

Day 24, 04.16.2019 Particle Physics 1

18 days until MSU graduation

Bon Jovi week



April 2019



TUESDAY, April 16	Feynman Diagrams, particle zoo, the weak and strong interactions
Required Readings:	<u>Chapter 12 in PCC</u>
	TOE chapter 5 and Appendix C
	<u>Chapter 17 in PCC</u>
	CP Section 4.2
Recommended Readings:	
Additional content:	primitiveDiagrams_0 (13m), primitiveDiagrams_1 (4m), primitiveDiagram_2 (
Tasks:	<u>3 movies on how to make Feynman Diagrams</u>
Homework available:	
Homework due:	

Quarks, W and Z Bosons, and the gluon THURSDAY, April 18

Required Readings:	TOE chapter 5
	<u>Chapter 17 in PCC</u>
	CP Section 4.2
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Recommended Readings:

Additional content:

Tasks:

Homework available: HW12: MasteringPhysics HW11: Sunday, April 21

Homework due:

anything posted?

<u>slides</u>



housekeeping

Poster selection:

reservations were due last Friday from within LON-CAPA

Some tutorial videos to watch

How to draw Feynman Diagrams



you know the drill:

from the mothership:

To: RAYMOND L BROCK

From: sirs@msu.edu

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

ISP 220 001: 4/15/2019 - 5/15/2019 ISP 220 002: 4/15/2019 - 5/15/2019

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

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

SIRS Online rating summaries are available to instructors and department chairs after 5/15/2019 at <u>https://sirsonline.msu.edu</u>. Instructors should provide copies of the rating summaries to graduate assistants who assisted in teaching their course(s). Rating information collected by SIRS Online is reported in summary form only and cannot be linked to individual student responses. Student anonymity is carefully protected.

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





Somehow early in the morning last Thursday ... I uploaded a stale version of the project page It was fixed by afternoon.

and, jeez...



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

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

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





vacuum is full

of fields

one for every "particle"

a little more specific

what the mathematics tells US



it's not like the photon is now "in" the electron

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

Feynman Diagrams

now for real.

Richard Feynman, Sin-Itiro Tomonaga, Julian Schwinger

1965 Nobel



Nobel Prize in Literature Nobel Peace Prize

Prize in Economic Sciences

Nobel Laureates Have Their Say

Nobel Prize Award Ceremonies

Nomination and Selection of Nobel Laureates



Julian S

The Nobel Prize in Physics 1965 was Julian Schwinger and Richard P. Feyr quantum electrodynamics, with deepelementary particles".

Photos: Copyright @ The Nobel Foundation

TO CITE THIS PAGE:

Sin-Itiro Tomonaga

MLA style: "The Nobel Prize in Physics 1965". No http://www.nobelprize.org/nobel_prizes/physics/la

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chwinger Richard P. Fey	mman
awarded jointly to Sin-Itiro Tomonag nman "for their fundamental work in ploughing consequences for the ph	ga, ysics of
obelprize.org. 23 Mar 2013 aureates/1965/	

the symbols of Feynman Diagrams

each line represents an entire "history" of trajectories

and "stand in" for many lines of mathematics

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



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

very efficient

avoids lots of technicalities.

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

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Sy(+,-x2)

-242 242 I in this work commution for to make a variation arres I constan succession in any in Commen 204 thermon (Photon und waters string , on when man Electronetros) 45 STER ermer YA YY Collens act Eval & collerated my which it in the (dig - that) an present - Again -w)(ha-w) 800 01 A= (12) A= (12) 102 B(120-1.2) g(h) Every (h) -14.(x.-K) (ush) (() () () () ~ (L) atur setart like before (m)]=-gui 2he (18) 35(2-2) non Propaga to Energia) Every (h) e the land) The Repairies relation mith the - would see (Immare Etress- - 2-) Jus. Same agent , we get a minutes consider on integul like 41. " " h" Dan " ") hard The (he at The)



4 (7) Do the standard Earn), at (m) i - ture

307

U"ZE & (P-P.) St. Sg. to Jes.

> TT) 3 2E S(P-P,) Srs Spr N: Ym tions can be

> > ip'x, -ipx Life (p) e e

- twice (which cancels the Friday minus night). A* (x,) 1Y>= JdK, Z Evil (h,) e (IT) 32W, Six, S(E-E,) 107 and we can do the momentum nit equals giving Y(11'x) 1: Ap(4.1 Ar(x)): 18(4x) >= $\epsilon_{\mu(\lambda')}(\omega') \epsilon_{\tau(\lambda)}(\omega) e e + \epsilon_{\tau(\lambda')}(\omega) \epsilon_{\mu(\lambda)}(\omega) e e^{i\omega' x_{\lambda} - ih \cdot x_{\lambda}}$ thingue, & terms merale (+ex) = -e' [d4x. f. P(p) un (p) e e

311

X u

14

Earliev, I attesched a graphical meaning to the which expansion terms, let's recorp that according to what we've calculated.

p) uppe pe

平(x)+(y) = COIT[平(x)+(y)]10>

× ?

14(x) y + +(y) St A(x)

So, the trist (O or () graph would be

Ar(x) -> A+(x) -> a generally: ¥(4) ¥(4) for our poster

and Dor @

 $A(x_{i}) \rightarrow A^{+} \rightarrow a$ $5 A(x_{i}) \rightarrow A^{-} \rightarrow a^{+}$



his rules eliminate all of that

and I can just write down the "answer"

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



325 NOW let's do the comptan calculation as it we have the rules all clong. I want the cross section for T(L) + e(p) -> X(L) + e(p) to 2th order D+U-m (-LESM) Entry (-ied) Evits u \$+4+m 1+1+ + 2p.h - H

but the pictures themselves are visually...informative

and I'm going to try to tell you how to do this without the geeky mathematics

theoretical papers each diagram is a complicated calculation



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







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

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

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

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

For the initial unpolarized electrons and laser photon beams, the energy spectrum of the back scattered

photon is given by [22]

$$F_{\frac{\gamma}{e}} = \frac{1}{D(\xi)} \left[1 - x + \frac{1}{1 - x} - \frac{4x}{\xi(1 - x)} + \frac{4x^2}{\xi^2(1 - x)^2} \right],$$
(14)
where $x = 2\omega/\sqrt{s}$ is the fraction of the energy of the

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

$$\begin{aligned} \mathcal{D}(\xi) &= \left(1 - \frac{4}{\xi} - \frac{8}{\xi^2}\right) \ln\left(1 + \xi\right) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2}, \end{aligned}$$
(15)
$$\xi &= \frac{2\sqrt{s\omega_0}}{m_e^2}, \end{aligned}$$
(16)

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

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



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



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

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

081201-3

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

$$\Gamma[H \rightarrow l]$$

unimportant.



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

depicted in Fig. 3] by the well-known expression [38–40]

$$\Gamma[H \to Q\overline{Q}] = \frac{3C}{4}$$

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

$$l^{-}] = \frac{G_F M_H}{4\sqrt{2}\pi} \ m_l^2 \beta^3 \tag{6}$$

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

For large Higgs masses the particle width for decays to b, c quarks [directly coupling] to the SM Higgs particle] is given up to three-loop QCD corrections [typical diagrams are

$$\frac{FM_H}{2\pi} \overline{m}_Q^2(M_H) \left[\Delta_{\rm QCD} + \Delta_t\right] \tag{7}$$

we really do use Feynman Diagrams





Feynman's approach is really sneaky and really cute

energy and time appear together in the equations:

In essence, this: $(\pm E)(t)$ either energy solution: (-E)(t)just the -E solution: (E)(-t)move the – sign:

Get a whole new interpretation of antimatter



<u>antiparticles</u>

can be intepreted as <u>particles</u> moving backwards in time.

that's it.





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 h
	entomology:	from Fermi's theo behavior of large r
	example:	electron, proton, r

half-integer spin retical work on the numbers of Fermions

neutron

jargon alert:	bosons	
	refers to:	any quantum objec
	entomology:	from Satyendra Nation the effects of maggregates
	example:	photon, pion, Higgs

ct with integer spin th Bose, who worked ultiple boson

s Boson

key the

the different kinds of lines

look at your Primitive **Diagram Sheet**

 (0000)

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

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

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

gluon, spin 1

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

space diagram



photograph





e-

e+



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.

ct



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



ct

Feynman's trick

depends on the in and out states.

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

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

fix it.
particles in time

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



is the same thing as An electron coming **out** of an **initial** state (?)



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



is the same thing as An electron coming **into** a **final** state (?)



Yes, this makes sense

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

Yes, this makes sense

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: e

electron comes along and and goes on its way

regular old radiation





electron comes along and spits out a photon, recoils

Rule 2.

notice that the arrows make the lines continuous

 \boldsymbol{e}

fermion lines must be continuous



 $e^{\dot{}}$



This and more is in these 3 movies: primitiveDiagrams_0 (13m) primitiveDiagrams_1 (4m) primitiveDiagram_2 (9m) primitiveDiagrams_OR primitiveDiagrams_1R primitiveDiagram_2R

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

full resolution Reduced resolution

primitive diagrams

are general

a puzzle piece to construct real physical reactions

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



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

Their diagrams are identical.



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Primitive Diagram Scorecard

your first entry

Primitive Diagrams	TIME alway
f f f	
2	3
6	7
4	5
8	9
10	11
ermion, spin 1/2, e.g., electron Vector Boson, spin 1, o	e.g., photon gluon, spir



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



е



particle physics



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

939.6 MeV/c²

I = -1/2, B = 1

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

938.2 MeV/c²

I = 1/2, B = 1

important realizations

weak force: neutrinos

exchange force

nuclear force

beta decay

the "weak force"

50

beta decay

something seriously wrong

51

remember: #neutrons doesn't affect the Chemistry

can add neutrons

as long as the nucleus is energetically stable

"isotopes"





¹³C: 1.1% & stable ¹⁴C: 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



54

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 energy and energy into because of the conservation of energy and two objects conservation





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





a particular value 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

and massless!

the idea hung around

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

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



cay 1933

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

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





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

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Nobel Laureates Have Their Say

🖶 Printe 1901 Sort and list Nobel Prizes and



The Nobel Prize in Physics 193

Nobel Prize Award Ceremony

Enrico Fermi



Enrico Fermi

The Nobel Prize in Physics 1938 was awarded to Enrico Fermi "for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons".

Photos: Copyright © The Nobel Foundation

Ceremonies

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Fermi Theory of Beta Decay

uses the Dirac ideas of quantum electrodynamics

particle creation and annihilation



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

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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: 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

P

D



analogy: a repulsive exchange force

a repulsive exchange force





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analogy: an attractive exchange force

an attractive exchange force



68

jargon alert:	exchange force	
	refers to:	the idea that the fore the propagated by qua
	entomology:	Heisenberg's pictu 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" ¹²C they have to attract one another NOT electromagnetism





remember: chemistry from # protons = #electrons

to "assemble" ¹²C

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





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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
particle nameexample:"nucleon force"

jargon alert:	hadron	
	refers to:	any particle that Strong Force
	entomology:	αδρόσ "hadros" "I
	example:	proton and neutinot 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

~10⁻¹⁵ m

Yukawa knew that.





uncertainty certainly to the rescue

brilliant observation by Yukawa

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

another exchange force/particle?



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

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

$$m_{\scriptscriptstyle U} = \Delta E/c^2$$

 $m_U \approx 100 \times 10^6 eV = 100 MeV$

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



Nitrogen nucleus in cosmic rays



...you guessed it.

many of these sort:

something unknown...

20,000 stereo photos --> 1600 usable tracks in 3 cm² 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 μ sec

too long to be a meson

The winning proposal:

"U" now called the "pion"

 ν



particle:	pion	
	symbol:	π
	charge:	+, -, 0
	mass:	139 MeV/c ² ,
	spin:	0
	category:	Boson, hadron, n

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 ²
	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

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

ish eV/c²

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

ish eV/c²

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,

ctron, muon,

), "fine, small, thin" neutrino, tau!
back to the 1940s and 1950s when all hell broke loose

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

d state) MeV/c²

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

particle:	Lambda	
	symbol:	Λ
	charge:	0
	mass:	1,115.683 MeV/c ²
	spin:	1/2
	category:	Fermion, baryon,

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

$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$ \begin{array}{c} \mathbf{r}_{1}(140) & \mathbf{r}_{1}(10) & \mathbf{r}_{1}(10) & \mathbf{r}_{1}(20) \\ \mathbf{r}_{1}(200) & \mathbf{r}_{1}(20) & \mathbf{r}_{1}(20) \\ \mathbf{r}_{1}(200) & \mathbf{r}_{1}(21) & \mathbf{r}_{1}(20) \\$
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c} \chi_{cd}(1P) \\ \circ \chi_{cl}(1P) \\ \psi(2) \\ \psi(3) \\ \psi($
$ \begin{array}{c} \hline z(1690) & \ast\ast\ast \\ \hline z(1800) & D_{13} & \ast\ast\ast \\ \hline z(1950) & \ast\ast\ast \\ \hline z(2030) & \ast\ast\ast \\ \hline z(2120) & \ast \\ \hline z(2250) & \ast\ast \\ \hline z(2380)^{-} & \ast\ast\ast \\ D(2470)^{-} & \ast\ast\ast \\ D(2470)^{-} & \ast\ast \\ D(1520) & D_{13} & \ast\ast \\ D(1650) & S_{11} & \ast\ast \\ D(1700) & D_{13} & \ast\ast \\ D(1650) & D_{13} & \ast\ast \\ D(1700) & D_{13} & \ast\ast \\ D(1700) & D_{13} & \ast\ast \\ D(1650) & D_{13} & \ast\ast \\ D(1700) & D(170) & \otimes\ast \\ D(170) & D(170) & \otimes\ast \\ D(170) & D(170) & \otimes\ast \\ D(170) & D$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $
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$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} \text{LIGHT UNFL} (S=C+E) \\ f^{G}(f^{PC}) \\ \bullet \pi^{\pm} & 1^{-(0^{-1})} \\ \bullet \pi^{0} & 1^{-(0^{-1})} \\ \bullet \pi^{0} & 0^{+}(0^{-+}) \\ \bullet f_{0}(600) & 0^{+}(0^{++}) \\ \bullet \rho(770) & 1^{+}(1^{}) \\ \bullet \phi(122) & 0^{-}(1^{}) \\ \bullet \phi(120) & 0^{-}(1^{}) \\ \bullet \phi(1200) & 0^{-}(1^{}) \\ \bullet f_{0}(1200) & 0^{-}(1^{}) \\ \bullet f_{0}(1200) & 1^{-}(0^{++}) \\ \bullet f_{0}(1235) & 1^{+}(1^{+-}) \\ \bullet f_{1}(1235) & 1^{+}(1^{+-}) \\ \bullet f_{1}(1265) & 0^{+}(1^{++}) \\ \bullet f_{1}(1285) & 0^{+}(0^{-+}) \\ \bullet \pi(1300) & 1^{-}(0^{-+}) \\ \bullet \pi(1300) & 1^{-}(0^{-+}) \\ \bullet \pi(1400) & 1^{-}(1^{-+}) \\ \bullet \pi(1400) & 1^{-}(1^{}) \\ \bullet \pi(1400) & 0^{+}(1^{-+}) \\ \bullet f_{1}(1420) & 0^{+}(1^{++}) \\ \bullet (1420) & 0^{-}(1^{}) \\ \bullet f_{1}(1450) & 1^{-}(0^{-+}) \\ \bullet \rho(1450) & 1^{-}(0^{-+}) \\ \bullet \rho(1450) & 1^{+}(1^{}) \\ \bullet f_{1}(1510) & 0^{+}(1^{++}) \\ \bullet f_{1}(1510) & 0^{+}(1^{++}) \\ \bullet f_{1}(1500) & 0^{+}(0^{++}) \\ \bullet f_{1}(1500) & 0^{+}(0^{++}) \\ \bullet f_{1}(1500) & 0^{+}(0^{++}) \\ \bullet f_{1}(1500) & 0^{+}(1^{+-}) \\ \bullet f_{1}(1500) & 0^{+}(1^{+-}) \\ \bullet f_{1}(1500) & 0^{+}(1^{+-}) \\ \bullet f_{1}(1500) & 0^{-}(1^{}) \\ \bullet f_{1}(1600) & 1^{-}(1^{-+}) \\ \bullet f_{1}(1600) & 1^{-}(1^{-+}) \\ \bullet f_{2}(1640) & 0^{+}(2^{++}) \\ \bullet f_{2}(1640) & 0^{+}(2^{++}) \\ \bullet f_{2}(1650) & 0^{-}(1^{}) \\ \bullet \omega_{3}(1670) & 0^{-}(3^{}) \\ \end{array}$

By the mid-1950's

things are officially out of control.

by 1955

 ν_{13}

 $\begin{array}{c} S_{11} \\ S_{11} \\ D_{15} \\ F_{15} \\ D_{13} \\ P_{11} \\ P_{13} \\ P_{13} \\ F_{17} \\ F_{15} \\ D_{13} \\ S_{11} \\ P_{11} \\ G_{17} \\ D_{15} \\ H_{19} \\ G_{19} \\ I_{1,11} \end{array}$

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)

N(2200) N(2220) N(2250) N(2600)

 P_{33} P_{33} S_{31}

 $\begin{array}{c} D_{33} \\ P_{31} \\ S_{31} \\ F_{35} \\ P_{31} \\ P_{33} \\ D_{35} \\ D_{33} \\ F_{35} \\ S_{31} \\ G_{37} \\ H_{39} \\ D_{35} \end{array}$

F37

∆(1232)

 $\Delta(1600)$

 $\Delta(1620)$

∆(1700)

 $\Delta(1750)$

 $\Delta(1900)$

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Δ(1910) Δ(1920)

 $\Delta(1930)$

∆(1940)

 $\Delta(1950)$

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

∆(2200)

∆(2300)

 $\Delta(2350)$

 $\Delta(2390)$

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 P_{11}

 P_{11}

P₁₁ D₁₃

 S_{11}

 S_{11}

 D_{15}

F₁₅ D₁₃

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 F_{17}

 F_{15}

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 S_{11}

 P_{11}

 G_{17}

N(2700) K_{1,13} **

N(1440)

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N(1535)

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N(2100) N(2190)

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A(2100) A(2110) A(2325) A(2350)	G ₀₇ F ₀₅ D ₀₃ H ₀₀	*** 2 * 2	E(1775) E(1840) E(1880) E(1915)	$P_{13} * P_{11} * F_{15} * * * *$	Ω(22 Ω(23 * Ω(24	250)- * 380)- * 170)- *	**	$1^+(3^-)$ $1^+(1^-)$ $1^-(2^+)$	N(20 N(20 N(21	80) L 90) S 00) F	D ₁₃ ** 5 ₁₁ * P ₁₁ *							• π^{\pm} • π^{0} • η		$1^{-}(0^{-})$ $1^{-}(0^{-})$ $0^{+}(0^{-})$	$(+) = (-1)^{+} + (-1$	(1670) 1680) (1690)	1 0 1	$^{-(2^{-}+)}_{-(1^{-}-)}$ $^{+(3^{-}-)}$	• K [±] • K ⁰ • K ⁰ _S		1/2(0) 1/2(0) 1/2(0)	• B [±] • B ⁰ • B [±] /B ⁰ Al
A(2585)	1	** 2	E(1940)	D ₁₃ ***	A ⁺		***	0 ⁺ (0 ⁺ 0 ⁺ (0 ⁻	N(21 N(22	90) (00) [G ₁₇ **** D ₁₅ **							 f₀(600) ρ(770) 		$0^+(0^+)^+(1^+)^+(1^-)^+(1^+)(1^+)$	(1) (1) (1)	(1700) (1700)	1	$^{+(1)}_{-(2++)}$	• K ⁰ L K:(8	300)	$1/2(0^{-})$ $1/2(0^{+})$	 B[±]/B⁰/B MIXTURE

 $\eta_b(1S)$

T(15)

χ_{b0}(1P)

 χ_{b1}(1P) χ_{b2}(1P)
 τ(25)

 $\Upsilon(1D)$

χ_{b0}(2P)

χ_{b1}(2P)
 χ_{b2}(2P)

Υ(35)

T(45)

T(10860)

r(11020)

NON-qq CA

a mess what's so

"(er		e		a	r\	"
• π [±]	$1^{-}(0^{-})$ $1^{-}(0^{-})$	 π₂(1670) φ(1680) 	$1^{-}(2^{-+})$	• K±	$1/2(0^{-})$ $1/2(0^{-})$			

 ρ(770) 	1+(1)	$\partial_2(1700)$	$1^{-}(2^{++})$	K [*] ₀ (800)	$1/2(0^+)$		MAA AAAAAA
 ω(782) 	$0^{-}(1^{-})$	 f₀(1710) 	$0^{+}(0^{+}+)$	 K*(892) 	$1/2(1^{-})$	V _{cb} and V _{ub} C	
 n'(958) 	0 + i0 - + i	p(1760)	$0^{+}(0^{-}+1)$	• K. (1270)	1/2(1+)	Elements	1/0(1-)
6(980)	0+(0++)	• (1800)	1-(0-+)	+ K(1400)	1/2(1+)	• D	2/2(1)
• J ₁ (900)	1 = (0 + +)	£(1810)	a + (2 + +)	• A1(1400)	1/2(1)	B ⁻² (5732)	
 a₀(300) a₀(300) 		/2(1010)	27/2 - +1	• K*(1410)	1/2(1)	BOTTOM	STRANGE
 φ(1020) φ(1020) 		X(1835)	f (f = ')	• K ₀ (1430)	1/2(0+)	$(B - \pm 1)$	5 1)
 h₁(1170) 	0 (1)	 φ₃(1850) 	0-(3)	 K[*]₂(1430) 	$1/2(2^+)$	(v - ±1)	5 - +x)
 b₁(1235) 	$1^+(1^+)$	$\eta_2(1870)$	$0^+(2^{-+})$	K(1460)	$1/2(0^{-})$	• B ⁰ _s	0(0-)
 a₁(1260) 	$1^{-}(1^{++})$	ρ(1900)	$1^{+}(1^{-})$	K ₂ (1580)	$1/2(2^{-})$	B*	0(1-)
 f₂(1270) 	$0^{+}(2^{++})$	f ₂ (1910)	$0^{+}(2^{++})$	K(1630)	$1/2(?^{?})$	B, (5850)	?(??)
 f₁(1285) 	$0^{+}(1^{++})$	 f₂(1950) 	$0^{+}(2^{++})$	K ₁ (1650)	1/2(1+)		
 n(1295) 	$0^{+}(0^{-}+)$	p3(1990)	$1^{+}(3^{-})$	• K*(1680)	1/2(1-)	BOTTOM,	CHARMED
 π(1300) 	1-(0-+)	 fs(2010) 	0+(2++)	- K (1770)	1/2(1)	(B = C	$= \pm 1$)
 a)(1320) 	1-(2++)	6(2020)	$0^{+}(0^{+}+)$	• N2(1770)	1/2(2)	• B [±] _c	0(0-)
• £(1370)	$n^{+}(n^{+}+)$	a.(2040)	$1^{-(4^{++})}$	• K ₃ (1780)	1/2(3)	- ·	. ,
 h(1300) 	$\frac{3}{2}(1+-)$	• a1(2040)	$a^+(4^++)$	 K₂(1820) 	1/2(2-)	C	5
/1(1360)	(1 - 1)	• <i>I</i> ₄ (2050)	(4 - 1)	K(1830)	1/2(0-)	• $\eta_c(15)$	$0^{+}(0^{-+})$
 π₁(1400) 	$1(1 \cdot)$	$\pi_2(2100)$	$1^{-}(2^{-1})$	$K_0^*(1950)$	$1/2(0^{+})$	 J/ψ(15) 	$0^{-}(1^{-})$
 η(1405) 	0 (0)	f ₀ (2100)	0 (0)	K [*] ₂ (1980)	$1/2(2^+)$	• Y (1P)	0+(0++)
 f₁(1420) 	$0^{+}(1^{++})$	$f_2(2150)$	$0^+(2^{++})$	 K[*]₂(2045) 	$1/2(4^+)$	• X=1(1P)	$0^{+}(1^{+}+1)$
 ω(1420) 	$0^{-}(1^{-})$	ρ(2150)	$1^{+}(1^{-})$	K ₂ (2250)	1/2(2-)	h (1P)	2?(2??)
$f_2(1430)$	$0^{+}(2^{++})$	f ₀ (2200)	$0^{+}(0^{+})$	K ₂ (2320)	$1/2(3^+)$	"c(1P)	0+(2++)
 a₀(1450) 	$1^{-}(0^{++})$	f _J (2220)	0 ⁺ (2 or 4 ⁺ ⁺)	K*(2380)	1/2(5-)	• Xc2(1P)	$a^{+}(a^{-}+)$
 ρ(1450) 	$1^{+}(1^{-})$	$\eta(2225)$	$0^{+}(0^{-+})$	K (2500)	1/2(5)	• η _c (25)	0.(0 .)
 η(1475) 	$0^{+}(0^{-+})$	$\rho_3(2250)$	$1^{+}(3^{-})$	A4(2500)	1/2(4)	 ψ(25) 	0 (1)
 f₀(1500) 	$0^+(0^{++})$	 f₂(2300) 	$0^{+}(2^{+}+)$	K(3100)	£*(£**)	 ψ(3770) 	0-(1)
6 (1510)	$0^{+}(1^{+}+)$	£(2300)	$0^+(4^{++})$	CHAR	MED	 X(3872) 	0:(?:+)
$f'_{-}(1525)$	$0^+(2^++)$	• f (2340)	0+(2++)	(C =	+1)	 χ_{c2}(2P) 	$0^{+}(2^{+})$
£ (1666)	$0^{+}(2^{+}^{+})$	a (2350)	1+(5)	(c -		Y(3940)	?!(?!!)
h (1505)	$0^{-(1+-)}$	2(2450)	1-(6++)	• D-	1/2(0)	 ψ(4040) 	$0^{-}(1^{-})$
n1(1595)	0(1 - 1)	a6(2450)	1(6+1)	• D ⁰	$1/2(0^{-})$	 ψ(4160) 	$0^{-}(1^{-})$
 π₁(1600) 	1 (1 ')	16(2510)	0.(0)	 D*(2007)⁰ 	$1/2(1^{-})$	Y(4260)	$?^{?}(1)$
$a_1(1640)$	$1^{-}(1^{+})$	ОТН	FR LIGHT	 D[*](2010)[±] 	$1/2(1^{-})$	 \$\psi(4415)\$ 	$0^{-}(1^{-})$
$f_2(1640)$	$0^+(2^+)$	Eusther Sta	ter	$D_0^*(2400)^0$	$1/2(0^{+})$	• • • • • • • • • • • • • • • • • • • •	- (-)
 η₂(1645) 	$0^{+}(2^{-+})$	Further Sta	Les	$D_0^*(2400)^{\pm}$	$1/2(0^{+})$	bi	b .
 ω(1650) 	$0^{-}(1^{-})$			 D₁(2420)⁰ 	$1/2(1^+)$	n (15)	$0^{+}(0^{-}+)$
 ω₃(1670) 	0-(3)			$D_1(2420)^{\pm}$	$1/2(?^{?})$	T(15)	$0^{-}(1^{-})$
				D (2430)0	1/2(1+)	• / (15)	$0^+(0^++)$
				D*(2460)0	1/2(2+)	• Xb0(1P)	$a^{+}(a^{+}+b^{+})$
				• D ₂ (2400)*	1/2(2)	• $\chi_{b1}(1P)$	0 (1 ' ')
				 D[*]₂(2460)[⊥] 	1/2(2)	• $\chi_{b2}(1P)$	$0^+(2^++)$
				D*(2640) [±]	1/2(?*)	 T(25) 	0-(1)
				CHARMED	STRANCE	T(1D)	0-(2)
				CHARMED,	= +1)	 χ_{b0}(2P) 	$0^{+}(0^{+})$
				(c = 5)	- ++)	 χ_{b1}(2P) 	$0^{+}(1^{++})$
				• D [±] _s	0(0_)	 	$0^{+}(2^{++})$
				 D^{*±}_s 	0(? ^r)	 T(35) 	$0^{-}(1^{-})$
				 D[*]_{≤0}(2317)[±] 	$0(0^{+})$	• T(45)	$0^{-}(1^{-}-1)$
				 D_{c1}(2460)[±] 	$0(1^+)$	• T(10860)	$0^{-}(1^{-})$
				 D_{s1}(2536)[±] 	0(1+)	T(11020)	0-(1)
		-			101 A 2	• • • • • • • • • • • • • • • • • • •	

				. (-)		· (-)		-1- 1	
			• π^{\pm}	$1^{-}(0^{-})$	 π₂(1670) 	$1^{-}(2^{-+})$	• K [±]	1/2(0-)	 B[±]
			• π ⁰	1-(0-+)	 \$\phi(1680)\$ 	0 - (1)	• K ⁰	$1/2(0^{-1})$	• B ⁰
				0+(0-+)	• co(1690)	1+(2)	- K ⁰	1/2(0-)	R [±] /R ⁰ ∆Γ
			£ (600)	0 (0) 0+(0++)	• p3(1050)	1 (3)		1/2(0)	P+ (P) (P)
		_	• /0(600)	0.(0)	 ρ(1700) 	1.(1)	• K ^v _L	1/2(0)	
		_	• p(770)	1 (1)	$\partial_2(1700)$	$1^{-}(2^{++})$	K ₀ (800)	$1/2(0^+)$	V and V
****			 ω(782) 	0-(1)	 f₀(1710) 	0+(0++)	 K*(892) 	$1/2(1^{-})$	Elements
**		2	 η'(958) 	$0^+(0^-+)$	$\eta(1760)$	0+(0 - +)	 K₁(1270) 	$1/2(1^+)$	• B*
**		2	 f₀(980) 	$0^{+}(0^{+}+)$	 π(1800) 	$1^{-}(0^{-+})$	 K₁(1400) 	$1/2(1^+)$	R*(5732)
		5	 a₀(980) 	$1^{-}(0^{+}+)$	£(1810)	$0^+(2^++1)$	• K*(1410)	1/2(1-)	5 (51 52)
				0 = (1 = -)	X(1835)	$2^{?}(2-1)$	• K*(1420)	1/2(1)	BOTTO
		4	• (1120)	0-(1+-)	A (1055)	· (:)	• N ₀ (1450)	1/2(0 ')	(B =)
		14	• //(1170)	0 (1 ·)	• \phi_3(1050)	0(3)	• K ₂ (1430)	1/2(2+)	- 00
		2	• D ₁ (1235)	1 (1 + -)	$\eta_2(1870)$	0 (2 ')	K(1460)	$1/2(0^{-})$	• B [*] _S
		2	• a ₁ (1260)	$1^{-}(1^{+}^{+})$	$\rho(1900)$	1+(1)	$K_2(1580)$	$1/2(2^{-})$	B _s
		2	 f₂(1270) 	$0^+(2^{++})$	$f_2(1910)$	0+(2++)	K(1630)	$1/2(?^{?})$	B*, (5850)
			 f₁(1285) 	$0^{+}(1^{++})$	 f₂(1950) 	$0^{+}(2^{+})$	K. (1650)	1/2(1+)	
	_		 n(1295) 	$0^+(0^-+)$	pp(1990)	$1^{+}(3^{-})$	- K*(1690)	1/2(1-)	BOTTO
			• $\pi(1300)$	$1^{-}(0^{-}+1)$	• 6 010)	$0^+(2^++1)$		1/2(1)	(B =
			• 2-(1320)	1-(2++	6 0203	0±(0±±)	 K₂(1770) 	1/2(2-)	• B [±]
							$\gamma_{3}^{*}(1780)$	$1/2(3^{-})$	c
			• <i>f</i> ₀ (12 <i>f</i>)	0.(0.	• 2. 240)	1 (* 1)	• K ₂ (182	$1/2(2^{-})$	
		LIGHT	$h_1(1, 0)$?=(1 + -	• <i>t</i> ₄ 050)		K(183	$1/2(0^{-})$	• = (15)
			1 (7, 0)	$1^{-}(1^{-})$	π 2100)		K:(1977)	$1/2(0^{+})$	• <i>U</i> (<i>u</i>)(15)
			(Later)	0+(0 - +)	f _{0x=} 100)		K*(19801	1/2(2+)	• 5/0(15)
	 π[±] 	$1^{-}(0^{-})$	 f₁(1420) 	$0^{+}(1^{++})$	f ₂ (2150)	$0^{+}(2^{+})$	K2(2045)	1/2(4+)	• $\chi_{c0}(1P)$
		1=(0 - 1	 ω(1420) 	$0^{-(1)}$	o(2150)	1+(1)	• N ₄ (2045)	1/2(4 *)	• $\chi_{c1}(1P)$
		0+10-1	£(1430)	$0^+(2^++1)$	6(2200)	$0^{+}(0^{+}+1)$	$K_2(2250)$	1/2(2-)	$h_c(1P)$
	- 6 (600)	0+(0++	• 20(1450)	1-(0++)	6.(2220)	$0^{+}(2 \propto 4^{+})$	K ₃ (2320)	$1/2(3^+)$	• $\chi_{c2}(1P)$
	• /0(000)	0.0	• <i>s</i> ((1450)	1+(1)	-(2226)	0 (2 0 4 - +)	K [*] ₅ (2380)	$1/2(5^{-})$	 η_c(2S)
	 ρ(770) 	1 ' (1	 ρ(1450) (1450) 	$1^{(1)}$	$\eta(2225)$	0.(0)	K ₄ (2500)	$1/2(4^{-})$	 ψ(25)
	• ω(782)	0-(1	 η(1475) 	0 (0)	$\rho_3(2250)$	1+(3)	K(3100)	??(???)	• vb(3770)
	 η'(958) 	0+(0-+	• f ₀ (1500)	0+(0++)	 f₂(2300) 	$0^+(2^{++})$. (. /	• X(3872)
	 f₀(980) 	0+(0++	f ₁ (1510)	$0^{+}(1^{++})$	f ₄ (2300)	$0^{+}(4^{+})$	CHAR	MED	(3072)
	 a₀(980) 	$1^{-}(0^{++})$	 f'_2(1525) 	$0^{+}(2^{+})$	 f₂(2340) 	$0^{+}(2^{+})$	(C =	±1)	• $\chi_{c2}(2F)$
	 \$\phi(1020)\$ 	0-(1	f ₂ (1565)	$0^{+}(2^{++})$	$\rho_5(2350)$	$1^{+}(5^{})$	• D±	1/2(0=)	r (3940)
	 b (1170) 	0-(1+-	h (1595)	0-(1+-)	a ₄ (2450)	1-(6++)	- 00	1/2(0-)	 ψ(4040)
	h (1235)	1+(1+-	• T (1600)	1-(1-+)	£(2510)	$0^+(6^{++})$	D*/200730	1/2(0)	 ψ(4160)
	• 21(1255)	1-(1++	2 (1640)	1 - (1 + +)	(2010)	0 (0)	• D*(2007)*	1/2(1)	Y(4260)
D	• a1(1260)	1 (1 -	a1(1040)	1 (1 · ·)	OTHE	R LIGHT	 D[*](2010)[±] 	1/2(1-)	 ψ(4415)
	 f₂(1270) 	0 (2	f2(1640)	0 (2 · ·)	Eurther Stat	.ac	$D_0^*(2400)^0$	$1/2(0^+)$	
	 f₁(1285) 	$0^{+}(1^{+})$	 η₂(1645) 	$0^+(2^{-+})$	Further Stat	.05	$D_0^*(2400)^{\pm}$	$1/2(0^{+})$	
	 η(1295) 	$0^+(0^-)^+$	 ω(1650) 	$0^{-}(1^{-})$			 D₁(2420)⁰ 	$1/2(1^+)$	$n_{\rm b}(15)$
	 π(1300) 	$1^{-}(0^{-})$	 ω₃(1670) 	0-(3)			D1(2420)±	1/2(??)	7(15)
	 a₂(1320) 	$1^{-}(2^{++})$					D. (2430)0	1/2(1+)	• (15)
	 f₀(1370) 	0 + i 0 + +					D1(2450)	1/2(1)	• $\chi_{b0}(1P)$
	h (1380)	7-(1 + -					• D ₂ (2400)*	1/2(2)	• $\chi_{b1}(1P)$
	(1400)	1-(1-+					 D[*]₂(2460)[±] 	1/2(2+)	• $\chi_{b2}(1P)$
	• *1(1400)	a+(a - +					D*(2640) [±]	1/2(?*)	 <i>r</i>(25)
	 η(1405) 	0.(0							T(1D)
	 In(1420) 	0 . (1					CHARMED,	STRANGE	• $\chi_{b0}(2P)$
	 ω(1420) 	0-(1-					(C = 5	= ±1)	• Yh1(2P)
	f ₂ (1430)	0+(2++					• D_5	$0(0^{-})$	• Xtra(2P)
	 a₀(1450) 	$1^{-}(0^{++})$					• D ^{*±}	$0(?^{?})$	- 22(25)
	 <i>o</i>(1450) 	$1^{+}(1^{-})$					D* (2317)±	0(0+)	• 7(35)
	 n(1475) 	0 + i0 - +					D (24(0)+	0(0)	• 7 (45)
CA	 £(1500) 	0+(0++)					• D _{s1} (2460)*	0(1 ·)	 T(10860)
	6 (1510)	$a^{+}(1 + 1)$					 D_{\$1}(2536)[±] 	0(1 +)	 <i>\(\tau\)</i> (11020)
	/(1510)	0+(2++					 D₅₂(2573)[±] 	0(?')	NON
	• P ₂ (1525)	0 * (2 *							NON-qq
	$f_2(1565)$	0 * (2 *							
	$h_1(1595)$	$0^{-}(1^{+})$. (adjust die 1		-//	• v(4100)	0 11 11	
	 π₁(1600) 	$1^{-}(1^{-+})$	f ₆ (2510)	0+(6++)	 D*(2007)⁰ 	$1/2(1^{-})$	Y(4260)	7?(1)	_
	a ₁ (1640)	$1^{-}(1^{++})$	OTHER I	ICHT.	 D[*](2010)[±] 	$1/2(1^{-})$	• ++(4415)	0-(1)	
	f ₂ (1640)	$0^{+}(2^{++})$	OTHERL	IGHT	$D_{0}^{*}(2400)^{0}$	$1/2(0^+)$	• <i>\phi</i> (4425)		
	 η₂(1645) 	$0^{+}(2^{-+})$	Further States		D*(2400)±	1/2(0+)	hħ		
	 <i>w</i>(1650) 	0 - (1)			D (2400)	1/2(0)	4.0		
	• (m (1670)	0-(3)			 D1(2420)* D (2420)* 	1/2(1.)	$\eta_b(1S)$	0+(0-+)	
	- w3(=010)	~ (°)			$D_1(2420)^{\pm}$	1/2(?*)	 T(15) 	0-(1)	
					$D_1(2430)^0$	$1/2(1^+)$	• $\chi_{b0}(1P)$	$0^{+}(0^{+})$	
					 D[*]₂(2460)⁰ 	1/2(2+)	 χ_{b1}(1P) 	$0^{+}(1^{++})$	
					 D[*]₂(2460)[±] 	$1/2(2^+)$	• $\chi_{PO}(1P)$	$0^{+}(2^{+}+)$	
					D*(2640)±	$1/2(?^{?})$	• T(25)	0 - (1)	
					- (-,-(-)	2(10)	0-121	
		1							
				Г	CHARMED,	STRANGE	· (10)	0+(0++)	
				Γ	CHARMED, (C = S	STRANGE = ±1)	• χ _{b0} (2P)	$0^+(0^++)$	
L					CHARMED, (C = S D^{\pm}	STRANGE = ±1) 0(0)	• $\chi_{b0}(2P)$ • $\chi_{b1}(2P)$	$0^+(0^++)$ $0^+(1^++)$ $0^+(2^++)$	
				-	CHARMED, (C = S) • D_s^{\pm} • $D^{*\pm}$	$STRANGE = \pm 1$) 0(0)	• $\chi_{b0}(2P)$ • $\chi_{b1}(2P)$ • $\chi_{b2}(2P)$	$0^+(0^{++})$ $0^+(1^{++})$ $0^+(2^{++})$	
				-	CHARMED, (C = S) D_{S}^{\pm} D_{S}^{\pm}	STRANGE = ±1) 0(0) 0(? [?])	• $\chi_{b0}(2P)$ • $\chi_{b1}(2P)$ • $\chi_{b2}(2P)$ • $\Upsilon(3S)$	$0^+(0^++)$ $0^+(1^++)$ $0^+(2^++)$ $0^-(1^)$	1

D_{s1}(2460)[±]

D_{s1}(2536)[±]

D_{e2}(2573)[±]

 $0(1^+)$

0(1⁺) 0(?[?])

τ(10860)

 τ(11020)

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

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 qua	ntum number
	refers to:	quantities that are inh particles, which are coordinate or decays
	entomology:	historical to Bohr and
	example:	electric charge, baryo 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

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" - a conserved quantum number

the dominant Baryons

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



the dominant Mesons

Particle	Symbol	anti- particle	Rest Mass MeV/c ²	spin	Q	В	S	Lifetime
Pion	π^+	π^{-}	139.6	0	+1	0	0	2.6 x 10 ⁻⁸
Pi-zero	π^0	π^0	135	0	0	0	0	920
Kaon	K^+	K^{-}	493.7	0	+1	0	+1	1.24 x 10 ⁻⁸
K-short	K_S^0	K_S^0	497.7	0	0	0	+1	0.89 x 10 ⁻¹⁰
K-long	K_L^0	K_L^0	497.7	0	0	0	+1	5.2 x 10 ⁻⁸
Eta	η^0	η^0	548.8	0	0	0	0	< 10 ⁻¹⁸
Eta-prime	η^0 ′	η^0 ′	958	1	0	0	0	
Rho	ρ^+	$ ho^-$	770	1	+1	0	0	0.4 x 10 ²³
Rho-naught	$ ho^0$	$ ho^0$	770	1	0	0	0	0.4 x 10 ²³
Omega	ω^0	ω^0	782	1	0	0	0	0.8 x 10 ²²
Phi	ϕ	ϕ	1020	1	0	0	0	20 x 10 ⁻²³





anyhow...back to the Zoo problem

all those particles.

There were some hints

patterns emerged

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



p n N(1440) N(1520) N(1535) N(1650) N(1675) N(1680) N(1700) N(1710) N(1720) N(1710) N(1720) N(1720) N(1720) N(1900) N(2000) N(2000) N(2000) N(2100) N(2200) N(2200) N(2200) N(2200) N(2200) N(2200) N(2200) N(2700)	$\begin{array}{c} P_{11} \\ P_{11} \\ P_{11} \\ P_{11} \\ D_{13} \\ S_{11} \\ D_{15} \\ F_{15} \\ D_{13} \\ P_{13} \\ P_{13} \\ P_{13} \\ P_{13} \\ P_{13} \\ P_{13} \\ P_{11} \\ P_{13} \\ P_{11} \\ P_{13} \\ P_{11} \\ P_{11} \\ G_{17} \\ D_{15} \\ H_{19} \\ G_{19} \\ h_{,11} \\ K_{1,13} \end{array}$	$\begin{array}{c} \varDelta(1232)\\ \varDelta(1600)\\ \varDelta(1620)\\ \varDelta(1700)\\ \varDelta(1750)\\ \varDelta(1900)\\ \varDelta(1905)\\ \varDelta(1905)\\ \varDelta(1910)\\ \varDelta(1920)\\ \varDelta(1920)\\ \varDelta(1930)\\ \varDelta(1950)\\ \varDelta(1940)\\ \varDelta(1950)\\ \varDelta(2000)\\ \varDelta(2150)\\ \varDelta(2200)\\ \varDelta(2350)\\ \varDelta(2350)\\ \varDelta(2350)\\ \varDelta(2420)\\ \varDelta(2420)\\ \varDelta(2750)\\ \varDelta(2950)\\ \end{array}$	$\begin{array}{c} P_{33} \\ P_{33} \\ S_{31} \\ P_{31} \\ S_{31} \\ P_{33} \\ D_{35} \\ P_{33} \\ D_{35} \\ S_{31} \\ G_{37} \\ H_{39} \\ D_{35} \\ F_{37} \\ G_{39} \\ H_{3,113} \\ K_{3,15} \end{array}$	····· ···· ···· ···· ··· ··· ··· ··· ·	A A(1405) A(1520) A(1600) A(1670) A(1690) 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)	$\begin{array}{c} P_{01} \\ S_{01} \\ P_{01} \\ S_{01} \\ P_{01} \\ P_{01} \\ P_{03} \\ S_{01} \\ P_{03} \\ P_{03} \\ P_{03} \\ F_{07} \\ F_{05} \\ D_{03} \\ H_{09} \end{array}$		$\begin{array}{c} \Sigma^+ \\ \Sigma^0 \\ \Sigma^- \\ \Sigma(138) \\ \Sigma(166) \\ \Sigma(156) \\ \Sigma(166) \\ \Sigma(167) \\ \Sigma(167) \\ \Sigma(167) \\ \Sigma(177) \\ \Sigma(177) \\ \Sigma(177) \\ \Sigma(177) \\ \Sigma(184) \\ \Sigma(191) \\ \Sigma(191) \\ \Sigma(203) \\ \Sigma(203$	$\begin{array}{c} P_{11} \\ P_{11} \\ P_{11} \\ P_{11} \\ P_{13} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ $		$\begin{array}{c} \overline{z}^{0} \\ \overline{z}^{-} \\ \overline{z}(1530) \\ \overline{z}(1620) \\ \overline{z}(1690) \\ \overline{z}(1820) \\ \overline{z}(1950) \\ \overline{z}(2230) \\ \overline{z}(2250) \\ \overline{z}(2250) \\ \overline{z}(2250) \\ \overline{z}(2370) \\ \overline{z}(2250)^{-} \\ \Omega(2250)^{-} \\ \Omega(2250)^{-} \\ \Omega(2470)^{-} \\ \Omega(2470)^{-} \\ \Lambda_{c}^{c}(2593)^{+} \\ \Lambda_{c}(2625)^{+} \\ \Lambda_{c}(2625)^{+} \\ \Lambda_{c}(2625)^{+} \\ \Lambda_{c}(2625)^{+} \\ \Lambda_{c}(2800)^{+} \\ \overline{z}_{c}(2520) \\ \overline{z}_{c}(2500) \\ $	P ₁₁ P ₁₁ P ₁₃ D ₁₃				
							LIGH		AVORED			(5	STRAN	NGE = 8 = 0)	BO	TTOM
							1 ^G (J ^{PC})	<i>y</i> = 0)		$I^G(J^{PC})$	(5	- ±1, с	$I(J^{P})$	(5	$I^{G}(J^{PC})$
					• π [±]		1-(0-	-)	 π₂(1670) 		$1^{-}(2^{-+})$	• K±		1/2(0-)	• B [±]	1/2(0-)
					• π ⁵ • n		0+(0-	-+1	 φ(1680) φ(1690) 		$\binom{1}{1+(3)}$	• K ⁰		$1/2(0^{-})$ $1/2(0^{-})$	• B* • B±/B ⁰ ADM	I/2(0)
					 f₀(600) 		0+(0+	++j i	 ρ(1700) 		1+(1)	• K ⁰ _L		1/2(0-)	 B[±]/B⁰/B⁰_s 	b-baryon AD-
					 ρ(770) 		1+(1-)	$a_2(1700)$		$1^{-}(2^{++})$	K ₀ (80	0)	$1/2(0^+)$	MIXTURE V and V	CKM Matrix
		 -		1.1	 ω(782) ω'(958) 		0-(1-)	• $f_0(1710)$ = (1760)		$0^+(0^++)$ $0^+(0^-+)$	 K*(89) 	2)	$1/2(1^{-})$	Elements	Crow machine
					 f₀(980) 		0+(0+	++)	• $\pi(1800)$		$1^{-}(0^{-}+)$	 K₁(12) K₁(14) 	70) 30)	$\frac{1}{2(1^+)}$ $\frac{1}{2(1^+)}$	• B* B*(5732)	$\frac{1}{2(1^{-})}$
					 a₀(980) 		1-(0-	+ +ĵ	f ₂ (1810)		$0^+(2^+)$	• K*(14	10)	$1/2(1^{-})$	B J(5132)	:(:)
					 φ(1020) 		0-(1)	X(1835)		??(?-+)	 K[*]₀(14) 	30)	$1/2(0^+)$	BOTTON	1, STRANGE
					 h₁(1170) h₁(1235) 		$0^{-}(1^{-})$	+-)	 φ₃(1850) φ₃(1870) 		$0^{-(3)}_{0^{+(2-+)}}$	 K[*]₂(14) 	30)	$1/2(2^+)$	(<i>D</i> − ±	0(0-)
					 <i>b</i>₁(1255) <i>a</i>₁(1260) 		1-(1-	++	$\eta_2(1870)$ $\rho(1900)$		$1^{+}(1^{-}-)$	K(146	0) 20)	1/2(0-)	• <i>B</i> ^s	0(1-)
					 f₂(1270) 		0+(2+	+ +ý 📔	f2(1910)		0+(2++)	K(163	0)	$1/2(2^{\circ})$ $1/2(?^{\circ})$	B* (5850)	?(??)
					 f₁(1285) 		0+(1-	++)	 f₂(1950) 		$0^{+}(2^{++})$	K1(16	50)	1/2(1+)	BOTTOM	CHARMED
					 η(1295) (1200) 		0+(0-	-+)	$\rho_3(1990)$		$1^+(3^{})$	 K*(16) 	80)	$1/2(1^{-})$	(B =	$C = \pm 1$
					 π(1300) a₂(1320) 		1 (0	++	 f₂(2010) f_b(2020) 		$0^{+}(2^{+})$	 K₂(17) 	70) 90)	$1/2(2^{-})$	• B [±] _c	0(0-)
					 f₀(1370) 		0+(0+	++j •	 a₄(2040) 		1-(4++)	 K₃(17) K₂(18) 	20)	$1/2(3^{-})$ $1/2(2^{-})$		c7
					$h_1(1380)$?-(1	+-)	 f₄(2050) 		0+(4 + +)	K(183	0)	1/2(0-)	• n-(15)	0+10-+
					• $\pi_1(1400)$ • $\pi(1405)$		1-(1-	-+)	$\pi_2(2100)$ 6(2100)		$1^{-}(2^{-+})$ $0^{+}(0^{++})$	$K_{0}^{*}(19)$	50)	1/2(0+)	 J/ψ(15) 	0-(1
					 f₁(1403) f₁(1420) 		0+(1+	++j	f2(2100)		$0^{+}(2^{+})$	$K_{2}^{*}(19)$	80) 45)	$1/2(2^+)$ $1/2(4^+)$	 χ_{c0}(1P) 	0+(0++
					 ω(1420) 		0-(1)	p(2150)		1+(1)	• K ₄ (20 K ₂ (22)	40) 50)	$1/2(4^{-1})$ $1/2(2^{-1})$	• $\chi_{c1}(1P)$ h _c (1P)	2 [?] (2 [?])
					f2(1430)		$0^+(2^-)$	++)	$f_0(2200)$	0+1	$0^+(0^{++})$	K3(23)	20)	1/2(3+)	 χ_{c2}(1P) 	0+(2++
					 a₀(1450) a(1450) 		1+(1-		n(2225)	0.1	$0^+(0^{-+})$	K ₅ (23	80)	1/2(5-)	 η_c(2S) 	0+(0-+
					 η(1475) 		0+(0-	- +ĵ	ρ ₃ (2250)		1+(3)	K(310	00)	$\frac{1}{2(4^{-})}$	 ψ(25) ψ(2770) 	0-(1
					 f₀(1500) 		0+(0-	++)	 f₂(2300) 		0+(2++)	N(310	0)	r(r.)	• $\psi(3770)$ • X(3872)	$0^{?}(7^{?+})$
					f ₁ (1510)		$0^+(1^-)$	++) .	$f_4(2300)$		$0^+(4^{++})$ $0^+(2^{++})$		CHARN	AED	 χ_{c2}(2P) 	0+(2++
					fs(1565)		0+(2+	++1	ρ ₅ (2350)		1+(5)	• D±	(c = 1	1/2(0-)	Y(3940)	??(???)
					h1(1595)		0-(1-	+-)	a ₆ (2450)		1-(6++)	 D⁰ 		1/2(0-)	 ψ(4040) ψ(4160) 	0-(1
					 π₁(1600) 		1-(1-	-+)	f ₆ (2510)		0+(6++)	• D*(20	07) ⁰	$1/2(1^{-})$	Y(4260)	??(1)
					$a_1(1640)$ $f_2(1640)$		$1^{-}(1^{-})$	++;[OT	HER LIG	НТ	 D*(20) 	10) [±]	$1/2(1^{-})$	 ψ(4415) 	0-(1
					 η₂(1645) 		0+(2-	- +í [Further S	tates		D*(24	00)* 00)±	$1/2(0^+)$ $1/2(0^+)$		hħ
					 ω(1650) 		0-(1-	í				• D ₁ (24)	20) ⁰	$1/2(0^{+})$ $1/2(1^{+})$	n+(15)	0+(0-+
					 ω₃(1670))	0-(3-)				D1(24)	20)±	1/2(??)	• T(15)	0-(1
												$D_1(24)$	30) ⁰	$1/2(1^+)$	 χ_{b0}(1P) 	0+(0++
												 D[*]₂(24) D[*]₂(24) 	60) ⁰	$1/2(2^+)$	 χ_{b1}(1P) 	0+(1++
												 D₂(24) D[*](26) 	40)±	$1/2(2^{+})$ $1/2(2^{?})$	• $\chi_{b2}(1P)$ • $\chi_{c2}(2S)$	$0^{+}(2^{+})^{+}$
												D (20	-0)	*/2(÷)	T(1D)	0-(2
												CHA	RMED, S	STRANGE	(2P)	0+(0++



5 e d Ne'eman in 1964

family arrangements





quarks

the mathematical description of such patterns

1964



Murray Gell-Mann

1929 -

theoretician

Nobel Laureate 1969

genius...ask him

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

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

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

Worries a lot now about the nature of physical law.

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

Not known for his humility.

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

Gell-Mann found that the patterns work

if every particle is composed of smaller bits



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

with fractional electric charge:

charge of up quark: charge of down quark: charge of strange quark:

"Quarks"

FINNEGANS WAKE BY JAMES JOYCE ER AND

+2/3 e -1/3 e -1/3 e

fundamental particles, circa...now

quarks and leptons

hadrons are composite: made of quarks

electrons and cousins are fundamental on their own

quarks on their own

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

Quarks

- 1964 version
- fundamental fermions

in same league as electrons and neutrinos



Quark	Symbol	Rest Mass MeV/c ²	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 ²	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 ²	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 ²	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 ²	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 Λ^0 Λ + 0 D -1 $\sum *0$ **Ξ***0 -2 $\mathbf{T}\mathbf{0}$ -3 $-\frac{1}{2}$ <u>1</u> 2 <u>1</u> 2 3 <u>1</u> 2 0 -1 1 -1 1 0 Ι



most famous bubble chamber picture in history, 1964



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

particle:	Omega minus					
	symbol:	Ω^{-}				
	charge:	-1				
	mass:	1672.45 MeV/c ²				
	spin:	3/2				
	category:	Fermion, baryon,				

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

the dominant Baryons

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

quark content	
uud	
ddu	
uds	
uus	
uds	
dds	
иии	
uud	
udd	
ddd	
uss	
dss	
888	

mesons

Quark	Symbol	Rest Mass MeV/c ²	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

a little different

	Particle	Symbol	anti- particle	Rest Mass MeV/c ²	spin	Q	В	S
The pion:	Pion	π^+	π^{-}	139.6	0	+1	0	0

$$\pi^{+} = \begin{pmatrix} u & \& & \bar{d} \\ 0 & +1 & +2/3 & +-(-1) \\ 0 & 1/3 & +-(1/3) \\ 0 & 0 & 0 \end{pmatrix}$$

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


a similar thing happens for the mesons



meson quark content





the dominant Mesons

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

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

 Δ^+ $u \uparrow u \uparrow d \uparrow$ 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 books that we carry

"I laughed, I cried"



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:











how about a strong interaction decay?

a little nonintuitive. $\Delta^0 \to \pi^- + p$

the old way:



the quark way:



3 quarks

some quark-creation required!



stay tuned.