hi

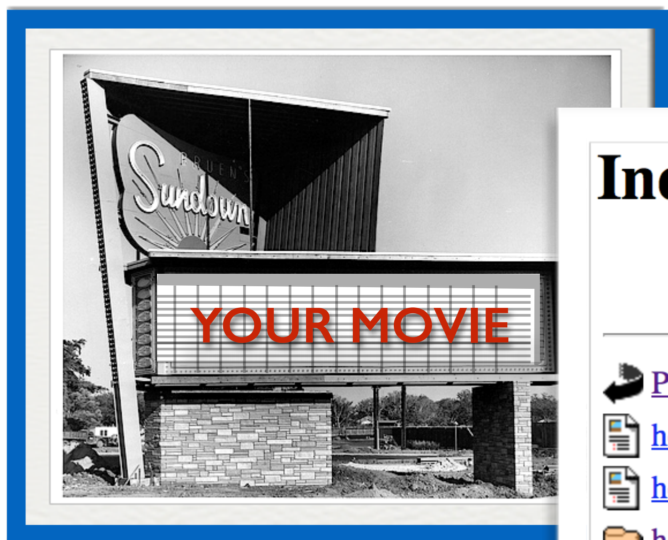
Lecture 28, 04.20.2017

Particle Physics 3

housekeeping

Question about anything?

I'll make a movie for you:



Poster selection:

outline due April 20...read the instructions.

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

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

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

Final:

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

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

Homework:

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

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

posters:

Here's the workflow:

By 5pm April 13, enter into the Wiki page in the appropriate place, you and your partner's names and the experiment you're reviewing. Each must be different, and so get there early before the good ones are gone. (They're all good.) (You can do it earlier!)

By 5pm April 20, complete your outline of the project. Post its top level items in a Facebook post to the QS&BB Group. (You can do it earlier!)

By 5pm May 1, project is done, mounted, and ready to present. I'll provide storage if you would like prior to Final Exam day.

Instructions are pretty clear:

Those who signed up for Parity Violation, Helium, & Cyclotron at the end of the wiki reservation list were too late:

Ojubanire, Cooper, Richards, These, Ballnik, McPeak, Eveland, and Davis

here's what we have:

1 The Discovery of the Bottom Quark at Fermilab OK

2 The Discovery of the Neutron by Chadwick OK

3 The Discovery of the Neutrino by Reines and Cowan OK

4 The Discovery of Cosmic Rays by Hess OK

5 The R ratio and the Color Quantum Number at SLAC still open

6 The Discovery of the Omega Minus at Brookhaven **OK**

7 The Discovery of Neutrino Oscillations in in South Dakota and Japan OK

8 The First Observation of a Black Hole in Cygnus X OK

9 The Discovery of Neutrinos from Supernova 1987a from IMB and Kamiokande OK

10 The Search for Proton Decay at IMB and Super-Kamiokande OK

11 The Discovery of the Longest Redshift Object, GRB090423 OK

12 The Invention of the Cyclotron by Lawrence OK

13 The Discovery of the Top Quark at Fermilab OK

14 The Discovery of Weak Neutral Currents at CERN OK

15 The Discovery of the Z Boson at CERN OK

16 The Discovery of Partons by the SLAC-MIT Experiment at SLAC OK

17 The Discovery of Parity Violation by Madame Chien-Shiung Wu at Columbia OK

18 The Discovery of Helium OK

now hear this

To: RAYMOND L BROCK

From: sirs@msu.edu

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

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

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

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

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

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

also:

I'll have an optional anonymous course review with points

Honors Project

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

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

Read the Second of two sets of instructions:

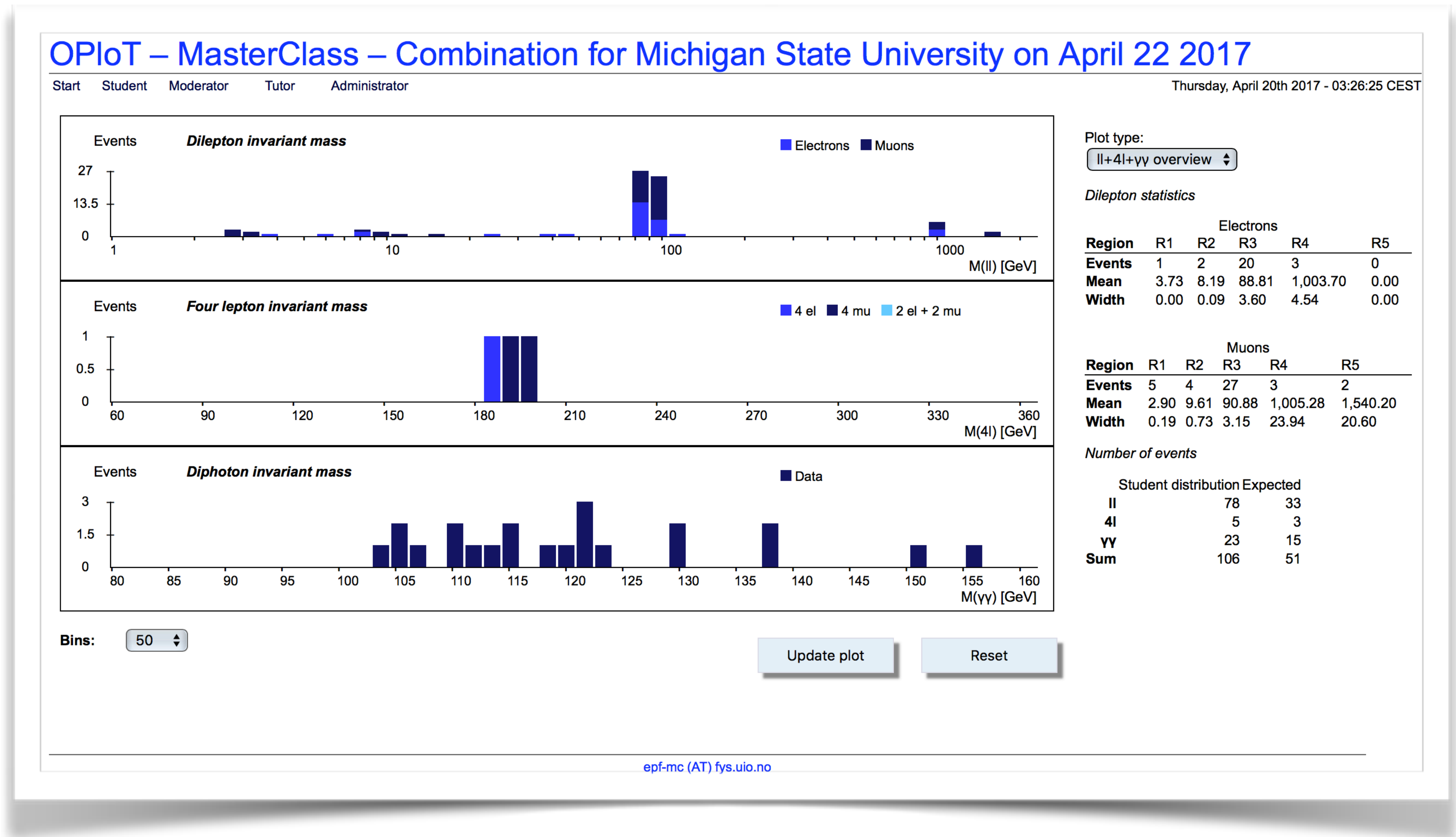
`MinervaInstructions2_2017.pdf` in

<u>`www.pa.msu.edu/~brock/file_sharing/QSandBB/2017homework/honors_project_2017/`</u>

I had a 

Ms Faustino got it to work fine.

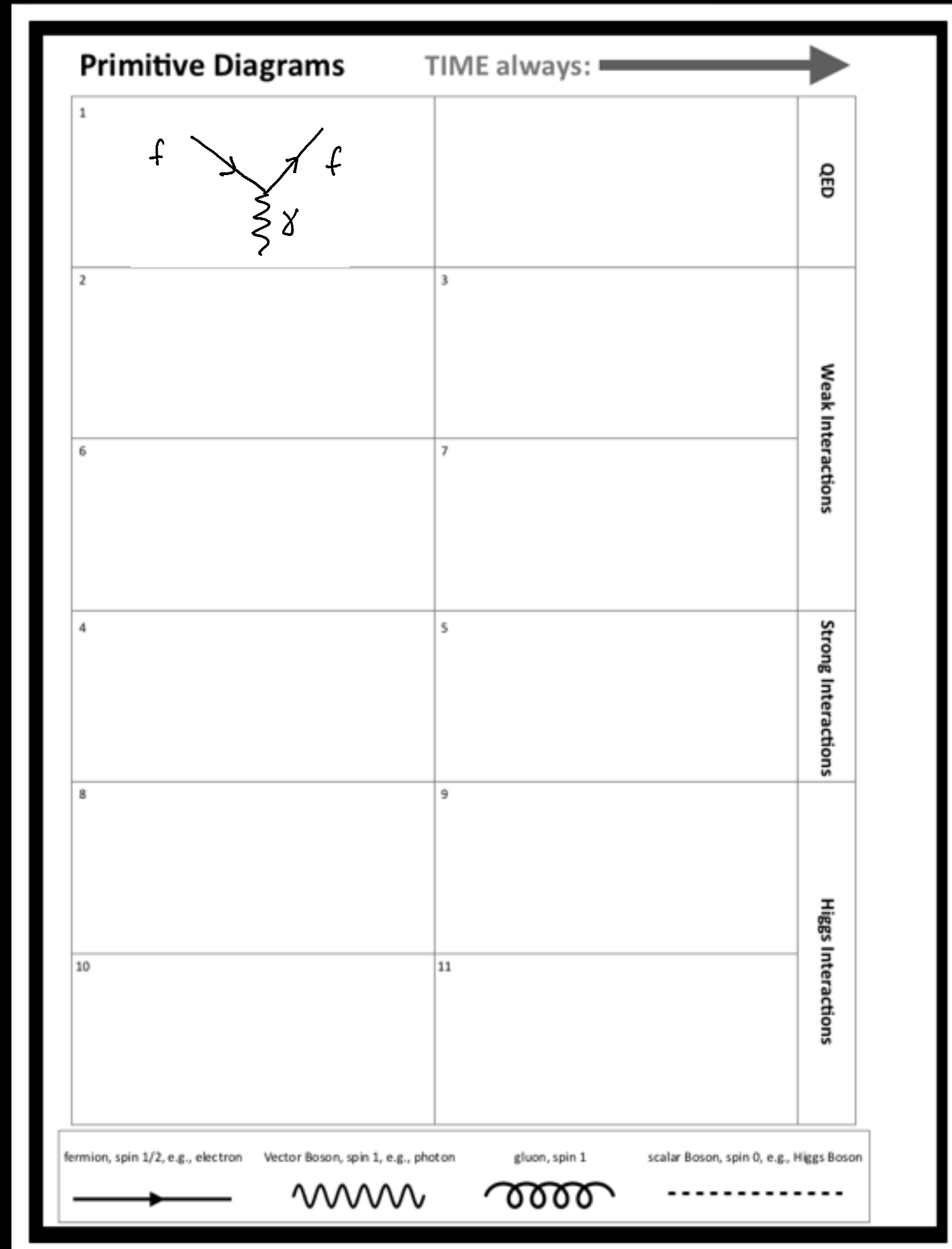
Thanks!



http://www.pa.msu.edu/~brock/file_sharing/QSandBB/2017homework/honors_project_2017/UploadInstructions

Primitive Diagram Scorecard

your first entry



particle physics

important realizations

weak force: neutrinos

exchange force

nuclear force

beta decay

the "weak force"

Fermi Theory of Beta Decay

uses the Dirac ideas of quantum electrodynamics

particle creation and annihilation

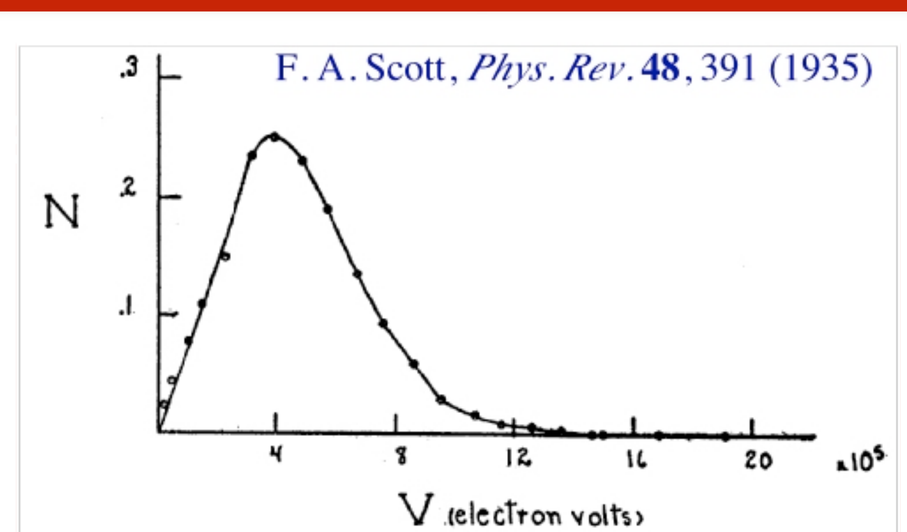
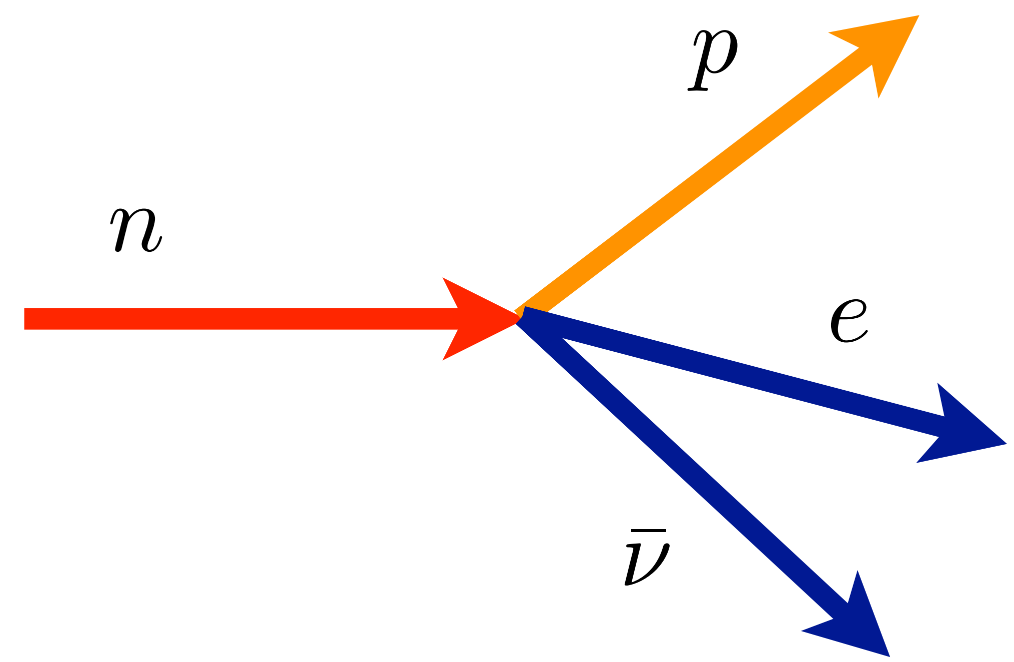


FIG. 5. Energy distribution curve of the beta-rays.

$m_{neutron} > m_{proton}$

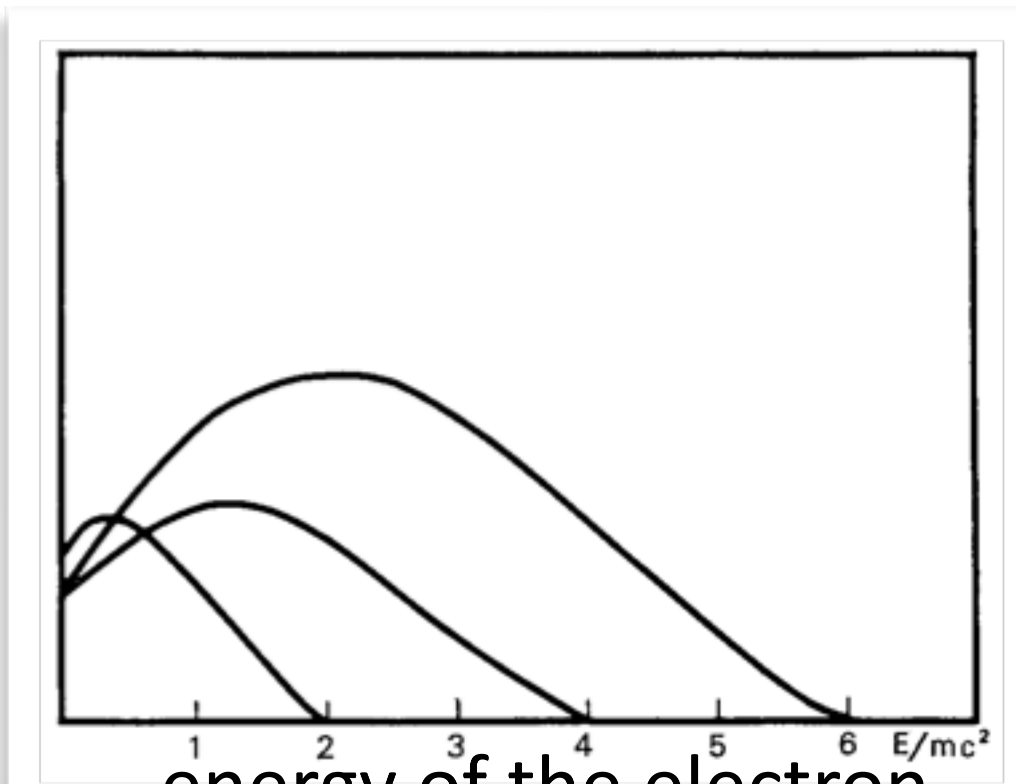
a smidgen.



a free neutron has a lifetime of about 11 minutes.

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

"it contained speculations which were too remote from reality"



from his original paper for different nuclear species parameters

exchange force

the modern view:

if there’s a force…there’s a field

if there’s a field…there’s a particle

we know one force

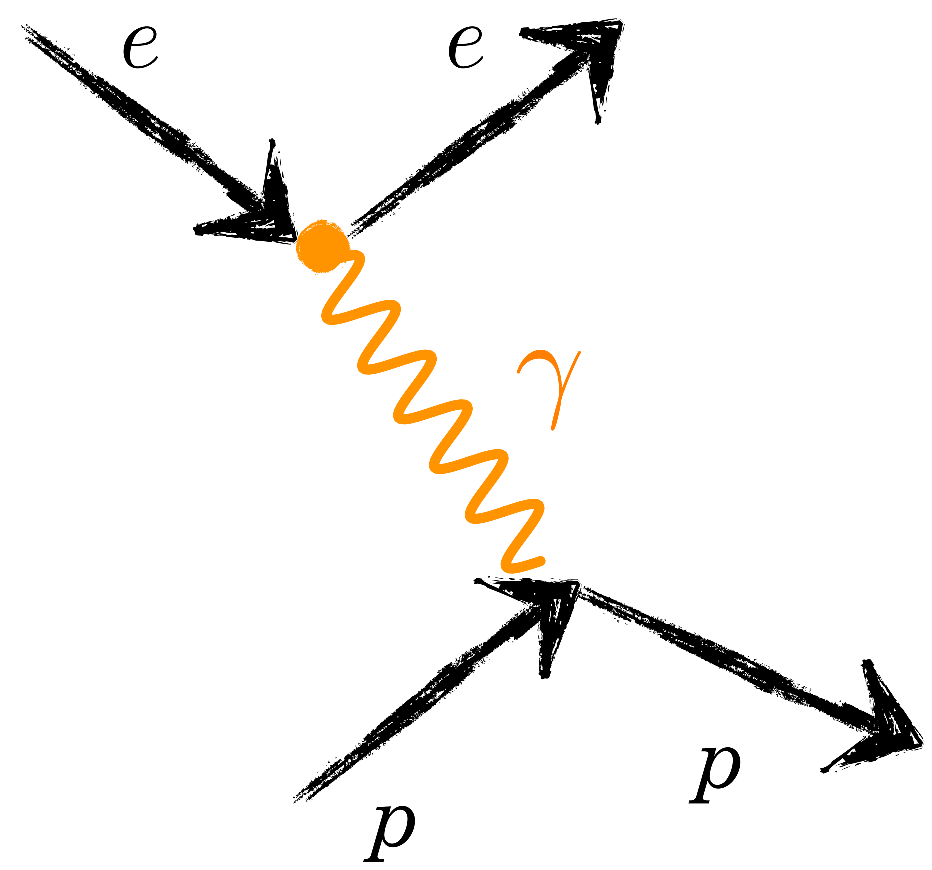
electromagnetism

electricity

magnetism

united by Relativity

remember?



The modern idea:

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

Multiple names: "propogator"
"Intermediate Vector Boson"

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

charge independence

Heisenberg's original idea was before the neutron

his protons playing catch with electrons?

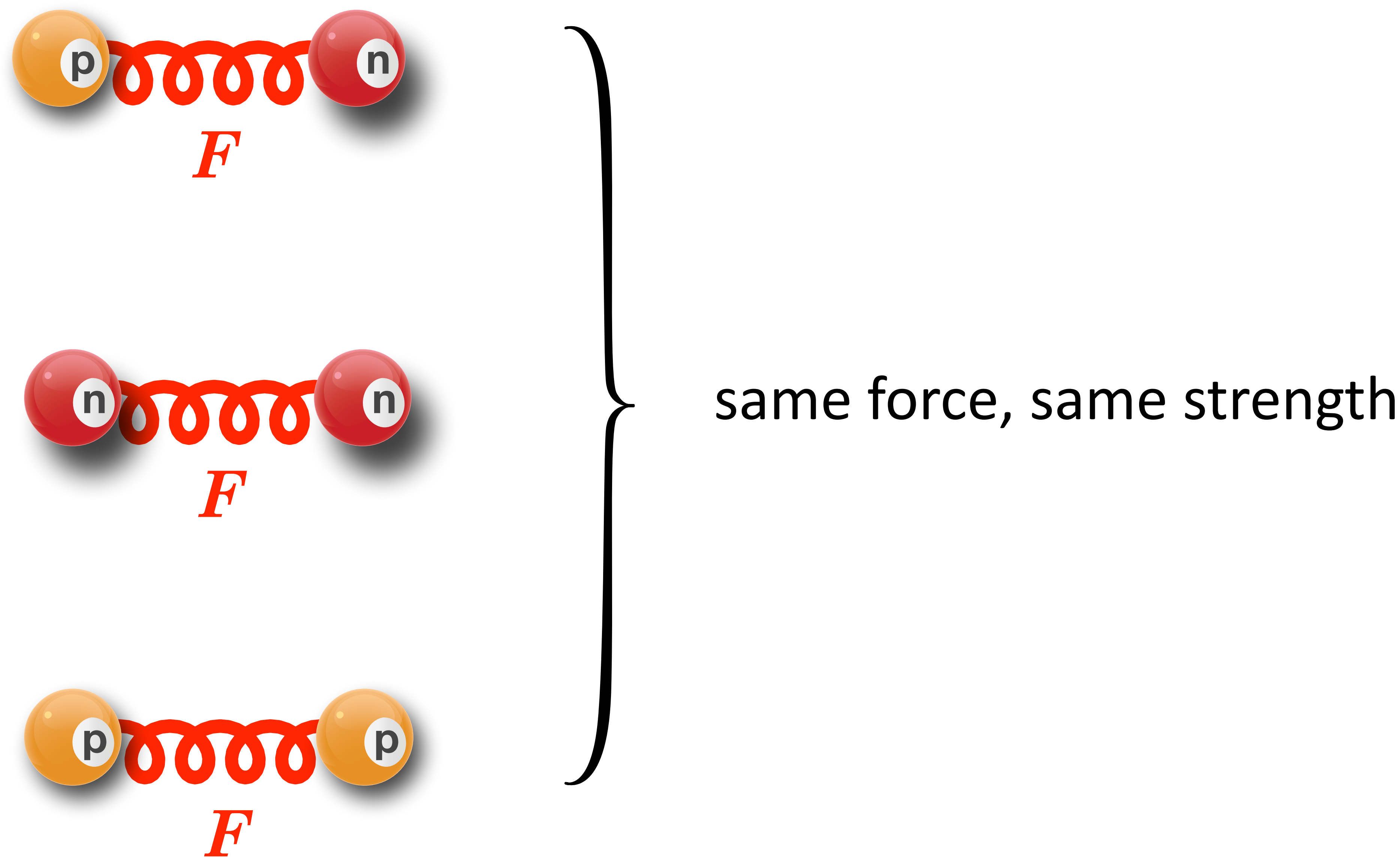
nope.

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**."

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

neutrons and protons

act like they are identical particles

the electric charge?

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

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

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

"nucleon"

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

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

How?

jargon alert: **nucleon**

refers to: either a proton or a neutron

entomology: from “nucleus”...the “-on” tends to be a particle name

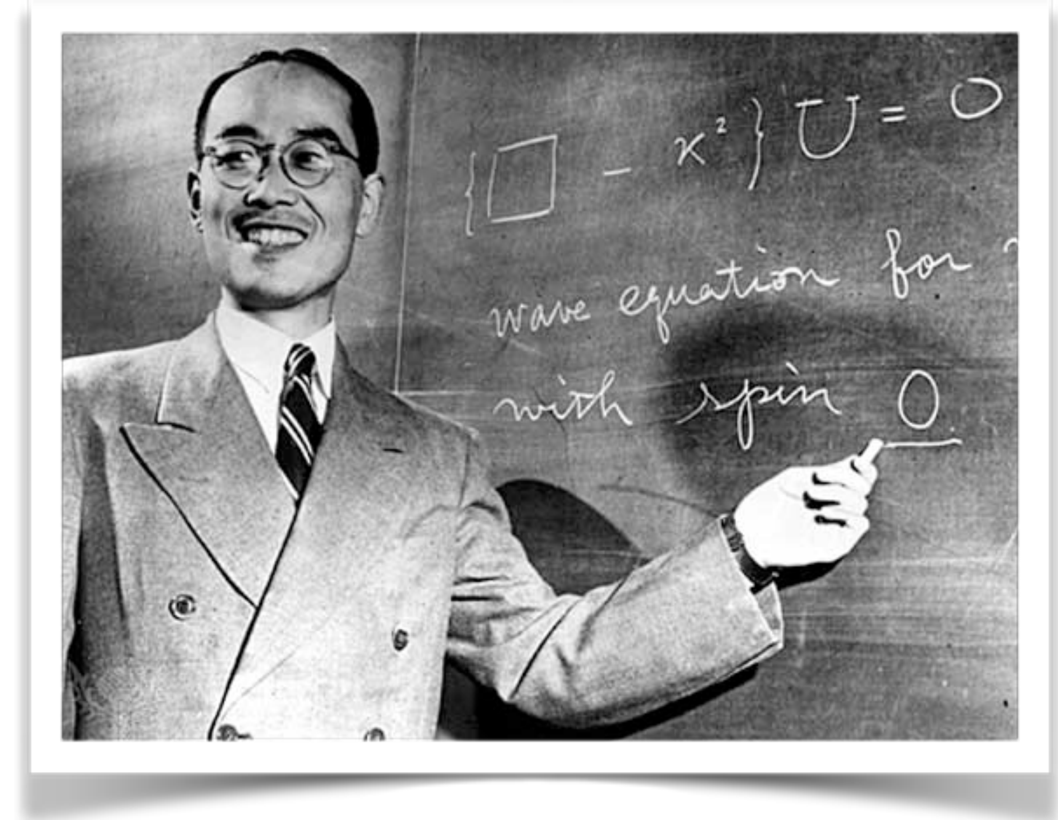
example: “nucleon force”

jargon alert: **hadron**

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

Yukawa Particle

So: $p \rightarrow n + U$?



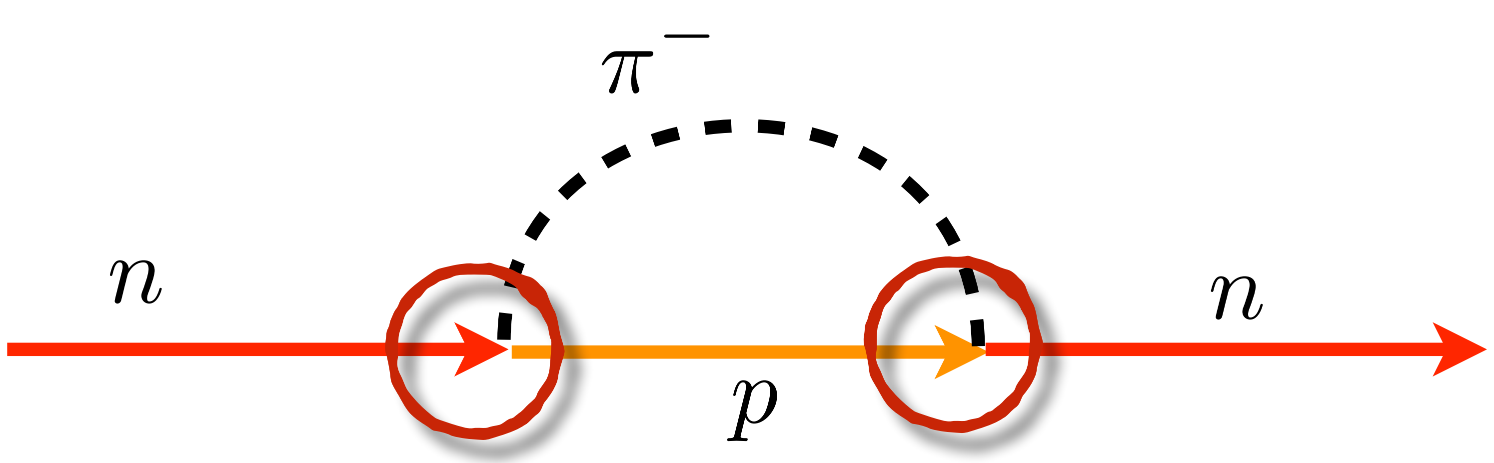
$$m_U \stackrel{?}{=} 195 \times 10^6 \text{eV} = 195 \text{ MeV}/c^2$$

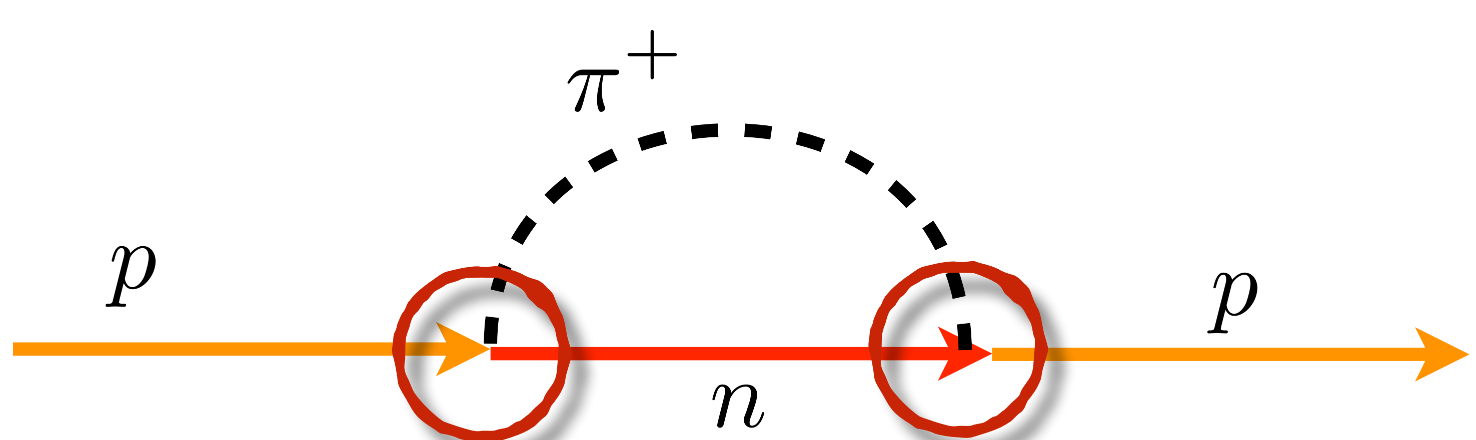
"pion": $m_\pi = 139 \text{ MeV}/c^2$

brilliant observation by Yukawa

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

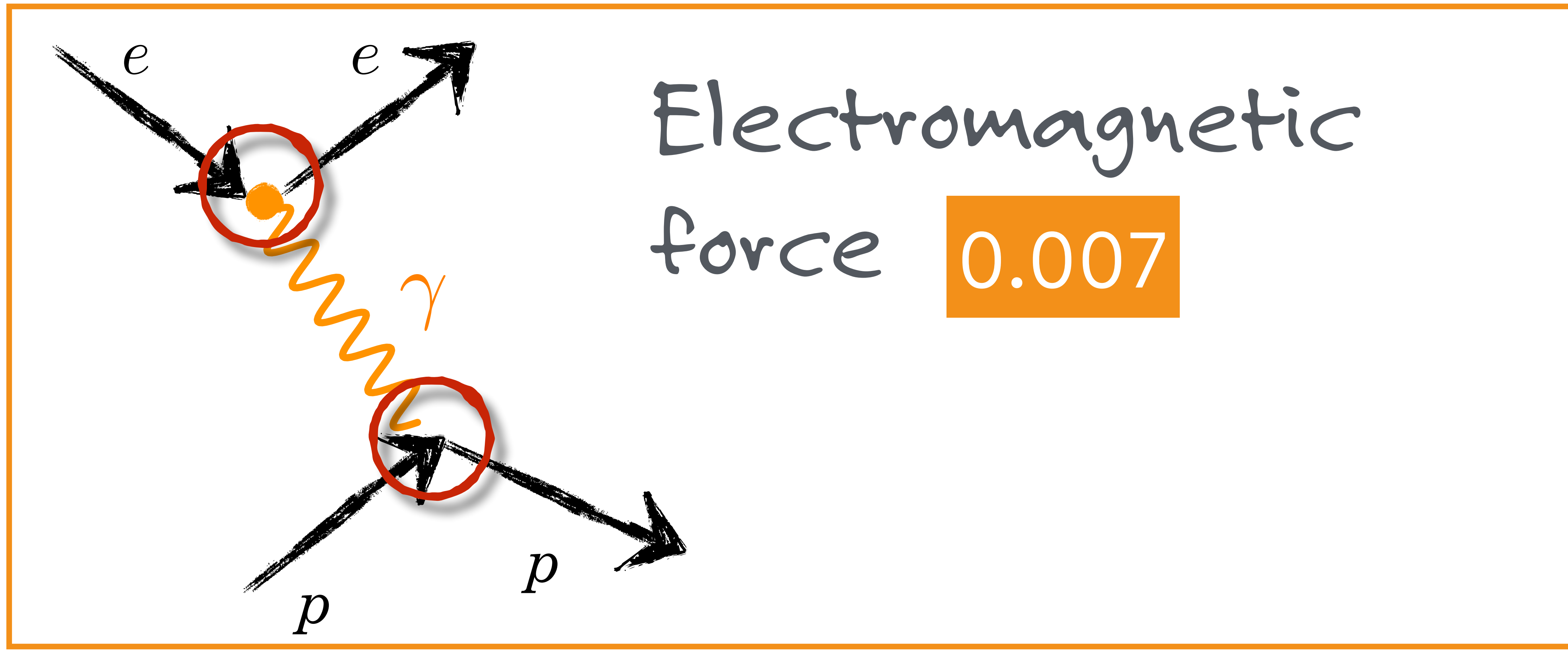
another exchange force/particle?

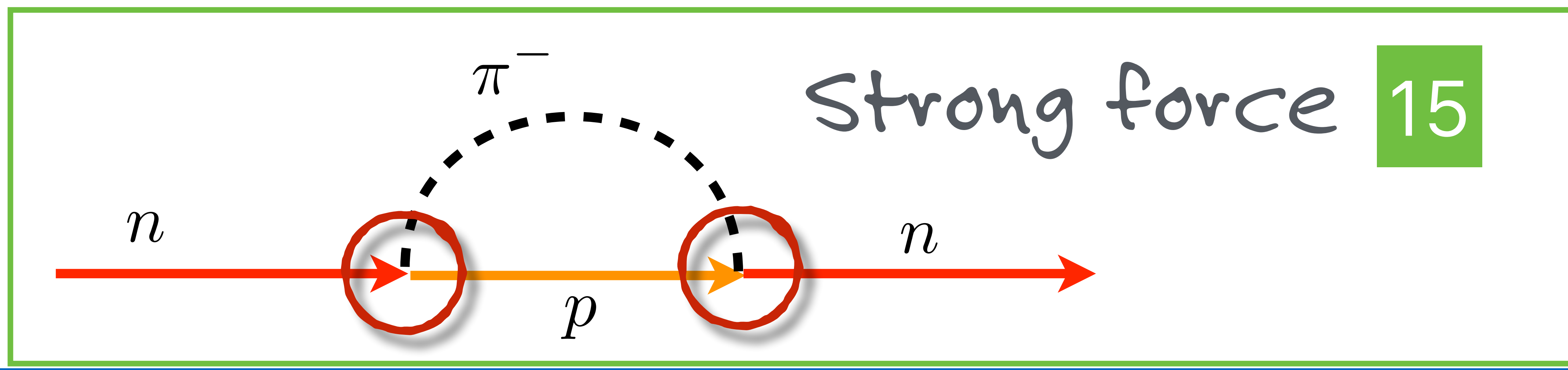


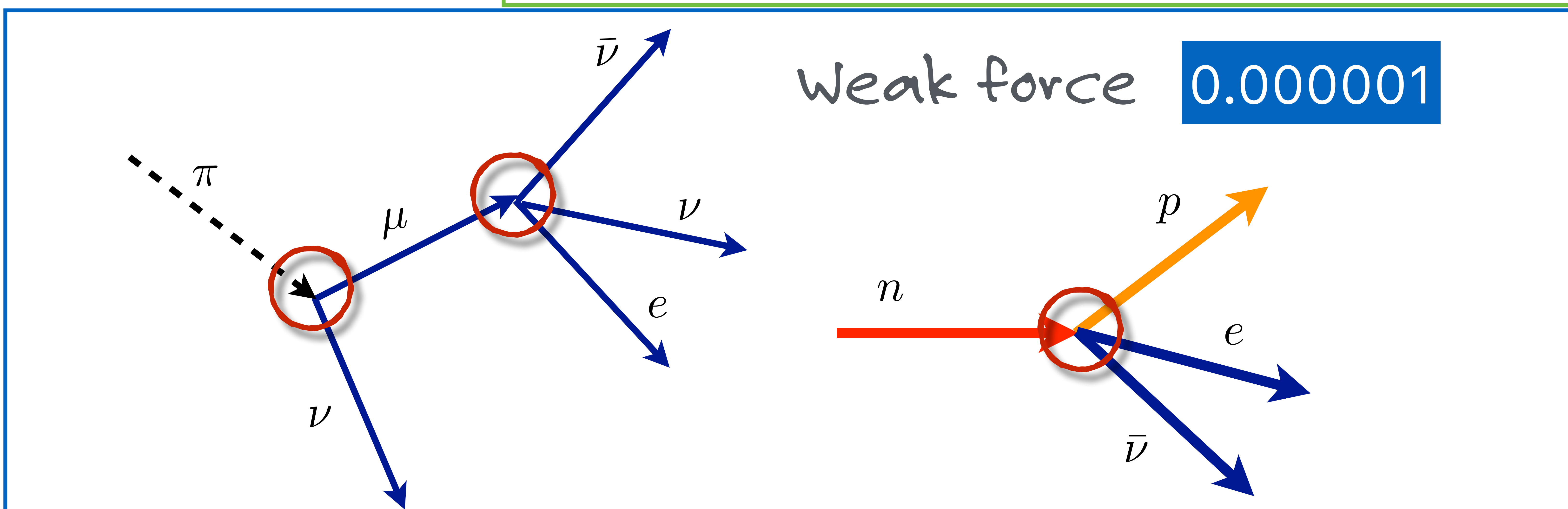


three forces now

of vastly different strengths

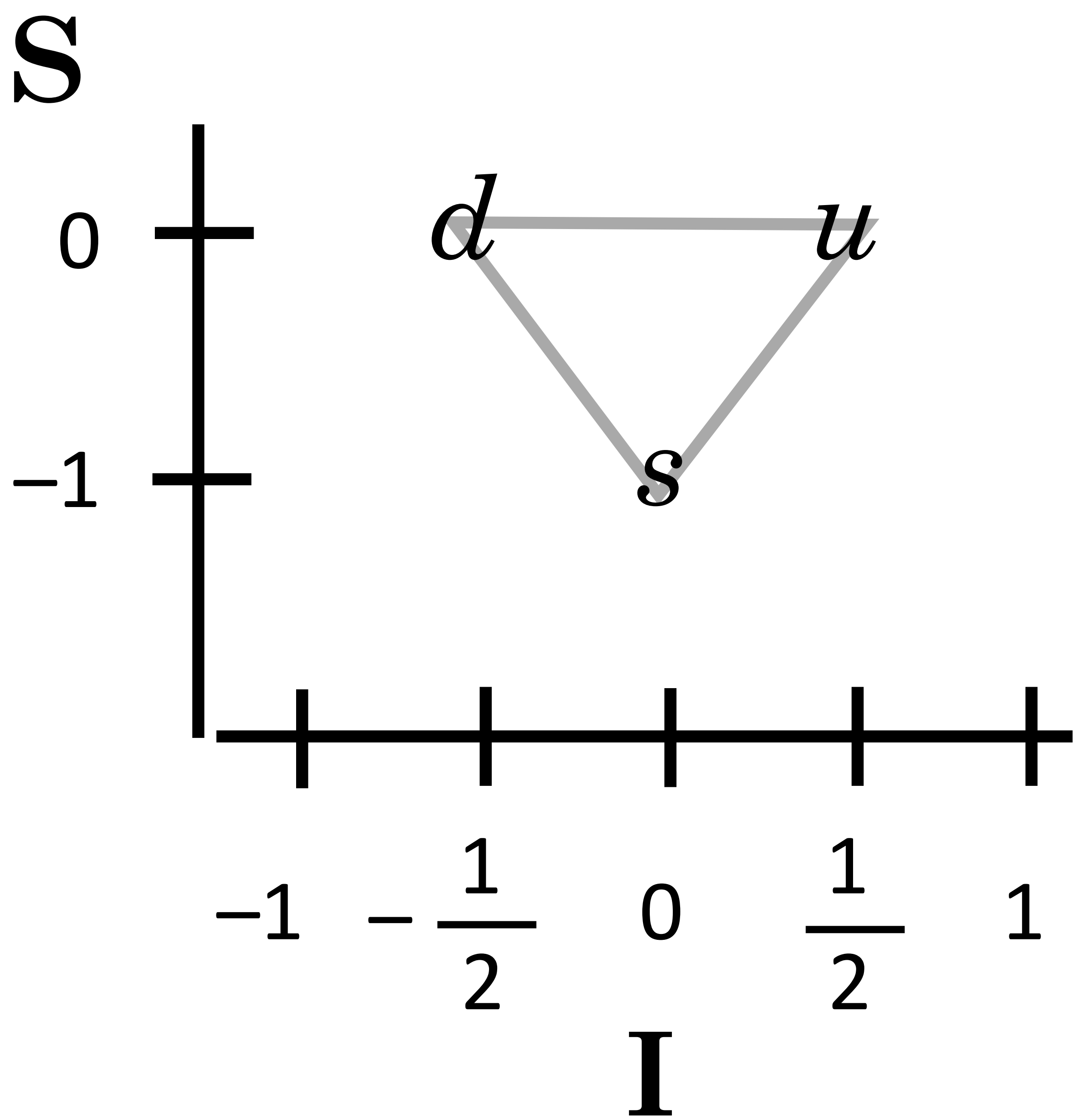






"quarks"

designed as a mental model...to account for the plethora of particles found in accelerators



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

"baryons" (like proton and neutron): 3 quarks..."qqq"

"mesons" (like pion) : 1 quark+1 antiquark..."$q\bar{q}$"

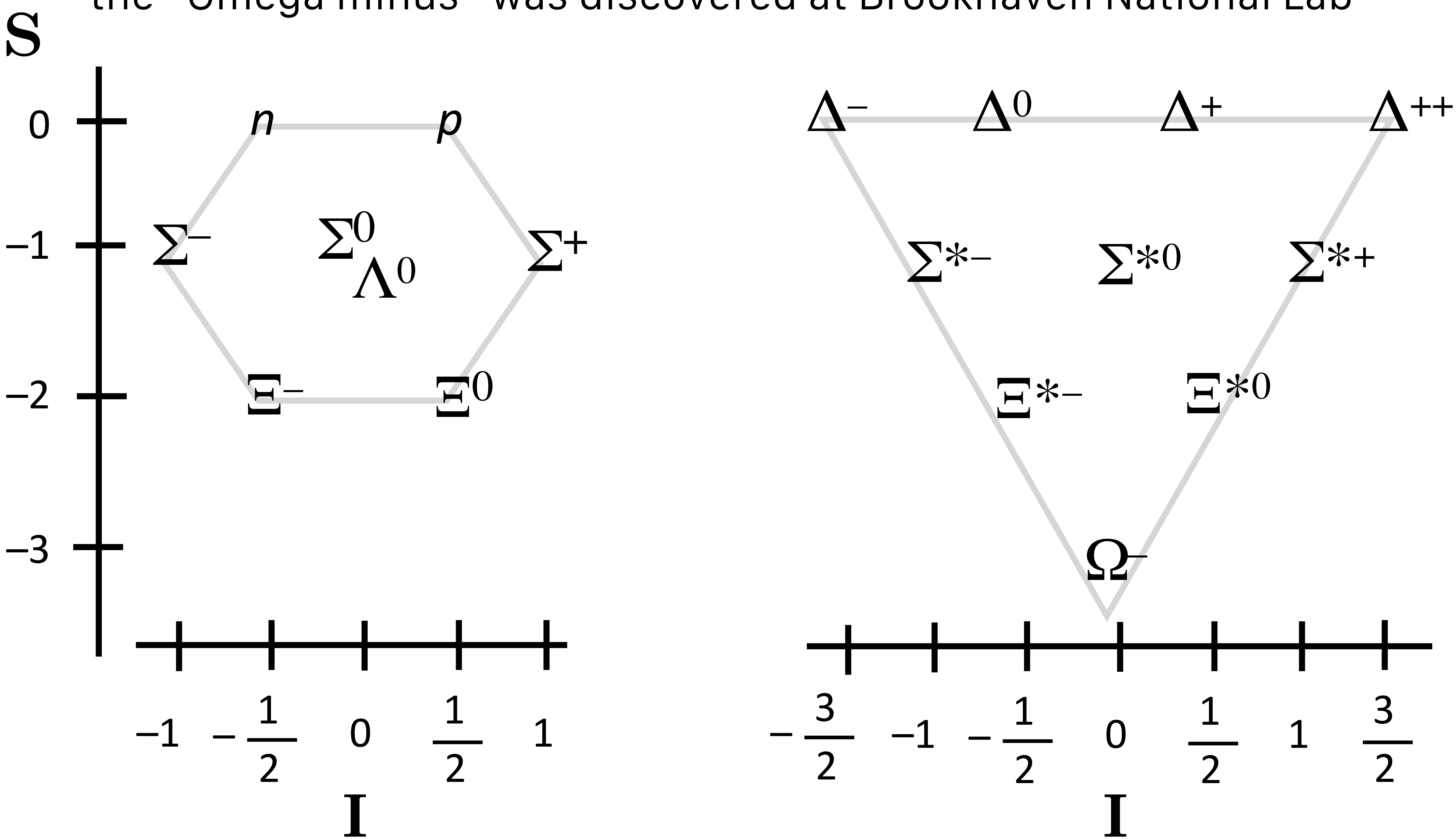
"leptons" (like electron and muon): no quarks! on par with quarks

the dominant Baryons

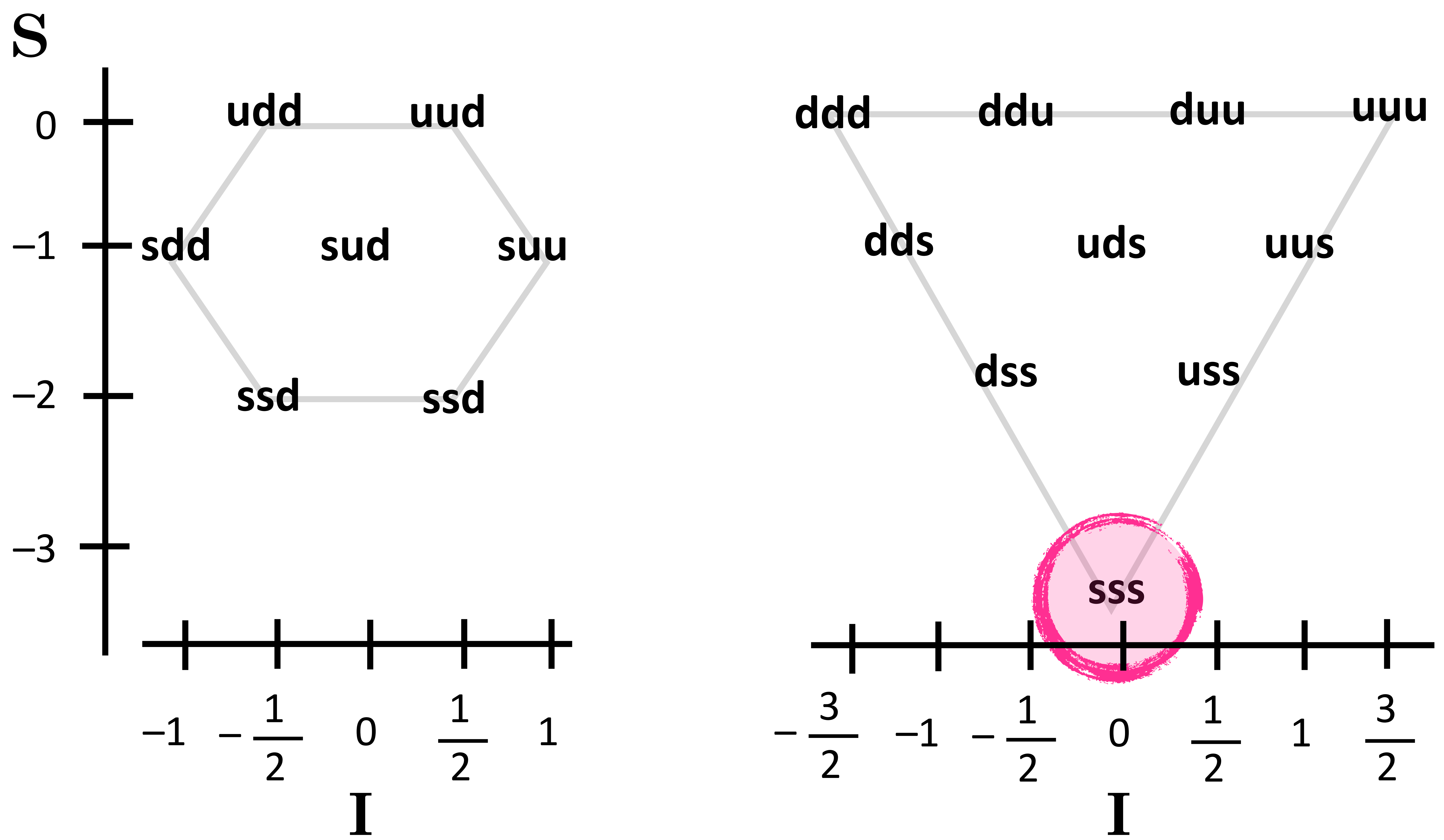
Particle	Symbol	Rest Mass MeV/c²	spin	Q	B	S	Lifetime	dominant decay modes	quark content
proton	p	938.3	1/2	+1	+1	0	> 10^{31} y		uud
neutron	n	939.6	1/2	0	+1	0	920	$pe^{-}\bar{\nu}_e$	ddu
Lambda	Λ^0	1115.6	1/2	0	+1	–1	2.6 x 10^{-10}	$p\pi^{-},\ n\pi^0$	uds
Sigma	Σ^+	1189.4	1/2	+1	+1	–1	0.8 x 10^{-10}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

discovered at Brookhaven within a year

the “Omega minus” was discovered at Brookhaven National Lab



like a glove



S
0
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−1
$-\frac{1}{2}$
0
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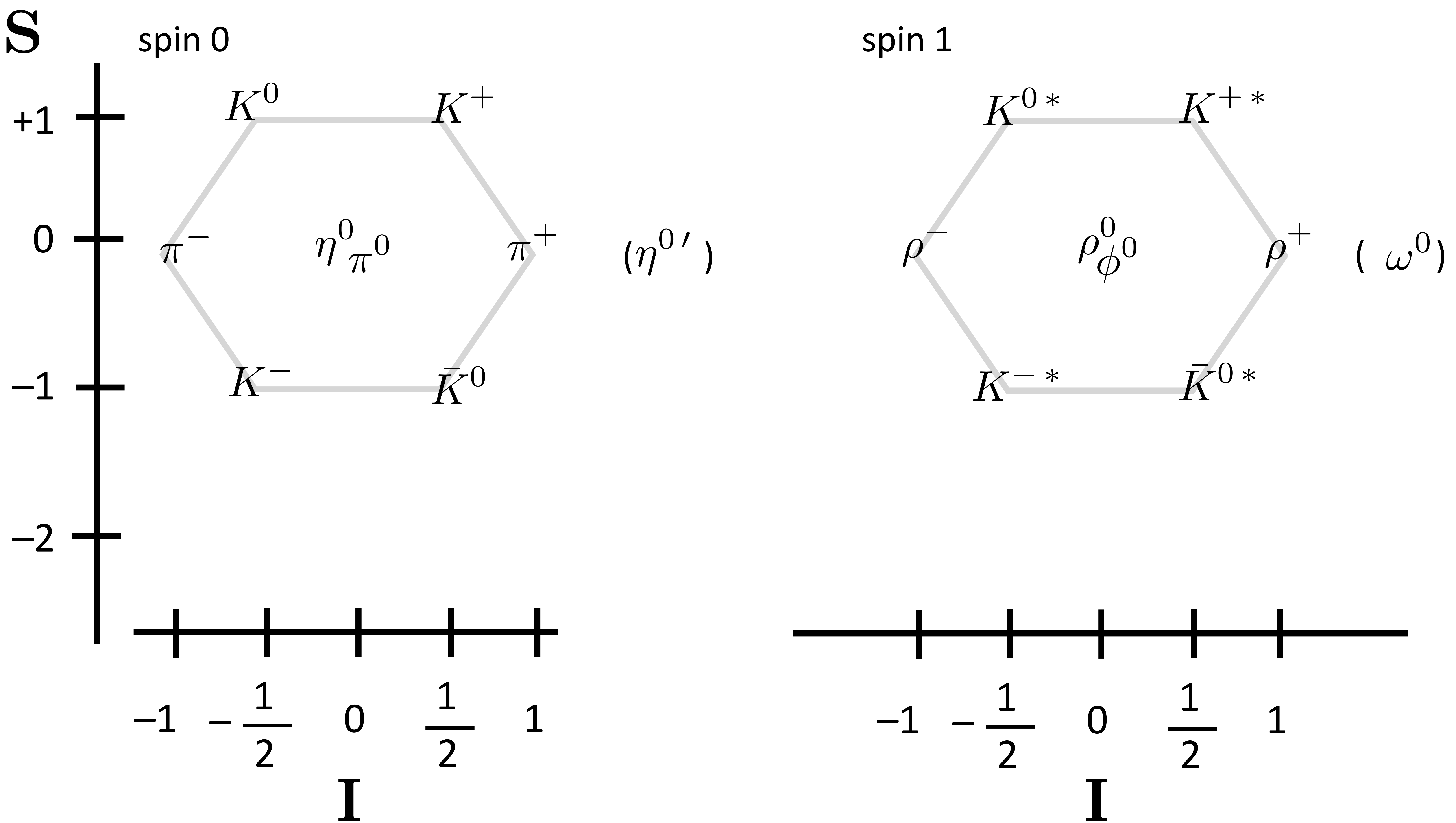
−1
$-\frac{1}{2}$
0
$\frac{1}{2}$
1
$\frac{3}{2}$
I

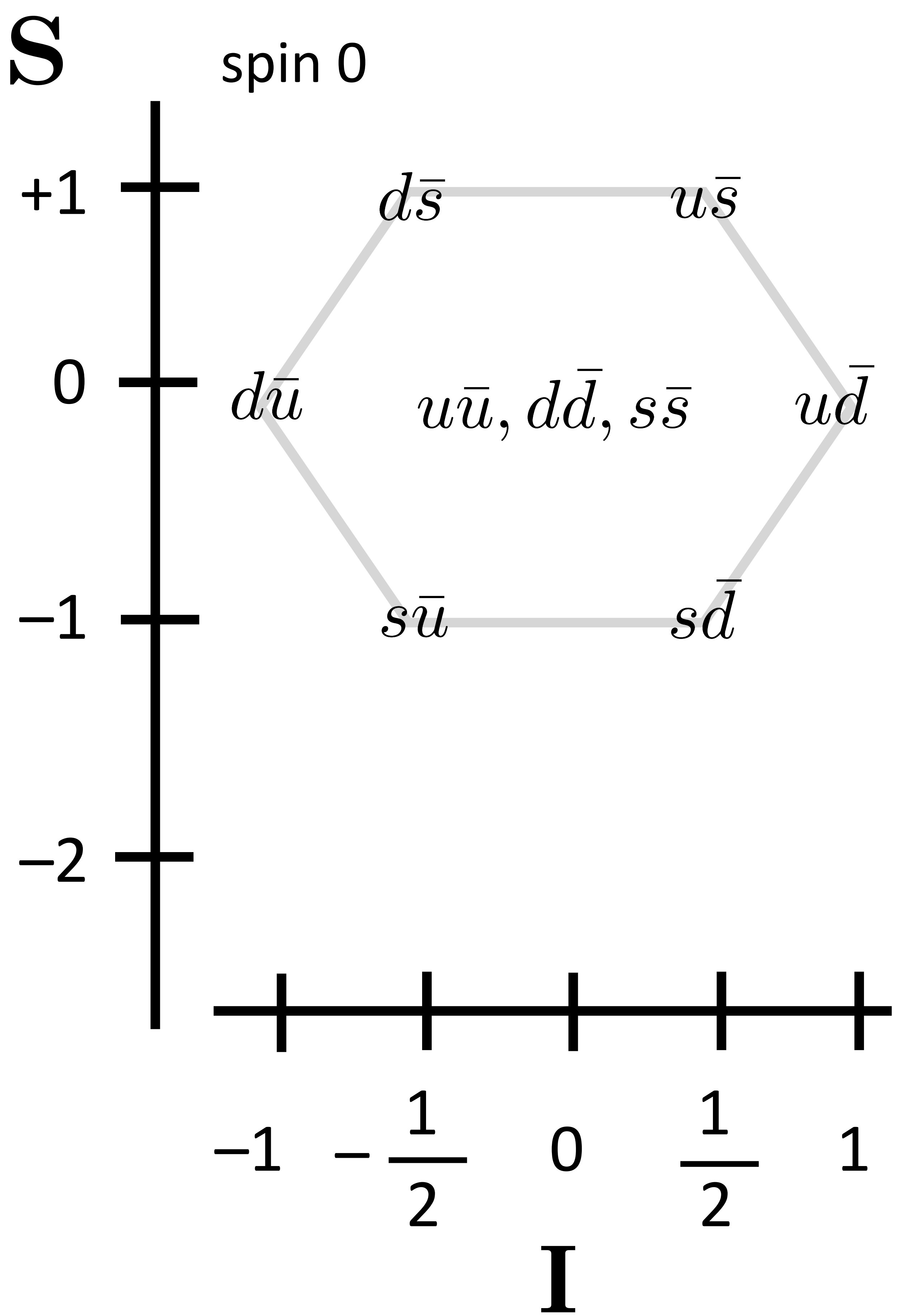
the dominant Mesons

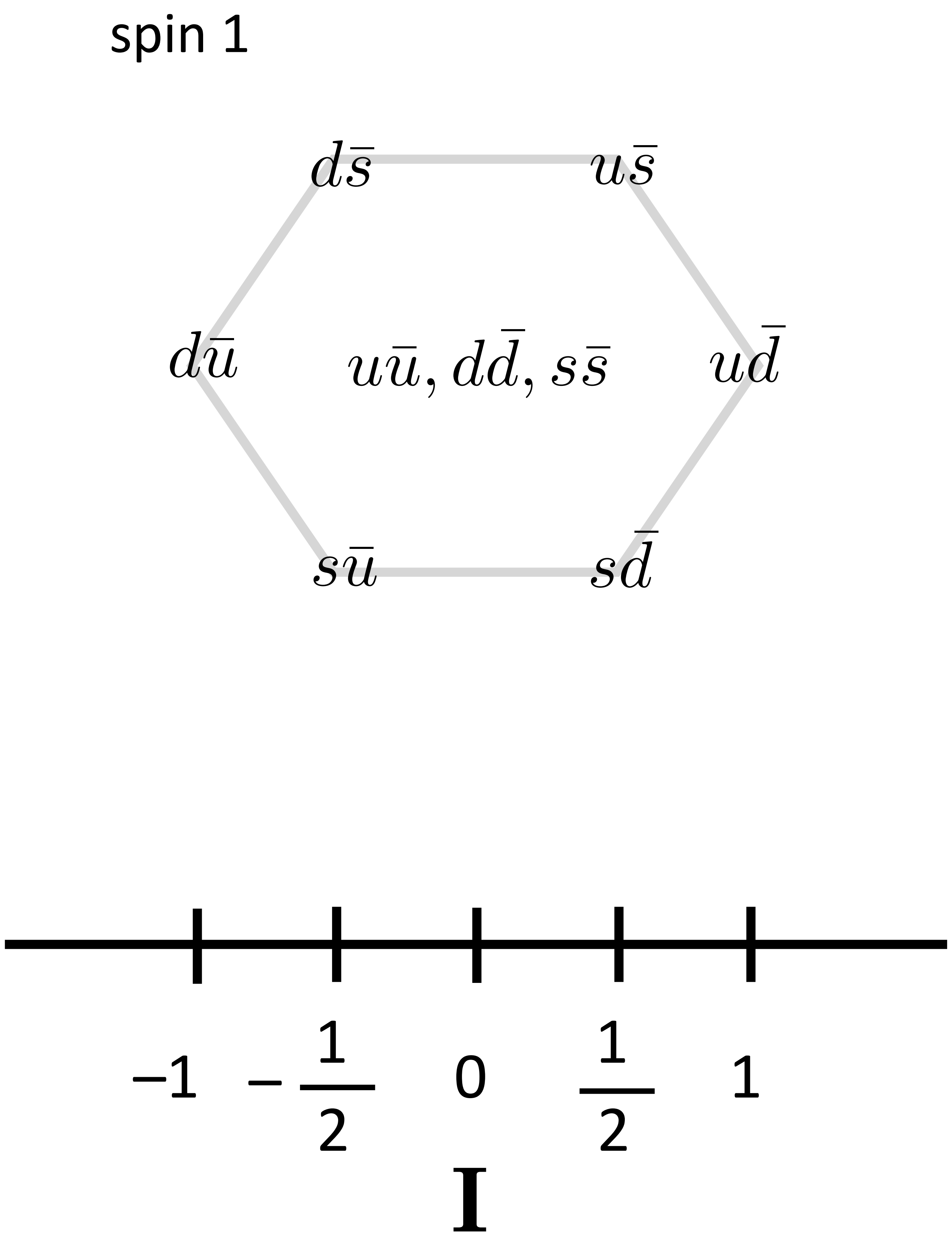
Particle	Symbol	anti-particle	Rest Mass MeV/c²	spin	Q	B	S	Lifetime	dominant decay modes	quark content
Pion	π^+	π^-	139.6	0	+1	0	0	2.6 x 10^{-8}	$\mu^+\nu_\mu$	$u\bar{d}$
Pi-zero	π^0	π^0	135	0	0	0	0	920	2γ	$\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$
Kaon	K^+	K^-	493.7	0	+1	0	+1	1.24 x 10^{-8}	$\mu^+\nu_\mu,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

a similar thing happens for the mesons



meson quark content





now the jargon

gets a little more straightforward

now defined:

Hadrons: particles made of quarks.

now defined:

Baryons: particles made of 3 quarks.

now defined:

Mesons: particles made of 1 quark and 1 antiquark.

a variety of consequences

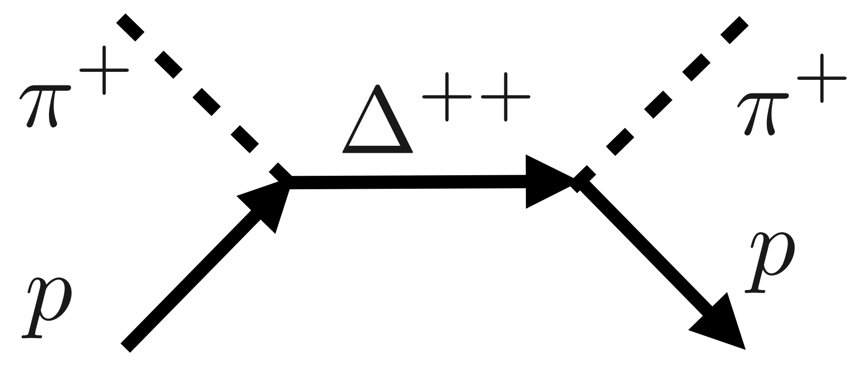
became apparent

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

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

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

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



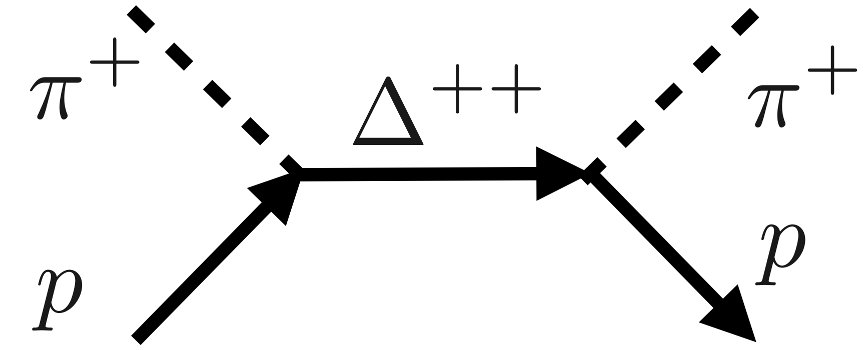
* I call them "pseudo" as doing real calculations with them are kind of ad-hoc

scatterings now are thought of diferently

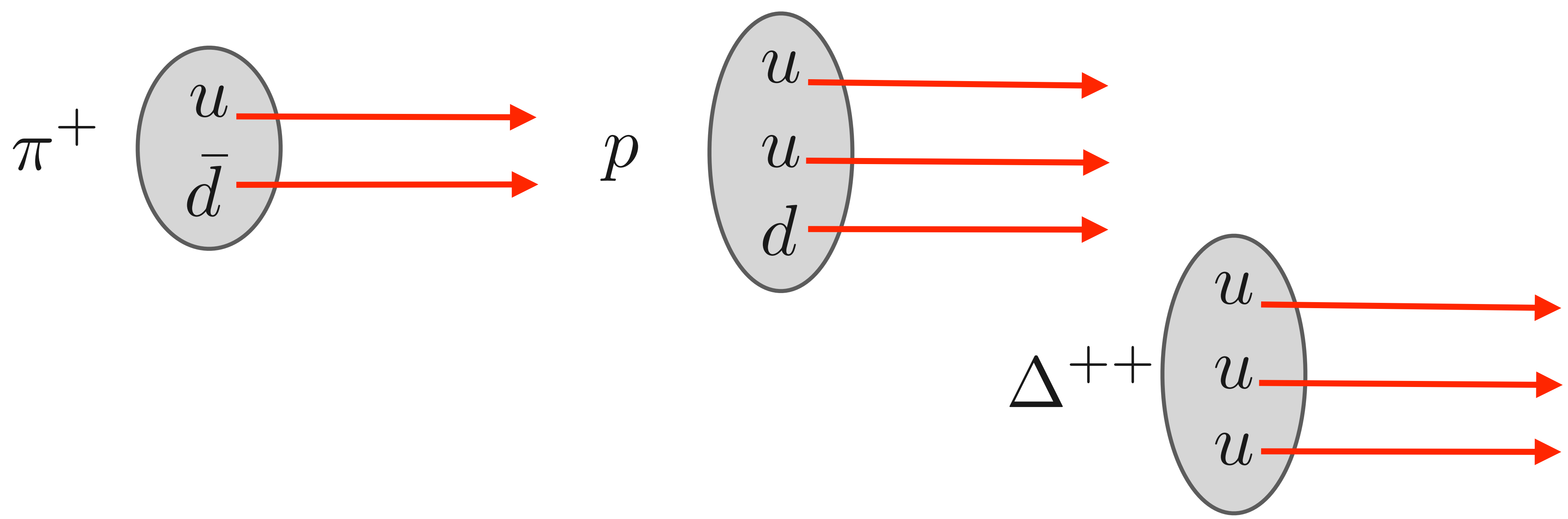
by following the lines...

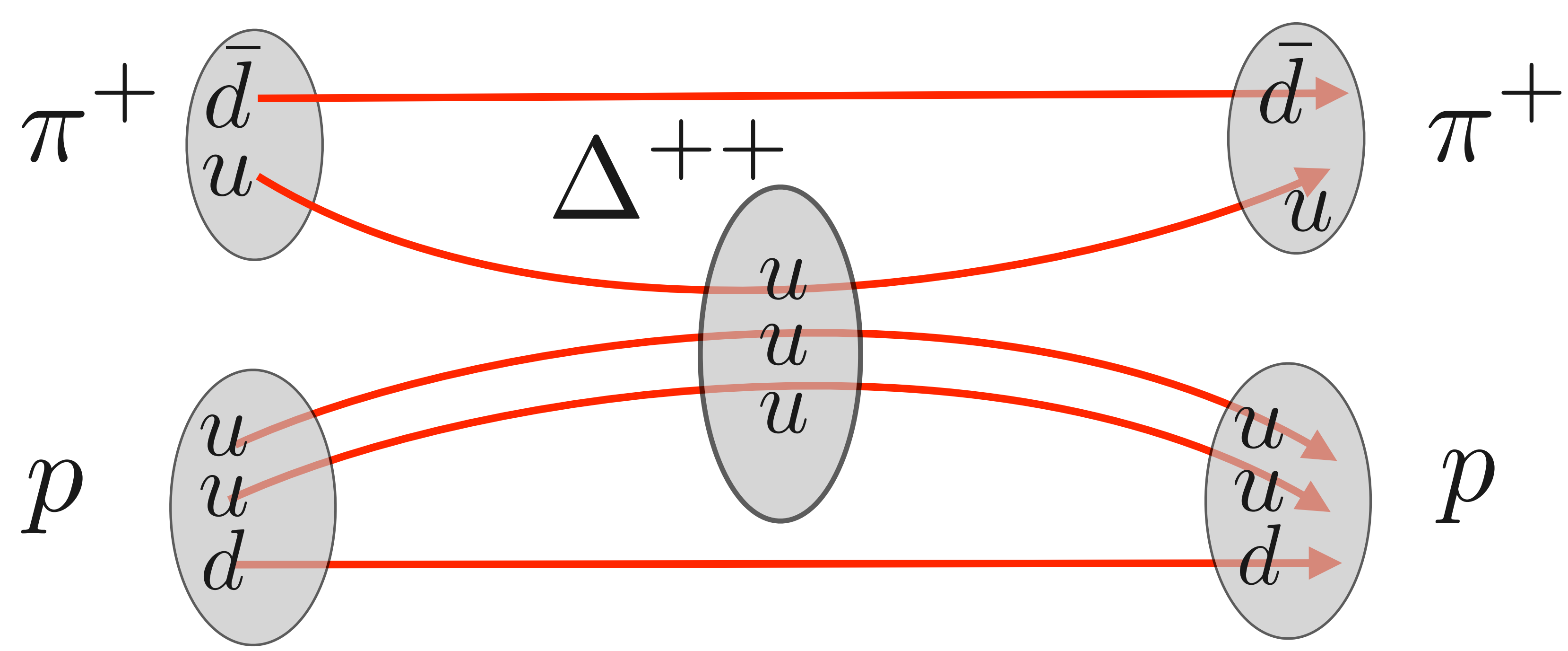
$$\pi^+ + p \to \Delta^{++} \to \pi^+ + p$$

Feynman Diagram, pre-1964:



in quark language:



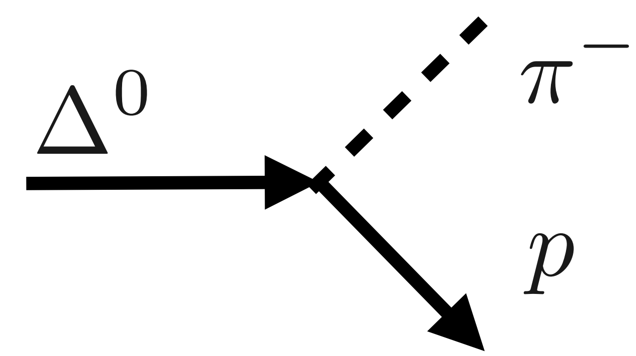


how about a strong interaction decay?

a little non-intuitive.

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

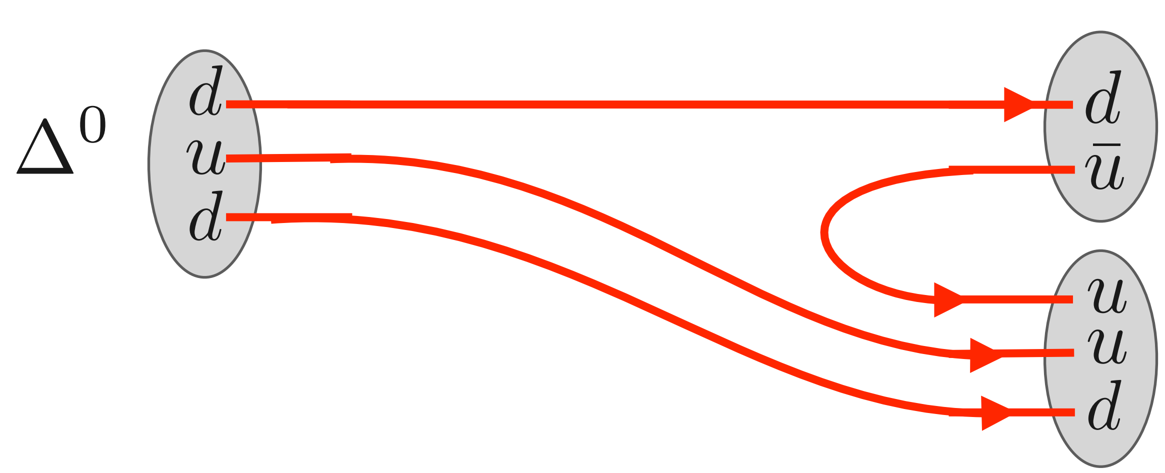
the old way:



the quark way:

5 quarks

some quark-creation required!



stay tuned.

is the world made of actual quarks?

or is this just a convenient organizing scheme

that’s all Gell-Mann thought

But evidence started to accumulate that surprised everyone

quarks are indeed as real as electrons.

First piece of convincing evidence:

we can bang on them

individually…Feynman saw this first.

remember.

the crucial thing in order to “see” something?

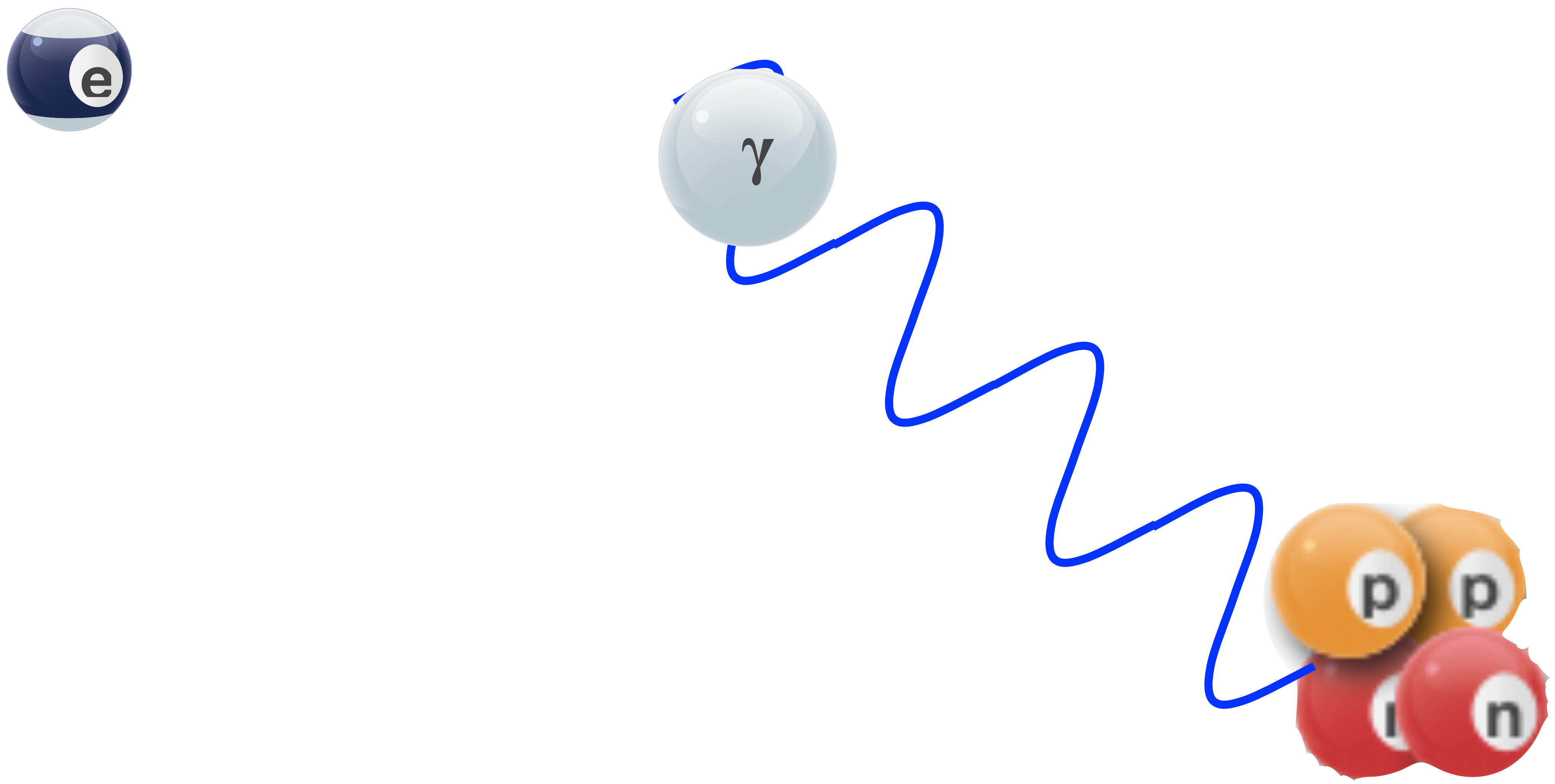
wavelength has to be about the size of the object

larger the momentum

the smaller the spatial resolving capability

scattering of an electron from a nucleus

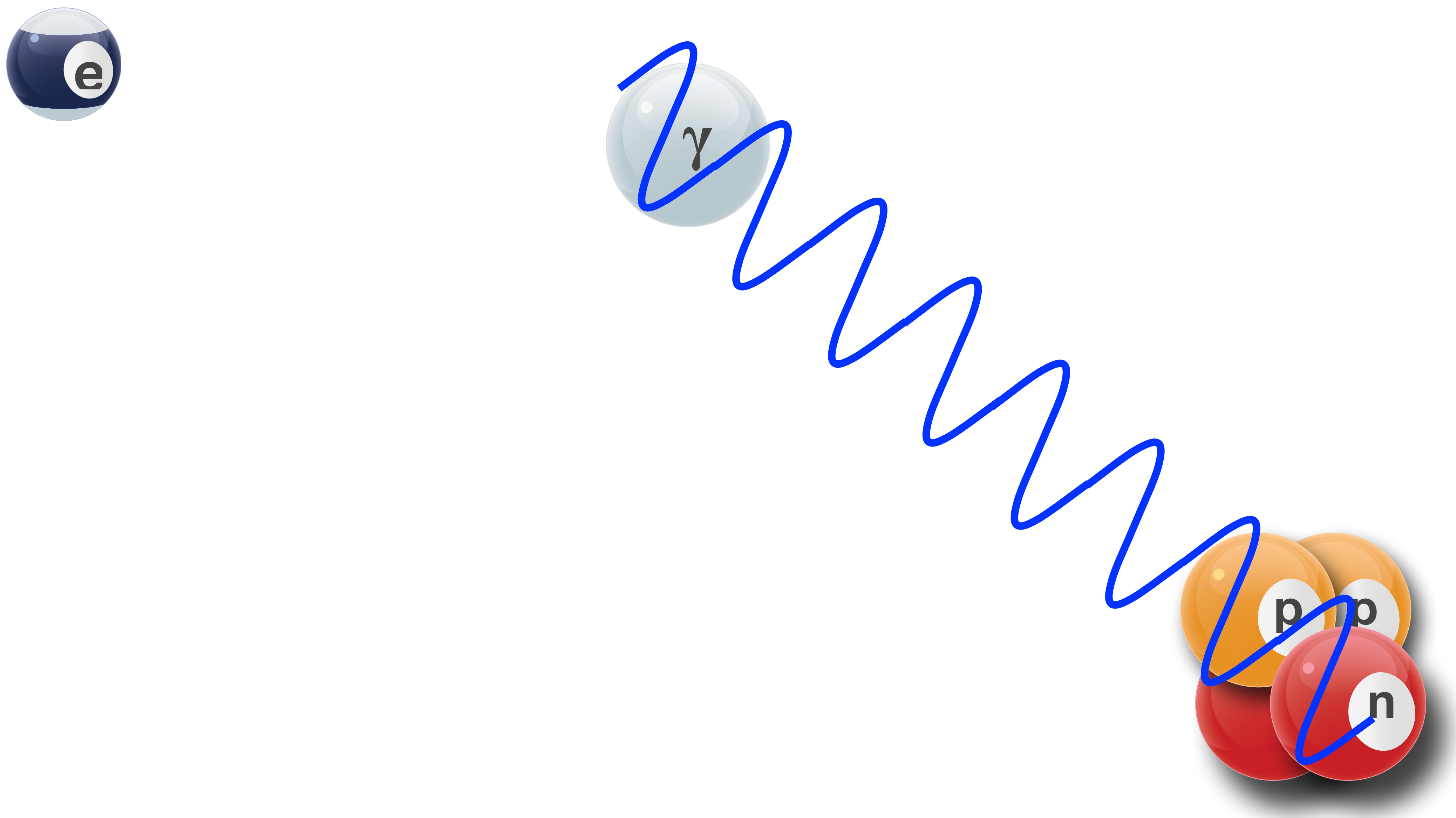
slow electron, long wavelength photon



“sees” the whole nucleus

scattering of an electron from a nucleus

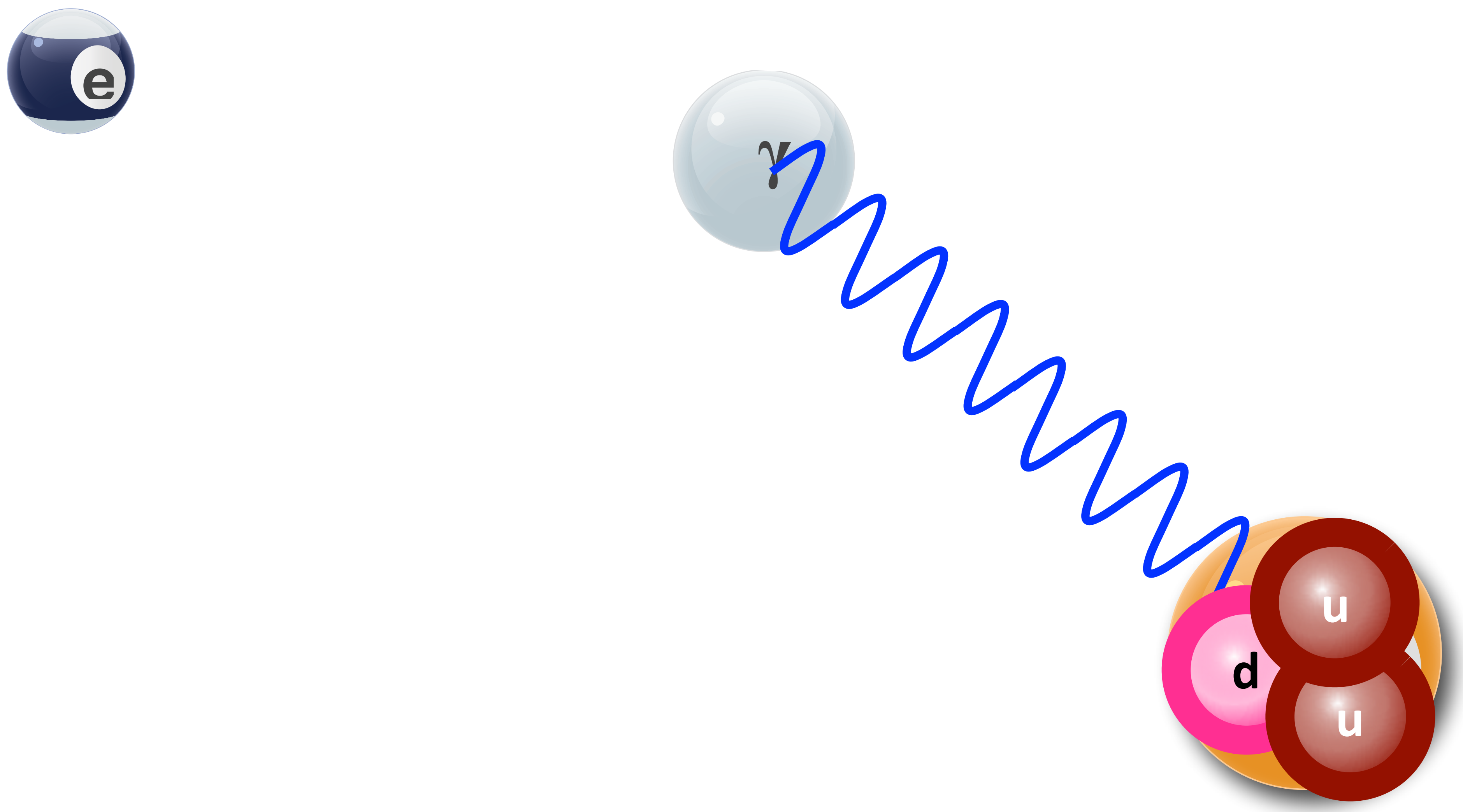
fast electron, **medium-short** wavelength photon



"sees" an individual proton in the nucleus

scattering of an electron from a nucleus

very fast electron, **very-short** wavelength photon



“sees” an individual quark in a proton or neutron

That’s how we became convinced in 1969 –

the same sort of backwards scattering as Rutherford’s

The Nobel Prize in Physics 1990
Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

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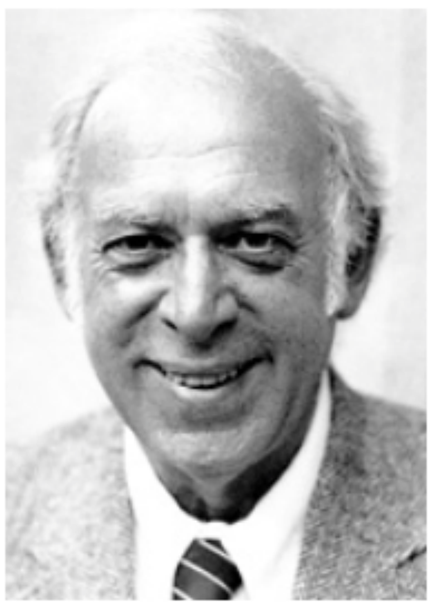
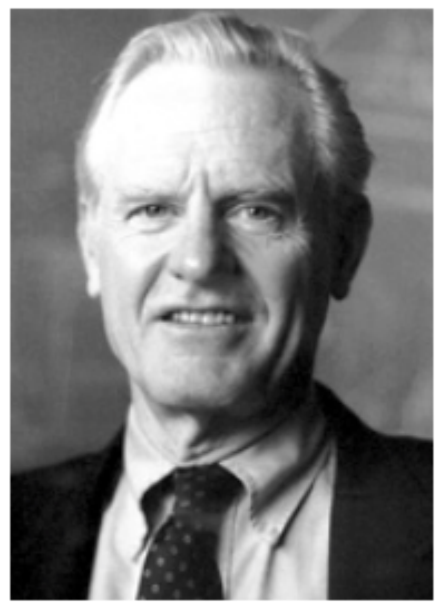
The Nobel Prize in Physics 1990



Jerome I. Friedman
Prize share: 1/3



Henry W. Kendall
Prize share: 1/3

Photo: T. Nakashima
Richard E. Taylor
Prize share: 1/3

The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor *"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"*.

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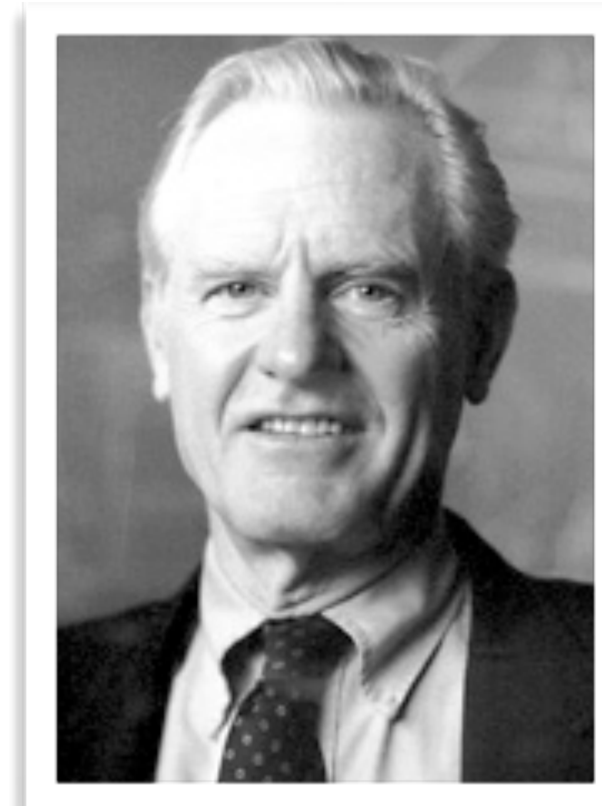
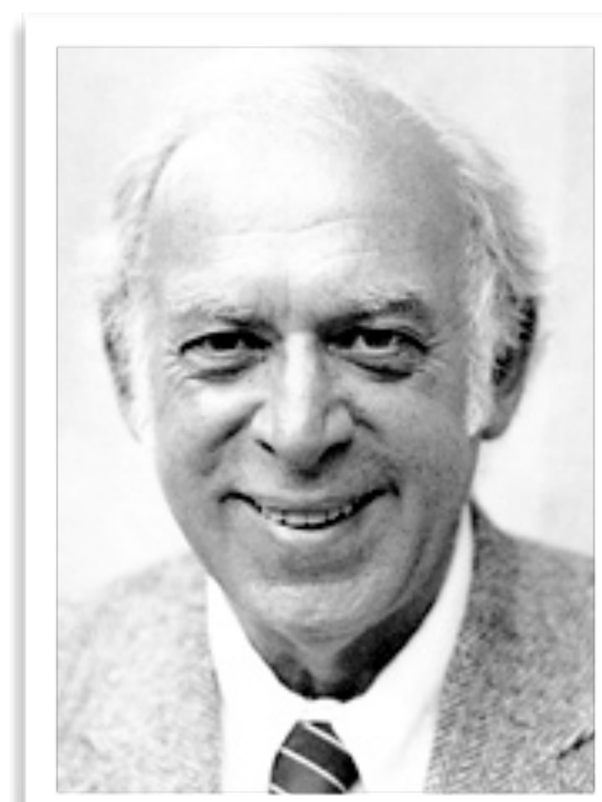




particle: **up quark**

symbol:	*u*
charge:	+2/3
mass:	1.7 to 3.3 MeV/c^2
spin:	1/2
category:	Fermion, I=+1/2, B=1/3, S=0

particle: **down quark**

symbol: *d*

charge: –1/3

mass: 4.1 to 5.8 MeV/c^2

spin: 1/2

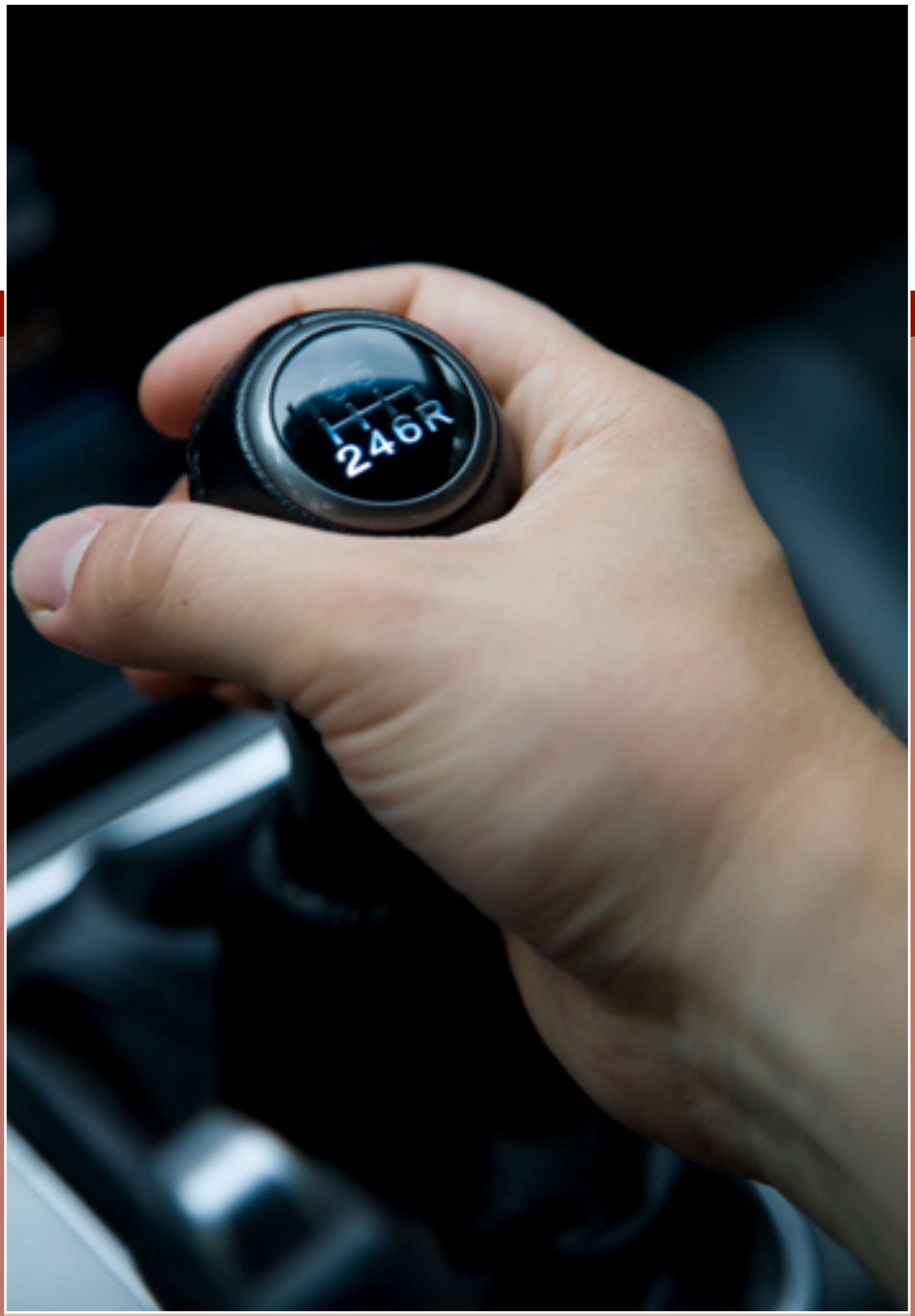
category: Fermion, I=–1/2, B=1/3, S=0

particle: **strange quark**

symbol:	*s*
charge:	–1/3
mass:	101 MeV/c^2
spin:	1/2
category:	Fermion, I=–1/2, B=1/3, S=–1

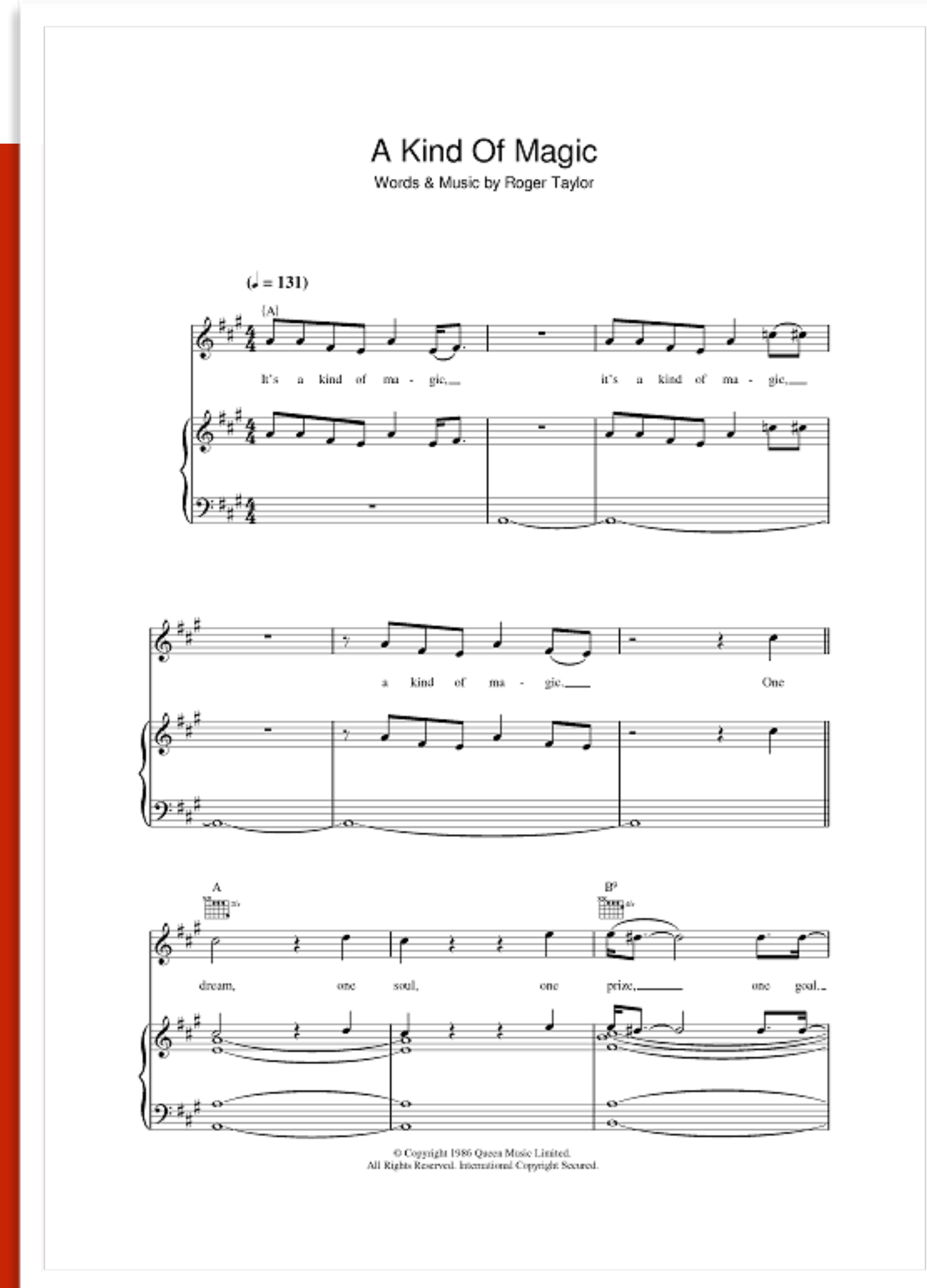
shifting gears

the weak interaction needs a boson



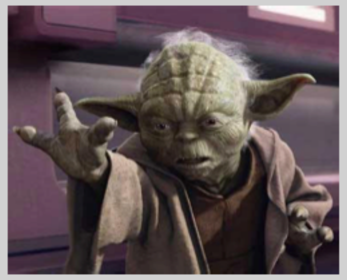
the quantum relativistic field theory

theme song:



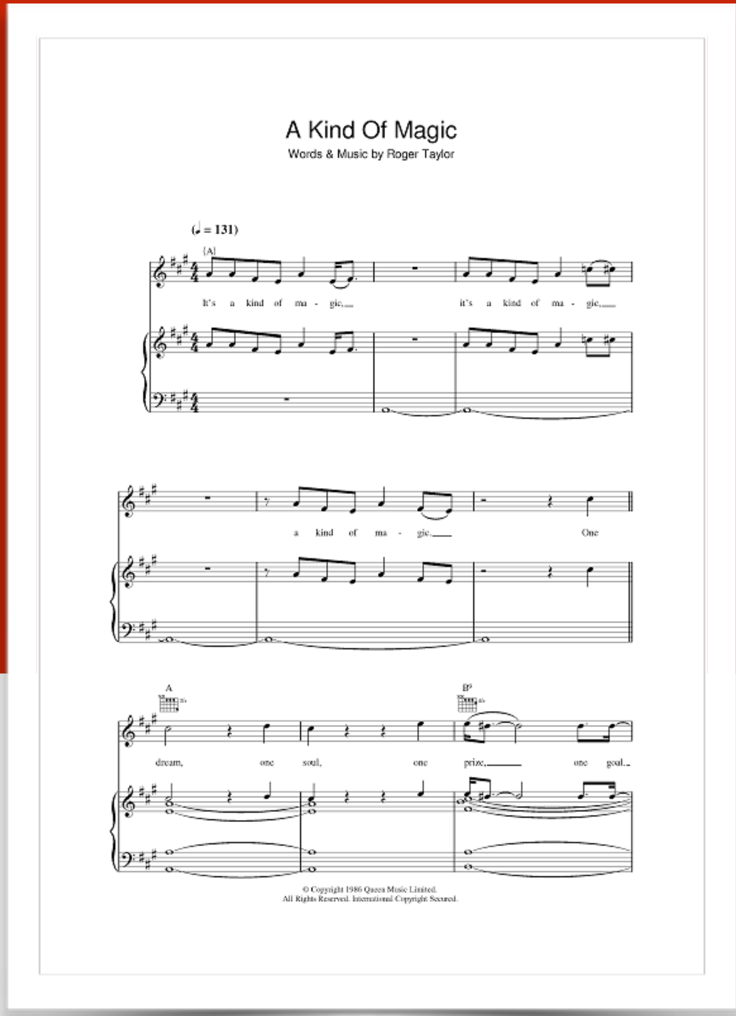
this kind of magic:

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



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

Because Nature
is Clumpy.



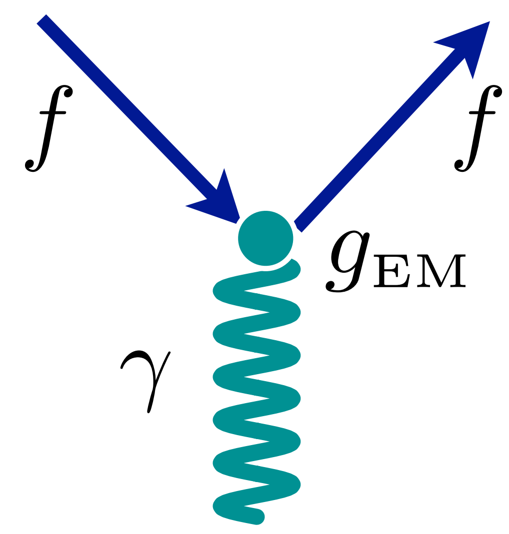
for the electromagnetic interaction:

the force is the electromagnetic force

the field is E & B

the clumpiness – the quantum – is:

The photon: γ

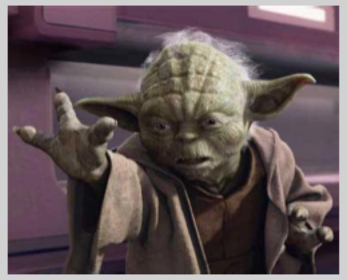


Well, the Weak Force

must have a field

...yadda yadda yadda

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



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

Because Nature is Clumpy.

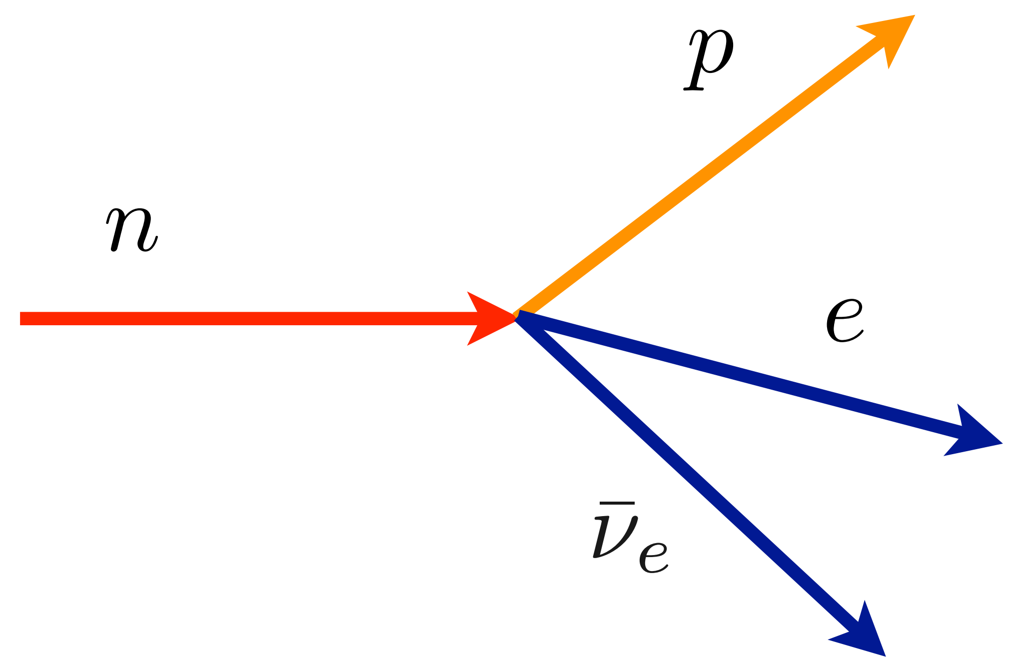
for weak interaction:

the field must be a weak field…& Massive & electrically charged

the clumpiness —the quantum — must be *Something else.*

here's a weak interaction

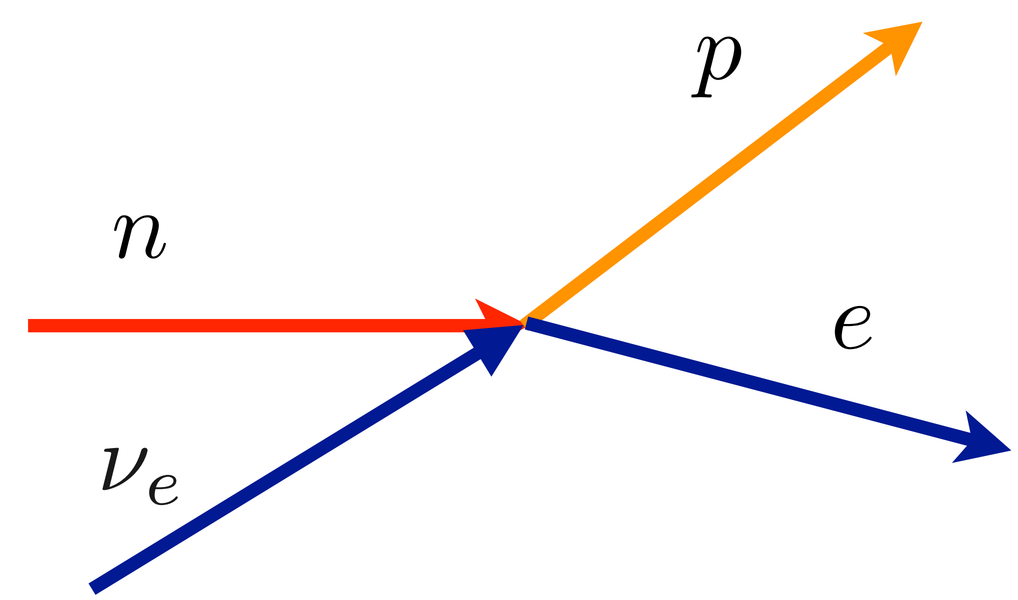
neutron beta decay



changes electric charge

the weak interaction here changes the bottom and the top of these doublets $\begin{pmatrix} p \\ n \end{pmatrix}$

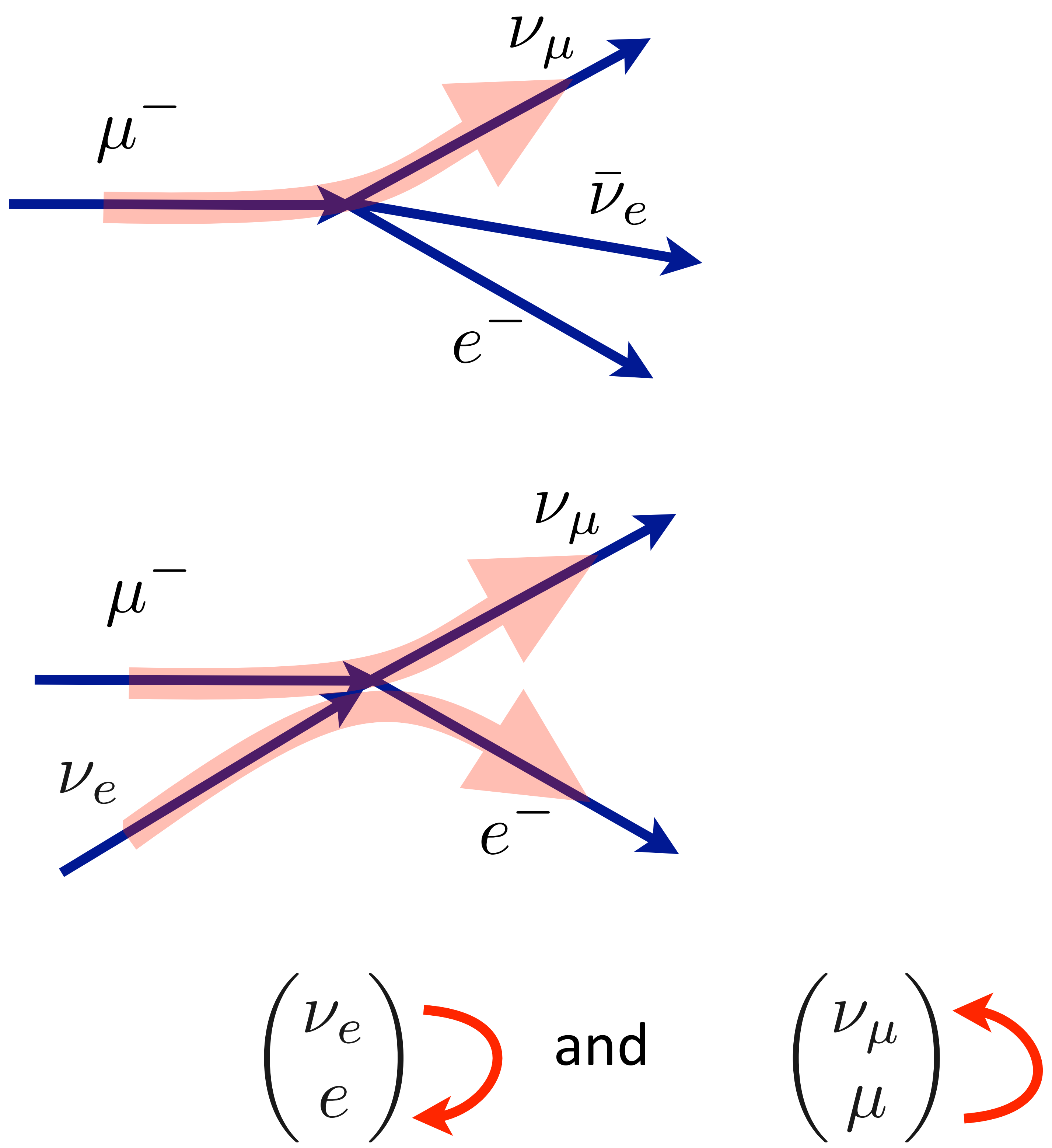
Manipulate the graph in the now familiar way:



$\begin{pmatrix} p \\ n \end{pmatrix}$ and $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$

the muon decay is the same sort of

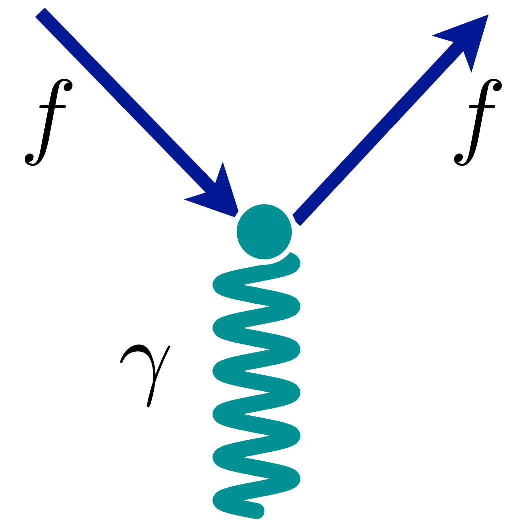
in that second way of looking at it:



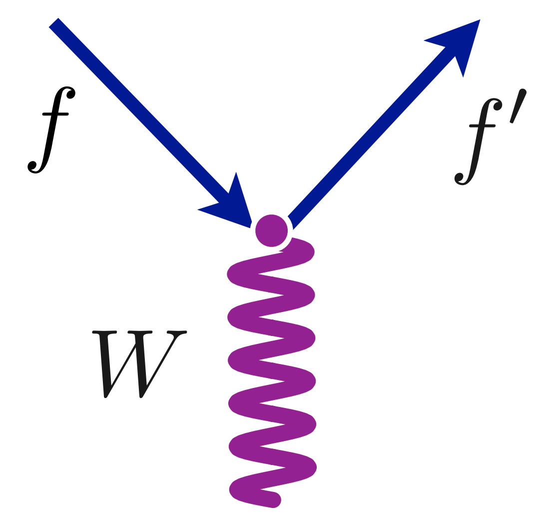
do it again?

can a “photon” be forced to exist that governs the weak interaction?

It was a dream that the electromagnetic interaction



could have a weak interaction counterpart.



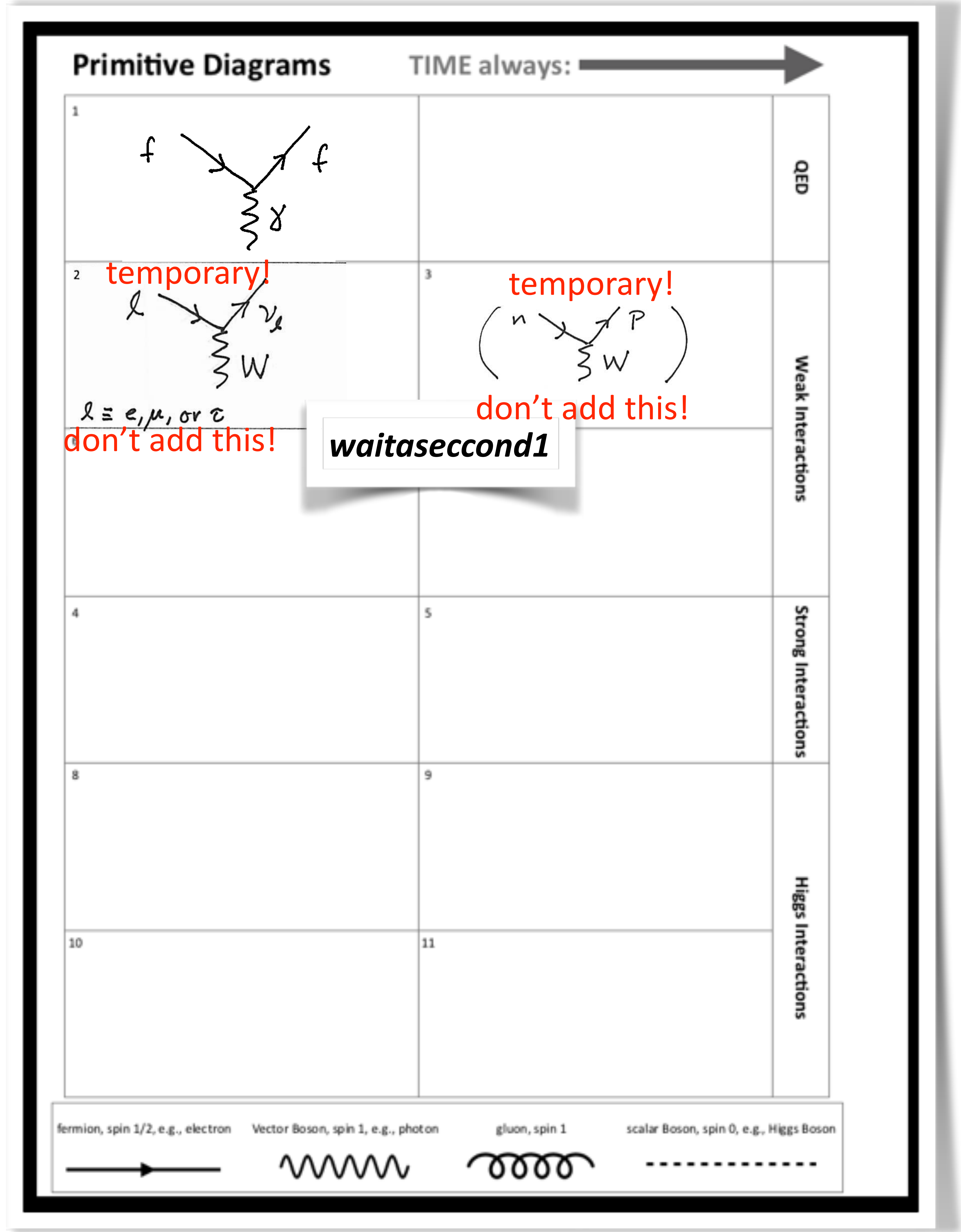
“W” for “Weak”

Feynman and Murray Gell-Mann worked out a consistent theory based on the idea of a “heavy” photon with electric charge.

Notice that f and f' and $W^{\pm}$ all have to have their electric charges assigned so that electric charge is conserved.

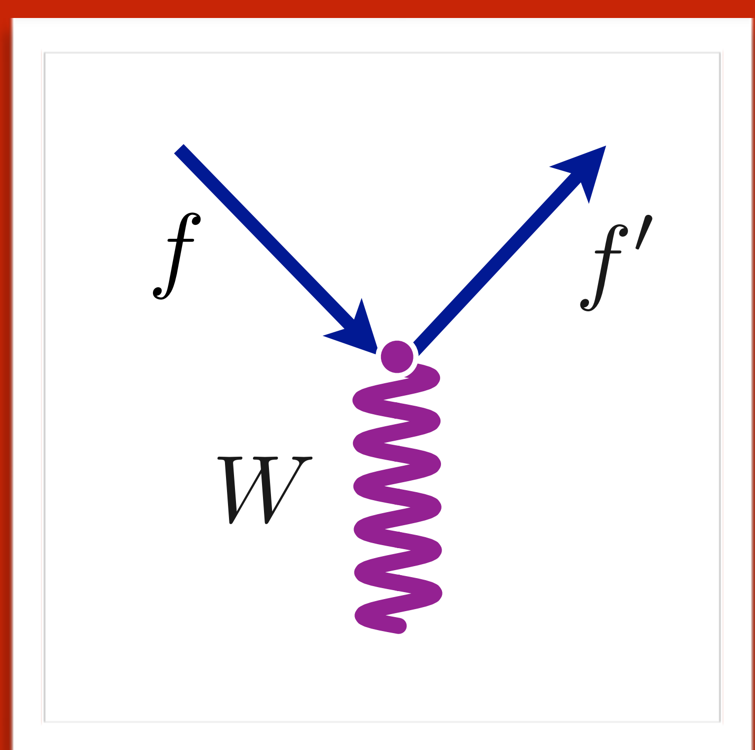
temporary entries into your

table of primitive diagrams



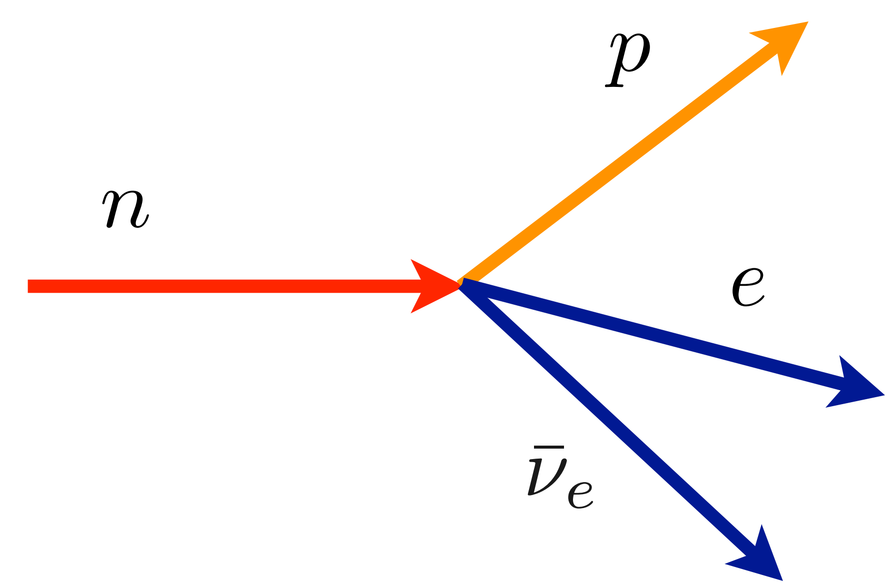
so, a new primitive diagram

for the Weak Interaction

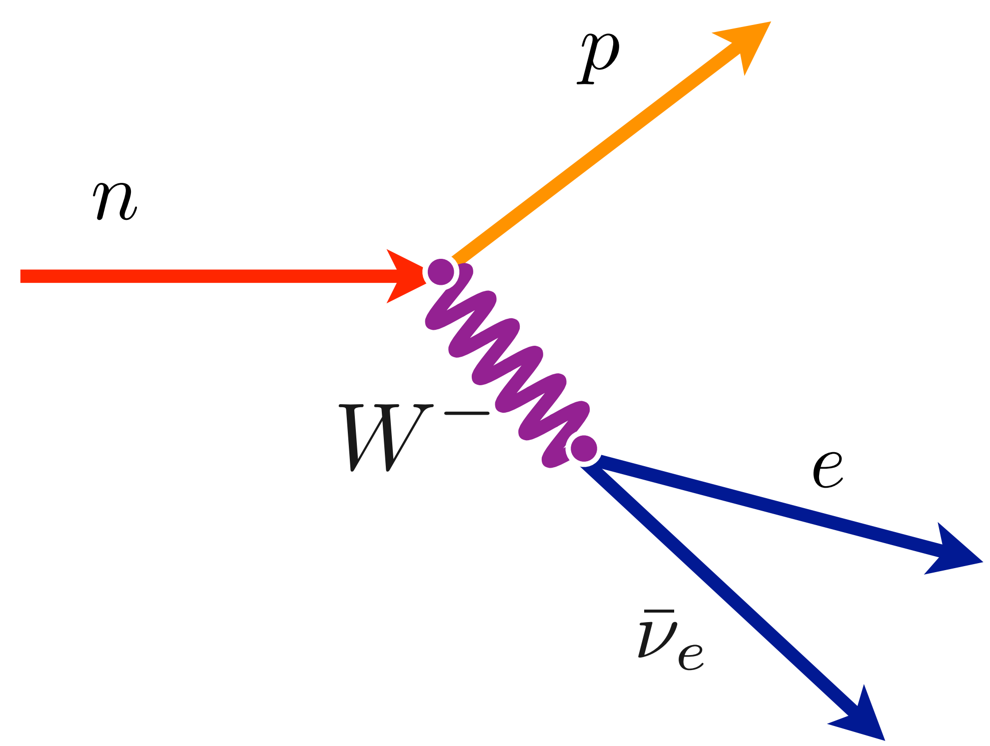


pretend this is primitive for a moment.

Neutron beta decay:

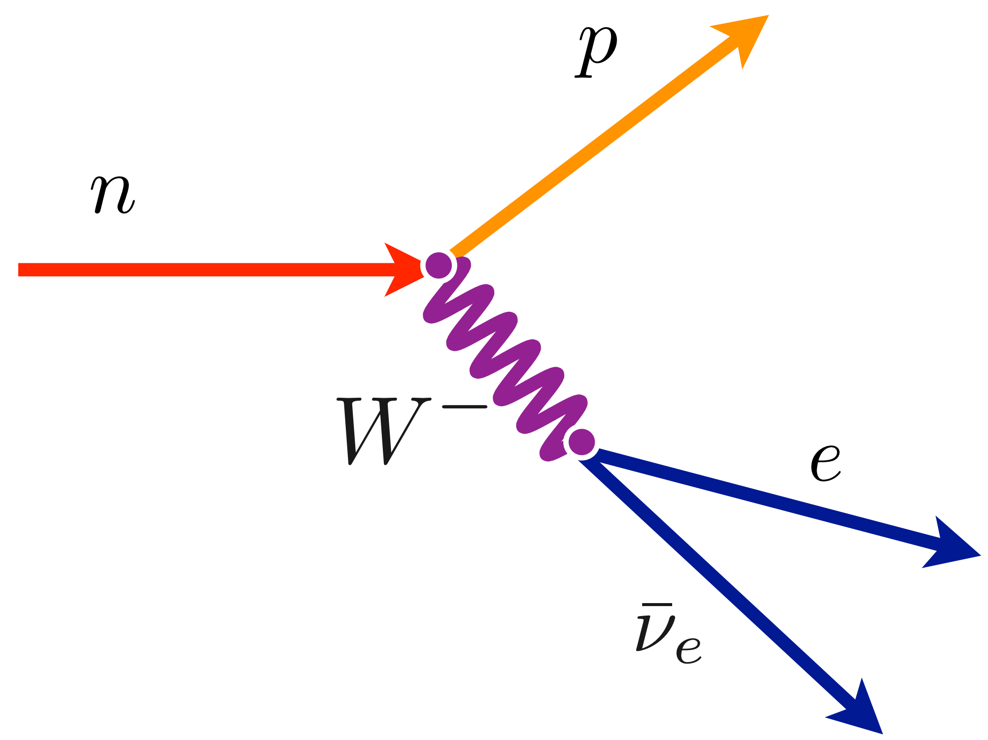


becomes:



keep track of the charge flow

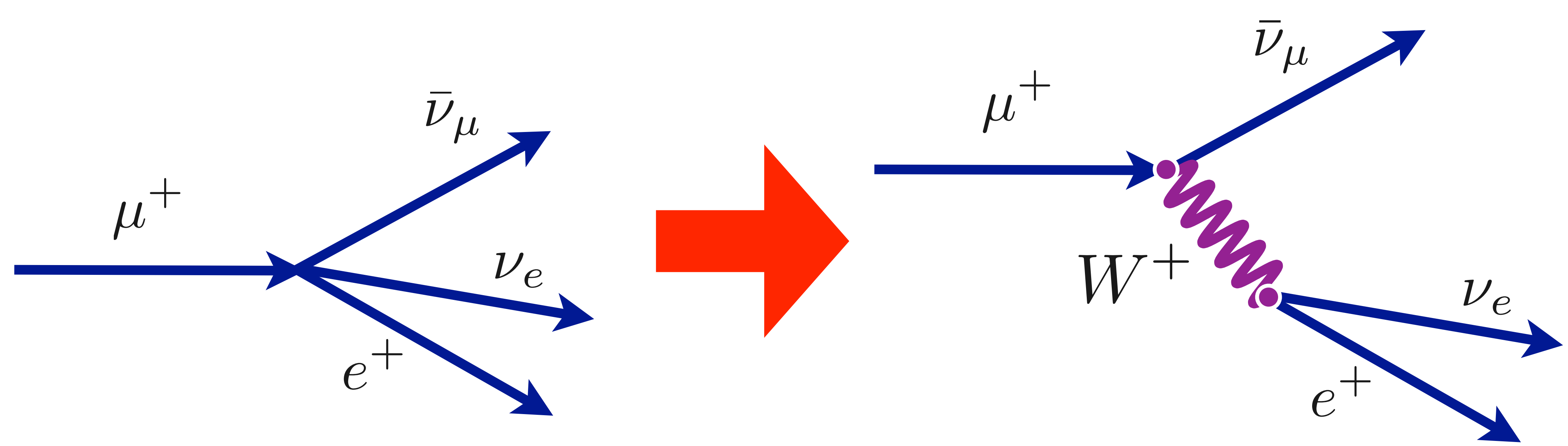
there are 2 W charged states



$$n \rightarrow p + W^- \rightarrow p + e^- + \bar{\nu}_e$$

Q: 0 = +1 + −1 = +1 + −1 + 0 = 0

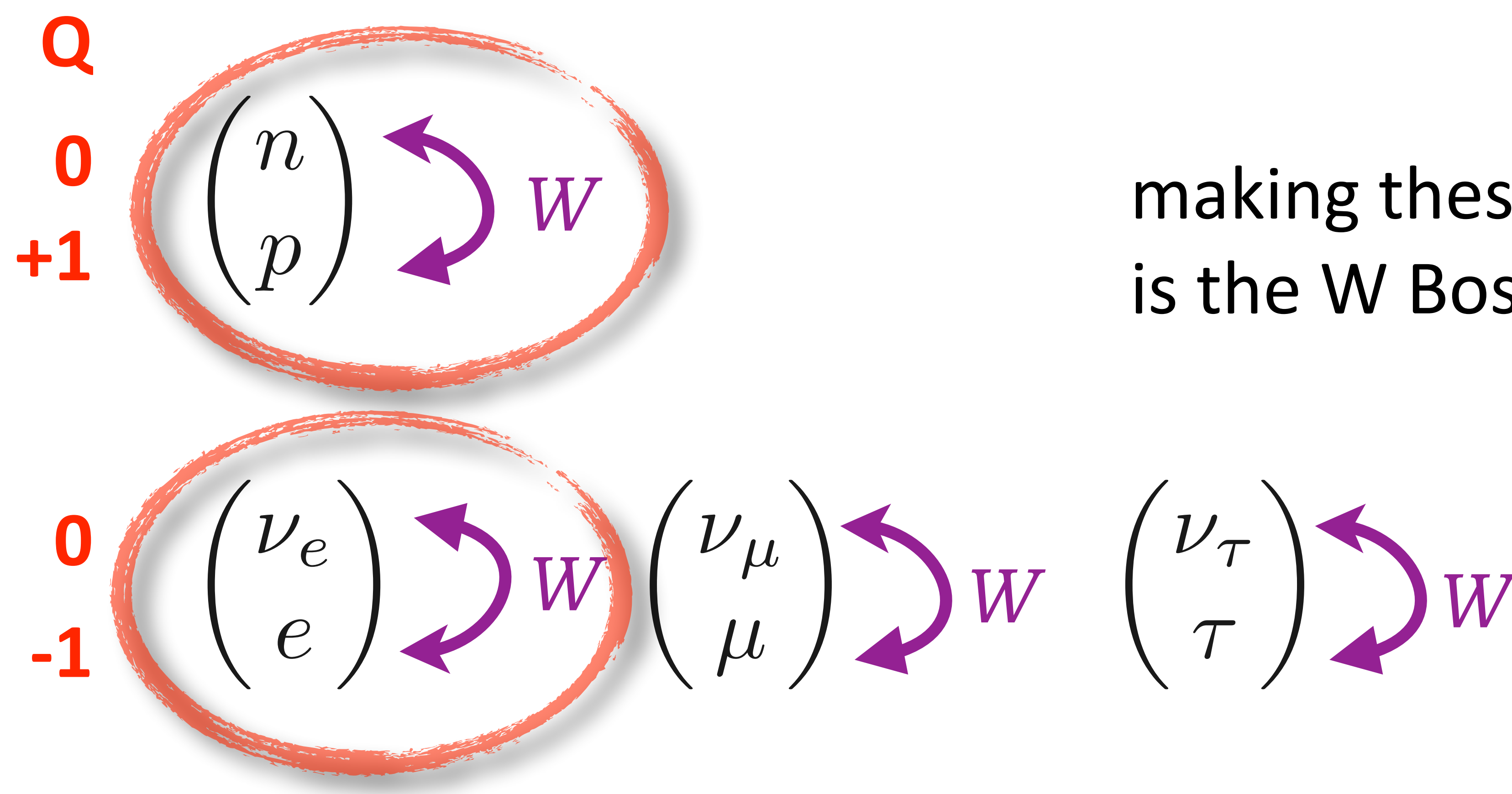
So: W^- lowers the electrical charge by 1
W^+ raises the electrical charge by 1



here is where those weak “doublets” come in

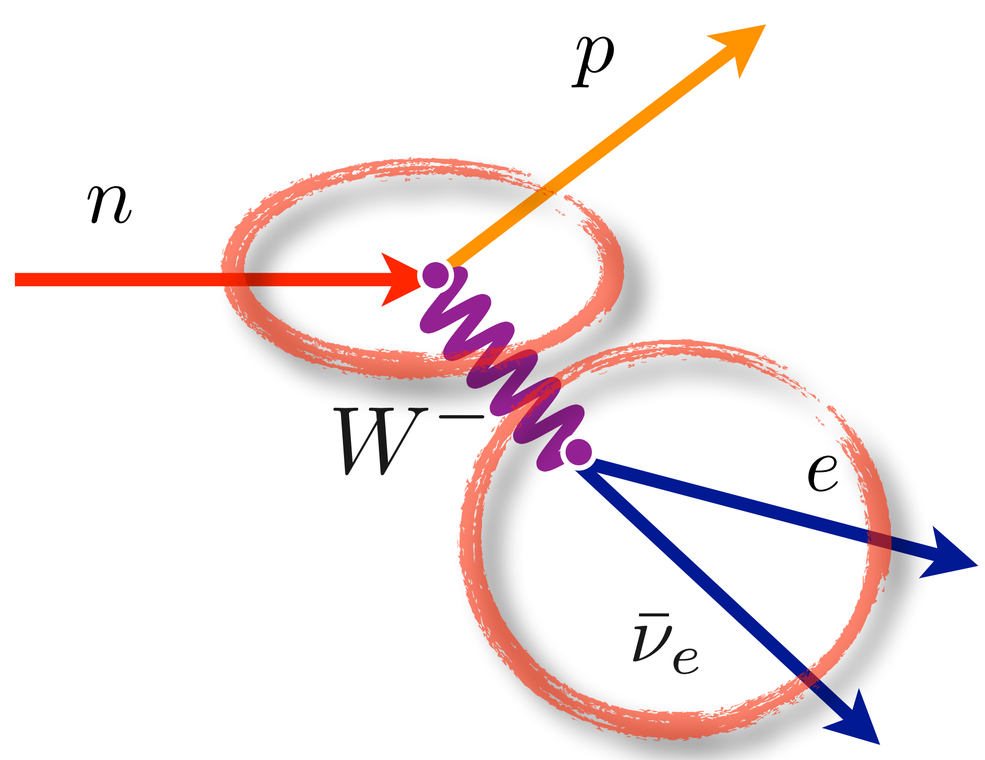
the Weak Interaction connects them

The particle doublets that we know so far:



making these transitions is the W Boson’s job.

Notice, that all of these transitions change the electric charge as well as the particle type



call a generic lepton, “ℓ“

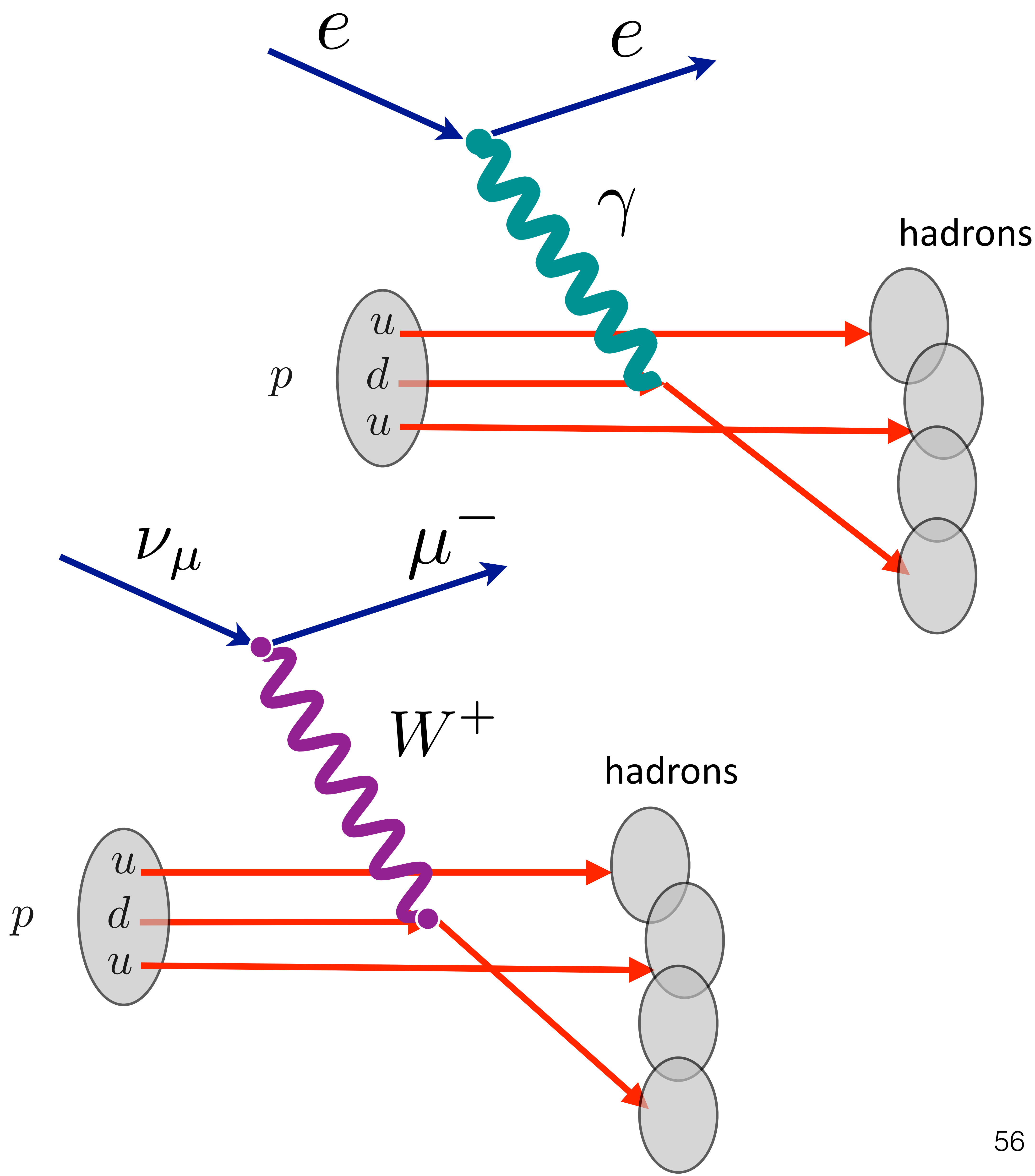
$\ell = e, \mu, \tau$

“deep inelastic scattering”

hitting quarks individually

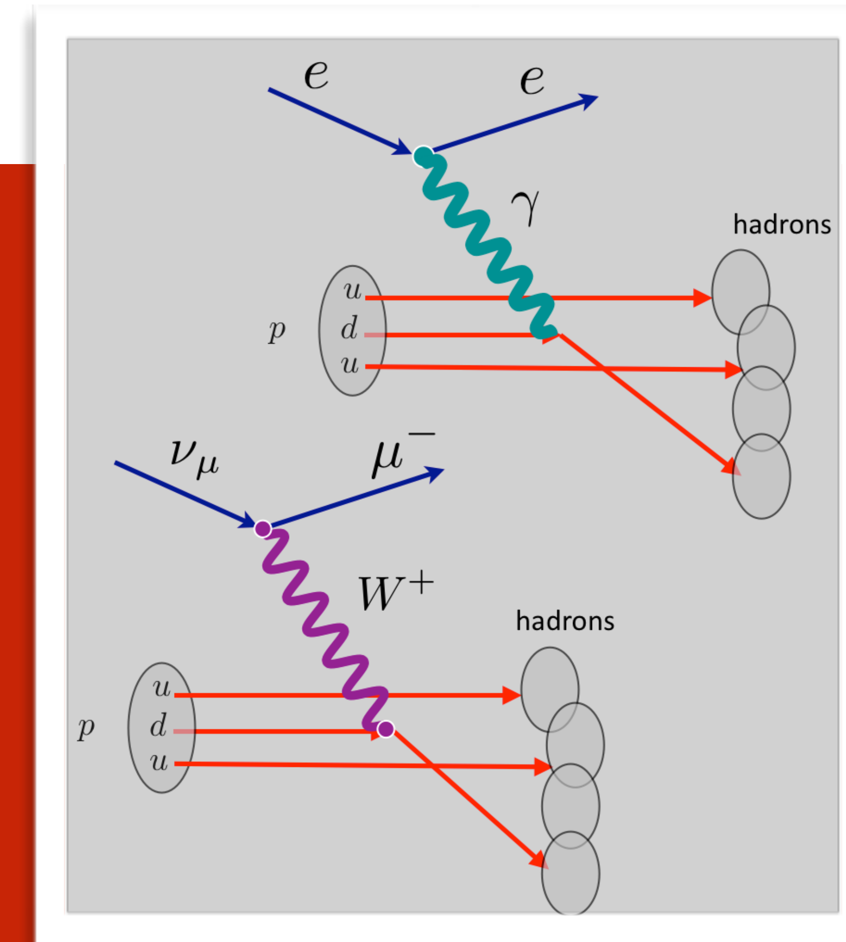
of course in a statistical fashion

neutrinos do it too…



analyses of these reactions,

$$\nu N \to \mu X \qquad eN \to eX$$



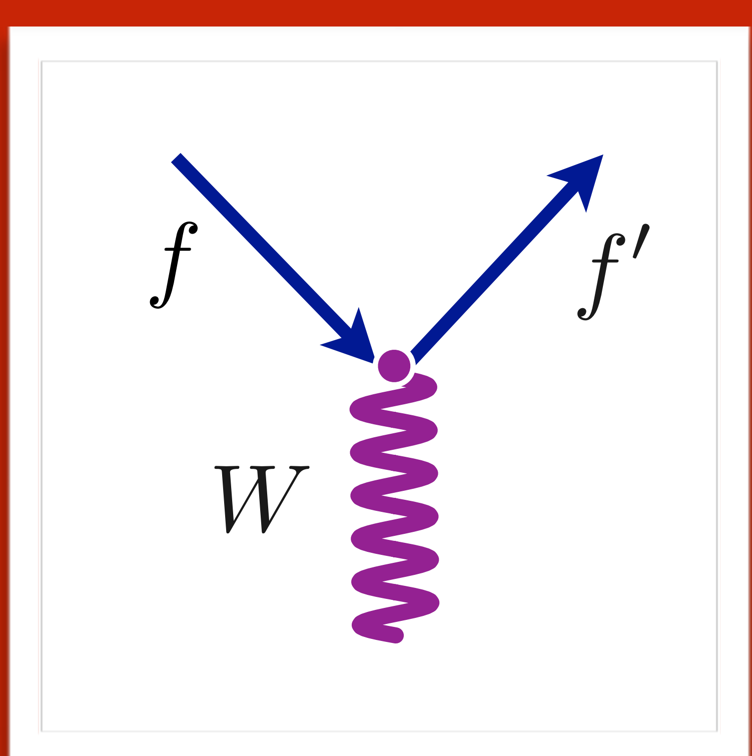
confirm the point-like (?) nature of quarks

confirm their apparent loose-binding within nucleons (in a second)

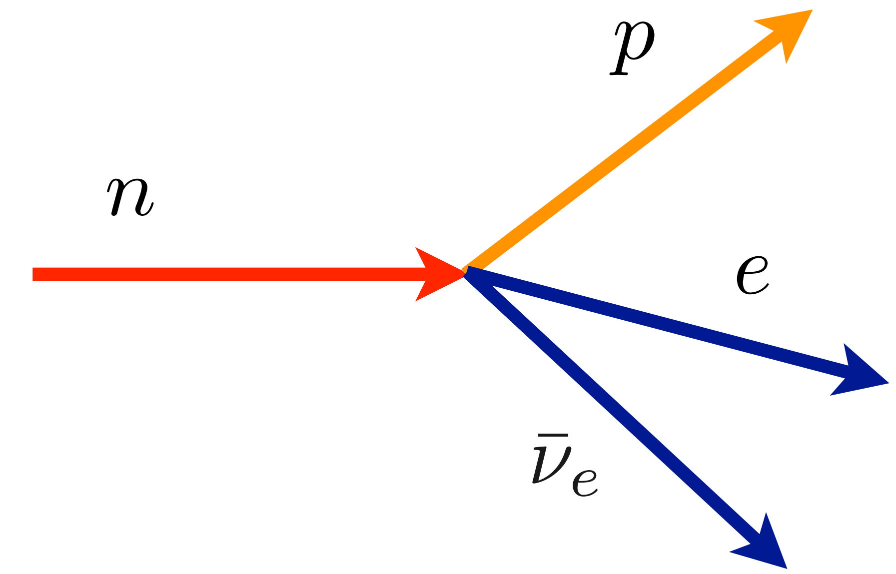
confirm their fractional electric charges!

so, a new primitive diagram

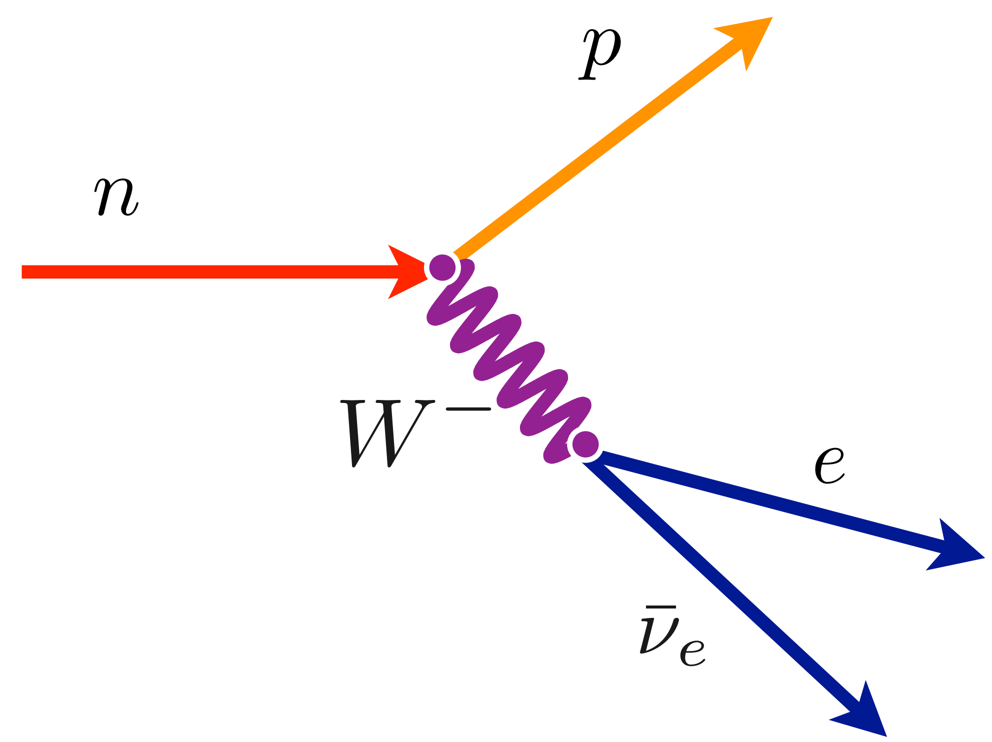
for the Weak Interaction with quarks, to go with the leptons



Neutron beta decay:

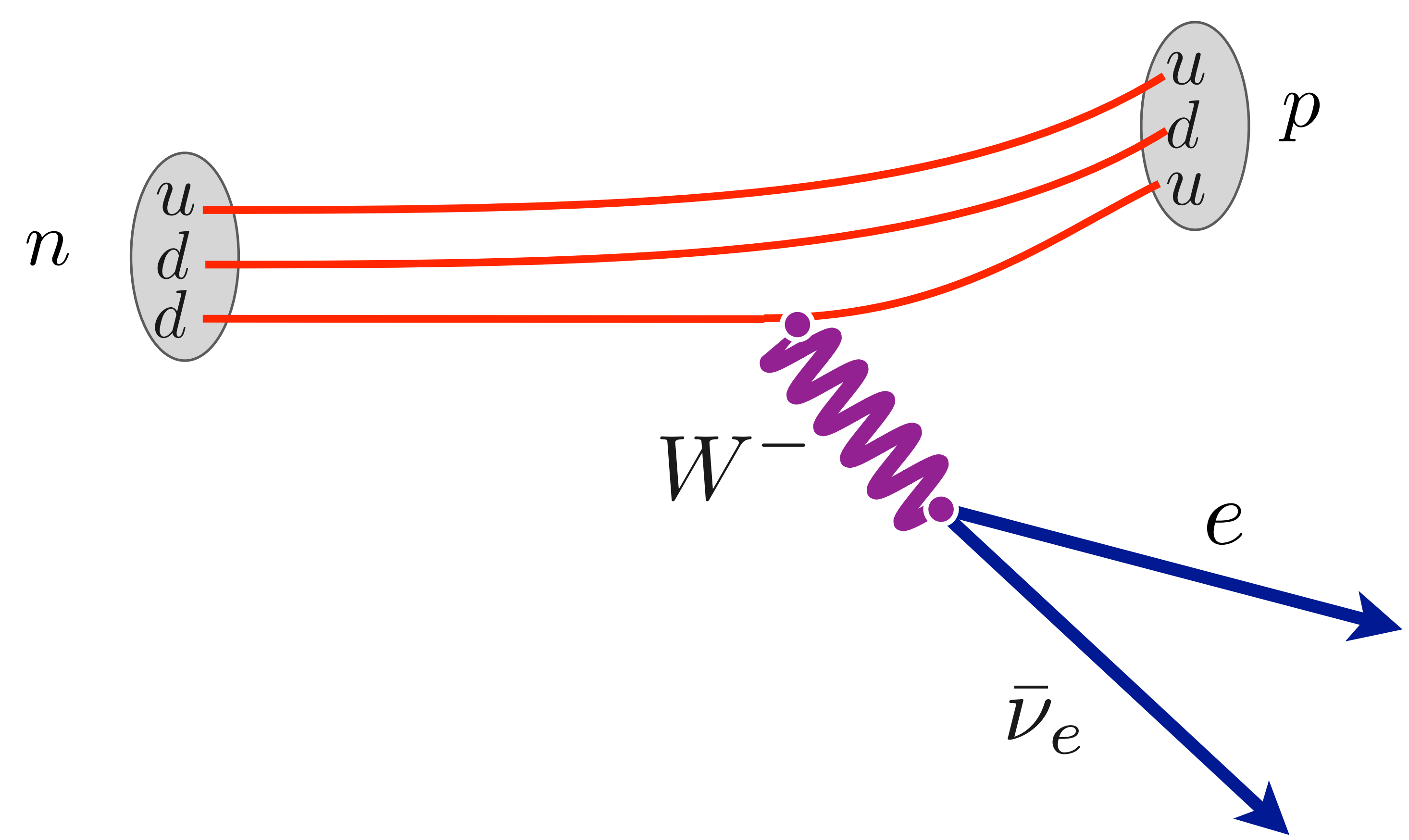


becomes:



and in the quark interpretation:

the reason W does: $\begin{pmatrix} p \\ n \end{pmatrix}$ is because it does: $\begin{pmatrix} u \\ d \end{pmatrix}$



instead of what I had before:

there are still weak interactions

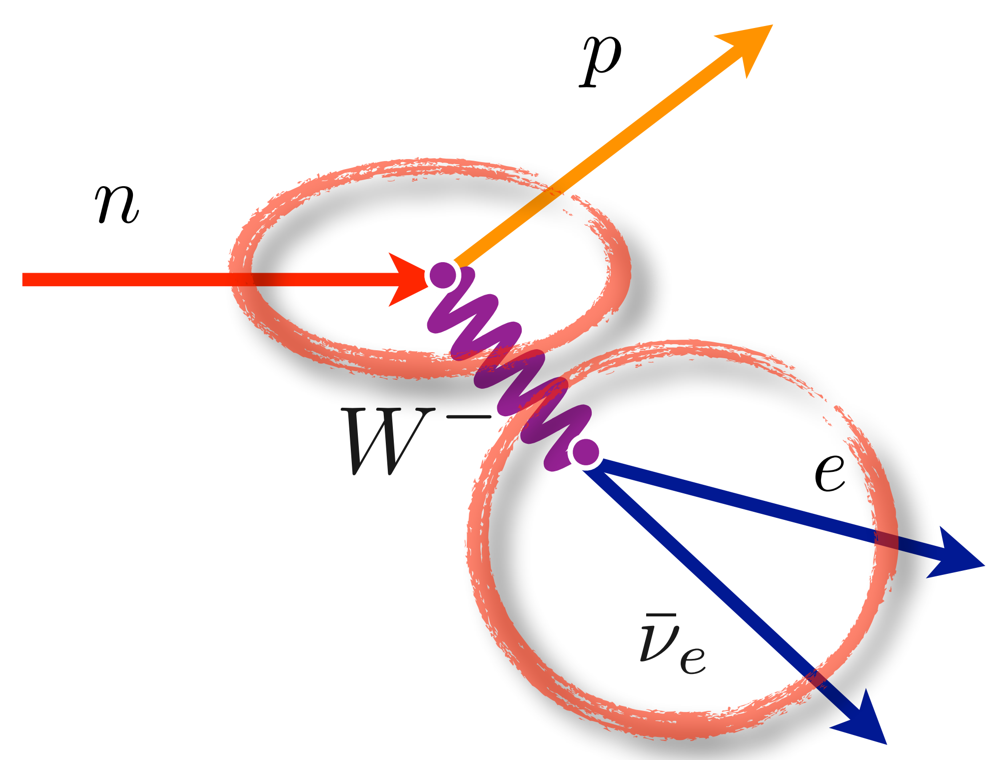
including transitions among quarks

The particle doublets that we know so far:

Q	
0 +1	$\begin{pmatrix} n \\ p \end{pmatrix} \circlearrowright W$
0 -1	$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \circlearrowright W \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \circlearrowright W \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \circlearrowright W$

making these transitions is the W Boson’s job.

Notice, that all of these transitions change the electric charge as well as the particle type



call a generic lepton, “ℓ“

$$\begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix} \circlearrowright W$$

$$\ell = e, \mu, \tau$$

there are still weak interactions

including transitions among quarks

The particle doublets in quark language:

Q			
+2/3, -1/3	$\begin{pmatrix} u \\ d \end{pmatrix} \circlearrowright W$	$\begin{pmatrix} ? \\ s \end{pmatrix} \circlearrowright W$	
0, -1	$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \circlearrowright W$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \circlearrowright W$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \circlearrowright W$

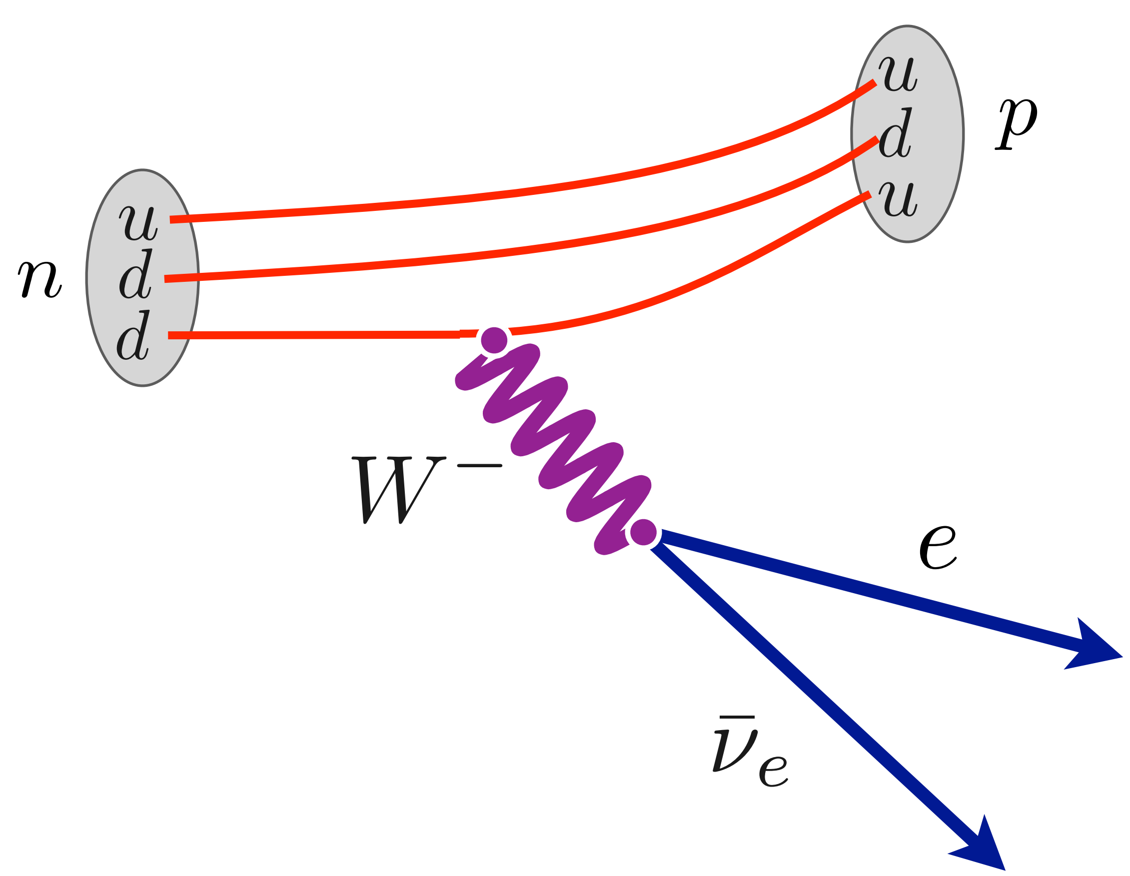
making these transitions is *still* the W Boson's job.

Notice, that all of these transitions change the electric charge as well as the particle type

call a generic lepton, "ℓ"
call a generic quark, "q"

$$\begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix} \circlearrowright W \qquad \begin{pmatrix} q \\ q' \end{pmatrix} \circlearrowright W$$

$$\ell = e, \mu, \tau \qquad q = u, d, s$$



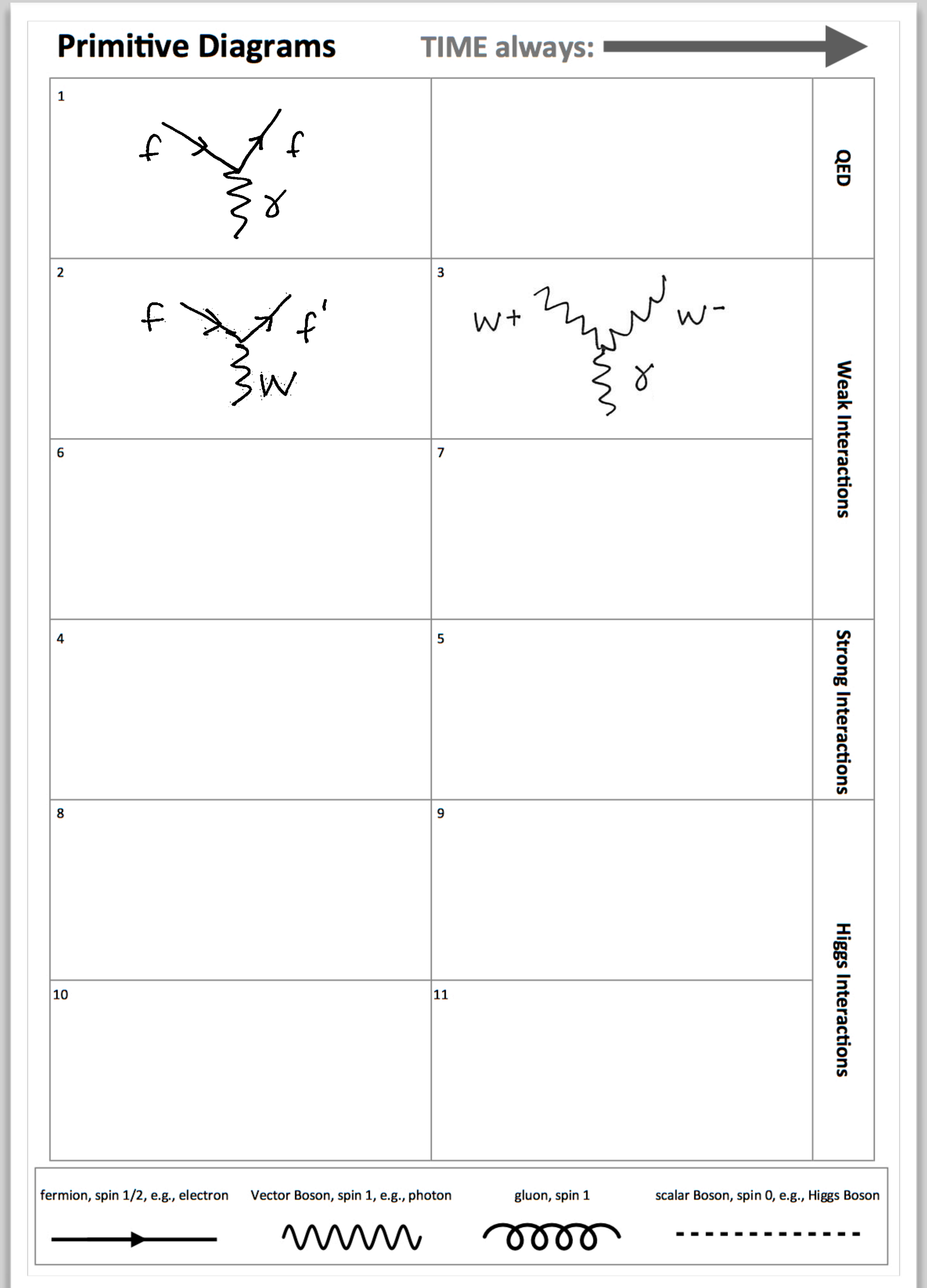
or:
call a generic fermion, "f"

$$\begin{pmatrix} f \\ f' \end{pmatrix} \circlearrowright W$$

$$f = \ell, q$$

NOW...your second entry into your

table of primitive diagrams



particle: **charm quark**

symbol: *c*

charge: +2/3

mass: 1,270 MeV/c^2

spin: 1/2

category: Fermion, I=0, B=1/3, S=0, C=+1

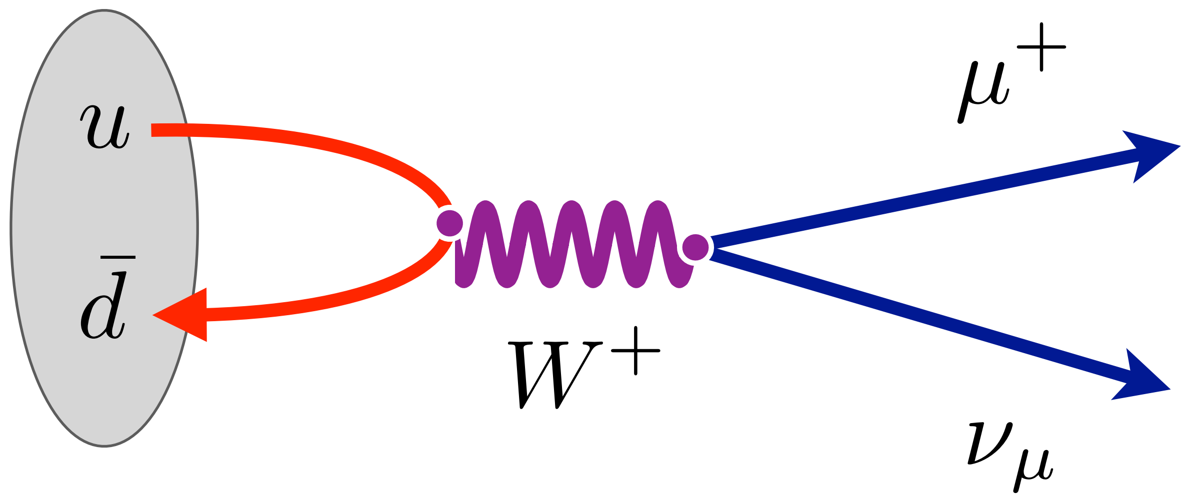
so, decays we've seen

just put in the decaying quark and let the other "spectator quarks"

come along for the ride

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

responsible for making neutrino beams from proton accelerators



Strong interaction, again:

The original question about nuclei...

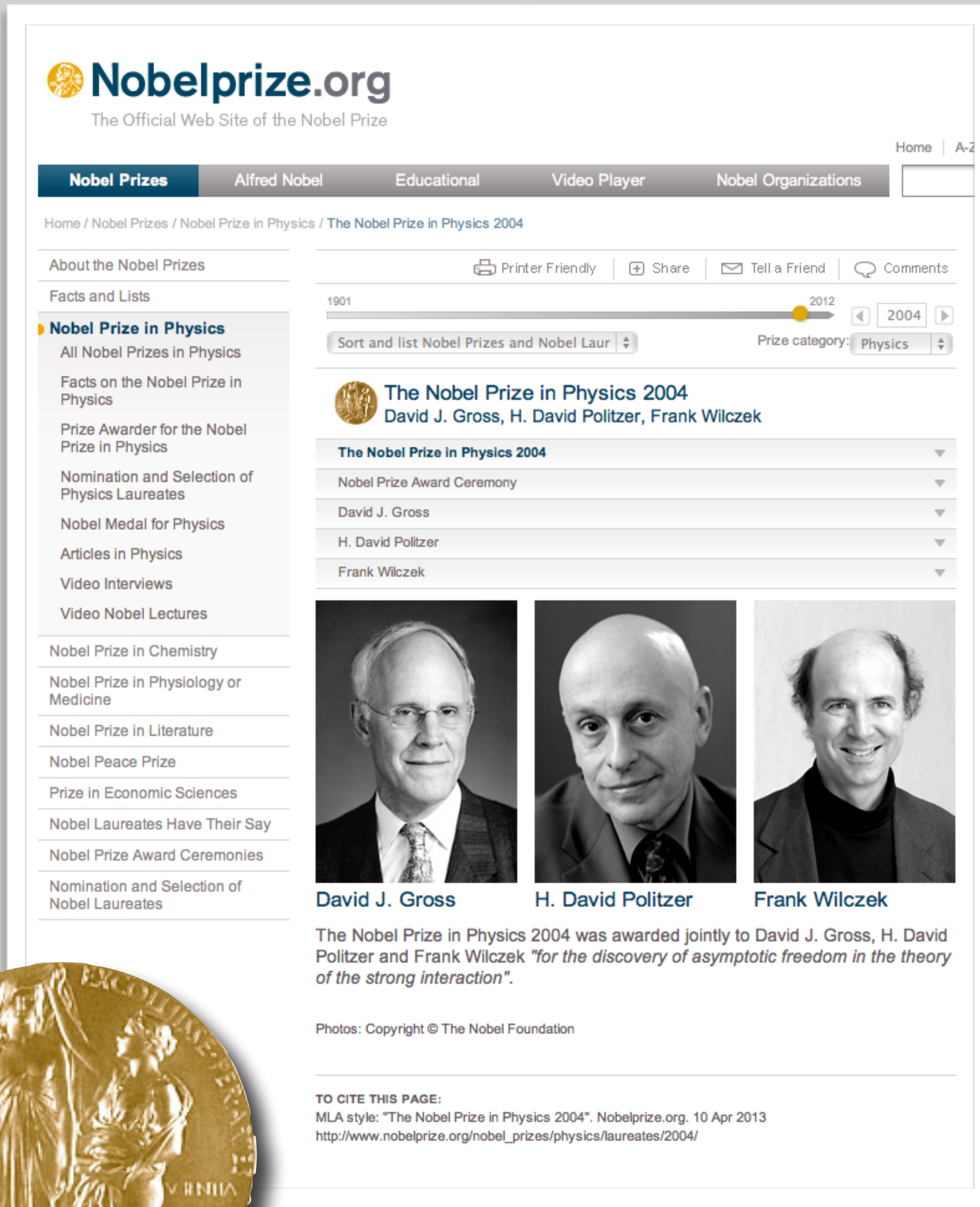
now in play for quarks:

what holds the quarks inside of the baryons and mesons?

Gross, Politzer, and Wilczek

2004

"asymptotic freedom" in strong interactions

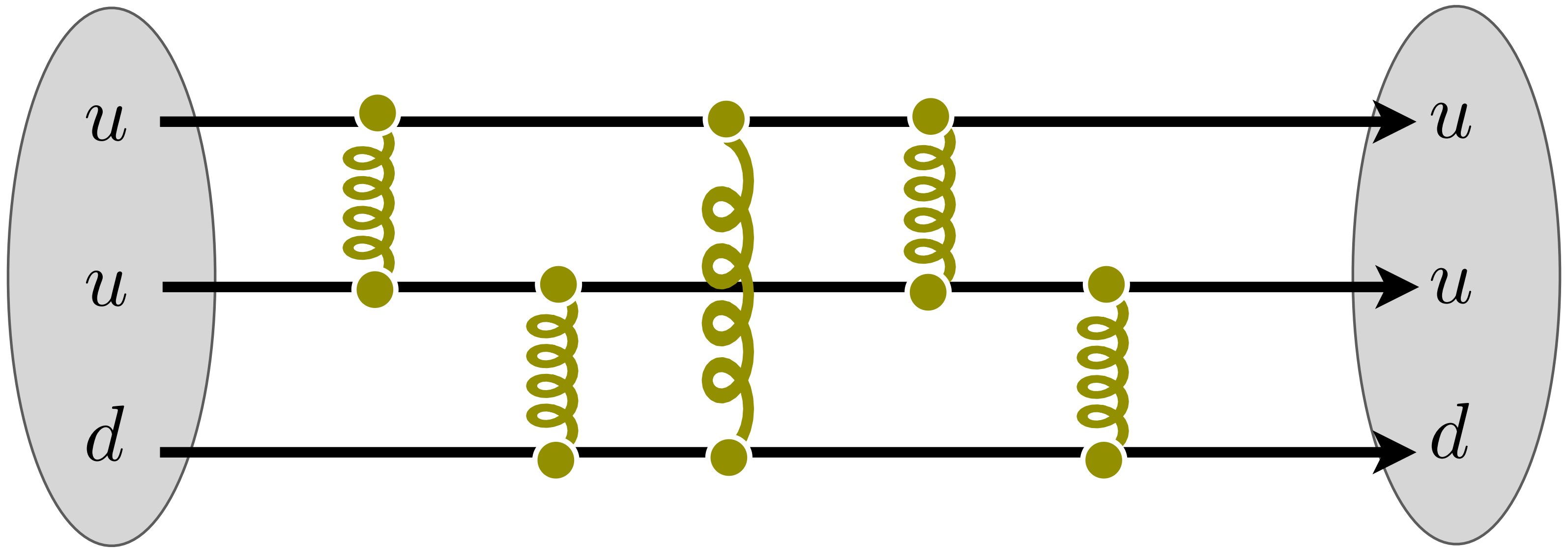


it's the glue that holds everything together

virtually

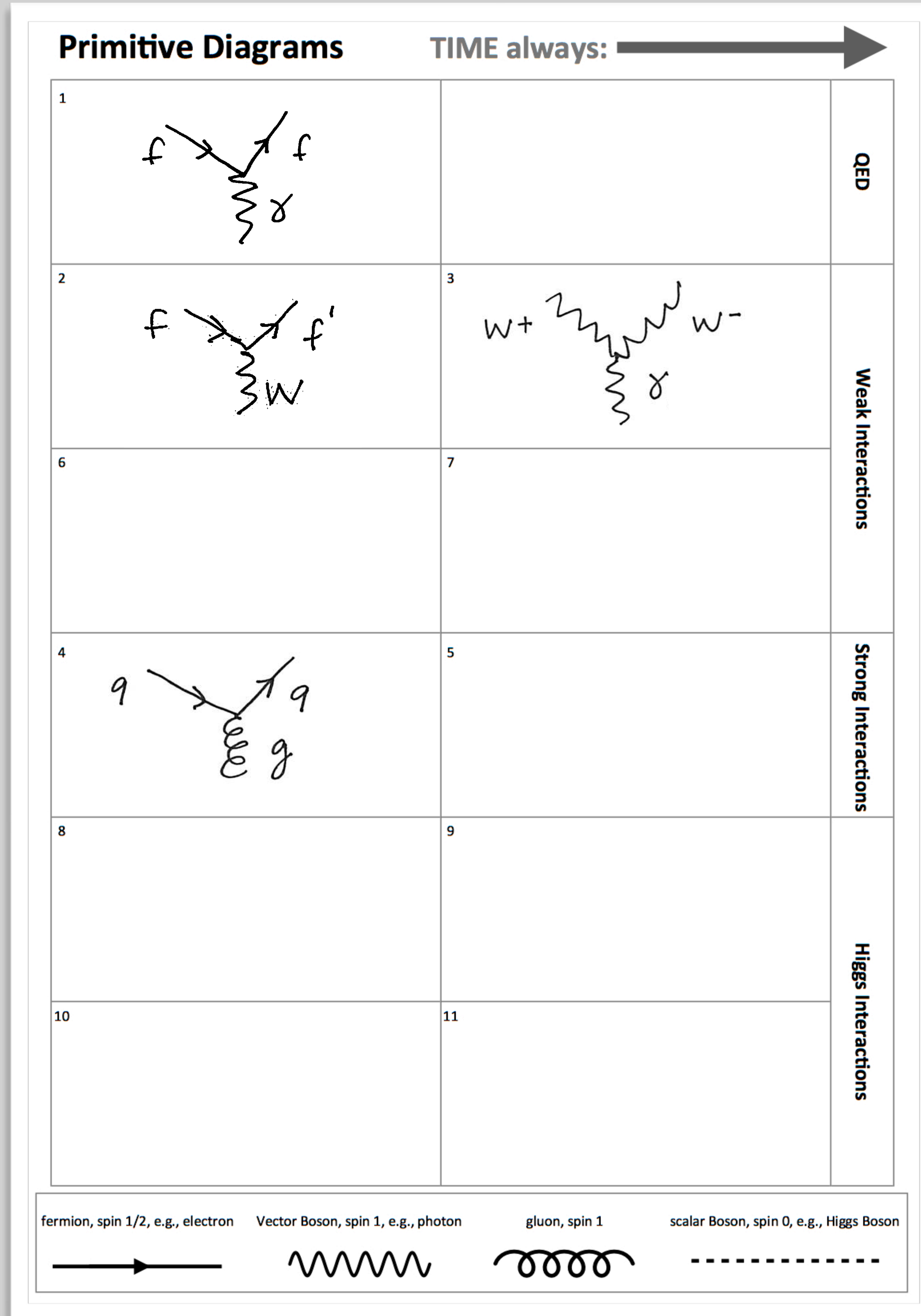
Predicted the existence of the Strong Messenger Particle:

the Gluon



third entry into your

table of primitive diagrams

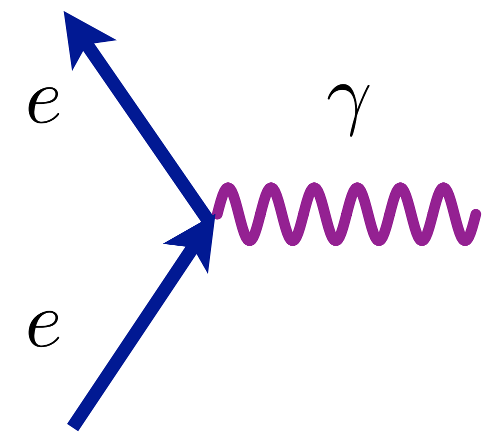


there are two amazing things

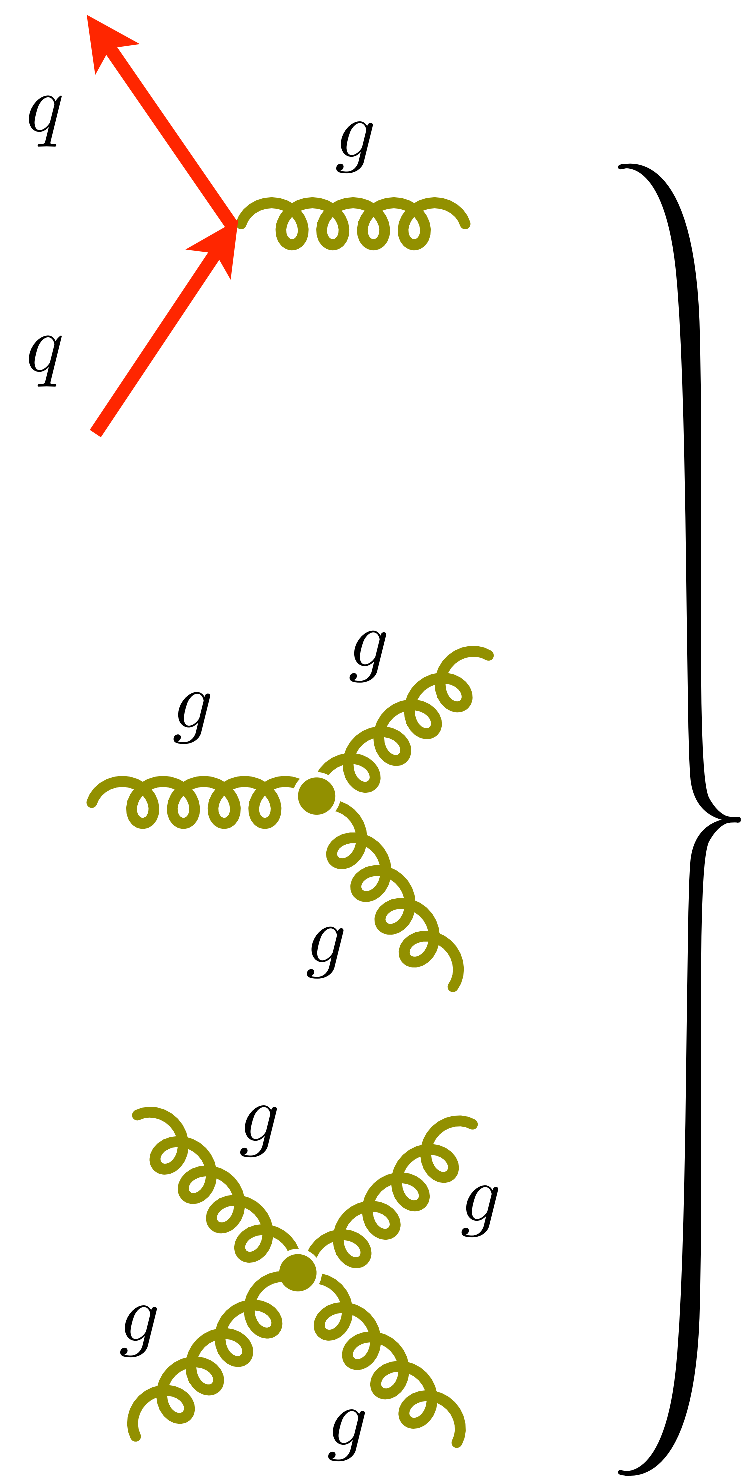
about gluons

thing 1

they self-interact



a photon propagates the electromagnetic force...but it does not have an electric charge

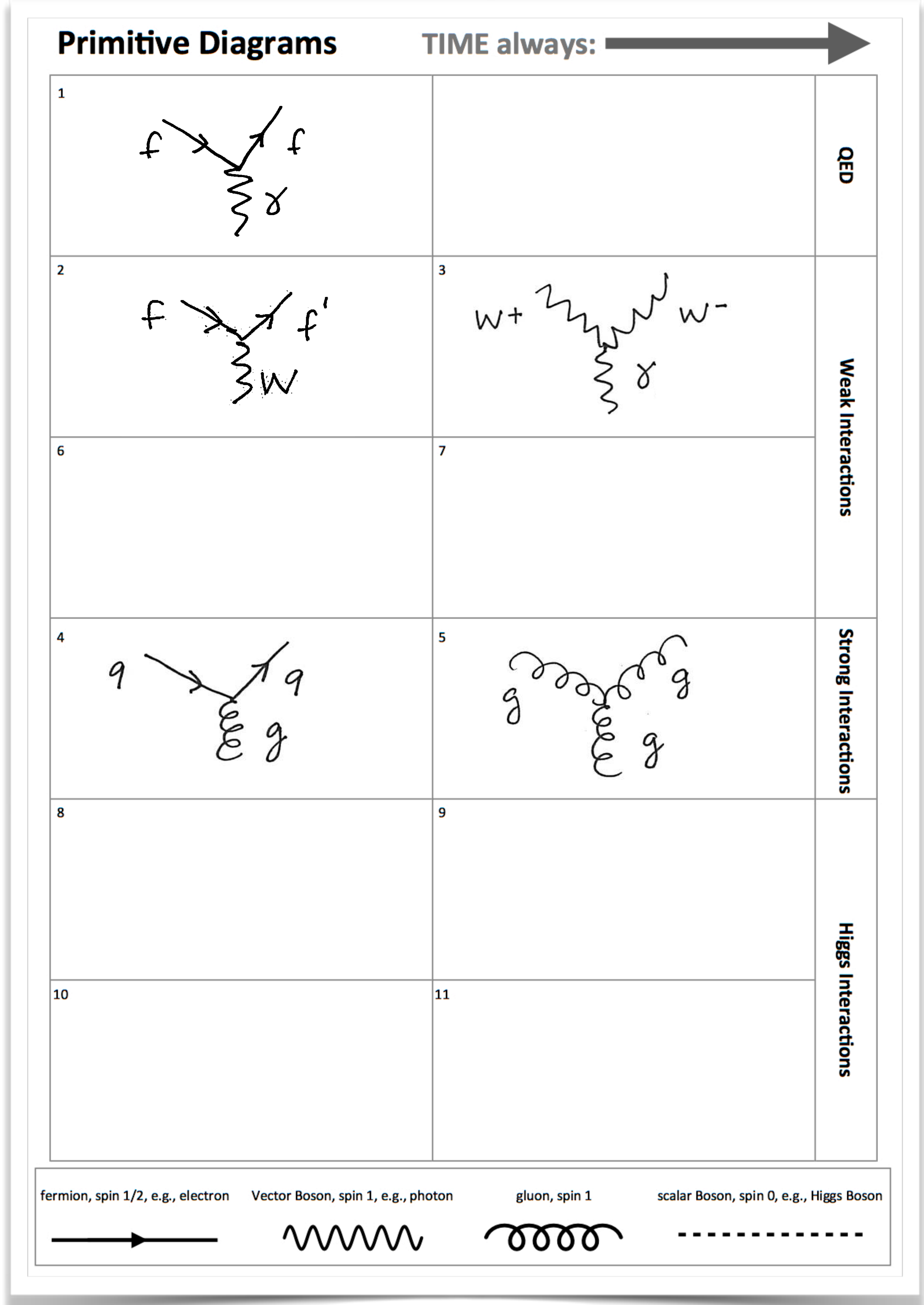


the gluon propagates the strong force...and it DOES have a strong charge

This has significant consequences...almost magical

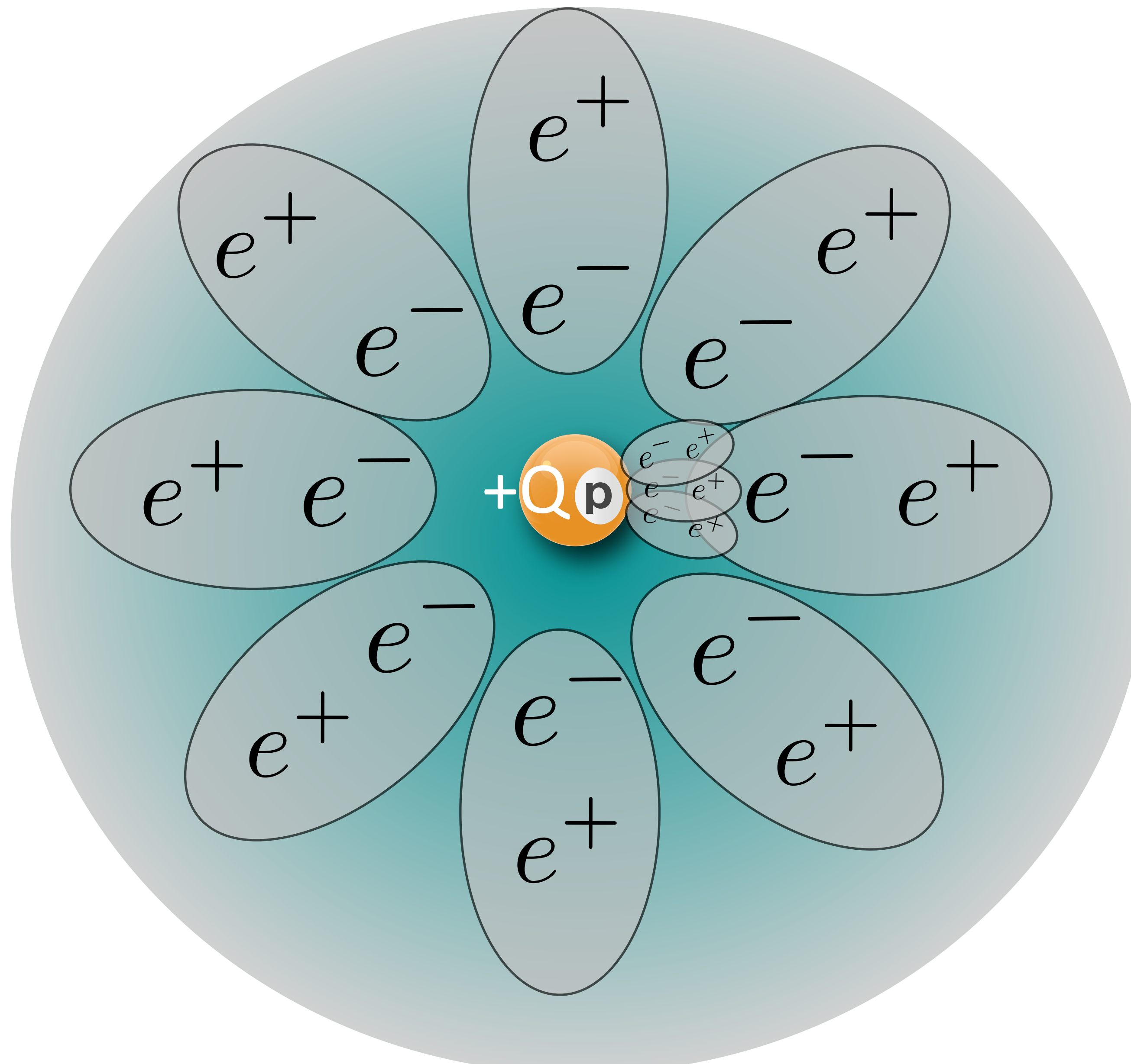
fourth and fifth entries into your

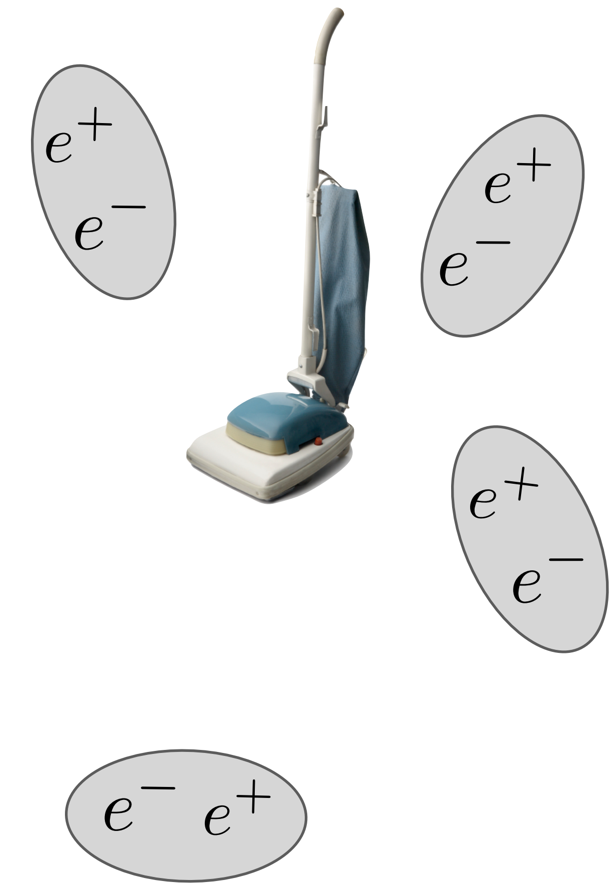
table of primitive diagrams



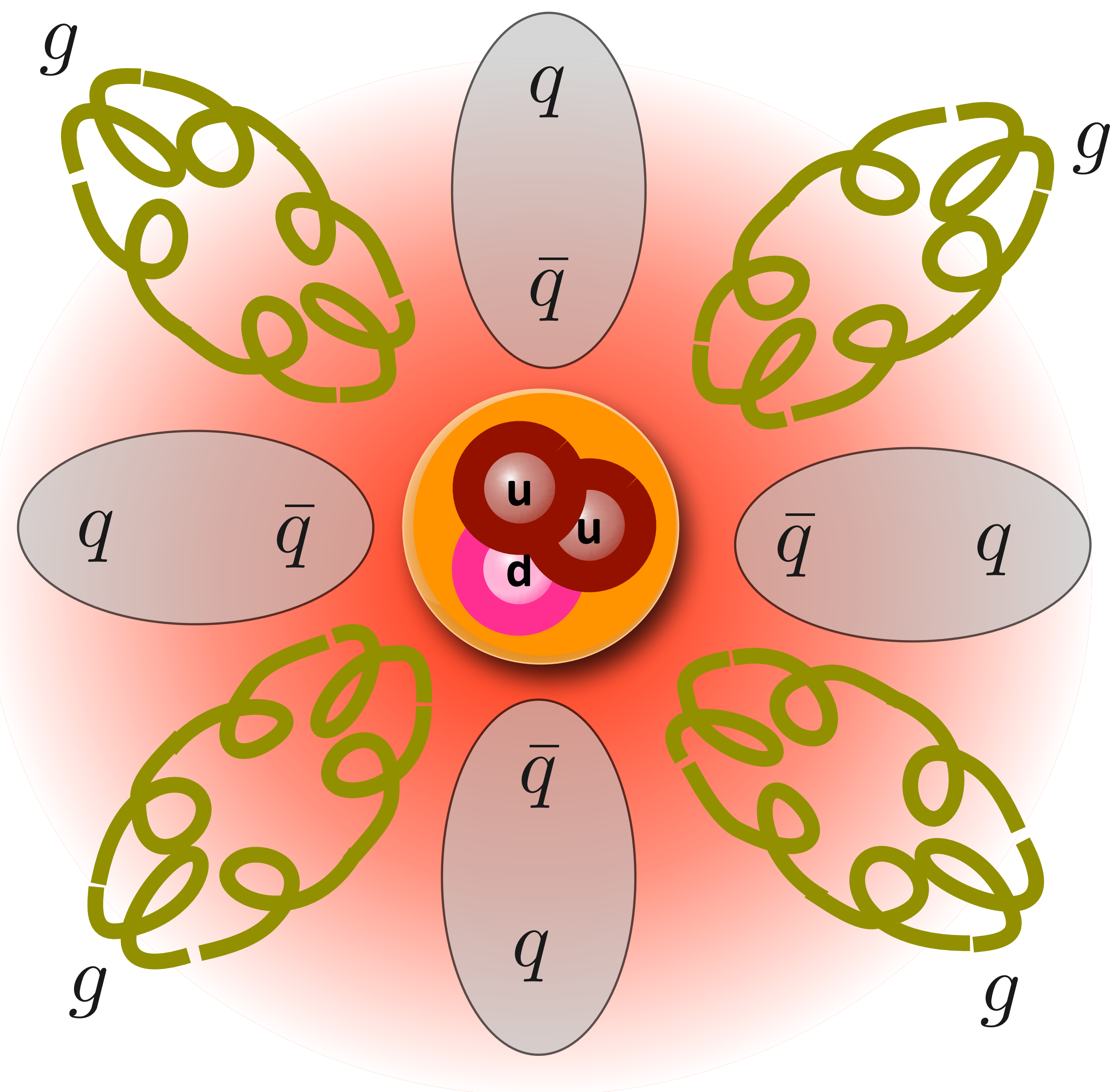
thing 2

their force field is the opposite of electromagnetism, or gravity

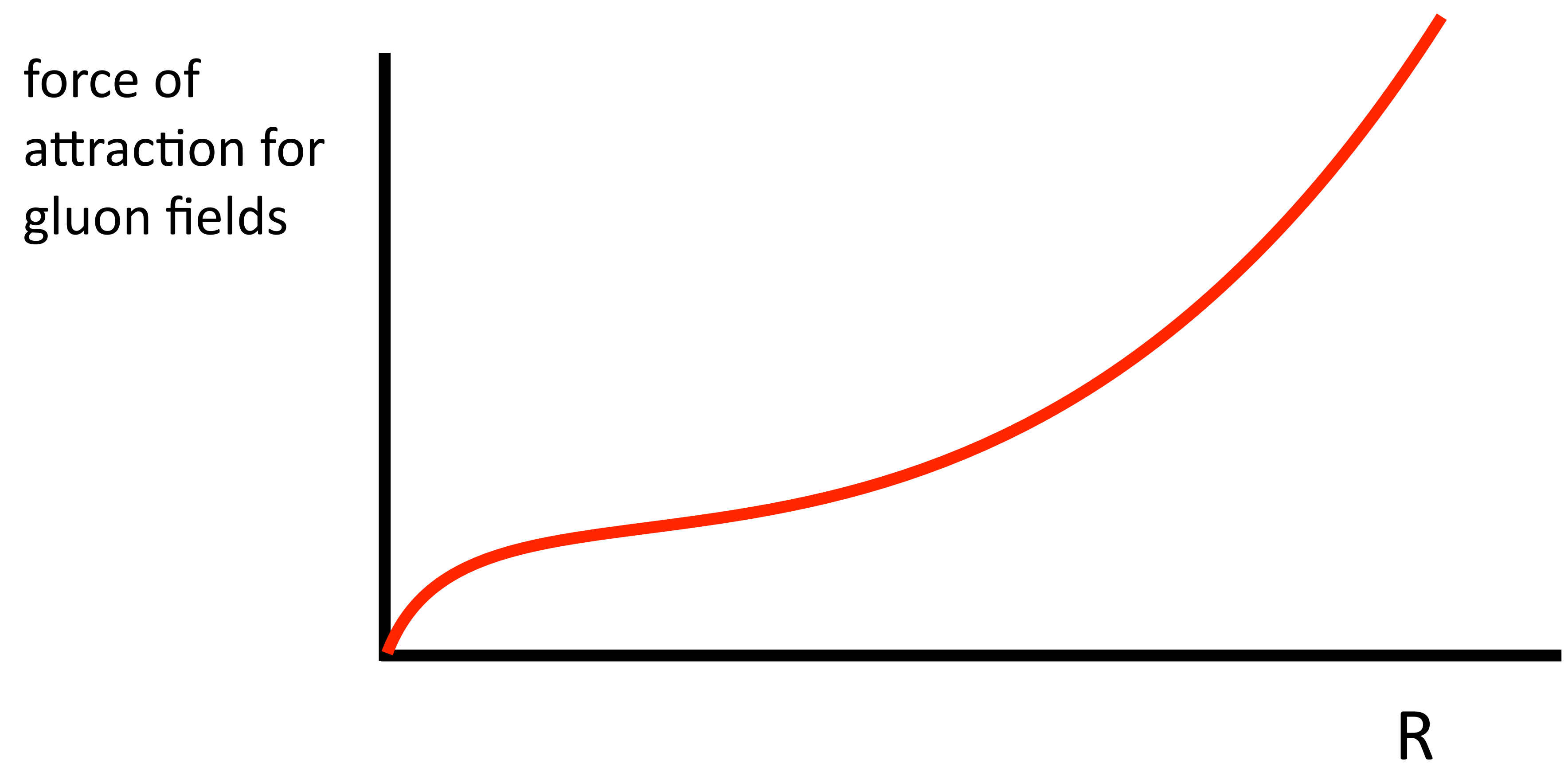




ah, but the gluon is odd



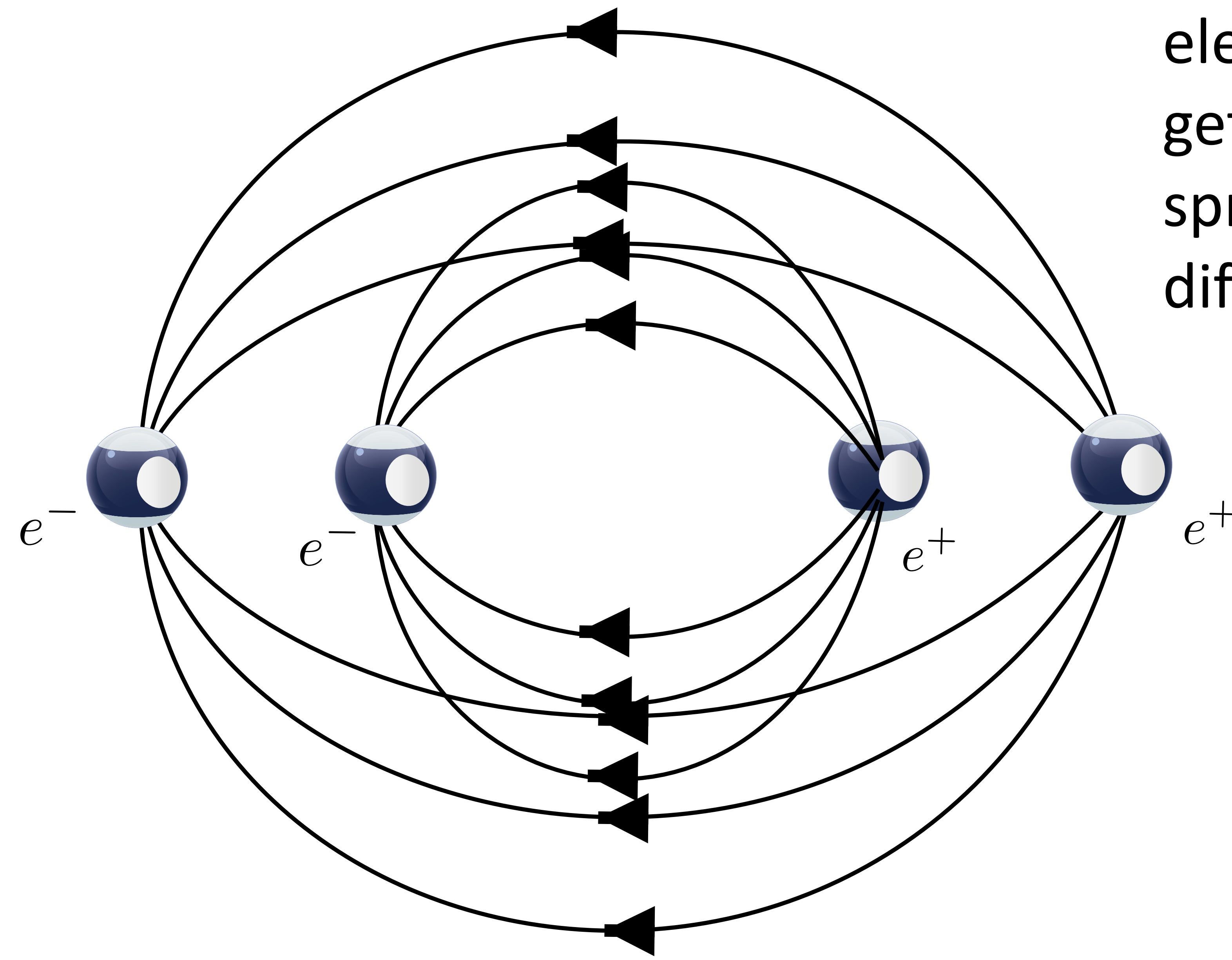
the further away you get, the **STRONGER** the quark-quark attraction is!



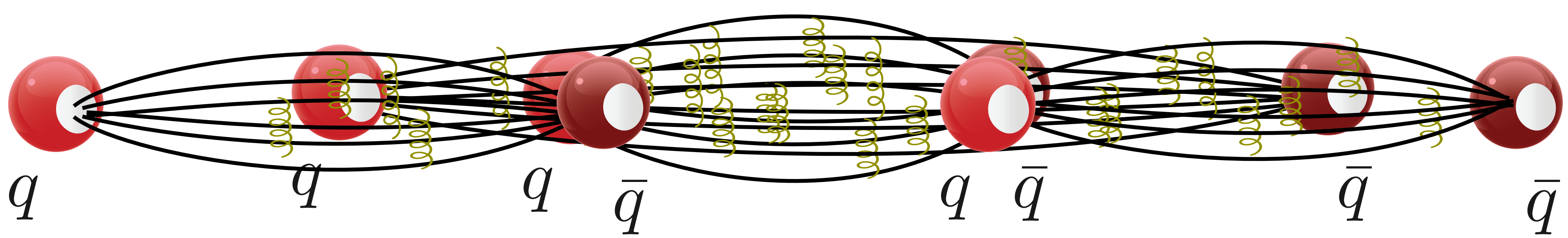
pull 'em apart

called

quark confinement



electric fields get more spread out – diffuse



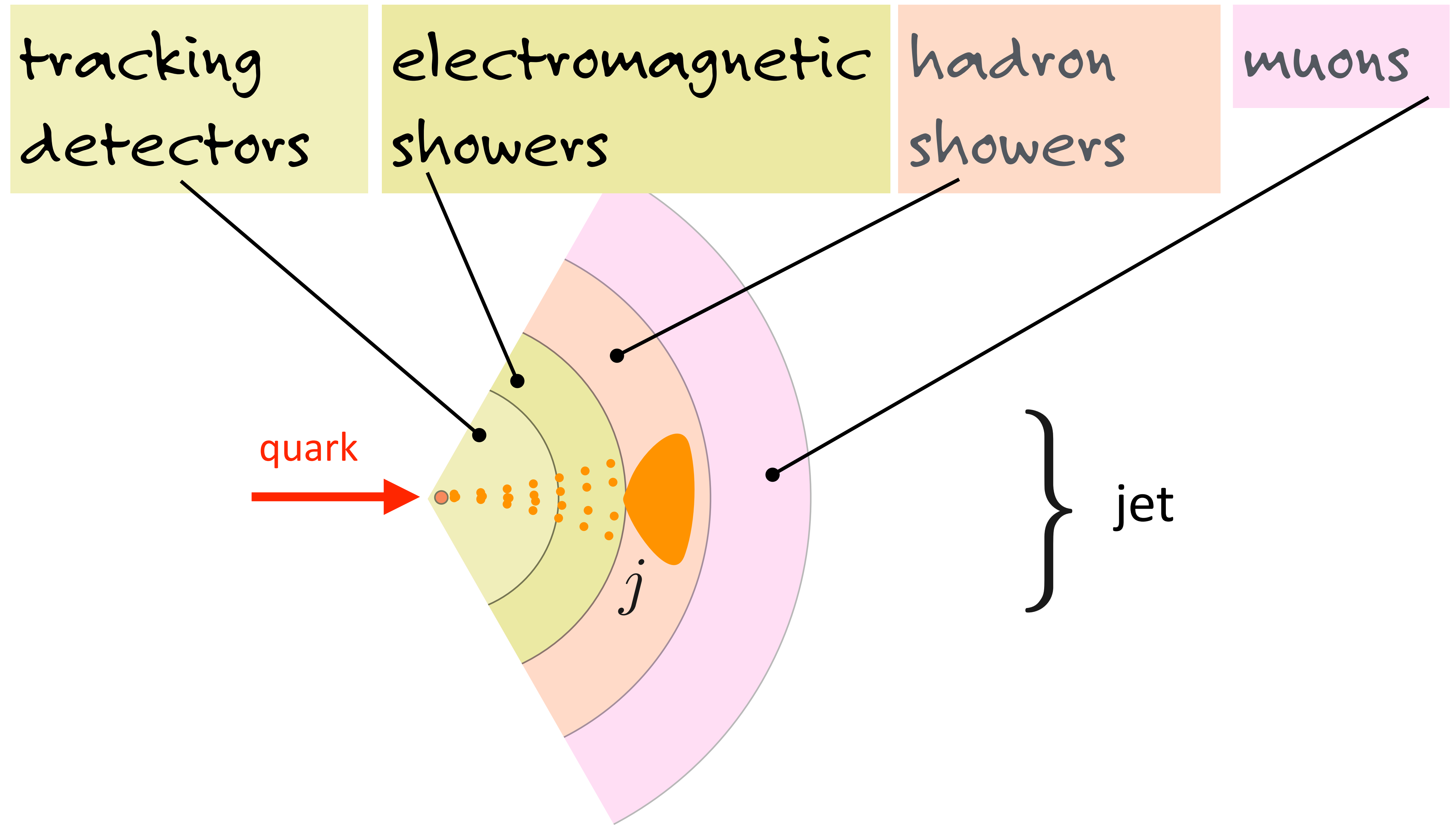
The energy in the field is so high...that it pops a new quark-antiquark pair out of the vacuum.

We don't see individual quarks or gluons

they make more quarks and gluons

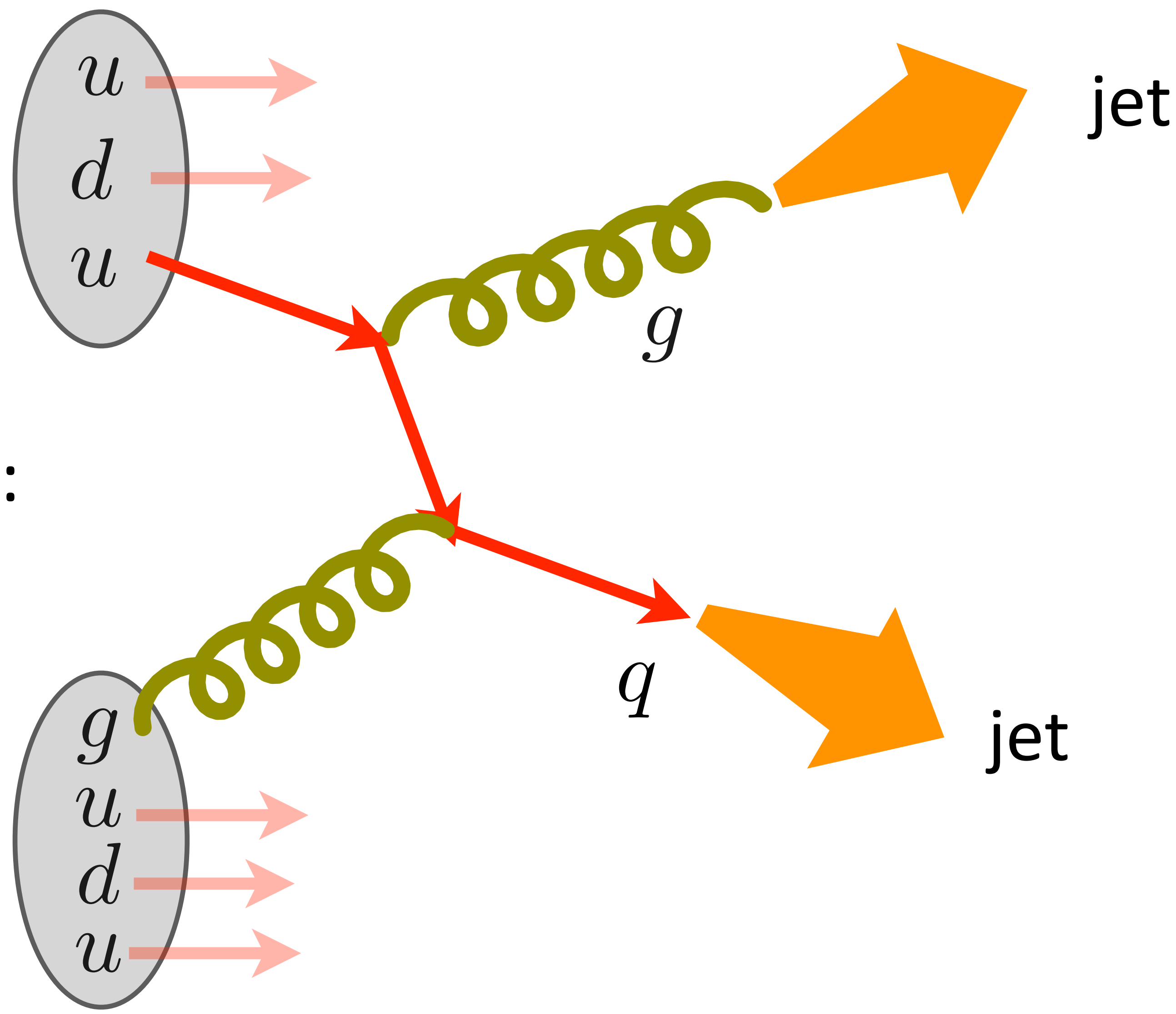
and interact very quickly into a cascade of particles

"quark-gluon **jets**"

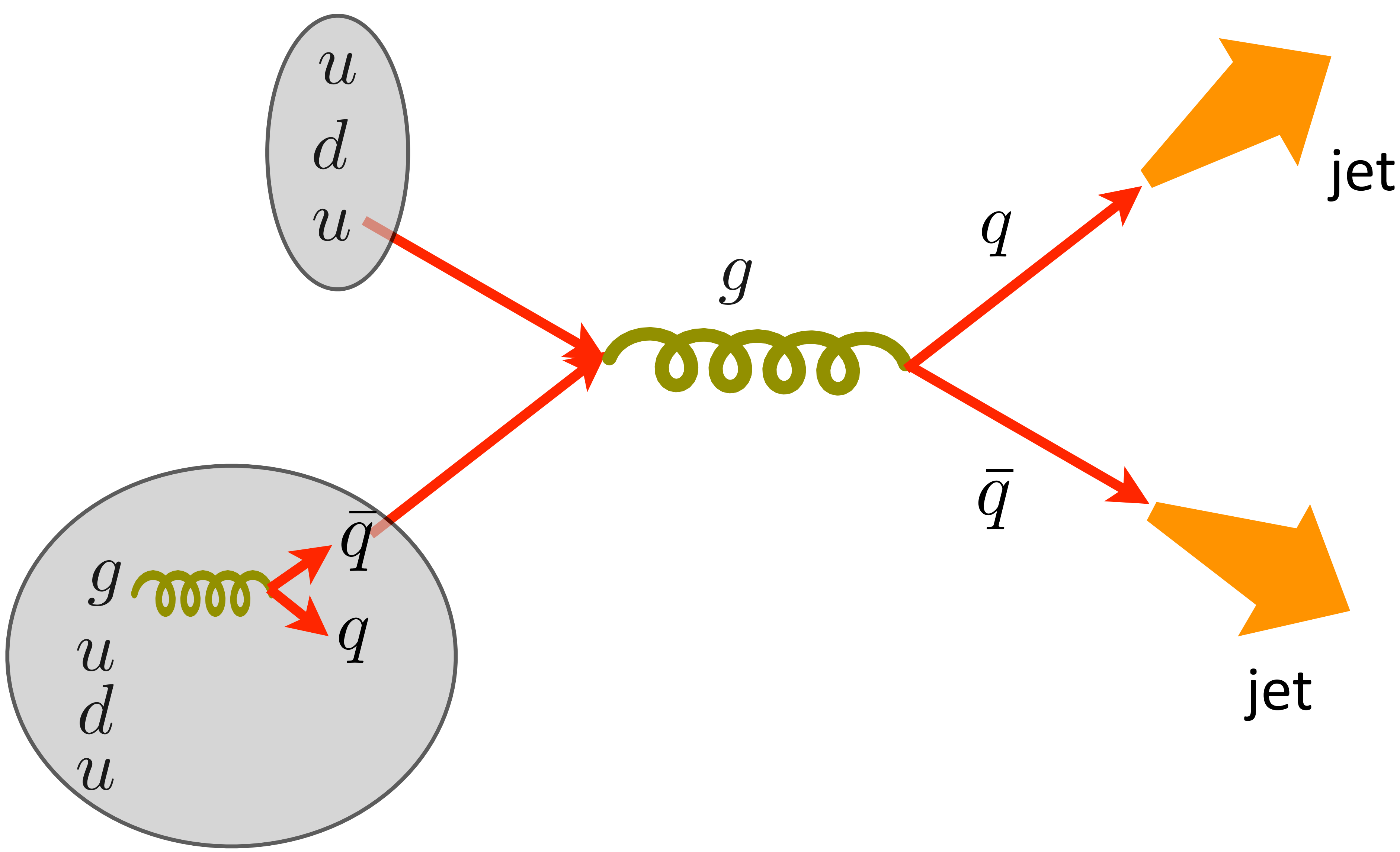


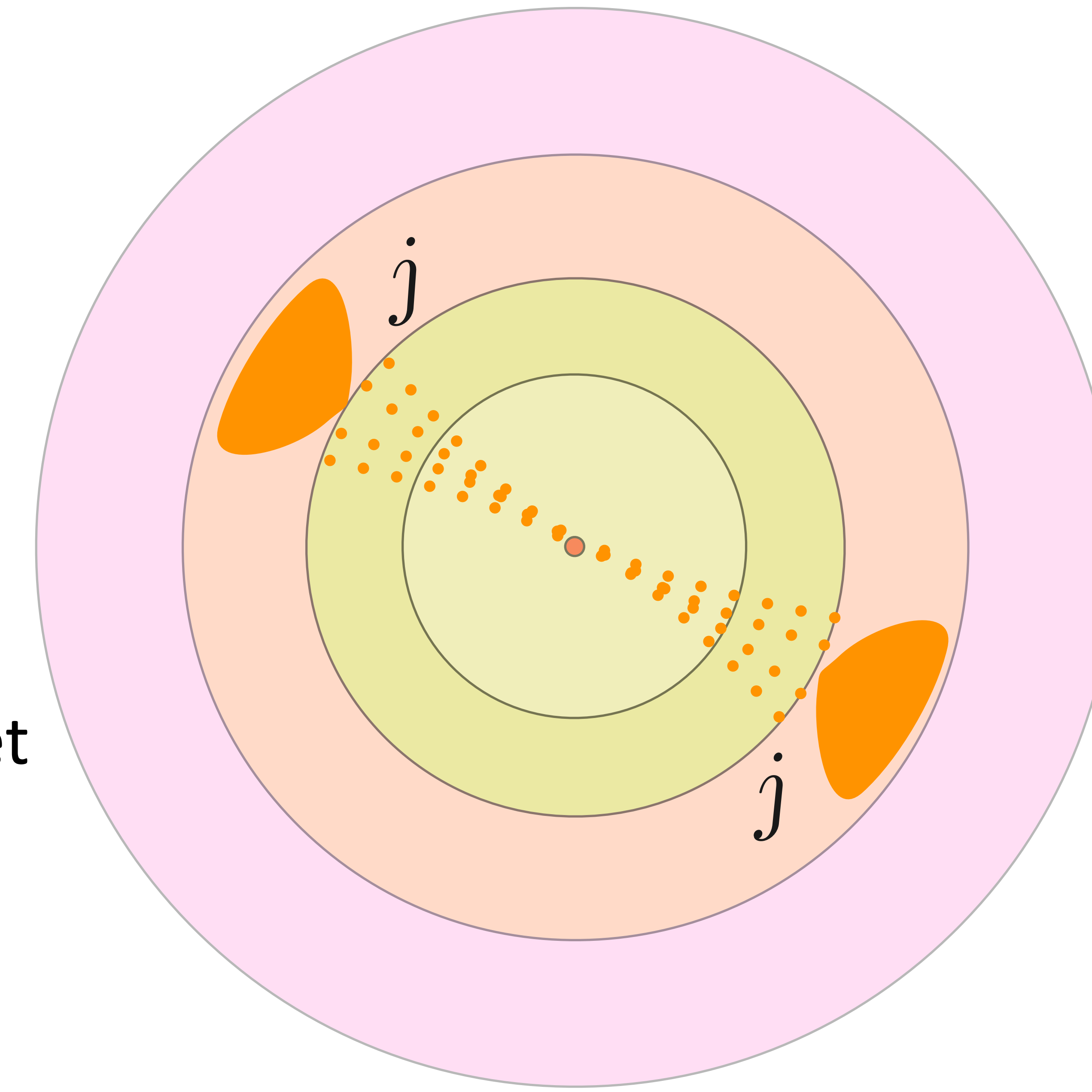
in ATLAS

maybe:

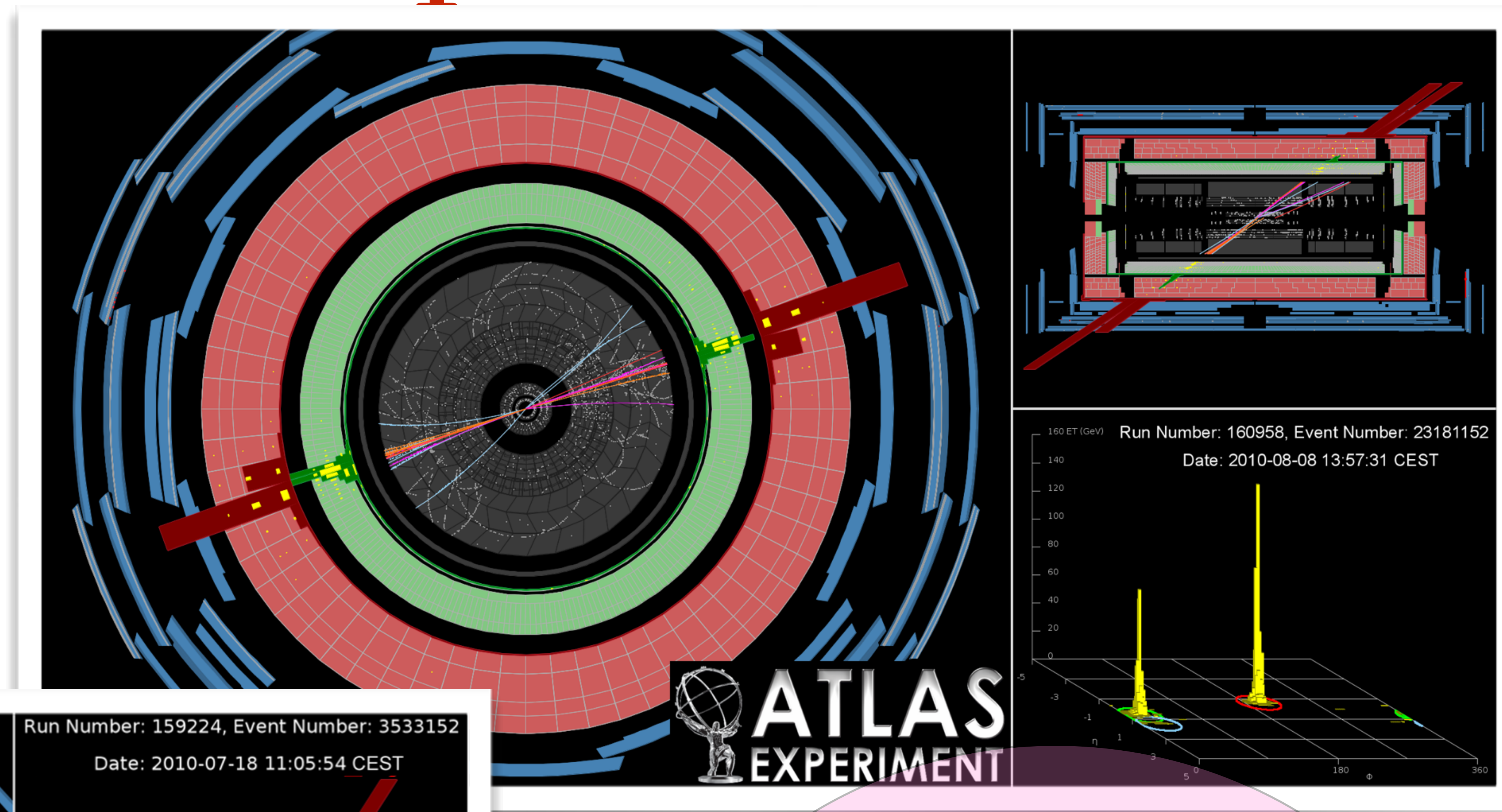


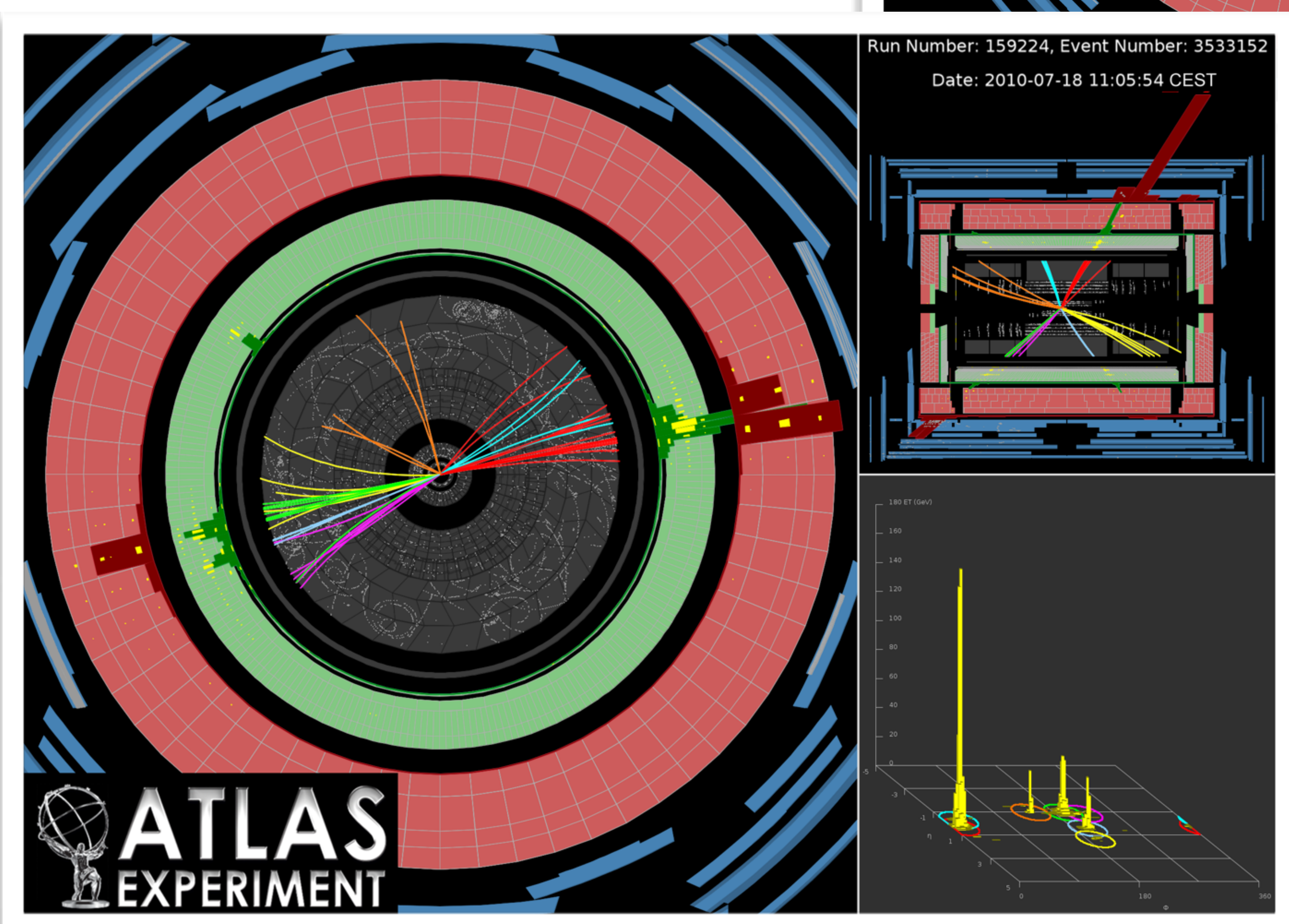
or:

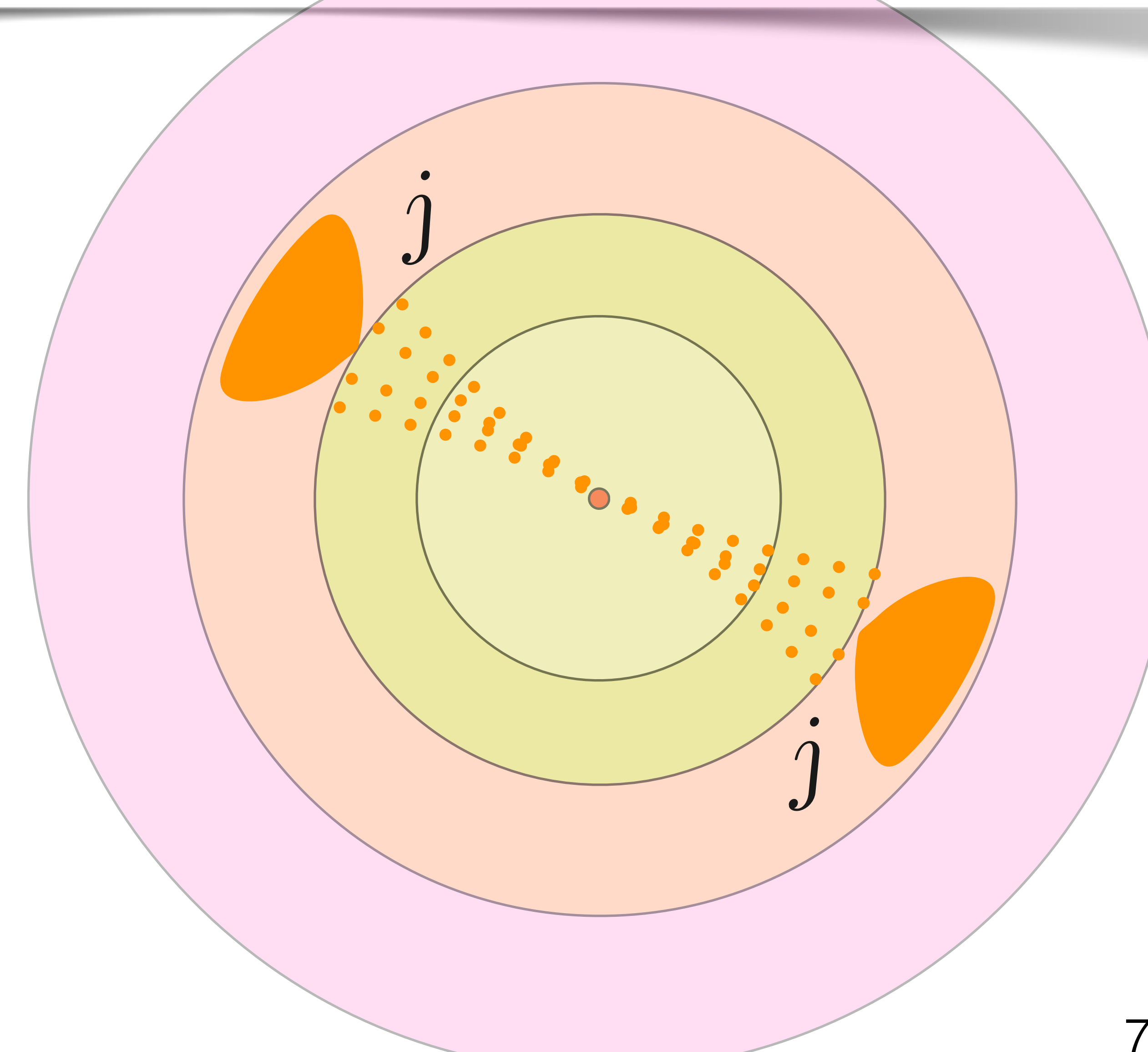




‘‘hard’’ quark production





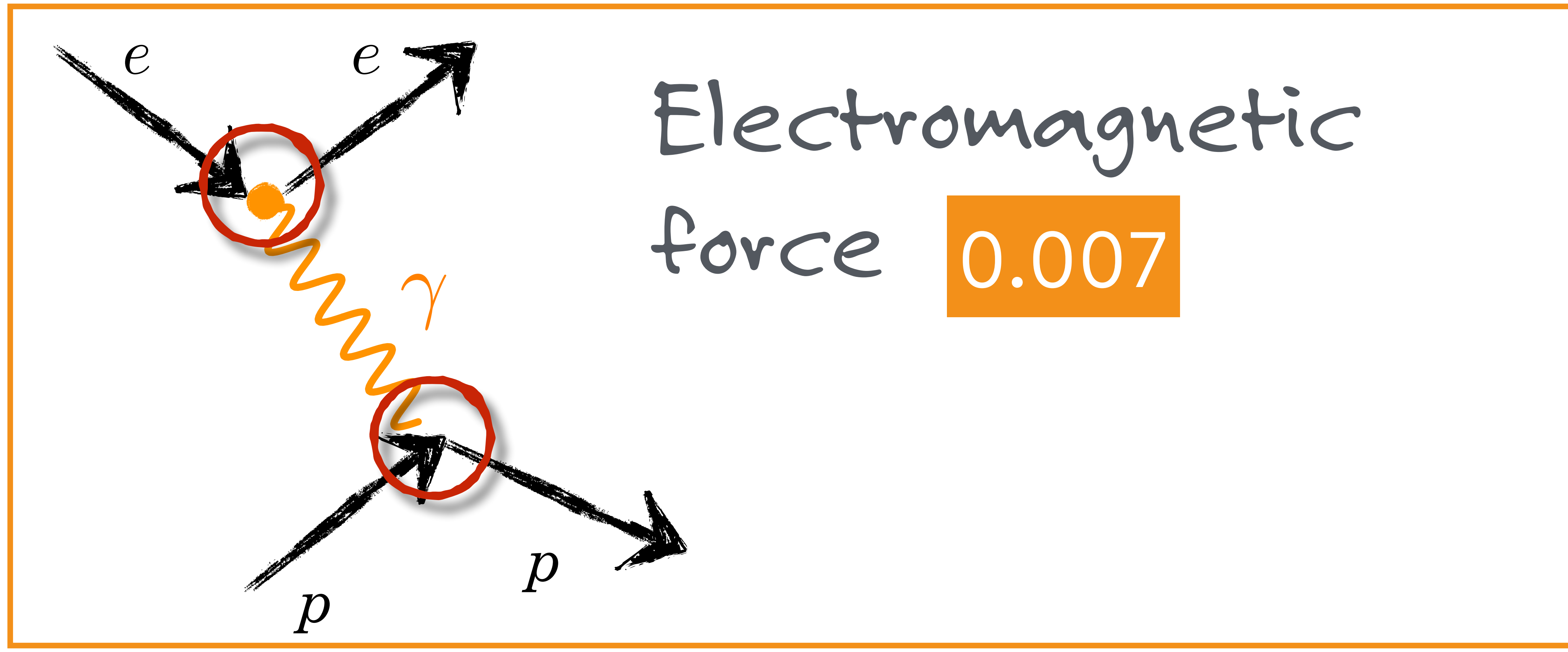


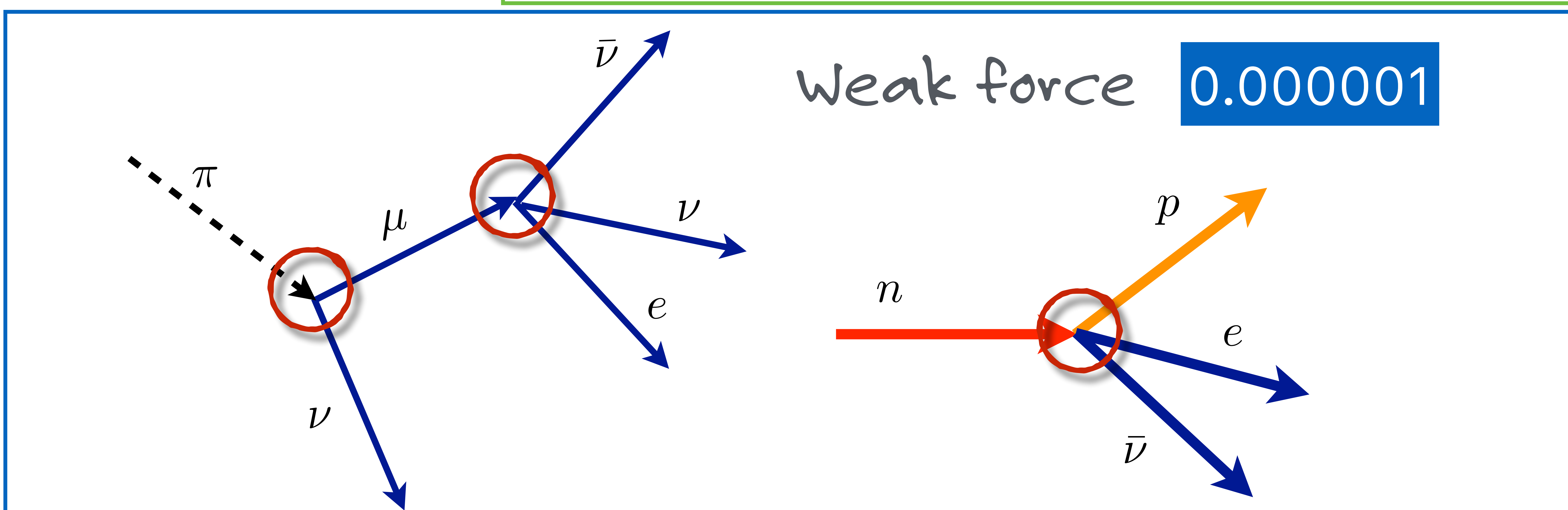
particle: **gluon**

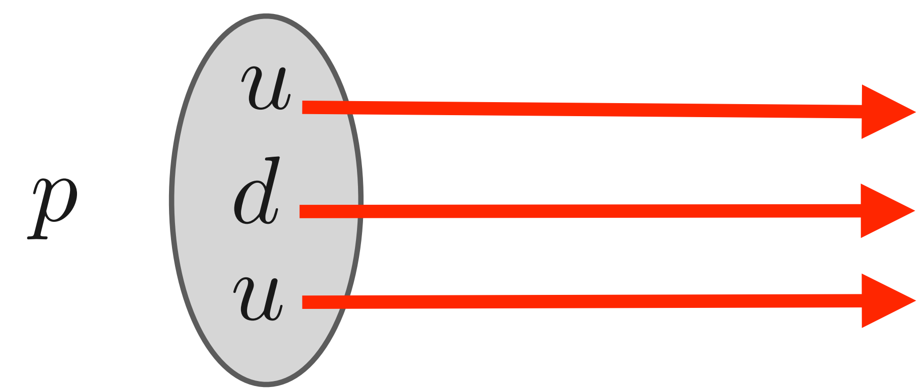
symbol:	*g*
charge:	0
mass:	0
spin:	1
category:	Strong Vector Boson

three forces now

of vastly different strengths







particle: **proton**

symbol: *p*

charge: +1*e*

mass: 1.6726 x 10^{-2}[illegible] kg, 938.2 MeV/c^2

spin: 1/2

category: fermion, baryon, I = 1/2, B = 1

particle: **down quark**

symbol: *d*

charge: –1/3

mass: 4.1 to 5.8 MeV/c^2

spin: 1/2

category: Fermion, I=–1/2, B=1/3, S=0

particle: **up quark**

symbol: *u*

charge: +2/3

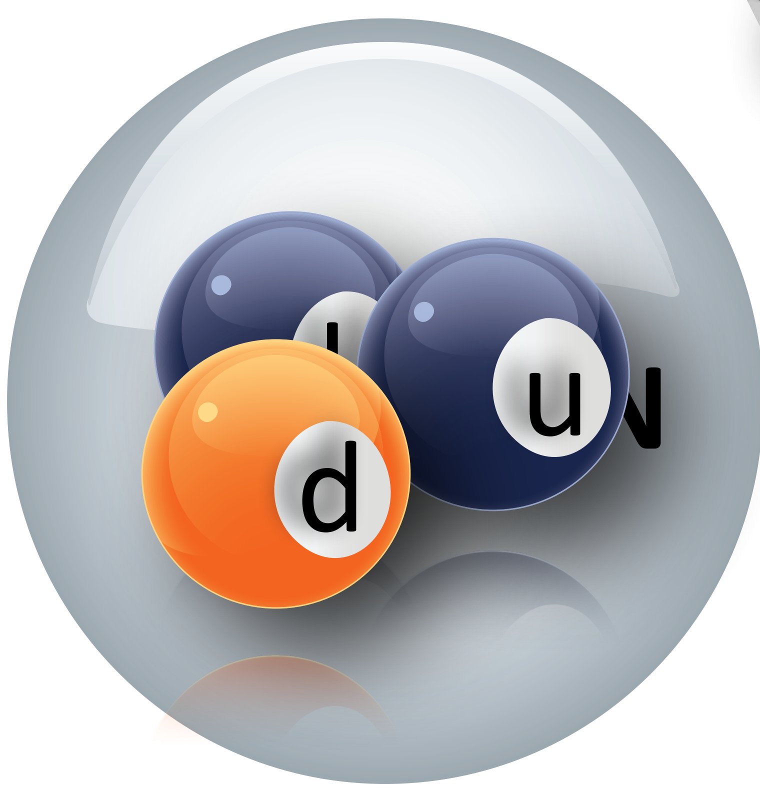
mass: 1.7 to 3.3 MeV/c^2

spin: 1/2

category: Fermion, I=+1/2, B=1/3, S=0

why does the proton weigh?


1 Ton
1 Ton


u
d

Field Energy

so:

$$m = \frac{E}{c^2}$$

here's the elementary particles story

circa 1975

the messengers

spin 1 Bosons

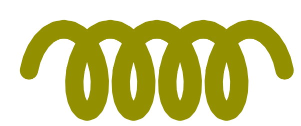
circa 1980

the photon

"propagates the electromagnetic force"

the W Boson

"propagates the weak force"



the gluon

"propagates the strong force"

say tuned.

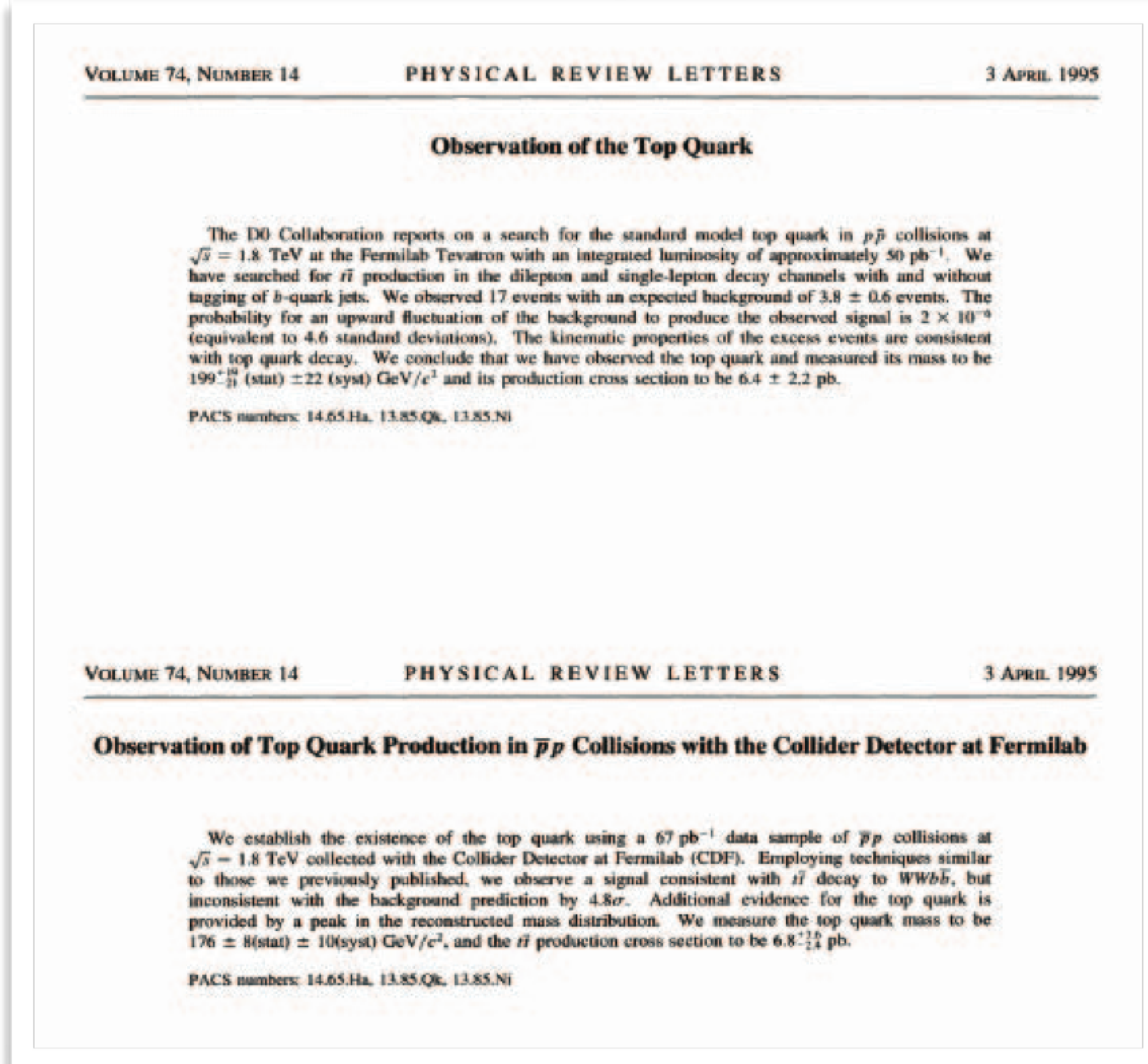
particle: **bottom quark**

symbol:	*b*
charge:	-1/3 e
mass:	4.5 GeV/c^2 = 4.5 p
spin:	1/2
category:	Fermion, quark

the “top quark” was discovered in 1995

by two experiments at Fermilab

with MSU faculty and students intimately involved



Volume 74, Number 14 PHYSICAL REVIEW LETTERS 3 April 1995

Observation of the Top Quark

The D0 Collaboration reports on a search for the standard model top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron with an integrated luminosity of approximately 50 pb^{-1}. We have searched for $t\bar{t}$ production in the dilepton and single-lepton decay channels with and without tagging of b-quark jets. We observed 17 events with an expected background of 3.8 ± 0.6 events. The probability for an upward fluctuation of the background to produce the observed signal is 2×10^{-6} (equivalent to 4.6 standard deviations). The kinematic properties of the excess events are consistent with top quark decay. We conclude that we have observed the top quark and measured its mass to be 199^{+19}_{-21} (stat) ± 22 (syst) GeV/c^2 and its production cross section to be 6.4 ± 2.2 pb.

PACS numbers: 14.65.Ha, 13.85.Qk, 13.85.Ni

Volume 74, Number 14 PHYSICAL REVIEW LETTERS 3 April 1995

Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be 176 ± 8(stat) ± 10(syst) GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

PACS numbers: 14.65.Ha, 13.85.Qk, 13.85.Ni

February 24th, 11AM, we submitted our discovery paper to Physical Review Letters

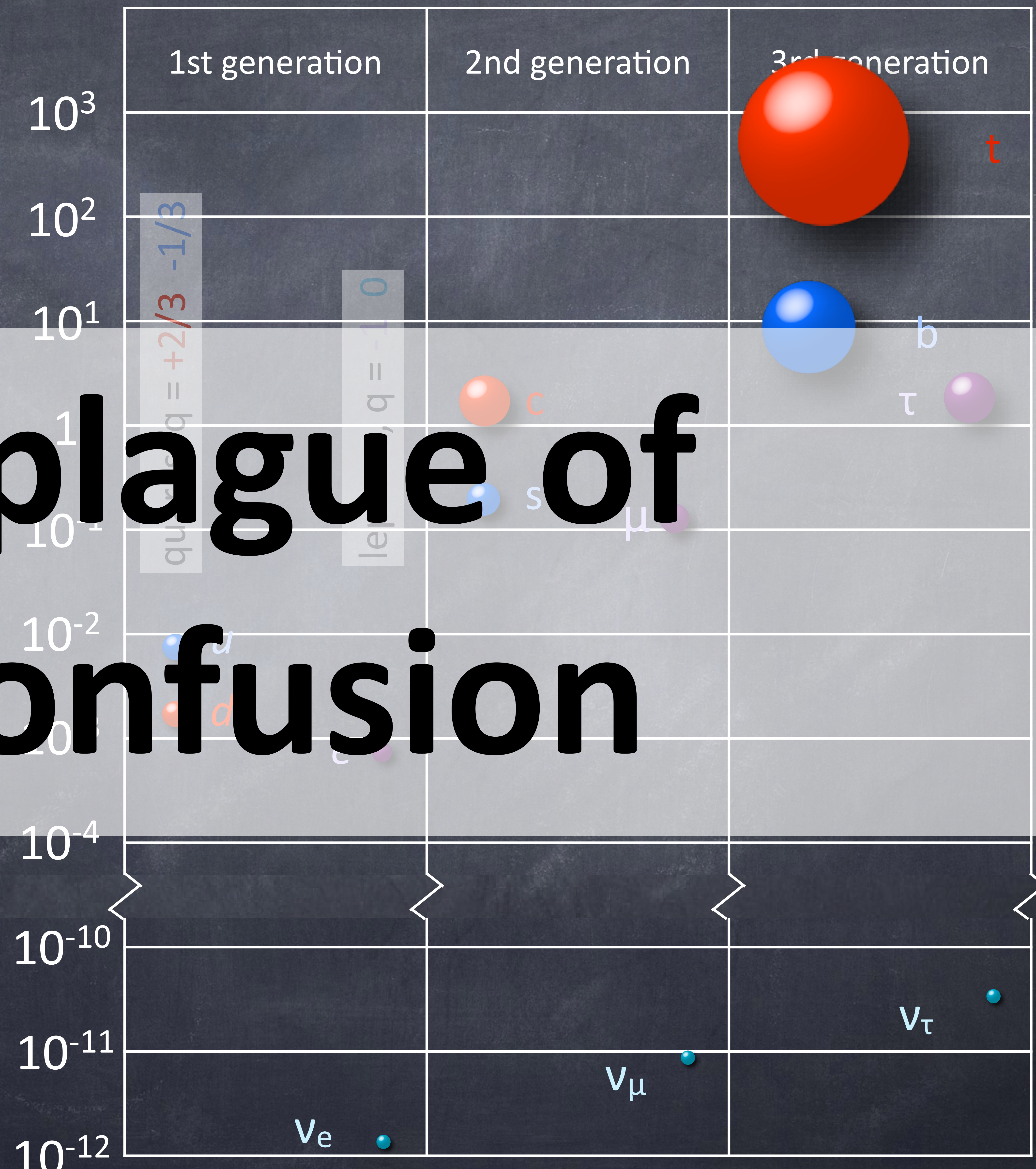
March 2, 1995 the announcement was made at Fermilab

Cultura e Spettacoli
quark discovery
Dove vai, cacciatore di quark?
Alles Quark, oder was?
predatori del quark perduto
Nation
For physicists, last piece of a puzzl
RICERCA ITALIANA
EPPUR SI MUOVE
Truth by Consensus
Tajemniczy szósty kwark
AUJOURD'HUI
Quand les particules livrent leur dernier secret
The Quark Is a Porker
Physicists Weigh In
LA STAMPA
tuttoscien
Kwark T - najtajemniczej z szóstkowej rodziny
LES BRICOLAGES DE LA VIE
Ora la fisica è al Top
Topquark-jagers eindigen ex aequo

particle: **top quark**

symbol:	*t*
charge:	+2/3 e
mass:	172.0±2.2 GeV/c^2 = 172 p
spin:	1/2
category:	Fermion, quark

quarks & leptons



a plague of confusion

the weak interactions

still operate with the increased doublet sets

The complete (circa 2000) particle doublets:

Q			
+2/3 -1/3	$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$
0 -1	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

the weak interactions

still operate with the increased doublet sets

The complete (circa 2000) particle doublets:

Q			
+2/3 -1/3	$\begin{pmatrix} u \\ d \end{pmatrix}$ W	$\begin{pmatrix} c \\ s \end{pmatrix}$ W	$\begin{pmatrix} t \\ b \end{pmatrix}$ W
0 -1	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ W	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$ W	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$ W

the modern picture

of the elementary particle patterns

circa 2000

and still current

the lepton families...lepton "doublets"

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

and their interactions: ✗ no, ✓ yes.

leptons	ν_e	e	ν_μ	μ	ν_τ	τ
strong g	✗	✗	✗	✗	✗	✗
electromagnetic γ	✗	✓	✗	✓	✗	✓
weak W	✓	✓	✓	✓	✓	✓
gravitational	✓	✓	✓	✓	✓	✓

the modern picture

of the elementary particle patterns

circa 2000

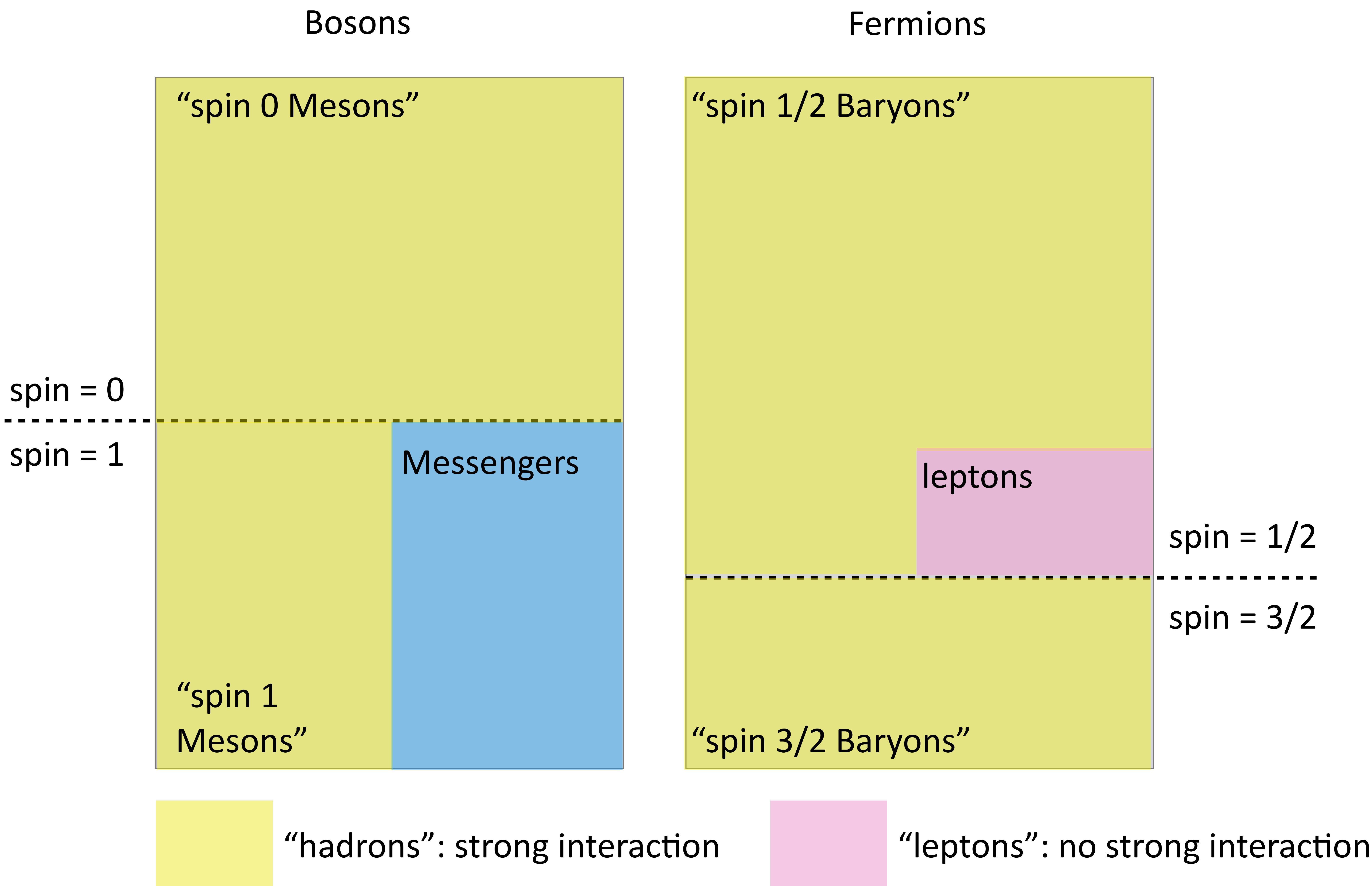
the quark families...quark “doublets”

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

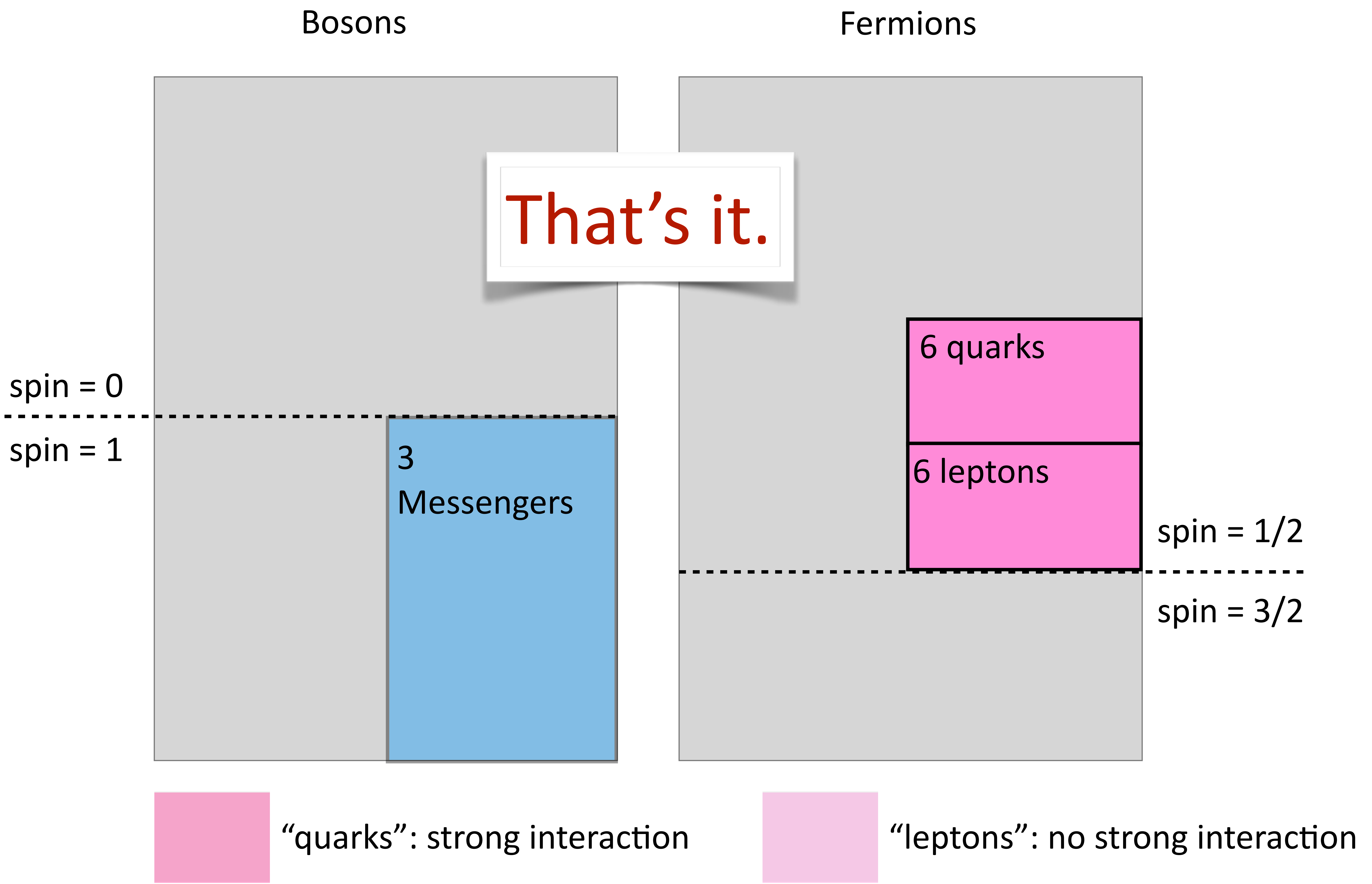
and their interactions: ✘ no, ✔ yes.

quarks	u	d	c	s	t	b
strong g	✔	✔	✔	✔	✔	✔
electromagnetic γ	✔	✔	✔	✔	✔	✔
weak W	✔	✔	✔	✔	✔	✔
gravitational	✔	✔	✔	✔	✔	✔

The Particle Zoo?

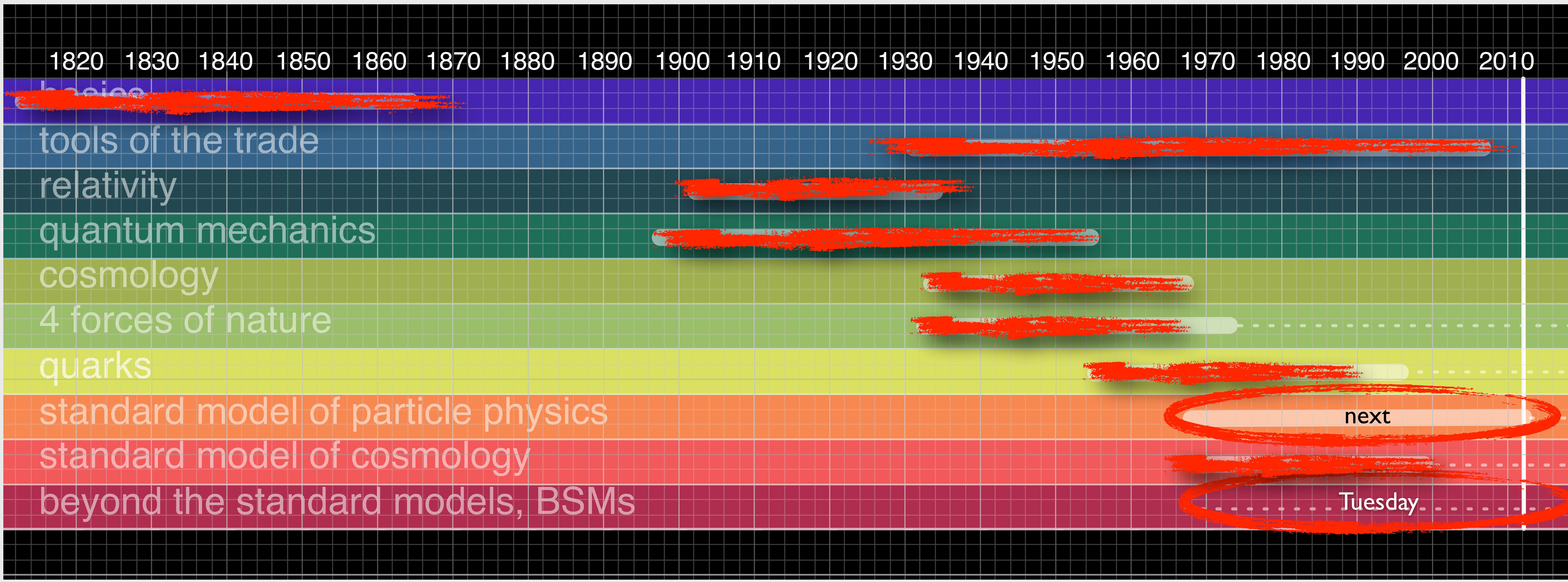


The Particle Zoo? *tamed*.



shifting gears

the weak and electromagnetic forces are one.


1820
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1950
1960
1970
1980
1990
2000
2010
basics
tools of the trade
relativity
quantum mechanics
cosmology
4 forces of nature
quarks
standard model of particle physics
next
standard model of cosmology
beyond the standard models, BSMs
Tuesday

“phase transitions”

not a subject of Particle Physics

we thought

but we stole a theory from materials scientists

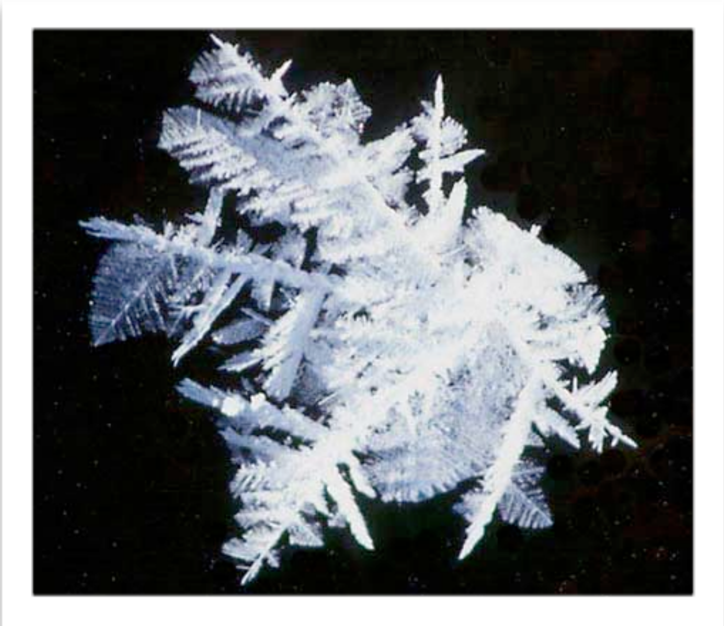
think about a phase transition

what a physicist sees

is a change of symmetry

before: every direction is identical

when there has been a symmetry change, that’s essentially the definition of a phase change:
Pierre Curie



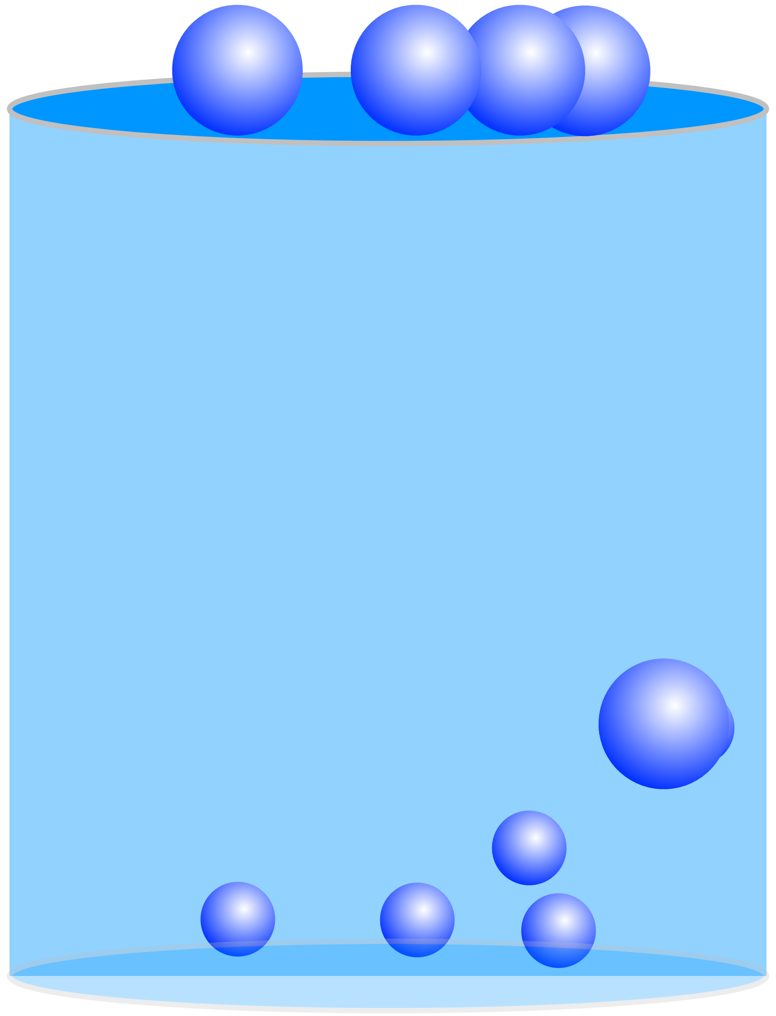
after: now there are special directions

http://www.youtube.com/watch?v=hGmC0W6ejFg&feature=related

there are basically 2 kinds

1st Order - nucleation

2d Order - continuous



Boiling starts in various locations inside of liquid water

Other kinds of phase transitions happen uniformly throughout the substance.

you probably are mostly familiar with:

freezing

melting

boiling

These “2nd Order,” phase transitions are continuous-everywhere:

crystallization
changes of density
magnetism
superconductivity
superfluidity
plasma transition
electron gases
Bose gases

a ferromagnet

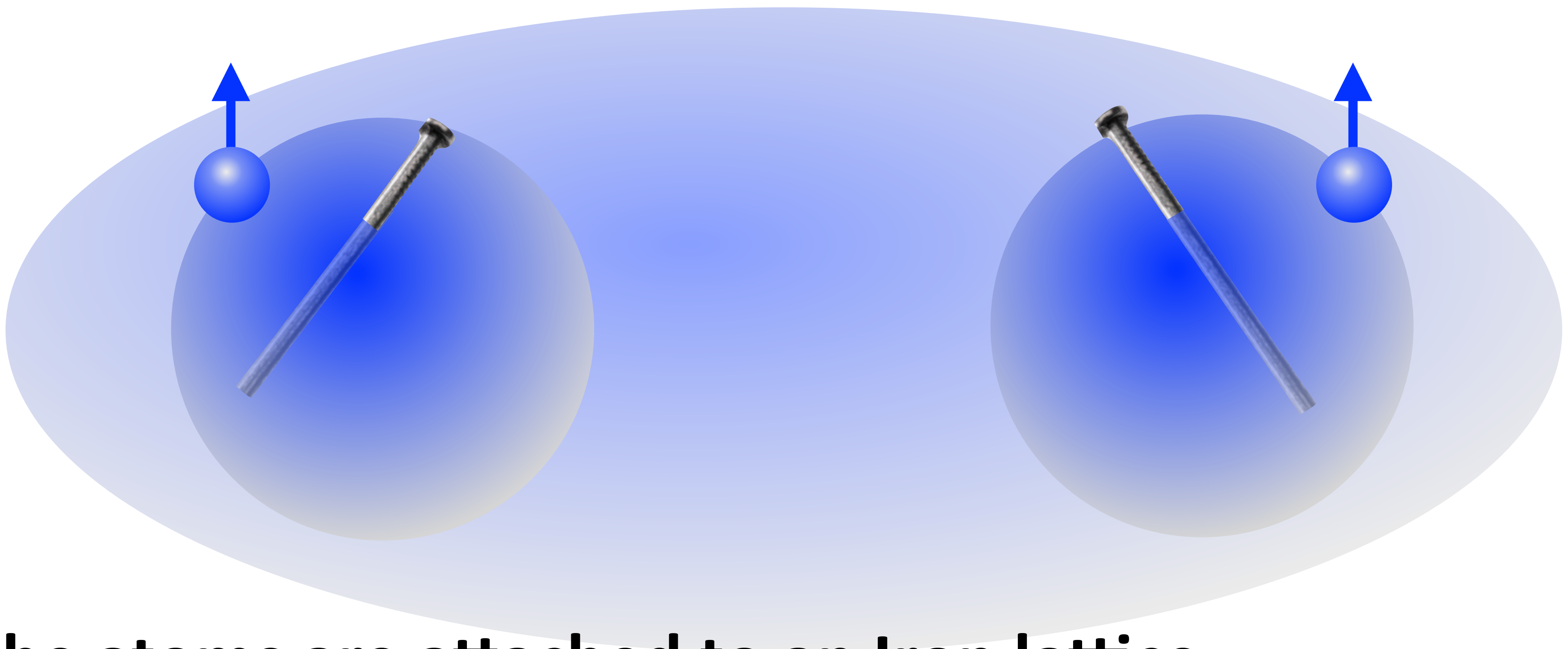
most familiarly:

iron

also:Co, Ni, Li gas

many compounds

If atoms are far apart...a quantum mechanical effect keeps the spins aligned, minimizing the electrostatic energy



if the atoms are attached to an Iron lattice... the spins can add up

that's a permanent ferromagnet

in 2 - dimensions