# hi

## Lecture 27, 04.18.2017 Particle Physics 2



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

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

#### Homework:

13 points-worth in MasteringPhysics + 17 points-worth on paper http://www.pa.msu.edu/~brock/file\_sharing/QSandBB/2017homework/

# now hear this

To: RAYMOND L BROCK

From: sirs@msu.edu

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

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

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

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

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

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

also:

I'll have an optional anonymous course review with points



# Honors Project

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

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

Read the Second of two sets of instructions:

MinervaInstructions2 2017.pdf

www.pa.msu.edu/~brock/file sharing/QSandBB/2017homework/

#### in

# I need a

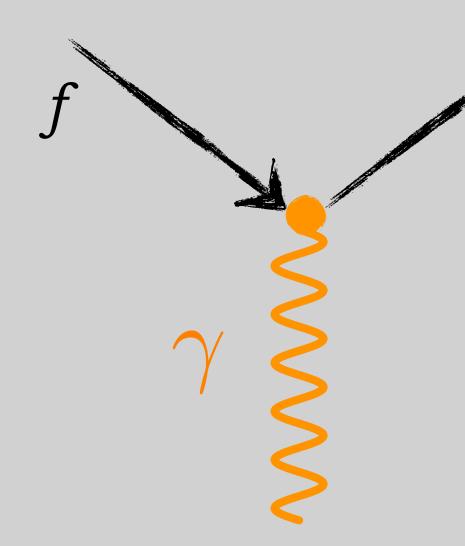
### to test the Z-path uploading machinery and instructions



# primitive diagrams

#### are general

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



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

Their diagrams are identical.



## Primitive Diagram Scorecard

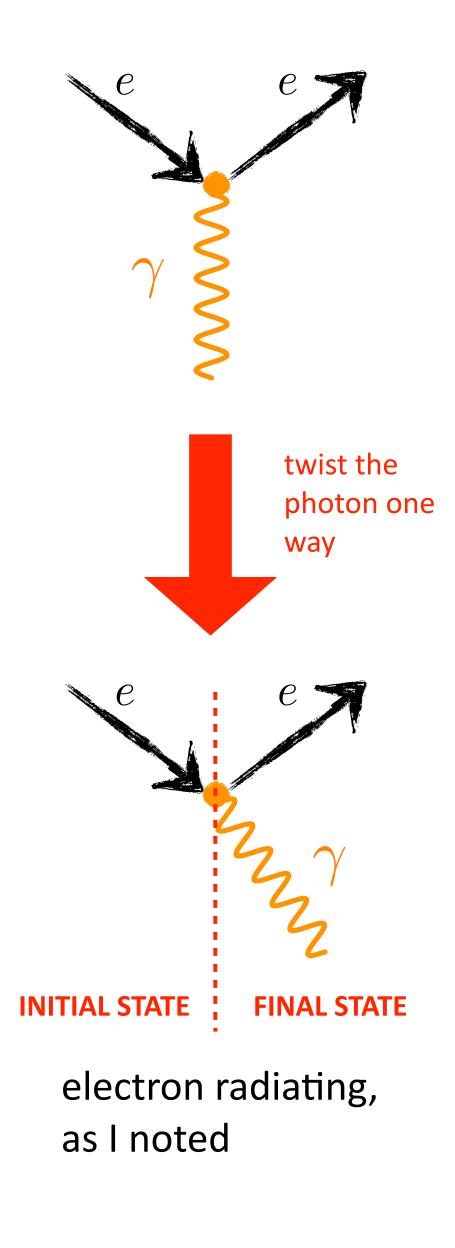
your first entry

Primitive Diagrams	TIME always:	
t t t		QED
2	3	Weak Interactions
6		ractions
4	5	Strong Interactions
8	9	
10	11	Higgs Interactions
ermion, spin 1/2, e.g., electron Vector Boson, spin 1, e.		scalar Boson, spin 0, e.g., Higgs Boson

# for example

## from my primitive, I can make two standard processes

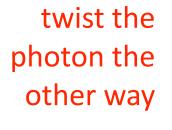
the photon is its own antiparticle

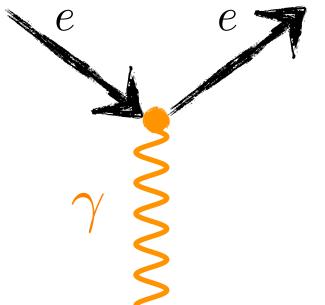


#### electron reacting to a electric Coulomb force or a magnetic Lorentz force

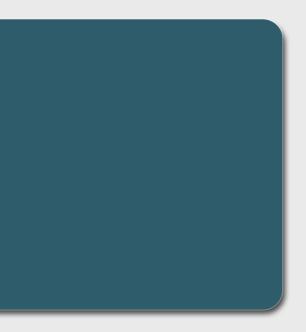
#### **INITIAL STATE**

**FINAL STATE** 





# particle physics



particle:	neutron	
	symbol:	n
	charge:	0
	mass:	1.6749 x 10 <sup>-27</sup> kg,
	spin:	1/2
	category:	fermion, baryon,

## 939.6 MeV/c<sup>2</sup>

## I = -1/2, B = 1

particle:	proton	
	symbol:	p
	charge:	+1 <i>e</i>
	mass:	1.6726 x 10 <sup>-27</sup> kg,
	spin:	1/2
	category:	fermion, baryon,

## 938.2 MeV/c<sup>2</sup>

## 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"



#### <sup>13</sup>C: 1.1% & stable <sup>14</sup>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?

e

Suppose we have a firecracker exploding into two pieces:

beta decay seemed like this when you expect this

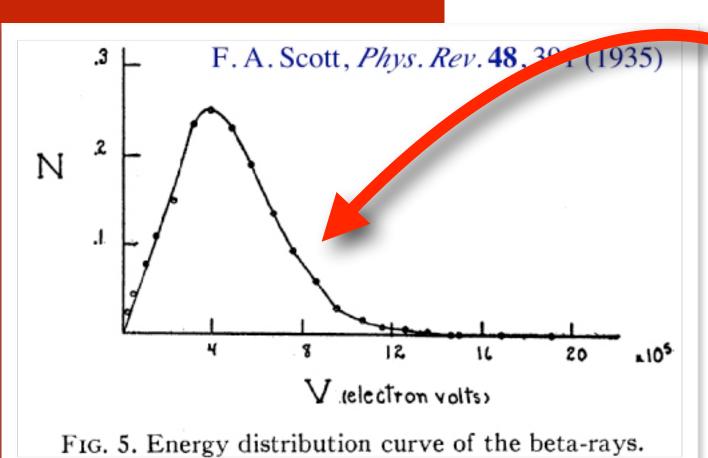


energies
in a "two
body
decay"
are single-valued

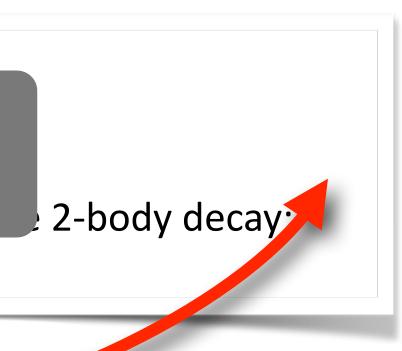
Beta decay was ass Nucleus ---> e and Nucleus'

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

Should get a particular speed for the electron # of right hand
speeds



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



#### because of the conservation of energy and momentum

 ${\cal U}$ 

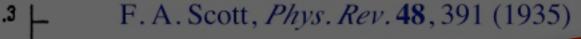
#### a particular value

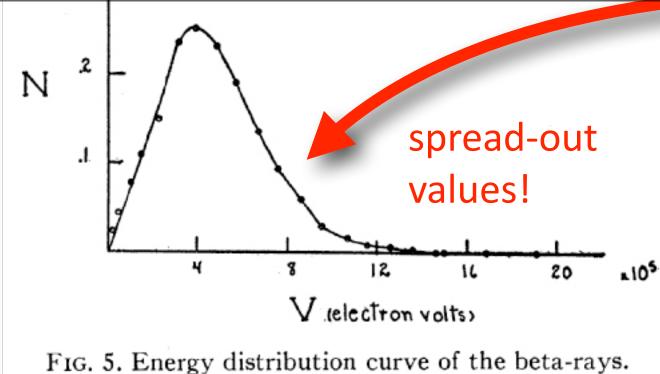
suppose you have a "two

body

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

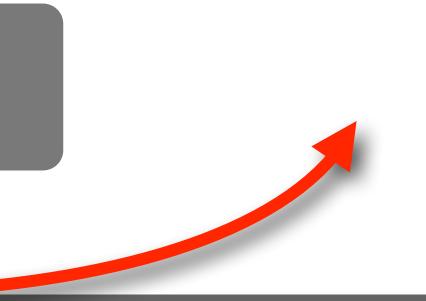
# because of the conservation of energy and endergy and endegy and endergy and energy and energy and





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

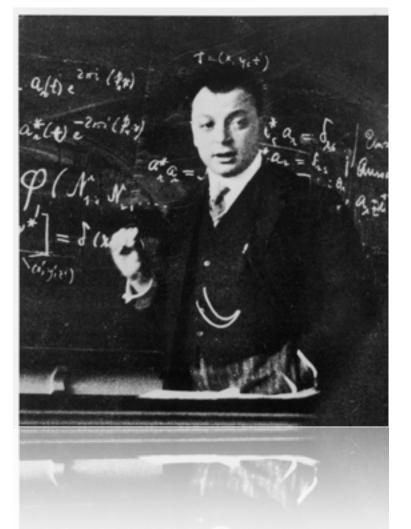




a particular value

"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 G G electron...I admit that my way out may not seem very probable...But only he who dares wins

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



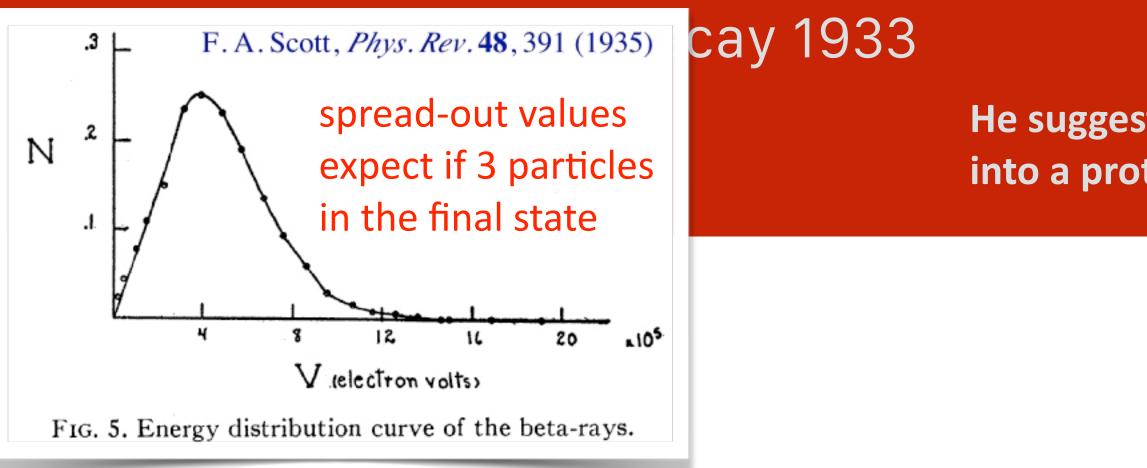
Wolfgang Pauli, distressed at the crisis and unwilling to part with energy conservation-like Bohr suggested!-in 1930 made a bold proposal, in an off-hand way

Naming problem: Chadwick called his particle "neutron" Fermi called Pauli's the *neutrino*...little neutron

and massless!

## the idea hung around

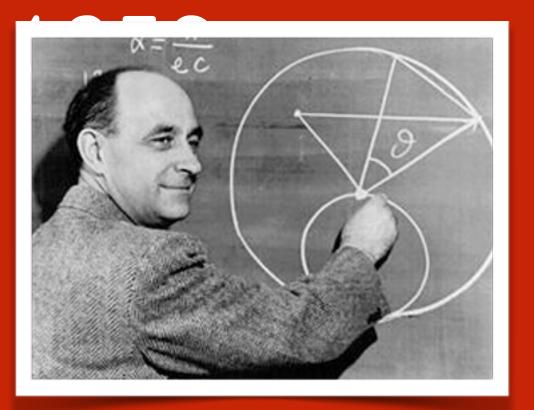
## the discovery of the neutron in 1932 gave Enrico Fermi an idea



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



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



Enrico Fermi 1901-1954 experimental & theoretical physicist! Nobel Laureate 1938

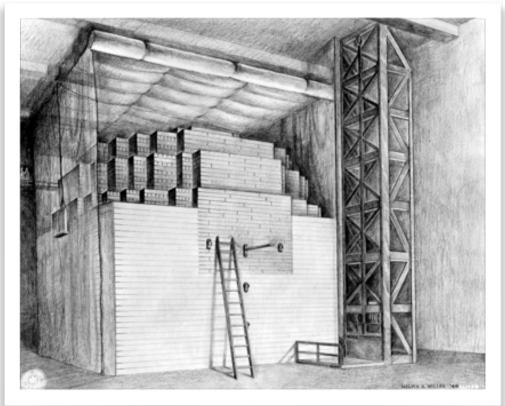
Probably 2, maybe 3 Nobel prize-worthy experiments. Probably 2, maybe 3 Nobel prize-worthy theoretical products. There will never be anyone like Enrico Fermi again.

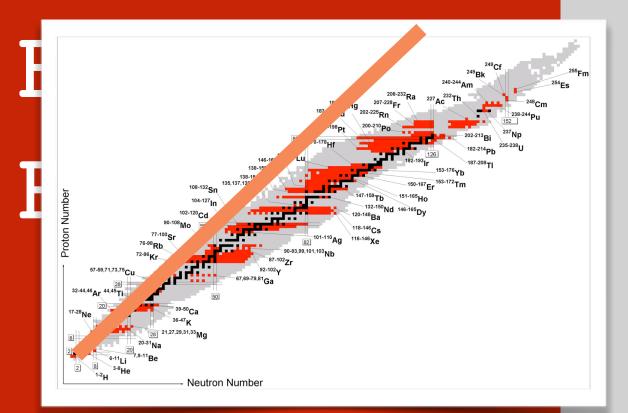




**Enrico Fermi** 1901-1954 (actually in a cafeteria in Ann Arbor, 1935)







## Nobel 1938

not for beta decay

for bombarding nuclei with neutrons and causing fission

#### Nobelprize.org

The Official Web Site of the Nobel Prize

**Nobel Prizes** 

Alfred Nobel

Educational

Home / Nobel Prizes / Nobel Prize in Physics / The Nobel Prize in Physics 1938

About the Nobel Prizes

Facts and Lists

#### **Nobel Prize in Physics**

All Nobel Prizes in Physics

Facts on the Nobel Prize in Physics

Prize Awarder for the Nobel Prize in Physics

Nomination and Selection of Physics Laureates

Nobel Medal for Physics

Articles in Physics

Video Interviews

Video Nobel Lectures

Nobel Prize in Chemistry

Nobel Prize in Physiology or Medicine

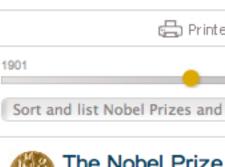
Nobel Prize in Literature

Nobel Peace Prize

Prize in Economic Sciences

Nobel Laureates Have Their Say

Ceremonies





#### The Nobel Prize in Physics 193

Nobel Prize Award Ceremony

Enrico Fermi



Enrico Fermi

The Nobel Prize in Physics demonstrations of the existe neutron irradiation, and for h about by slow neutrons".

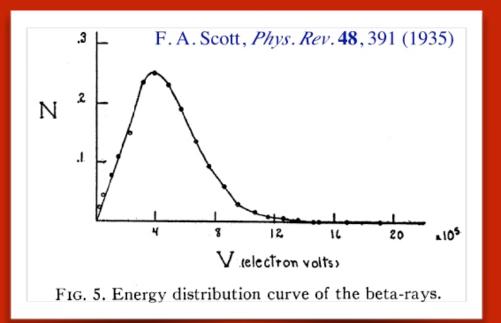
Photos: Copyright @ The Nobel Foundation

Video Player Nobel Organizations	ome   A			
er Friendly 🛛 🕂 Share 🛛 🖂 Tell a Friend 📿 Com	ments			
2012     193       Nobel Laur     Prize category: Physics	8			
in Physics 1938				
38				
	<b>V</b>			
1938 was awarded to Enrico Fermi "for his ence of new radioactive elements produced by his related discovery of nuclear reactions brought				

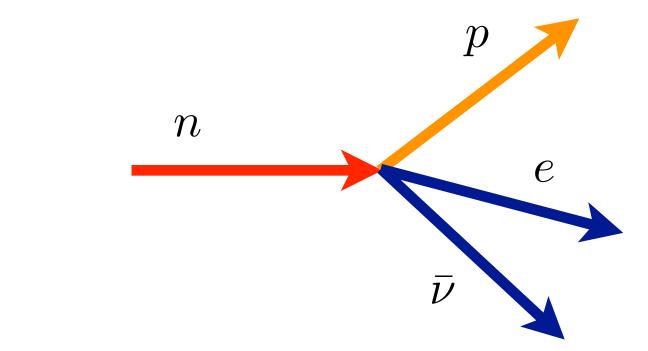
Fermi Theory of Beta Decay

uses the Dirac ideas of quantum electrodynamics

particle creation and annihilation

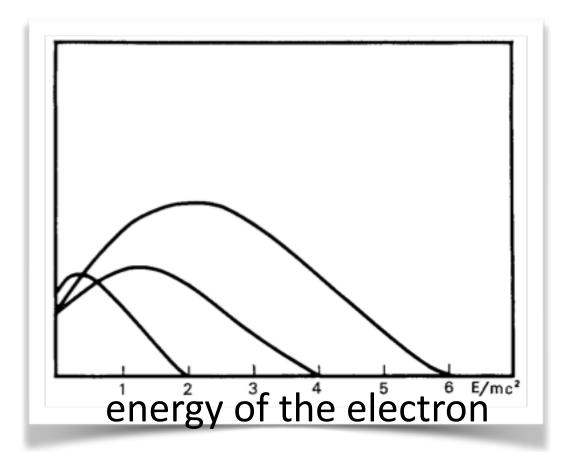


m<sub>neutron</sub> > m<sub>proton</sub> a smidgen.



#### 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

lightyears of lead to stop one!

# Neutrinos very weakly interact in matter

# exchange force

the modern view:

if there's a force...there's a field

if there's a field...there's a particle

## eld ticle

# in 1932 Heisenberg had good idea: "Exchange Force" the simplest, but most important notion yet

## Heisenberg: hmm. electrons appear out of nuclei

## maybe they're in the nucleus? maybe they're even holding it together?



# Exchange Force

## The proton is playing catch with itself

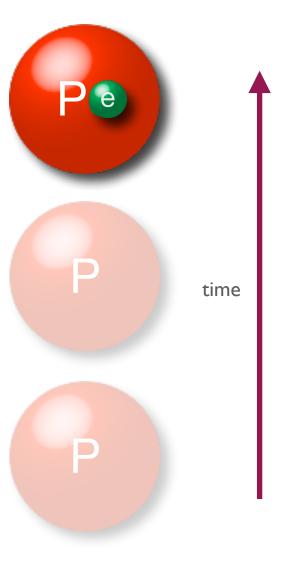
with all he knew about: electrons and protons

maybe beta decay?

He knew that sometimes nuclei just spit out an electron. Rutherford's beta decay

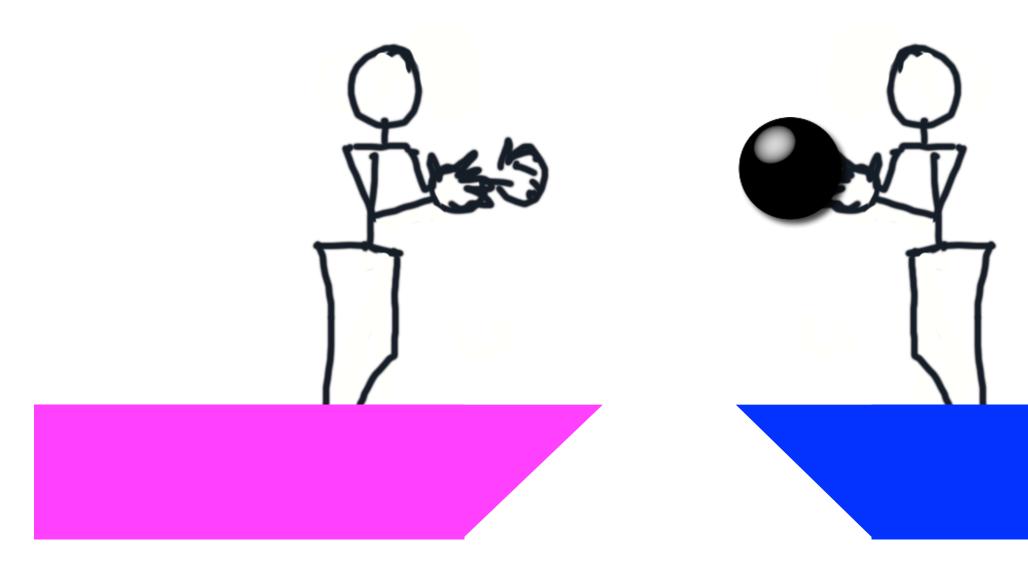
P

D



## analogy: a repulsive exchange force

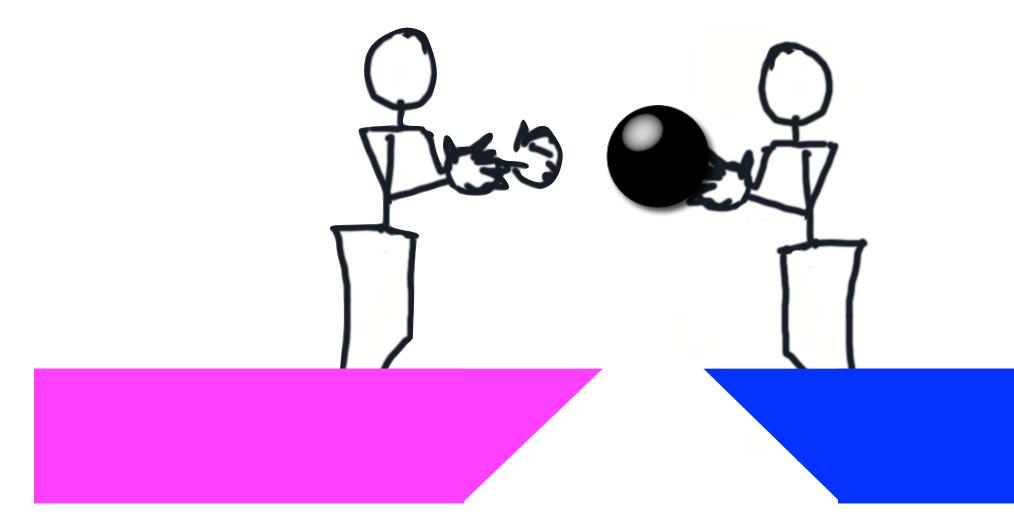
a repulsive exchange force





## analogy: an attractive exchange force

an attractive exchange force



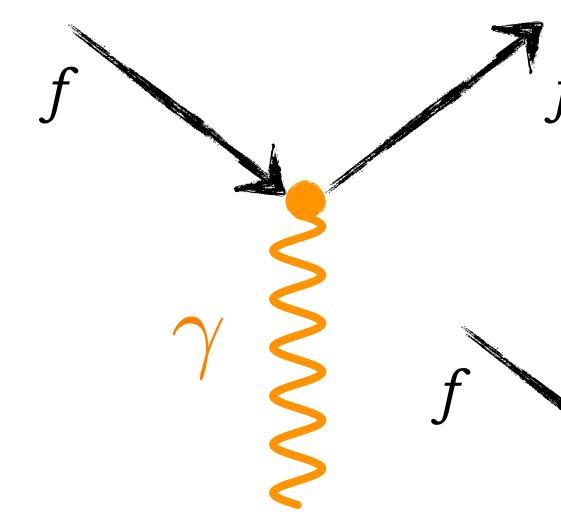
jargon alert:	exchange force	
	refers to:	the idea that the fo propagated by qua
	entomology:	Heisenberg's pictur them
	example:	the photon!

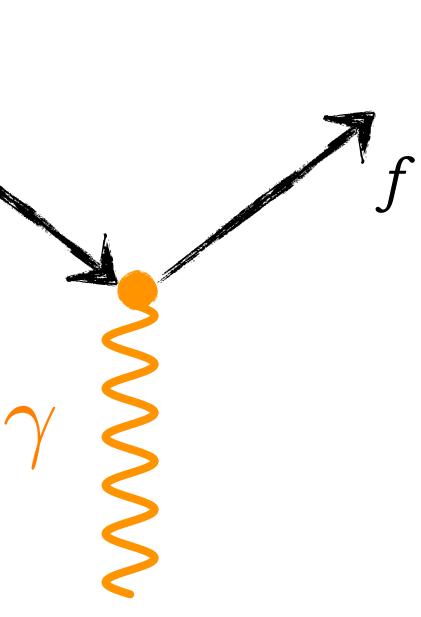
## orces of nature are anta

#### re of exchanging

piece the
primitives
together

## sharing a leg





## know We one force

#### electromagnetism

electricity

magnetism

united by Relativity

remember?

e

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

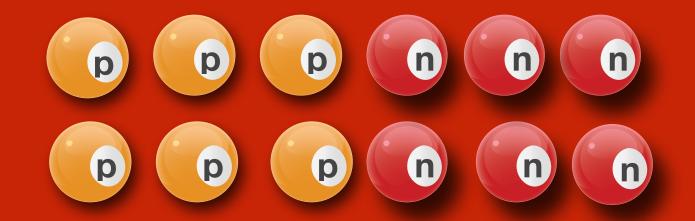
Heisenberg's original idea was before the neutron

his protons playing catch with electrons?

nope.

# remember: chemistry from # protons = #electrons

to "assemble" <sup>12</sup>C they have to attract one another NOT electromagnetism



# remember: chemistry from # protons = #electrons

# to "assemble" <sup>12</sup>C

### they have to attract one another



## But how does it hold together?

why does any nucleus beyond Hydrogen hang together?

those protons want to get away from one another

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

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



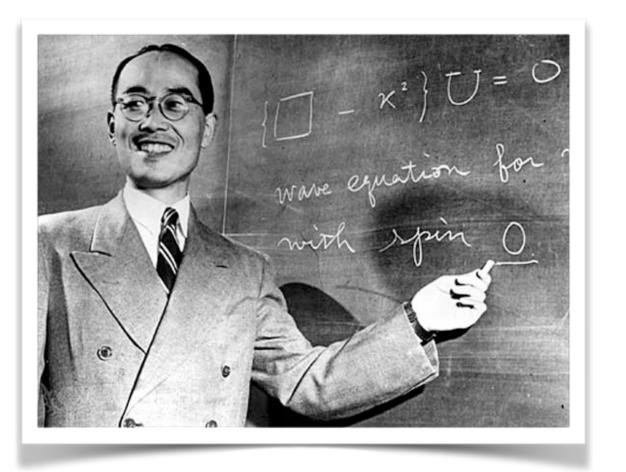


39

# Strong Force

1934

# Hideki Yukawa



Yukawa's force *finite* in extent

### electromagnetic force infinite in extent



The Strong Force is a stronger than...<u>anything</u> in the universe. two competing forces:

**Electromagnetic Force** 





# Strong is stronger than...<u>anything</u>. two competing forces:

**Electromagnetic Force** 







# Strong is stronger than...<u>anything</u>. two competing forces:

**Strong Force** 

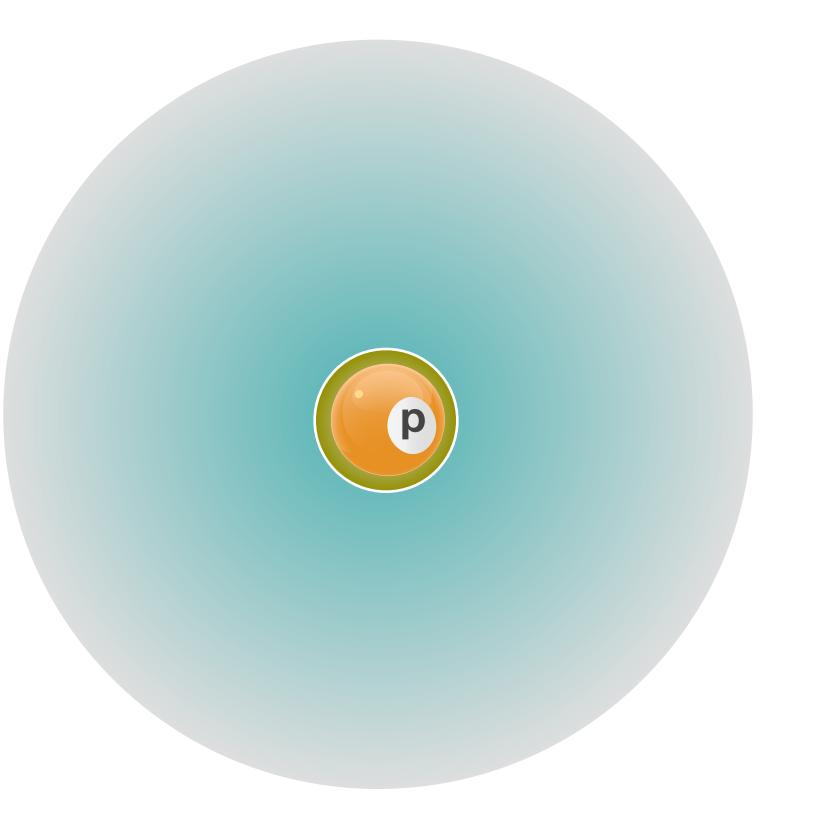






# Strong is stronger than...<u>anything</u>. two competing forces:

**Strong Force** 







# the STRONG force

# overwhelms the electromagnetic force

### but only over a very short range...





# the STRONG force

# overwhelms the electromagnetic force

### but only over a very short range...



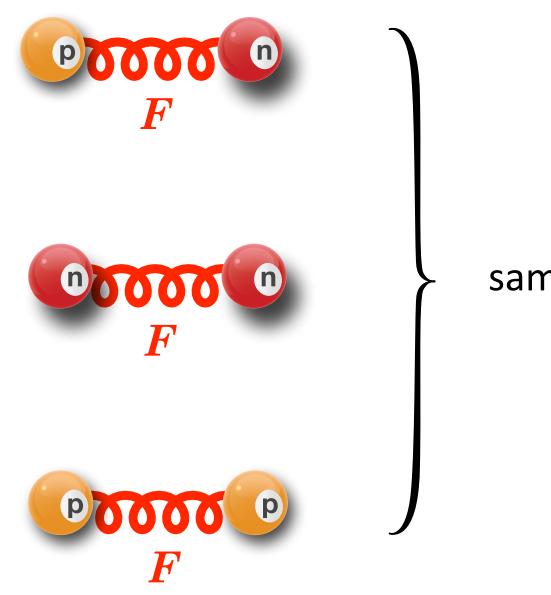


neutrons and protons

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



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

### same force, same strength

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

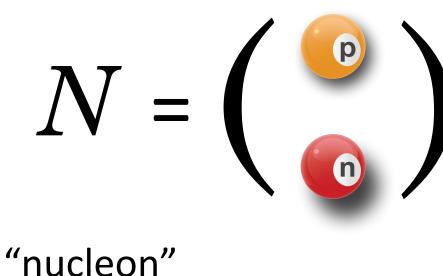
neutrons and protons

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"



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

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

How?





+ 1/2

-1/2

# jargon alert:nucleonrefers to:either a proton or a neutronentomology:from "nucleus"...the "-on" tends to be a<br/>particle nameexample:"nucleon force"

jargon alert:	hadron	
	refers to:	any particle that i Strong Force
	entomology:	αδρόσ "hadros" "la
	example:	proton and neutr not electron, not

# interacts via the

# arge", "massive"

ron *photon* 

# remember

# Nature is clumpy

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



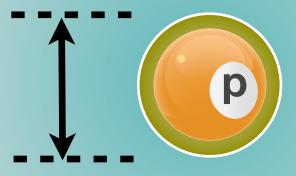
# If there's a field, there's a quantum to go with it.

The nuclear force is "active" over a short distance

~10<sup>-15</sup> m

Yukawa knew that.





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uncertainty certainly to the rescue

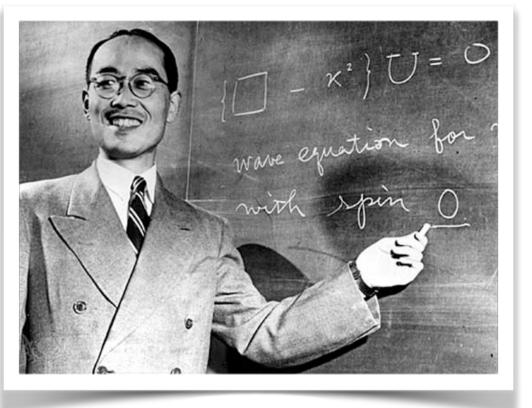
brilliant observation by Yukawa

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

another exchange force/particle?







the most important thing in particle physics?

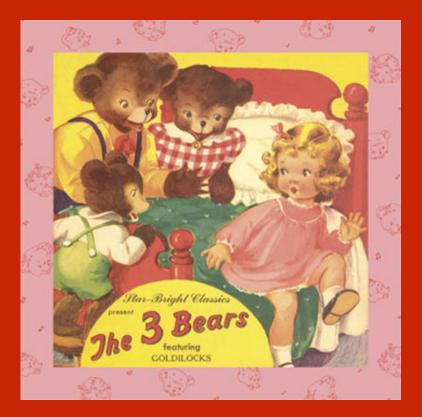
getting the name right.

the "Yukon"? thankfully, no.

the "meson?" Why yes, I think I like it.

medium mass...

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



# the hunt was on

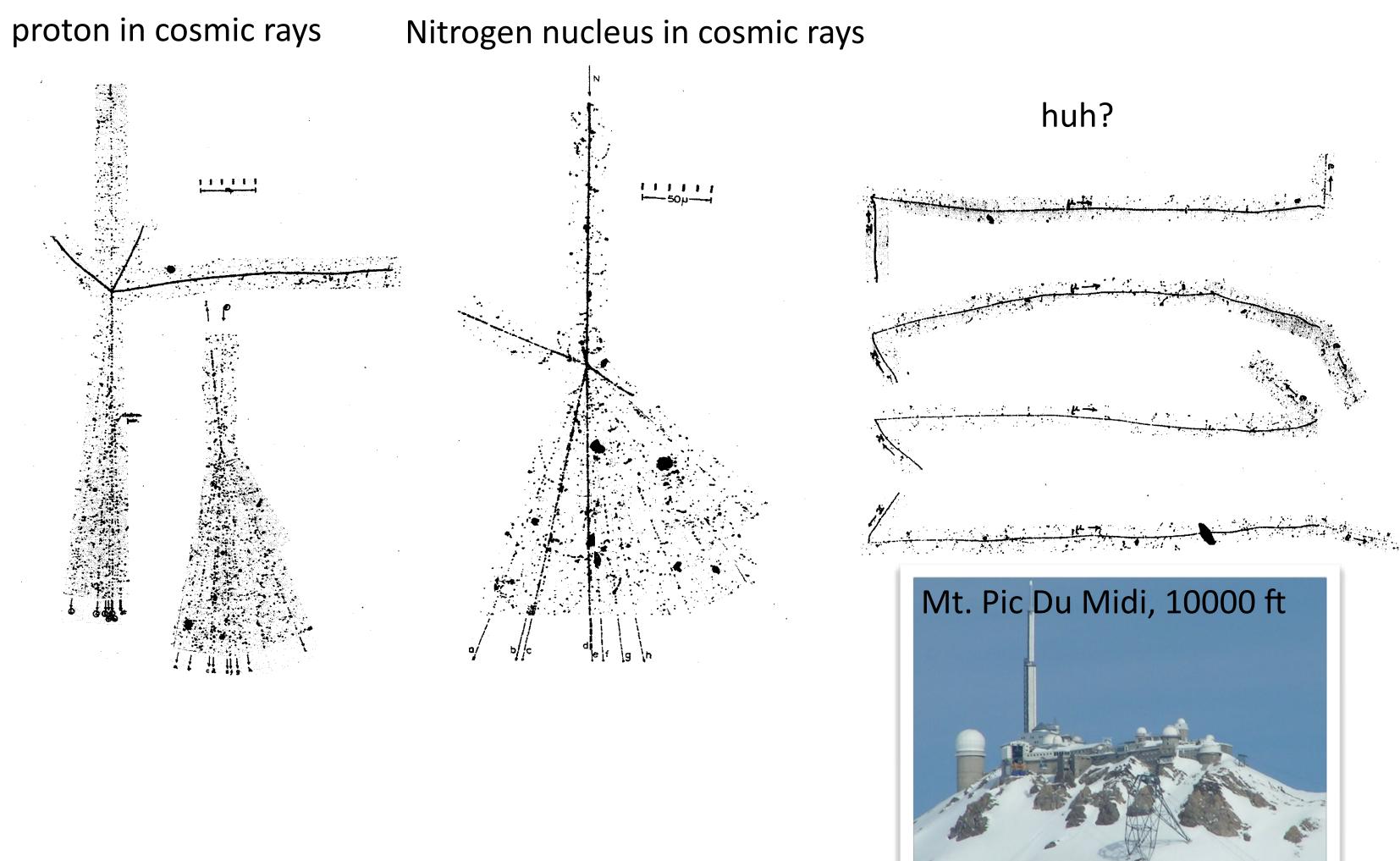
# to find the Yukawa Particle

but WWII got in the way





## Post-war emulsion exposures were startling



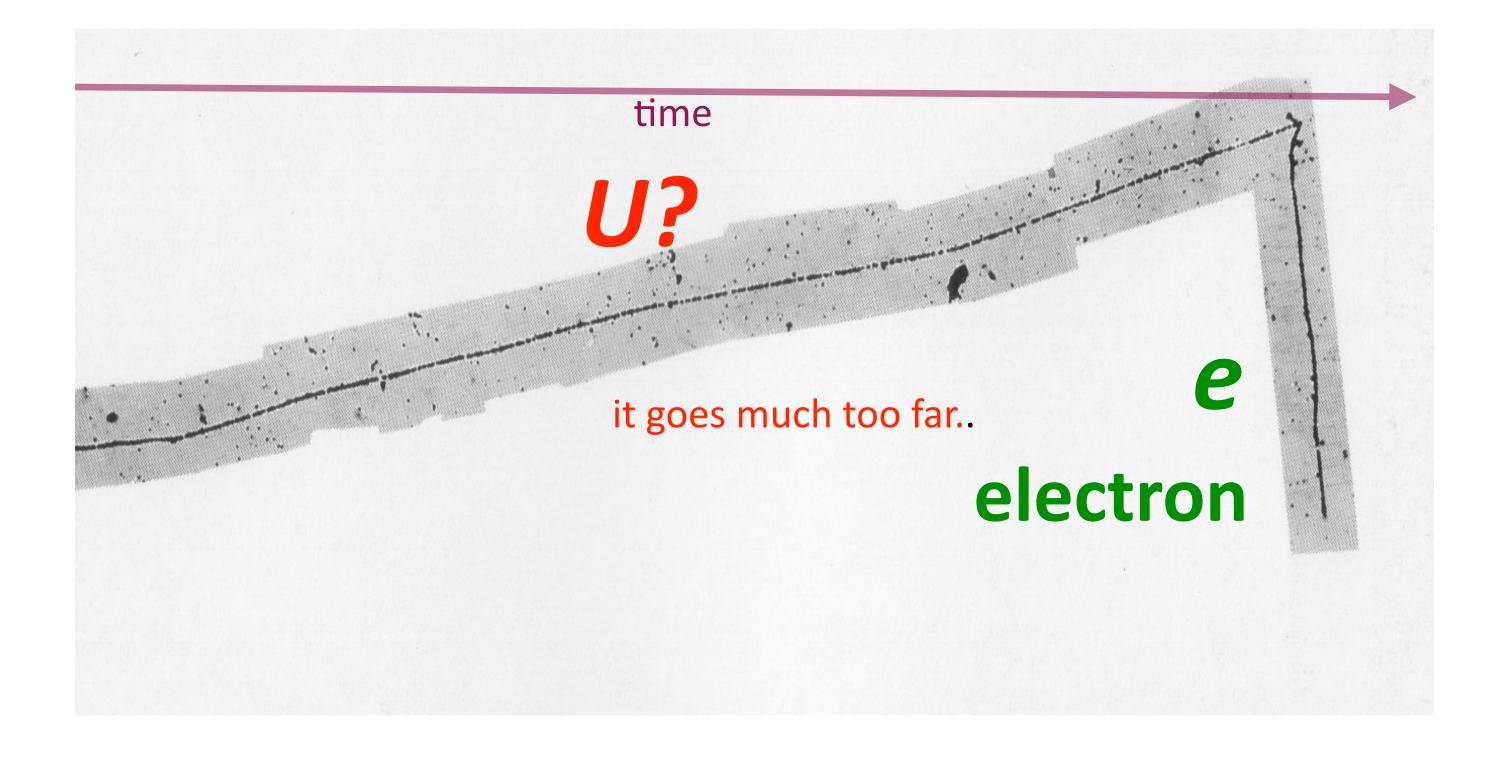
from Cecil Powell's Nobel lecture... a former student of?

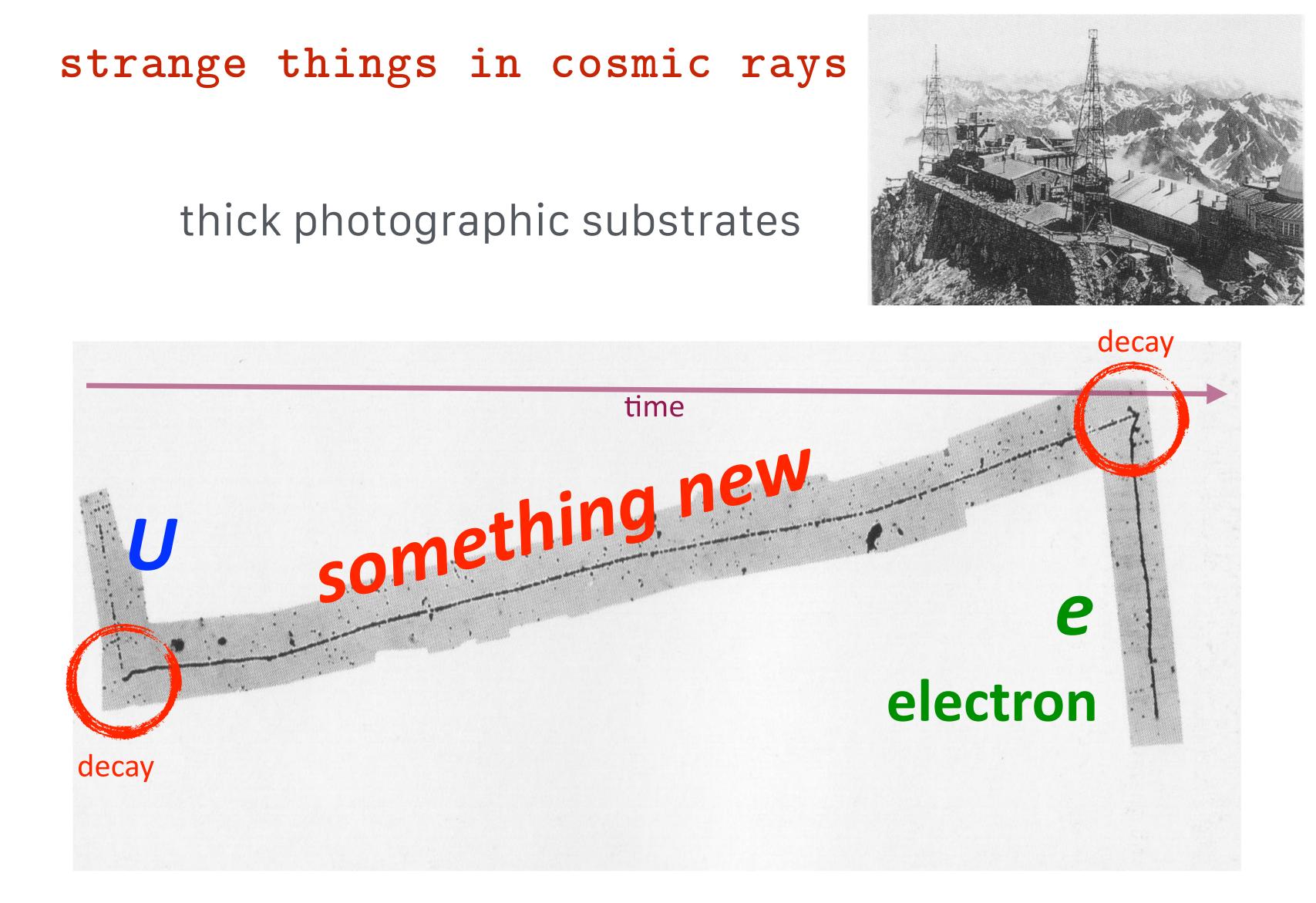
...you guessed it.

# many of these sort:

# something unknown...

# 20,000 stereo photos --> 1600 usable tracks in 3 cm<sup>2</sup> plate





two discoveries

# for the price of one

now called the "muon"

# This took some unraveling.

μ

 ${\cal V}$ 

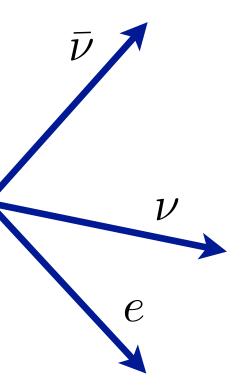
The "meson" appeared in and initiated nuclear collisions

The unknown particle seemed to live about a 6  $\mu$ sec too long to be a meson

The winning proposal:

now called the "pion"

 $\cdot \nu$ 

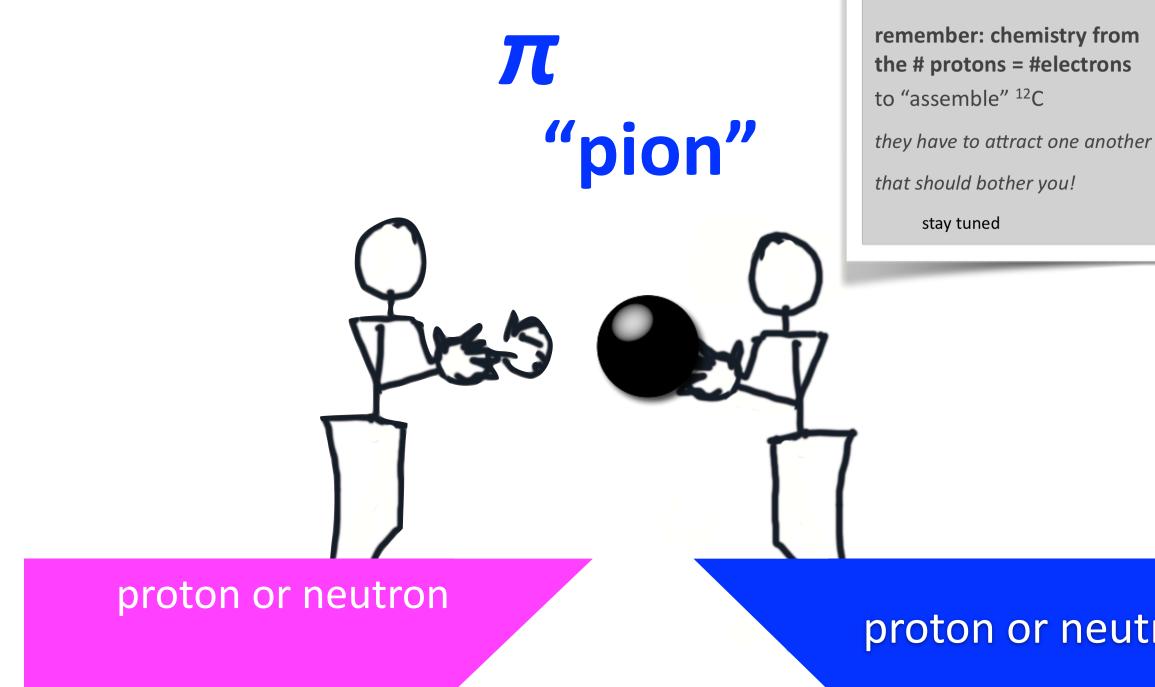


particle:	pion	
	symbol:	$\pi$
	charge:	+, -, 0
	mass:	139 MeV/c <sup>2</sup> ,
	spin:	0
	category:	Boson, hadron, m

### neson



# an attractive exchange force



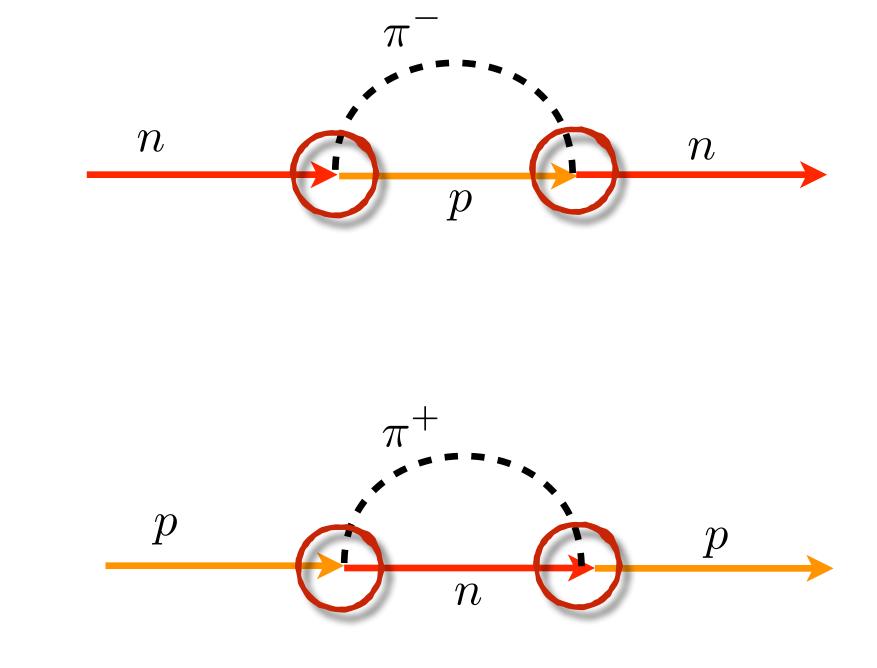
### remember: chemistry from the **#** protons = **#**electrons



### proton or neutron

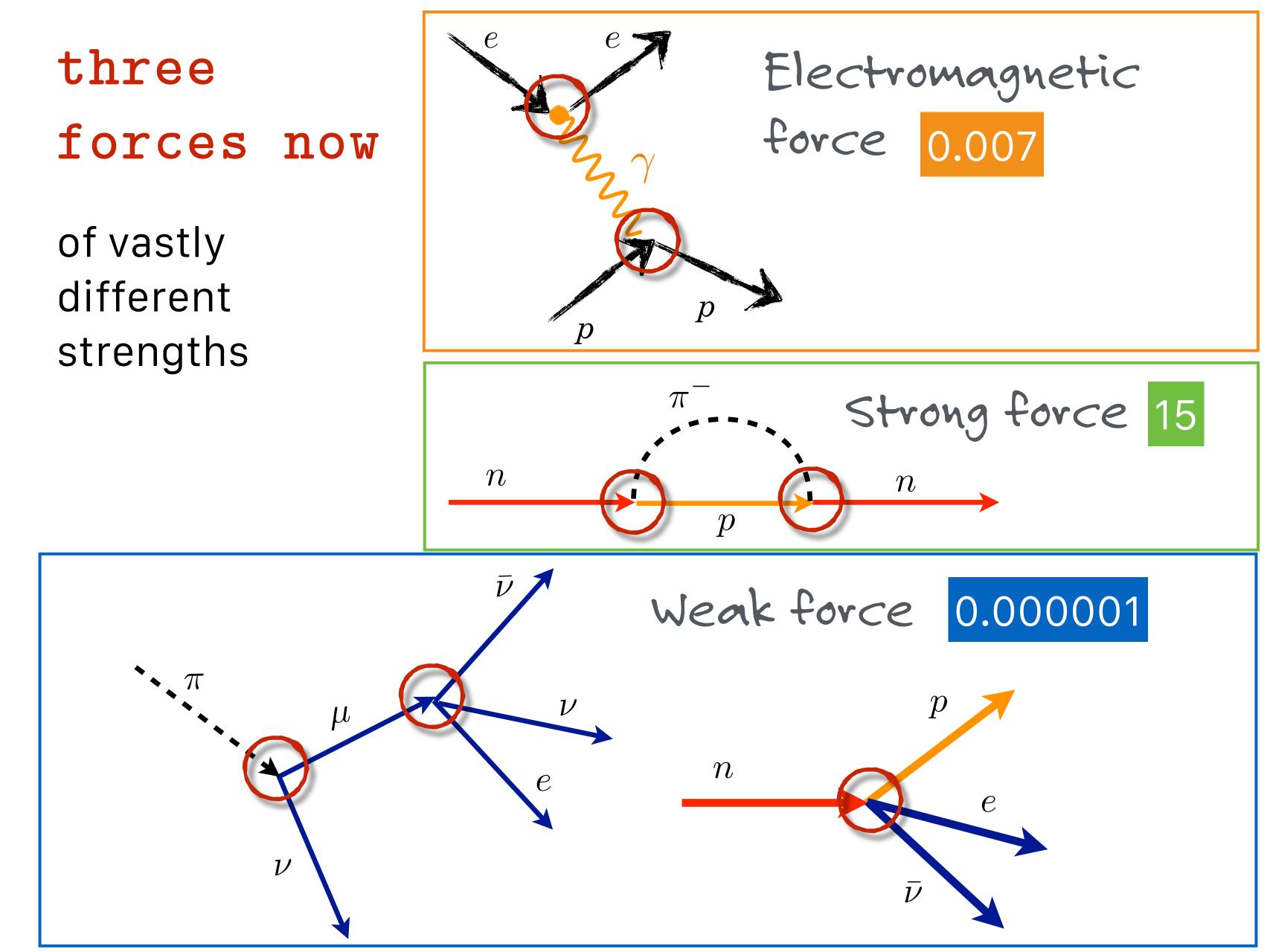
# the Yukawa particle

# is the pion



These coupling strengths are large - strong.

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



particle:	muon	
	symbol:	μ
	charge:	+, —
	mass:	105.7 MeV/c <sup>2</sup>
	spin:	1/2
	category:	Fermion, lepton

# particle: muon The smpl: Specific constraints of the second secon

category:

Fermion, lepton

# Vier.

# The Tau is exactly like an Electron just more spin: cate cate of the second second



# 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

66

particle:	muon-neutrino	
	symbol:	${\cal V}_{\mu}$
	charge:	0
	mass:	0 or 0.4-ish to 1-is
	spin:	1/2
	category:	Fermion, lepton

ish eV/c<sup>2</sup>

particle:	tau-neutrino	
	symbol:	${\cal V}_{ au}$
	charge:	0
	mass:	0 or 0.4-ish to 1-is
	spin:	1/2
	category:	Fermion, lepton

ish eV/c<sup>2</sup>

# FAMILIES

# Nature prefers

like-particles



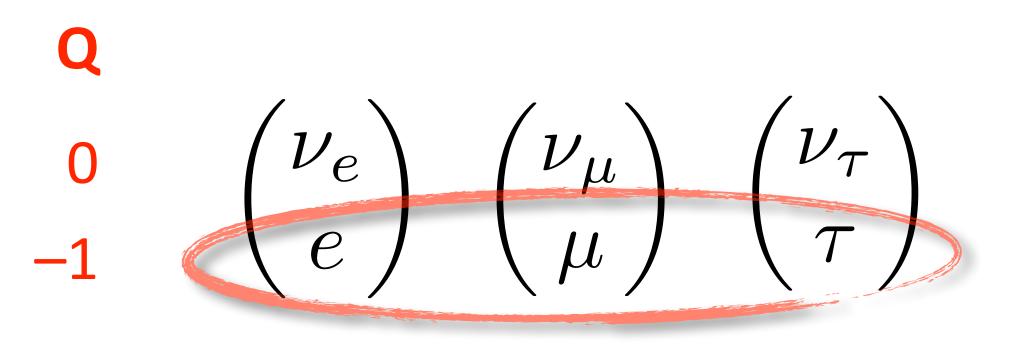
# Lepton Families

electrons and a neutrino

muons and a neutrino

taus and a neutrino

# These sorts of patterns are a huge deal.



Identical in every way...except mass

$$m_e \sim \frac{1}{1835} \times m_p$$
$$m_\mu \sim 10\% \times m_p$$

 $m_{\tau} \sim 1.8 \times m_p \parallel$ 



jargon alert:	lepton	
	refers to:	originally, an elec neutrino
	entomology:	"λεπτός" (leptos),
	example:	electron, muon, r

### ctron, muon,

# ), "fine, small, thin" neutrino, tau!

# back to the 1940s

72

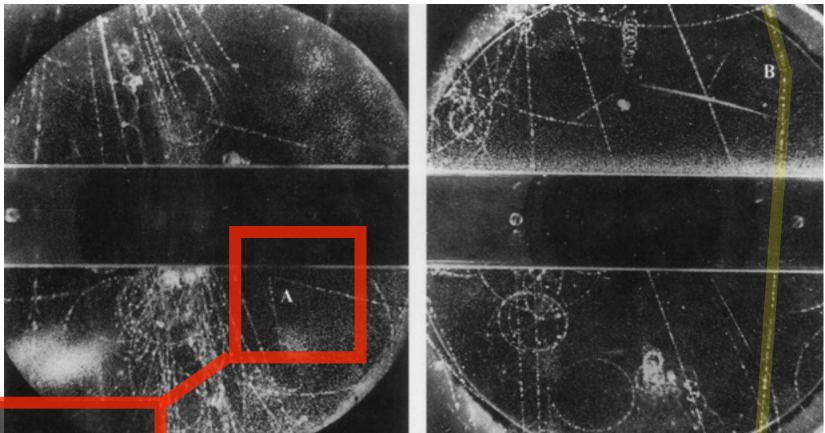
cosmic rays continue to surprise **Cloud chamber...w**ith Pb sheet

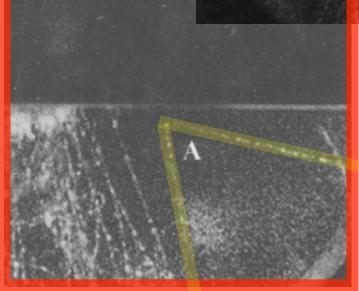
Manchester University academic home for many years of...? who else.

## Mysterious "Vees" began to crop up...

"Vee"  $\rightarrow \pi^+ + \pi^-$  "Vee"  $\rightarrow \mu + \nu$ ?

 $\pi$ 





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

"strange"

1946

 $K^{\pm} \to \mu^{\pm} + \nu$ 

dubbed "Kaons"...they were

particle:	Kaon	
	symbol:	K
	charge:	±1, 0
	mass:	493.677 (charged
	spin:	0
	category:	Fermion, baryon,

### d state) MeV/c<sup>2</sup>

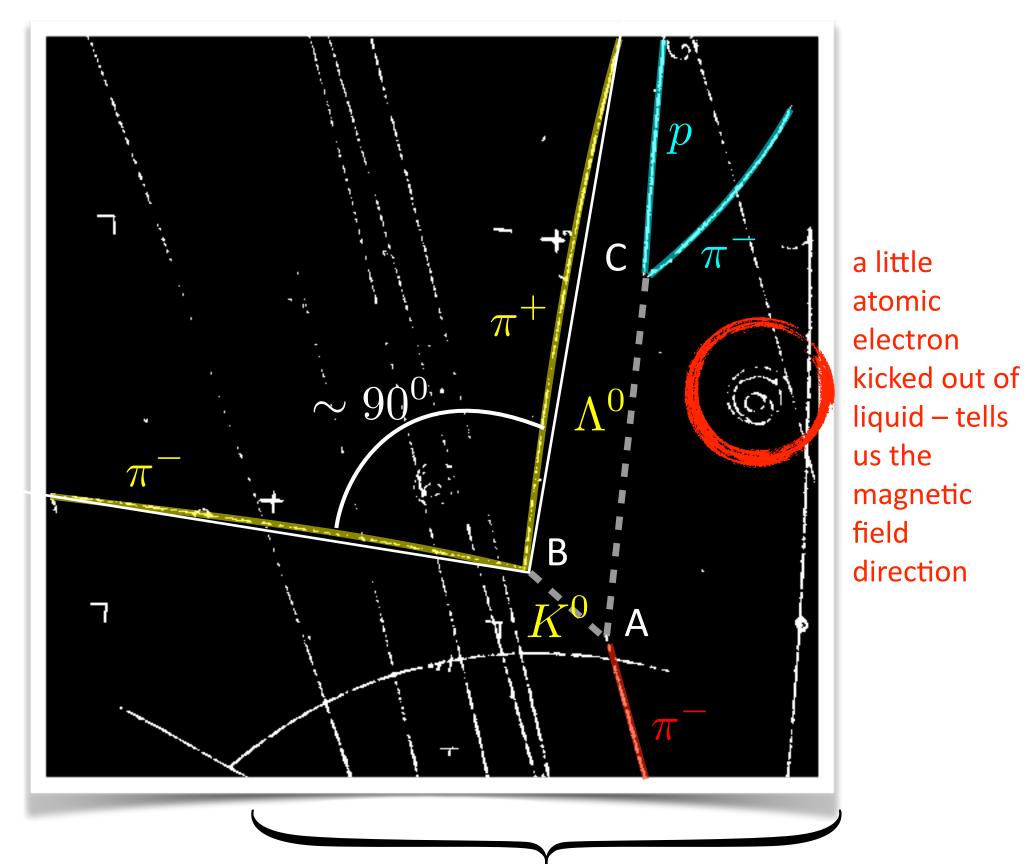
## $I = \pm 1/2, B=1, S=-3$

## the at Bevatron

"cosmic ray" events could be manufactured on earth

at will.

### Without knowing details, we can decipher a lot:



### 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

$$\pi^{-}$$

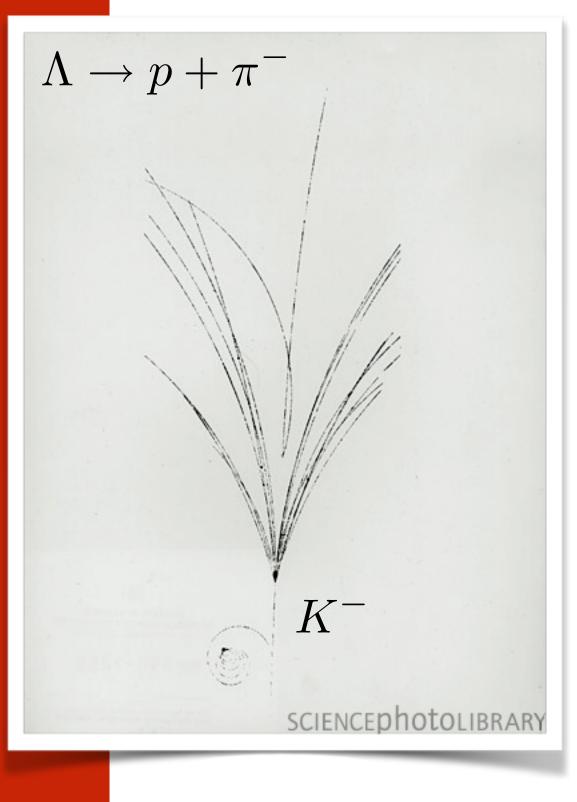
75

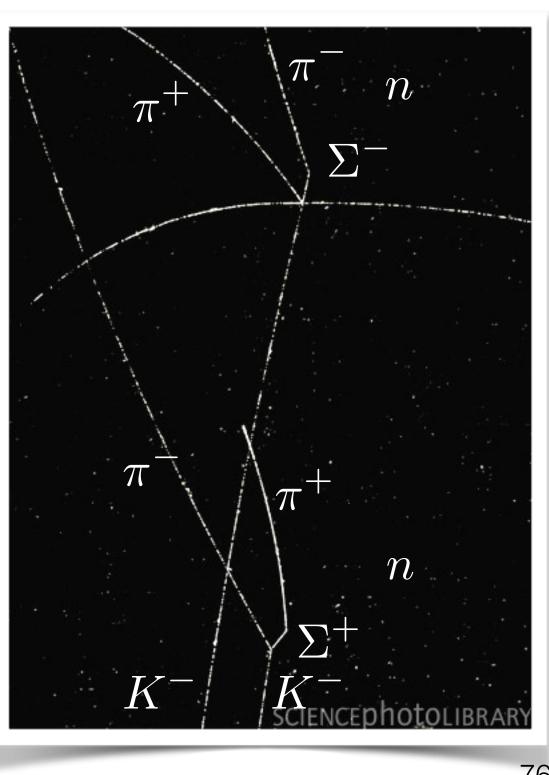
yes, more strange particles

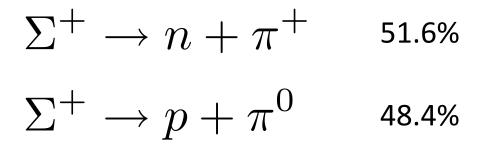
$$\Lambda 
ightarrow p + \pi^-$$
 64%  $\Lambda 
ightarrow n + \pi^0$  36%

"Lambdas" "Sigmas" "Cascades"

"K-stars"







particle:	Lambda	
	symbol:	Λ
	charge:	0
	mass:	1,115.683 MeV/c <sup>2</sup>
	spin:	1/2
	category:	Fermion, baryon, I
		rennon, baryon,

## I = 0, B=1, S=-1

* *	$\begin{array}{c} \text{IED, STRA} \\ = S = \pm 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\$
* ** *** *** *** *** *** ***	$\begin{array}{c} D^{\pm} & (0,0,0) \\ D^{\pm} & D^{+}(2007) \\ \bullet & D^{+}(2007) \\ \bullet & D^{+}(2010) \\ B^{+}_{0}(2400) \\ D^{+}_{0}(2420) \\ \bullet & D_{1}(2420) \\ \bullet & D_{1}(2420) \\ \bullet & D_{1}(2420) \\ \bullet & D_{2}(2460) \\ \bullet & D_{2}(2460) \\ \bullet & D_{2}(2460) \\ \bullet & D_{1}(2640) \\ \bullet$
$a^{-} \equiv -$ $\equiv (1530)$ $\equiv (1620)$ $\equiv (1620)$ $\equiv (1820)$ $\equiv (1950)$ $\equiv (2030)$ $\equiv (2120)$ $\equiv (2250)$ $\equiv (2500)$ $\equiv (2500)$ $= (2500)^{-}$ $\Omega(2250)^{-}$ $\Omega(2380)^{-}$ $\Omega(2470)^{-}$ $\Lambda_{c}^{+}$	$\frac{1}{2}(1)$ $1/2(1^+)$ $1/2(1^-)$ $1/2(2^-)$ $1/2(2^-)$ $1/2(2^-)$ $1/2(0^-)$ $1/2(0^+)$ $1/2(2^+)$ $1/2(2^+)$ $1/2(2^-)$ $1/2(1^-)$ $1/2(1^-)$ $1/2(1^-)$ $1/2(1^-)$ $1/2(1^+)$ $1/2(2^+)$ 1/
$\begin{array}{c} 0) & & & & & \\ 0) & D_{13} & & & \\ 0) & S_{11} & & & & \\ 0) & S_{11} & & & & \\ 0) & P_{11} & & & & \\ 0) & D_{13} & & & & \\ 0) & D_{13} & & & & \\ 0) & P_{11} & & & \\ 0) & P_{11} & & & \\ 0) & P_{13} & & & \\ 0) & S_{11} & S_{11} & \\$	$\pi_2(2100) = G = G = G = G = G = G = G = G = G = $
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$ \begin{array}{c} f_{0} f_{0} (0 - +) \\ i 0^{+} (1 + +) \\ 0 0^{-} (1) \\ i 0^{+} (2 + +) \\ i 1^{-} (0 + +) \\ i 1^{-} (0 + +) \\ i 0^{+} (2 + +) \\ 0 0^{+} (2 + +) \\ 0 0^{+} (2 + +) \\ 0 0^{+} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 0^{-} (2 + +) \\ 0 + (2 + +) \\ 0^{+} (2 + +) \\ 0 + (2 + + +) \\ 0 + (2 + + +) \\ 0 + (2 + + +) \\ 0 + (2 + + +) \\ 0 + (2 +$
$\begin{array}{c} A(1405) & S_{0}\\ A(1520) & D_{1}\\ A(1520) & D_{1}\\ A(1600) & P_{1}\\ A(1600) & S_{0}\\ A(1690) & D_{1}\\ A(1800) & S_{0}\\ A(1810) & P_{1}\\ A(1820) & F_{0}\\ A(1830) & D_{1}\\ A(1830) & D_{1}\\ A(1830) & D_{1}\\ A(1830) & D_{1}\\ A(1200) & F_{0}\\ A(2100) & F_{0}\\ A(210) & F_{0}\\ A(210) & F_{0}\\ A(210) & F_{0}\\ A($	<ul> <li>η(1405)</li> </ul>
) $P_{33}$ *** ) $S_{311}$ *** ) $P_{31}$ * ) $P_{31}$ * ) $F_{35}$ *** ) $P_{31}$ *** ) $P_{31}$ *** ) $P_{31}$ *** ) $P_{33}$ *** ) $P_{33}$ *** ) $P_{33}$ *** ) $P_{33}$ *** ) $P_{33}$ *** ) $P_{35}$ *** ) $P_{35}$ *** ) $F_{37}$ ** ) $F_{37}$ ** ) $F_{37}$ ** ) $F_{37}$ * )	$f^{5}(f^{8C})$ $1^{-}(0^{-})$ $1^{-}(0^{-})$ $1^{-}(0^{-})$ $0^{+}(0^{-} +$
(1600) Pat (1600) Sat (1600) Pat (1600)	$ \begin{array}{c} \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\$
$\begin{array}{c} P_{11} \\ P_{11$	$\begin{array}{c} 0 - (1) \\ 0 - (1) \\ 0 - (1) \\ 0^{2}(2^{2} +) \\ 1^{2}(2^{2}) \\ 0 - (1) \\ 0 - (1) \\ 0 - (1) \\ 0 - (1) \\ 0 - (1) \\ 0 - (1) \\ 0 - (1) \\ 0 + (1 + +) \\ 0 - (1) \\ 0 + (1 + +) \\ 0 - (2) \\ 0 + (0 + +) \\ 1^{2} \\ 0 - (2) \\ 0 + (0 + +) \\ 1^{2} \\ 0 - (2) \\ 0 + (0 + +) \\ 1^{2} \\ 0 - (2) \\ 0 + (0 + +) \\ 1^{2} \\ 0 - (2) \\ 0 - (1) \\ 0 - (1) \\ 2^{2} \\ 0 - (1) \\ 2^{2} \\ 0 - (1) \\ 2^{2} \\ 0 - (1) \\ 2^{2} \\ 0 - (1) \\ 2^{2} \\ 0 - (1) \\ 0 - (1) \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ $
$\begin{array}{c} & & & & & & & & & & & & & & & & & & &$	• $\psi(2S)$ • $\psi(3770)$ • $\chi(3872)$ • $\chi(22)$ • $\chi(22)$ • $\chi(22)$ • $\chi(240)$ • $\psi(4415)$ •
$\begin{array}{c} \begin{array}{c} 111\\ P_{11}\\ P_{11}\\ P_{11}\\ P_{11}\\ P_{11}\\ P_{11}\\ P_{11}\\ P_{11}\\ P_{12}\\ P_{11}\\ P_{12}\\ P_{12$	$\begin{array}{c} &   1/2(4^-) \\ ?^2(?^2) \\ \hline \\ RMED \\ = \pm 1) \\ \hline \\ 1/2(1^-) \\ (1/2(1^-) \\ (1/2(1^-) \\ (1/2(1^+) \\ (1/2(1^+) \\ (1/2(1^+) \\ (1/2(2^+) $
$\begin{array}{c} & & & & & & & & & & & & & & & & & & &$	K4(2500) K(3100) B D <sup>±</sup> D
$1^{-}(4^{+}+)$	$\begin{array}{c} 1,1^+(3,)\\ 1,0^+(2,+)\\ 1,0^+(2,-)\\ 1,0^+(2,-)\\ 1,0^+(2,-)\\ 1,1^+(5,-)\\ 1,1^-(6,-)\\ 1,1^-(6,-)\\ 1,0^+(6,-)$
$\begin{array}{c} 1385) & P_{13} \\ 1480) \\ 1560) & D_{13} \\ 1620) & S_{11} \\ 1620) & S_{11} \\ 1660) & P_{11} \\ 1670) & D_{13} \\ 1670) & D_{13} \\ 1670) & D_{13} \\ 1680) & P_{11} \\ 1775) & D_{15} \\ 1840) & P_{13} \\ 1880) & P_{11} \\ 1775) & D_{15} \\ 1840) & P_{13} \\ 1880) & P_{11} \\ 1915) & F_{15} \\ 1940) & D_{13} \\ 2000) & S_{11} \\ 2000) & $	ρ <sub>3</sub> (2250)
$\begin{array}{c} \sum_{i=1}^{n} \sum_{i=1}^{n}$	0+(0-+)
*** $A(1600)$ A(1670) A(1670) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(1800) A(250	$= p_{c}(1475)$ $= f_{c}(1500)$ $= f_{c}(1510)$ $= f_{c}(1510)$ $= f_{c}(1510)$ $= f_{c}(1525)$ $= f_{c}(1540)$ $= f_{c}(1640)$ $= f_{c}(1650)$ $= \omega_{c}(1650)$ $= f_{c}(2100)$ $= f_{c}(2300)$ $= f_{c}(230)$
00       031         00       731         00       731         00       731         00       731         00       731         01       733         020       733         030       033         040       733         050       737         050       737         050       737         050       737         050       737         050       737         050       737         050       737         050       737         060       737         07       737         08       737         09       737         101       737         102       737         103       737         104       1434         105       737         106       737         107       737         108       737         109       737         101       1434         102       737         103       140         104       140	$\begin{array}{c} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\$
A(1405) A(1520) A(1600) A(1600) A(1601) D A(1800) S A(1810) A(1800) S A(1810) P A(1820) A(1820) A(1820) A(1830) D A(2350) A(2350) D A(2350)	<ul> <li>         ω(782)     </li> </ul>
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	• $\chi_{c0}(1P)$ • $\chi_{c1}(1P)$ • $\chi_{c2}(2P)$ • $\chi_{c2}(2P)$ • $\chi_{c2}(2P)$ • $\chi_{c3}(400)$ • $\psi(4040)$ • $\psi(4040)$ • $\psi(4040)$ • $\psi(4160)$ • $\chi_{b1}(1P)$ • $\chi_{b0}(1P)$ • $\chi_{b0}(1P)$ • $\chi_{b1}(1P)$ • $\chi_{b1}(1P)$ • $\chi_{b1}(2P)$ • $\chi_{b2}(2P)$ • $\chi_{b2$
$\begin{array}{c} P_{11} & \ast\ast\ast\ast & \varDelta \\ D_{13} & \ast\ast\ast\ast & \varDelta \\ S_{11} & \ast\ast\ast\ast & \varDelta \\ S_{11} & \ast\ast\ast\ast & \varDelta \\ S_{13} & \ast\ast\ast\ast & \varDelta \\ P_{13} & \ast\ast\ast\ast & \varDelta \\ P_{13} & \ast\ast\ast & \varDelta \\ P_{13} & \ast\ast & \varDelta \\ P_{14} & \ast\ast & \Delta \\ P_{14} & \ast\ast & \Delta \\ P_{15} & \ast\ast & \Delta \\ P_{15} & \ast\ast & \Delta \\ P_{14} & \ast\ast & \Delta \\ P_{15} & \ast\ast & \Delta \\ P_{14} & \ast\ast & \Delta \\ P_{15} & \ast\ast & \Delta \\ P_{14} & \ast\ast & \Delta \\ P_{15} & \ast\ast & \Delta \\ P_{14} & \ast\ast & \Delta \\ P_{15} & \ast\ast & \Delta \\ P_{14} & \ast\ast & \Delta \\ P_{15} & \ast\ast & \Delta \\ P_{14} & \ast\ast & \Delta \\ P_{14} & \ast\ast & \Delta \\ P_{15} & \ast\ast & \Delta \\ P_{15} & \ast\ast & \Delta \\ P_{14} & \ast\ast & \Delta \\ P_{15} & \ast & \Delta \\ P_{15} & \ast & \Delta \\ P_{15} & \ast\ast & \Delta \\ P_{15} & \ast\ast & \Delta \\ P_{15} & \ast & \Delta $	Matrix 1/2(1 <sup>-</sup> )/2( 7(7 <sup>2</sup> )/2( 1)/
+ * *** + * * P n N(1440) = N(1520) = N(1535) = N(1650) = N(1650) = N(1675) = N(1650) = N(1700) = N(1700) = N(1700) = N(1700) = N(1900) = N(1900) = N(1900) = N(1900) = N(1900) = N(2000) = N(2000) = N(2200) = N(200)	$b = 0 V_{ub} CKh ements b = 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0 + 0$
1 (2 0 <sup>+</sup> (0 <sup>+</sup>	$\begin{array}{c} \mathbf{a} = 0 & 0 & (2) \\ \mathbf{f}(\mathcal{P}) & \mathbf{i} + (1 - 1) \\ \mathbf{f}(\mathcal{P}) & \mathbf{i} + (1 - 1) \\ \mathbf{f}(\mathcal{P}) & \mathbf{i} + (1 - 1) \\ \mathbf{f}(\mathcal{P}) & \mathbf{f}(\mathcal{P}) & \mathbf{f}(\mathcal{P}) \\ \mathbf{f}(\mathcal{P}) & \mathbf{f}$
$\begin{array}{c} \Sigma(1560) \\ \Sigma(1580) \\ \Sigma(1580) \\ \Sigma(1620) \\ S(1620) \\ S(1600) \\ \Sigma(1670) \\ D_{13} \\ \Sigma(1670) \\ D_{13} \\ \Sigma(1670) \\ S(1750) \\ S_{11} \\ \Sigma(1775) \\ D_{15} \\ \Sigma(1840) \\ P_{11} \\ \Sigma(1775) \\ D_{15} \\ \Sigma(1840) \\ P_{13} \\ \Sigma(1880) \\ P_{11} \\ \Sigma(1915) \\ F_{15} \\ \Sigma(1940) \\ D_{13} \\ \Sigma(2000) \\ S_{11} \\ \Sigma(200) \\ \Sigma(200$	$(S = \pm 1, C =$ $(S = \pm 1, C $
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$1^{-}(2^{+})$ $1^{-}(2^{+})$ $1^{-}(0^{-})$ $1^{-}(0^{-})$ $1^{-}(0^{-})$ $1^{-}(0^{-})$ $1^{-}(0^{-})$ $1^{-}(0^{-})$ $1^{-}(2^{-})$ $1^{-}(1^{-})$ $1^{-}(2^{-})$ $1^{-}(1^{-})$ $1^{-}(2^{+})$ $1^{+}(1^{-})$ $1^{+}(2^{+})$ $1^{+}(3^{-})$ $0^{+}(2^{+})$ $1^{+}(3^{-})$ $0^{+}(2^{+})$ $1^{-}(4^{+})$ $1^{-}(4^{+})$ $1^{-}(4^{+})$ $1^{-}(4^{+})$ $1^{-}(4^{+})$ $1^{-}(4^{+})$ $1^{-}(4^{+})$ $1^{-}(4^{+})$ $1^{-}(2^{-})$ $0^{+}(2^{+})$ $1^{+}(1^{-})$ $0^{+}(2^{+})$ $1^{+}(1^{-})$ $0^{+}(2^{+})$ $1^{+}(3^{-})$ $0^{+}(2^{+})$ $1^{+}(5^{-})$ $1^{-}(6^{+})$ $0^{+}(6^{+})$ $1^{-}(5^{-})$ $1^{-}(6^{+})$ $0^{+}(6^{+})$ $1^{-}(5^{-})$ $1^{-}(5^{-})$ $1^{-}(6^{+})$ $0^{+}(6^{+})$ $1^{-}(5^{-})$ $1^{-$
** ** P <sub>11</sub> P <sub>11</sub> P <sub>11</sub> P <sub>11</sub> P <sub>11</sub> P <sub>11</sub> P <sub>13</sub> 1480) 1560) 1580) D <sub>13</sub> 1660) P <sub>14</sub> 1660) P <sub>14</sub> 1660) P <sub>14</sub> 1670) D <sub>13</sub> 1690) 1775) D <sub>15</sub> 1840) P <sub>13</sub> <sup>-1</sup> 1880) P <sub>13</sub> <sup>-1</sup> 1880) P <sub>13</sub> <sup>-1</sup> 1940) D <sub>13</sub> <sup>-1</sup> 1940 D <sub>13</sub>	$\begin{array}{c} + B = 0 \\ & \pi_2(1670) \\ & \phi(1680) \\ & \rho_3(1690) \\ & \rho_1(1690) \\ & \rho_1(1700) \\ & \sigma_1(1700) \\ & \sigma_1(1700) \\ & \sigma_1(1700) \\ & \sigma_1(1700) \\ & \sigma_1(1800) \\ &$
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	
$S_{11}$ ***** $S_{11}$ ***** $D_{15}$ ***** $P_{13}$ **** $P_{13}$ **** $P_{13}$ **** $P_{13}$ *** $P_{13}$ *** $P_{13}$ ** $P_{13}$ ** $P_{13}$ ** $P_{11}$ ** $P_{13}$ ** $P_{11}$ ** $P_{12}$ **	$\begin{array}{c} \pi^{\pm} \\ \pi^{0} \\ \eta \\ \hline f_{0}(600) \\ \rho(770) \\ \omega(782) \\ \eta'(958) \\ f_{0}(980) \\ a_{0}(980) \\ \phi(1020) \\ h_{1}(1170) \\ b_{1}(1235) \\ a_{1}(1260) \\ f_{2}(1270) \\ f_{1}(1285) \\ \eta(1295) \\ \pi(1300) \\ a_{2}(1320) \\ f_{0}(1370) \\ h_{1}(1380) \\ \pi_{1}(1400) \\ \eta(1405) \\ f_{1}(1320) \\ h_{1}(1380) \\ \pi_{1}(1400) \\ \eta(1405) \\ f_{1}(1420) \\ \omega(1420) \\ f_{2}(1430) \\ a_{0}(1450) \\ \eta(1475) \\ f_{0}(1500) \\ f_{1}(1510) \\ f_{1}(1640) \\ h_{2}(1640) \\ \omega_{3}(1670) \\ \end{array}$

### By the mid-1950's

things are officially out of control.

79

# by 1955

				23(2100)	
	N(1535)	$S_{11}$	****	$\Delta(1750)$	$P_3$
	N(1650)	$S_{11}$	****	$\Delta(1900)$	$S_3$
	N(1675)	D15	****	$\Delta(1905)$	$F_3$
	N(1680)	F <sub>15</sub>	****	<b>∆</b> (1910)	$P_3$
	N(1700)	$D_{13}$	***	$\Delta(1920)$	$P_3$
	N(1710)	$P_{11}$	***	$\Delta(1930)$	$D_3$
	N(1720)	$P_{13}$	****	<b>∆</b> (1940)	$D_3$
	N(1900)	$P_{13}$	**	$\Delta(1950)$	$F_3$
	N(1990)	F <sub>17</sub>	**	$\Delta(2000)$	$F_3$
	N(2000)	F <sub>15</sub>	**	$\Delta(2150)$	$S_3$
	N(2080)	D13	**	∆(2200)	$G_3$
	N(2090)	$S_{11}$	*	$\Delta(2300)$	
	N(2100)	$P_{11}$	*	$\Delta(2350)$	
	N(2190)	G17	****	$\Delta(2390)$	
	N(2200)	D15	**	$\Delta(2400)$	
	N(2220)	$H_{19}$	****	$\Delta(2420)$	
	N(2250)	$G_{19}$	****	$\Delta(2750)$	
	N(2600)	I1,11	***	$\Delta(2950)$	

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A(1405) A(1520) A(1600)

A(1670)

A(1690)

A(1800) A(1810) A(1820)

A(1830)

A(1890)

A(2000) A(2020) A(2100) A(2110)

A(2325) A(2350) A(2585)

 $P_{01}$   $S_{01}$   $P_{01}$   $S_{01}$   $S_{01}$   $P_{01}$   $F_{05}$   $D_{05}$ 

P<sub>03</sub>

F<sub>07</sub> G<sub>07</sub> F<sub>05</sub> D<sub>03</sub> H<sub>09</sub>

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 Σ(1620)

 \*\*\*\*
 Σ(1660)

 \*\*\*\*
 Σ(1670)

 \*\*\*\*
 Σ(1670)

 \*
 Σ(1670)

 \*
 Σ(1750)

 \*
 Σ(1770)

 \*
 Σ(1770)

Σ(1775)

 $\Sigma(1840)$   $\Sigma(1880)$   $\Sigma(1915)$   $\Sigma(1940)$ 

 $P_{33}$   $P_{33}$   $S_{31}$   $P_{31}$   $S_{31}$   $F_{35}$   $P_{33}$   $D_{35}$   $D_{33}$   $F_{35}$   $F_{35}$   $F_{31}$   $D_{35}$   $S_{31}$   $F_{35}$   $F_{37}$   $F_{3$ 

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 $P_{11}$ 

 $P_{11}$ 

P<sub>11</sub> D<sub>13</sub> S<sub>11</sub>

 $S_{11}$ 

 $D_{15}$ 

F<sub>15</sub> D<sub>13</sub> P<sub>11</sub>

 $P_{13}$ 

 $P_{13}$ 

F<sub>17</sub> F<sub>15</sub>

D13

 $S_{11}$ 

 $P_{11}$ 

G17

V(2700) K<sub>1.13</sub> \*\*

N(1440)

N(1520)

N(1535)

N(1650)

N(1675) N(1680)

N(1700)

N(1710)

N(1720)

N(1900)

N(1990)

N(2000)

N(2080)

N(2090)

N(2100) N(2190)

**∆**(1232)

 $\Delta(1600)$  $\Delta(1620)$  $\Delta(1700)$ 

∆(1750)

 $\Delta(1900)$ 

 $\Delta(1905)$ 

**∆**(1910)

 $\Delta(1920)$ 

 $\Delta(1930)$ 

**∆**(1940)

∆(1950)

 $\Delta(2000)$   $\Delta(2150)$   $\Delta(2200)$ 

À(2300)

 $\Delta(2350)$ 

**∆**(2390)

2350) 2390) 2400) 2420) 2750) 2950) ** ** ** ** **	1	.0	0	'S	0	f	t
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 $D_{13}$   $S_{11}$   $P_{11}$   $D_{13}$   $S_{11}$   $P_{11}$   $D_{15}$   $P_{13}$ 

 $\Xi(1690)$ 

 $\Xi(1820)$ 

Ξ(1950)

Ξ(2030)

 $\Xi(2120)$  $\Xi(2250)$  $\Xi(2370)$ 

Ξ(2500)

 $\Omega(2250)^{-1}$ 

Ω-

 $I^{G}(J^{PC}$ 

 $1^{-}(2^{-})$  $0^{-}(1^{-})$ 

 $1^{+}(3^{-})$   $1^{+}(1^{-})$   $1^{-}(2^{+})$   $0^{+}(0^{+})$   $0^{+}(0^{-})$ 

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 $D_{13}$ 

\*\*\* \*\*\* \* \*\* \*\* \*

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N(1700)

N(1710)

N(1720)

N(1900)

N(1990)

N(2000)

N(2080)

N(2090)

N(2100) N(2190) N(2200)

 $D_{13}$ 

 $P_{11}$   $P_{13}$   $P_{13}$   $F_{17}$   $F_{15}$   $D_{13}$   $S_{11}$   $P_{11}$   $G_{17}$ 

 $D_{15}$ 

\*\*\* \*\*\* \*\* \*\* \*\* \*\* \*\* \*

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 $\eta_b(1S)$ • T(1S)

χ<sub>b0</sub>(1P)

χ<sub>b1</sub>(1P)

T(25)

T(1D)

χ<sub>b0</sub>(2P)

χ<sub>b1</sub>(2P)
 χ<sub>b2</sub>(2P)

*Υ*(35)

T(45)

T(10860)

r(11020)

NON-qq CA

N(1440) N(1520) N(1535)

N(1650)

N(1675)

N(1680)

N(1700) N(1710) N(1720) N(1900)

N(1990)

 $F_{01}$   $S_{01}$   $S_{01}$   $P_{01}$   $F_{05}$   $D_{05}$   $P_{03}$ 

F<sub>07</sub> G<sub>07</sub> F<sub>05</sub>

r 01

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 $\Sigma(1480)$ 

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 Σ (1480)

 \*\*\*\*
 Σ (1560)

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 Σ (1580)

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 Σ (1620)

 \*\*\*\*
 Σ (1660)

 \*\*\*\*
 Σ (1670)

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 Σ (1670)

 \*\*\*\*
 Σ (1690)

\*  $\Sigma(1750)$ \*  $\Sigma(1770)$ \*\*\*\*  $\Sigma(1775)$ \*\*\*\*  $\Sigma(1775)$ 

A(1670) A(1690) A(1800)

A(1810)

A(1820) A(1830) A(1890) A(2000)

A(2020) A(2100) A(2110)

888

E(2250)

E(2370)

**Ξ**(2500)

Ω(2250)<sup>-</sup> Ω(2380)<sup>-</sup>

Ω(2470)

\*\*\*\* \*\* \* \* \* \* \* \* \* \*

 $D_{13}$ 

S<sub>11</sub> P<sub>11</sub> D<sub>15</sub> P<sub>13</sub> P<sub>11</sub> F<sub>15</sub> D<sub>13</sub>

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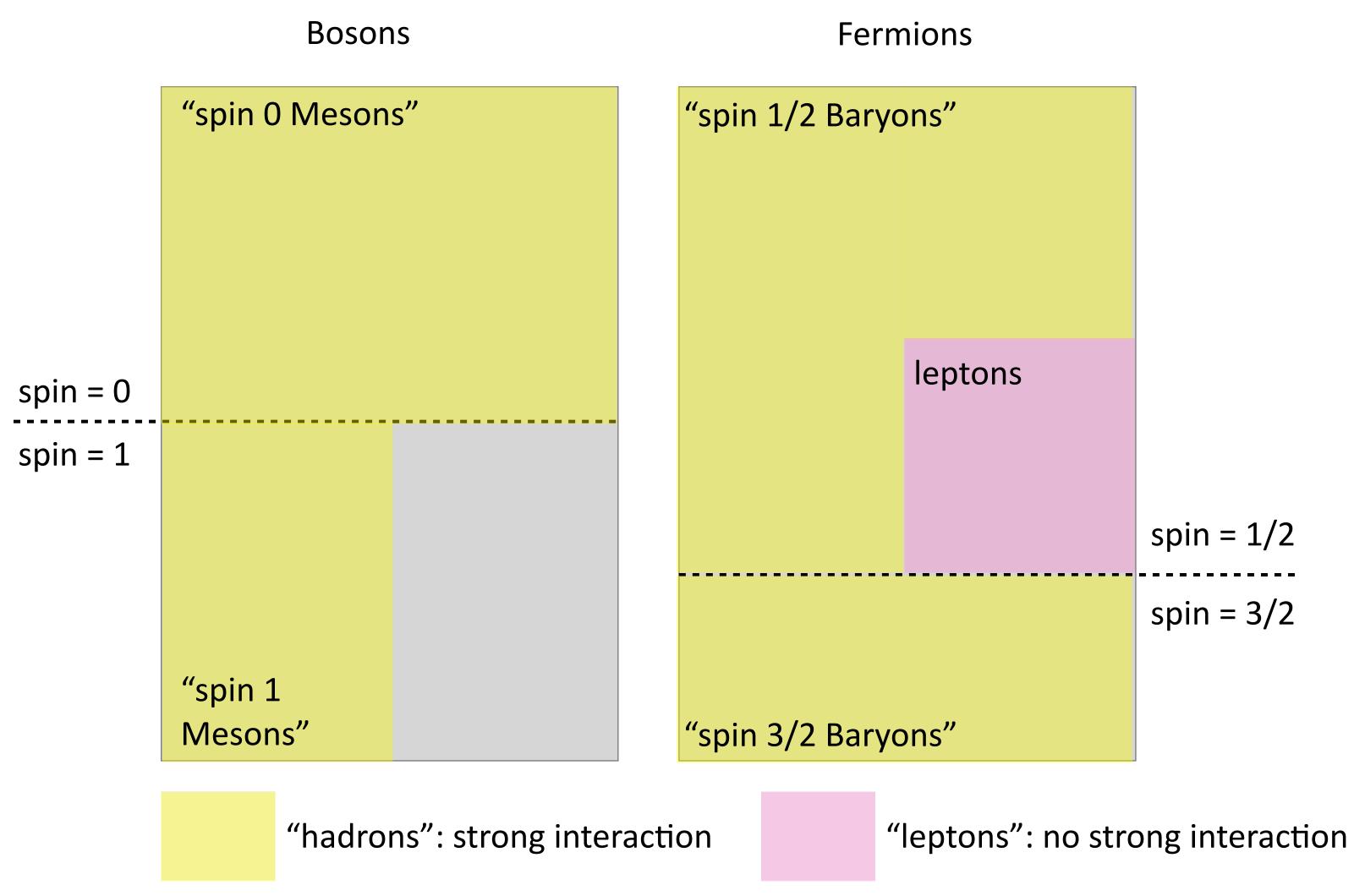
# things wer meschat's so

"(		er	=°c =.(2645) , (7°C	e		<b>.</b>	<b>r</b>	V
• $\pi^{\pm}$ • $\pi^{0}$ • $\eta$	$1^{-}(0^{-})$ $1^{-}(0^{-}+)$ $0^{+}(0^{-}+)$	<ul> <li>π<sub>2</sub>(1670)</li> <li>φ(1680)</li> <li>ρ<sub>3</sub>(1690)</li> </ul>	$1^{-}(2^{-}+)$ $0^{-}(1^{-}-)$ $1^{+}(3^{-}-)$	• K <sup>±</sup> • K <sup>0</sup> • K <sup>0</sup> <sub>5</sub>	1/2(0 <sup></sup> ) 1/2(0 <sup></sup> ) 1/2(0 <sup></sup> )			

• $\rho(rr0)$ 1 (1 )	a2(1700)	1(2+1)	K <sup>*</sup> <sub>0</sub> (800)	1/2(0+)	Vch and Vuh C	KM Matrix	
• $\omega(782)$ 0 <sup>-</sup> (1 <sup>-</sup> )	• f <sub>0</sub> (1710)	$0^+(0^{++})$	<ul> <li>K*(892)</li> </ul>	$1/2(1^{-})$	Elements		
• $\eta'(958)$ 0 <sup>+</sup> (0 <sup>-+</sup> )	$\eta(1760)$	0+(0 - +)	<ul> <li>K<sub>1</sub>(1270)</li> </ul>	1/2(1+)	• B*	$1/2(1^{-})$	
• f <sub>0</sub> (980) 0 <sup>+</sup> (0 <sup>++</sup> )	<ul> <li>π(1800)</li> </ul>	$1^{-}(0^{-+})$	<ul> <li>K<sub>1</sub>(1400)</li> </ul>	$1/2(1^+)$	B <sup>*</sup> <sub>2</sub> (5732)	?(??)	
• a <sub>0</sub> (980) 1 <sup>-</sup> (0 <sup>++</sup> )	$f_2(1810)$	$0^+(2^{++})$	<ul> <li>K*(1410)</li> </ul>	$1/2(1^{-})$			
• φ(1020) 0 <sup>-</sup> (1 <sup></sup> )	X(1835)	? <sup>?</sup> (? - +)	<ul> <li>K<sup>*</sup><sub>0</sub>(1430)</li> </ul>	$1/2(0^+)$	BOTTOM,	STRANGE	
<ul> <li>h<sub>1</sub>(1170)</li> <li>0<sup>-</sup>(1<sup>+-</sup>)</li> </ul>	<ul> <li>\$\phi_3(1850)\$</li> </ul>	0-(3)	<ul> <li>K<sup>*</sup><sub>2</sub>(1430)</li> </ul>	$1/2(2^+)$	(B = ±1,	5 = ∓1)	Π
<ul> <li>b1(1235)</li> <li>1<sup>+</sup>(1<sup>+-</sup>)</li> </ul>	$\eta_2(1870)$	$0^{+}(2^{-+})$	K(1460)	1/2(0-)	<ul> <li>B<sup>0</sup><sub>s</sub></li> </ul>	0(0-)	
• a1(1260) 1-(1++)	p(1900)	$1^{+}(1^{-})$	K <sub>2</sub> (1580)	1/2(2-)	B <sup>*</sup> <sub>s</sub>	0(1-)	
<ul> <li>f<sub>2</sub>(1270)</li> <li>0<sup>+</sup>(2<sup>++</sup>)</li> </ul>	f2(1910)	$0^{+}(2^{+})$	K(1630)	1/2(??)	$B_{sJ}^{*}(5850)$	?(??)	
• f1(1285) 0+(1++)	<ul> <li>f<sub>2</sub>(1950)</li> </ul>	$0^+(2^{++})$	K1(1650)	$1/2(1^+)$		. ,	
<ul> <li>η(1295)</li> <li>0<sup>+</sup>(0<sup>-+</sup>)</li> </ul>	$\rho_3(1990)$	$1^{+}(3^{-})$	<ul> <li>K*(1680)</li> </ul>	1/2(1-)	BOTTOM,		
<ul> <li>π(1300)</li> <li>1<sup>-</sup>(0<sup>-+</sup>)</li> </ul>	<ul> <li>f<sub>2</sub>(2010)</li> </ul>	$0^{+}(2^{+}+)$	<ul> <li>K<sub>2</sub>(1770)</li> </ul>	1/2(2-)	(B = C	$= \pm 1$ )	
• a2(1320) 1-(2++)	f <sub>0</sub> (2020)	$0^+(0^++)$	<ul> <li>K<sup>*</sup><sub>2</sub>(1780)</li> </ul>		<ul> <li>B<sup>±</sup><sub>c</sub></li> </ul>	0(0-)	
• f <sub>0</sub> (1370) 0 <sup>+</sup> (0 <sup>++</sup> )	<ul> <li>a<sub>4</sub>(2040)</li> </ul>	$1^{-(4^{++})}$		$1/2(3^{-})$			
h1(1380) ?-(1+-)	<ul> <li>f<sub>4</sub>(2050)</li> </ul>	$0^+(4^{++})$	<ul> <li>K<sub>2</sub>(1820)</li> </ul>	1/2(2-)	cī		
• $\pi_1(1400)$ 1 <sup>-</sup> (1 <sup>-+</sup> )	$\pi_2(2100)$	1-(2-+)	K(1830)	$1/2(0^{-})$	<ul> <li>η<sub>c</sub>(15)</li> </ul>	0+(0-+)	
• $\eta(1405)$ 0 <sup>+</sup> (0 <sup>-+</sup> )	f <sub>0</sub> (2100)	0+(0++)	K <sub>0</sub> (1950)	1/2(0+)	<ul> <li>J/ψ(15)</li> </ul>	0-(1)	
• f <sub>1</sub> (1420) 0 <sup>+</sup> (1 <sup>++</sup> )	f <sub>2</sub> (2150)	$0^+(2^++)$	$K_{2}^{*}(1980)$	$1/2(2^+)$	• $\chi_{c0}(1P)$	0+(0++)	
• ω(1420) 0 <sup>-</sup> (1 <sup>-</sup> )	ρ(2150)	$1^{+}(1^{-})$	<ul> <li>K<sup>*</sup><sub>4</sub>(2045)</li> </ul>	$1/2(4^+)$	<ul> <li>χ<sub>c1</sub>(1P)</li> </ul>	$0^{+}(1^{++})$	
$f_2(1430) = 0^+(2^{++})$		0+(0++)	$K_2(2250)$	$1/2(2^{-})$	$h_c(1P)$	??(???)	
	f <sub>0</sub> (2200)	0 <sup>+</sup> (2 or 4 <sup>+</sup> <sup>+</sup> )	K <sub>3</sub> (2320)	$1/2(3^+)$	• $\chi_{c2}(1P)$	$0^{+}(2^{+})$	
	f <sub>J</sub> (2220)		K <sup>*</sup> <sub>5</sub> (2380)	$1/2(5^{-})$	<ul> <li>η<sub>c</sub>(25)</li> </ul>	$0^{+}(0^{-+})$	
	$\eta(2225)$	$0^+(0^{-+})$	K <sub>4</sub> (2500)	$1/2(4^{-})$	<ul> <li>ψ(25)</li> </ul>	0-(1)	
• $\eta(1475)$ 0 <sup>+</sup> (0 <sup>-+</sup> )	$\rho_3(2250)$	$1^+(3^{})$	K(3100)	??(???)	<ul> <li>ψ(3770)</li> </ul>	$0^{-}(1^{-})$	
• $f_0(1500)$ 0 <sup>+</sup> (0 <sup>++</sup> )	<ul> <li>f<sub>2</sub>(2300)</li> </ul>	$0^+(2^{++})$			• X(3872)	0 <sup>?</sup> (? <sup>?+</sup> )	
$f_1(1510) = 0^+(1^{++})$	f <sub>4</sub> (2300)	$0^+(4^{++})$	CHAR		<ul> <li>xc2(2P)</li> </ul>	$0^{+}(2^{+})$	
• $f'_2(1525)$ 0 <sup>+</sup> (2 <sup>++</sup> )	<ul> <li>f<sub>2</sub>(2340)</li> </ul>	$0^+(2^{++})$	(C =	-	Y(3940)	??(???)	
$f_2(1565) = 0^+(2^{++})$	$\rho_5(2350)$	1+(5)	<ul> <li>D<sup>±</sup></li> </ul>	$1/2(0^{-})$	<ul> <li>ψ(4040)</li> </ul>	$0^{-}(1^{-})$	
$h_1(1595) = 0^-(1^{+-})$	a <sub>6</sub> (2450)	$1^{-}(6^{++})$	• D <sup>0</sup>	$1/2(0^{-})$	<ul> <li>ψ(4160)</li> </ul>	0-(1)	
• $\pi_1(1600)$ 1 <sup>-</sup> (1 <sup>-+</sup> )	f <sub>6</sub> (2510)	0+(6++)	<ul> <li>D<sup>*</sup>(2007)<sup>0</sup></li> </ul>	$1/2(1^{-})$	Y(4260)	??(1)	
$a_1(1640)$ $1^-(1^{++})$	ОТН	ER LIGHT	<ul> <li>D<sup>*</sup>(2010)<sup>±</sup></li> </ul>	$1/2(1^{-})$	<ul> <li>ψ(4415)</li> </ul>	0-(1)	
$f_2(1640) = 0^+(2^{++})$			$D_0^*(2400)^0$	$1/2(0^+)$	φ((1120)	° (* )	
• $\eta_2(1645)$ 0 <sup>+</sup> (2 <sup>-+</sup> )	Further Sta	tes	$D_0^*(2400)^{\pm}$	$1/2(0^{+})$	b	b	
<ul> <li>ω(1650)</li> <li>0<sup>-</sup>(1<sup></sup>)</li> </ul>			<ul> <li>D<sub>1</sub>(2420)<sup>0</sup></li> </ul>	$1/2(1^+)$	$\eta_b(1S)$	0+(0-+)	
<ul> <li>ω<sub>3</sub>(1670)</li> <li>0<sup>-</sup>(3<sup>-</sup>)</li> </ul>			$D_1(2420)^{\pm}$	1/2(??)	<ul> <li>T(15)</li> </ul>	0-(1)	
			$D_1(2430)^0$	$1/2(1^{+})$	<ul> <li>χ<sub>b0</sub>(1P)</li> </ul>	0+(0++)	
			<ul> <li>D<sup>*</sup><sub>2</sub>(2460)<sup>0</sup></li> </ul>	1/2(2+)	• $\chi_{b1}(1P)$	$0^{+}(1^{+})$	
			<ul> <li>D<sup>*</sup><sub>2</sub>(2460)<sup>±</sup></li> </ul>	$1/2(2^+)$	• $\chi_{b2}(1P)$	0+(2++)	
			D*(2640) <sup>±</sup>	1/2(??)	• T(25)	0-(1)	
			D (2040)	1/2(: )		0-(2)	
	1		CHARMED,	STRANGE	T(1D)	$0^{+}(0^{+}+)$	
			(C = 5	= ±1)	<ul> <li>         χ<sub>b0</sub>(2P) (2P)         </li> </ul>	$0^{+}(0^{+})^{+}(1^{+})^{+}$	
			• D_s^{\pm}	0(0-)	<ul> <li>χ<sub>b1</sub>(2P)</li> <li>(2P)</li> </ul>	$0^{+}(2^{+})$	
			• D <sup>*±</sup> <sub>s</sub>	0(? <sup>?</sup> )	<ul> <li>χ<sub>b2</sub>(2P)</li> <li>χ<sub>b2</sub>(2P)</li> </ul>	$0^{+}(2^{+})$	
	1			0(0+)	<ul> <li>T(35)</li> </ul>	0-(1)	
	1		<ul> <li>D<sup>*</sup><sub>s0</sub>(2317)<sup>±</sup></li> <li>D<sup>−</sup><sub>s0</sub>(2460)<sup>±</sup></li> </ul>		<ul> <li> <i>T</i>(45)     </li> </ul>	0-(1)	
	1		<ul> <li>D<sub>s1</sub>(2460)<sup>±</sup></li> <li>D<sub>s1</sub>(2526)<sup>±</sup></li> </ul>	$0(1^+)$	<ul> <li>\$\mathcal{T}\$(10860)</li> </ul>	0-(1)	
	1		<ul> <li>D<sub>s1</sub>(2536)<sup>±</sup></li> <li>D<sub>s1</sub>(2536)<sup>±</sup></li> </ul>	$0(1^+)$	<ul> <li> <i>Υ</i>(11020)     </li> </ul>	0-(1)	
			- D - (2572)±	07713			4

	H <sub>2,11</sub> I <sub>3,13</sub> K <sub>3,15</sub> K <sub>3,15</sub> (40) (40) (40) (60) (15) (7) (7) (7) (7) (7) (7) (7) (7) (7) (7	440) 520) 5355) 550) 775) 580) 700) 710) 720) 9900)
		$P_{11}$ $P_{11}$ $D_{13}$ $S_{11}$ $S_{11}$ $D_{15}$ $F_{15}$ $D_{13}$ $P_{11}$ $P_{13}$ $F_{17}$
$h_1(1) = \pi_1(1)$ $a_1(1) = \pi_1(1)$	$\begin{array}{c} \pi^{\pm} \\ \pi^{0} \\ \pi^{0} \\ \eta \\ \eta \\ \gamma \\ \kappa^{0} \\ \pi^{\prime} \\ \kappa^{\prime} \\ \kappa^{$	
595) 1600) 640) 640) 645) 650)	70) 82) 58) 58) 80) 120) 1470) 1235) 1260) 1270) 1285) 1260) 1270) 1285) 1285) 1295) 1200) 1320) 150 150 150 150 150 150 150 150	$\Delta(1600)$ $\Delta(1620)$ $\Delta(1700)$ $\Delta(1750)$ $\Delta(1905)$ $\Delta(1910)$ $\Delta(1920)$ $\Delta(1940)$ $\Delta(1940)$ $\Delta(1950)$ $\Delta(2000)$
0-(1- 1-(1- 1-(1- 0+(2- 0+(2- 0-(1- 0-(3-	IGH 1-(0- 1-(0- 0+(0- 0+(0- 1-(1- 0+(1-))))))))))))))))))))))))))))))))))))	P <sub>33</sub> S <sub>31</sub> P <sub>31</sub> F <sub>35</sub> P <sub>31</sub> P <sub>33</sub> D <sub>35</sub> D <sub>33</sub> F <sub>37</sub> F <sub>35</sub>
+ - - +) + +) - +) - +) )	s	
f <sub>6</sub> (2510) OTH Further St	• $\pi^{\pm}$ • $\pi^{0}$ • $\eta$ • $f_{0}(600)$ • $\rho(770)$ • $\omega(782)$ • $\eta'(958)$ • $f_{0}(980)$ • $a_{0}(980)$ • $\phi(1020)$ • $h_{1}(11235)$ • $a_{1}(1260)$ • $f_{1}(1285)$ • $\eta(1295)$ • $\pi_{1}(1285)$ • $\eta(1295)$ • $\pi_{1}(1285)$ • $\pi_{1}(1285)$ • $\pi_{1}(1285)$ • $\pi_{1}(1285)$ • $\pi_{1}(1420)$ • $\phi(1450)$ • $\rho(1450)$ • $\eta(1475)$ • $f_{0}(1500)$ • $f_{1}(1510)$ • $f_{1}(15102)$ • $f_{1}(15102)$ • $f_{1}(15102)$ • $\pi_{1}(1600)$ • $a_{1}(1640)$ • $f_{2}(1645)$ • $\omega_{3}(1670)$	A(1405) A(1520) A(1600) A(1600) A(1600) A(1800) A(1810) A(1820) A(1830) A(1830) A(1890) A(1890) A(2000) A(2020)
IER LIG	t	501 D03 P01 S01 P01 S01 P01 F05 P03 F07
0 <sup>+</sup> (6 <sup>+</sup>		
$\begin{array}{c} & D^{*} \\ & D^{*} \\$	) ) ) ) ) ) ) ) ) ) ) ) ) ) ) ) ) ) )	$\begin{array}{c} \Sigma^{-} \\ \Sigma^{-} \\ \Sigma(1385) \\ \Sigma(1560) \\ \Sigma(1560) \\ \Sigma(1560) \\ \Sigma(1660) \\ \Sigma(1670) \\ \Sigma(1670) \\ \Sigma(1670) \\ \Sigma(1670) \\ \Sigma(1770) \\ \Sigma(1770) \\ \Sigma(1770) \\ \Sigma(1770) \\ \Sigma(1880) \\ \Sigma(1880) \\ \Sigma(1880) \\ \Sigma(1915) \\ \Sigma(1915) \\ \Sigma(1940) \\ \Sigma(2000) \\ \Sigma(2100) \\ \Sigma(210) \\ \Sigma(2100) \\ \Sigma(2100) \\ \Sigma(2100) \\ \Sigma(21$
	0) 2(1670) (1680) 3(1690) (1700) (1700) (1710) (1710) (1710) (1800) (1810) (1835) 3(1850) 2(1870) (1900) (1900) (1910) (1900) (1910) (1900) (2150) (2150) (2150) (2225) (2225) (2220) (2250) (250) (2	$\begin{array}{c} P_{11} \\ P_{11} \\ P_{13} \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\$
1/ 1/		
	$\frac{G}{P^{PC}}$ $\frac{1-(2-+)}{(1)}$ $\frac{1+(3)}{(1)}$ $\frac{1+(3)}{(1)}$ $\frac{1+(3)}{(1)}$ $\frac{1+(2++)}{(1)}$ $1+(2++)$	$ \begin{array}{c} = \\ \equiv (1530) \\ \equiv (1620) \\ \equiv (1620) \\ \equiv (1620) \\ \equiv (1950) \\ \equiv (2030) \\ \equiv (2120) \\ \equiv (2250) \\ \equiv (2250) \\ \equiv (2250) \\ \equiv (2250) \\ \hline \Omega(2250)^{-} \\ \Omega(2250)^{-} \\ \Omega(2250)^{-} \\ \Omega(2470)^{-} \\ \Lambda_c(2625)^{+} \\$
• $\psi(44)$ Y(42) • $\psi(44)$ • $T(15)$ • $\chi_{b0}(1)$ • $\chi_{b1}(1)$ • $\chi_{b2}(1)$ • $\chi_{b2}(2)$ • $\chi_{b1}(2)$ • $\chi_{b1$	<ul> <li>K<sup>*</sup>(</li> <li></li></ul>	•
60) 15) 5) 5) 7) 7) 7) 7) 7) 7) 7) 7) 7) 7	$(5 = \pm 1, 0)$ $(5 = \pm 1, 0)$ $(892)$ $(270)$ $(1410)$ $(1410)$ $(1430)$ $(240)$ $(240)$ $($	····· ···· ···· ···· ···· ···· ···· ····
$\begin{array}{c} 0 & (1 \\ ?^{7}(1) \\ 0 - (1) \\ 0 - (1) \\ 0 + (1) \\ 0 + (1 + -) \\ 0 + (1 + +) \\ 0 + (2 + +) \\ 0 - (1) \\ 0 + (1 + +) \\ 0 + (2 + +) \\ 0 - (1) \\ 0 + (1) \\ 0 - (1) \\$	$\begin{array}{l} \textbf{ANGE} \\ C = B = 0) \\ \ell(J^P) \\ \hline 1/2(0^-) \\ 1/2(0^-) \\ 1/2(0^-) \\ 1/2(0^-) \\ 1/2(1^-) \\ 1/2(1^-) \\ 1/2(1^-) \\ 1/2(1^-) \\ 1/2(1^-) \\ 1/2(2^+) \\ 1/2(2^+) \\ 1/2$	e
	Elemen • $B^*$ $B_j(57)$ BOT ( $i$ • $B_s^0$ $B_s^*$ $B_{sJ}^*(58)$ BOT	
	<sup>0</sup> /B <sup>1</sup> /B <sup>1</sup> /B <sup>2</sup>	

# 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.

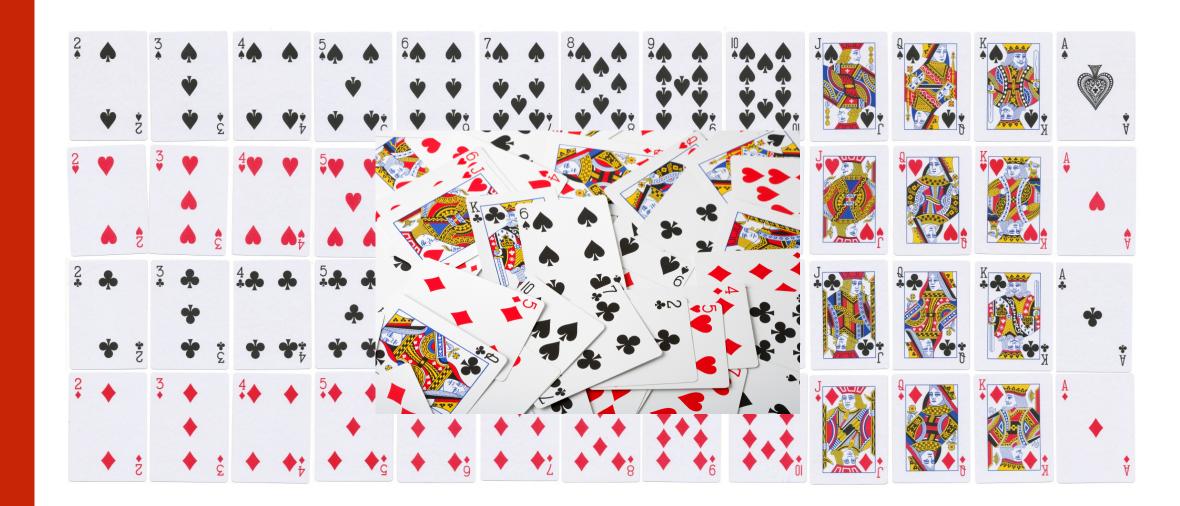


# organizing

## 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 numbe									
	refers to:	quantities that are inhore particles, which are coord or decays								
	entomology:	historical to Bohr and S								
	example:	electric charge, baryor number, isospin								

### S

# herently a part of onserved in interactions

### Schroedinger

### n number, lepton

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

86

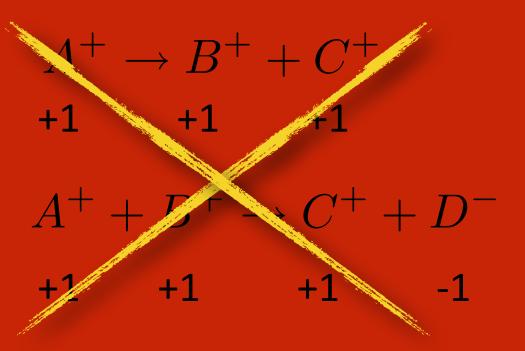
### something like these will never happen:

**Q:** 

**Q**:

### so, you'll always see:

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



## Quantum Number:

Strangeness

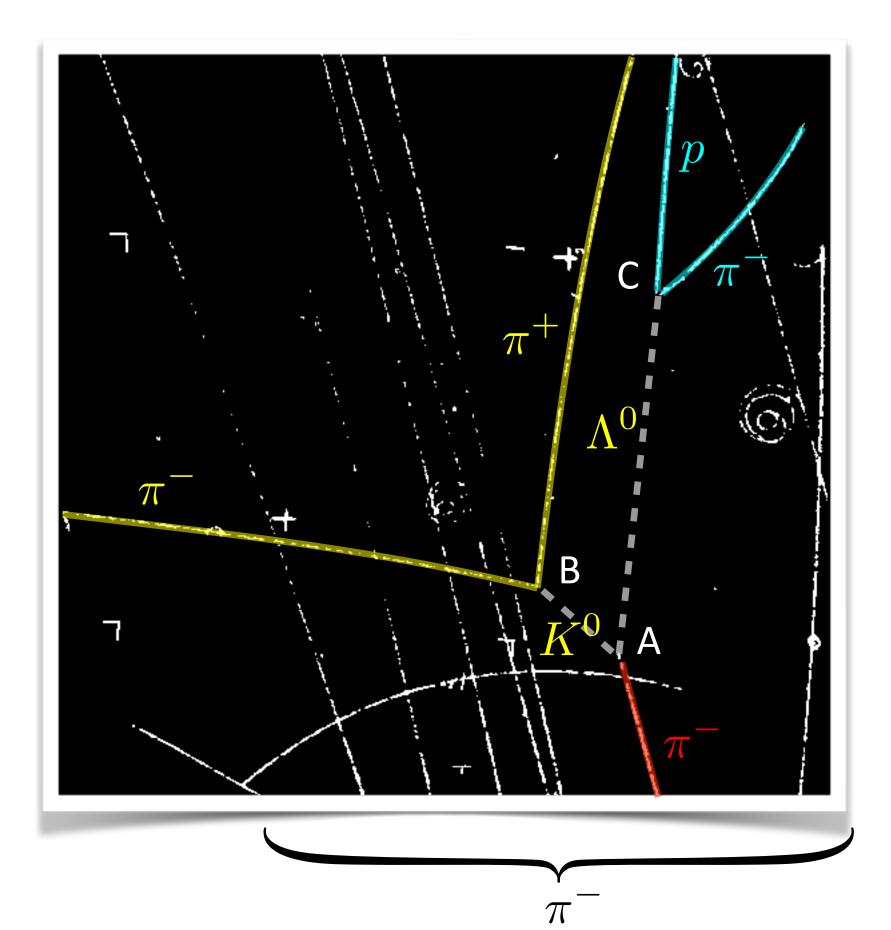
88

### clue a

## 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



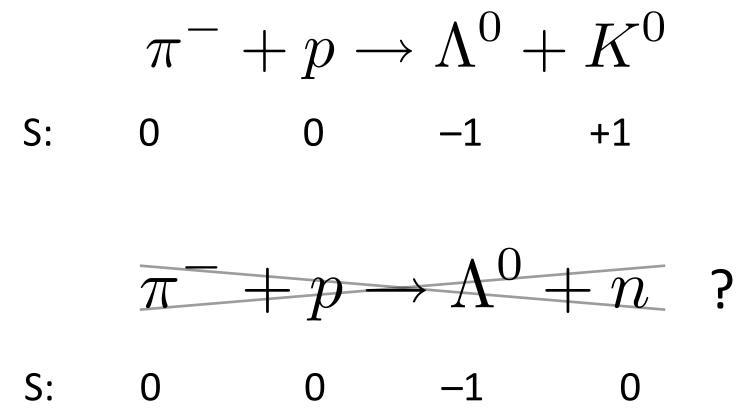
89

# Strangeness, S

strangeness seems to come in pairs

assign "strangeness" empirically.





and yet you *do* see:

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

S: -1 0 0

**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

Strong +1 interaction 0

### Weak interaction

# the dominant Baryons

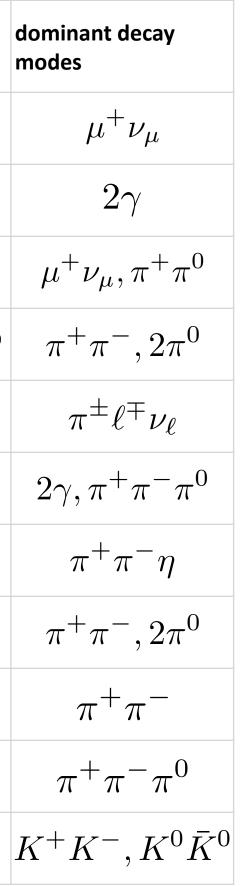
Particle	Symbol	Rest Mass MeV/c <sup>2</sup>	spin	Q	В	S	Lifetime	dominant decay modes
proton	p	938.3	1/2	+1	+1	0	> 10 <sup>31</sup> y	
neutron	n	939.6	1/2	0	+1	0	920	$pe^-\bar{\nu}_e$
Lambda	$\Lambda^0$	1115.6	1/2	0	+1	-1	2.6 x 10 <sup>-10</sup>	$p\pi^-, n\pi^0$
Sigma	$\Sigma^+$	1189.4	1/2	+1	+1	-1	0.8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



# the dominant Mesons

Particle	Symbol	anti- particle	Rest Mass MeV/c <sup>2</sup>	spin	Q	В	S	Lifetime
Pion	$\pi^+$	$\pi^{-}$	139.6	0	+1	0	0	2.6 x 10 <sup>-8</sup>
Pi-zero	$\pi^0$	$\pi^0$	135	0	0	0	0	920
Kaon	$K^+$	$K^{-}$	493.7	0	+1	0	+1	1.24 x 10 <sup>-8</sup>
K-short	$K_S^0$	$K_S^0$	497.7	0	0	0	+1	0.89 x 10 <sup>-10</sup>
K-long	$K_L^0$	$K_L^0$	497.7	0	0	0	+1	5.2 x 10 <sup>-8</sup>
Eta	$\eta^0$	$\eta^0$	548.8	0	0	0	0	< 10 <sup>-18</sup>
Eta-prime	$\eta^0$ '	$\eta^0$ '	958	1	0	0	0	
Rho	$\rho^+$	$\rho^{-}$	770	1	+1	0	0	0.4 x 10 <sup>23</sup>
Rho-naught	$ ho^0$	$ ho^0$	770	1	0	0	0	0.4 x 10 <sup>23</sup>
Omega	$\omega^0$	$\omega^0$	782	1	0	0	0	0.8 x 10 <sup>22</sup>
Phi	$\phi$	$\phi$	1020	1	0	0	0	20 x 10 <sup>-23</sup>





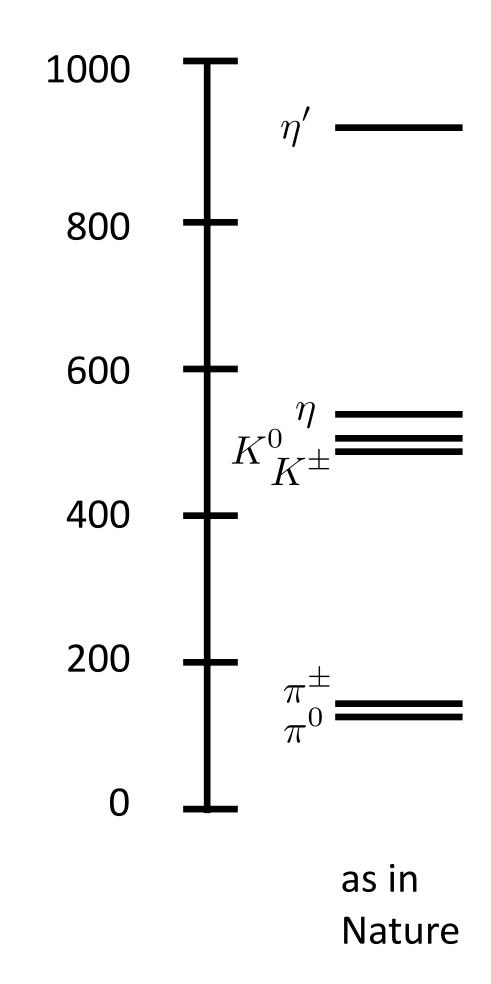
### anyhow...back to the Zoo problem

all those particles.

There were some hints:

# masses seem to clump

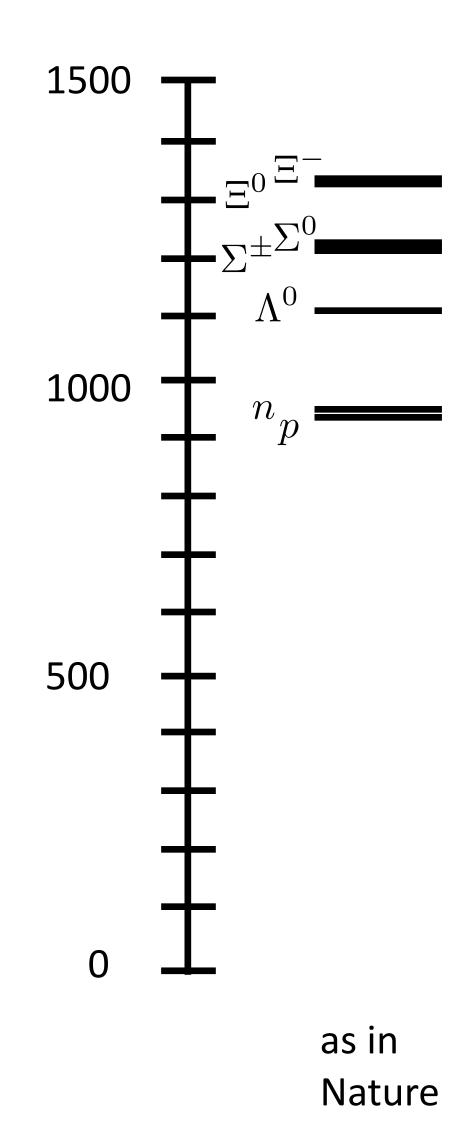
# look at a set of the mesons



 $\nabla$ 

masses seem to clump

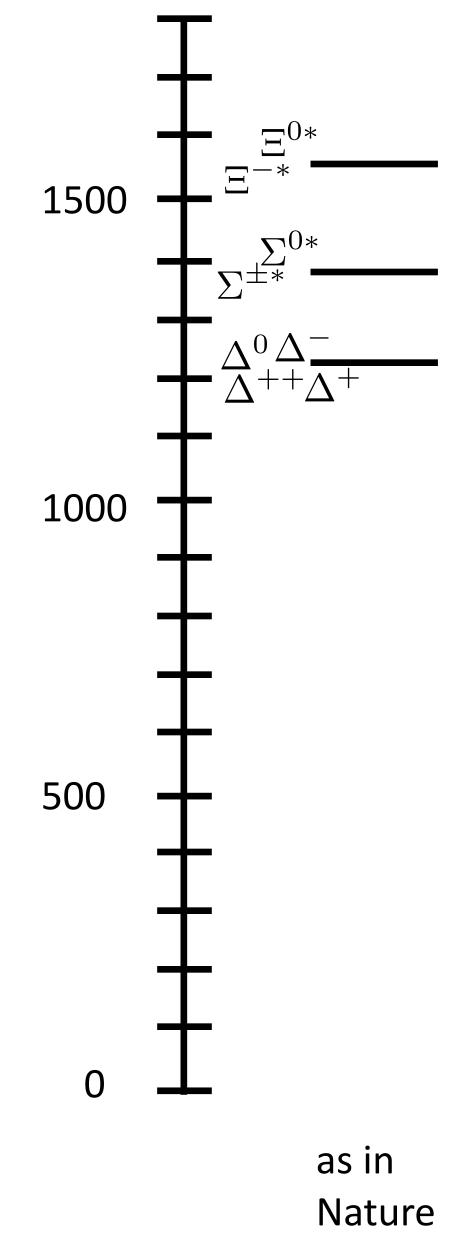
## look at the baryons



 $\overline{\mathbf{u}}$ 

masses seem to clump

## look at a different set of the baryons



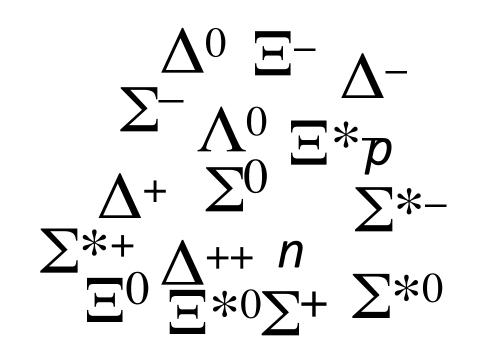
 $\overline{\mathbf{v}}$ 

# patterns emerged

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



$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Δ(150)           Δ(1600)           Δ(1600)           Δ(1620)           Δ(1700)           Δ(1750)           Δ(1900)           Δ(1905)           Δ(1910)           Δ(1940)           Δ(1950)           Δ(1950)           Δ(2000)           Δ(2150)           Δ(2300)           Δ(2300)           Δ(2420)           Δ(2420)           Δ(2750)	$\begin{array}{c} P_{33} \\ P_{33} \\ S_{31} \\ D_{33} \\ P_{31} \\ S_{31} \\ F_{35} \\ P_{33} \\ D_{35} \\ D_{33} \\ F_{37} \\ F_{35} \\ S_{31} \\ G_{37} \\ H_{39} \\ D_{35} \\ F_{37} \\ G_{39} \\ H_{3,11} \\ I_{3,15} \\ K_{3,15} \end{array}$	····· ···· ···· ··· ··· ··· ··· ··· ··	A A(1405) A(1520) A(1600) A(1670) A(1800) A(1800) A(1800) A(1800) A(1830) A(1890) A(1890) A(2000) A(2000) A(2100) A(2100) A(2100) A(2325) A(2350) A(2585)	$\begin{array}{c} P_{01} \\ S_{01} \\ D_{03} \\ P_{01} \\ D_{03} \\ S_{01} \\ P_{01} \\ F_{05} \\ D_{05} \\ P_{03} \\ F_{07} \\ F_{05} \\ D_{03} \\ H_{09} \end{array}$		$\begin{array}{c} \Sigma^+ \\ \Sigma^0 \\ \Sigma^- \\ \Sigma(138) \\ \Sigma(166) \\ \Sigma(158) \\ \Sigma(166) \\ \Sigma(167) \\ \Sigma(177) \\ \Sigma(177$	)) $D_{13}$ )) $D_{13}$ )) $P_{11}$ )) $P_{11}$ )) $P_{11}$ )) $P_{11}$ )) $P_{13}$ )) $P_{13}$ )) $P_{15}$ )) $P_{15}$ )) $P_{15}$ )) $P_{15}$ )) $P_{15}$ )) $P_{13}$ ))		$\begin{array}{c} \Xi^{0} \\ \Xi^{-} \\ \Xi(1530) \\ \Xi(1620) \\ \Xi(1620) \\ \Xi(1690) \\ \Xi(2030) \\ \Xi(2120) \\ \Xi(2250) \\ \Xi(2250) \\ \Xi(2500) \\ \Omega^{-} \\ \Omega(2250)^{-} \\ \Omega(2250)^{-} \\ \Omega(2380)^{-} \\ \Omega(2470)^{-} \\ \Lambda_{c}^{c} \\ (2380)^{-} \\ \Lambda_{c} \\ (2593)^{+} \\ \Lambda_{c} \\ (2625)^{+} \\ \Pi_{c} \\ \Pi_{c} \\ (2625)^{+} \\ \Pi_{c} \\ \Pi_{c} \\ (2625)^{+} \\ \Pi_{c} \\ (2625)^{+} \\ \Pi_{c} \\ (2625)^{+} \\ \Pi_{c} \\ \Pi_{c} \\ (2625)^{+} \\ \Pi_{c} \\ (2625)$	P <sub>11</sub> **** P <sub>13</sub> **** D <sub>13</sub> **** *** *** *** *** *** *** *** *** *				
$ \begin{array}{                                    $							(	s = c + i			. ,		1, $C = B = 0$			±1)
$ \begin{array}{c} \cdot c(22) & \circ -(1) \\ \cdot c(58) & \circ -(1) \\ \cdot c(120) & \circ -(1) \\ \cdot c(120) & \circ -(1) \\ \cdot c(120) & \circ -(1) \\ \cdot c(122) & \circ -(1)$					• π <sup>0</sup> • η • f <sub>0</sub> (600)		1 <sup>-</sup> (0 <sup>-</sup> 0 <sup>+</sup> (0 <sup>-</sup> 0 <sup>+</sup> (0 <sup>-</sup>	- +) - +) + +)	$\phi(1680)$ $\rho_3(1690)$ $\rho(1700)$		$0^{-}(1^{-})$ $1^{+}(3^{-})$ $1^{+}(1^{-})$	• K <sup>0</sup> • K <sup>0</sup> <sub>S</sub> • K <sup>1</sup> <sub>L</sub>	1/2(0 1/2(0 1/2(0	-) • B <sup>0</sup> -) • B <sup>4</sup> -) • B <sup>4</sup>	<sup>E</sup> /B <sup>0</sup> ADM <sup>E</sup> /B <sup>0</sup> /B <sup>0</sup> <sub>s</sub> /L	1/2(0 <sup></sup> )
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$				1	• $\omega(782)$ • $\eta'(958)$ • $f_0(980)$ • $a_0(980)$		0 <sup>-</sup> (1 - 0 <sup>+</sup> (0 - 0 <sup>+</sup> (0 - 1 <sup>-</sup> (0 -	) - +) + +) + +)	$f_0(1710)$ $\eta(1760)$ $\pi(1800)$ $f_2(1810)$		$0^+(0^{++})$ $0^+(0^{-+})$ $1^-(0^{-+})$ $0^+(2^{++})$	<ul> <li>K*(892)</li> <li>K<sub>1</sub>(1270)</li> <li>K<sub>1</sub>(1400)</li> </ul>	1/2(1 1/2(1 1/2(1	(-) (+)	(5732)	1/2(1 <sup></sup> ) ?(? <sup>?</sup> )
$\begin{array}{c c c c c c c c c c c c c c c c c c c $				L	<ul> <li>h<sub>1</sub>(1170)</li> <li>b<sub>1</sub>(1235)</li> <li>a<sub>1</sub>(1260)</li> </ul>		$0^{-}(1^{-})$ $1^{+}(1^{-})$ $1^{-}(1^{-})$	+ -) + -) + +)	$\phi_3(1850)$ $\eta_2(1870)$ $\rho(1900)$		$0^{-}(3^{-}-))$ $0^{+}(2^{-}+))$ $1^{+}(1^{-}-)$	<ul> <li>K<sup>*</sup><sub>2</sub>(1430)</li> <li>K(1460)</li> <li>K<sub>2</sub>(1580)</li> </ul>	1/2(2 1/2(0 1/2(2	(+) (-)	(B = ±1	$(5 = \mp 1)$ $0(0^{-})$ $0(1^{-})$
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$				L	<ul> <li>f<sub>1</sub>(1285)</li> <li>η(1295)</li> <li>π(1300)</li> </ul>		$0^+(1^-)^+(0^-$	+ +) - +) - +) + +)	$f_2(1950)$ $\rho_3(1990)$ $f_2(2010)$		$0^+(2^++)$ $1^+(3^)$ $0^+(2^++)$ $0^+(0^++)$	K1(1650) • K*(1680) • K2(1770)	1/2(1 1/2(1 1/2(2	+) -) -) B <sup>±</sup>	BOTTOM, (B = C	CHARMED $T = \pm 1$ )
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$				L	$h_1(1380)$ • $\pi_1(1400)$ • $\eta(1405)$		0 <sup>+</sup> (0 <sup>+</sup> ? <sup>-</sup> (1 <sup>+</sup> 1 <sup>-</sup> (1 <sup>+</sup> 0 <sup>+</sup> (0 <sup>+</sup>	+ +) + -) - +) - +)	$f_4(2050)$ $\pi_2(2100)$		$1^{-}(4^{+}+))$ $0^{+}(4^{+}+))$ $1^{-}(2^{-}+)))$ $0^{+}(0^{+}+))$	<ul> <li>K<sub>2</sub>(1820)</li> <li>K(1830)</li> <li>K<sub>0</sub><sup>*</sup>(1950)</li> </ul>	1/2(2 1/2(0 1/2(0	(-) (-) (+) (+) (-) (+) (-)	$(1S) \psi(1S)$	0 <sup>+</sup> (0 <sup>-+</sup> 0 <sup>-</sup> (1 <sup></sup>
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$				L	<ul> <li>ω(1420)</li> <li>f<sub>2</sub>(1430)</li> <li>a<sub>0</sub>(1450)</li> </ul>		$0^{-}(1^{-})^{+}(2^{-})^{+}(2^{-})^{+}(0^{$	) ++) ++)	$\rho(2150)$ $f_0(2200)$ $f_J(2220)$	0+(3	$1^+(1^{})$ $0^+(0^{++})$ $2 \text{ or } 4^{++})$	<ul> <li>K<sup>*</sup><sub>4</sub>(2045)</li> <li>K<sub>2</sub>(2250)</li> <li>K<sub>3</sub>(2320)</li> </ul>	1/2(4 1/2(2 1/2(3	$ \begin{array}{c} + \\ - \\ + \\ \end{array} ) \\ \begin{array}{c} \bullet \\ h_c \\ \bullet \\ \chi_c \\ \bullet \\ \chi_c \end{array} $	$_{2}^{(1P)}(1P)$ $_{2}^{(1P)}(1P)$	0+(1++
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$					<ul> <li>η(1475)</li> <li>f<sub>0</sub>(1500)</li> <li>f<sub>1</sub>(1510)</li> </ul>		$0^+(0^+)$ $0^+(0^+)$ $0^+(1^+)$	- +) + +) + +)	$\rho_3(2250)$ $f_2(2300)$ $f_4(2300)$		$1^+(3^-)$ $0^+(2^+)$ $0^+(4^+)$	K <sub>4</sub> (2500) K(3100)	1/2(4 ??(??	(-) (+)	25) 3770) (3872)	$0^{-}(1^{-}-0^{-$
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$					$f_2(1565)$ $h_1(1595)$ • $\pi_1(1600)$		$0^+(2^-)^+(2^-$	+ +) + -) - +)	$\rho_5(2350)$ $a_6(2450)$		$1^{+}(5^{-}-)$ $1^{-}(6^{+}+)$	<ul> <li>D<sup>±</sup></li> <li>D<sup>0</sup></li> <li>D<sup>*</sup>(2007)</li> </ul>	1/2(0 1/2(0 0 1/2(1	(-) (-)	(3940) 4040) 4160) (4260)	0-(1 0-(1 ? <sup>?</sup> (1
$\begin{array}{cccc} D_1(2430) & 1/2(1^+) & \bullet 7(15) & 0 & 0 & 0 \\ D_1(2430)^0 & 1/2(1^+) & \bullet \chi_{b0}(1P) & 0^+(0^++^-) \\ \bullet D_2(2460)^0 & 1/2(2^+) & \bullet \chi_{b1}(1P) & 0^+(1^++^-) \\ \bullet D_2(2460)^{\pm} & 1/2(2^+) & \bullet \chi_{b2}(1P) & 0^+(2^++^-) \\ \end{array}$					$f_2(1640)$ • $\eta_2(1645)$ • $\omega(1650)$		0 <sup>+</sup> (2 0 <sup>+</sup> (2 0 <sup>-</sup> (1	+ +) - +) )			HT	$D_0^*(2400)$ $D_0^*(2400)$ • $D_1(2420)$	0 1/2(0 ± 1/2(0 0 1/2(1	(+) (+)	4415) b (15)	0 <sup>+</sup> (0 <sup>-</sup>
$D^{\bullet}(2640)^{\pm} 1/2(?^{?}) \bullet \Upsilon(25) 0^{-}(1-7)^{-}$					<ul> <li>ω<sub>3</sub>(1670)</li> </ul>		U (3	,				D <sub>1</sub> (2430) • D <sub>2</sub> *(2460)	0 1/2(1 0 1/2(2 ± 1/2(2	(+) (+)	$_{1}^{0}(1P)$ $_{1}(1P)$	$0^+(0^+)^+$ $0^+(1^+)^+$ $0^+(2^+)^+$



# **5 ed** Ne'eman in 1964

# family arrangements

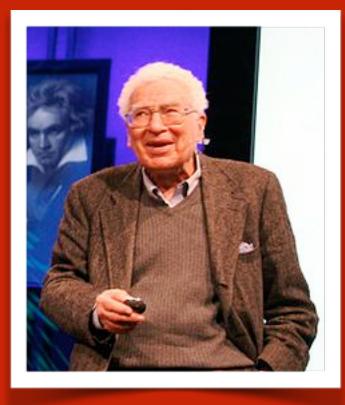




# quarks

### the mathematical description of such patterns

# 1964



### Murray Gell-Mann

1929 -

theoretician

Nobel Laureate 1969

genius

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

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

Unraveled many of the organization puzzles of the particle zoo: strangeness an empirical mass formula relating them

Worries a lot now about the nature of physical law.

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

Not known for his humility.

http://www.ted.com/talks/murray gell mann on beauty and truth in physics.html 100

# Gell-Mann found that the patterns work

## if every particle is composed of smaller bits

up down strange

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

with fractional electric charge:

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

## "Quarks"

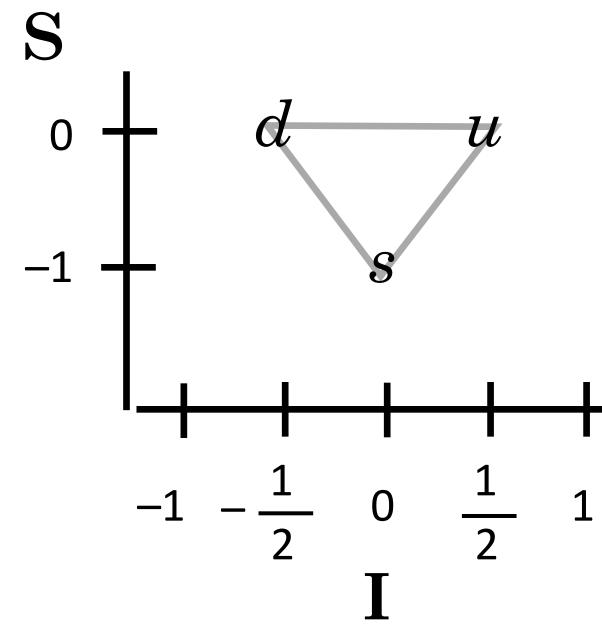
FINNEGANS WAKE BY JAMES IOYCE ER AND

Baryons & Mesons differ by quark-content Baryons are made of 3 quarks Mesons are made of 1 quark and 1 antiquark

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# Quarks

- 1964 version
- fundamental fermions
- in same league as electrons and neutrinos



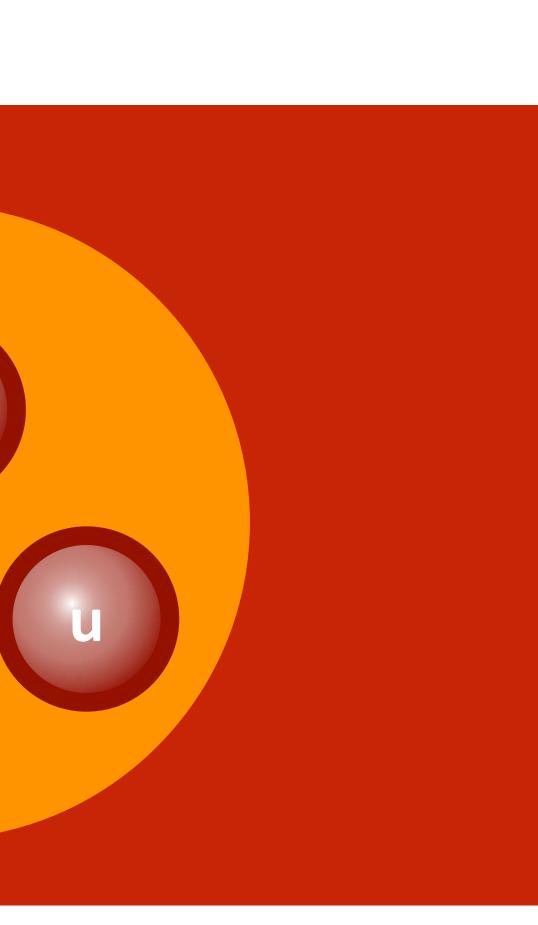
Quark	Symbol	Rest Mass MeV/c <sup>2</sup>	spin	Q	В	S
up	U	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	-1/3	1/3	0
strange	S	101	1/2	-1/3	1/3	-1



### proton

### electric charge = +1

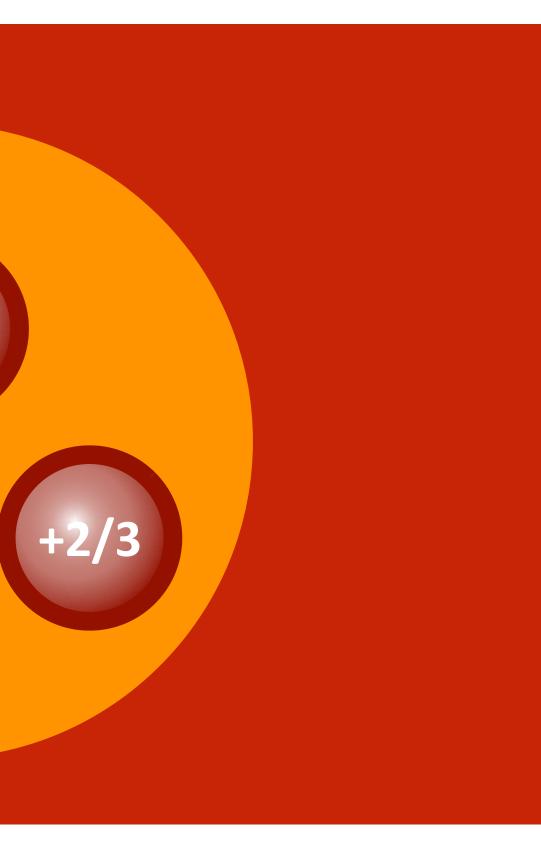
Quark	Symbol	Rest Mass MeV/c <sup>2</sup>	spin	Q	В	S
up	U	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	-1/3	1/3	0
strange	S	101	1/2	-1/3	1/3	-1



d

## proton electric charge = +1

Quark	Symbol	Rest Mass MeV/c <sup>2</sup>	spin	Q	В	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



+2/3

-1/3

### neutron

### electric charge = 0

Quark	Symbol	Rest Mass MeV/c <sup>2</sup>	spin	Q	В	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



d



neutron

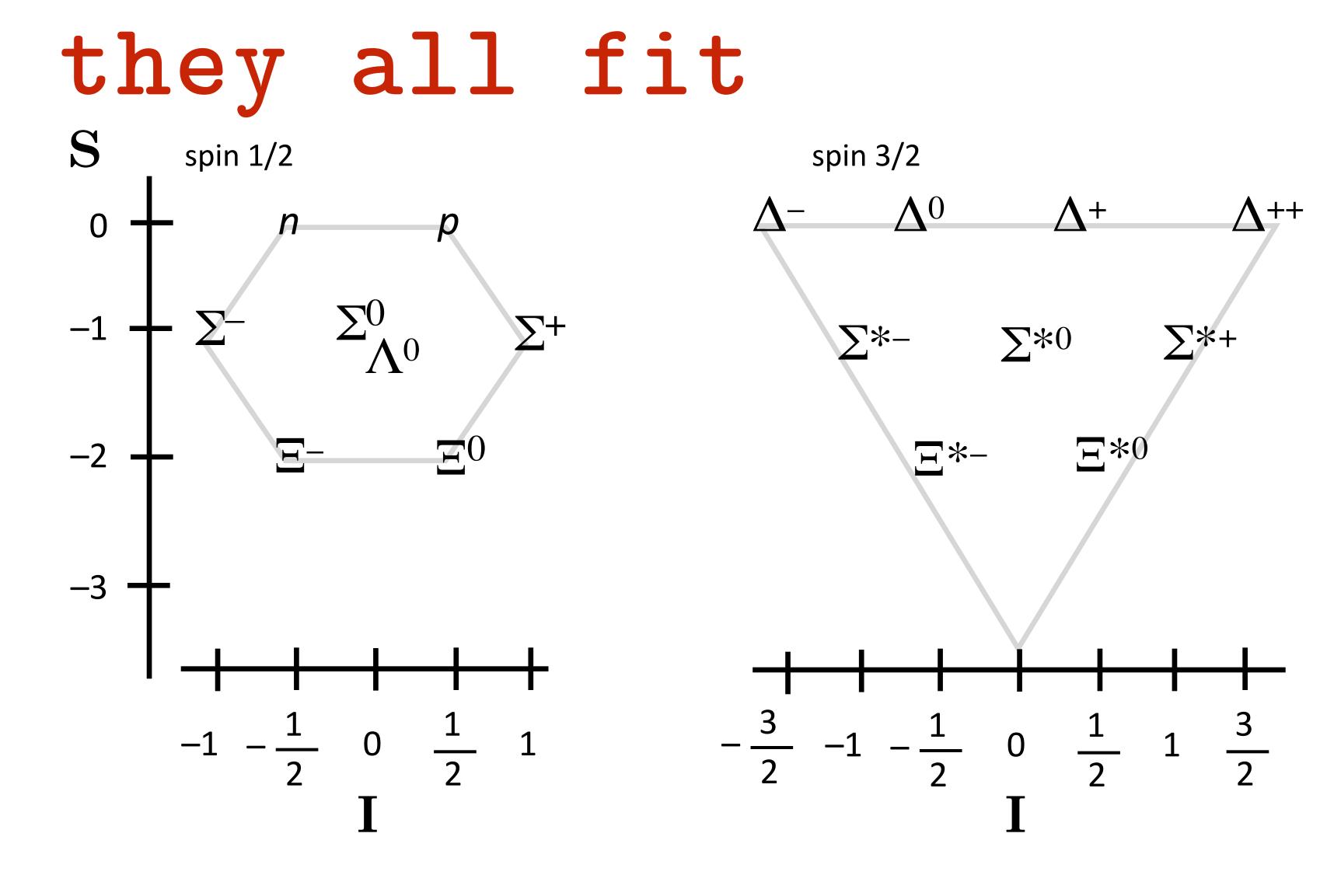
### electric charge = 0

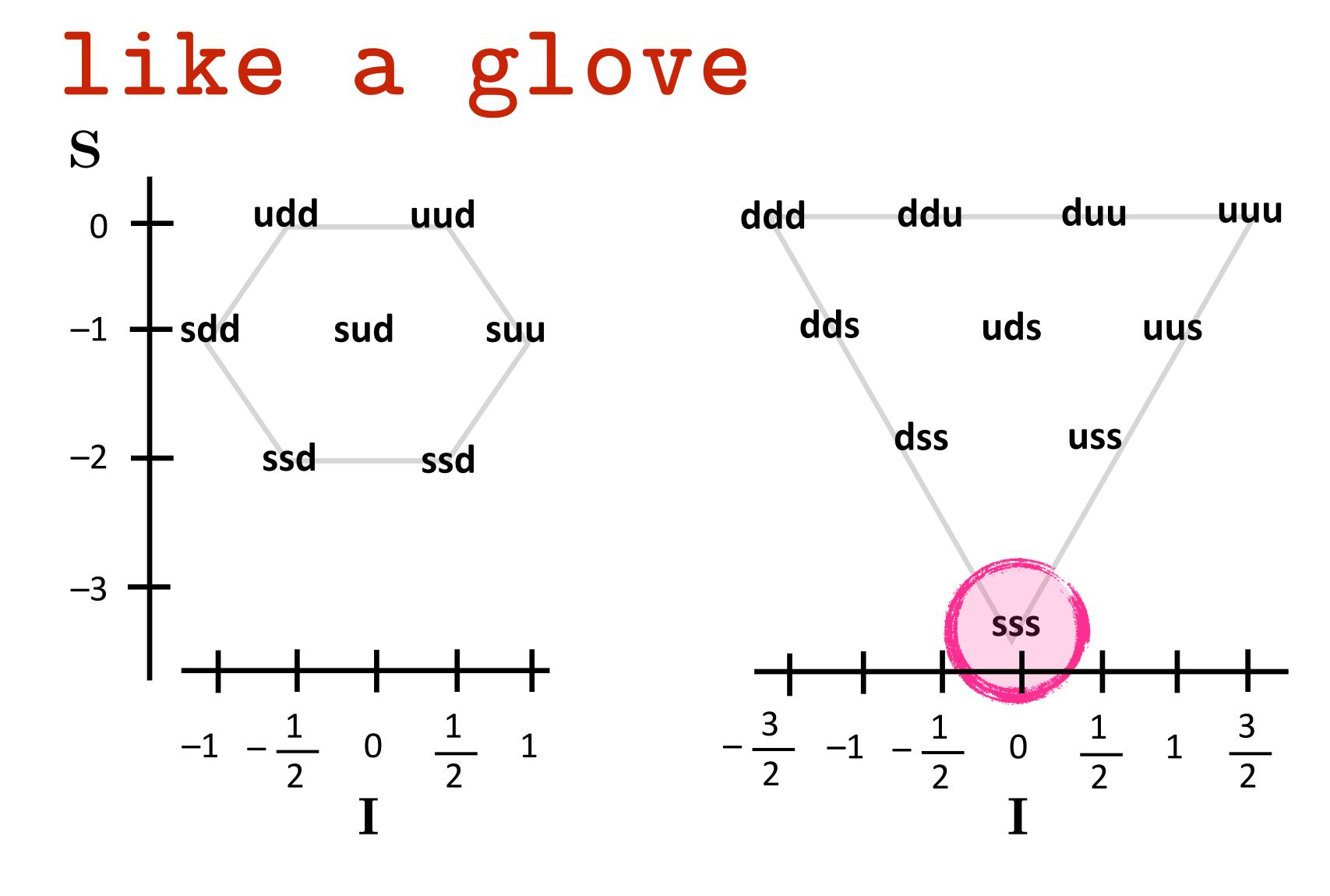
Quark	Symbol	Rest Mass MeV/c <sup>2</sup>	spin	Q	В	S
up	U	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	-1/3	1/3	0
strange	S	101	1/2	-1/3	1/3	-1



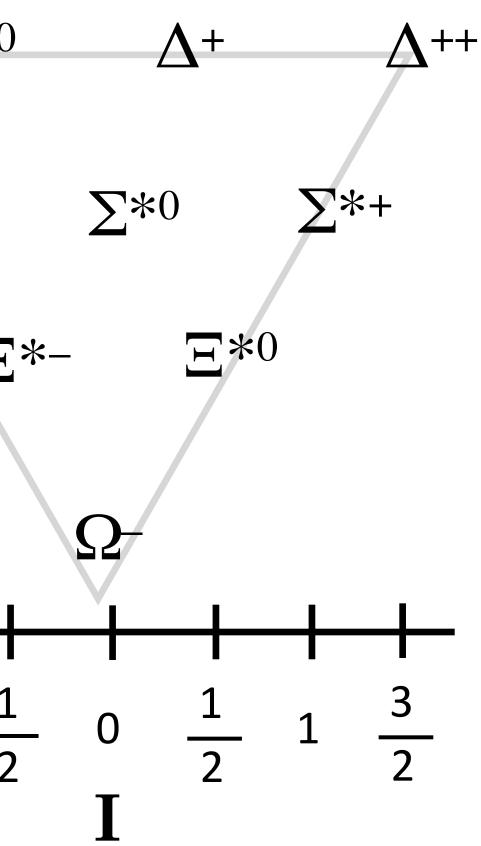
+2/3

-1/3



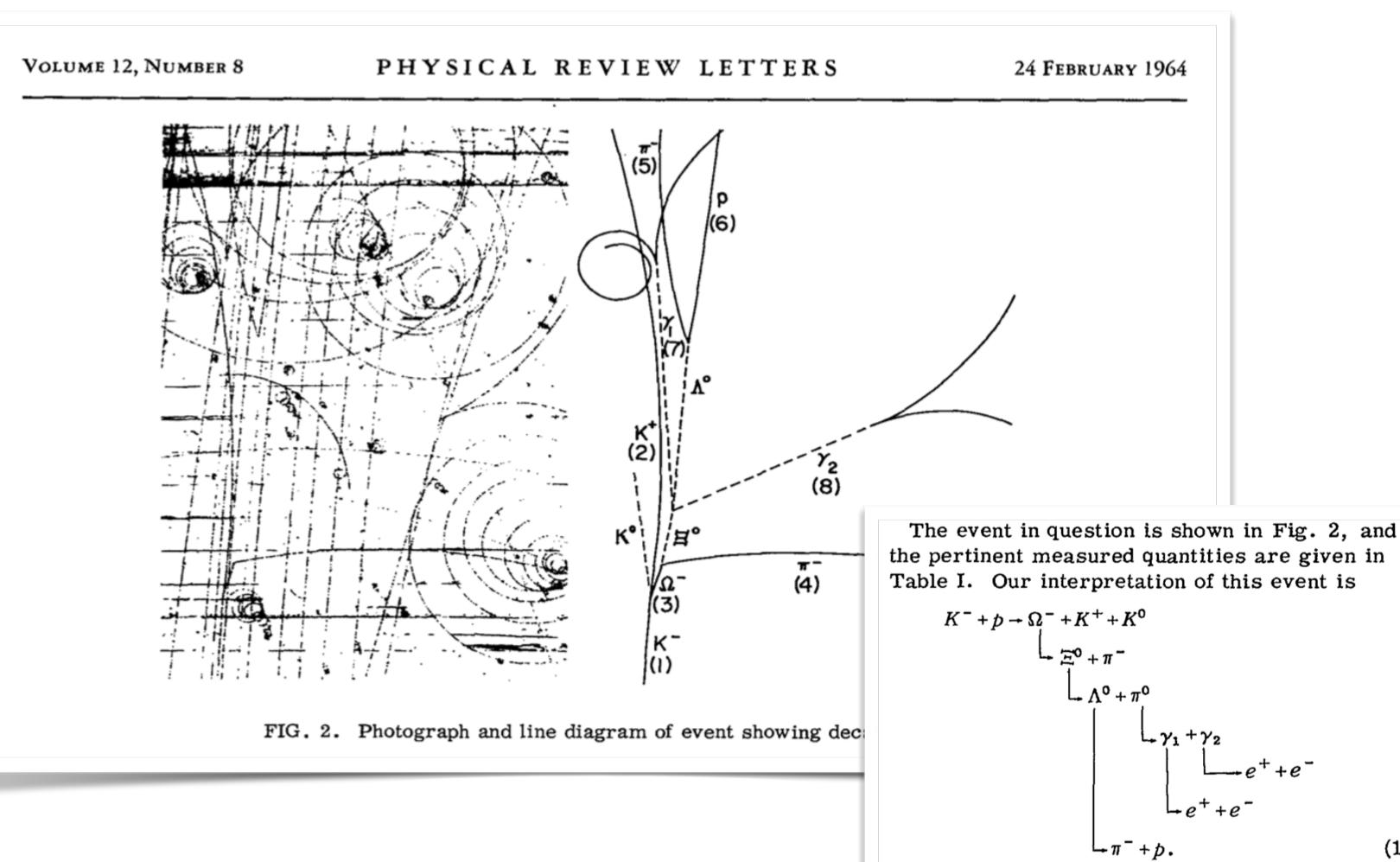


### discovered at Brookhaven within a year the "Omega minus" was discovered at Brookhaven National Lab S $\Lambda^0$ $\Lambda$ + 0 D -1 $\Sigma * 0$ **Ξ**\*0 -2 $\mathbf{T}$ -3 \_ <u>1</u> 2 <u>1</u> 2 <u>1</u> 2 3 <u>1</u> 2 0 -1 1 -1 1 0 Ι



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## most famous bubble chamber picture in history, 1964



$$\begin{array}{c} + \Omega^{-} + K^{+} + K^{0} \\ \downarrow \end{array} \\ \begin{array}{c} \Xi^{0} + \pi^{-} \\ \downarrow \end{array} \\ \Lambda^{0} + \pi^{0} \\ \downarrow \end{array} \\ \begin{array}{c} & \downarrow \end{array} \\ \gamma_{1} + \gamma_{2} \\ & \downarrow \end{array} \\ \begin{array}{c} & \downarrow \end{array} \\ e^{+} + e^{-} \\ & \downarrow \end{array} \\ e^{+} + e^{-} \\ \downarrow \end{array} \\ \begin{array}{c} & & \\ &$$

. . .

particle:	Omega minu	IS
	symbol:	$\Omega^{-}$
	charge:	-1
	mass:	1672.45 MeV/c <sup>2</sup>
	spin:	3/2
	category:	Fermion, baryon,

## I = 0, B=1, S=-3

# the dominant Baryons

Particle	Symbol	Rest Mass MeV/c <sup>2</sup>	spin	Q	В	S	Lifetime	dominant decay modes
proton	p	938.3	1/2	+1	+1	0	> 10 <sup>31</sup> 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 <sup>-10</sup>	$p\pi^-, n\pi^0$
Sigma	$\Sigma^+$	1189.4	1/2	+1	+1	-1	0.8 x 10 <sup>-10</sup>	$p\pi^0, n\pi^+$
Sigma	$\Sigma^0$	1192.5	1/2	0	+1	-1	6 x 10 <sup>20</sup>	$\Lambda^0\gamma$
Sigma	$\Sigma^{-}$	1197.3	1/2	-1	+1	-1	1.5 x 10 <sup>-10</sup>	$n\pi^-$
Delta	$\Delta^{++}$	1232	3/2	+2	+1	0	0.6 x 10 <sup>23</sup>	$p\pi^+$
Delta	$\Delta^+$	1232	3/2	+1	+1	0	0.6 x 10 <sup>23</sup>	$n\pi^+, \ p\pi^0$
Delta	$\Delta^0$	1232	3/2	0	+1	0	0.6 x 10 <sup>23</sup>	$n\pi^0$
Delta	$\Delta^{-}$	1232	3/2	-1	+1	0	0.6 x 10 <sup>23</sup>	$n\pi^-$
Xi	$\Xi^0$	1315	1/2	0	+1	-2	2.9 x 10 <sup>-10</sup>	$\Lambda^0\pi^0$
Xi	[I]	1321	1/2	-1	+1	-2	1.64 x 10 <sup>-10</sup>	$\Lambda^0\pi^-$
Omega	$\Omega^{-}$	1672	3/2	-1	+1	-3	0.82 x 10 <sup>-10</sup>	$\Xi^0\pi^-, \ \Lambda^0K^-$

quark content
uud
ddu
uds
uus
uds
dds
иии
uud
udd
ddd
USS
dss
<i>SSS</i>

## mesons

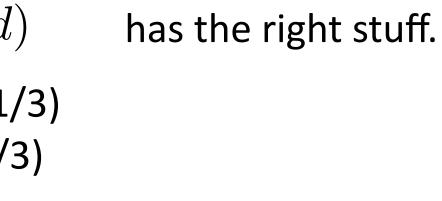
Quark	Symbol	Rest Mass MeV/c <sup>2</sup>	spin	Q	В	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	-1/3	1/3	0
strange	8	101	1/2	-1/3	1/3	-1

## a little different

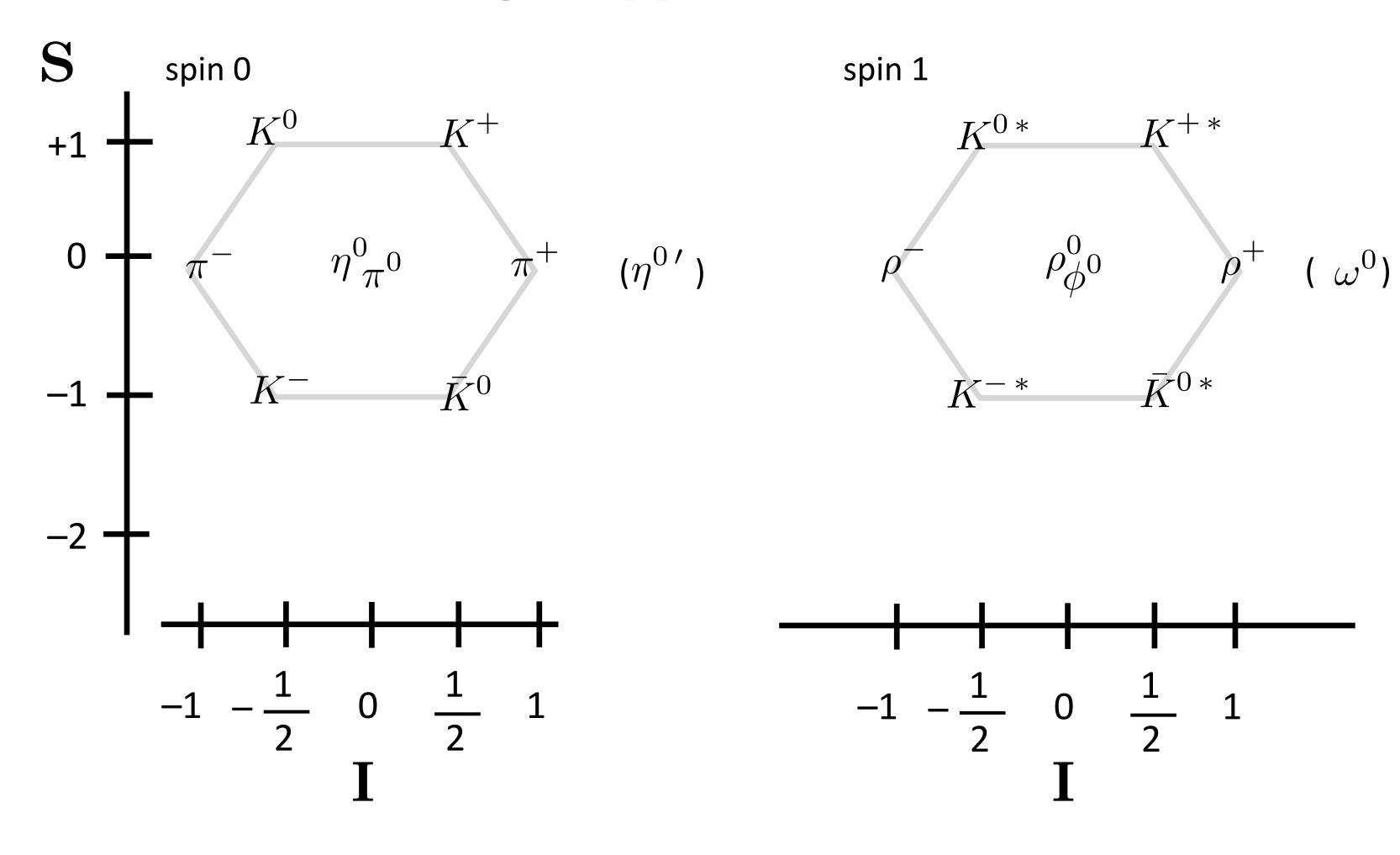
	Particle	Symbol	anti- particle	Rest Mass MeV/c <sup>2</sup>	spin	Q	В	S
The pion:	Pion	$\pi^+$	$\pi^{-}$	139.6	0	+1	0	0

$$\pi^{+} = \begin{pmatrix} u & \& & \bar{d} \\ +1 & +2/3 & +-(-1) \\ -1/3 & +-(1/3) \\ -1/3 & +-(1/3) \\ -1/3 & -(1/3$$

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

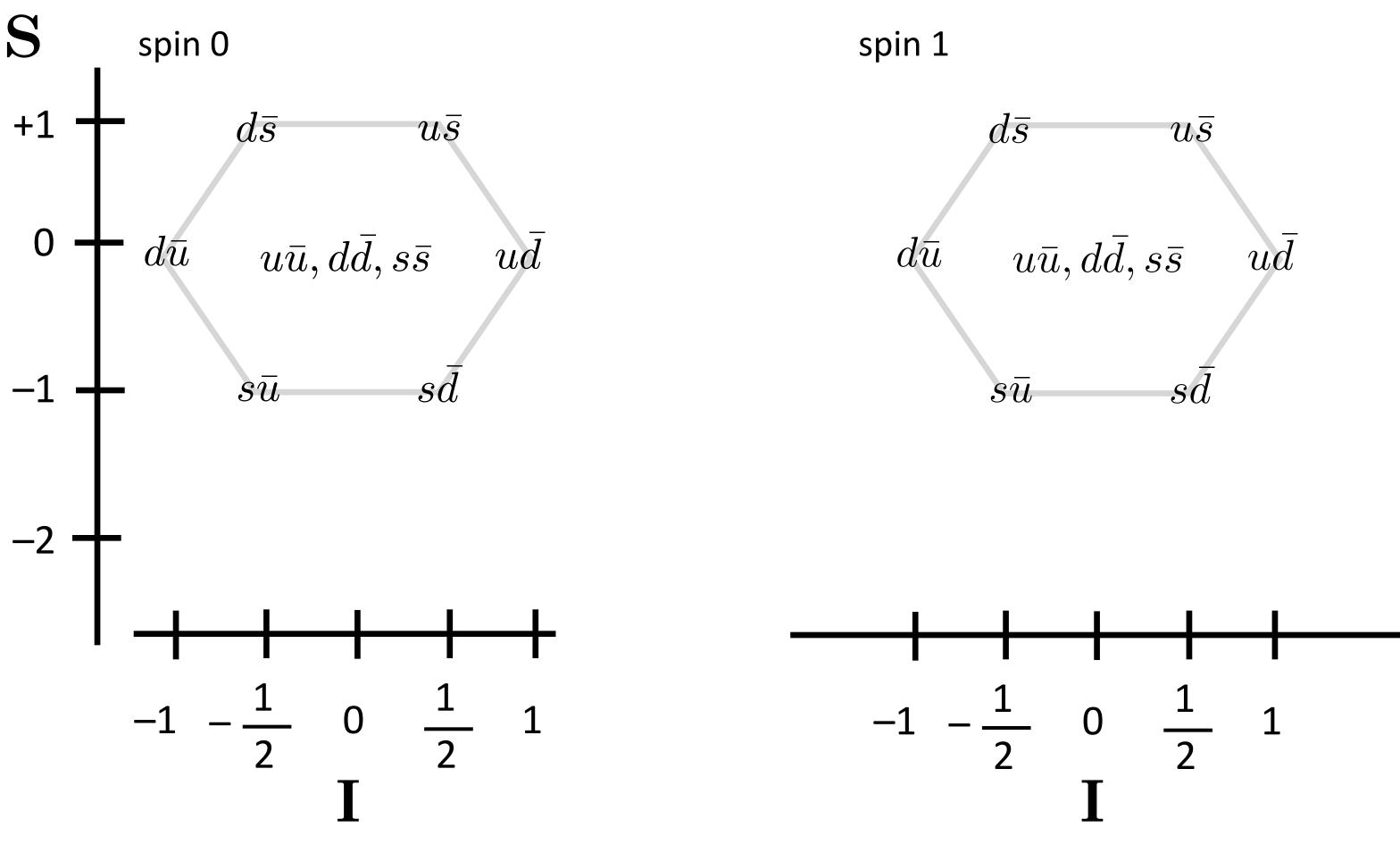


## a similar thing happens for the mesons



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meson quark content





# the dominant Mesons

Particle	Symbol	anti- particle	Rest Mass MeV/c <sup>2</sup>	spin	Q	В	S	Lifetime	dominant decay modes	quark content
Pion	$\pi^+$	$\pi^{-}$	139.6	0	+1	0	0	2.6 x 10 <sup>-8</sup>	$\mu^+ u_\mu$	$u \overline{d}$
Pi-zero	$\pi^0$	$\pi^0$	135	0	0	0	0	920	$2\gamma$	$\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$
Kaon	$K^+$	$K^{-}$	493.7	0	+1	0	+1	1.24 x 10⁻ <sup>8</sup>	$\mu^+ u_\mu, \pi^+\pi^0$	$u \overline{s}$
K-short	$K_S^0$	$K_S^0$	497.7	0	0	0	+1	0.89 x 10 <sup>-10</sup>	$\pi^+\pi^-, 2\pi^0$	$d\overline{s},s\overline{d}$
K-long	$K_L^0$	$K_L^0$	497.7	0	0	0	+1	5.2 x 10⁻ <sup>8</sup>	$\pi^{\pm}\ell^{\mp}\nu_{\ell}$	$d\overline{s},s\overline{d}$
Eta	$\eta^0$	$\eta^0$	548.8	0	0	0	0	< 10 <sup>-18</sup>	$2\gamma, \pi^+\pi^-\pi^0$	$uar{u}, dar{d}, sar{s}$
Eta-prime	$\eta^0$ '	$\eta^0$ '	958	1	0	0	0		$\pi^+\pi^-\eta$	$uar{u}, dar{d}, sar{s}$
Rho	$ ho^+$	$\rho^{-}$	770	1	+1	0	0	0.4 x 10 <sup>23</sup>	$\pi^+\pi^-, 2\pi^0$	$u \overline{d}$
Rho-naught	$ ho^0$	$ ho^0$	770	1	0	0	0	0.4 x 10 <sup>23</sup>	$\pi^+\pi^-$	$uar{u}, dar{d}$
Omega	$\omega^0$	$\omega^0$	782	1	0	0	0	0.8 x 10 <sup>22</sup>	$\pi^+\pi^-\pi^0$	$uar{u}, dar{d}$
Phi	$\phi$	$\phi$	1020	1	0	0	0	20 x 10 <sup>-23</sup>	$K^+K^-, K^0\bar{K}^0$	$s \overline{s}$

# spins work out

## add up the spins

Keep track of quark spins:

for example, a couple of baryons:

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

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

for example, a couple of mesons:

$$\pi^+ \qquad u \uparrow \bar{d} \downarrow$$

 $\rho^+ \qquad u \uparrow \bar{d} \uparrow$ 

spin +1/2  $q\uparrow$ spin –1/2  $q\downarrow$ 

total spin: 0

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.

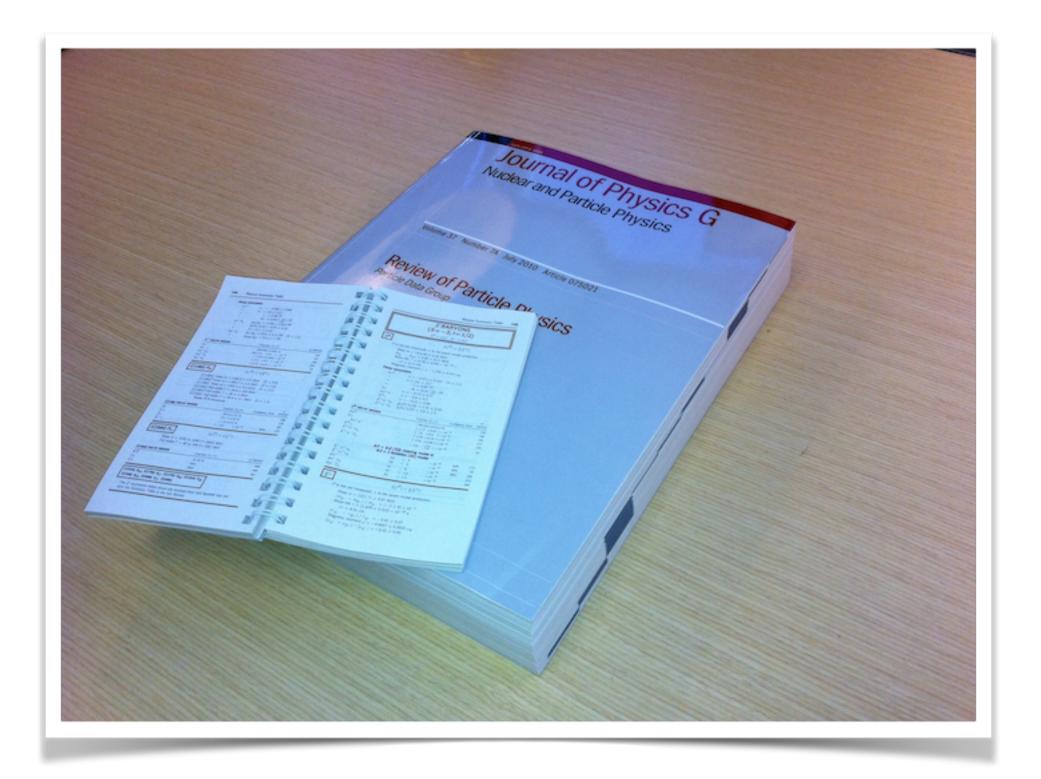
is a state with the same quark content as a proton  $N^*$ but which has a high orbital angular momentum

> dU U

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

d

you can tell a particle physicist by the book that they carry



# the now jargon

## gets a little more straightforward



### Hadrons: particles made of quarks.

Baryons: particles made of 3 quarks.

now defined:

now defined:

**Mesons**: particles made of 1 quark and 1 antiquark.

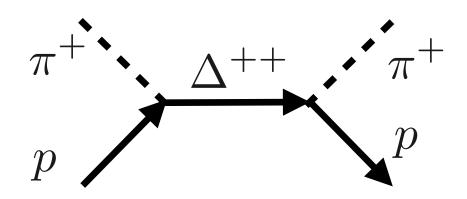
a variety of consequences

## became apparent

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

states

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



 $\pi^+ + p \rightarrow \pi^+ + p$  Fermi had produced "resonances" that suggested that something was "in between" the initial and final

scatterings
now are
thought of
diferently

by following the lines...

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

### Feynman Diagram, pre-1964:

### in quark language:

