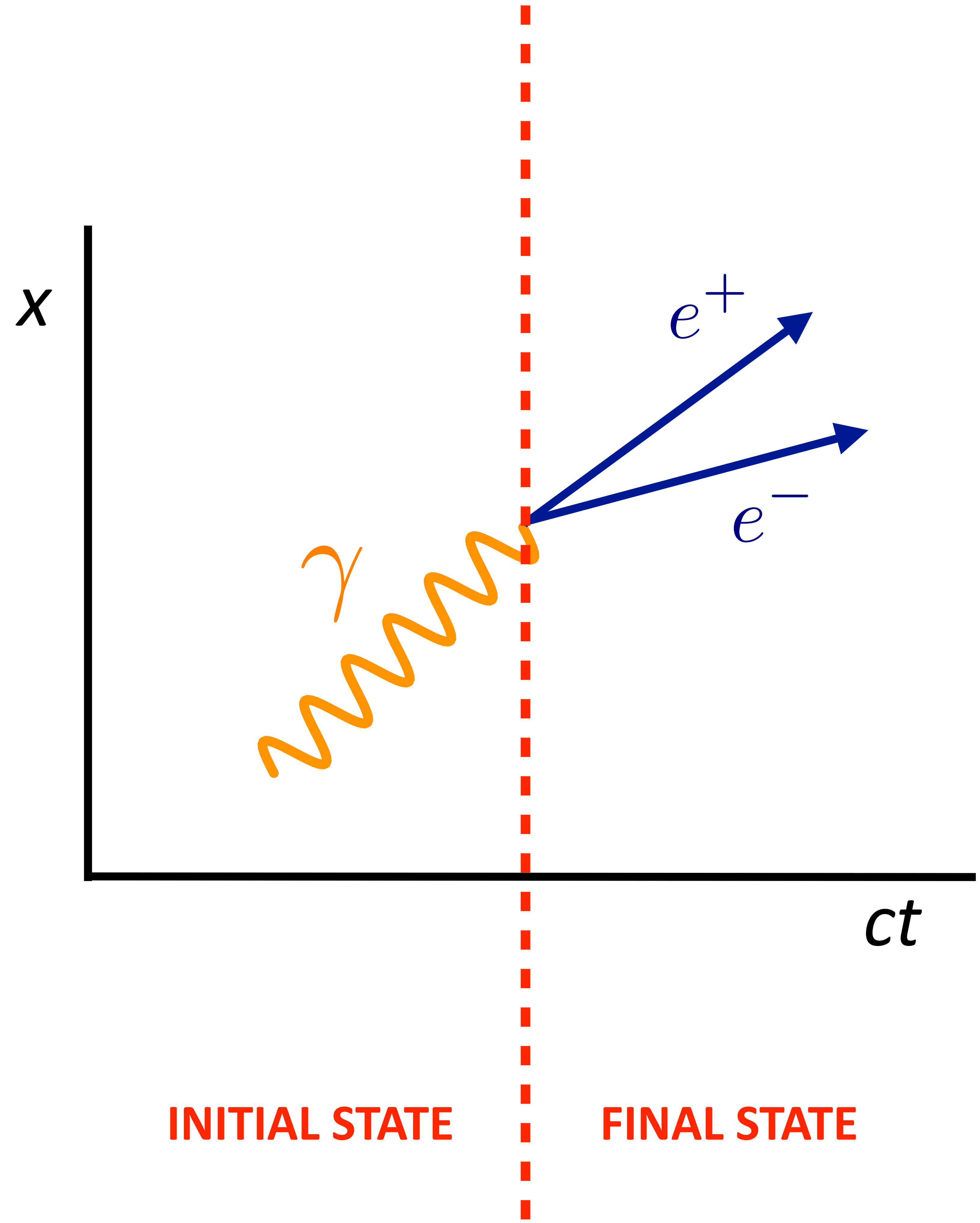
I’ve been banging on you to keep the slopes right

you know, photons have slope associated with c

We’ll relax that now.

# can always rotate any Feynman Graph

and get a new one



# BUT

We don't deal with particles moving backwards in time

when it happens...we fix it!

# Feynman's trick

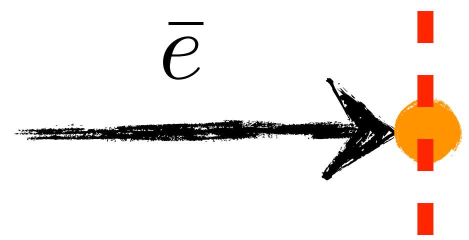
depends on the in and out states.

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

*fix it.*

# particles in time

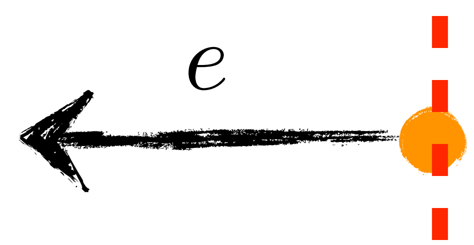
An anti-electron...coming **into** an **initial** state to a node:




Yes, this makes sense

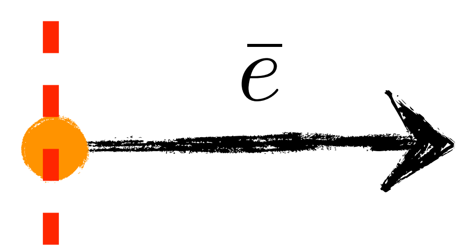
*is the same thing as*

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

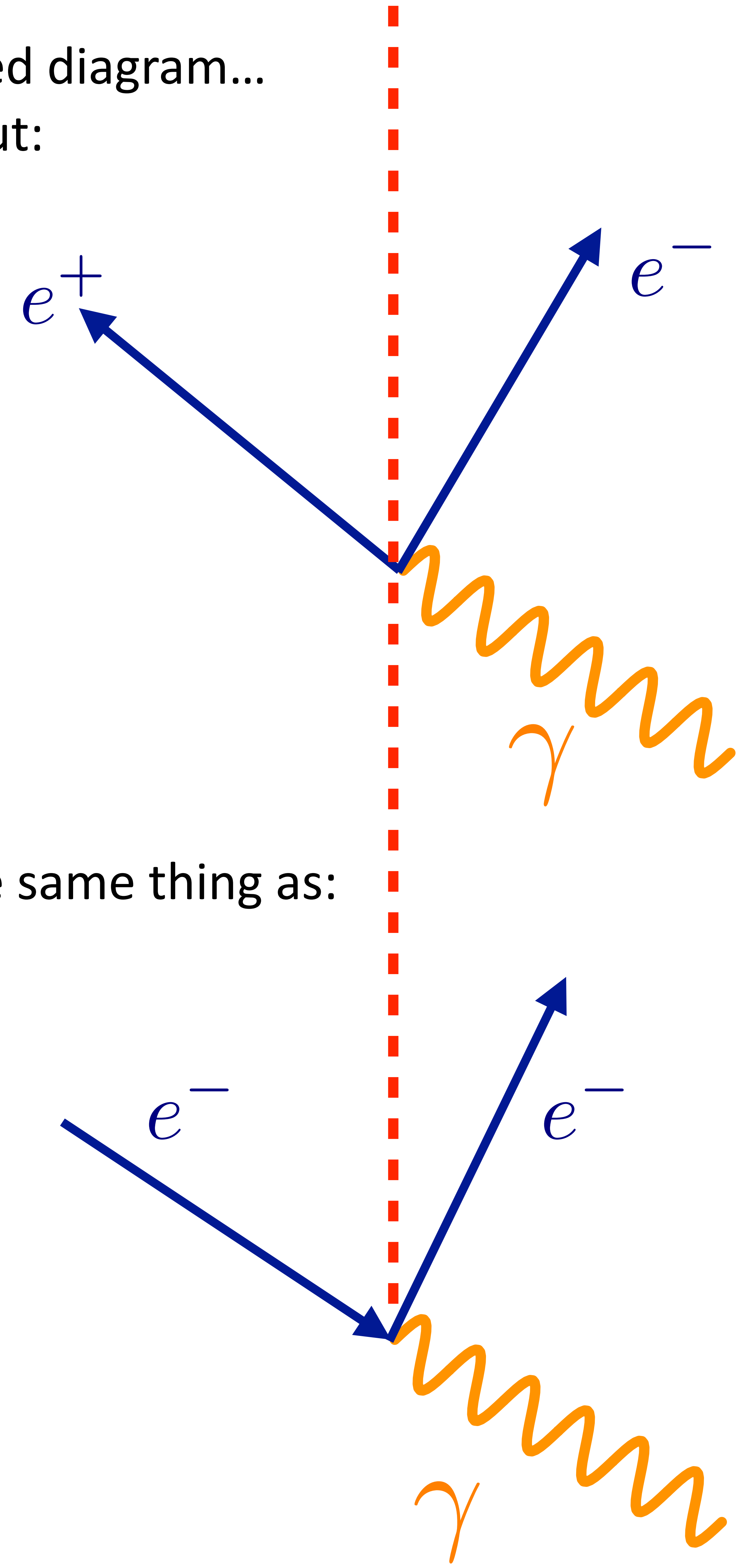
but similar in spirit

# 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:

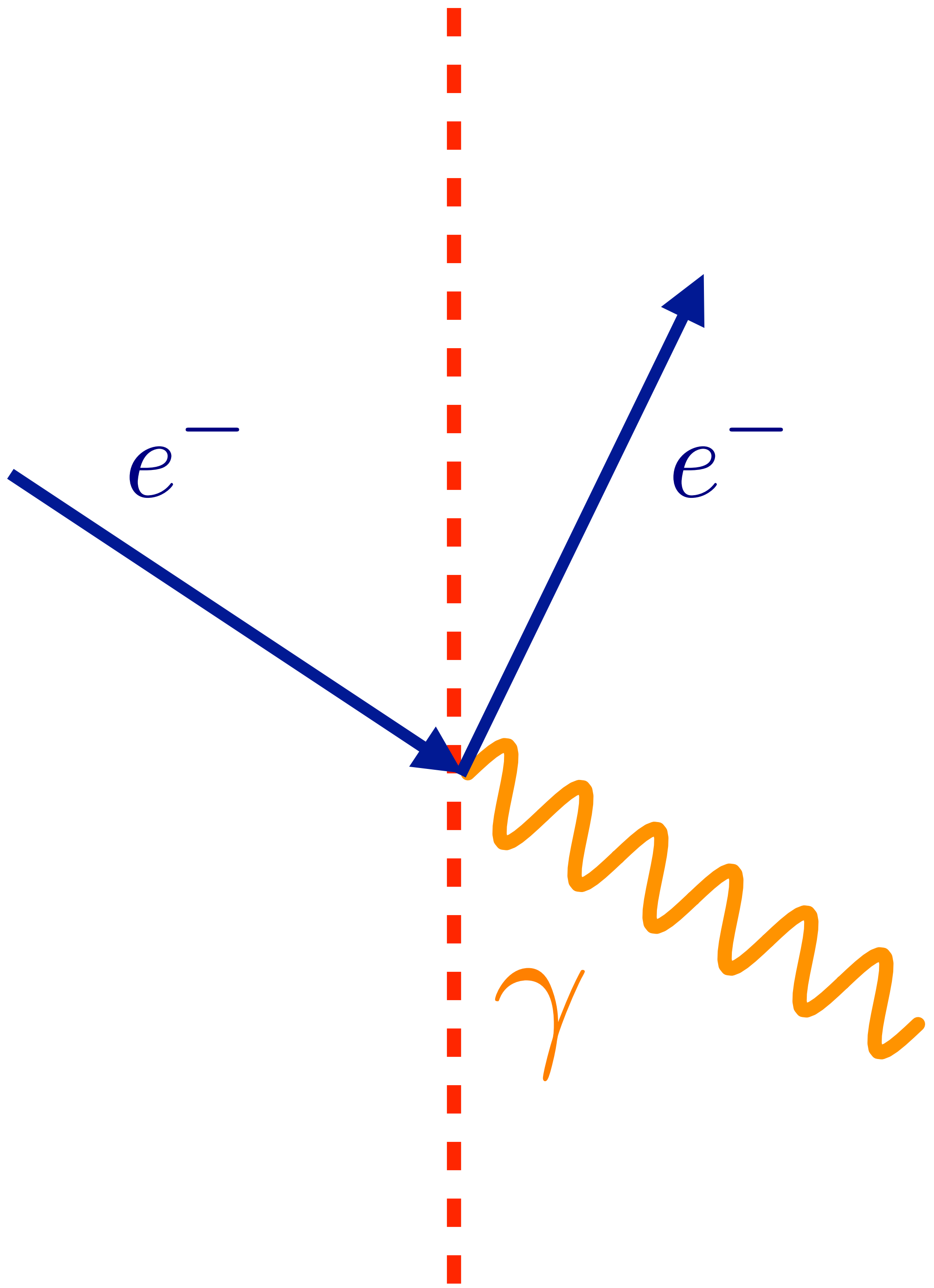
this is the same thing as:



# look at this

you know this.

familiar:



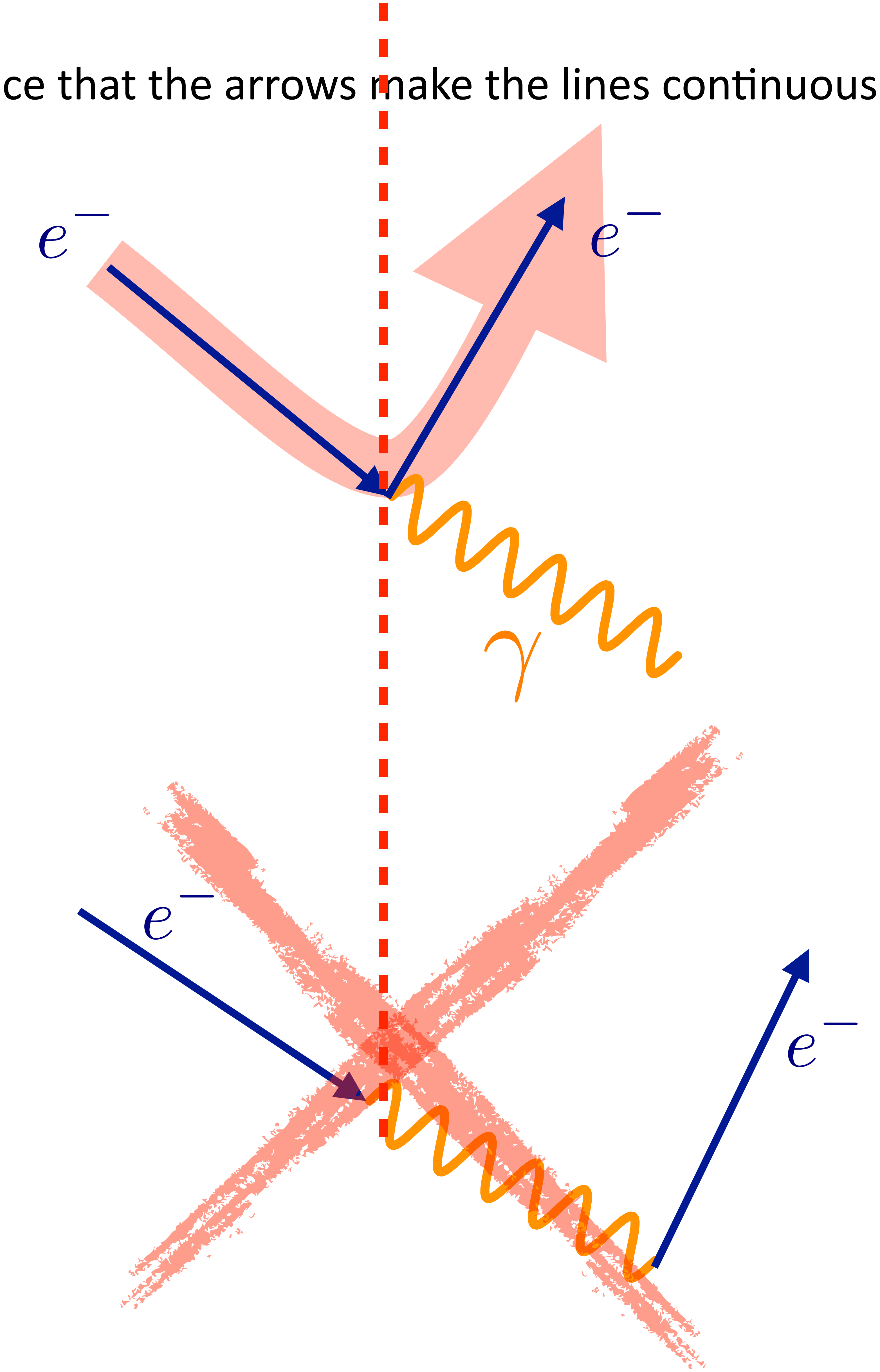

electron comes along and spits out a photon, recoils and goes on its way

**regular old radiation**

# Rule 2.

fermion lines must be continuous

notice that the arrows make the lines continuous

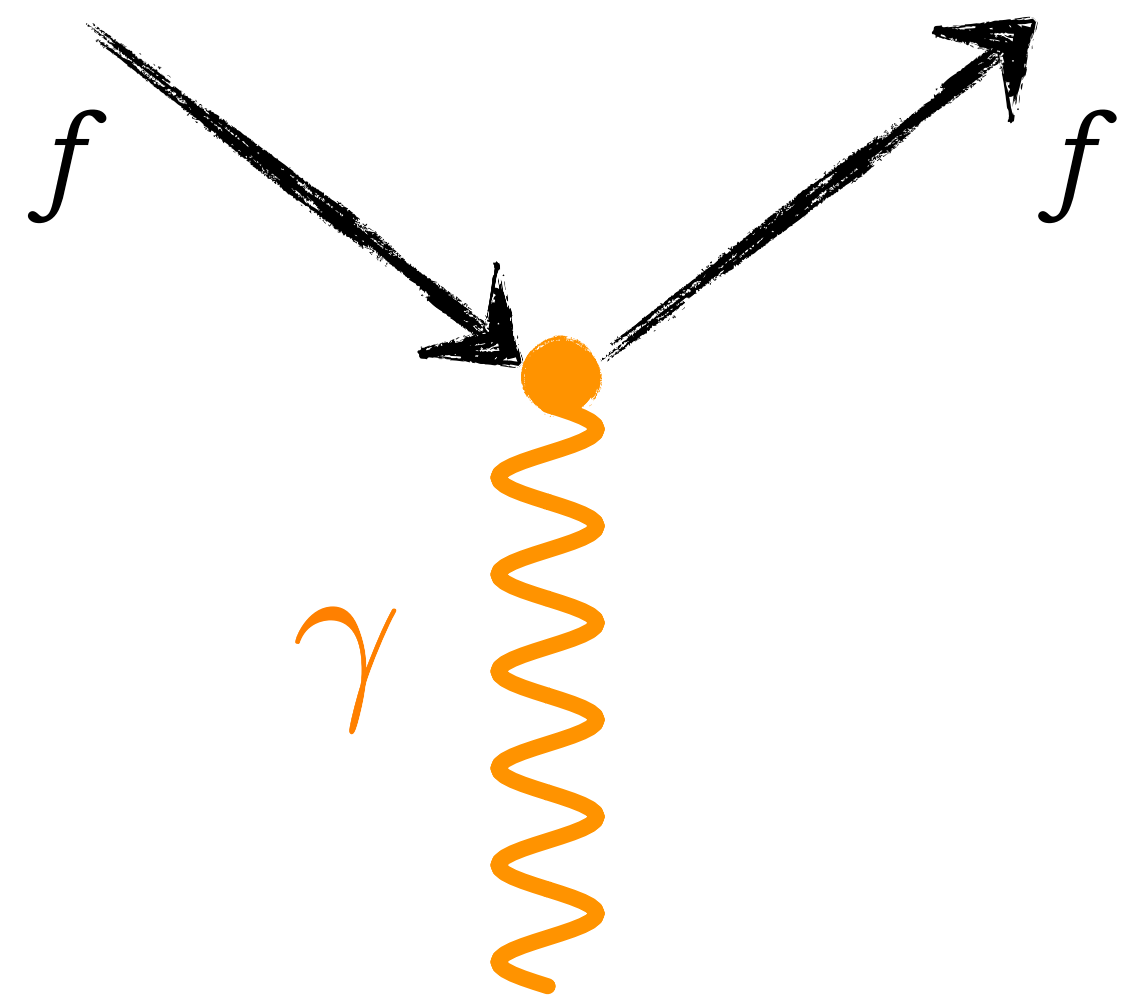



This and more is in those 3 movies

# primitive diagrams

are general

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

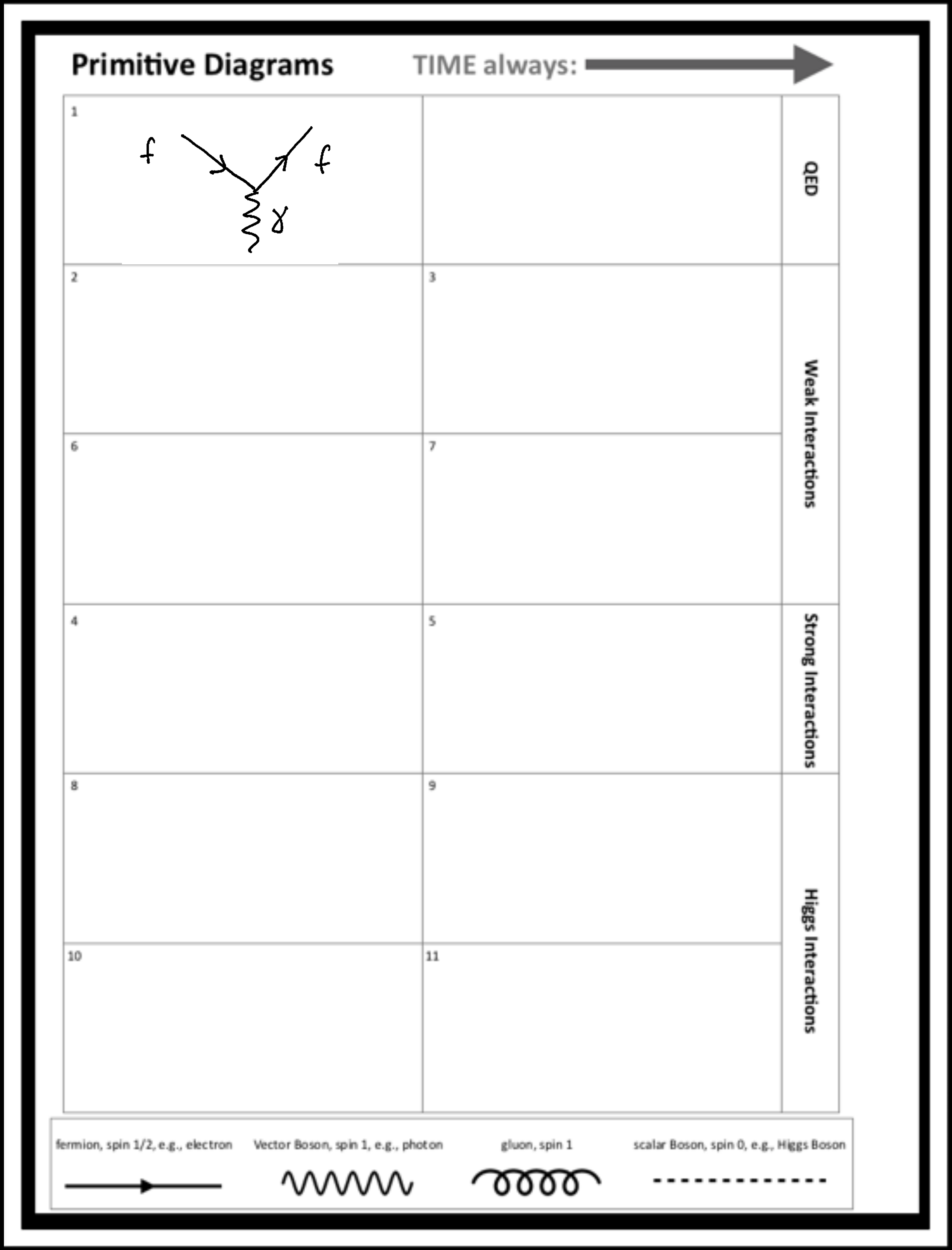



$f$ could be electron, positron, proton, antiproton...and more – any electrically charged **f**ermion.

Their diagrams are identical.

Primitive Diagram Scorecard

your first entry



# particle physics

particle:

# neutron

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

particle: **proton**

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

# important realizations

nuclear force

exchange force

weak force: neutrinos

# beta decay

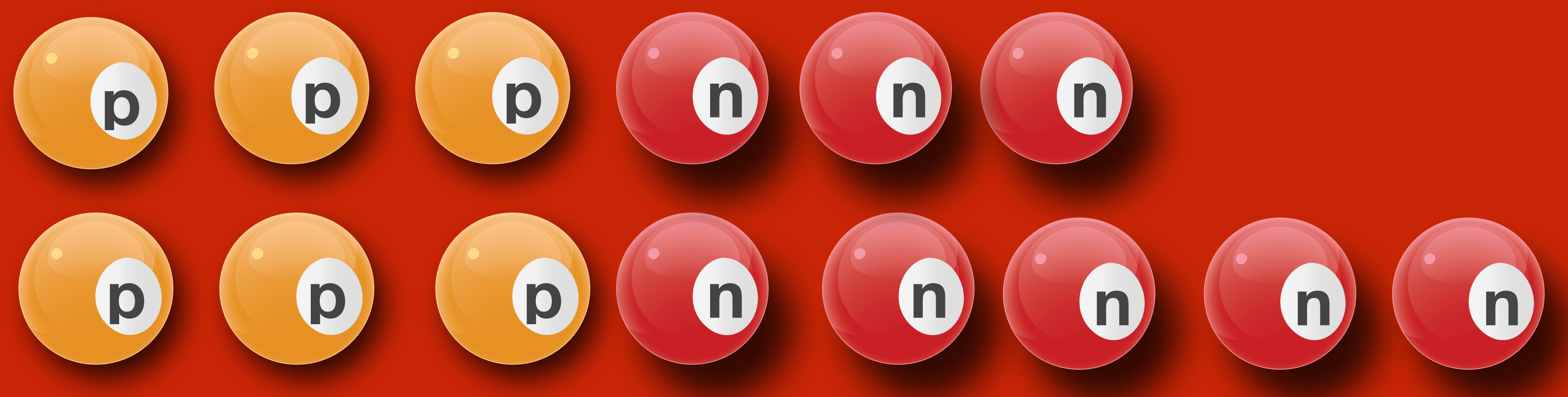
the "weak force"

## 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

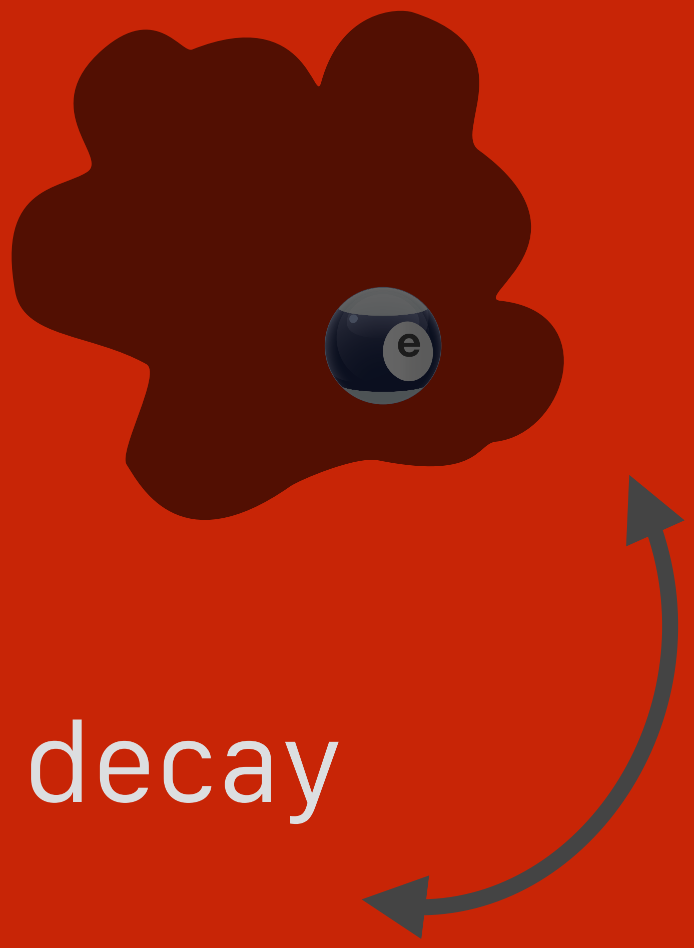
$^{14}C$: trace & unstable

# some isotopes are unstable

they beta-decay

14C: trace amounts & unstable

But there was a problem with beta decay

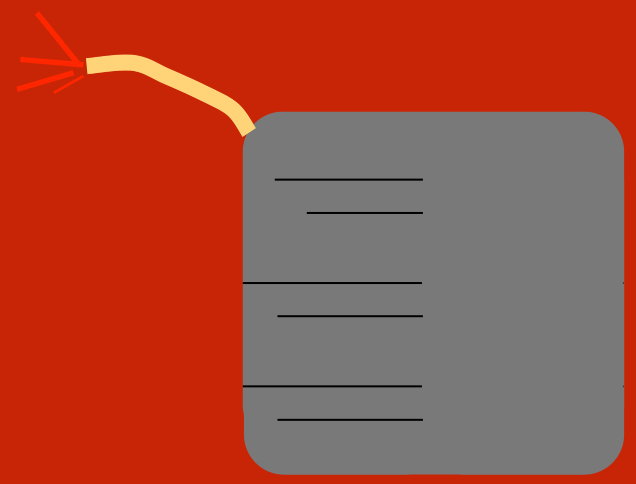



notice the funny recoil?

**Suppose we have a firecracker exploding into two pieces:**

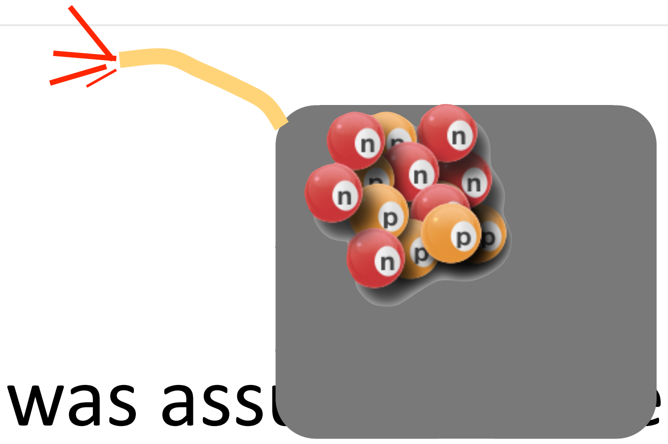
beta decay seemed like this

when you expect this



# energies in a “two body decay”

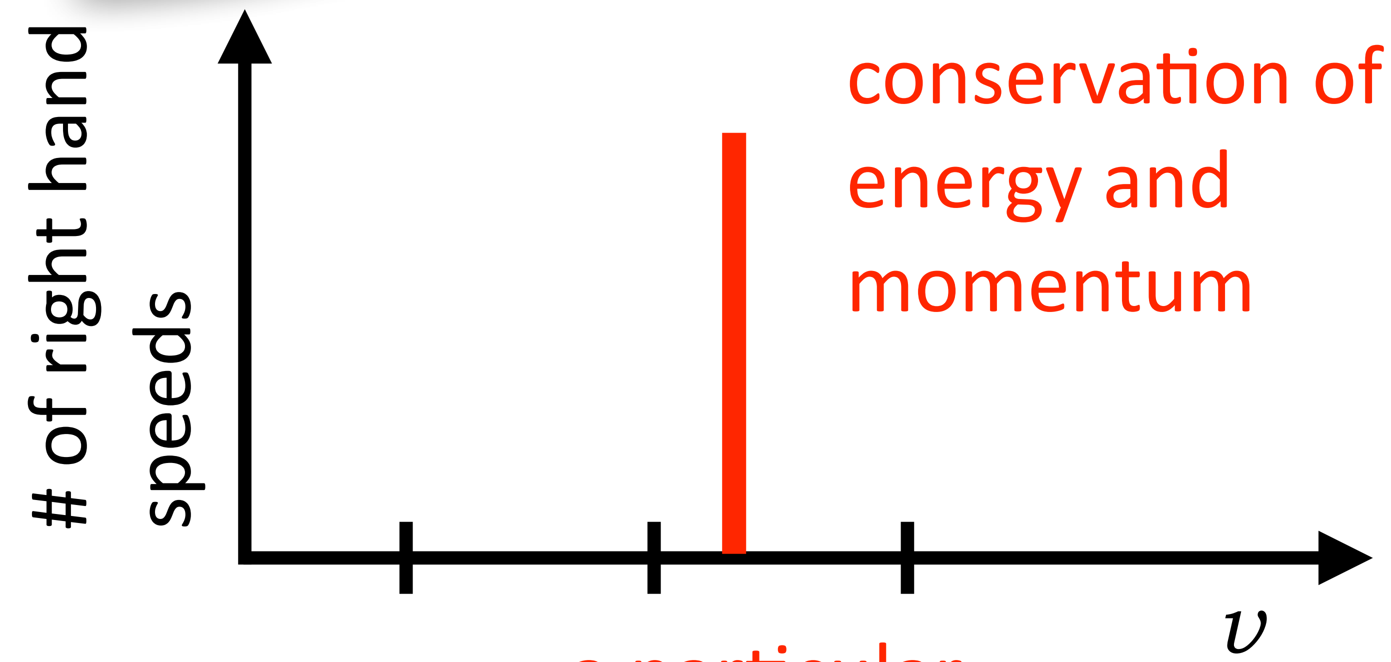
are single-valued



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

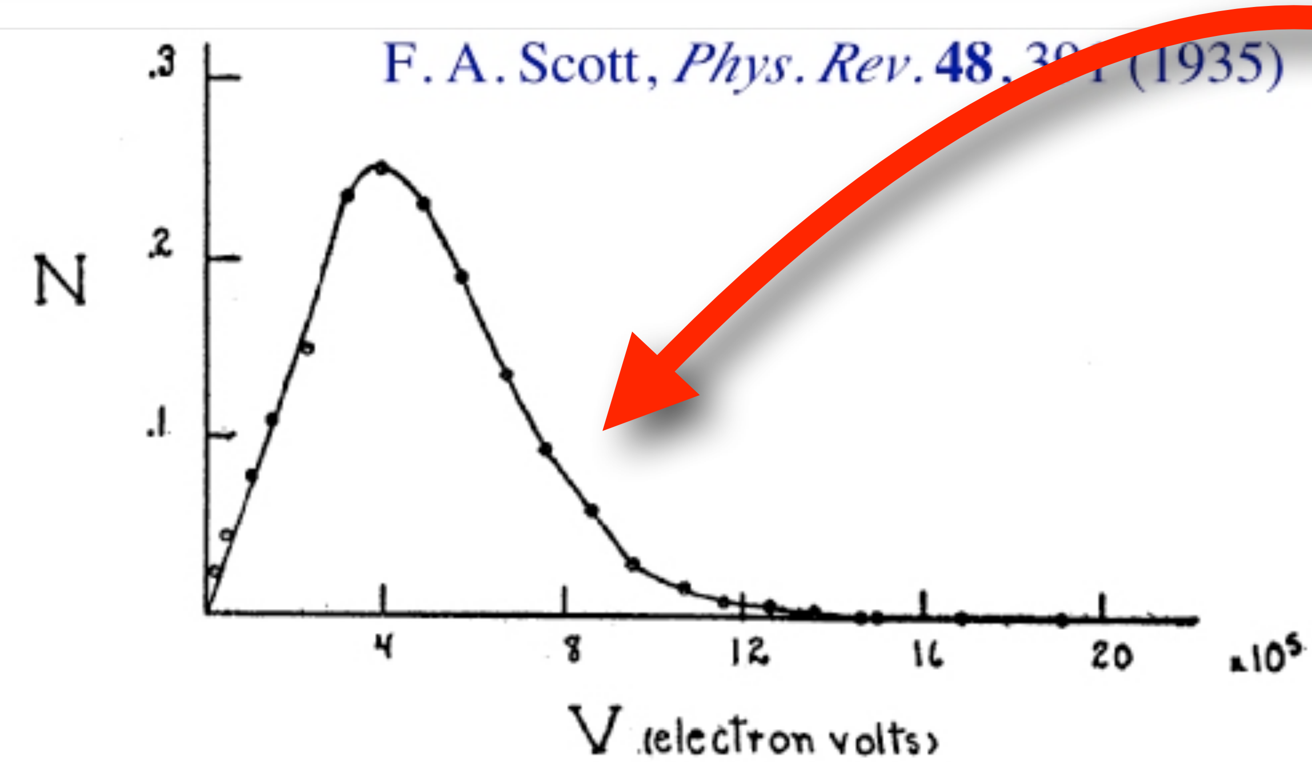


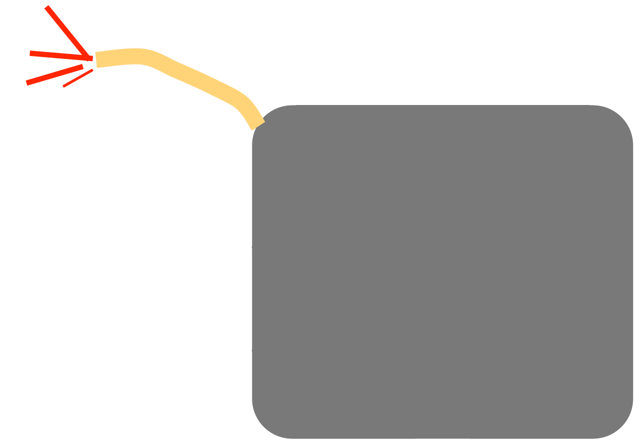

FIG. 5. Energy distribution curve of the beta-rays.

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

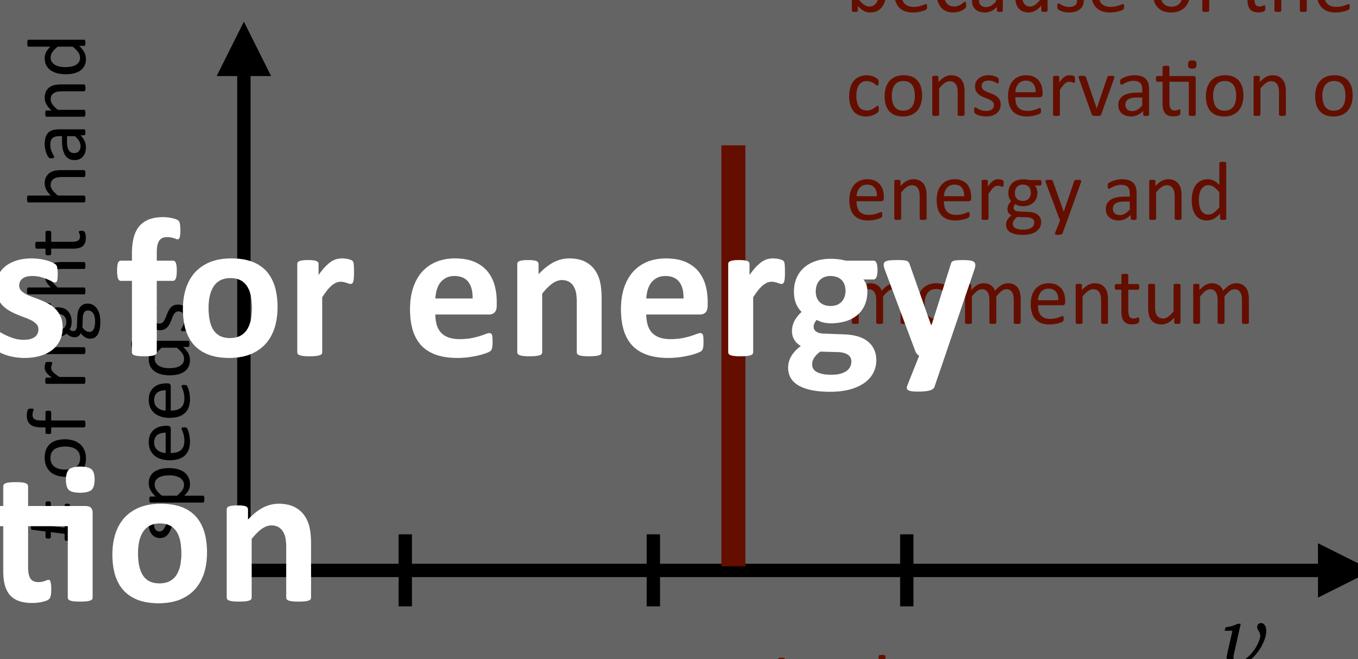
# suppose you have a "two body

a single object decays into two objects

# an apparent crisis for energy conservation



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




because of the conservation of energy and momentum

a particular value

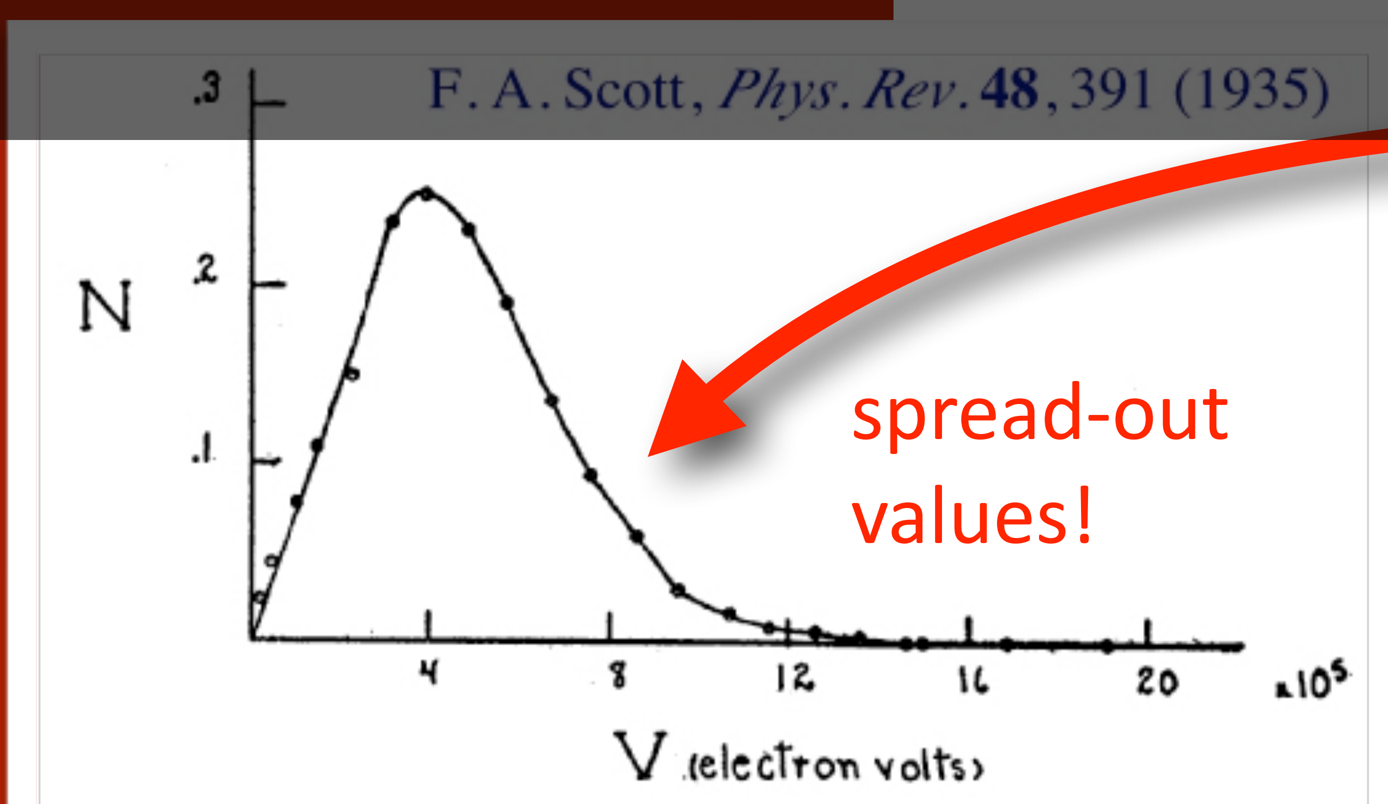
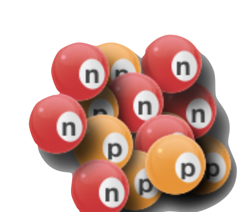



FIG. 5. Energy distribution curve of the beta-rays.

spread-out values!

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



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

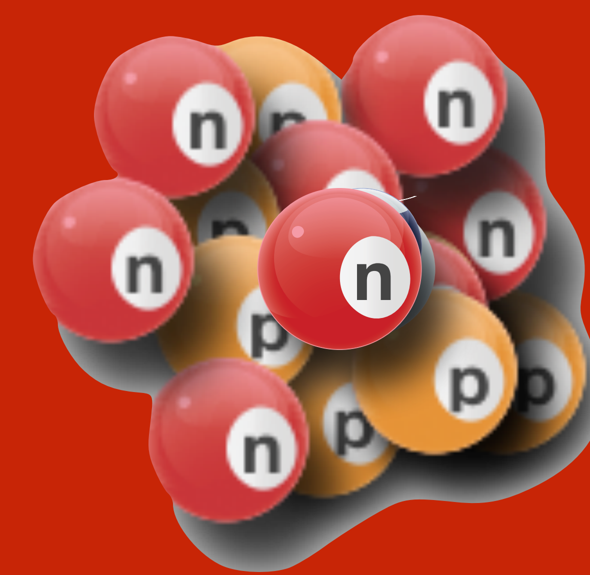
…unfortunately I cannot appear personally in Tubingen since a ball which takes place in Zurich makes my presence here indispensable.”

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



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

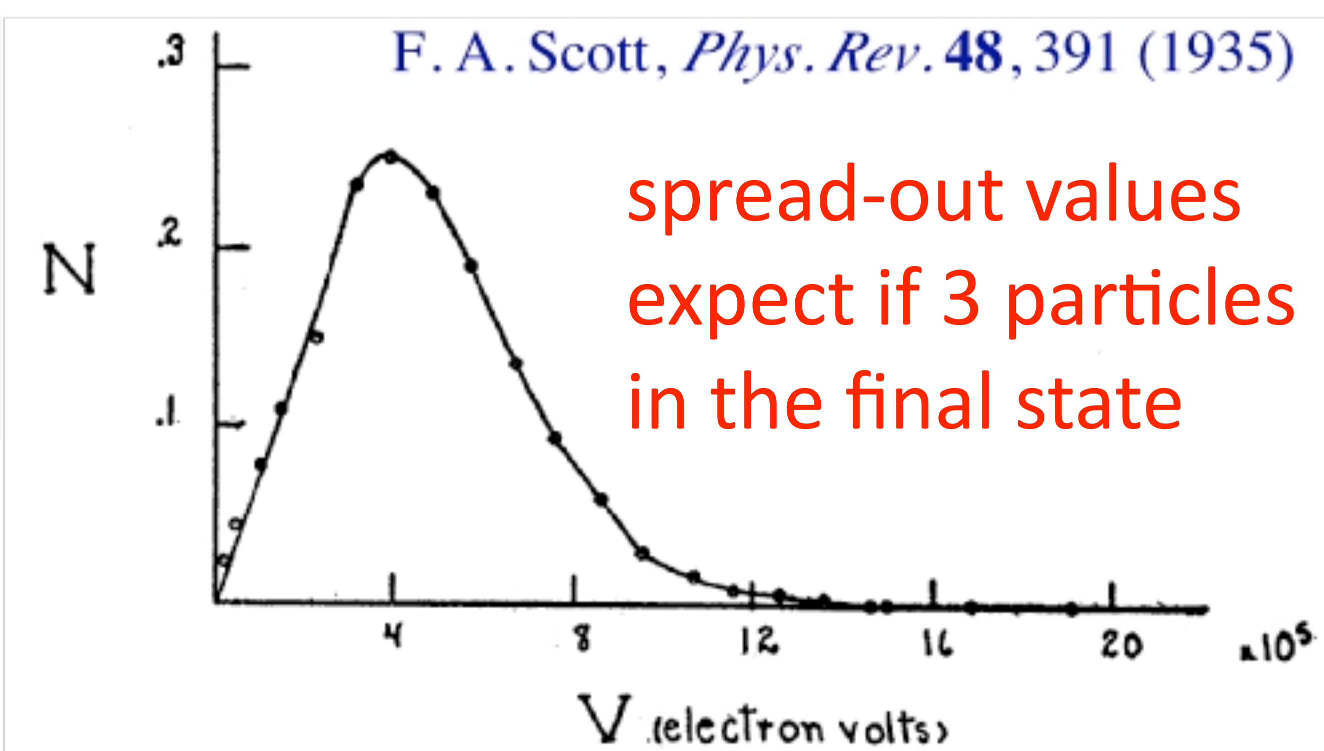
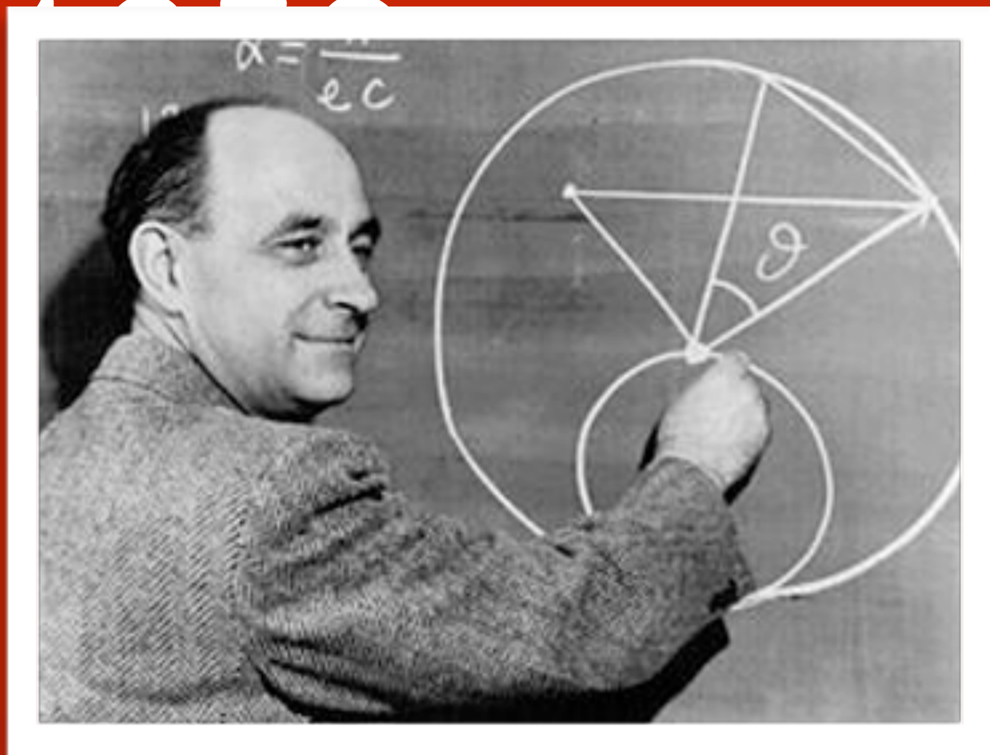


FIG. 5. Energy distribution curve of the beta-rays.

spread-out values
expect if 3 particles
in the final state

cay 1933

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



Enrico Fermi

1901-1954

experimental &

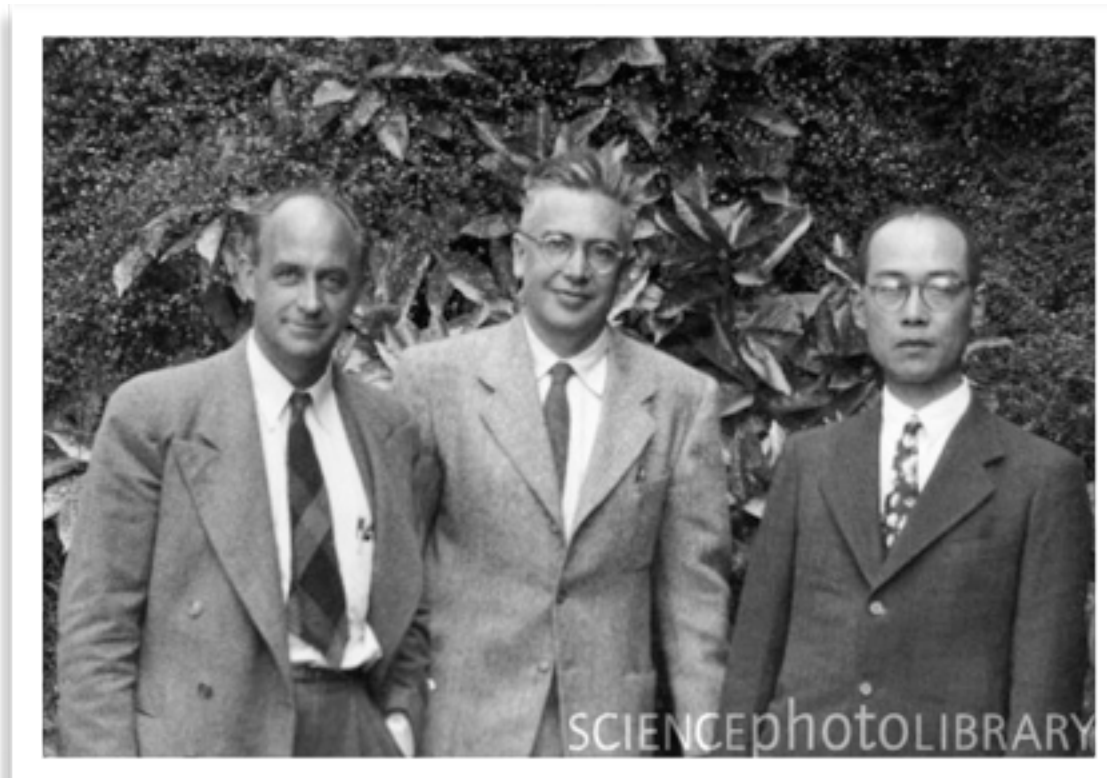
theoretical physicist!

Nobel Laureate 1938

Probably 2, maybe 3 Nobel prize-worthy experiments.

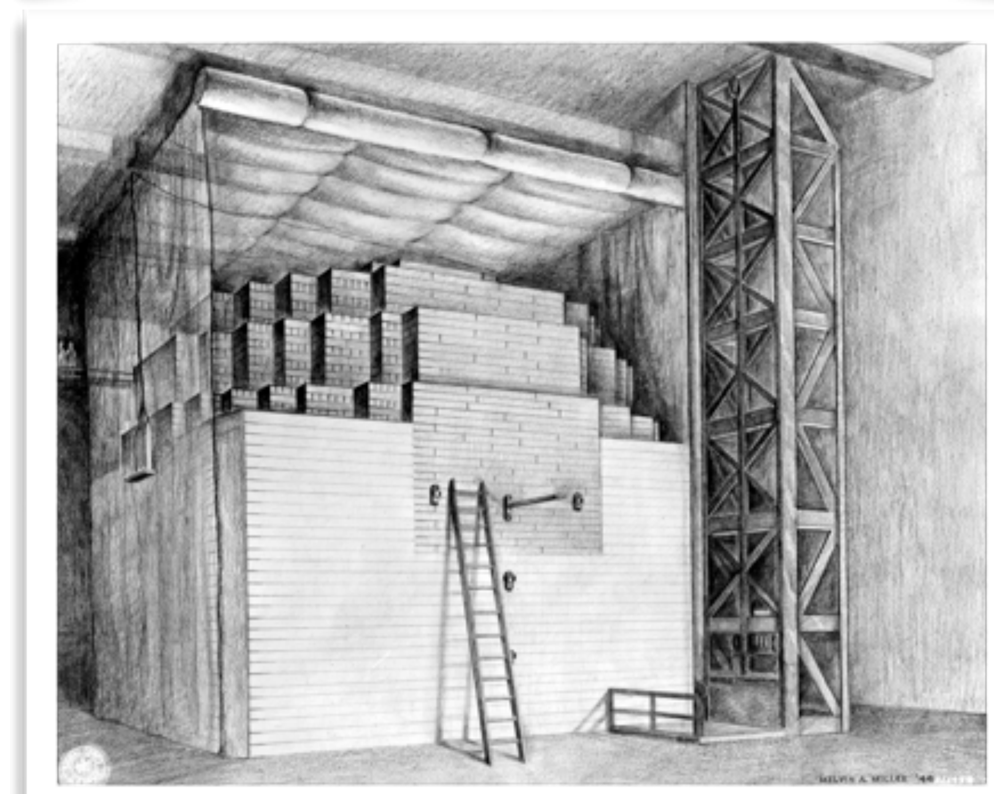
Probably 2, maybe 3 Nobel prize-worthy theoretical products.

**There will never be anyone like Enrico Fermi again.**





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



# 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

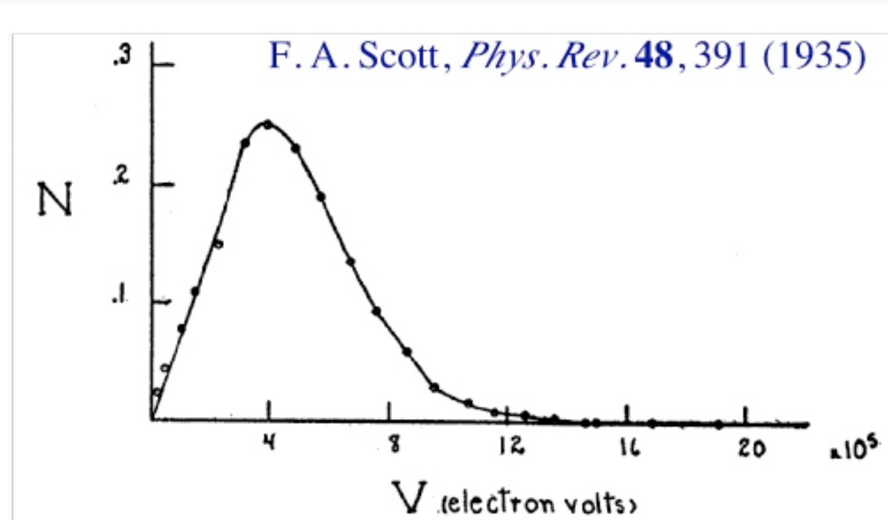
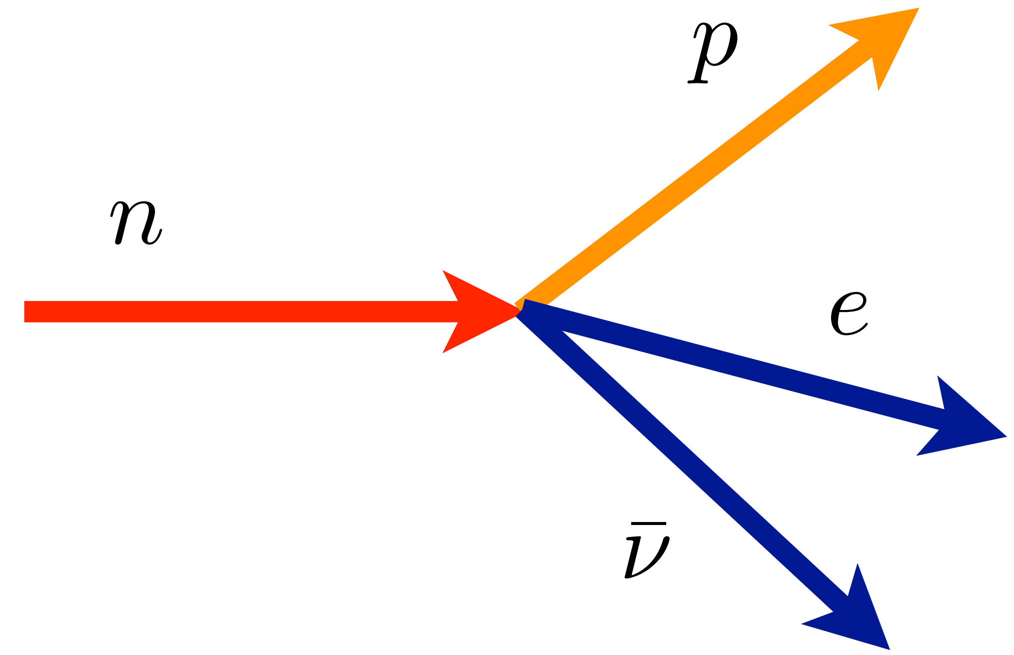



FIG. 5. Energy distribution curve of the beta-rays.

$m_{neutron} > m_{proton}$

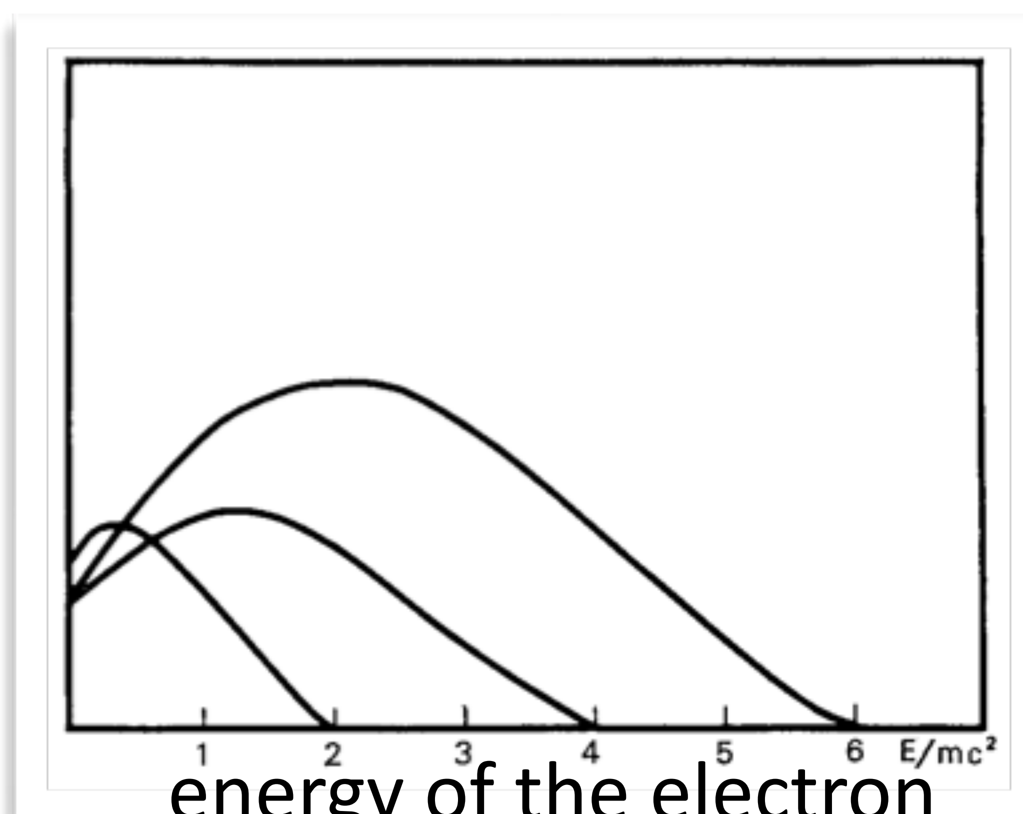
a smidgen.




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”




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

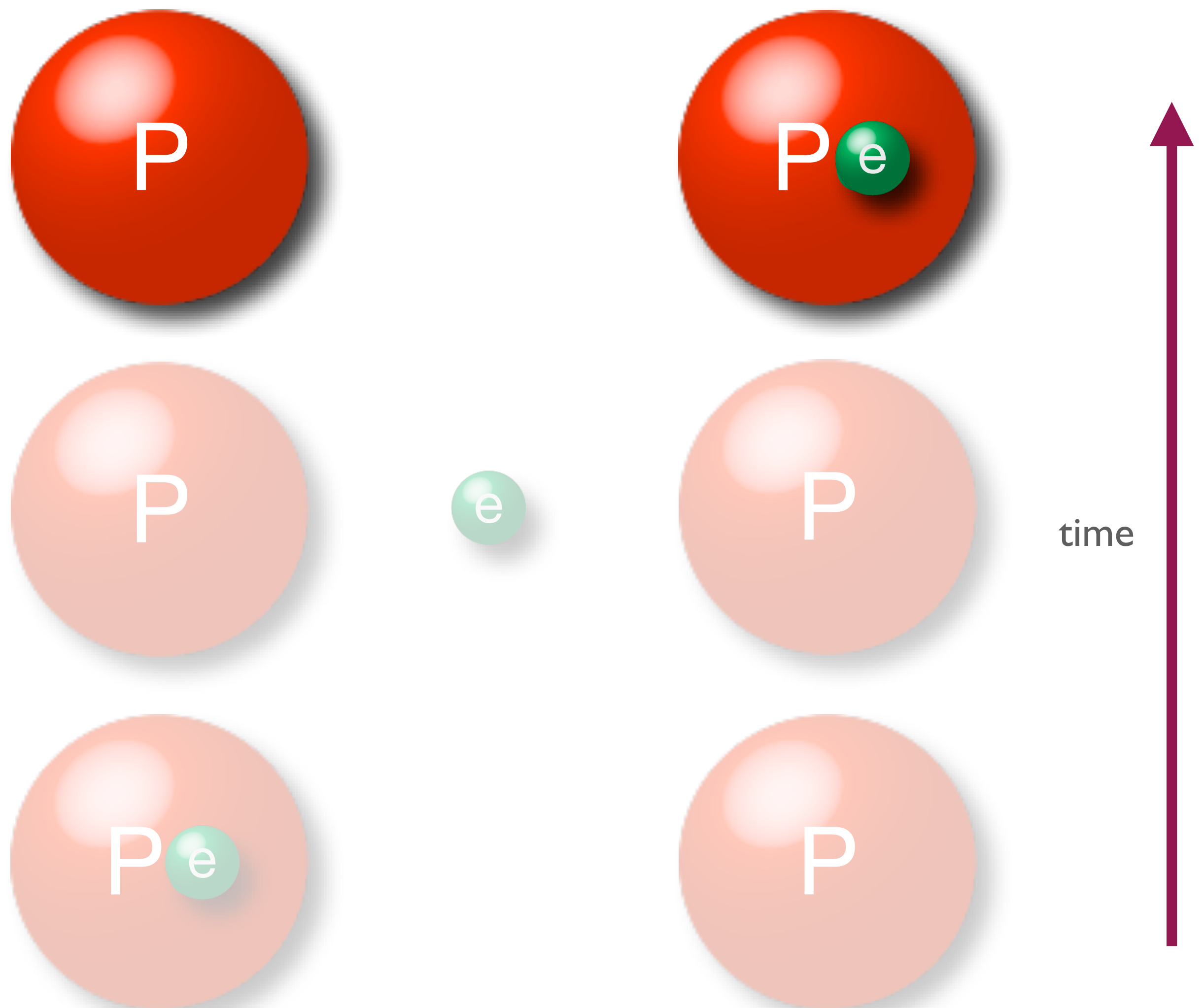
The proton is playing catch with itself

with all he knew about: electrons and protons

maybe beta decay?

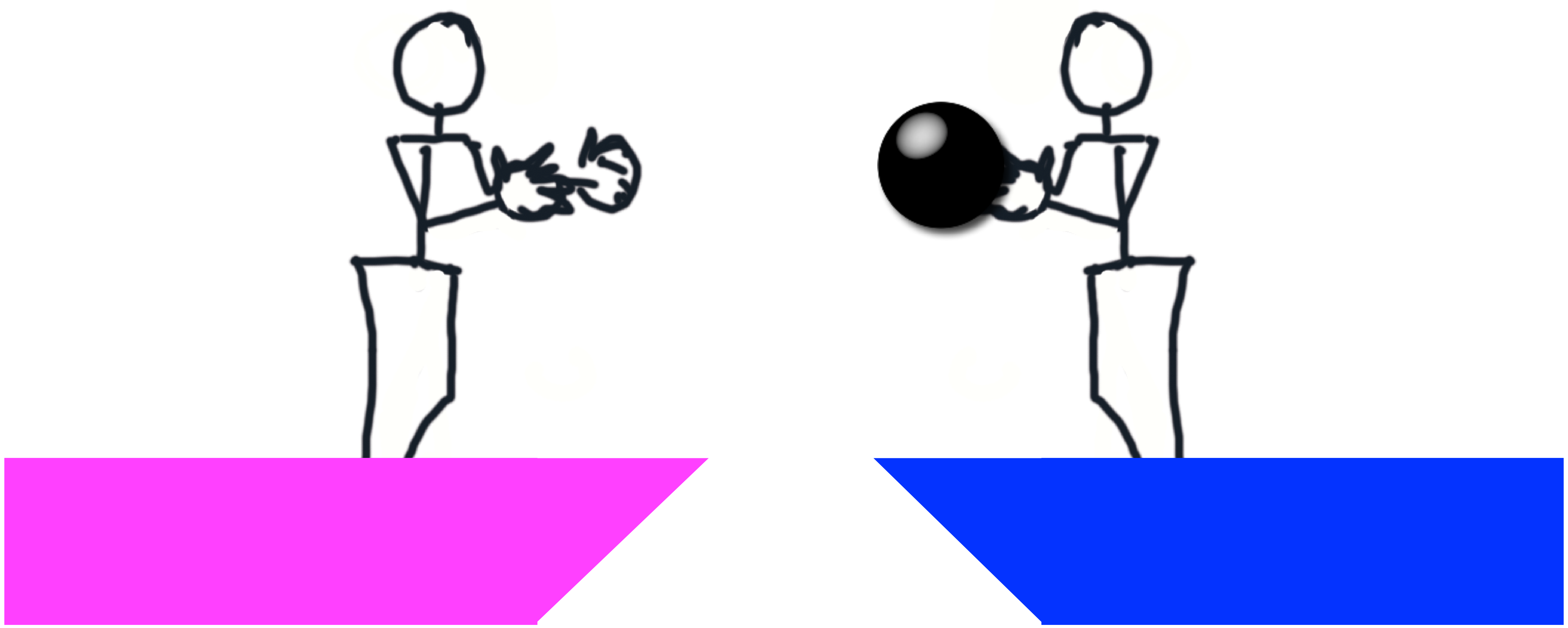
He knew that sometimes nuclei just spit out an electron.

*Rutherford's beta decay*



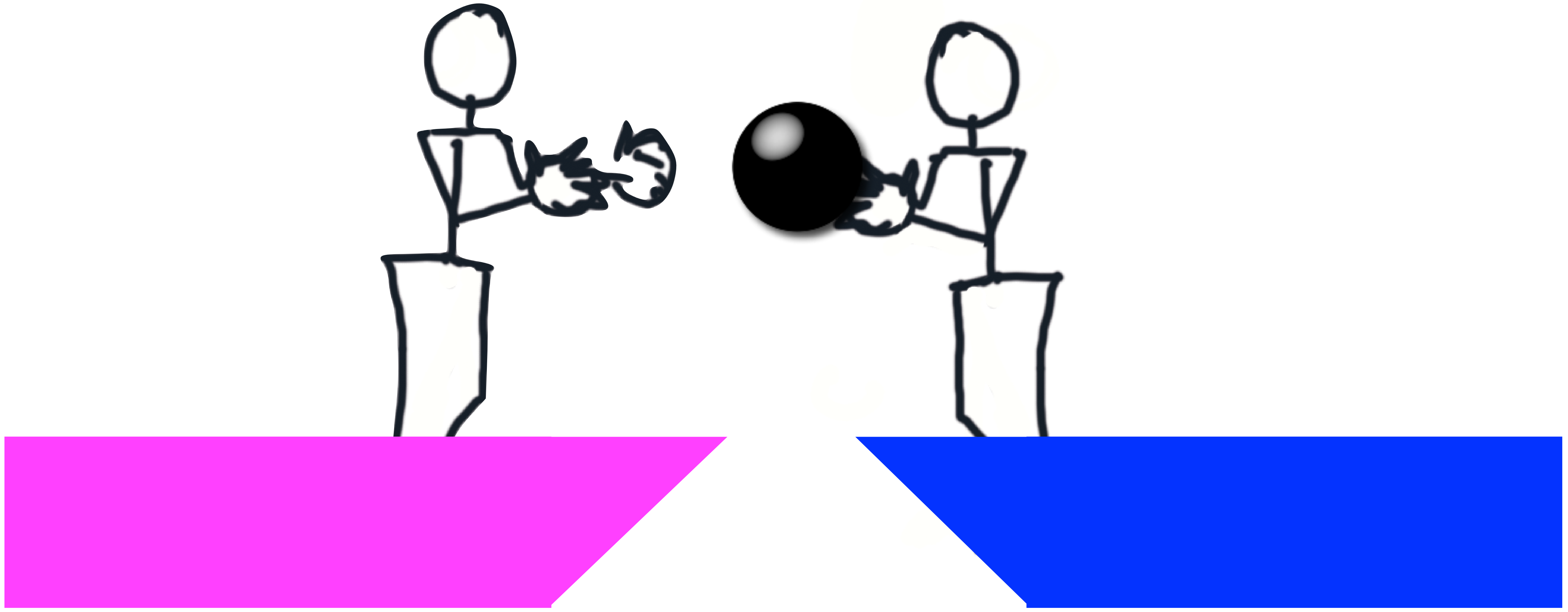
# analogy: a repulsive exchange force

a repulsive exchange force



# analogy: an attractive exchange force

an attractive exchange force

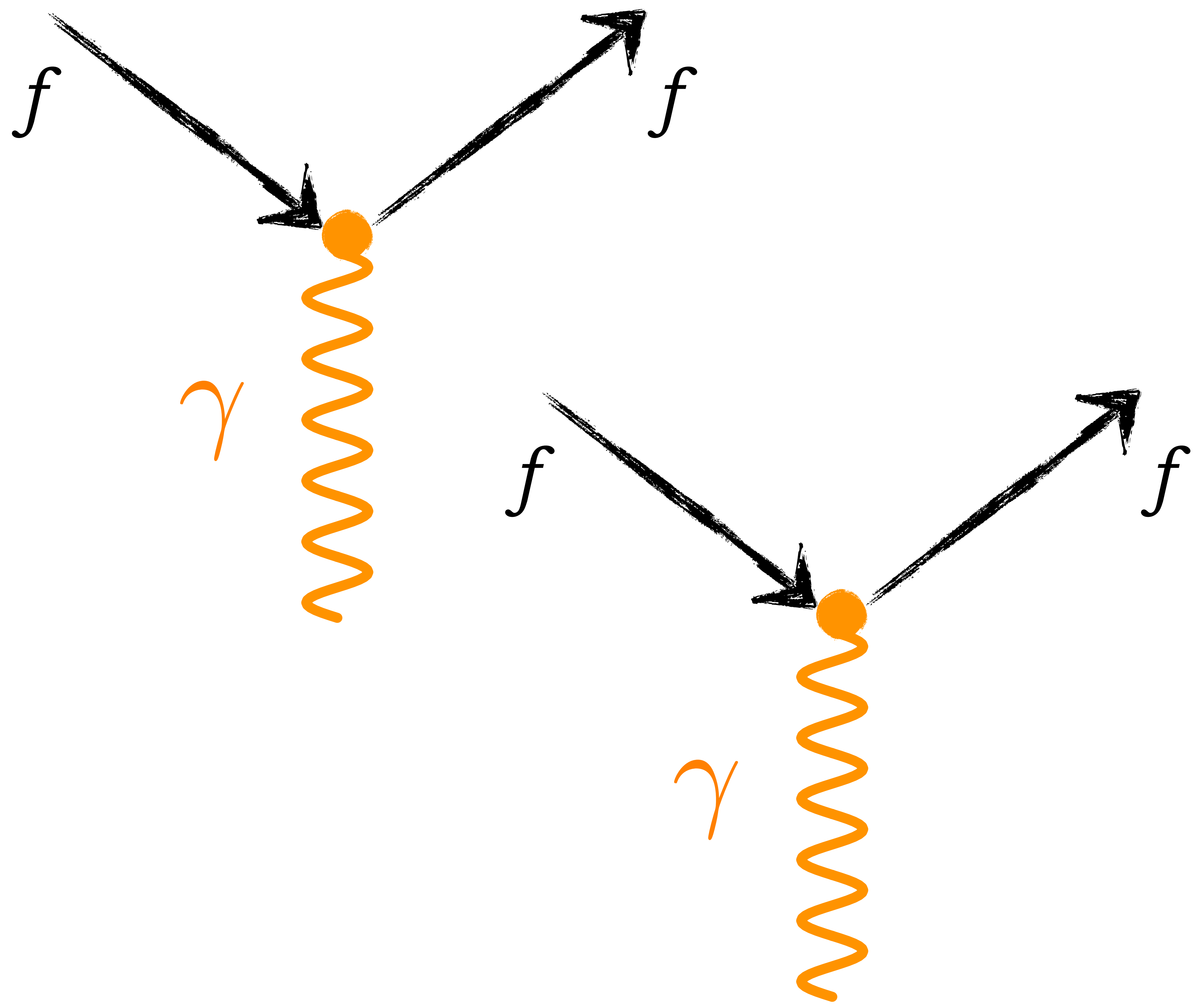


jargon alert: **exchange force**

| | |
|---|---|
| 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

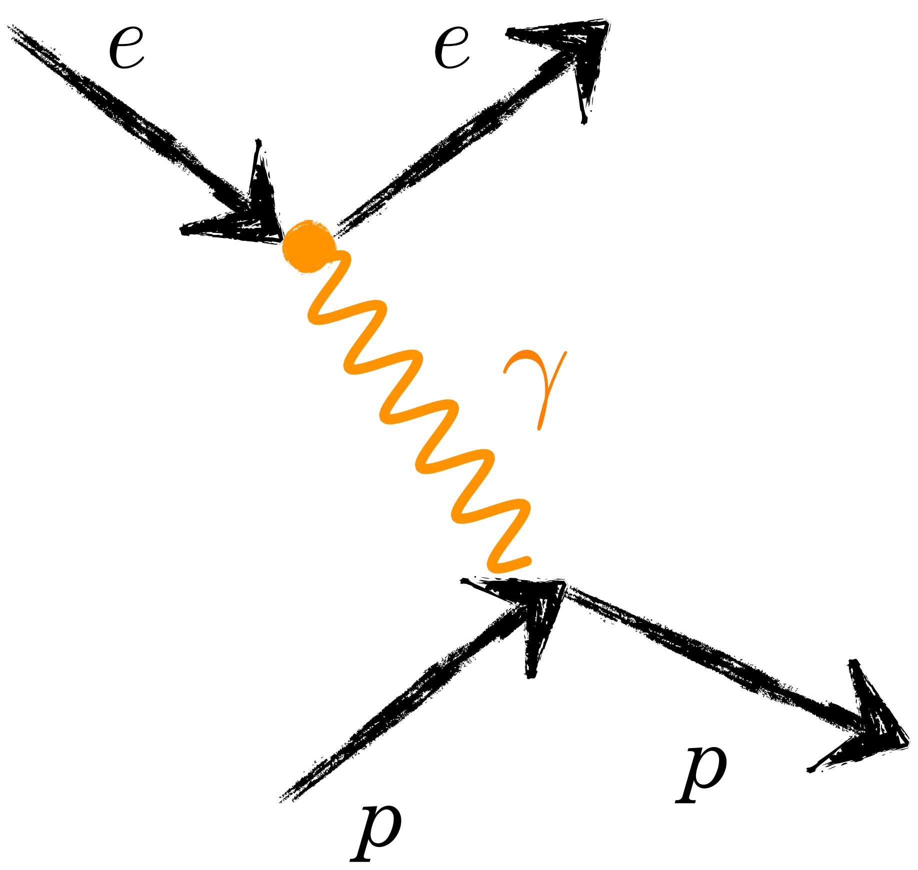
electromagnetism

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.

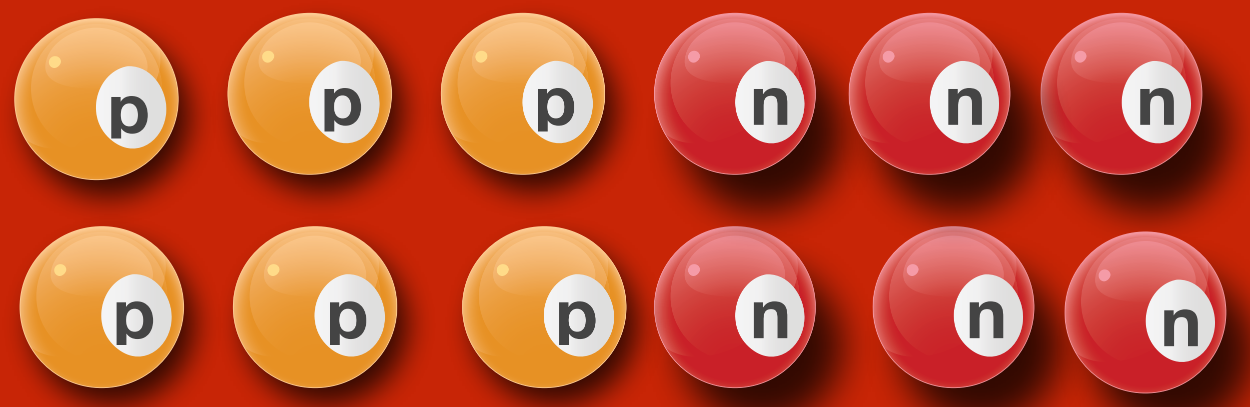
remember:

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

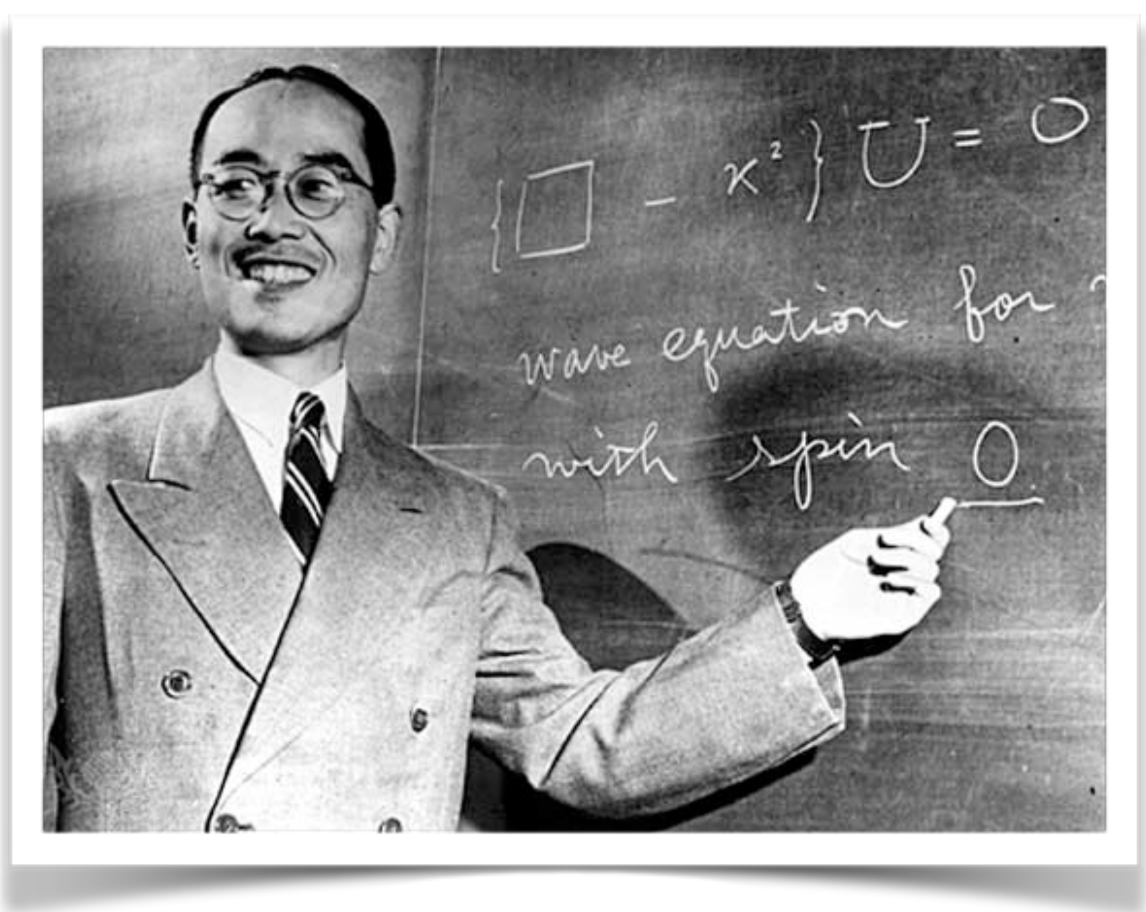
the electrostatic force of repulsion

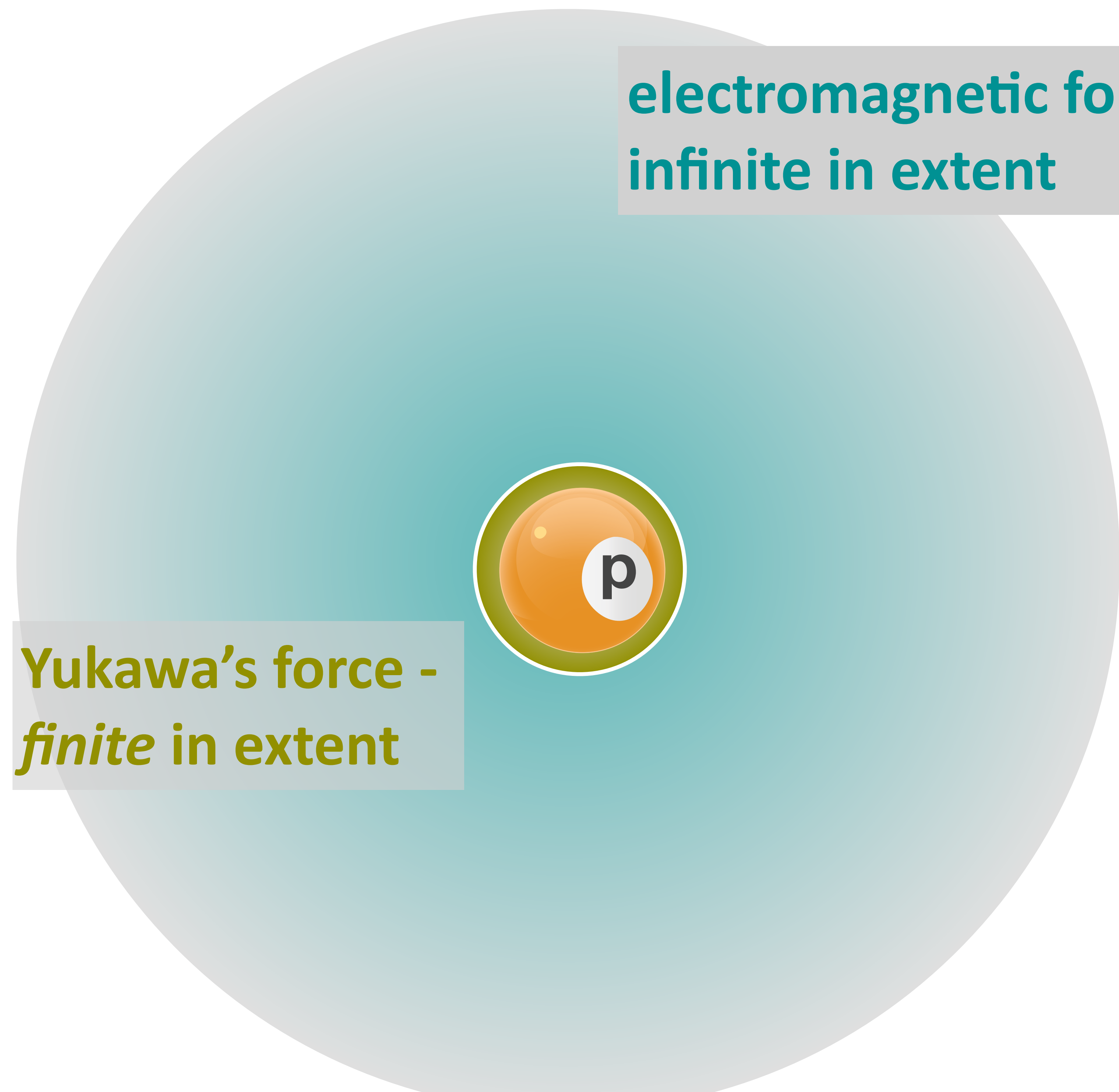
Is countered...by an even stronger force

# Strong Force

1934

Hideki Yukawa

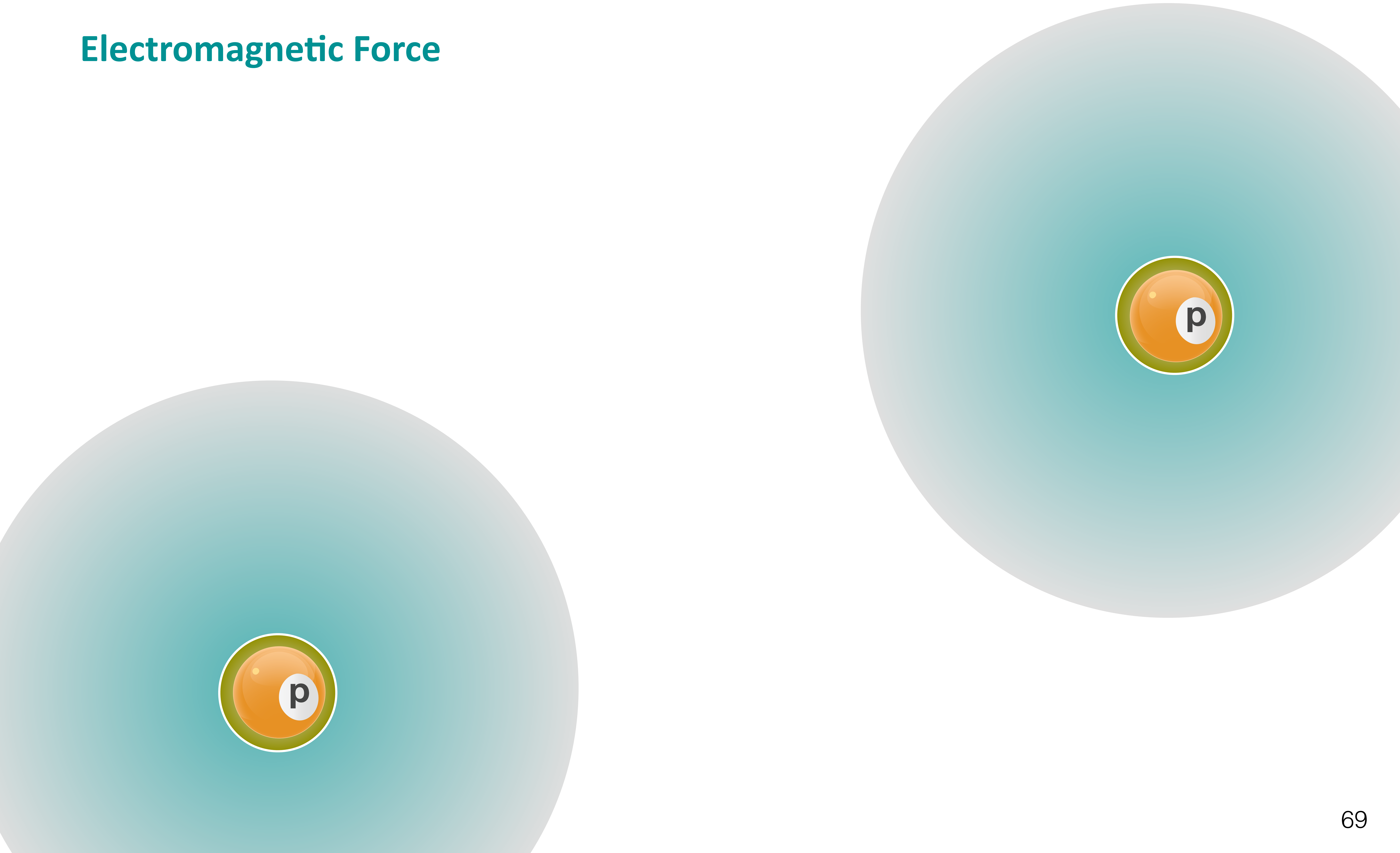




The Strong Force is a stronger than...anything in the universe.

two competing forces:

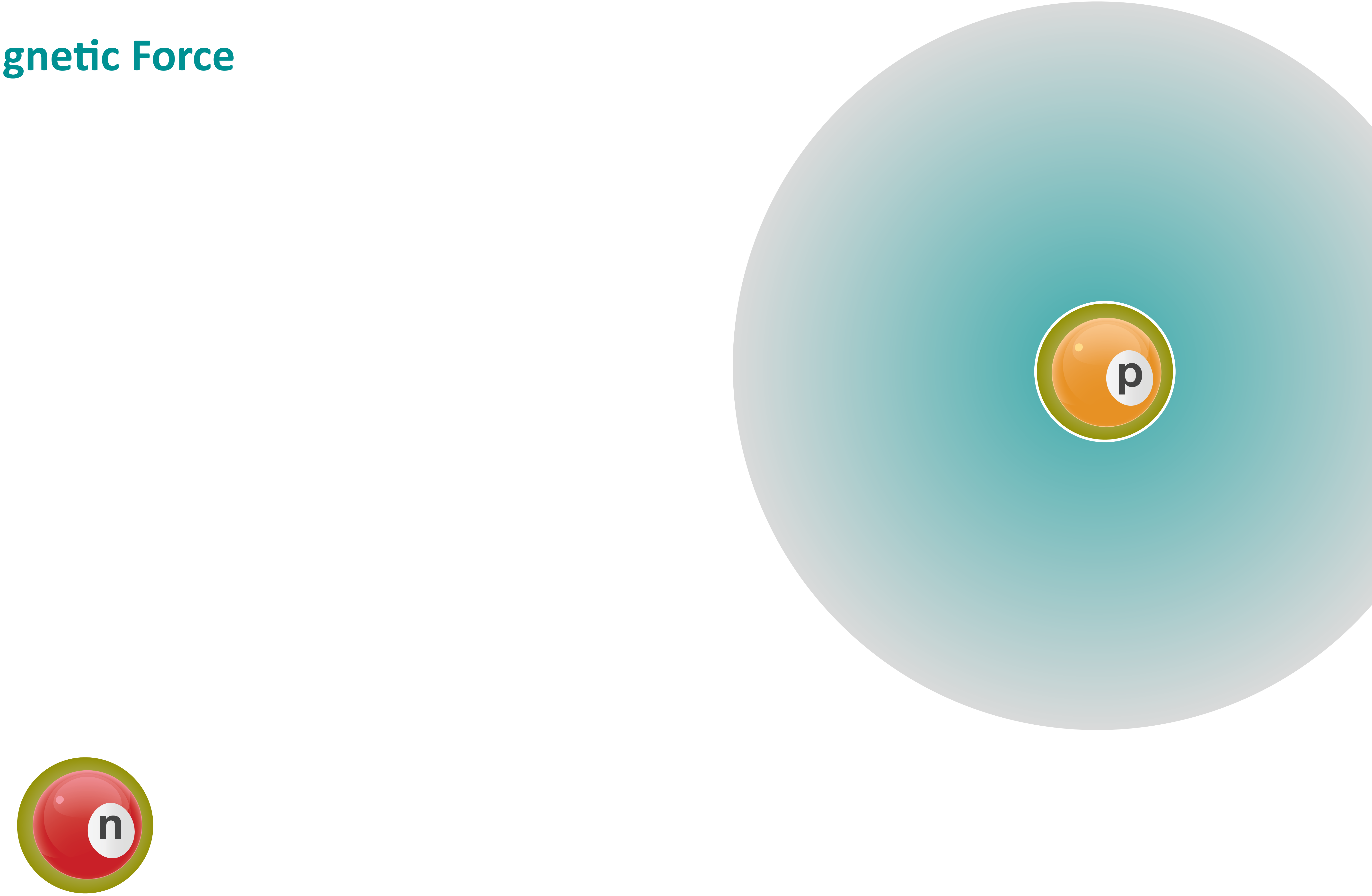
**Electromagnetic Force**



# Strong is stronger than...anything.

two competing forces:

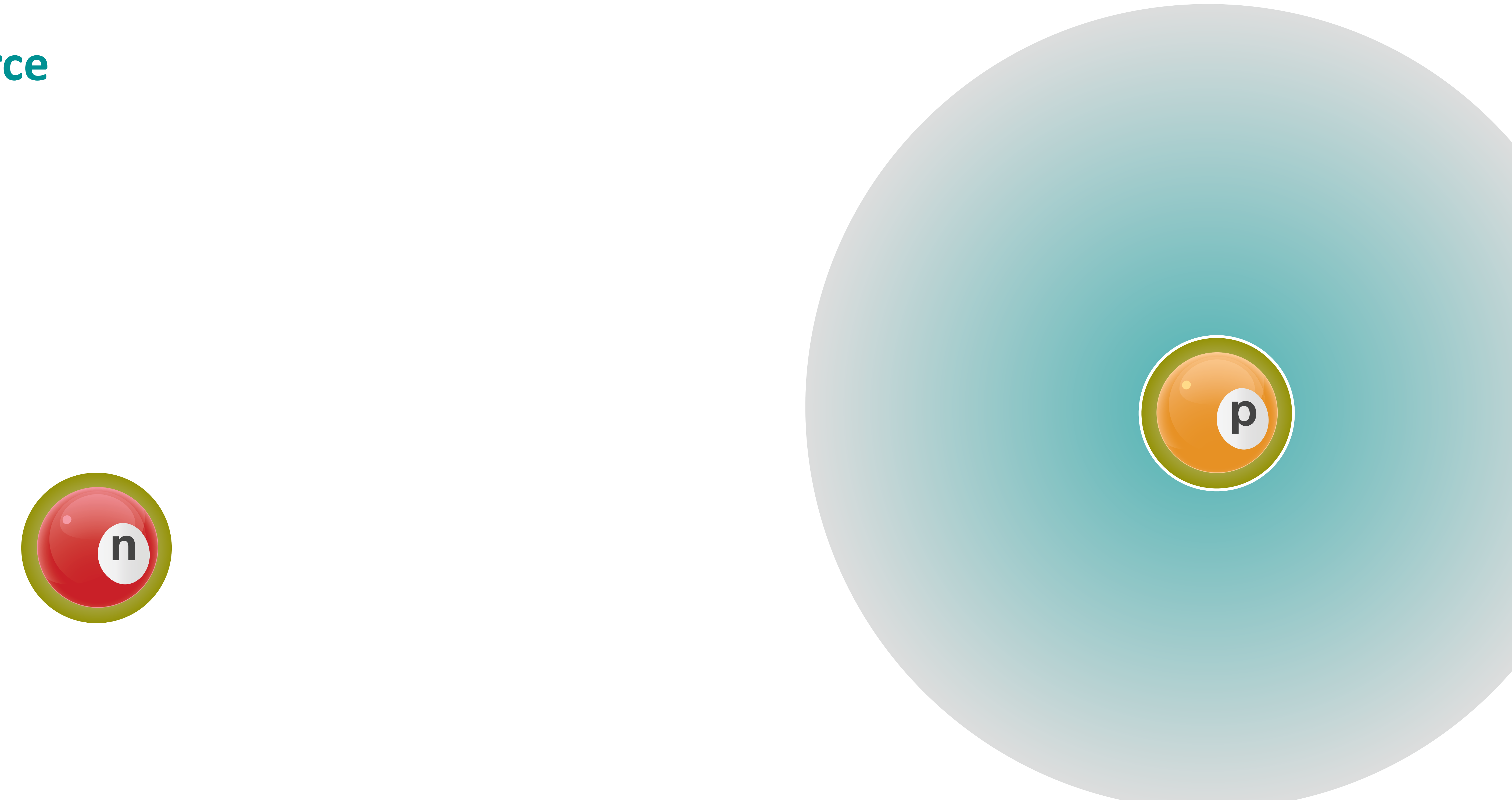
**Electromagnetic Force**



# Strong is stronger than...anything.

two competing forces:

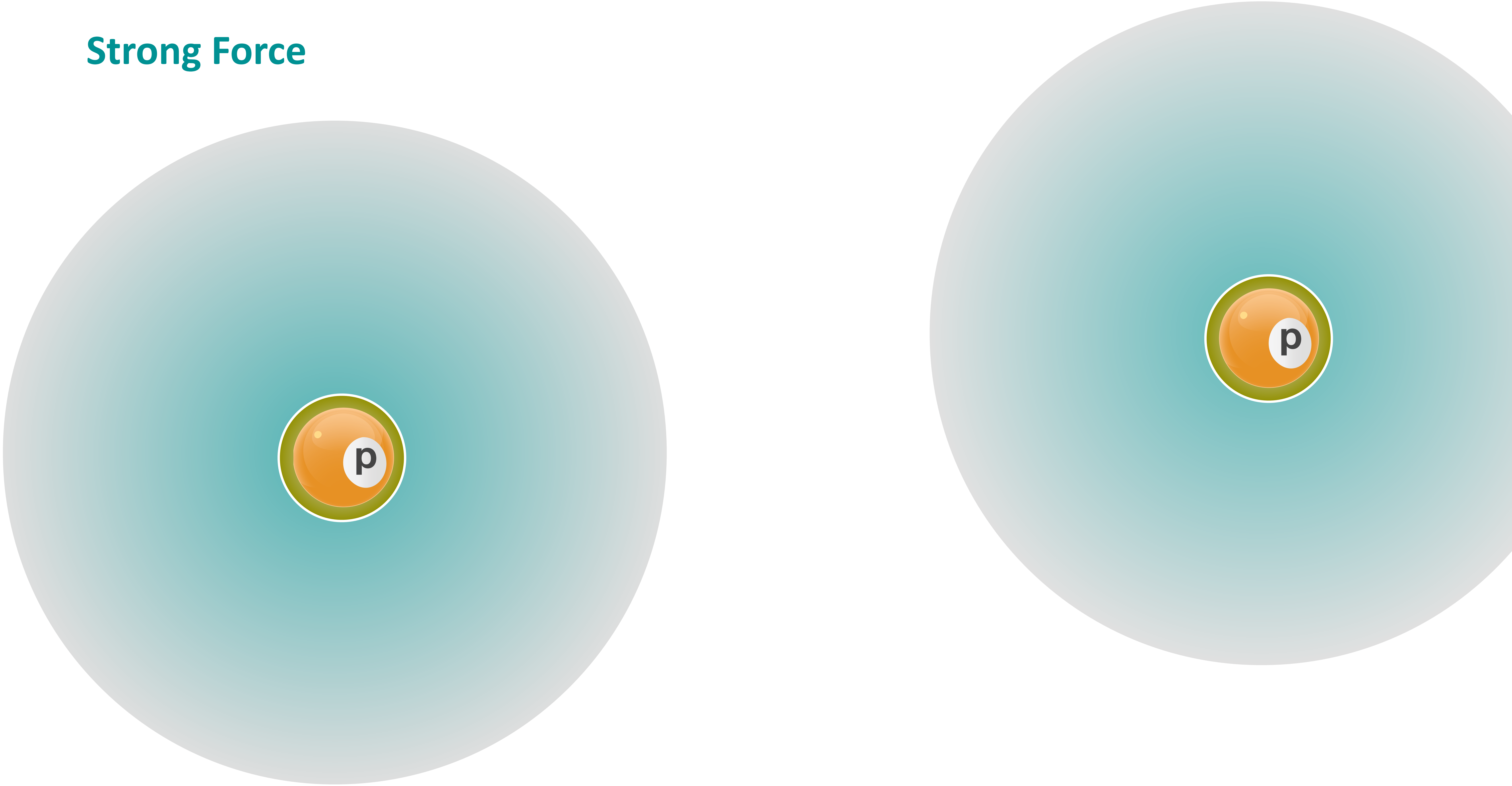
**Strong Force**



# Strong is stronger than...anything.

two competing forces:

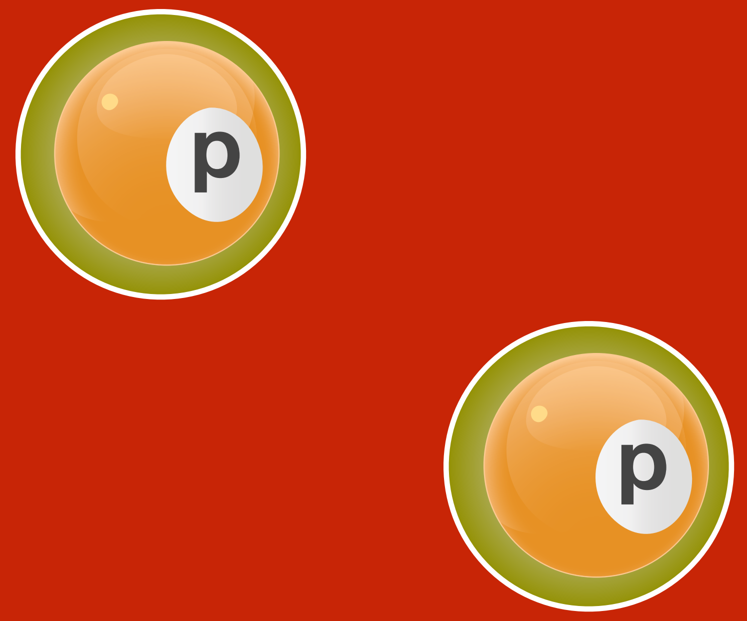
**Strong Force**



but only over a very short range...

# the STRONG force

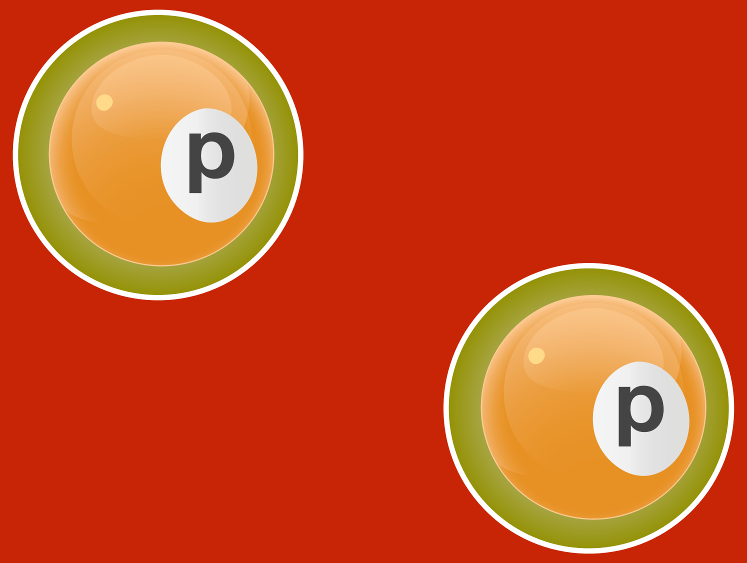
overwhelms the electromagnetic force



but only over a very short range...

# the STRONG force

overwhelms the electromagnetic force

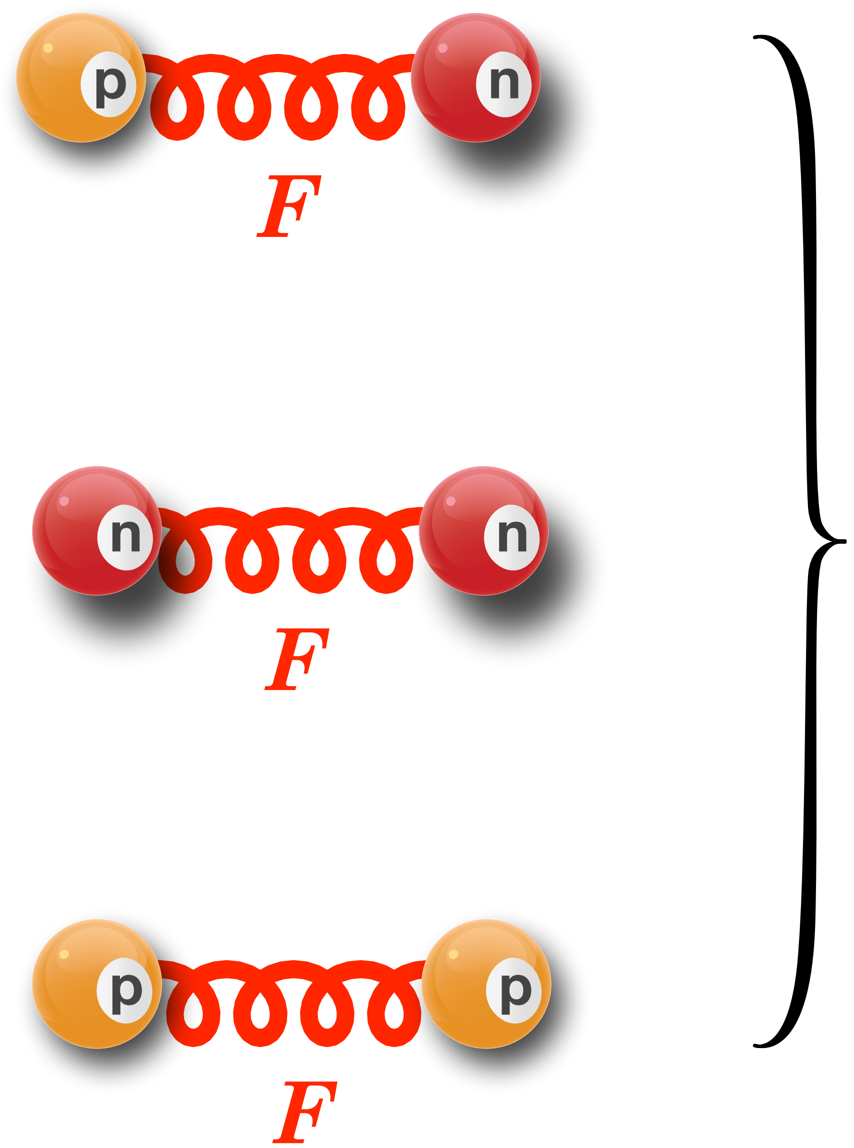


# neutrons and protons

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<br>*not electron, not photon* |

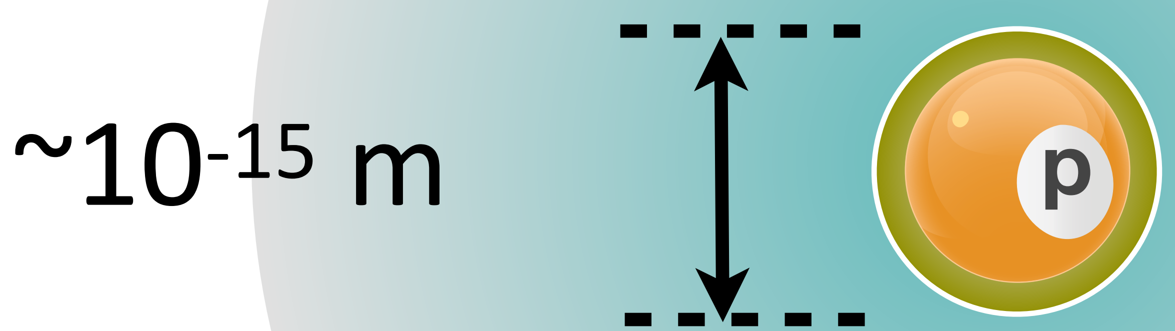
remember

**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




Yukawa knew that.

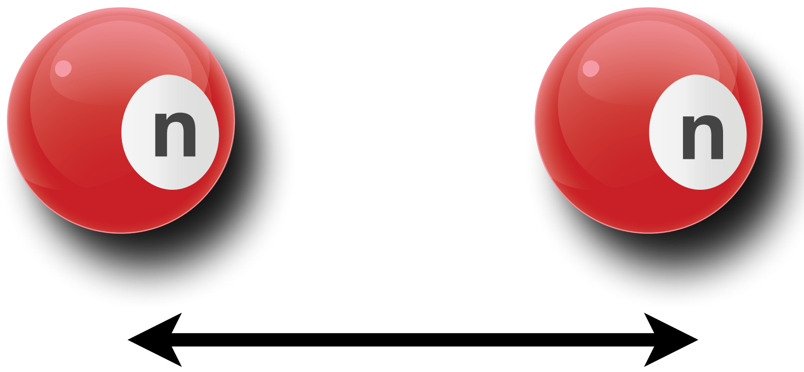
# uncertainty certainly to the rescue

brilliant observation by Yukawa

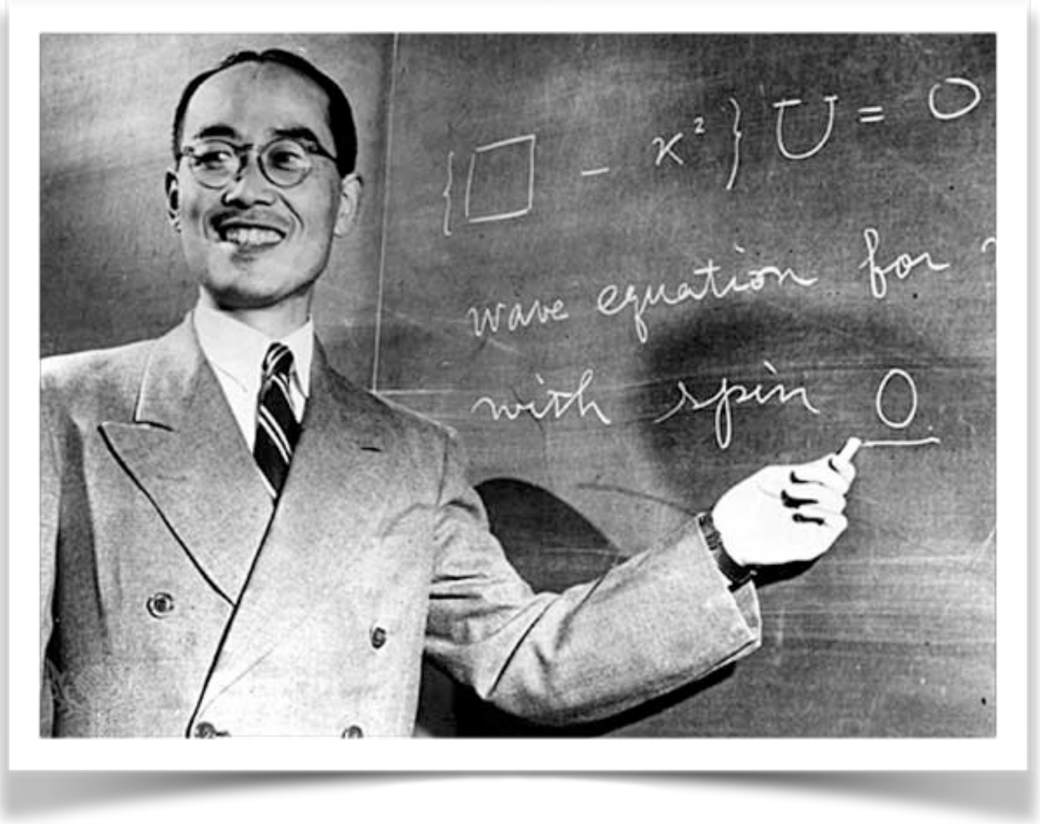
maybe there's a quantum that is active only over the size of a nucleus: "U"

another exchange force/particle?

So: $p \rightarrow n + U$ ?




$\Delta x = 10^{-15}$ 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.*

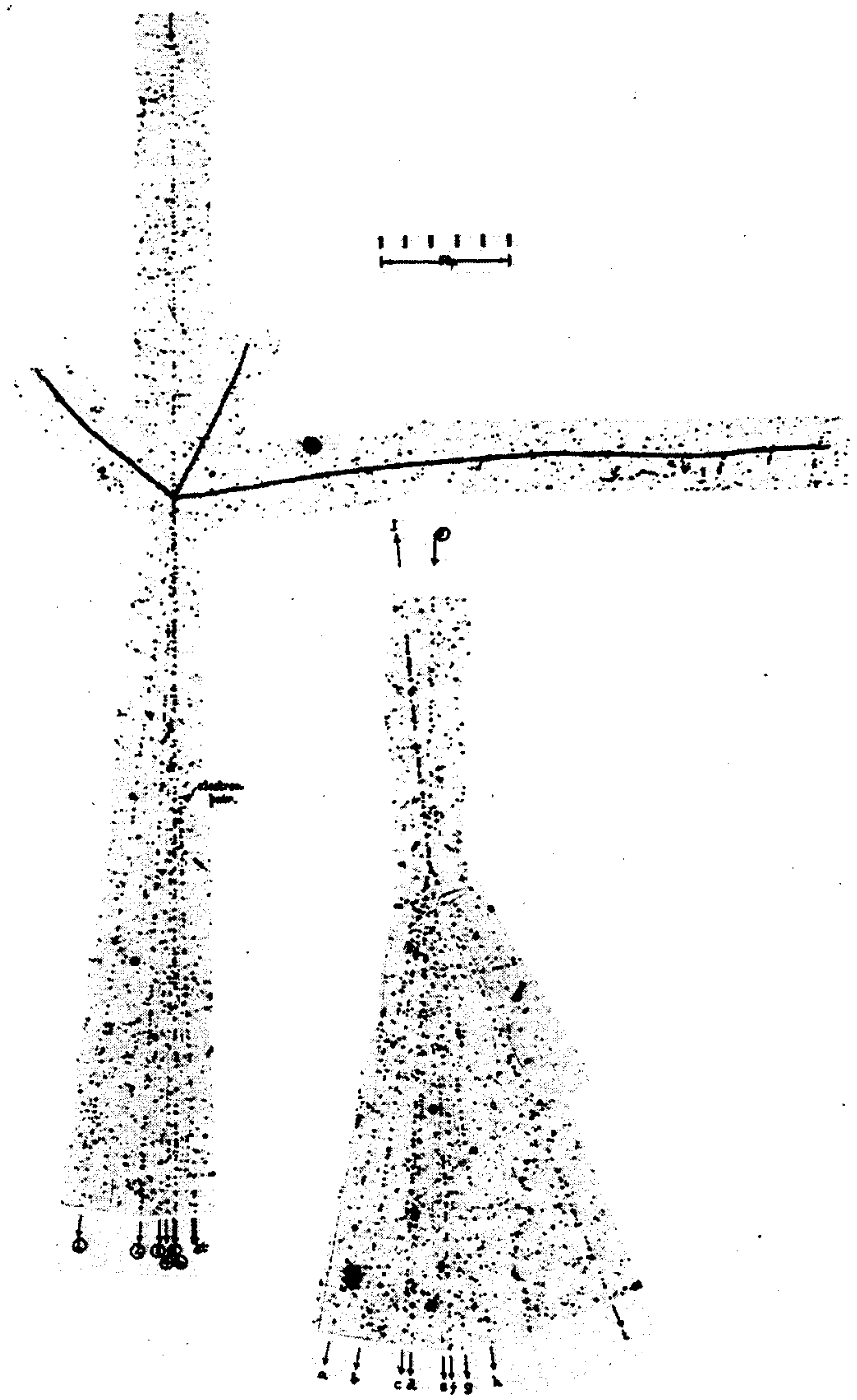
# the hunt was on

to find the Yukawa Particle

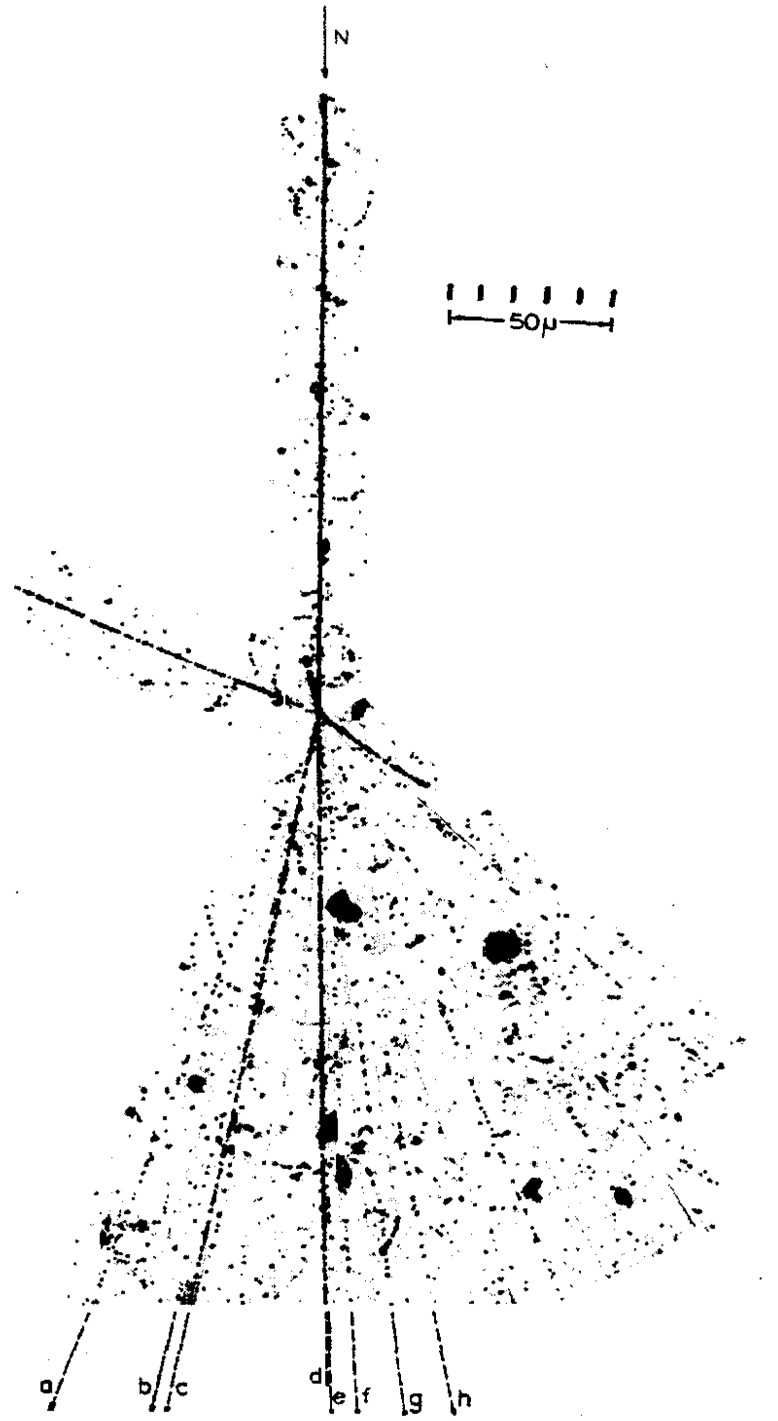
but WWII got in the way

# Post-war emulsion exposures were startling

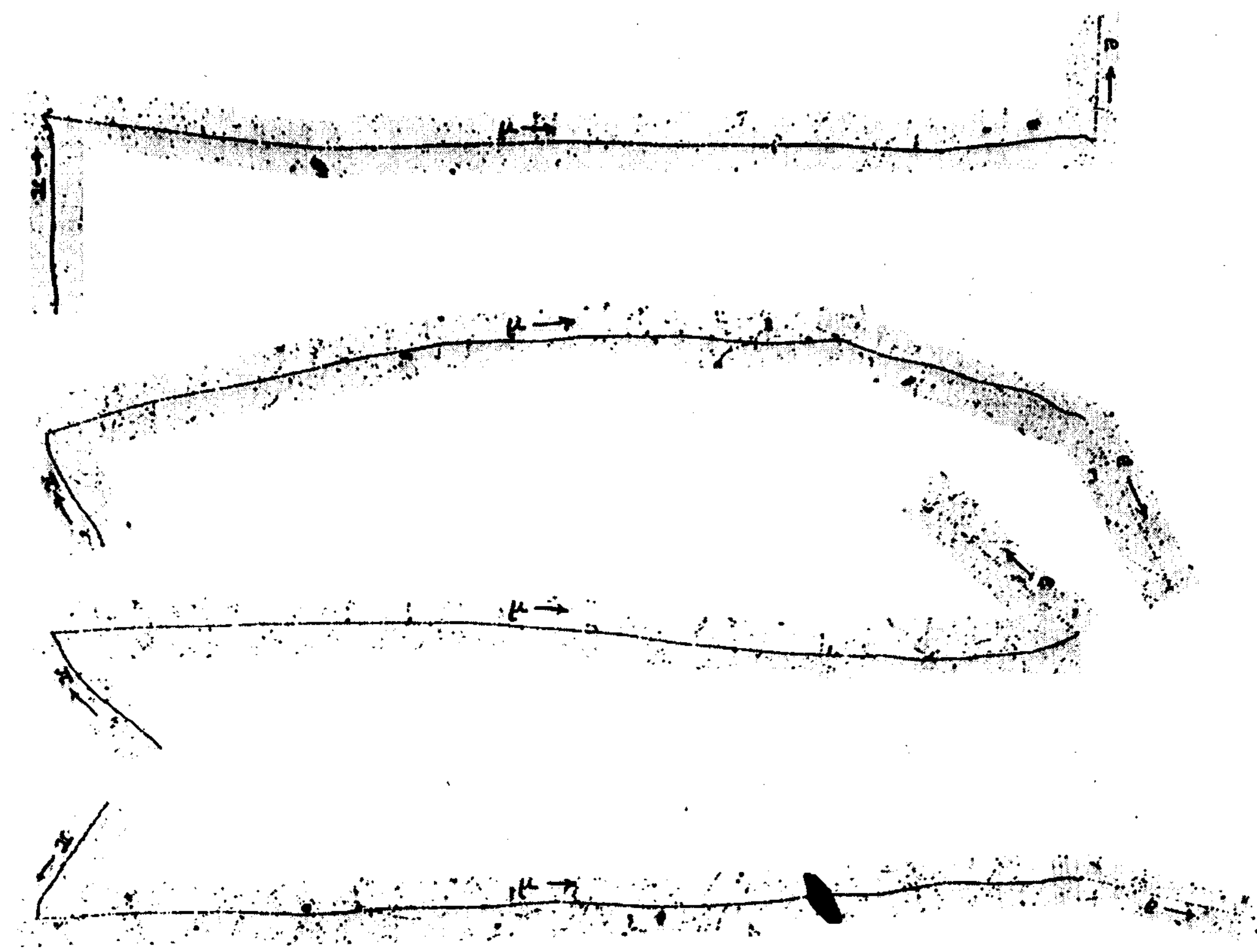
proton in cosmic rays



Nitrogen nucleus in cosmic rays




huh?

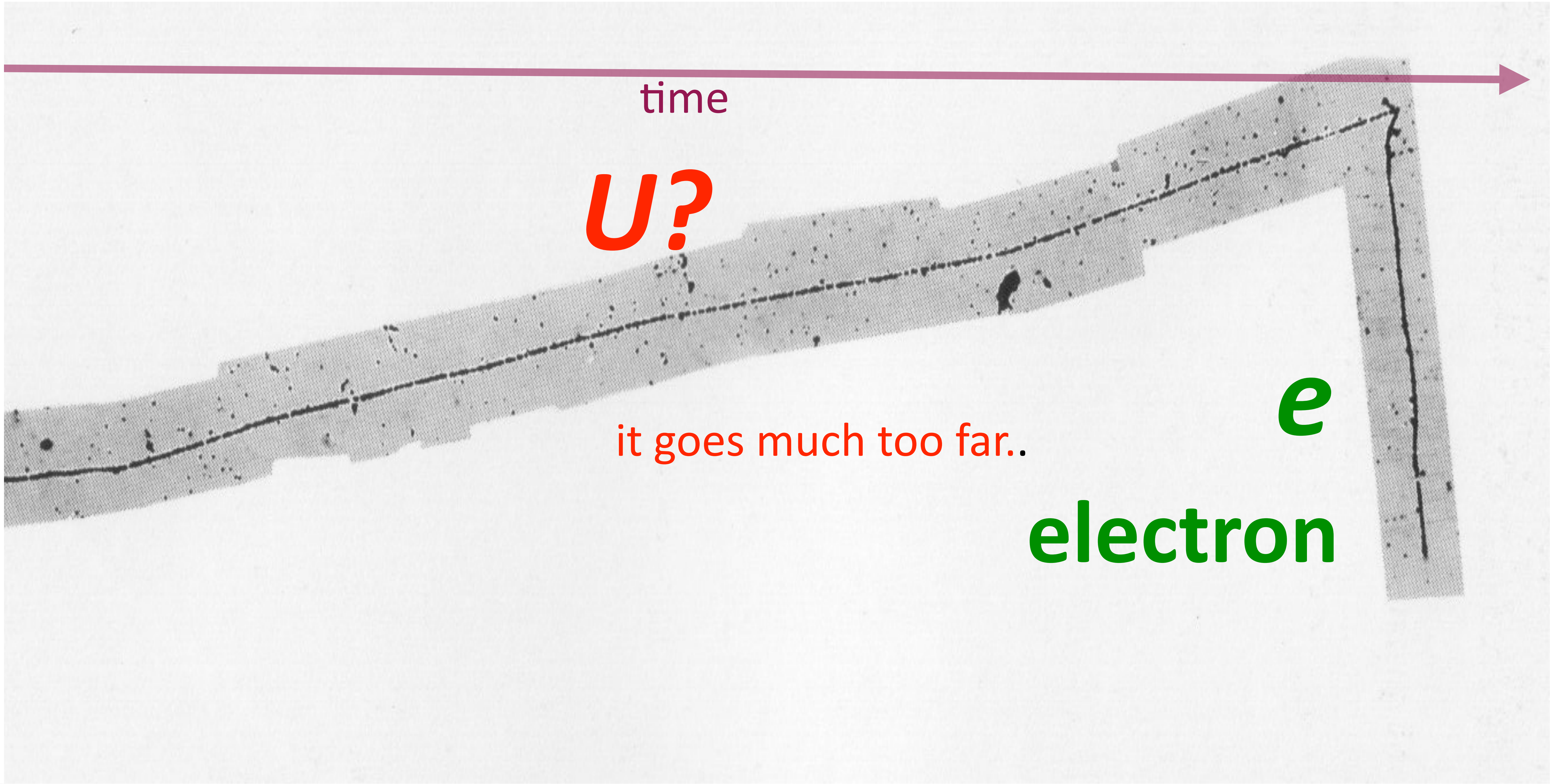



from Cecil Powell's Nobel lecture... a former student of? ...you guessed it.

# many of these sort:

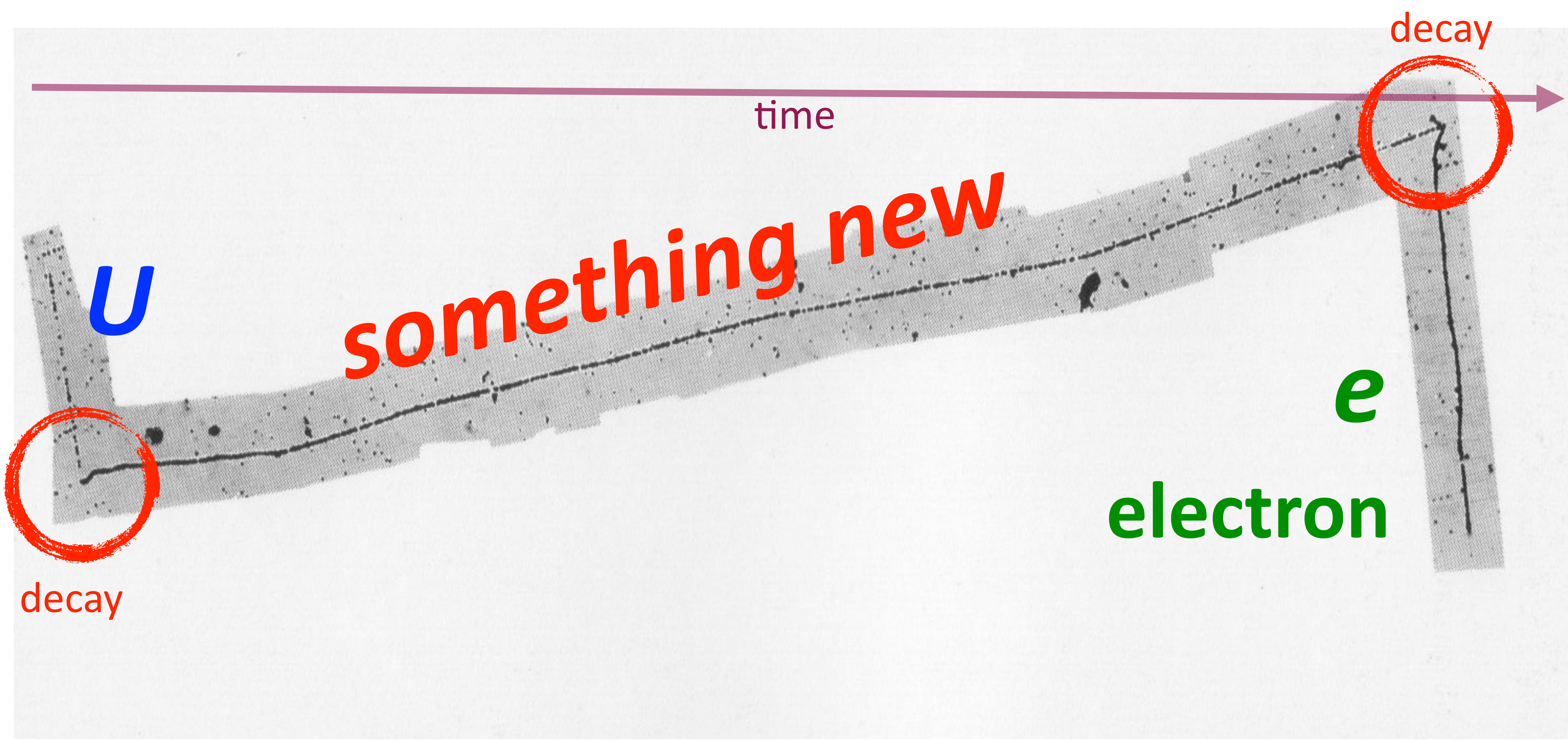
something unknown...

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



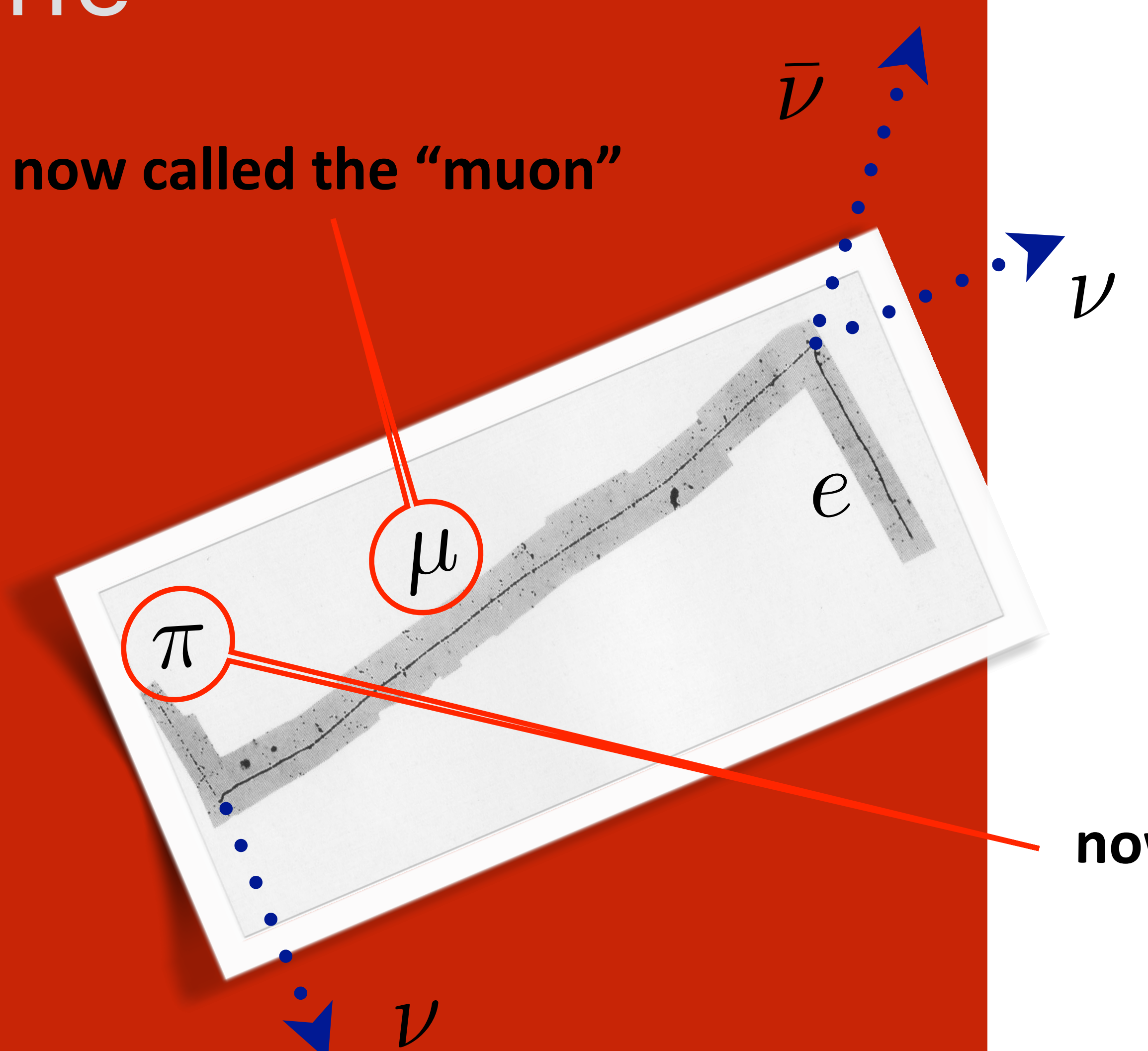
# strange things in cosmic rays

thick photographic substrates



# two discoveries

## for the price of one



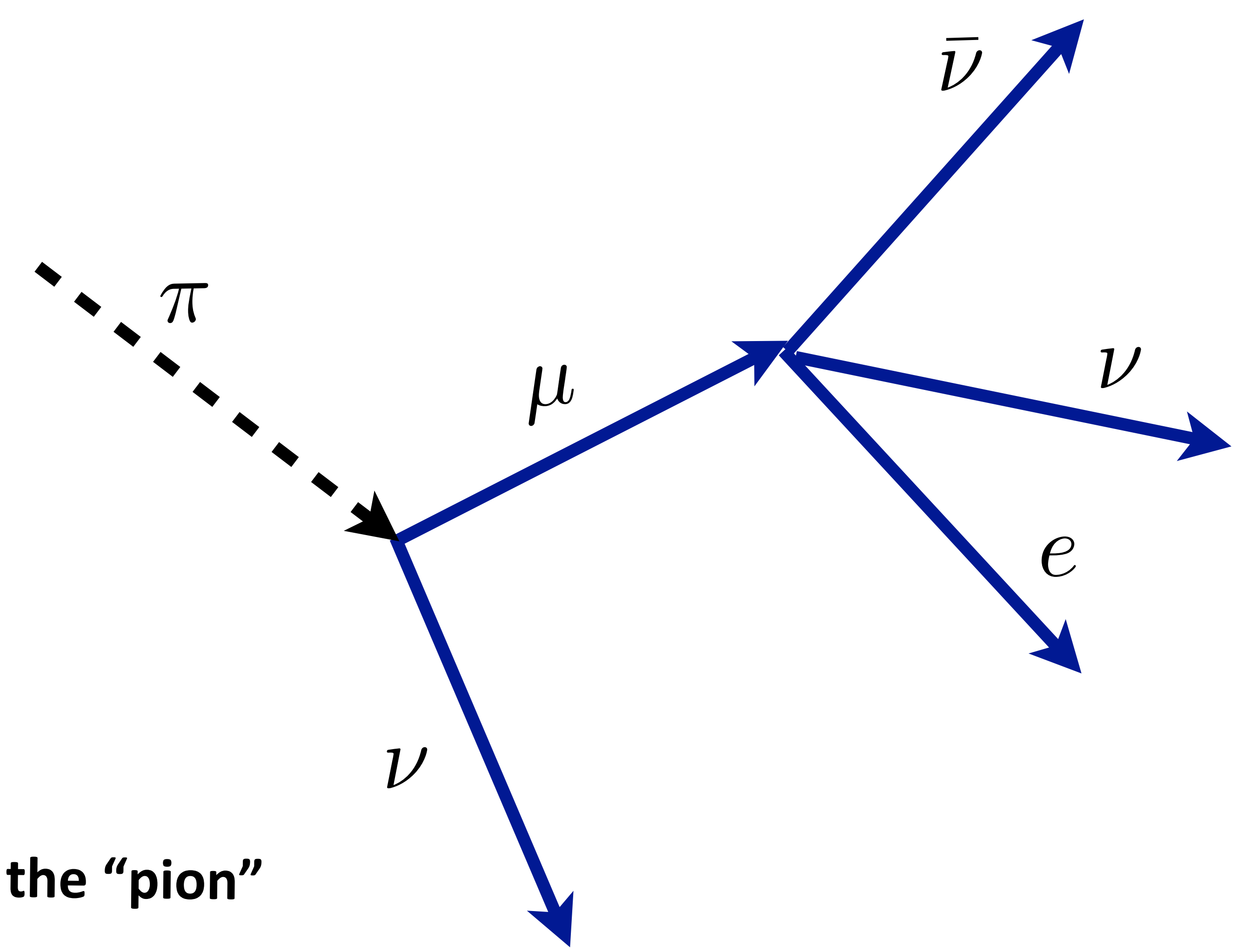

# This took some unraveling.

The “meson” appeared in and initiated nuclear collisions

The unknown particle seemed to live about a 6 $\mu$sec

too long to be a meson

**The winning proposal:**



particle: **pion**

symbol: $\pi$

charge: +, –, 0

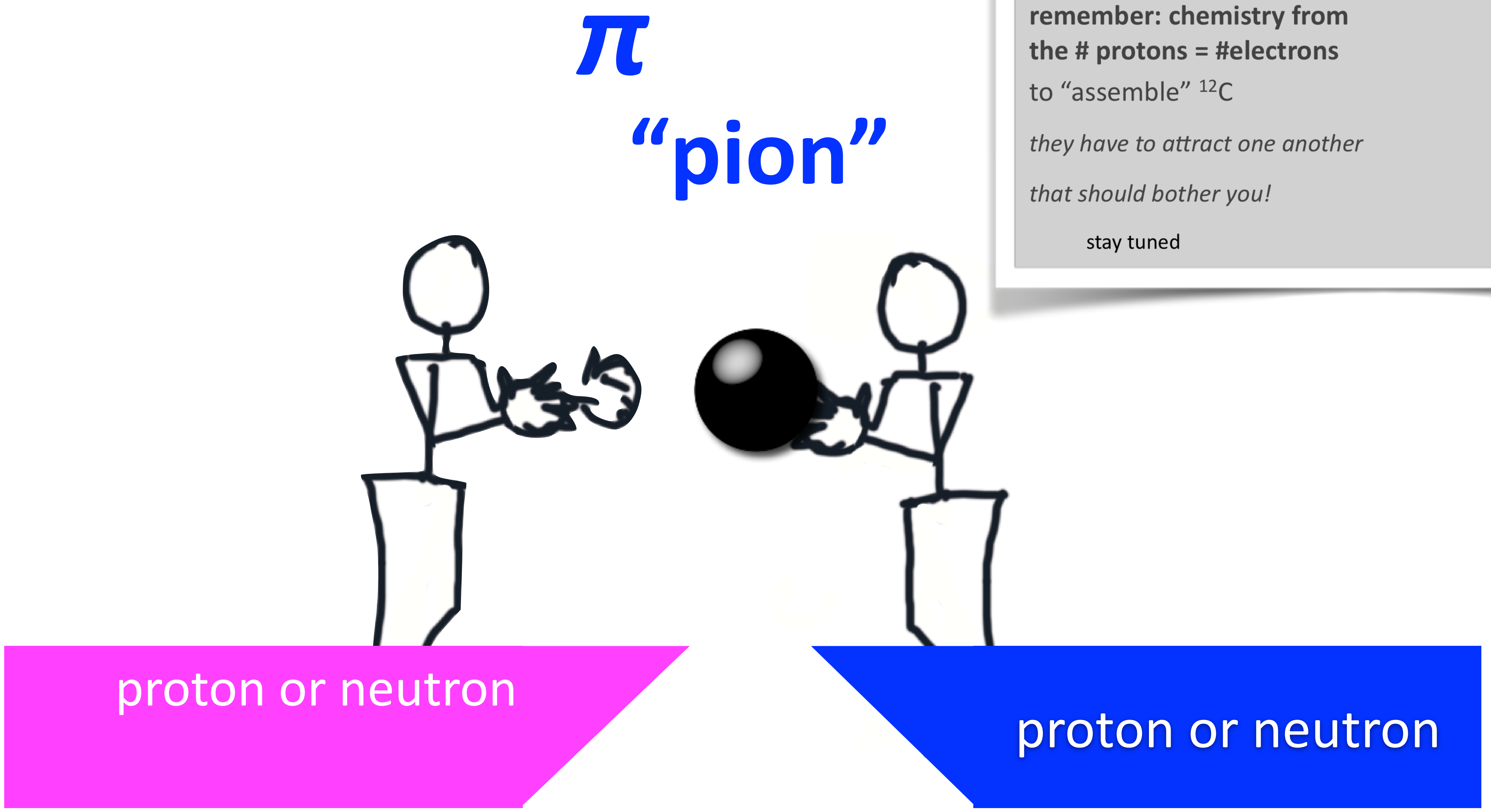
mass: 139 MeV/$c^2$,

spin: 0

category: Boson, hadron, meson

# analogy:

an attractive exchange force




**remember: chemistry from**
**the # protons = #electrons**
to "assemble" $^{12}C$

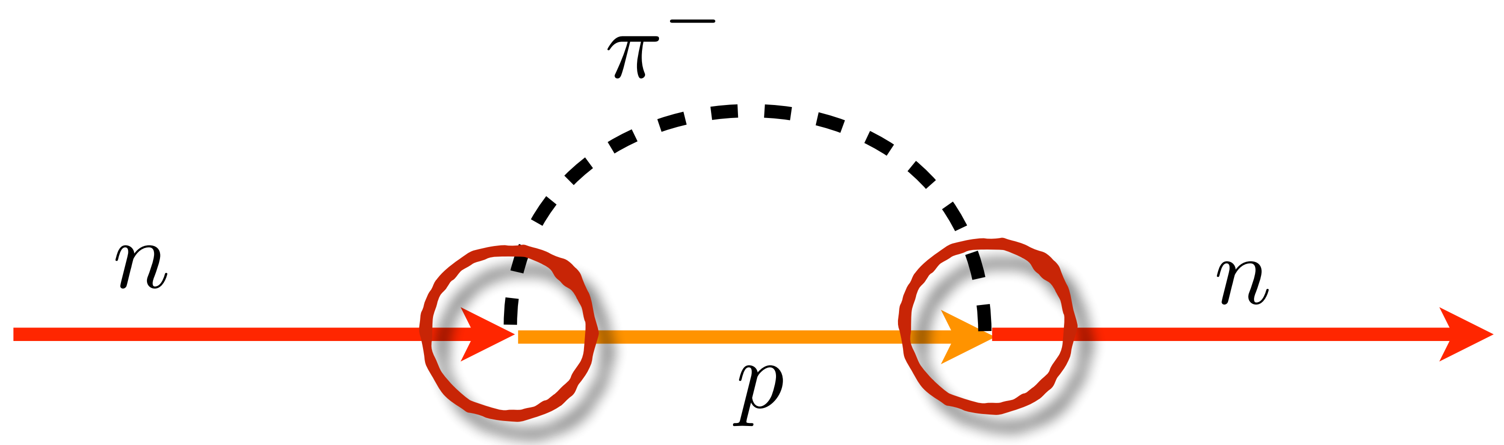
*they have to attract one another*

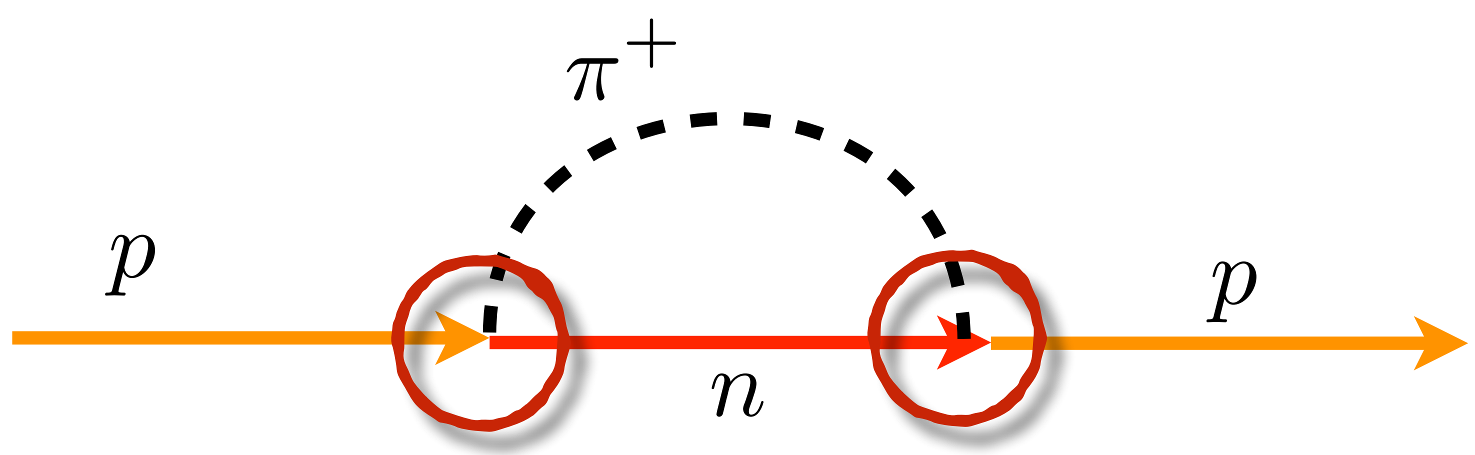
*that should bother you!*

stay tuned

# the Yukawa particle

is the pion



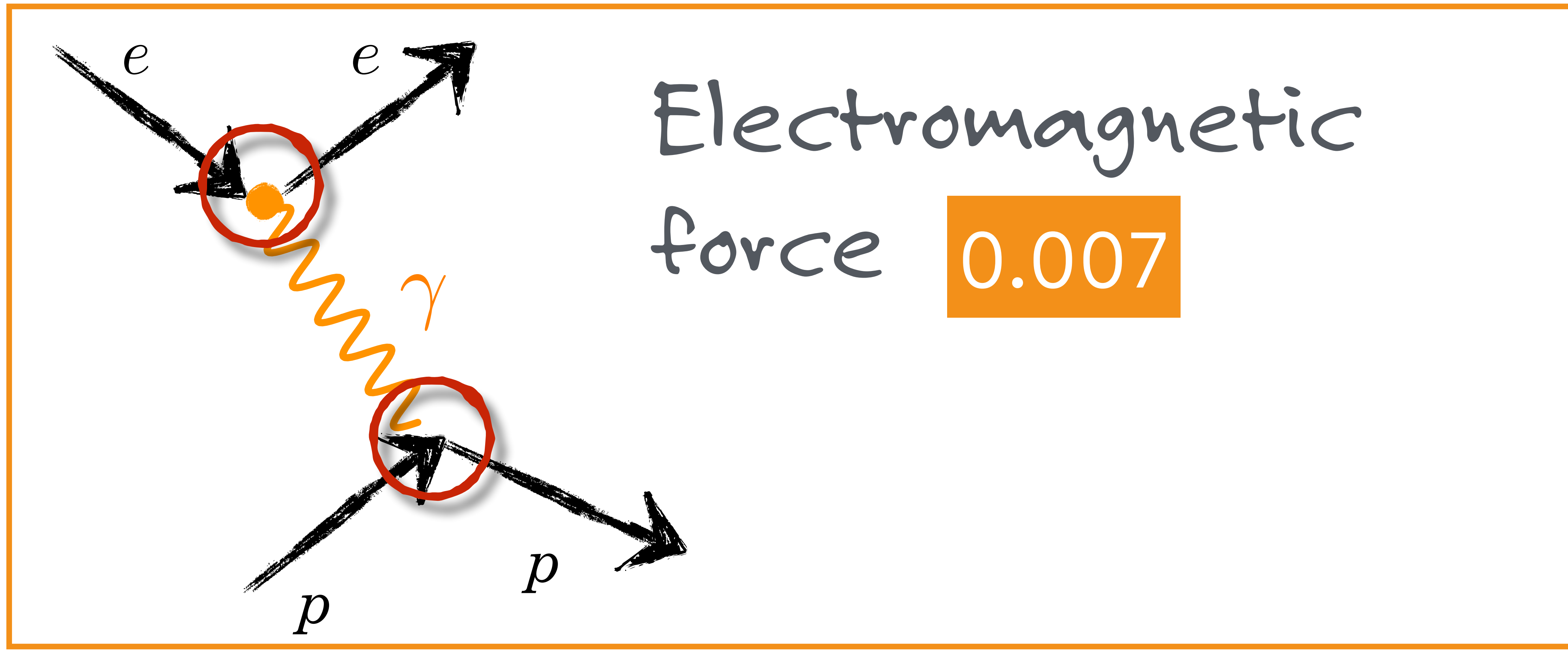




These coupling strengths are large - strong.

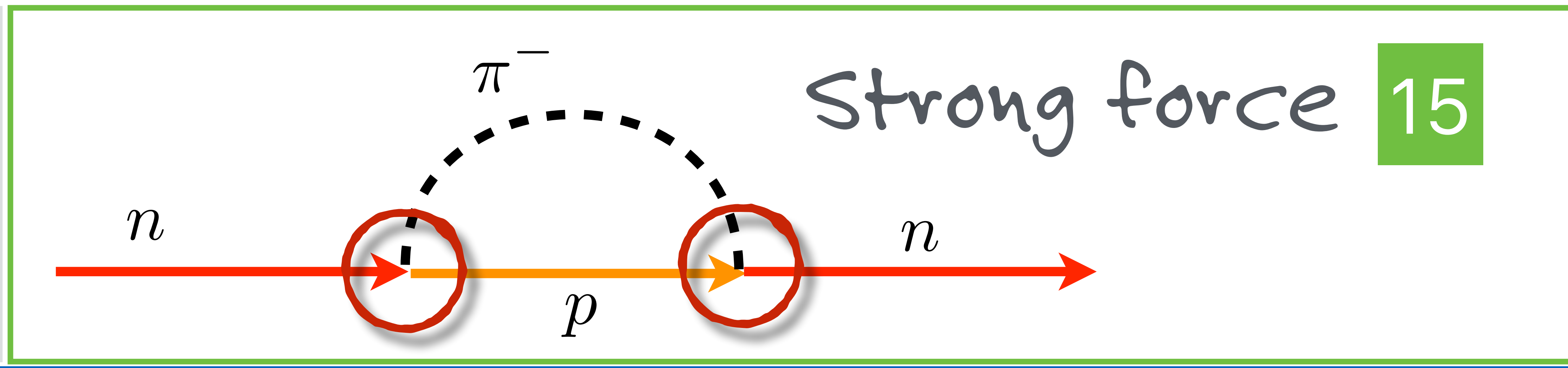
In technical terms we call this...the strong interaction.

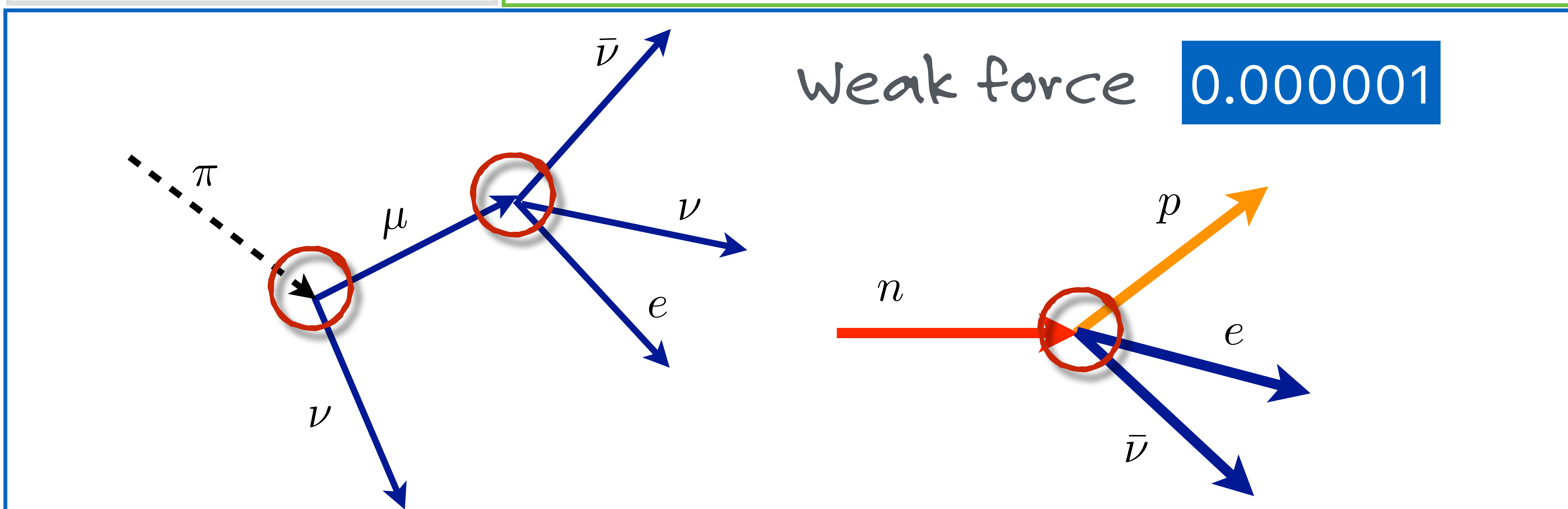
# three forces now

of vastly different strengths







particle:

# muon

| | |
|---|---|
| symbol: | $\mu$ |
| charge: | +, – |
| mass: | 105.7 MeV/$c^2$ |
| spin: | 1/2 |
| category: | Fermion, lepton |

# The Mu… y like an Ele… vier.

particle: **muon**

symbol:

charge:

mass:

spin:

category: Fermion, lepton

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

| | |
|---|---|
| particle: | **tau** |
| symbol: | $\tau$ |
| charge: | +, – |
| mass: | $1776.82 \pm 0.16\ MeV/c^2$ |
| 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: | $\nu_\mu$ |
| charge: | 0 |
| mass: | 0 or 0.4-ish to 1-ish $eV/c^2$ |
| spin: | 1/2 |
| category: | Fermion, lepton |

particle: **tau-neutrino**

| | |
|---|---|
| symbol: | $\nu_\tau$ |
| 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.

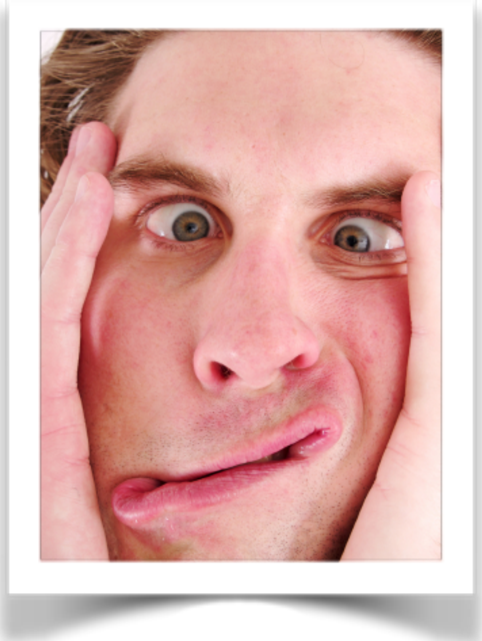
| Q | | | |
|---|---|---|---|
| 0 | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
| –1 | $e$ | $\mu$ | $\tau$ |

Identical in every way...except mass

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

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

$$m_\tau \sim 1.8 \times m_p \;!!$$



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

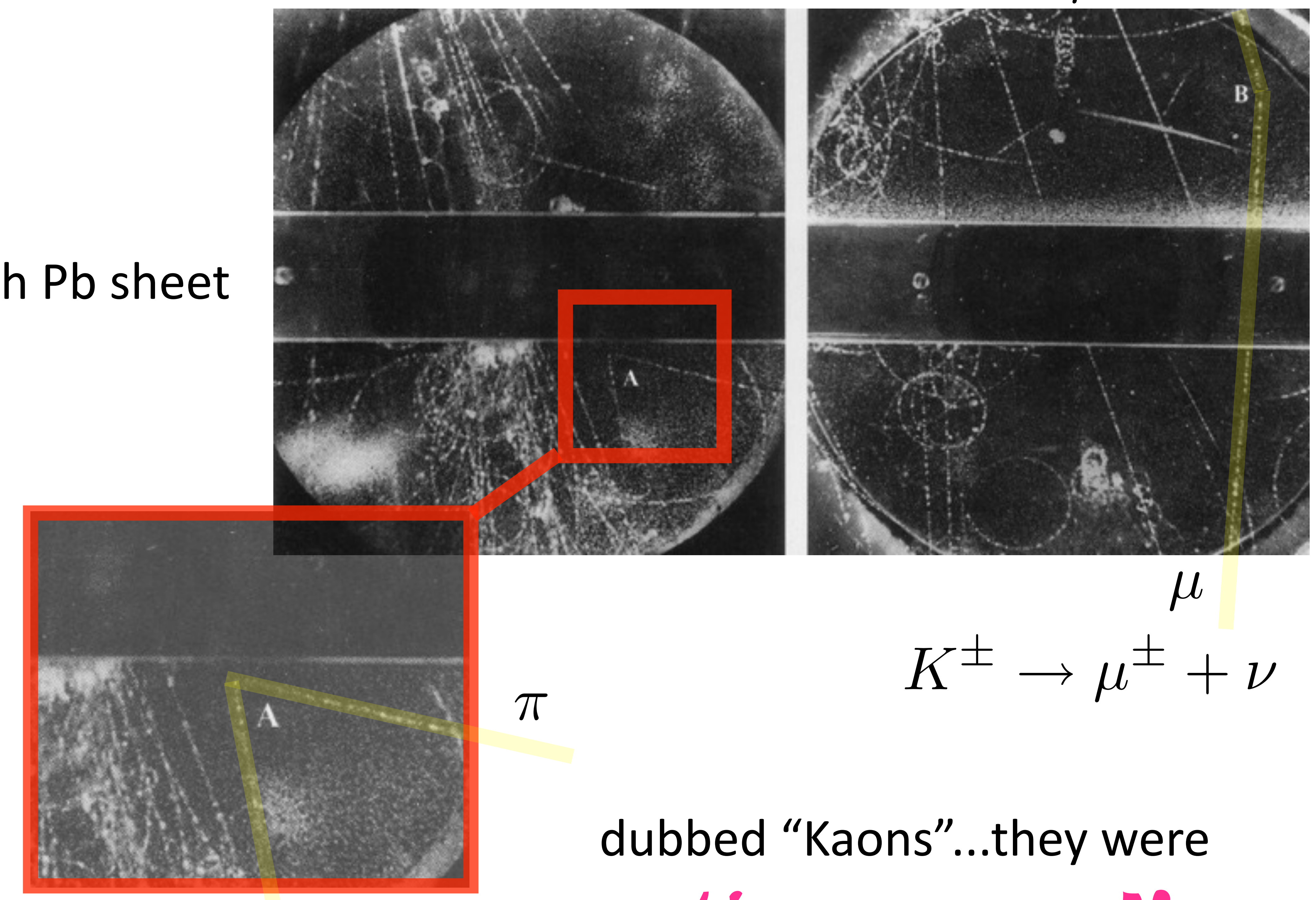
academic home for many years of...? who else.

## Mysterious “Vees” began to crop up...

Cloud chamber...with Pb sheet

$\text{“Vee”} \rightarrow \pi^+ + \pi^-$

$\text{“Vee”} \rightarrow \mu + \nu?$



$\pi$

$\pi$

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

$\mu$

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

dubbed “Kaons”...they were

“strange”

particle: **Kaon**

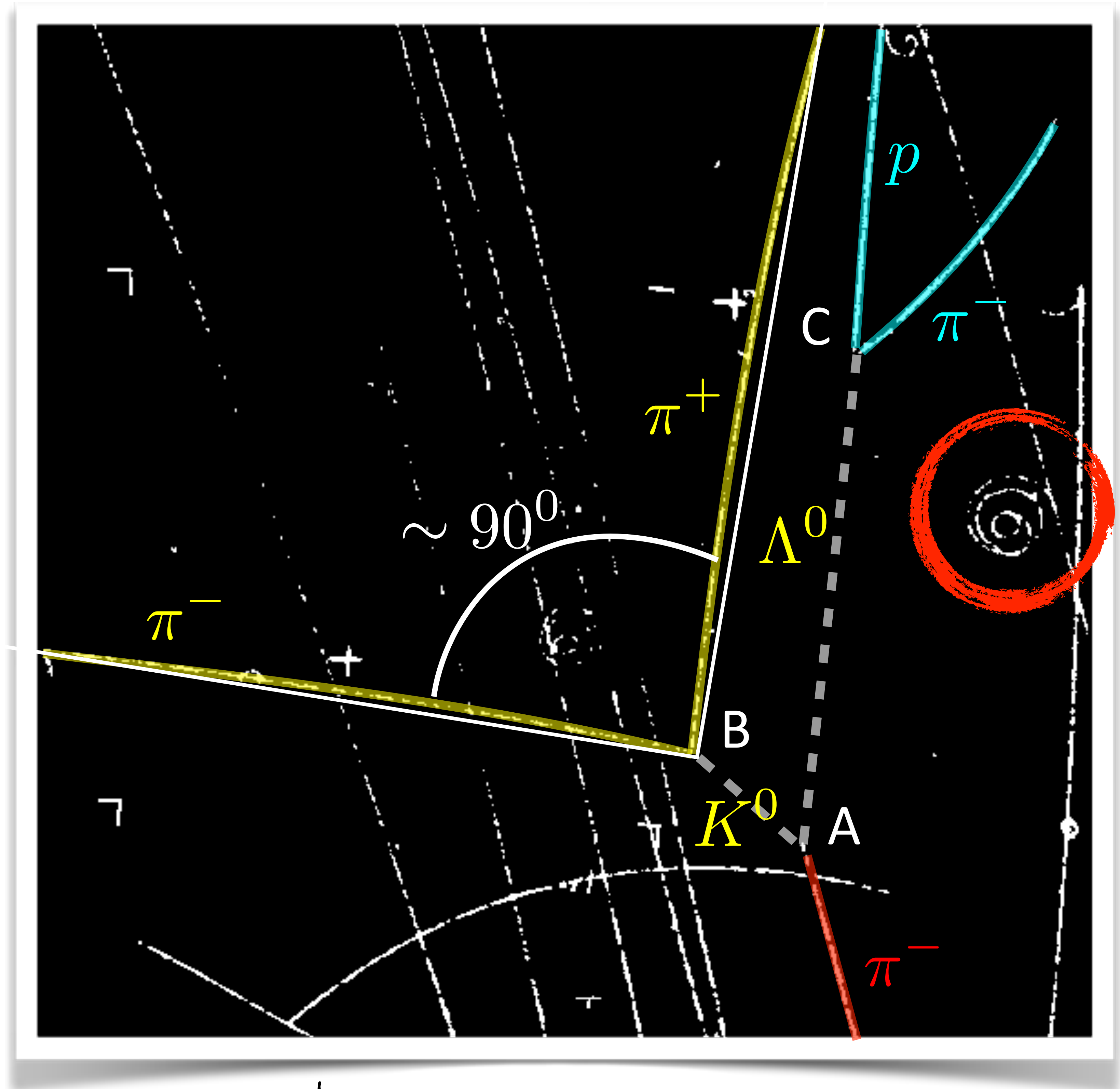
| | |
|---|---|
| symbol: | $K$ |
| charge: | ±1, 0 |
| mass: | 493.677 (charged state) MeV/$c^2$ |
| spin: | 0 |
| category: | Fermion, baryon, I = ±1/2, B=1, S=-3 |

# 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

$\pi^-$

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

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

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

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

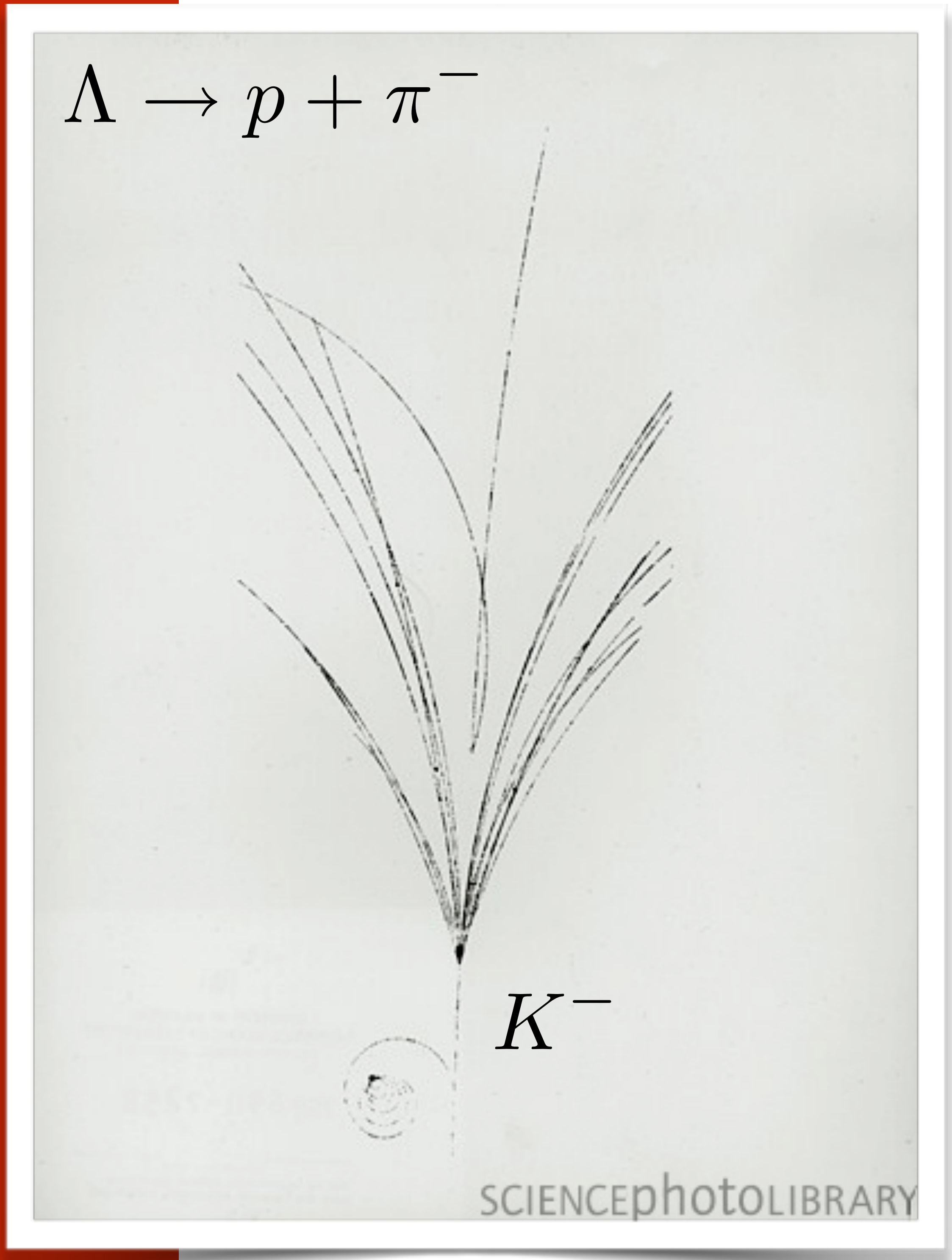
$$\Sigma^+ \rightarrow p + \pi^0 \quad 48.4\%$$

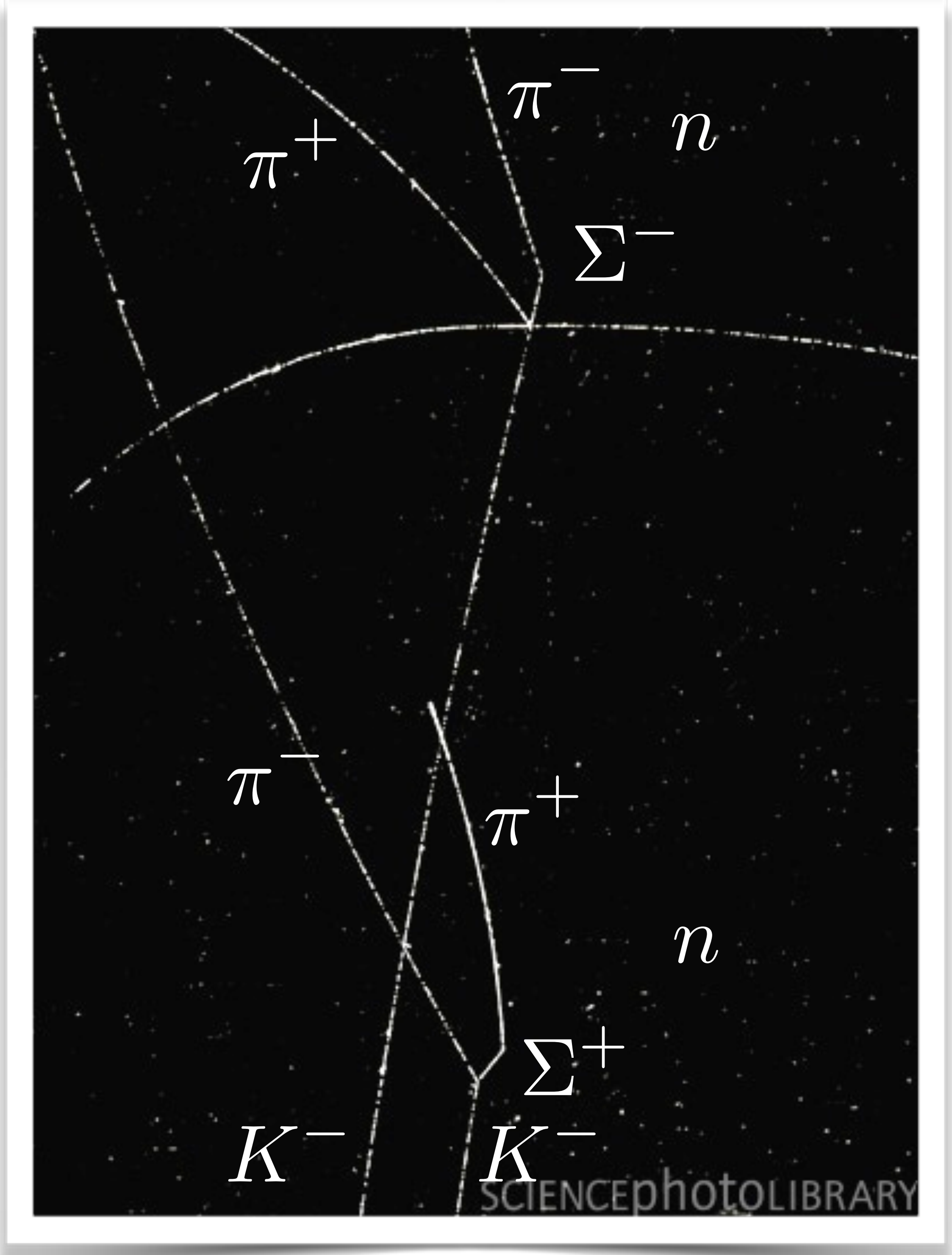
"Lambdas"

"Sigmas"

"Cascades"

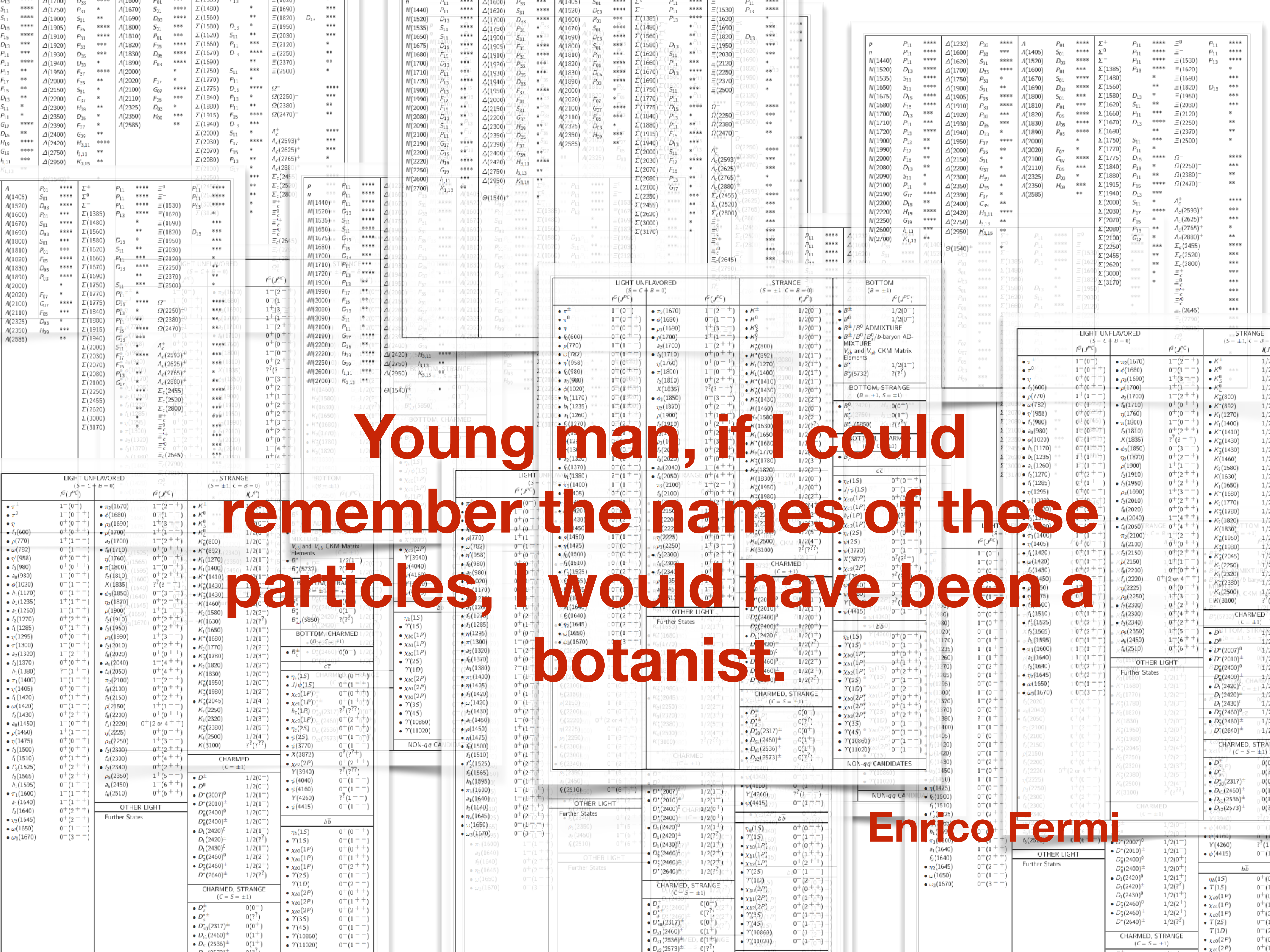
"K-stars"



particle: **Lambda**

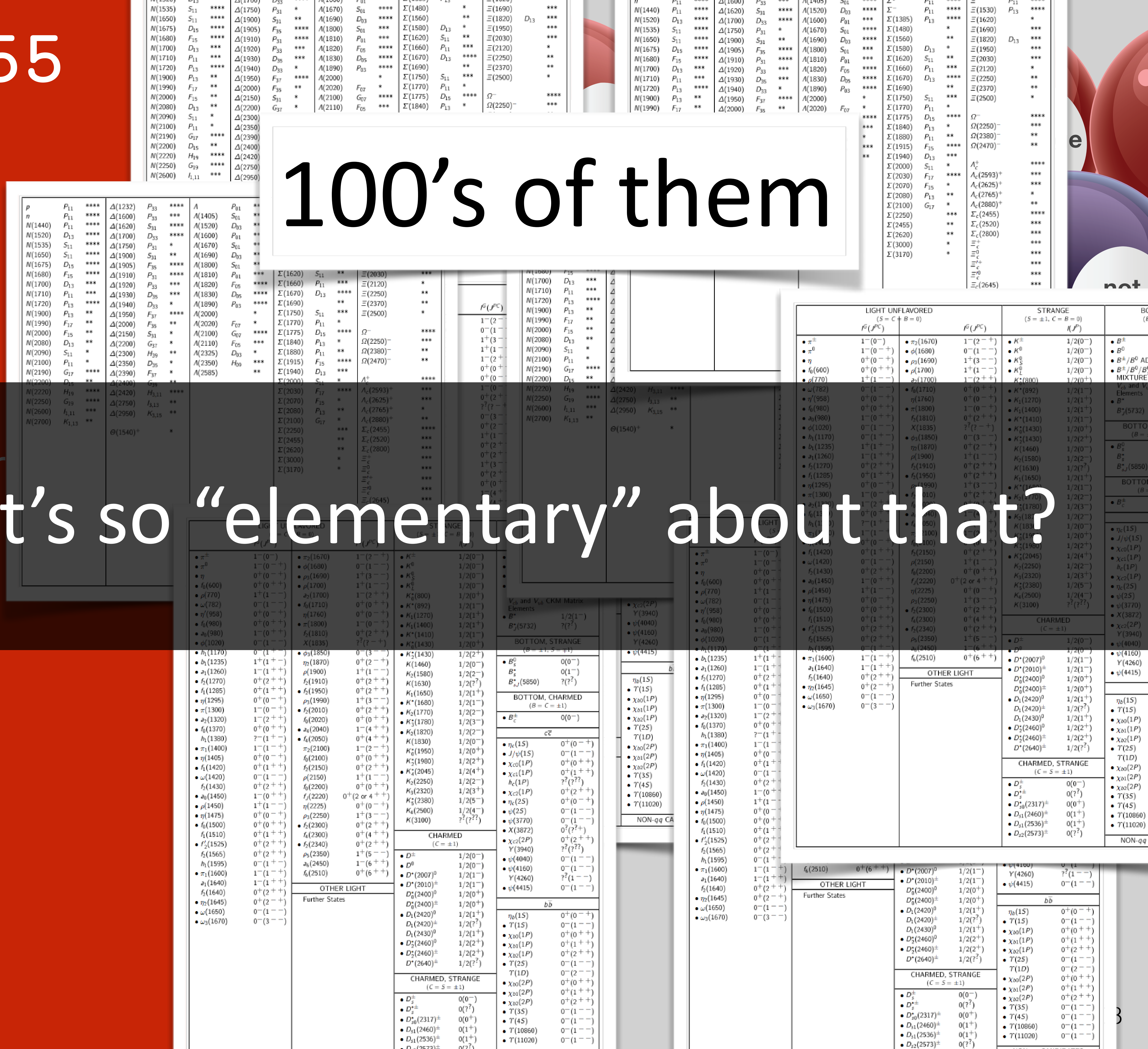
| | |
|---|---|
| symbol: | $\Lambda$ |
| charge: | 0 |
| mass: | 1,115.683 $MeV/c^2$ |
| spin: | 1/2 |
| category: | Fermion, baryon, I = 0, B=1, S=-1 |


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

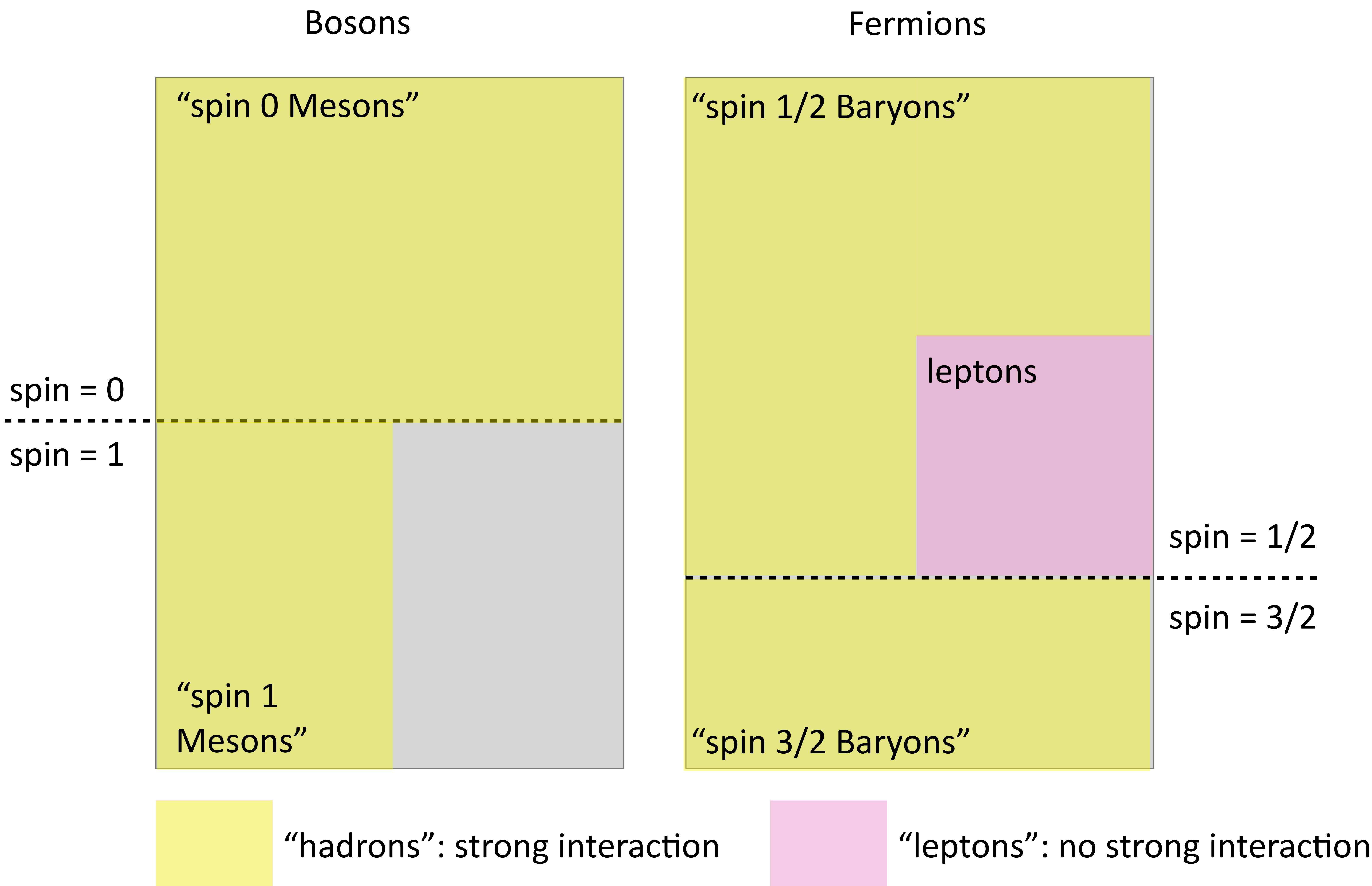


100’s of them

things wer
mess

what’s so “elementary” about that?

# The Particle Zoo?



# there were clues

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

patterns and organizing features

began to emerge in the pile of data

# 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:

$$A^+ \to B^+ + C^+$$

Q: +1 +1 +1

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

Q: +1 +1 +1 -1

# Quantum Number:

Strangeness

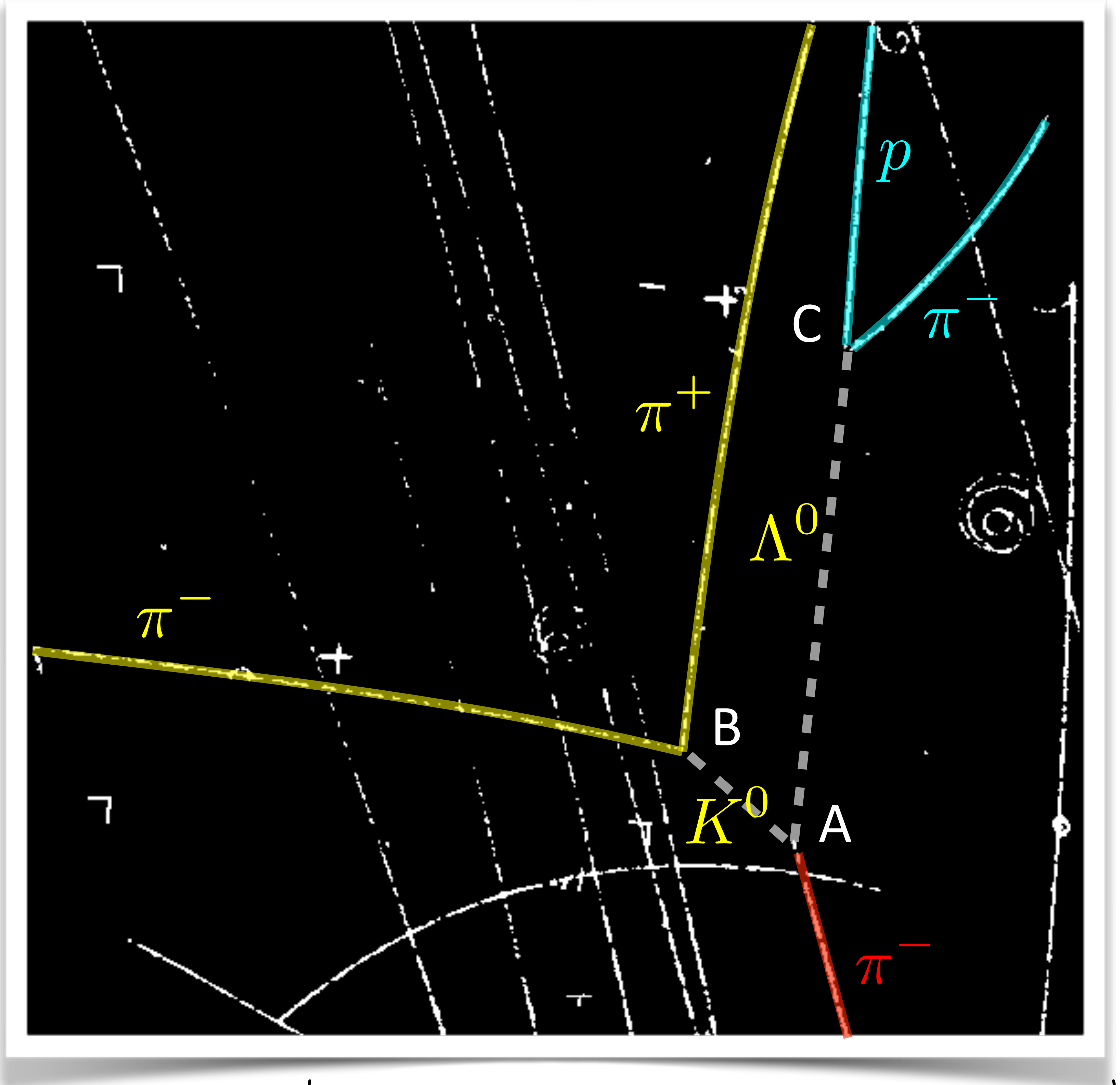
# a clue

of another kind of "number"

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

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

and they, in turn, are reluctant to decay




$\pi^-$

# 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 | $\Lambda^0$ | 1115.6 | 1/2 | 0 | +1 | −1 | 2.6 x $10^{-10}$ | $p\pi^-,\ n\pi^0$ |
| Sigma | $\Sigma^+$ | 1189.4 | 1/2 | +1 | +1 | −1 | 0.8 x $10^{-10}$ | $p\pi^0,\ n\pi^+$ |
| Sigma | $\Sigma^0$ | 1192.5 | 1/2 | 0 | +1 | −1 | 6 x $10^{-20}$ | $\Lambda^0\gamma$ |
| Sigma | $\Sigma^-$ | 1197.3 | 1/2 | −1 | +1 | −1 | 1.5 x $10^{-10}$ | $n\pi^-$ |
| Delta | $\Delta^{++}$ | 1232 | 3/2 | +2 | +1 | 0 | 0.6 x $10^{-23}$ | $p\pi^+$ |
| Delta | $\Delta^+$ | 1232 | 3/2 | +1 | +1 | 0 | 0.6 x $10^{-23}$ | $n\pi^+,\ p\pi^0$ |
| Delta | $\Delta^0$ | 1232 | 3/2 | 0 | +1 | 0 | 0.6 x $10^{-23}$ | $n\pi^0$ |
| Delta | $\Delta^-$ | 1232 | 3/2 | −1 | +1 | 0 | 0.6 x $10^{-23}$ | $n\pi^-$ |
| Xi | $\Xi^0$ | 1315 | 1/2 | 0 | +1 | −2 | 2.9 x $10^{-10}$ | $\Lambda^0\pi^0$ |
| Xi | $\Xi^-$ | 1321 | 1/2 | −1 | +1 | −2 | 1.64 x $10^{-10}$ | $\Lambda^0\pi^-$ |
| Omega | $\Omega^-$ | 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 | $\pi^+$ | $\pi^-$ | 139.6 | 0 | +1 | 0 | 0 | 2.6 x $10^{-8}$ | $\mu^+\nu_\mu$ |
| Pi-zero | $\pi^0$ | $\pi^0$ | 135 | 0 | 0 | 0 | 0 | 920 | $2\gamma$ |
| 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 | $\eta^0$ | $\eta^0$ | 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 | $\rho^+$ | $\rho^-$ | 770 | 1 | +1 | 0 | 0 | 0.4 x $10^{-23}$ | $\pi^+\pi^-, 2\pi^0$ |
| Rho-naught | $\rho^0$ | $\rho^0$ | 770 | 1 | 0 | 0 | 0 | 0.4 x $10^{-23}$ | $\pi^+\pi^-$ |
| Omega | $\omega^0$ | $\omega^0$ | 782 | 1 | 0 | 0 | 0 | 0.8 x $10^{-22}$ | $\pi^+\pi^-\pi^0$ |
| Phi | $\phi$ | $\phi$ | 1020 | 1 | 0 | 0 | 0 | 20 x $10^{-23}$ | $K^+K^-, K^0\bar{K}^0$ |

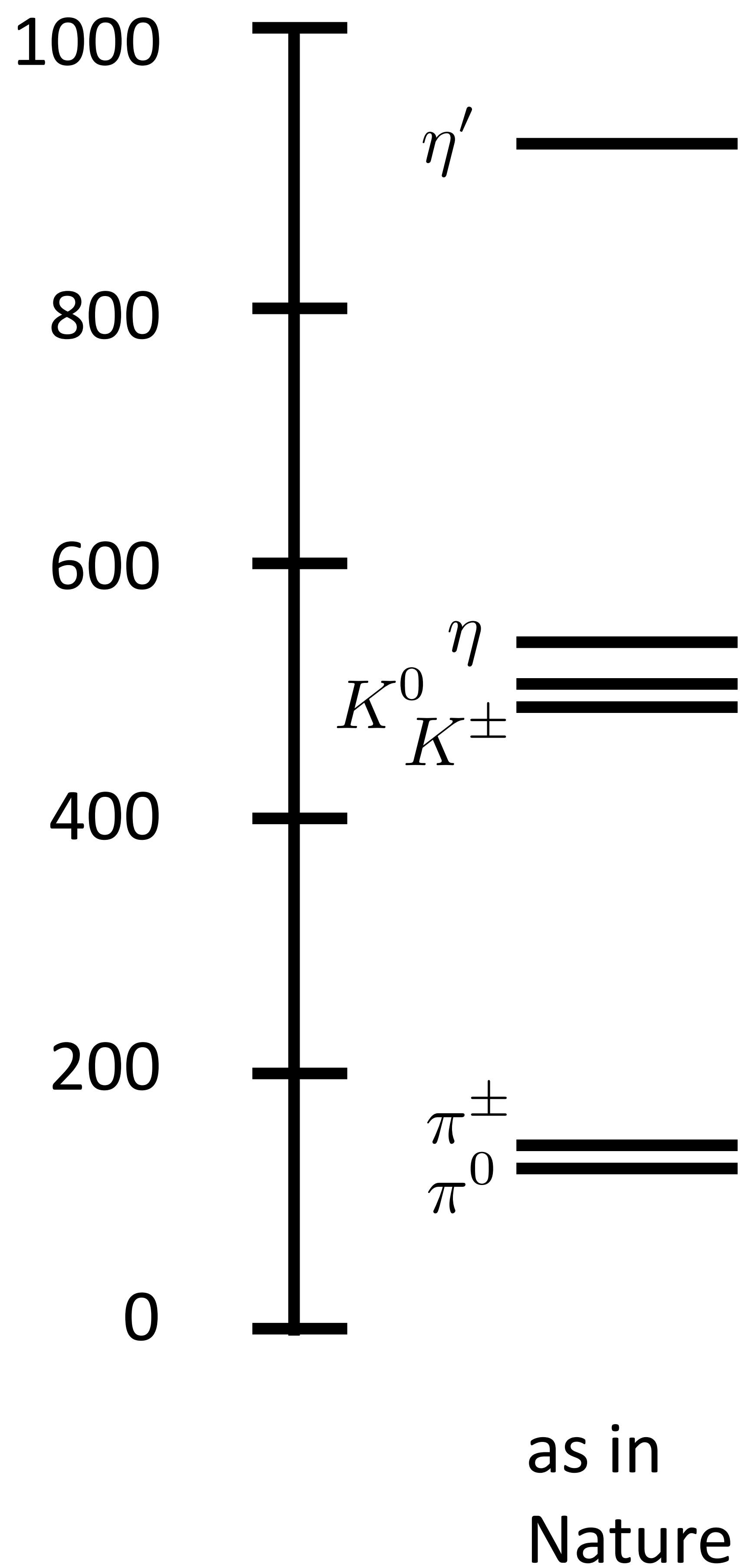
## anyhow...back to the Zoo problem

all those particles.

There were some hints:

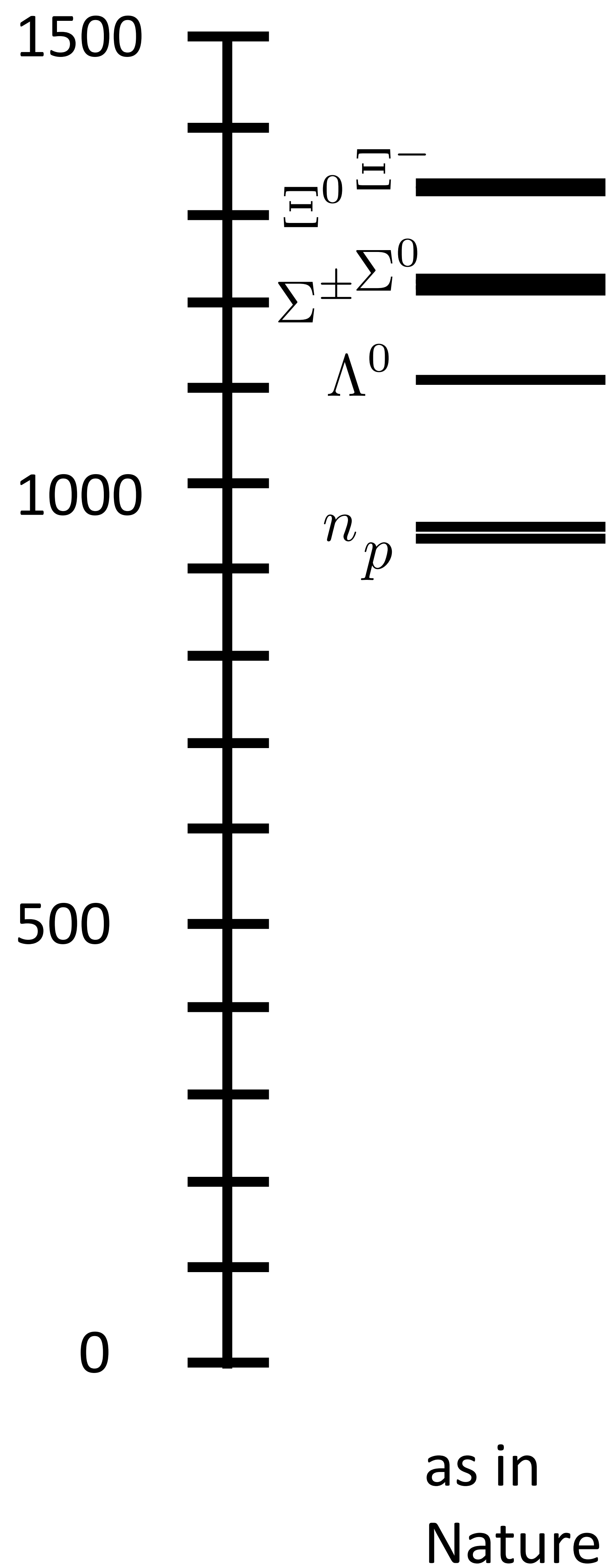
# masses seem to clump

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