hi

Day 25, 04.18.2019

Particle Physics 2

108 days until my 69th birthday

Bon Jovi week

April 2019

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

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

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

housekeeping

Poster selection:

reservations were due last Friday from within LON-CAPA

Some tutorial videos to watch

How to draw Feynman Diagrams

Remember my plea about the FFB posts?

now…I've extended the deadline until Saturday. duh.

you know the drill:

from the mothership:

To: RAYMOND L BROCK

From: sirs@msu.edu

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

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

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

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

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

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

KEEP CALM

AND

LET'S REVIEW

Feynman Diagrams

now for real.

out of his codifying of

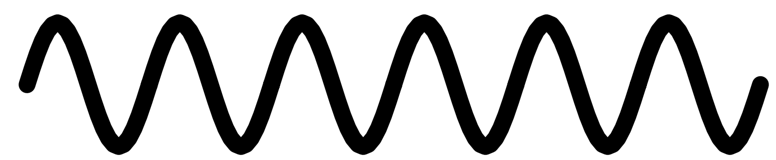
Quantum Electrodynamics (QED)

the key

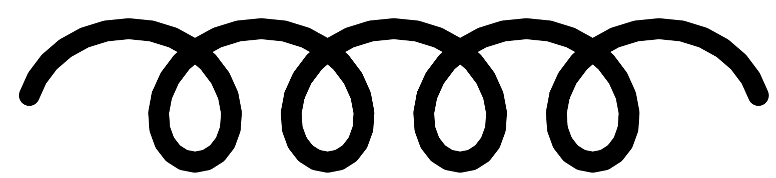
the different kinds of lines

look at your Primitive Diagram Sheet

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



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

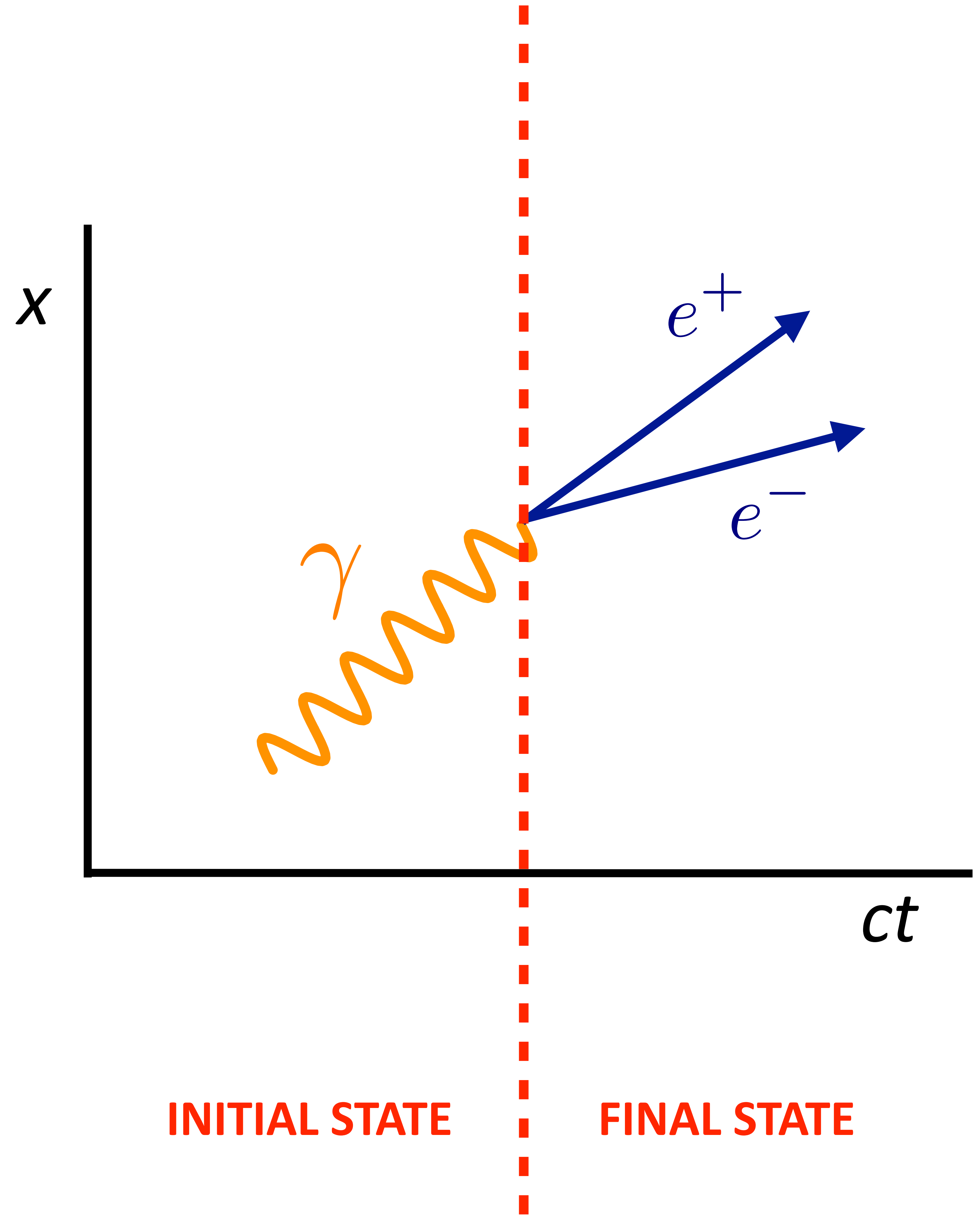


gluon, spin 1

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

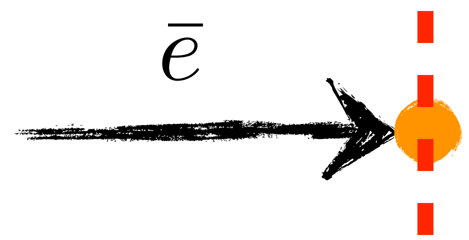
can always rotate any Feynman Graph

and get a new one



particles in time

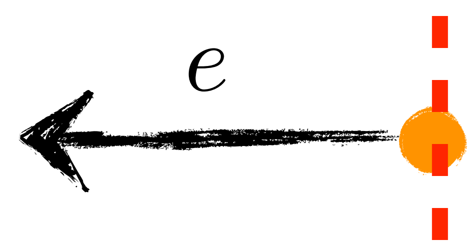
An anti-electron...coming **into** an **initial** state to a node:



Yes, this makes sense

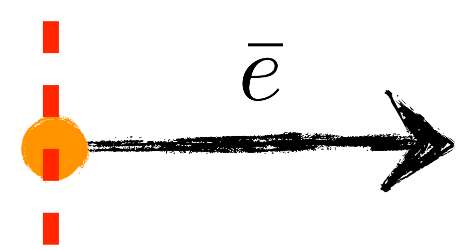
is the same thing as

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



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

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



Yes, this makes sense

is the same thing as

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

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

Feynman had rules

We'll have slightly different rules

but similar in spirit

This and more is in these 3 movies:

primitiveDiagrams_0 (13m)

primitiveDiagrams_1 (4m)

primitiveDiagram_2 (9m)

full resolution

primitiveDiagrams_0R

primitiveDiagrams_1R

primitiveDiagram_2R

Reduced resolution

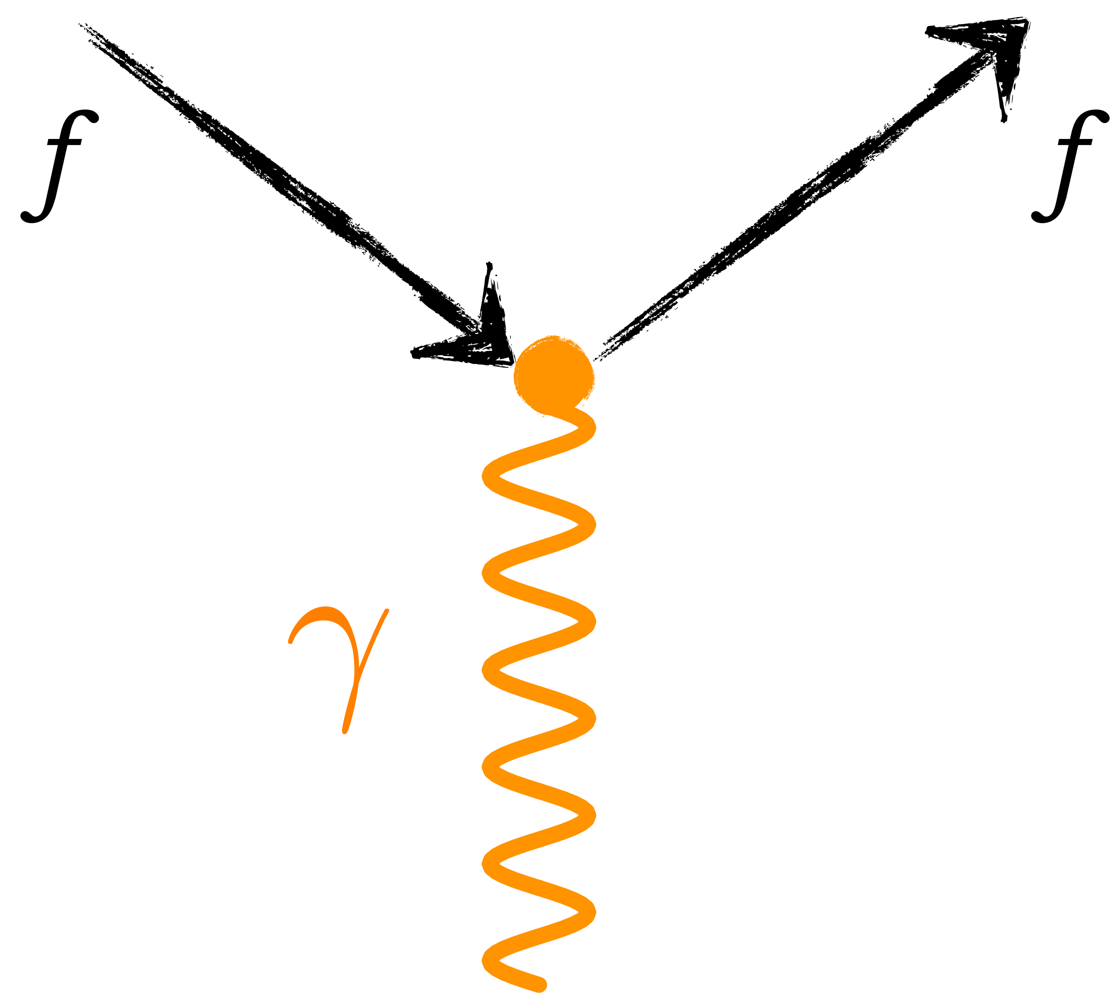
https://qstbb.pa.msu.edu/storage/QS&BB2019/videos_2019/FeynmanDiagrams/

primitive diagrams

are general

a puzzle piece to construct real physical reactions

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

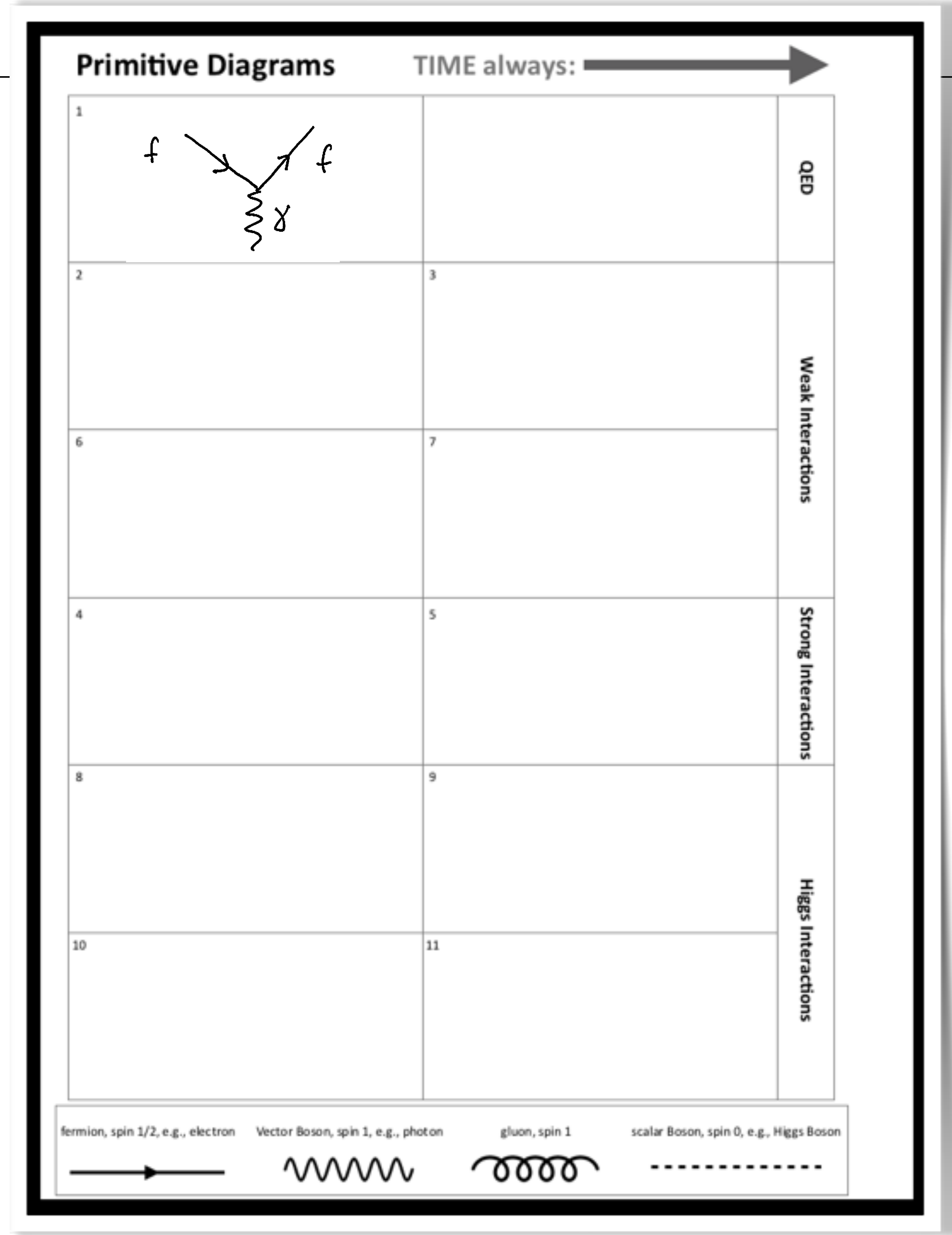


f could be electron, positron, proton, antiproton...and more – any electrically charged **f**ermion.

Their diagrams are identical.

Primitive Diagram Scorecard

your first entry



important realizations

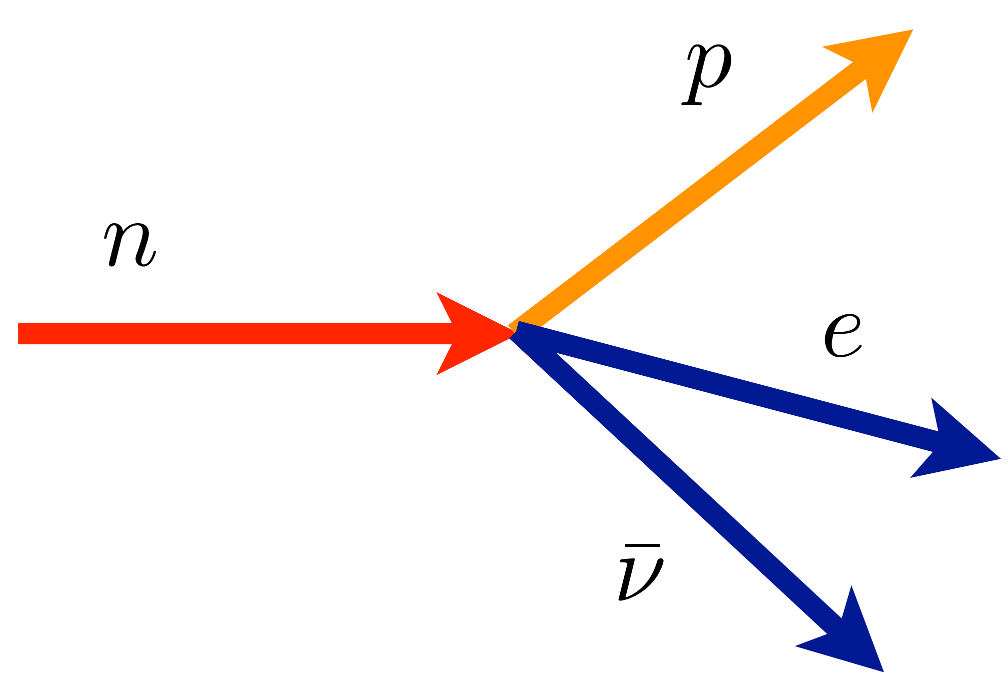
weak force: neutrinos

exchange force

nuclear force

beta decay

the “weak force”

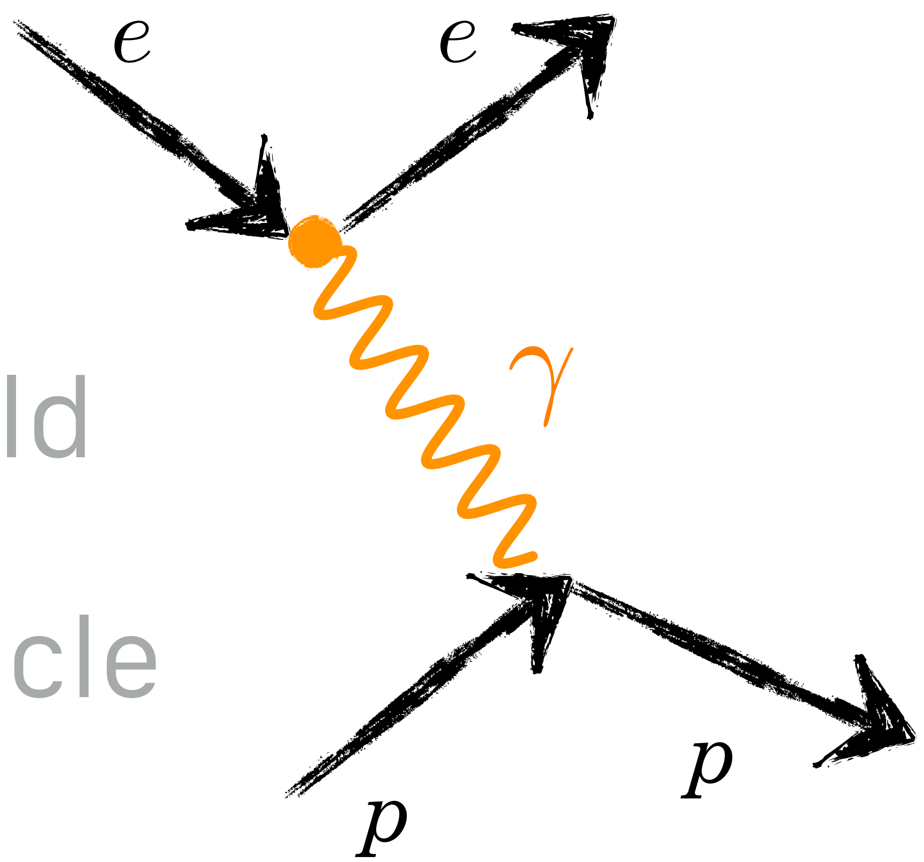


exchange force

the modern view:

if there’s a force…there’s a field

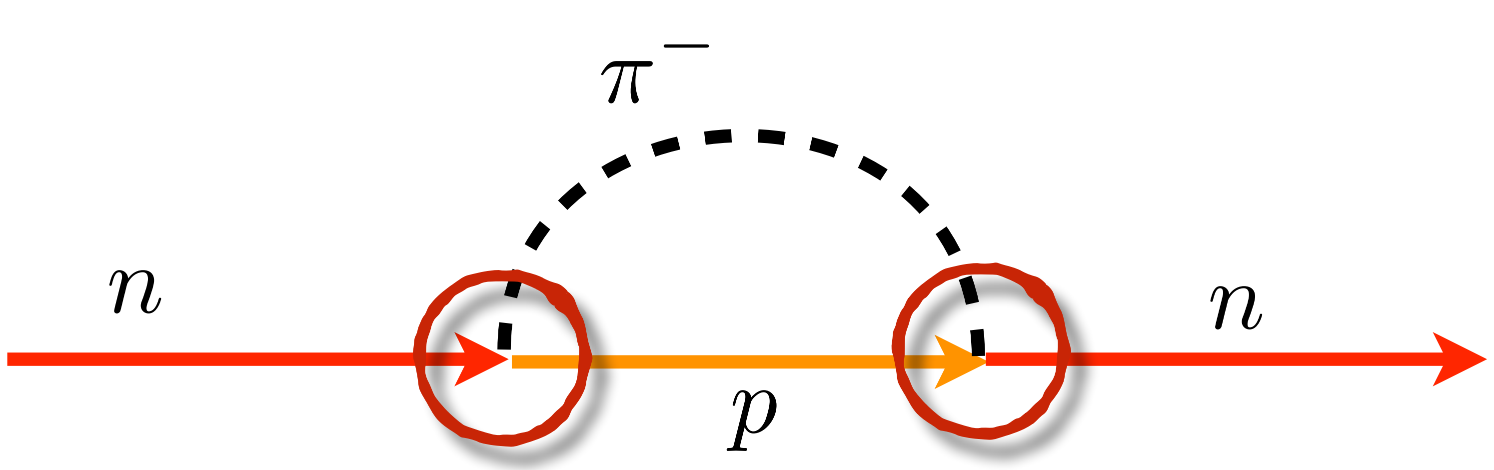
if there’s a field…there’s a particle

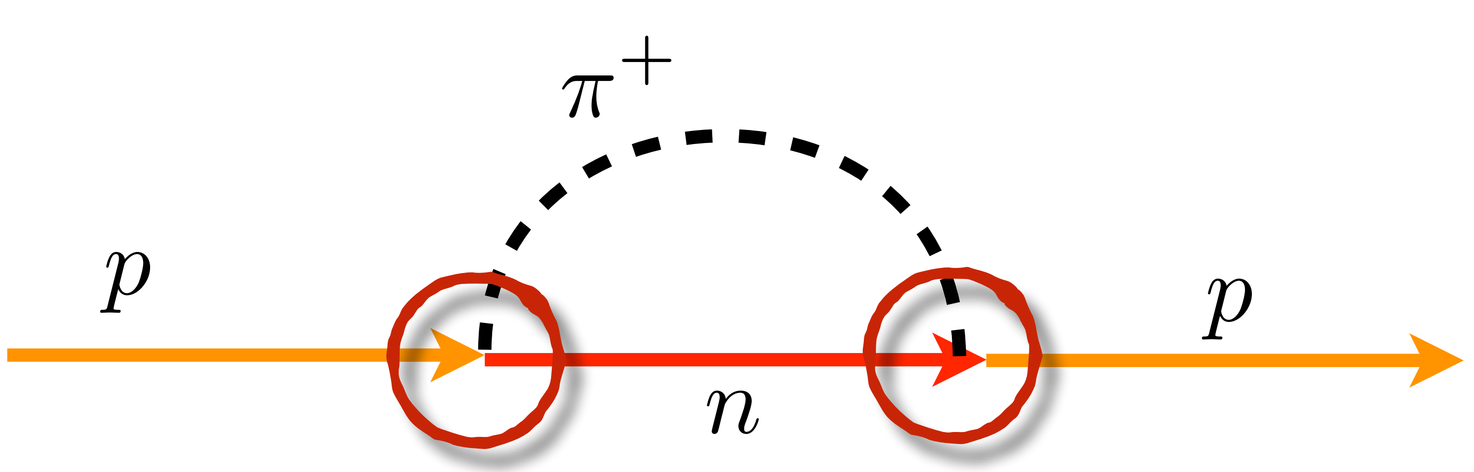


nuclear force

the force that holds protons and neutrons together

"strong"





4 forces of nature

differ from one another

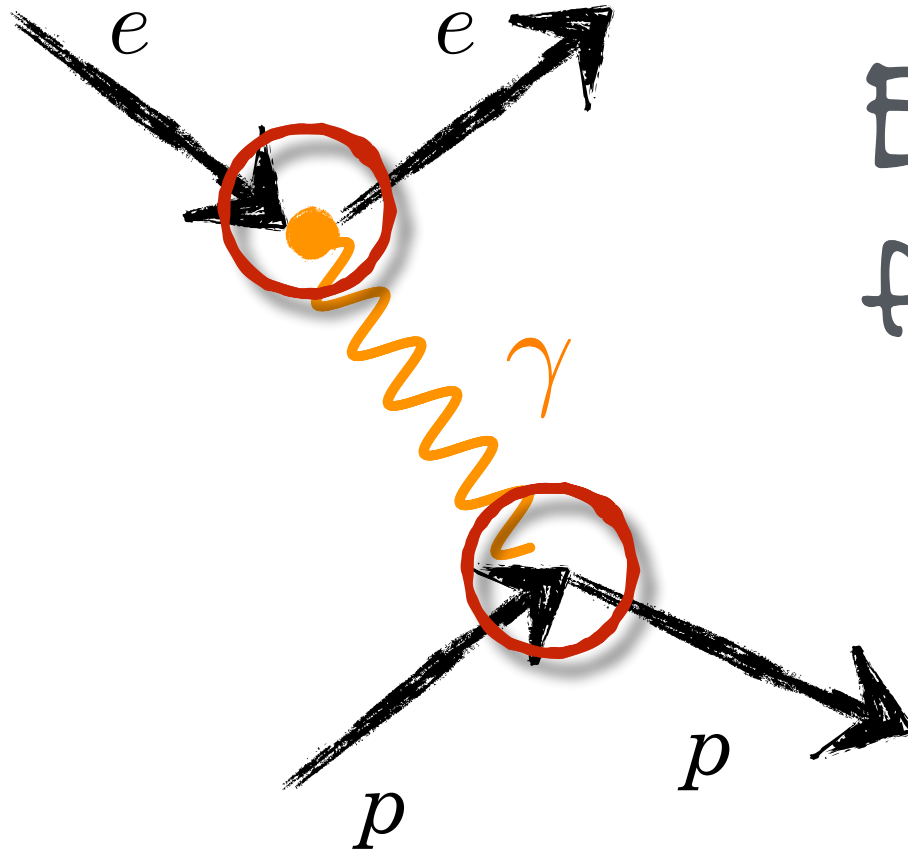
their relative “strengths”

the particles that “see” the individual forces

eg. electrons don’t experience the strong force

three forces now

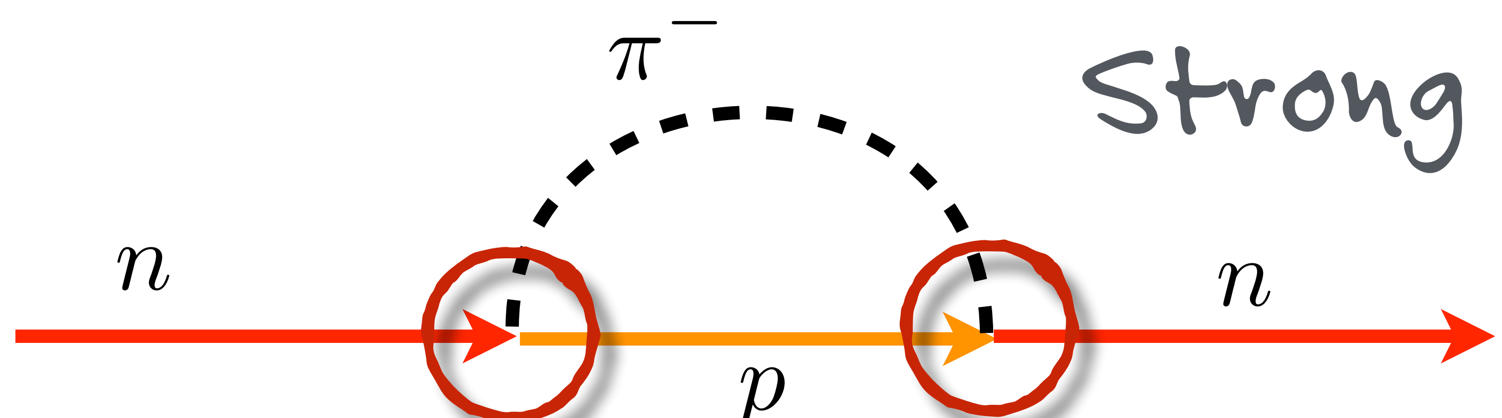
of vastly different strengths



Electromagnetic force 0.007

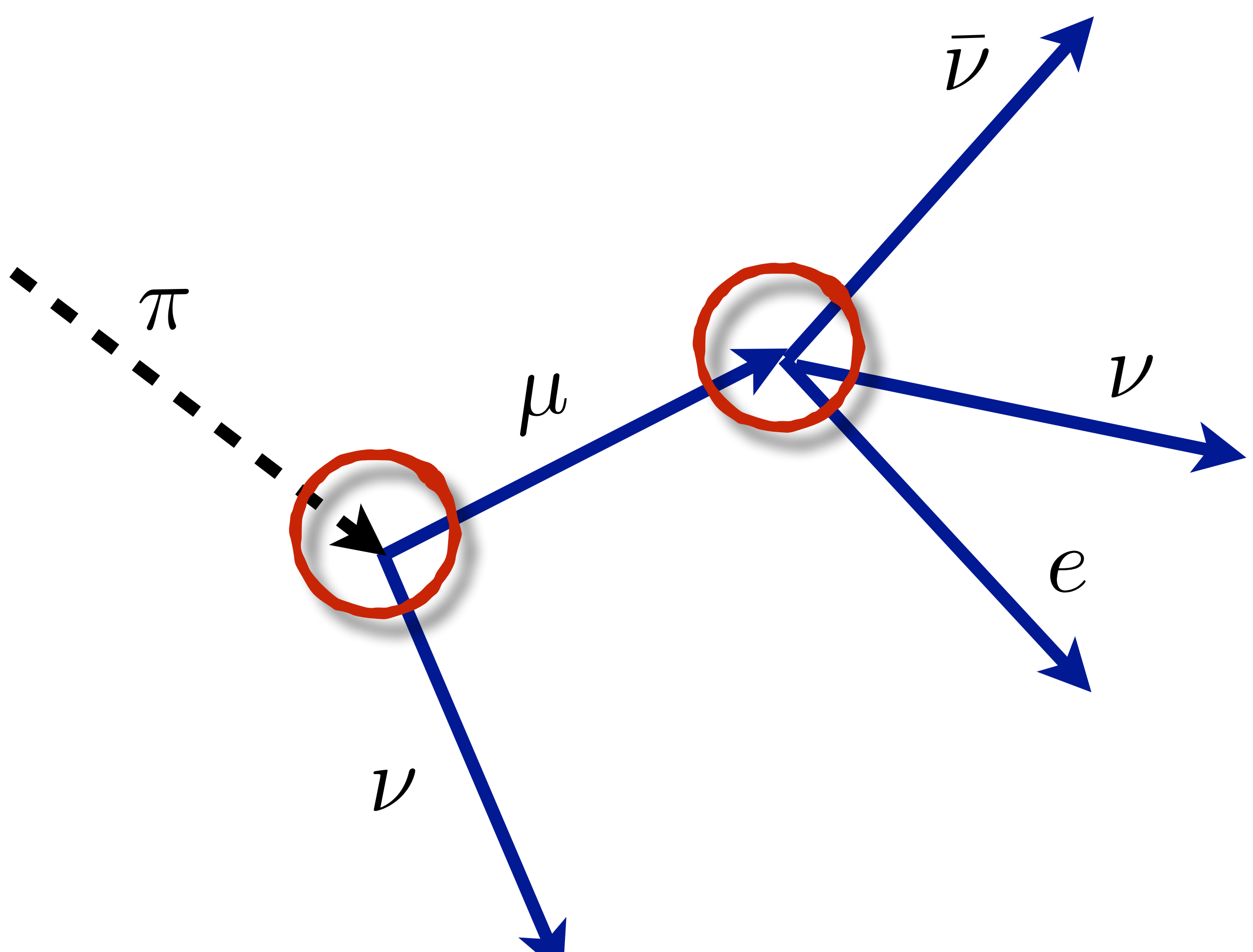
Gravitational force?

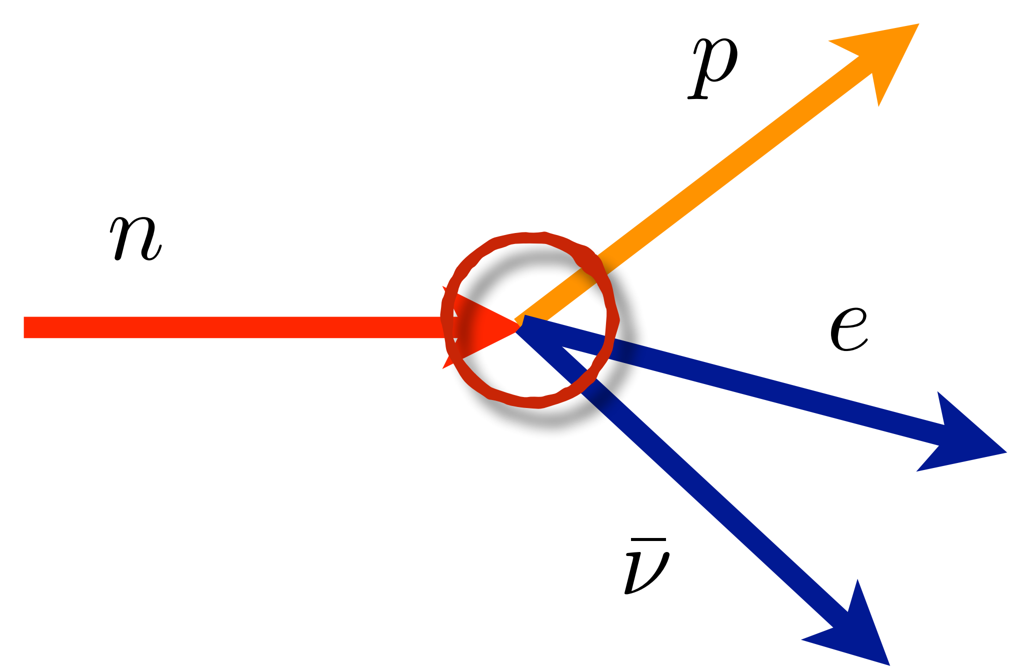
0.0000000000000000
00000000000000001



Strong force 15

Weak force 0.000001





`jargon`

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*

jargon alert: **lepton**

refers to:	originally, an electron, muon, neutrino
entomology:	"λεπτός" (leptos), "fine, small, thin"
example:	electron, muon, neutrino, tau!

`particles`

particle:

muon

symbol:	μ
charge:	+, –
mass:	105.7 MeV/c^2
spin:	1/2
category:	Fermion, lepton

particle: **pion**

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

particle: **Kaon**

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

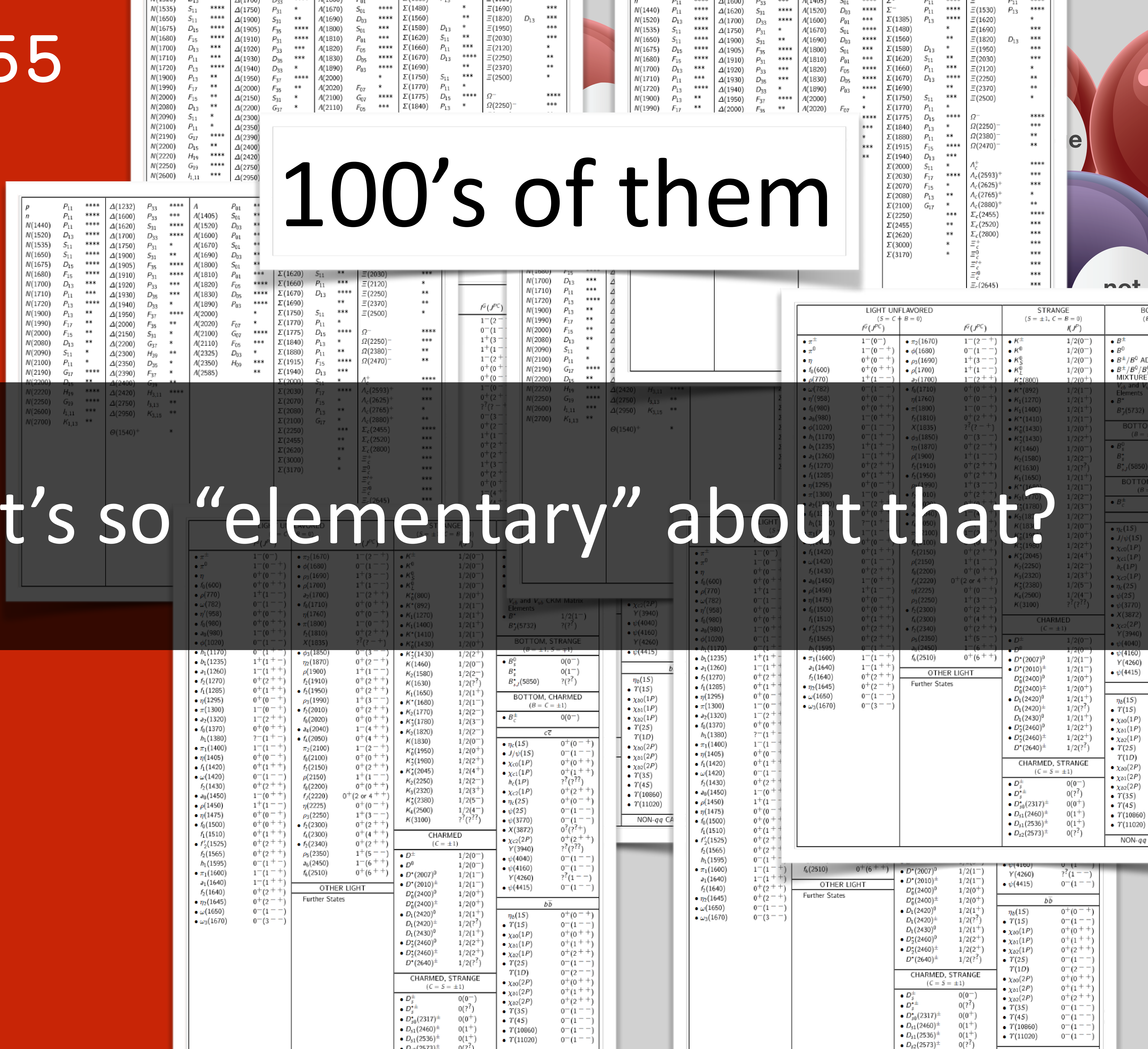
particle: **Lambda**

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

particle: **oodles more!**

symbol:	pretty much the Greek and Latin alphabets
charge:	+, ++, –, 0
mass:	1-10 x M_{proton}
spin:	1/2, 3/2, 1,0
category:	hadrons = baryons and mesons

by 1955



100’s of them

a mess

what’s so “elementary” about that?

Lepton Families

electrons and a neutrino

muons and a neutrino

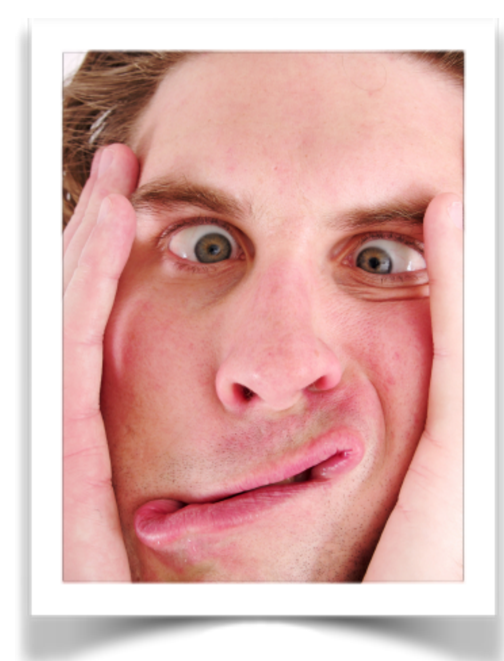
taus and a neutrino

These sorts of patterns are a huge deal.

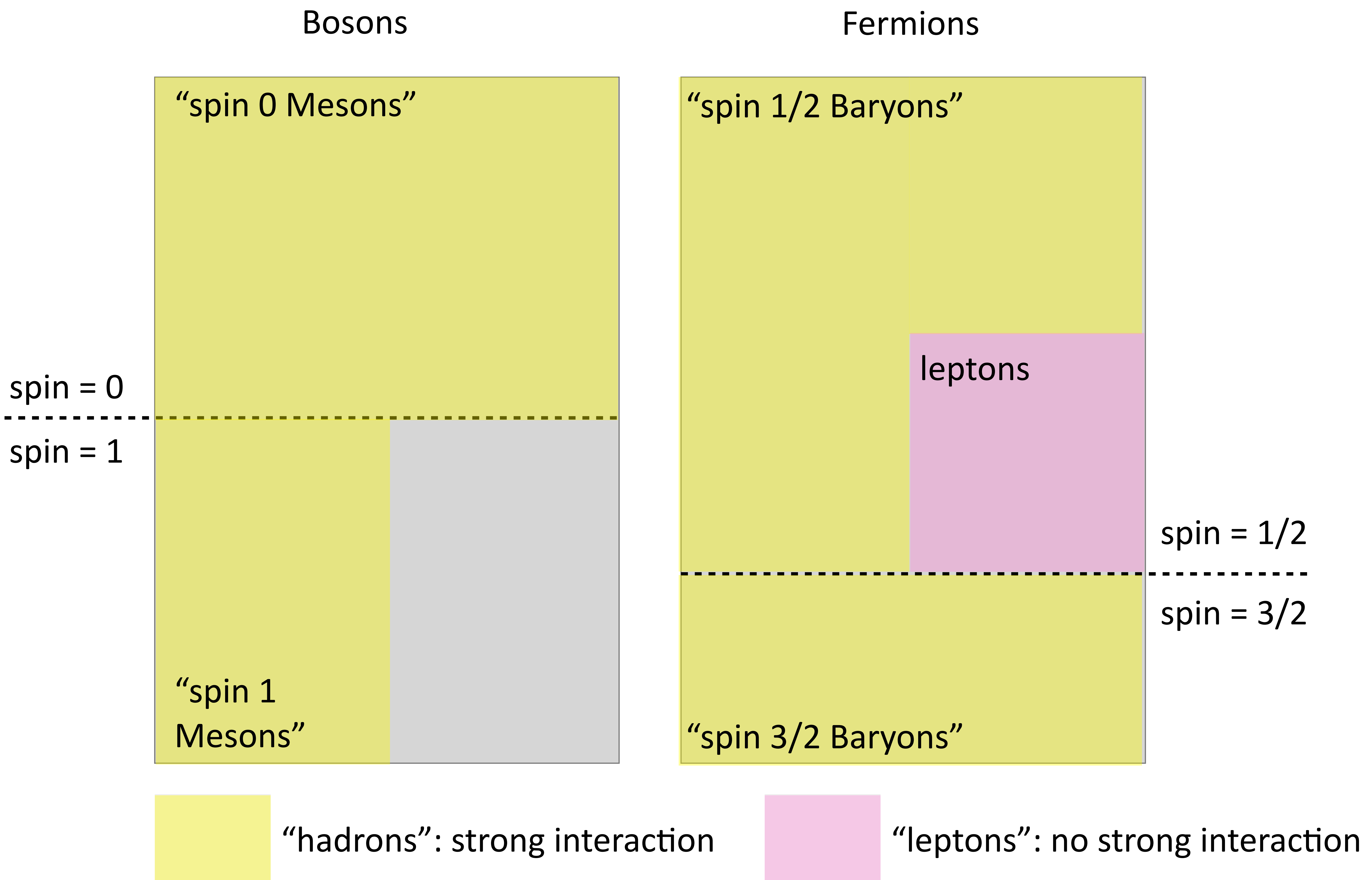
Q	
0	
−1	

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

Identical in every way...except mass



The Particle Zoo?

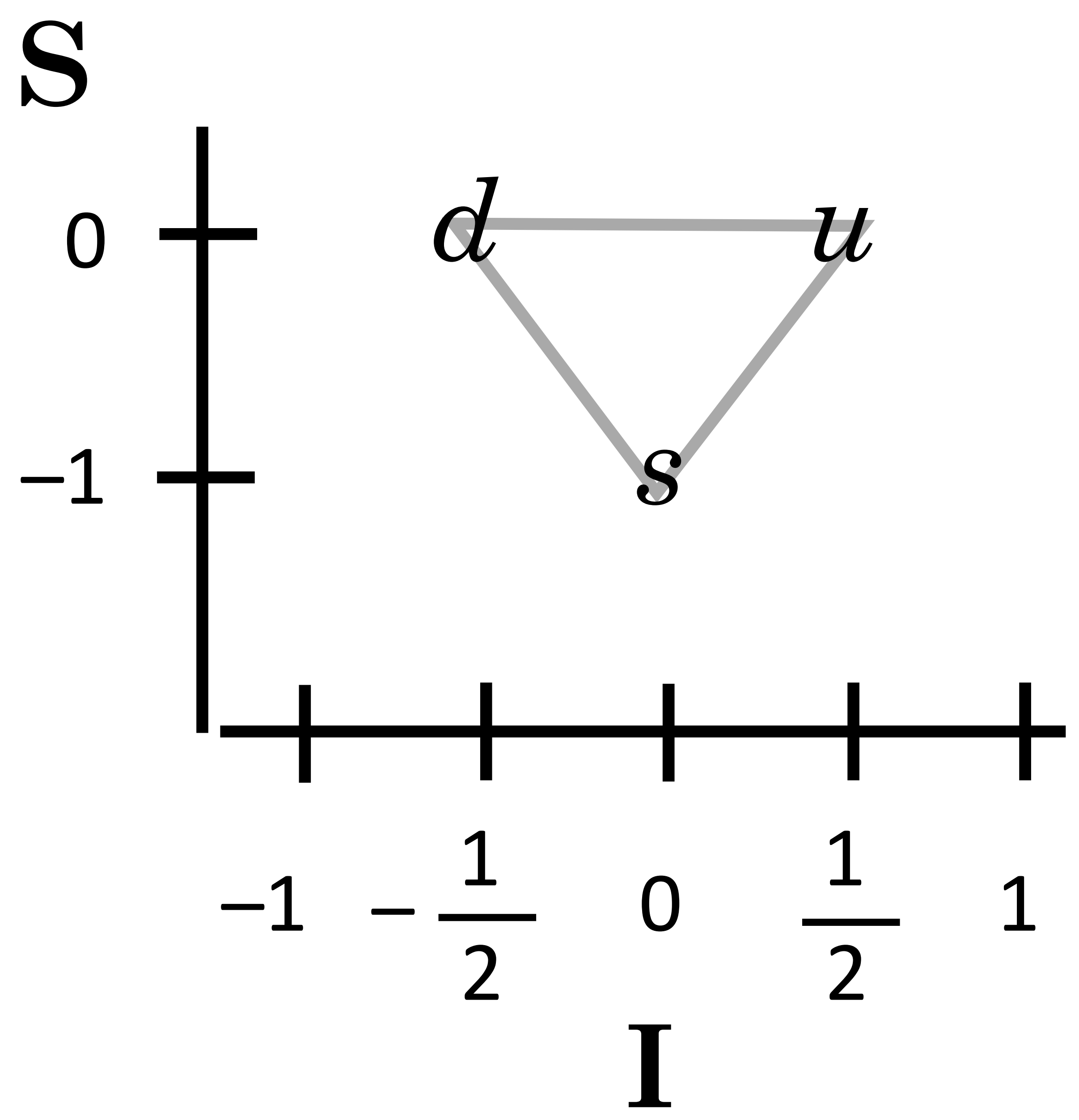


Quarks

Gell Mann's 1964 version

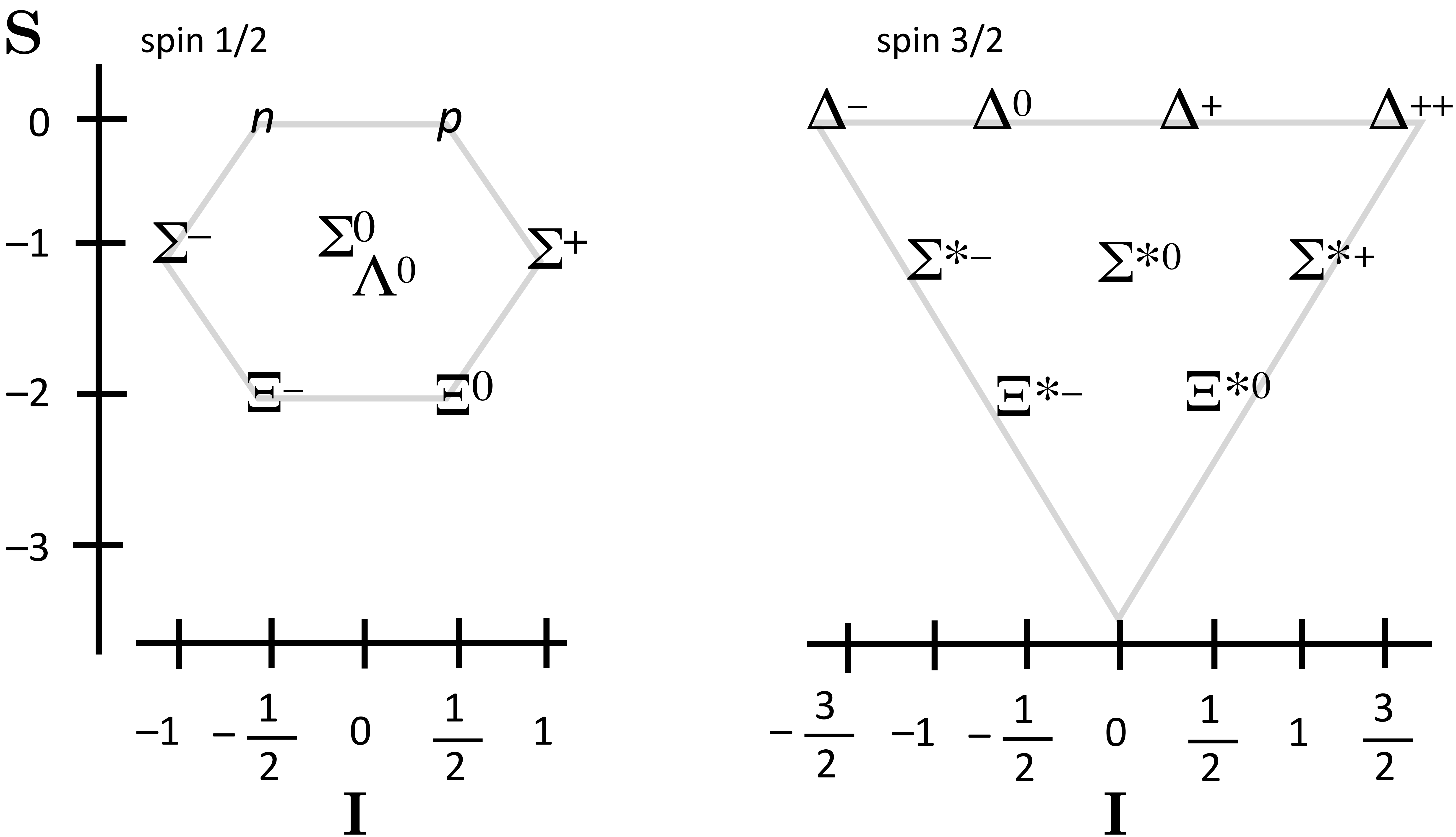
fundamental fermions

in same league as electrons and neutrinos



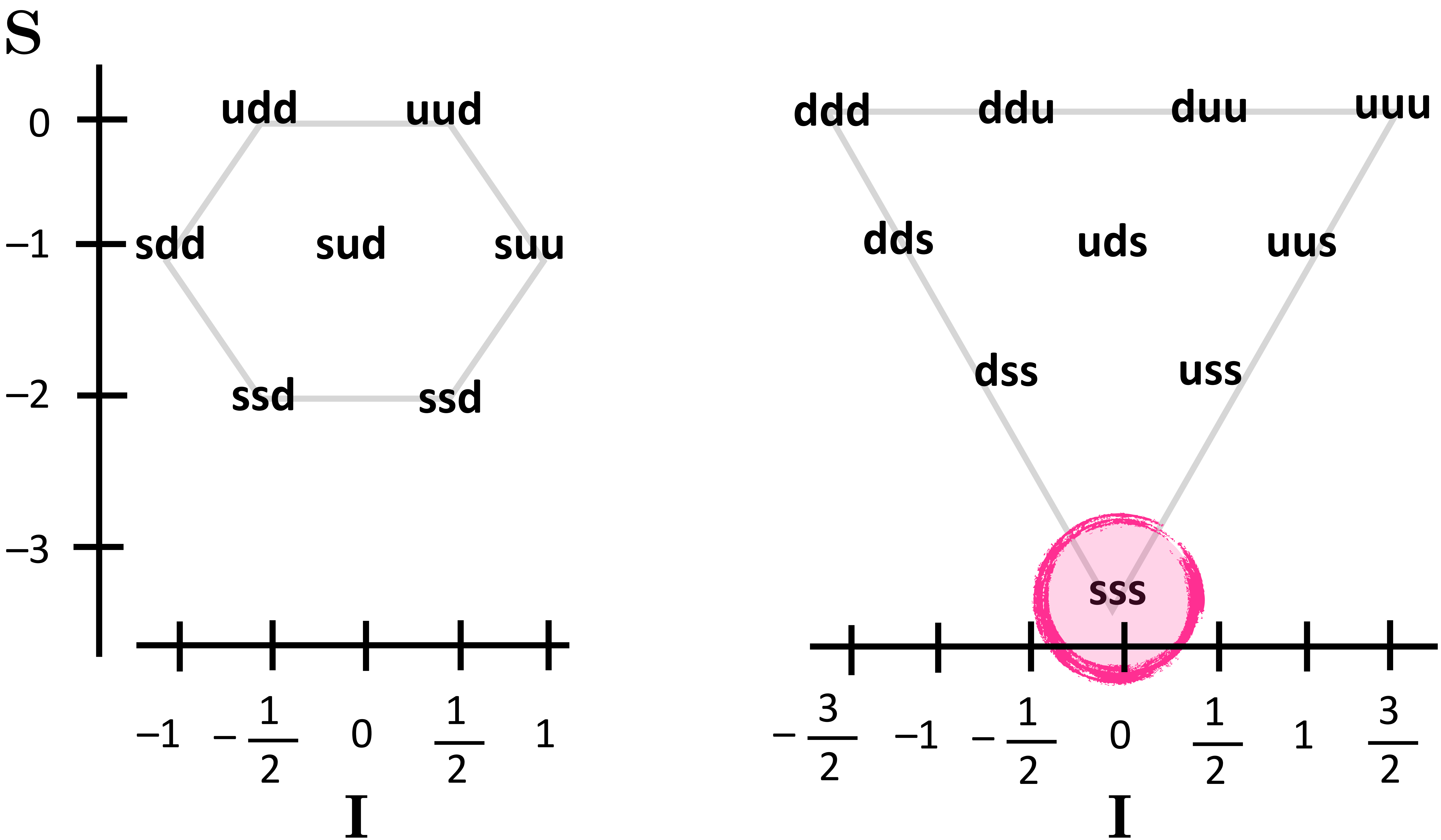
Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

they all fit



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

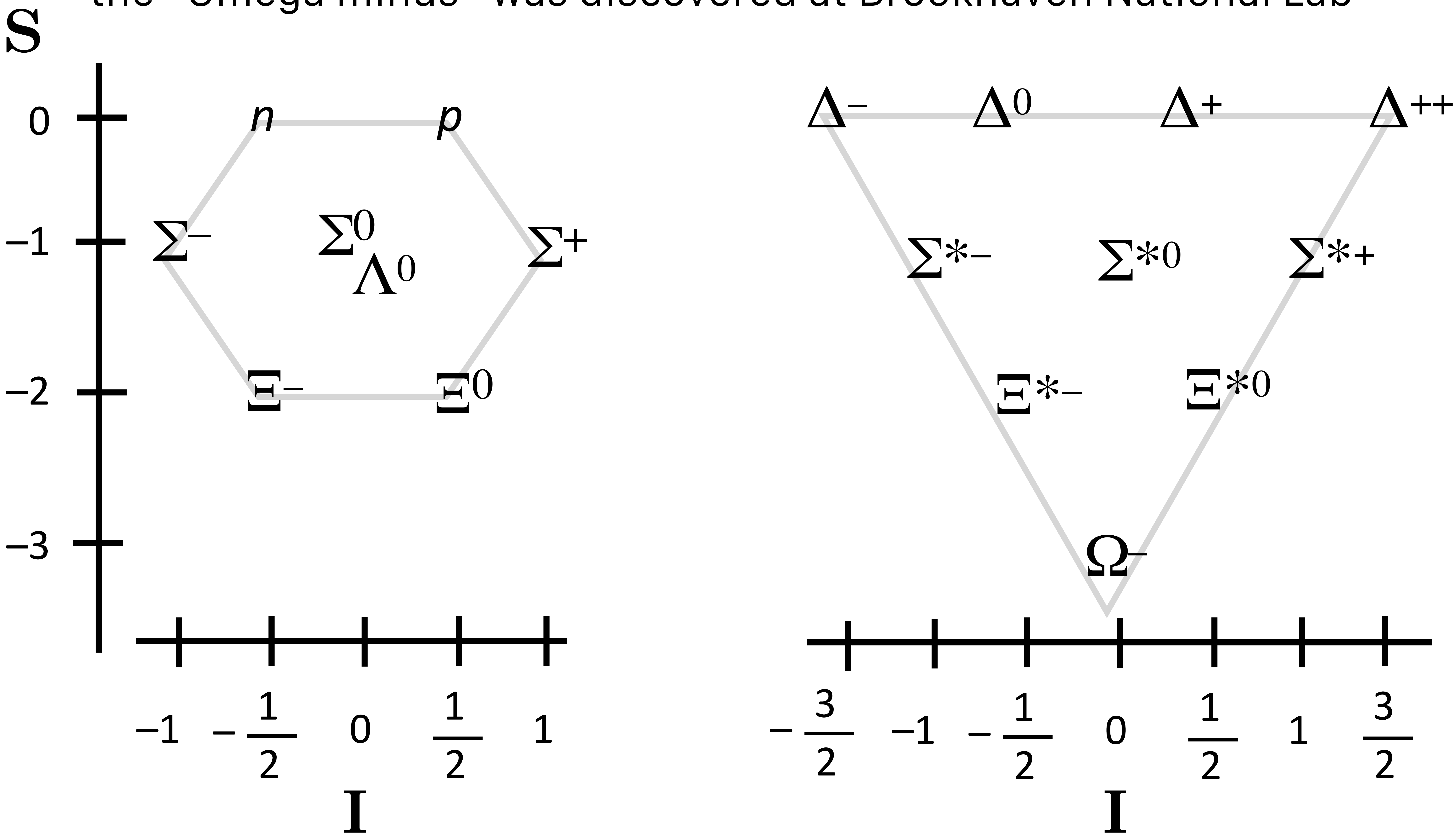
like a glove



S
0
−1
−2
−3
udd
uud
sdd
sud
suu
ssd
ssd
−1
$-\frac{1}{2}$
0
$\frac{1}{2}$
1
I
ddd
ddu
duu
uuu
dds
uds
uus
dss
uss
sss
$-\frac{3}{2}$
−1
$-\frac{1}{2}$
0
$\frac{1}{2}$
1
$\frac{3}{2}$
I

discovered at Brookhaven within a year

the "Omega minus" was discovered at Brookhaven National Lab



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}	$\Xi^0\pi^-,\ \Lambda^0 K^-$	sss

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}	$K^+K^-, K^0\bar{K}^0$	$s\bar{s}$

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:

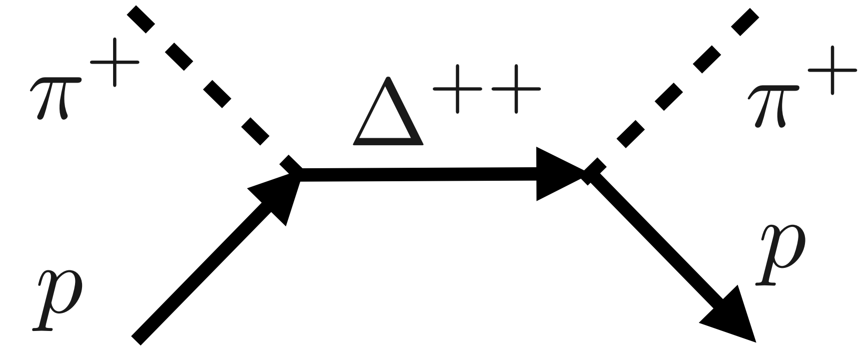
Mesons: particles made of 1 quark and 1 antiquark.

scatterings now are thought of diferently

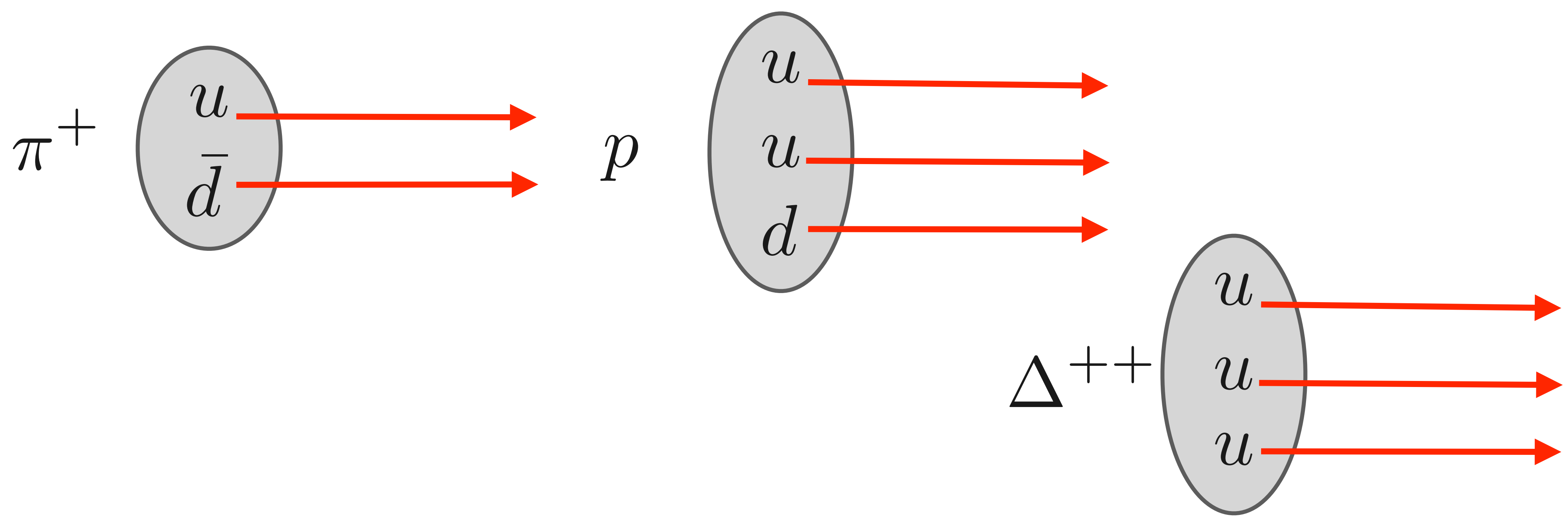
by following the lines...

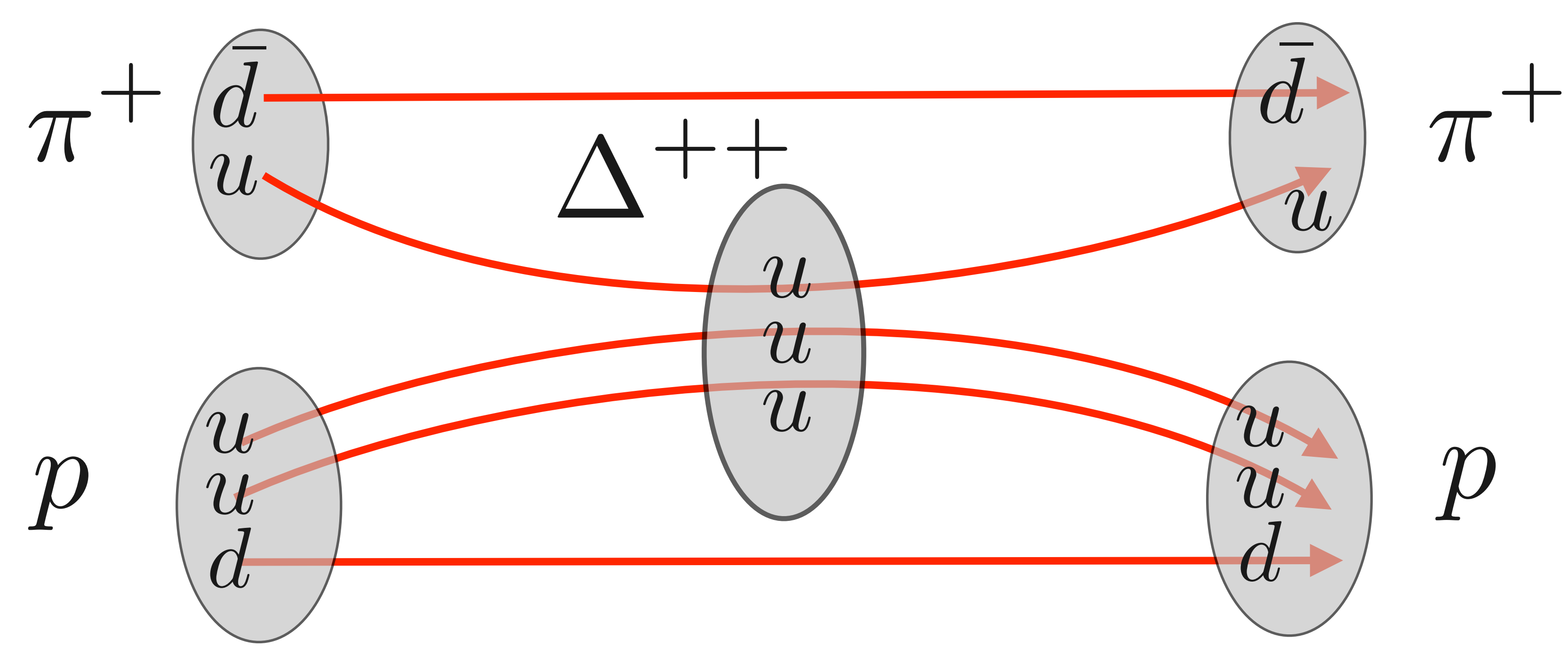
$$\pi^+ + p \to \Delta^{++} \to \pi^+ + p$$

Feynman Diagram, pre-1964:



in quark language:





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?

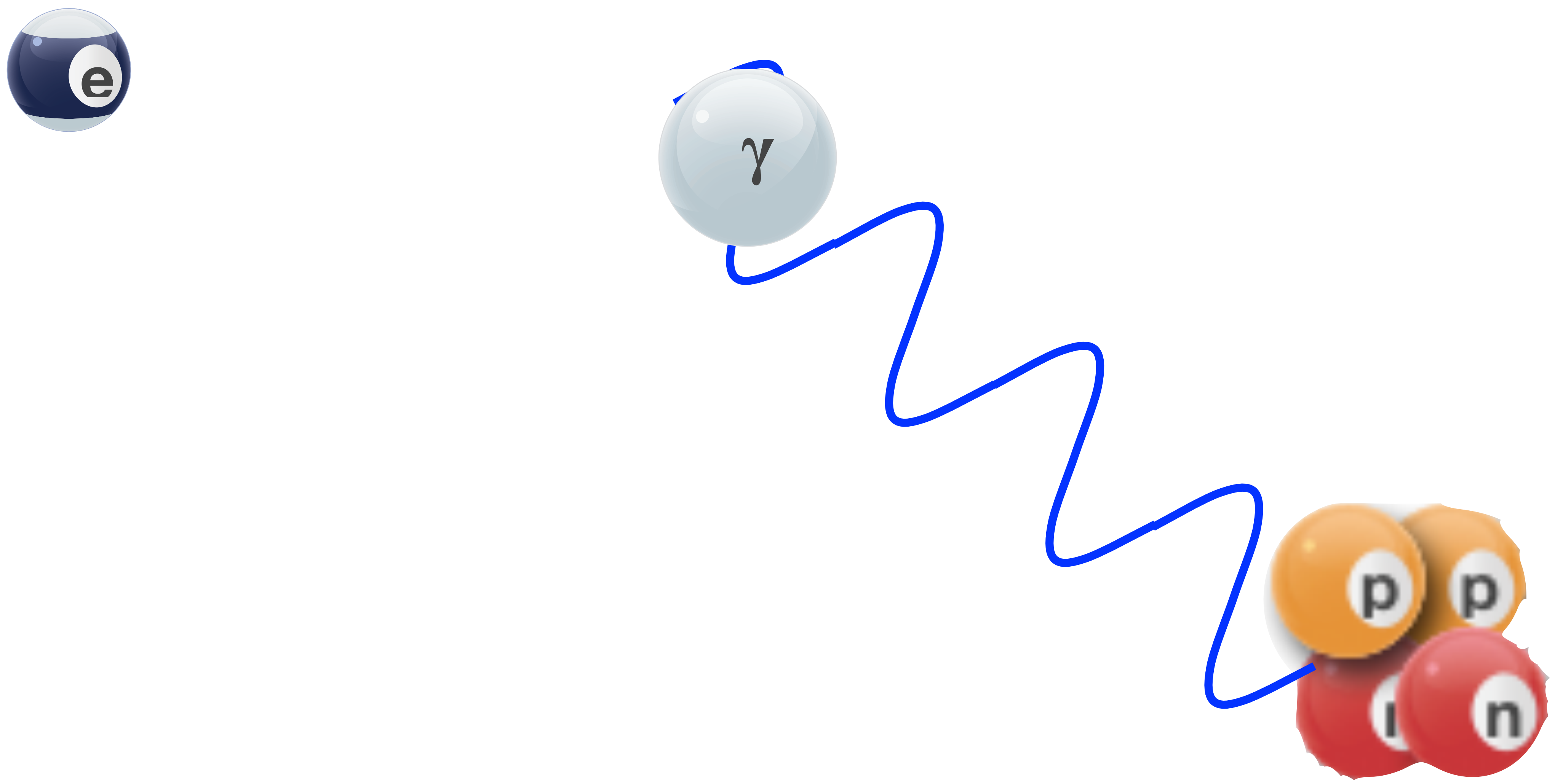
wavelength has to be about the size of the object

larger the momentum

the smaller the spatial resolving capability

scattering of an electron from a nucleus

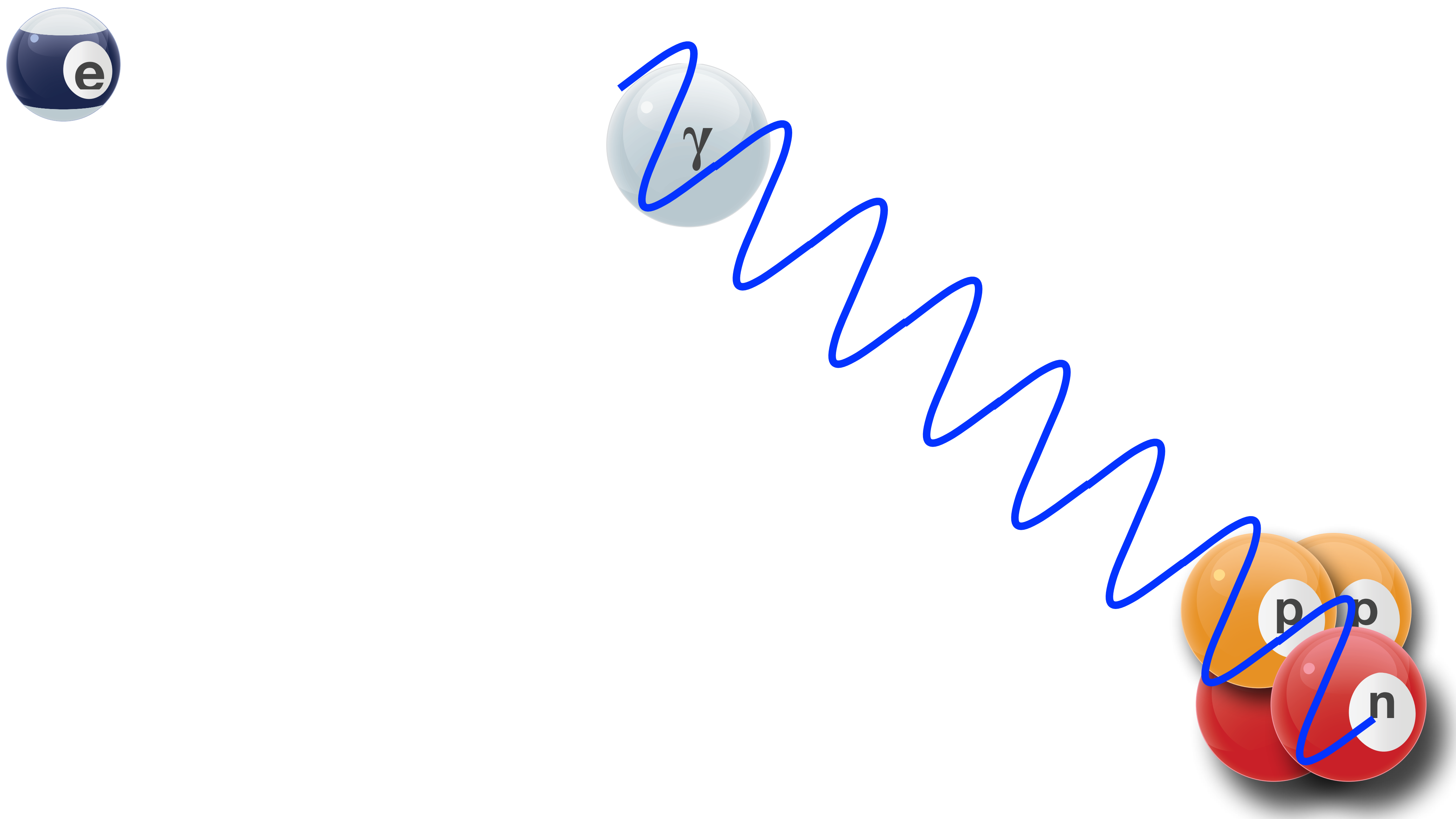
slow electron, long wavelength photon



“sees” the whole nucleus

scattering of an electron from a nucleus

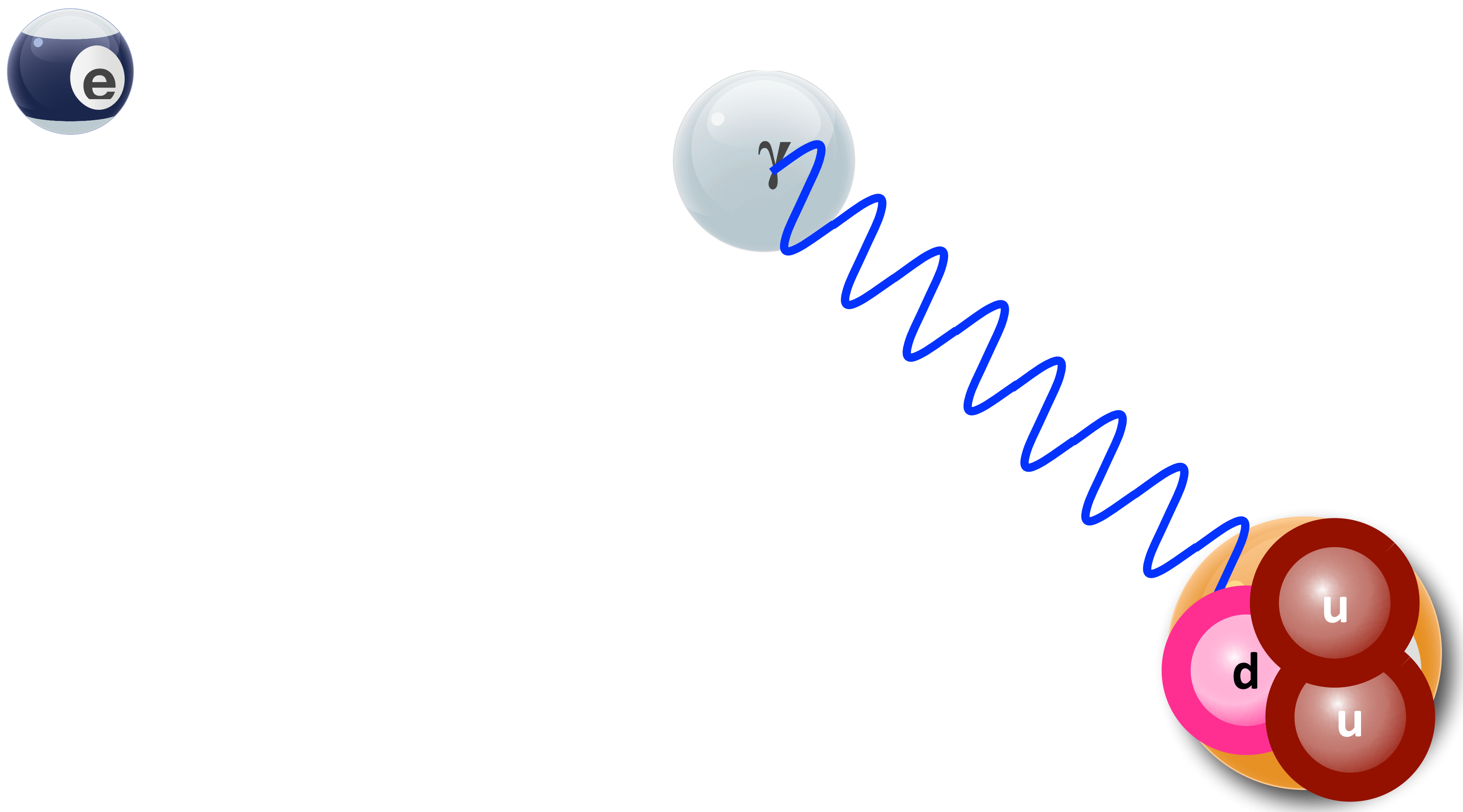
fast electron, **medium-short** wavelength photon



“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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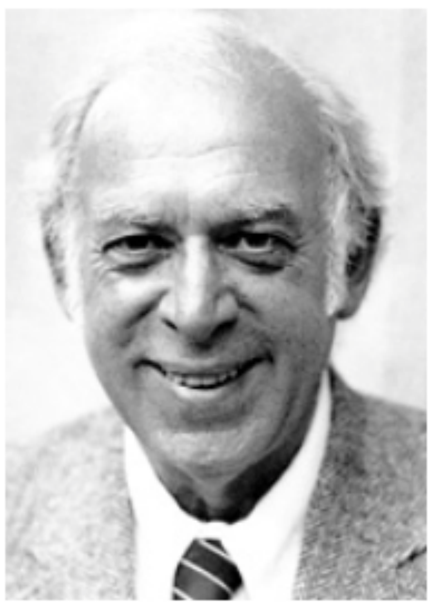
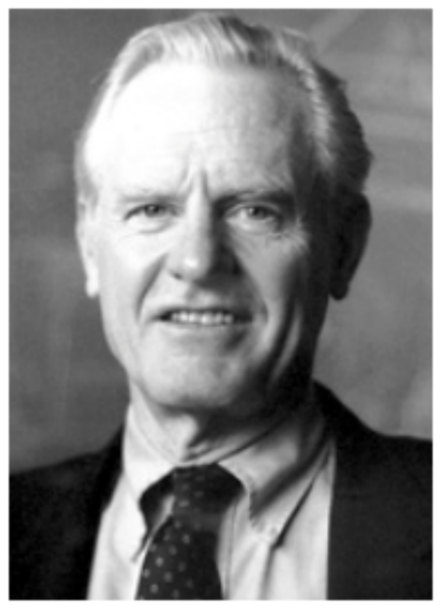
The Nobel Prize in Physics 1990



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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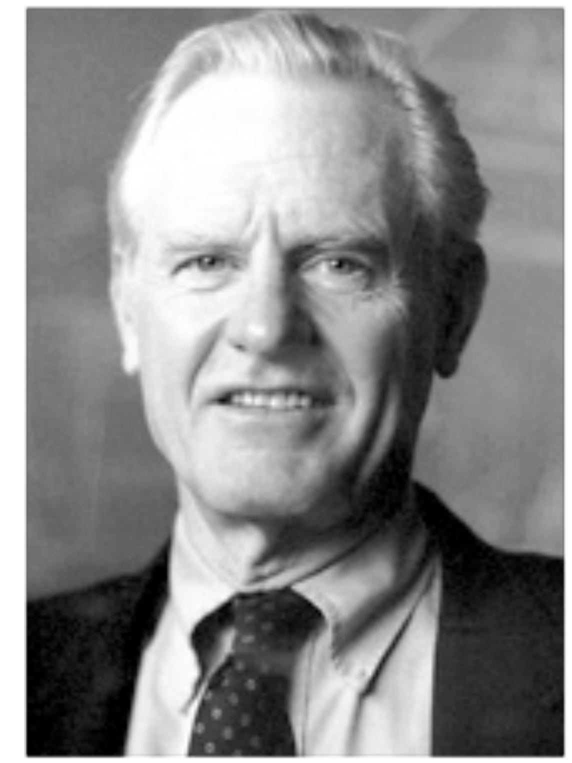
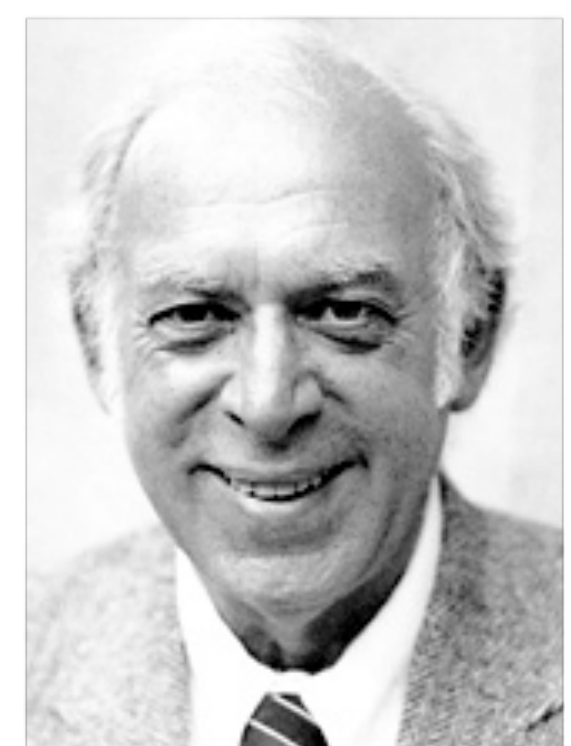




particle: **up quark**

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**

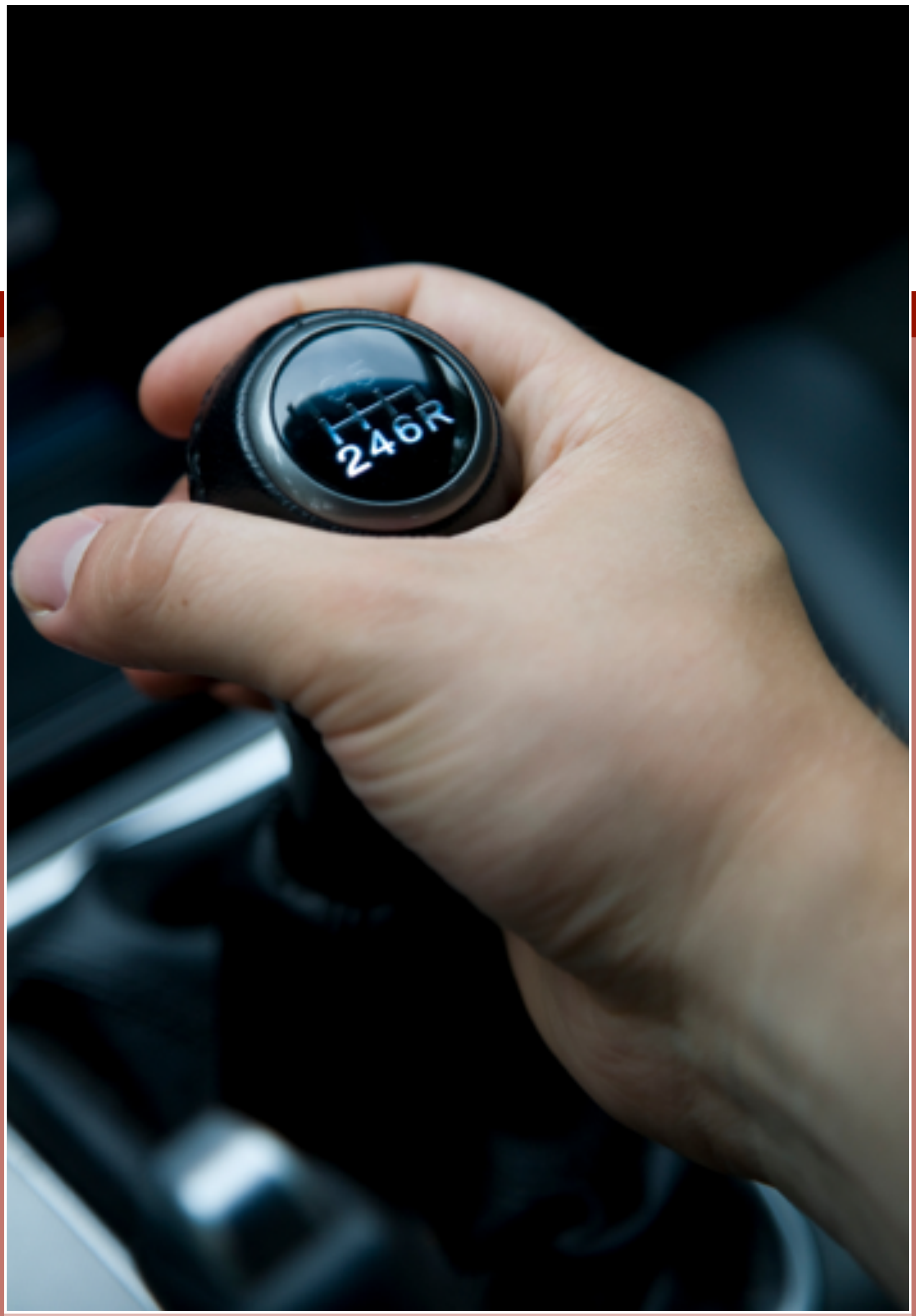
symbol:	*d*
charge:	–1/3
mass:	4.1 to 5.8 MeV/c^2
spin:	1/2
category:	Fermion, I=–1/2, B=1/3, S=0

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

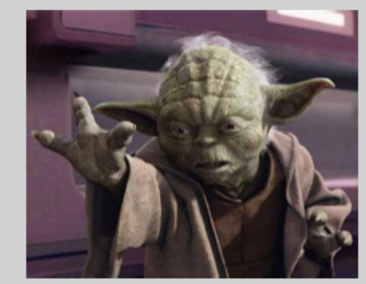


the quantum relativistic field theory

theme song:

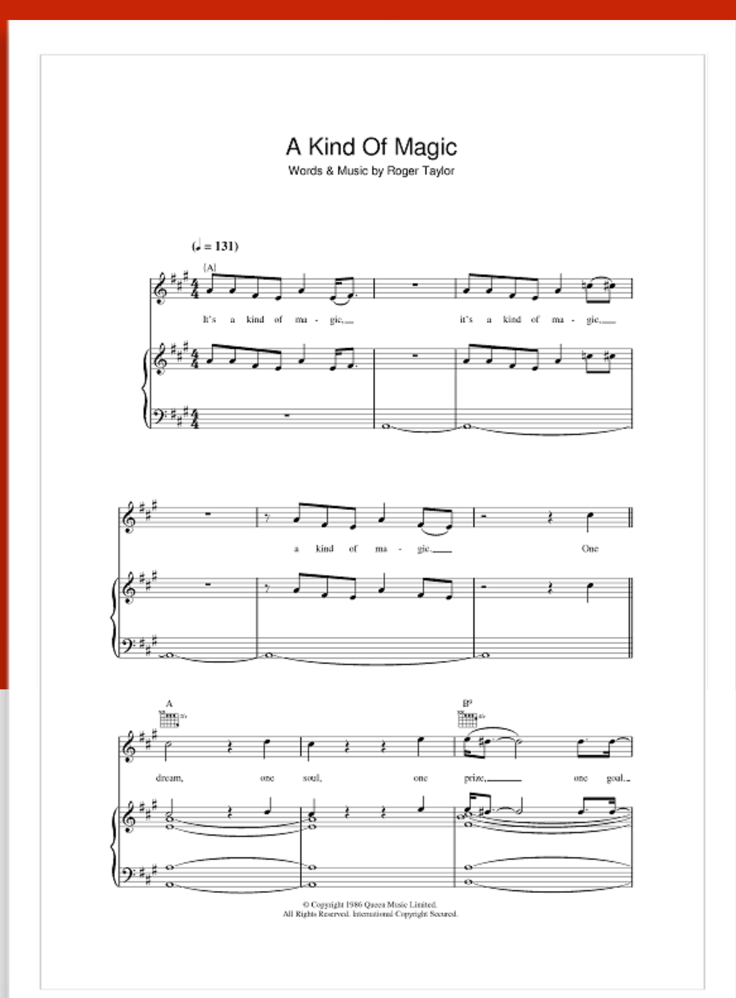
this kind of magic:

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.



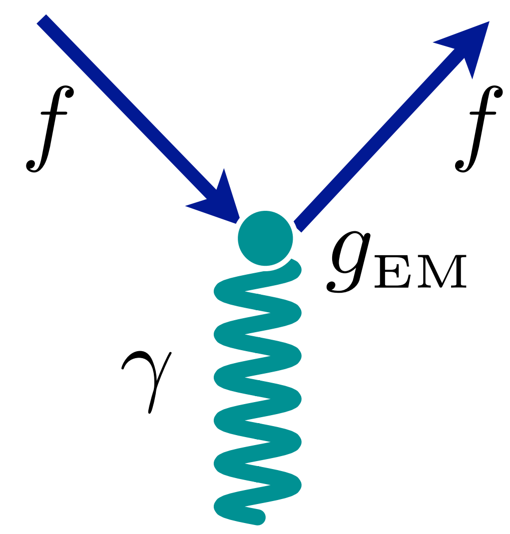
for the electromagnetic interaction:

the force is the electromagnetic force

the field is E & B

the clumpiness – the quantum – is:

The photon: γ

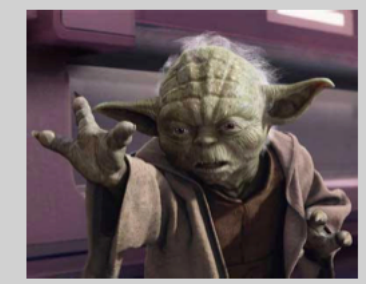


Well, the Weak Force

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.

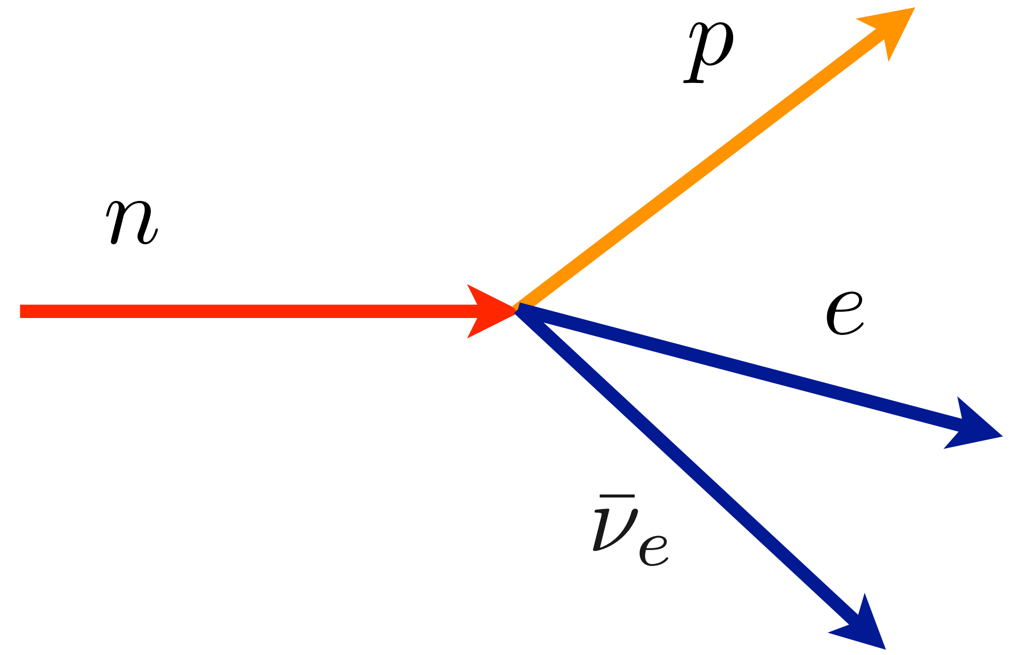
`for weak interaction:`

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

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

here's a weak interaction

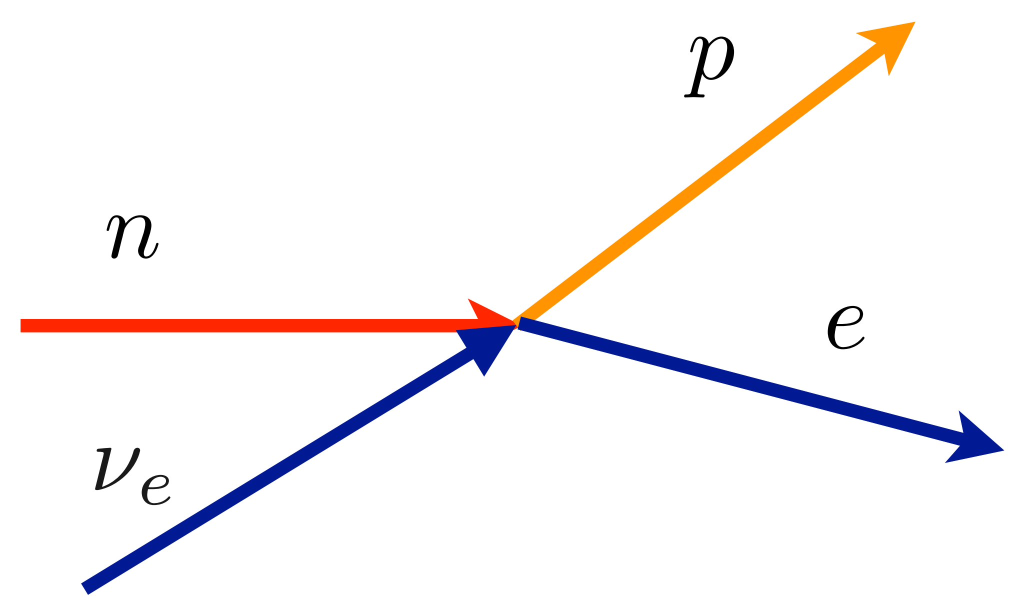
neutron beta decay



changes electric charge

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

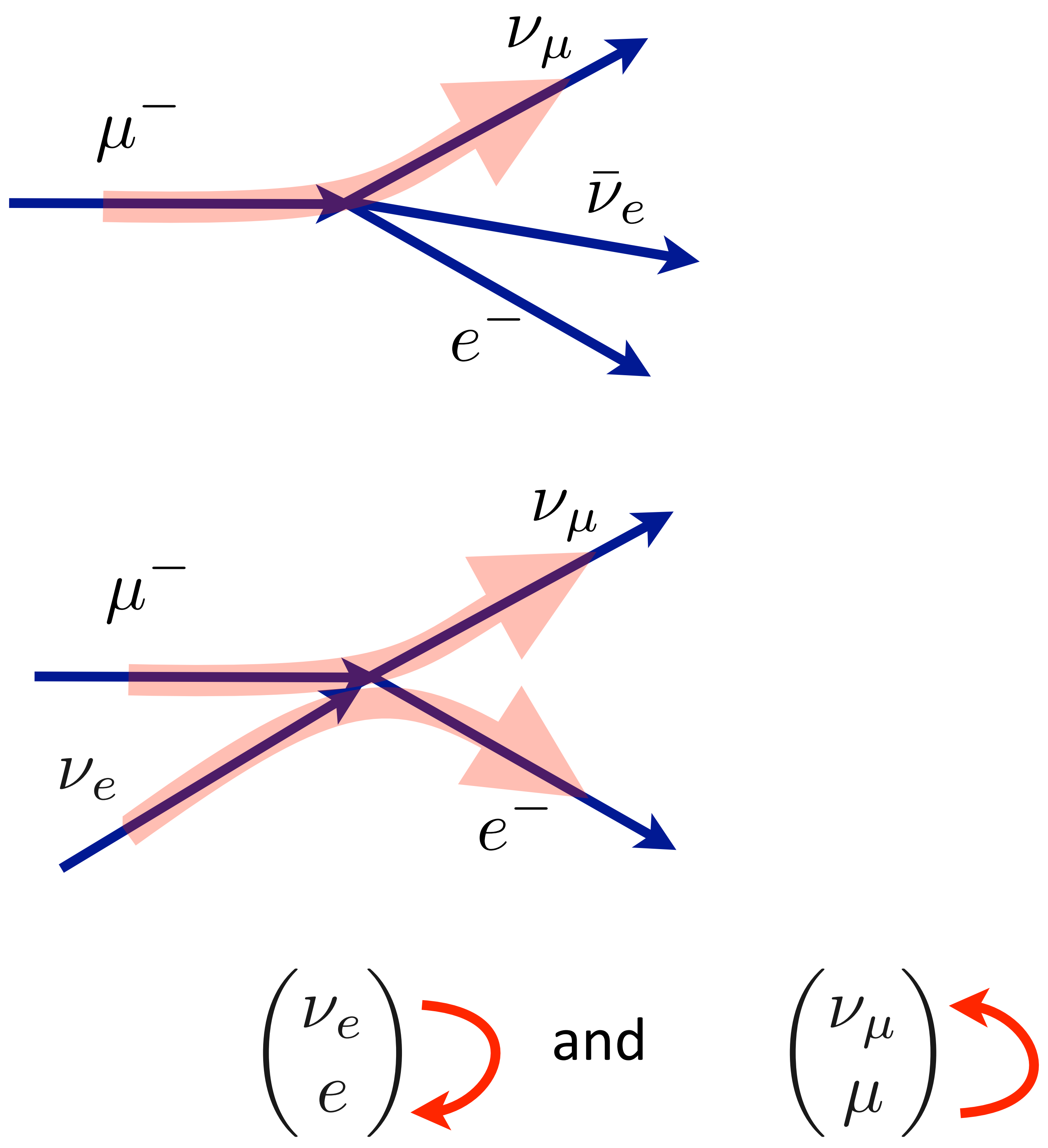
Manipulate the graph in the now familiar way:



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

the muon decay is the same sort of

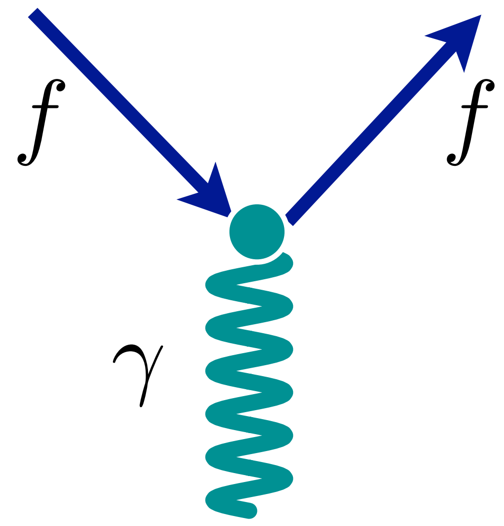
in that second way of looking at it:



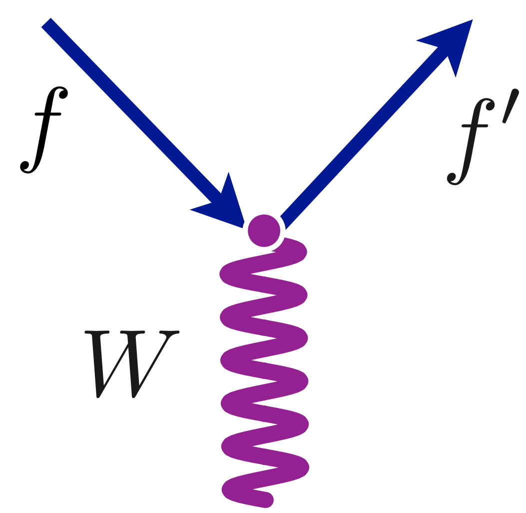
do it again?

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.



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

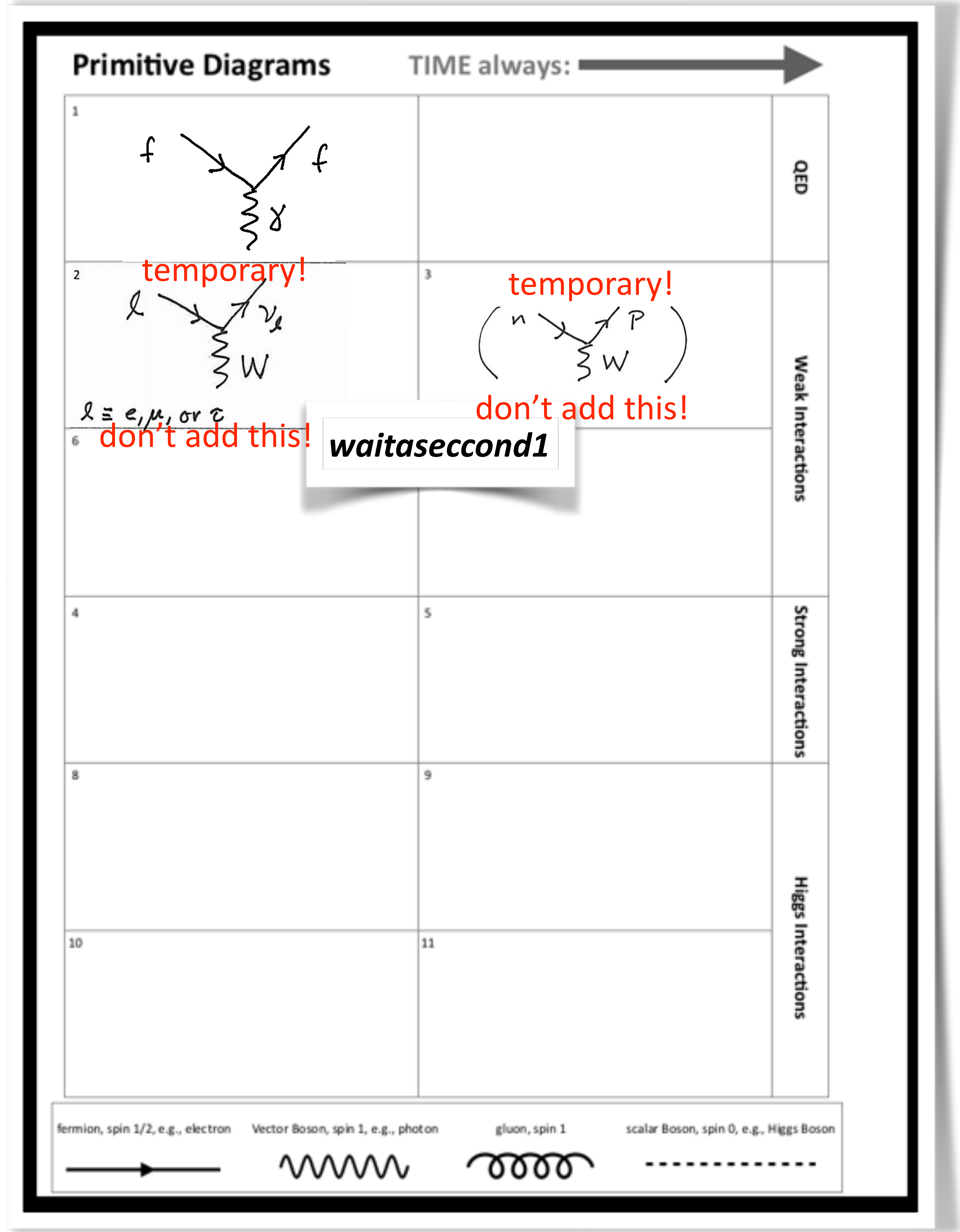
"W" for "Weak"

f and f' are different particles, but share the doublet

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

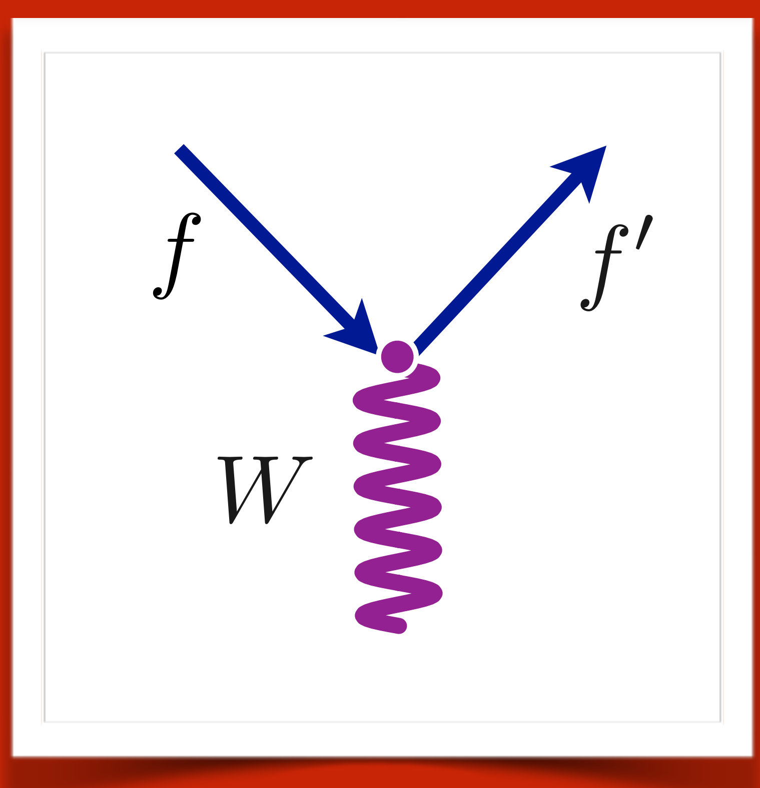
temporary entries into your

table of primitive diagrams



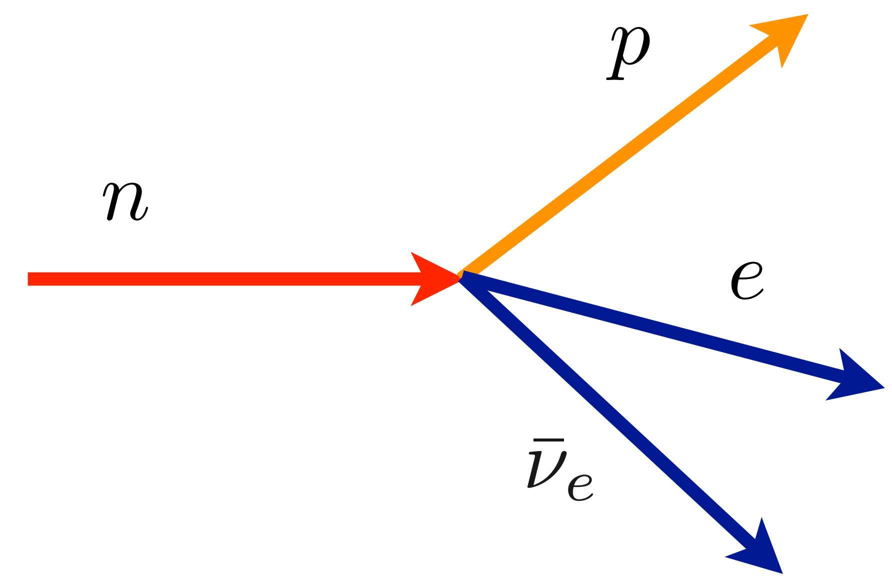
so, a new primitive diagram

for the Weak Interaction

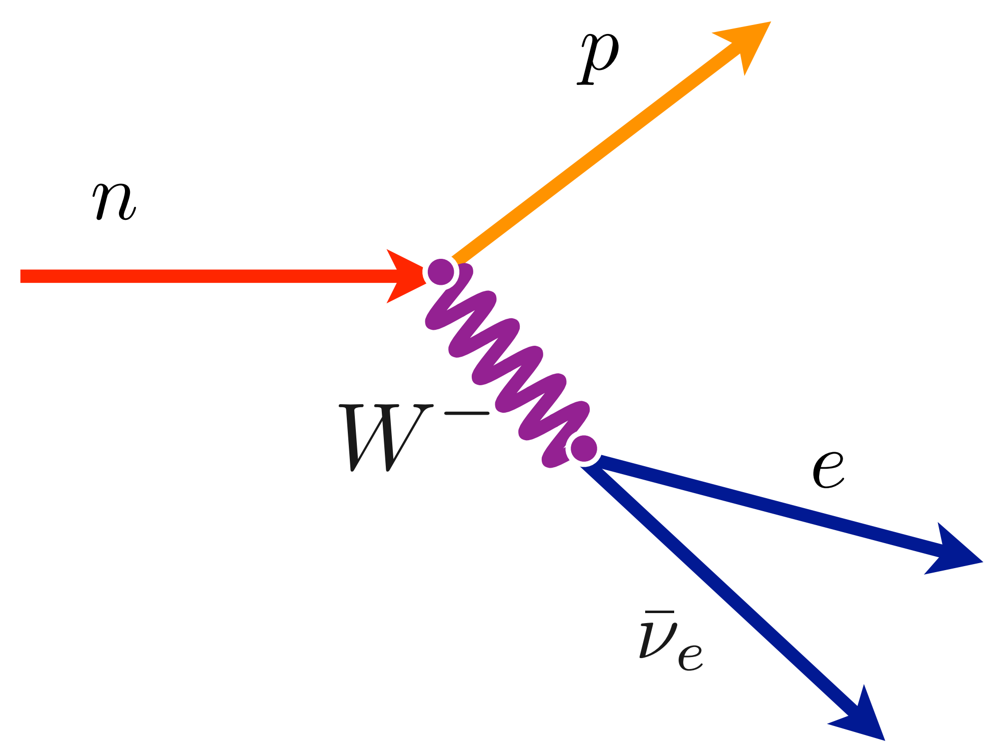


pretend this is primitive for a moment.

Neutron beta decay:

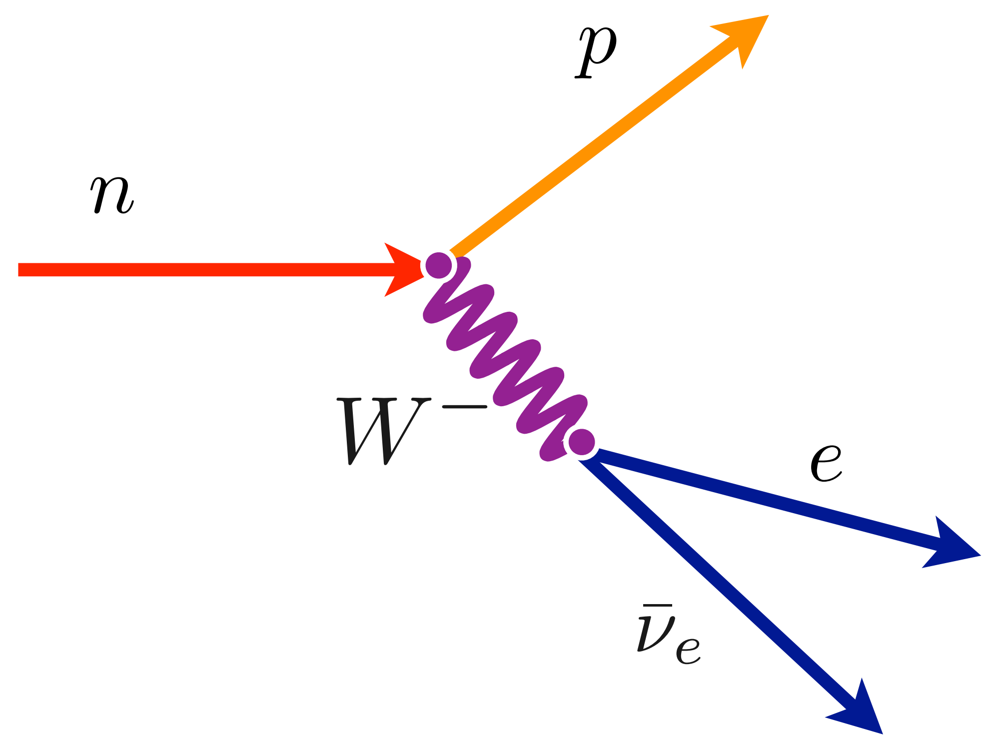


becomes:



keep track of the charge flow

there are 2 W charged states

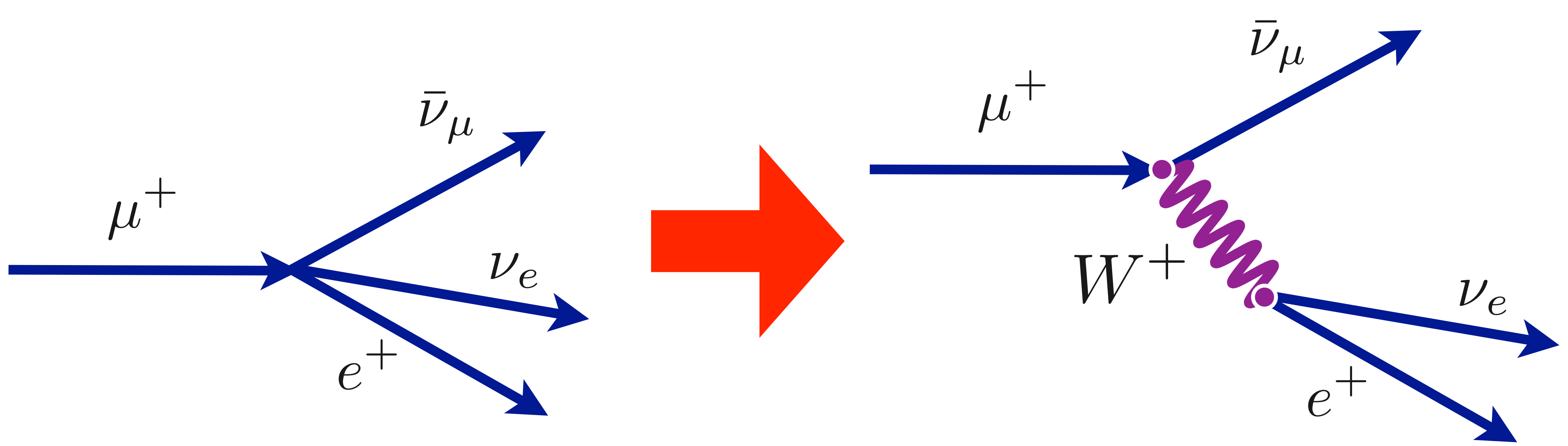


$$n \to p + W^- \to p + e^- + \bar{\nu}_e$$

Q: 0 = +1 + −1 = +1 + −1 + 0 = 0

So: W^- lowers the electrical charge by 1

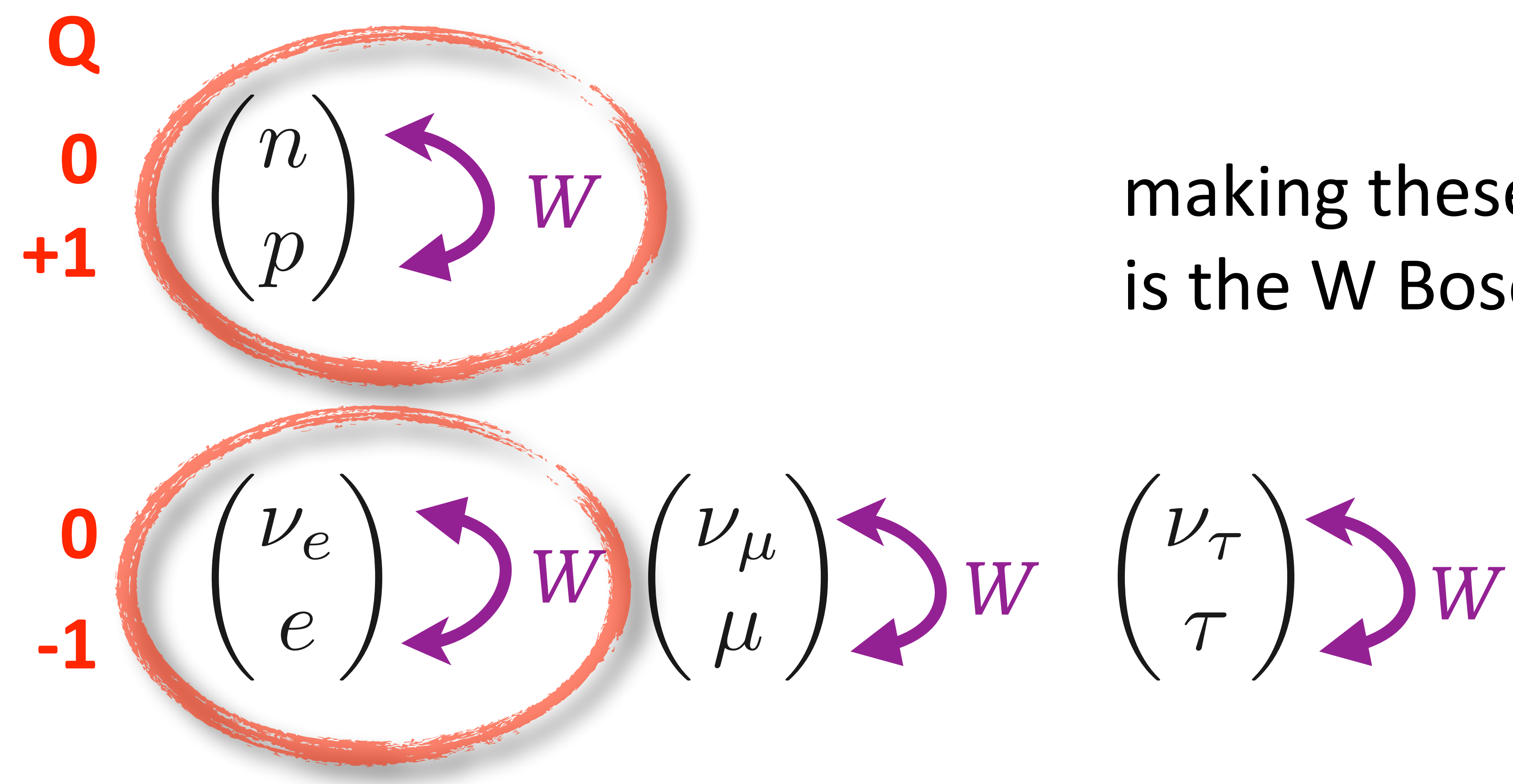
W^+ raises the electrical charge by 1



here is where those weak “doublets” come in

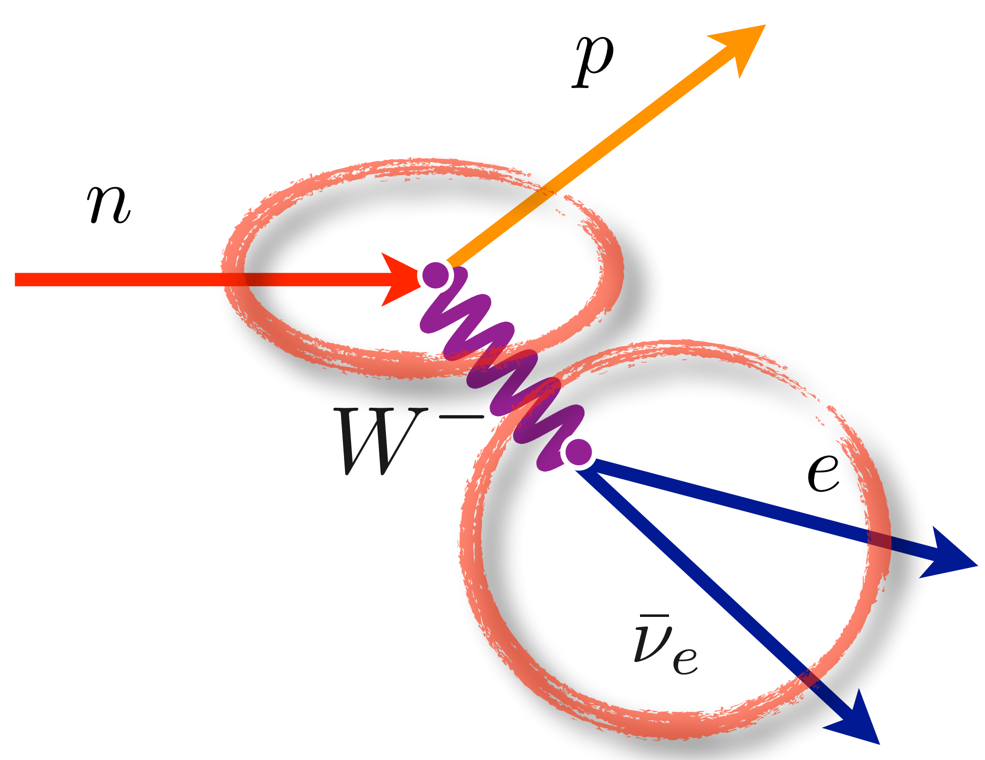
the Weak Interaction connects them

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“

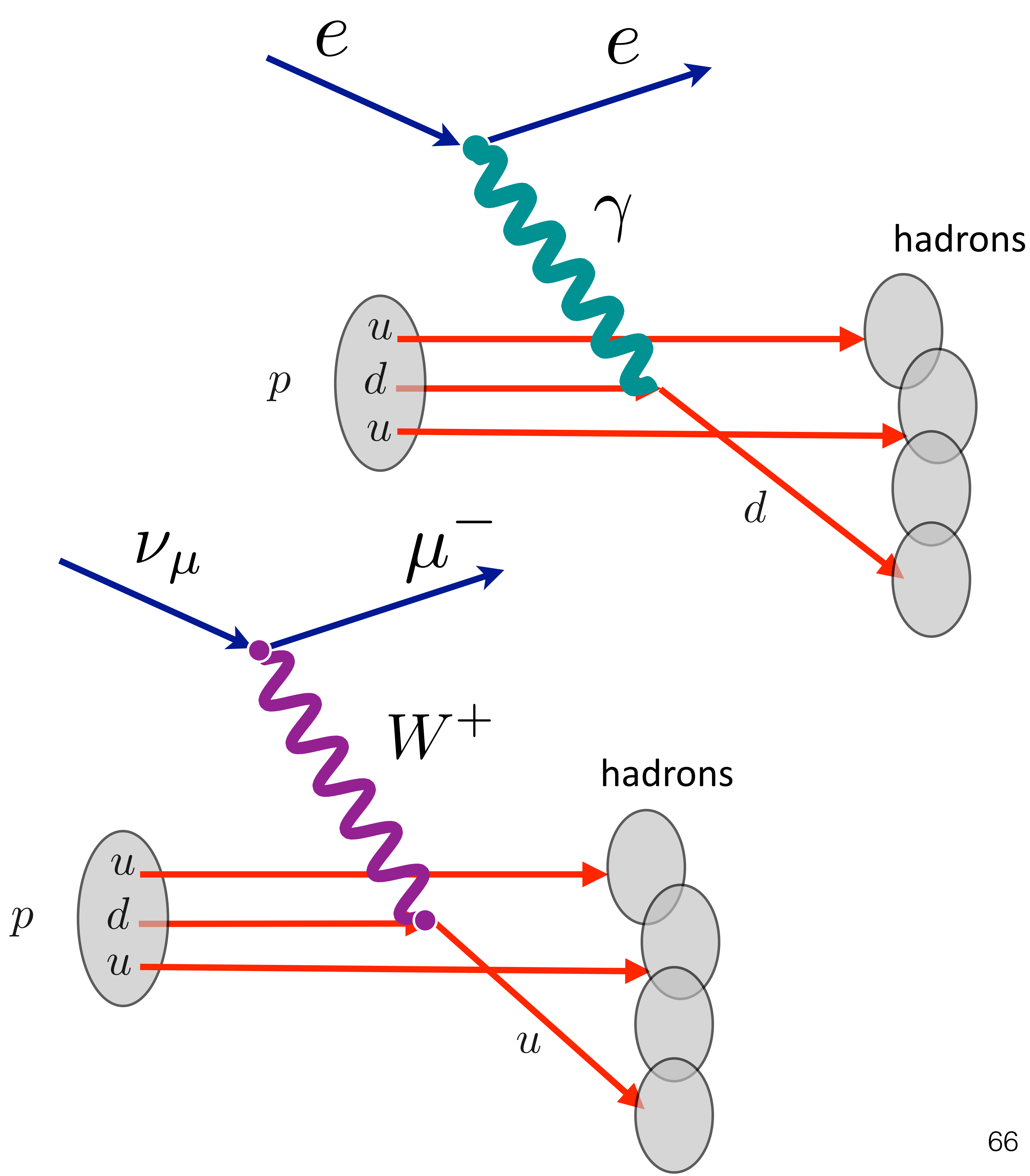
$$\ell = e, \mu, \tau$$

"deep inelastic scattering"

hitting quarks individually

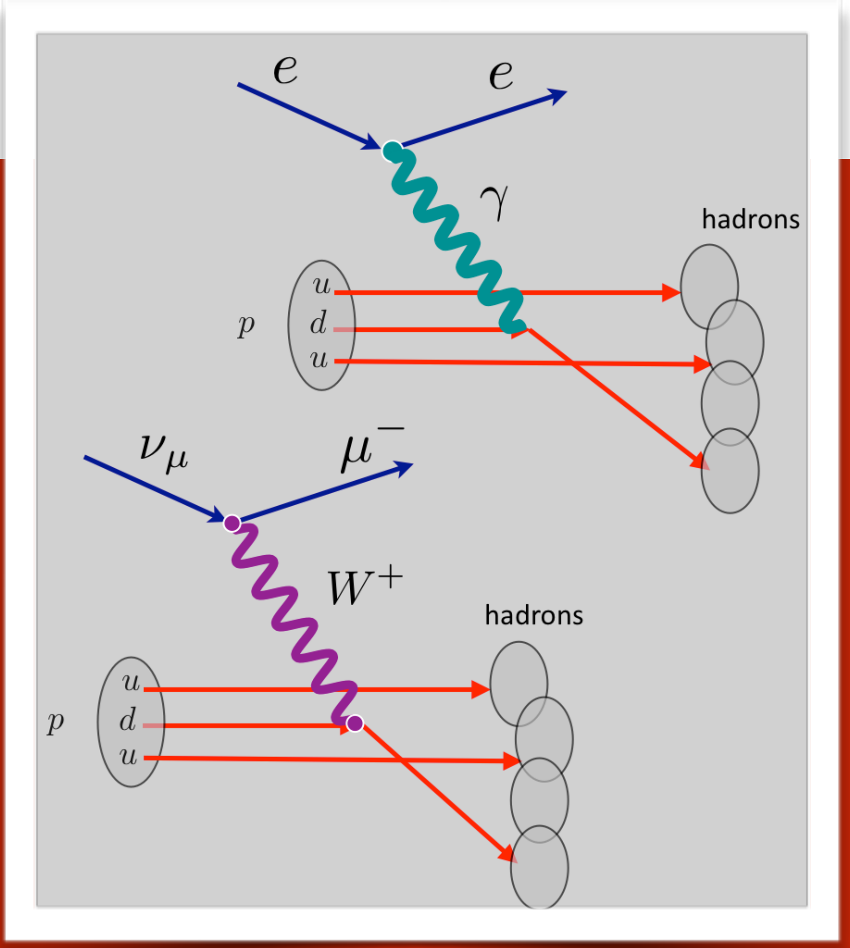
of course in a statistical fashion

neutrinos do it too...



analyses of these reactions,

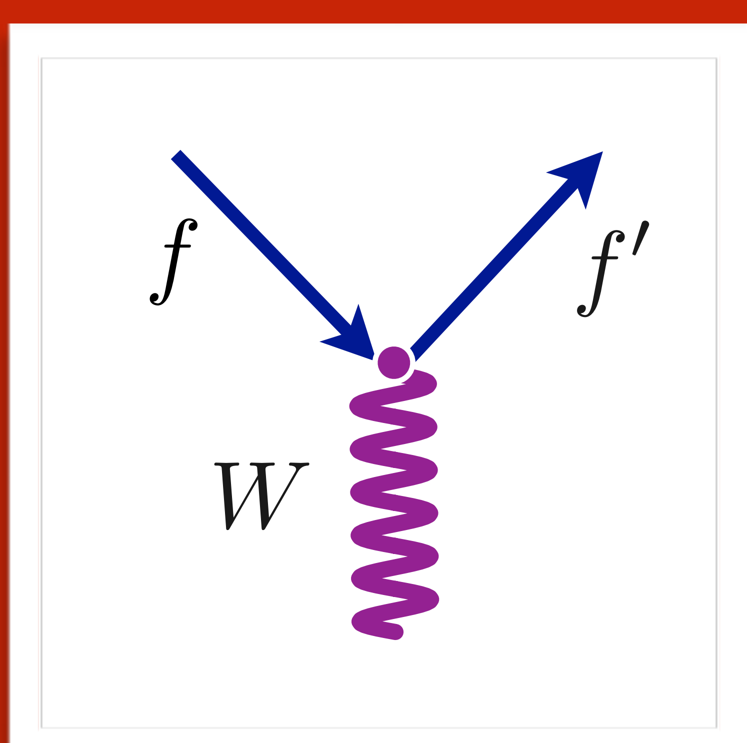
$$\nu N \to \mu X \qquad eN \to eX$$



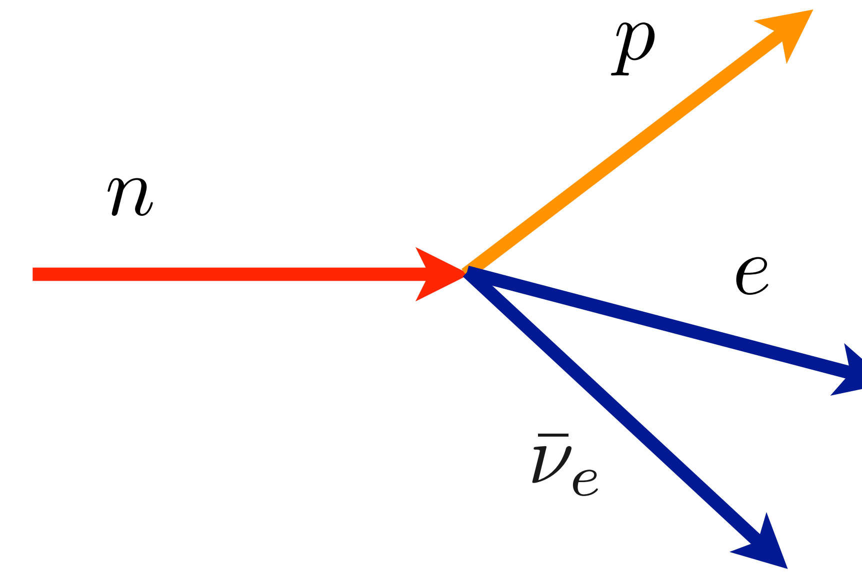
1. confirm the point-like (?) nature of quarks
2. confirm their apparent loose-binding within nucleons (in a second)
3. confirm their fractional electric charges!

so, a new primitive diagram

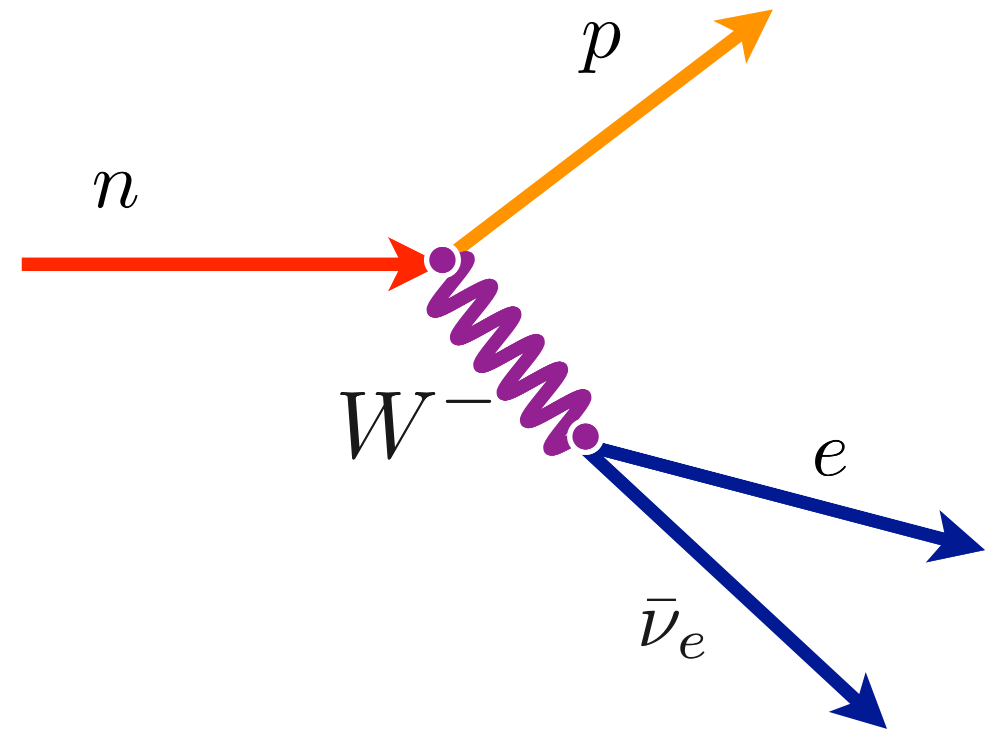
for the Weak Interaction with quarks, to go with the leptons



Neutron beta decay:

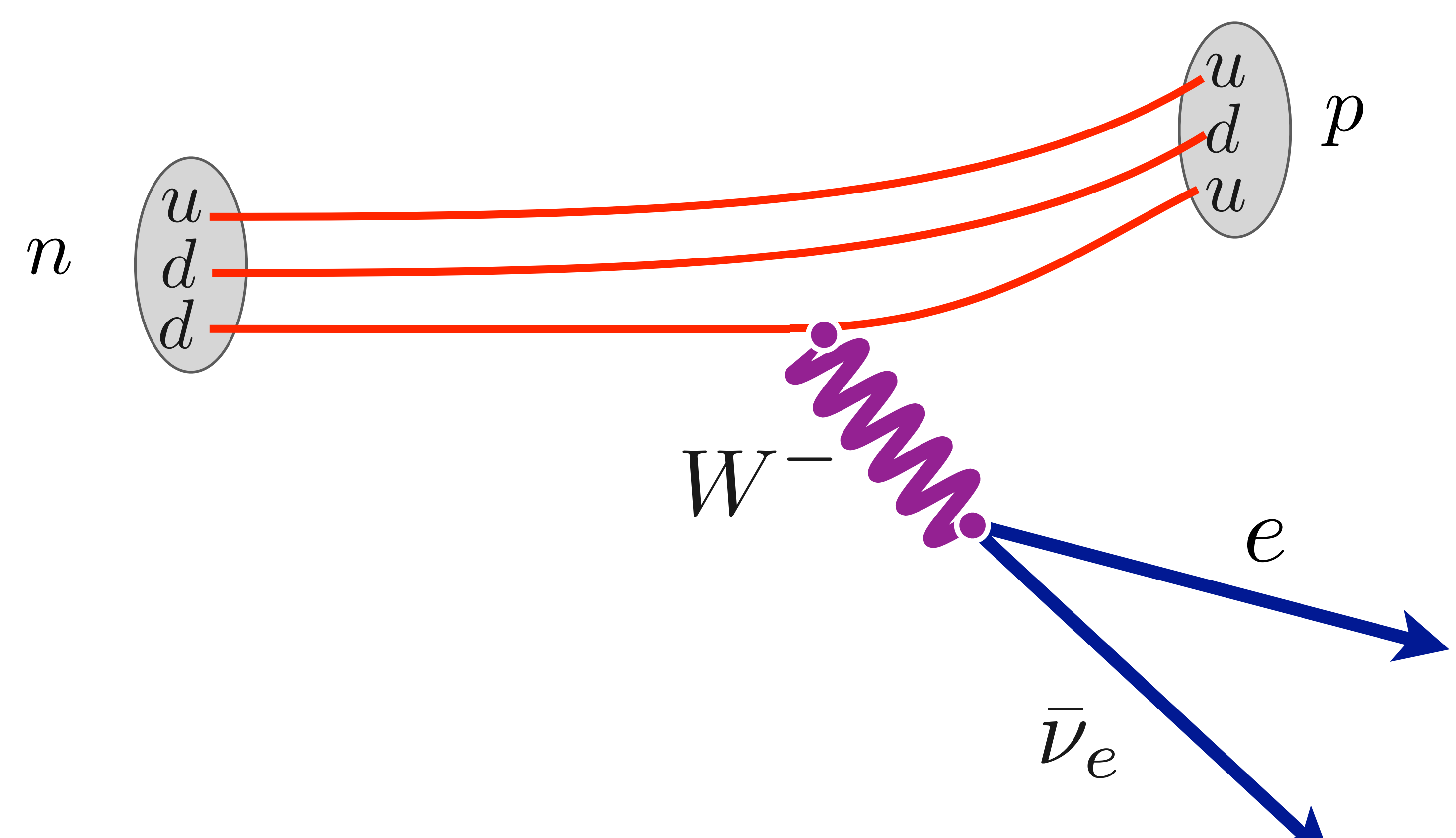


becomes:



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:

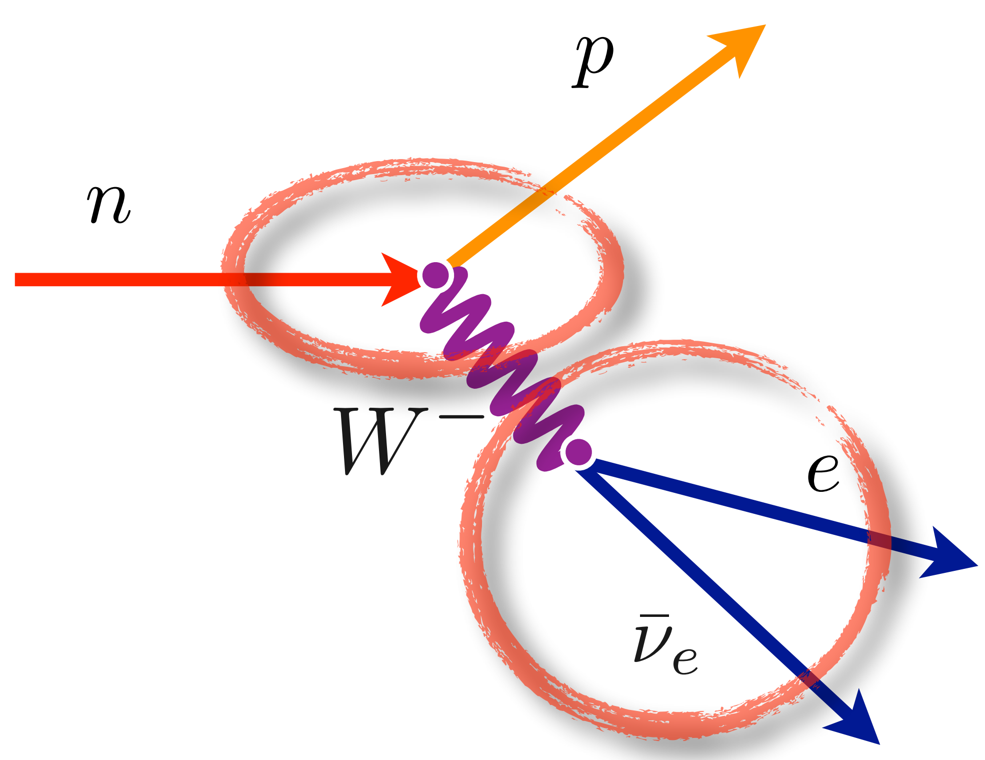
Q

0 / **+1**: $\begin{pmatrix} n \\ p \end{pmatrix} \circlearrowright W$

making these transitions is the W Boson's job.

0 / **-1**: $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \circlearrowright W \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \circlearrowright W \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \circlearrowright W$

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:

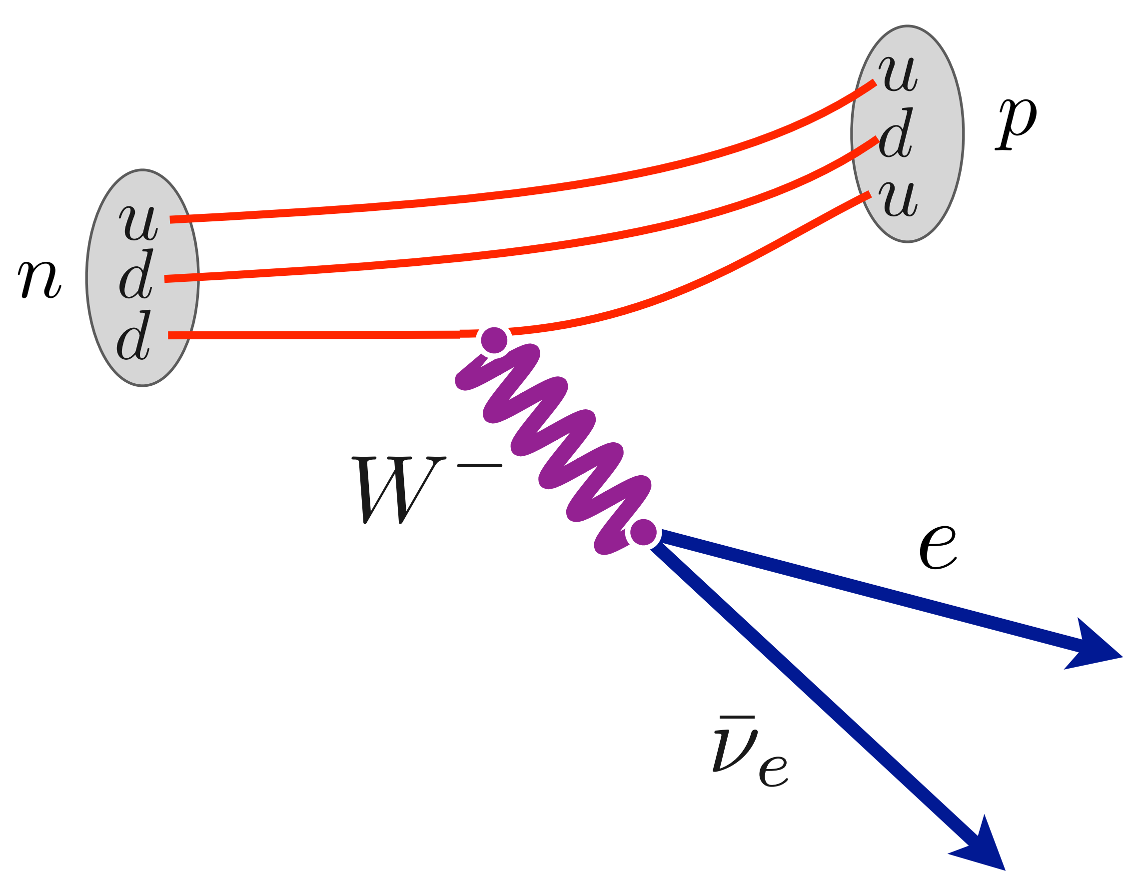
Q				making these transitions is *still* the W Boson's job.
+2/3 -1/3	$\begin{pmatrix} u \\ d \end{pmatrix}$ ⟲ W	$\begin{pmatrix} ? \\ s \end{pmatrix}$ ⟲ W		
0 -1	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ ⟲ W	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$ ⟲ W	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$ ⟲ W	

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"

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

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



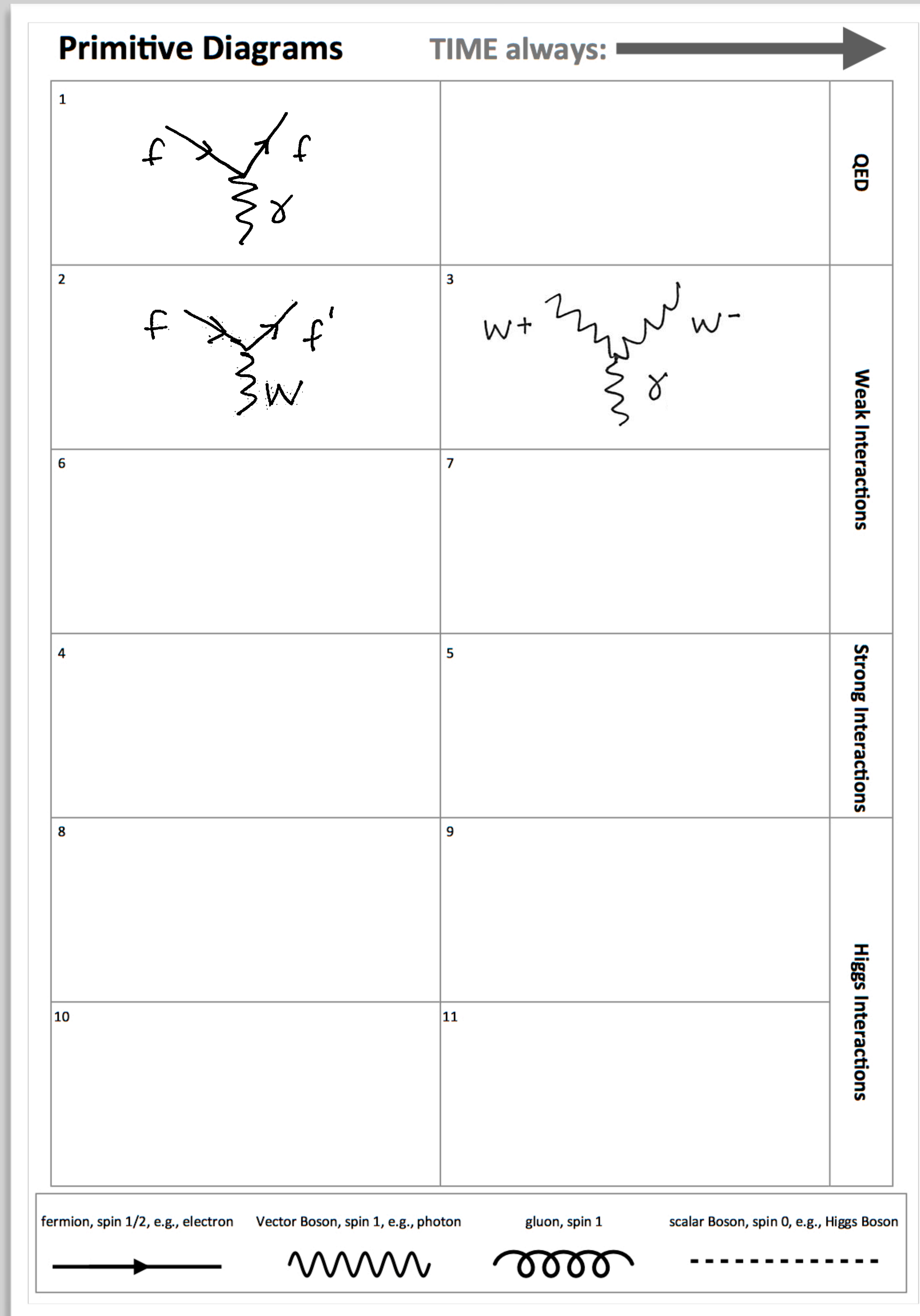
or:
call a generic fermion, "f"

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

$$f = \ell, q$$

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

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad \begin{pmatrix} c \\ s \end{pmatrix}$$

"1974 Revolution"

Strong interaction, again:

The original question about nuclei...

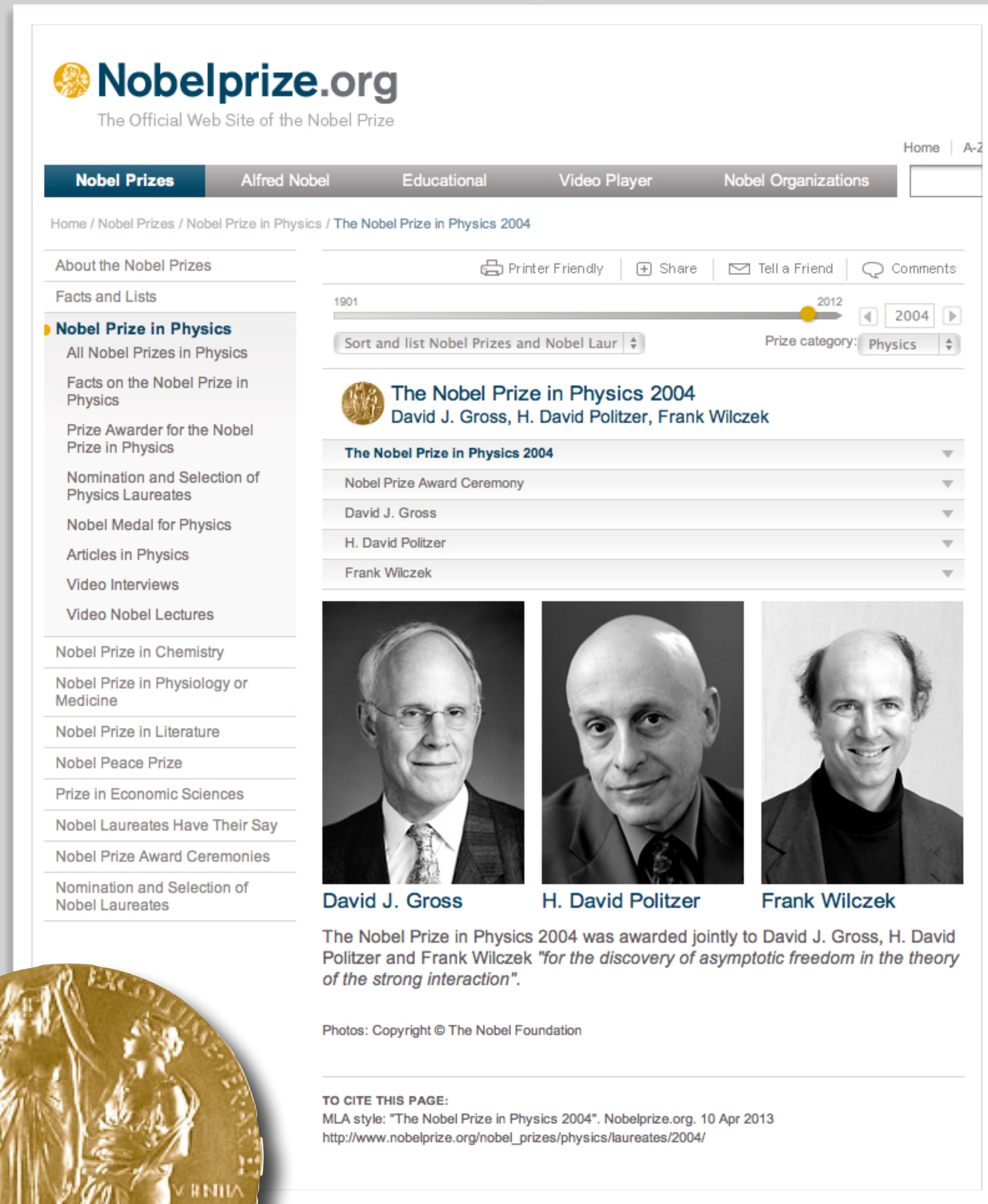
now in play for quarks:

what holds the quarks inside of the baryons and mesons?

Gross, Politzer, and Wilczek

2004

"asymptotic freedom" in strong interactions

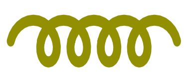


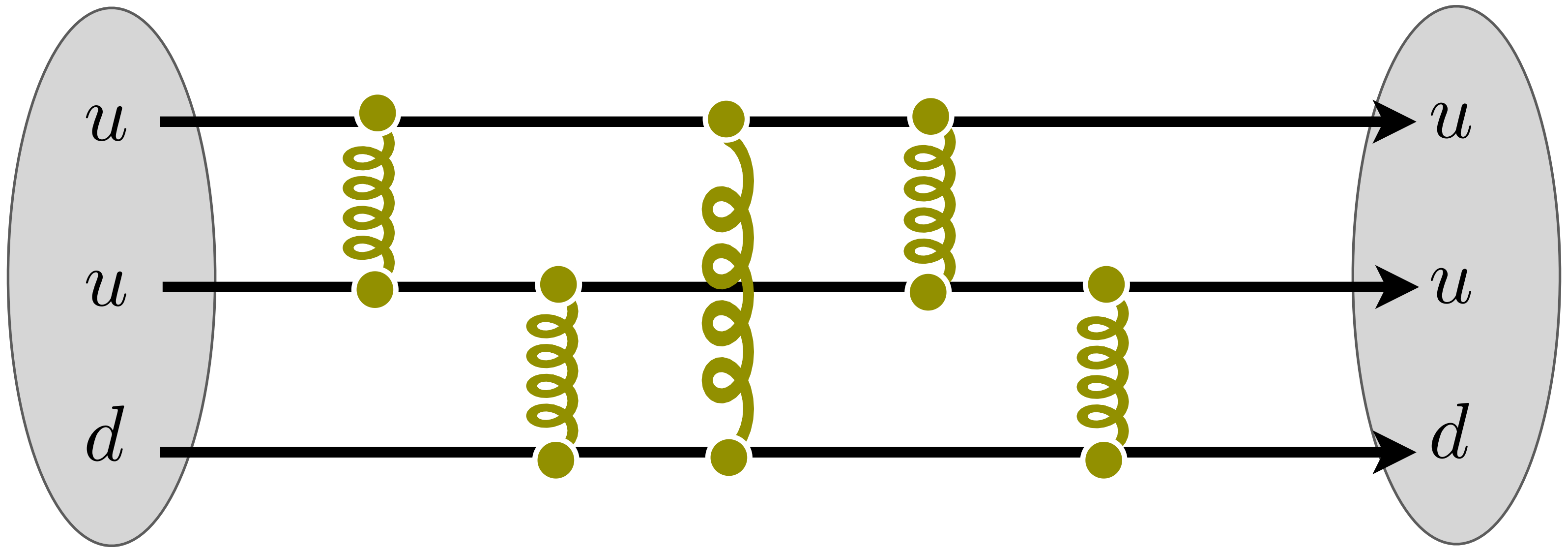
it's the glue that holds everything together

virtually

Predicted the existence of the Strong Messenger Particle:

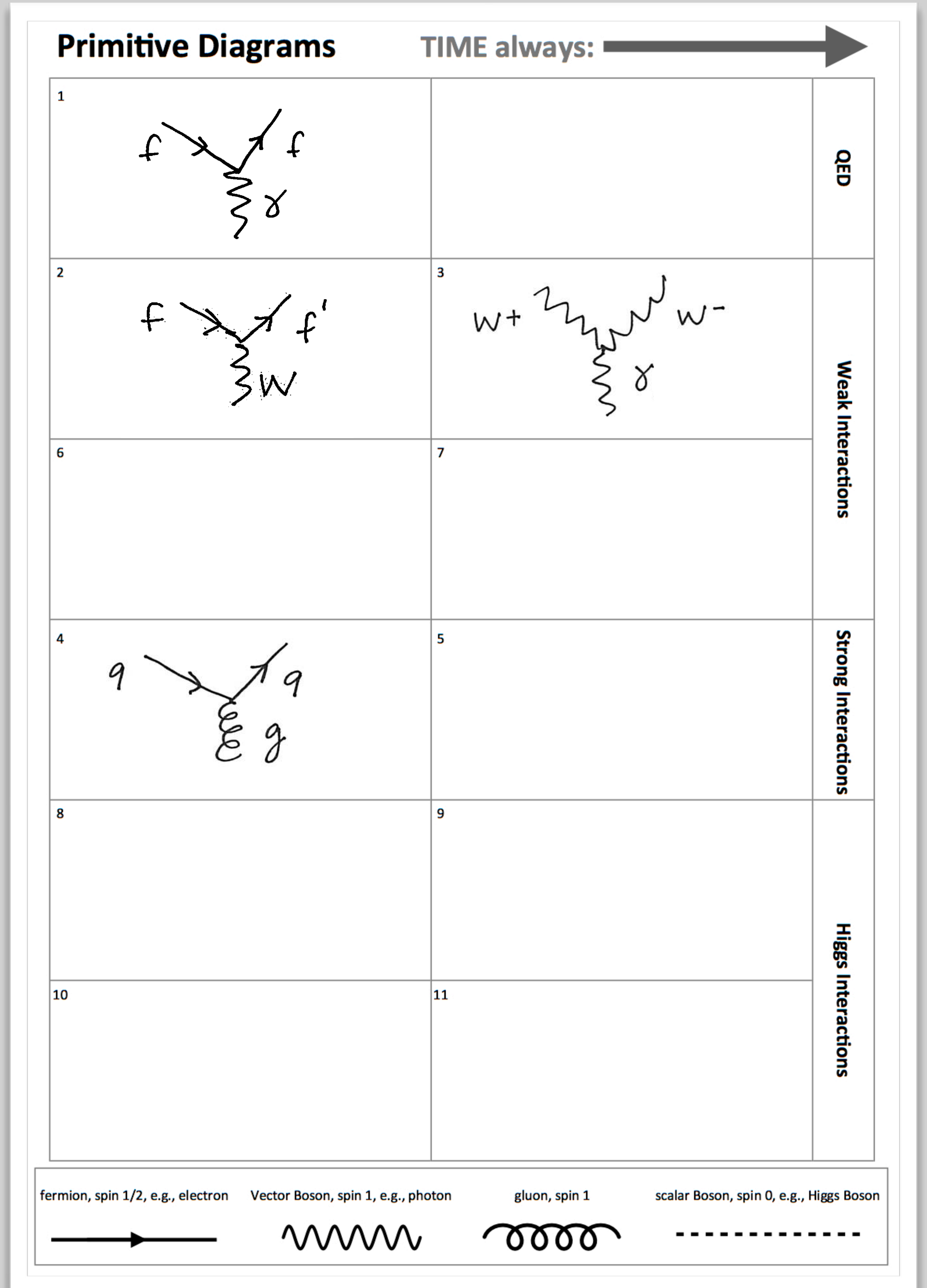
the Gluon





third entry into your

table of primitive diagrams

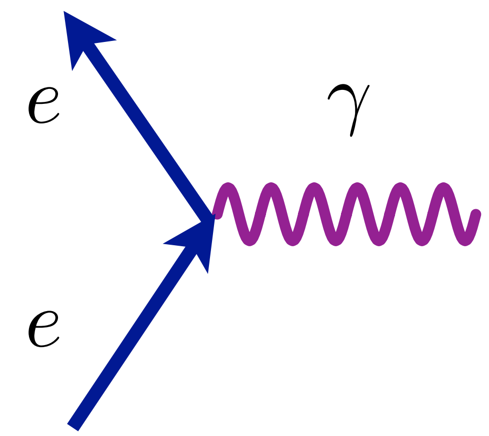


there are two amazing things

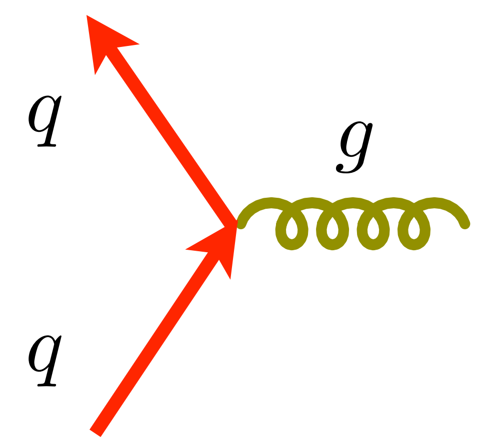
about gluons

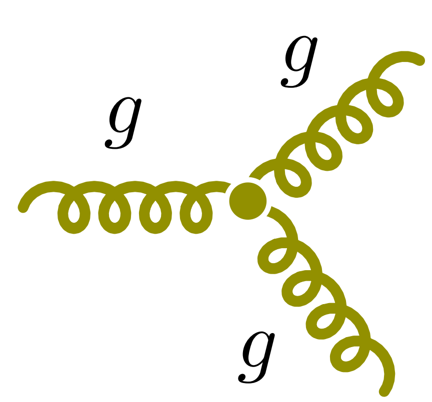
thing 1

they self-interact

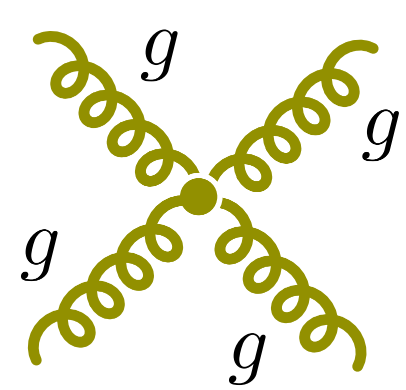


a photon propagates the electromagnetic force...but it **does not** have an electric charge





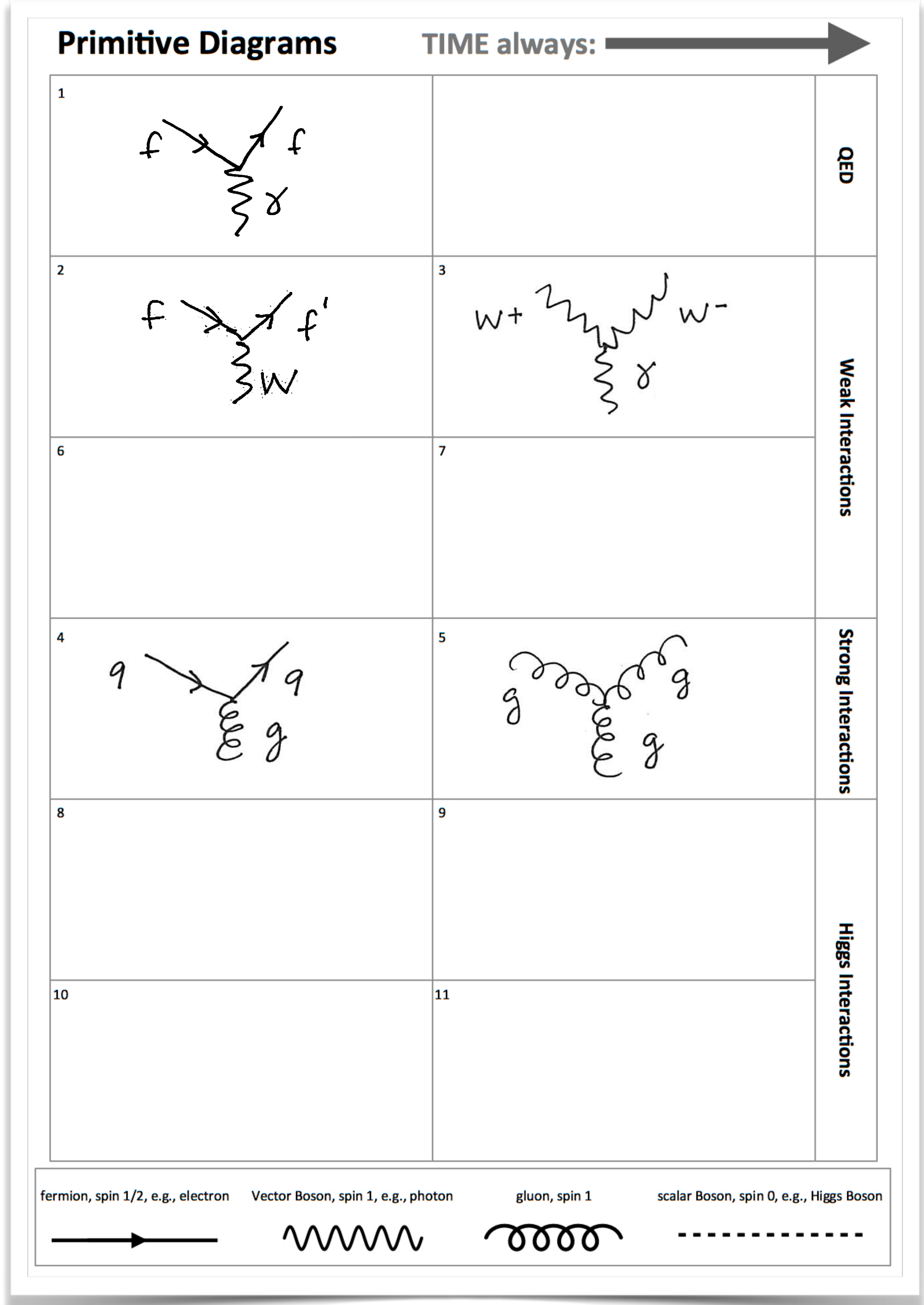
the gluon propagates the strong force...and it **DOES** have a “strong charge”



This has significant consequences...almost magical

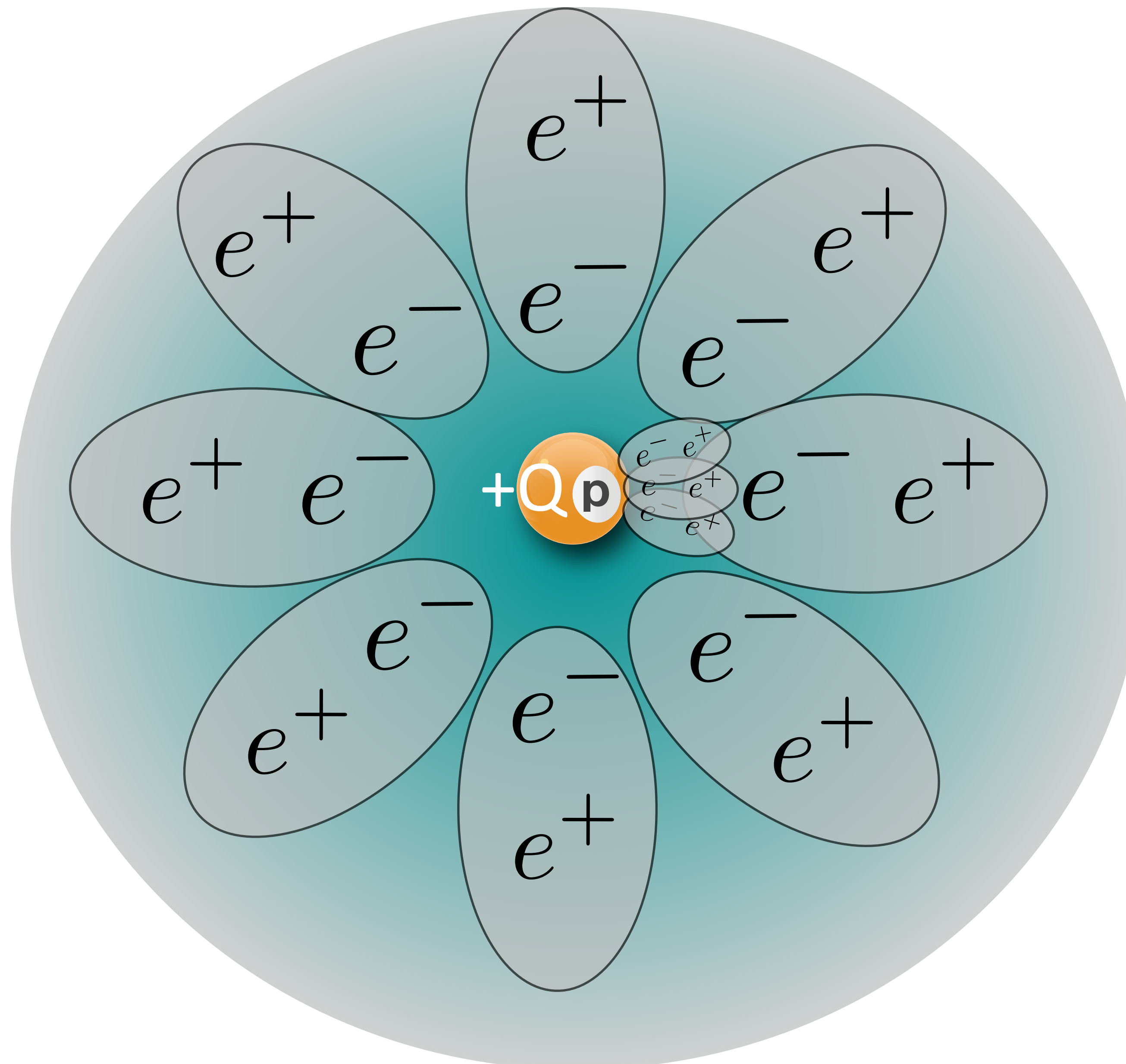
fourth and fifth entries into your

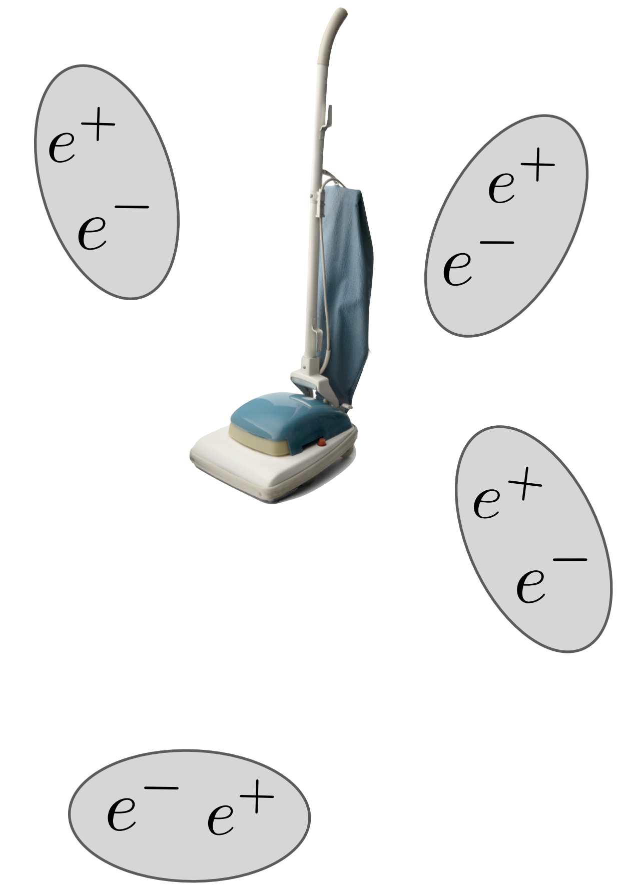
table of primitive diagrams



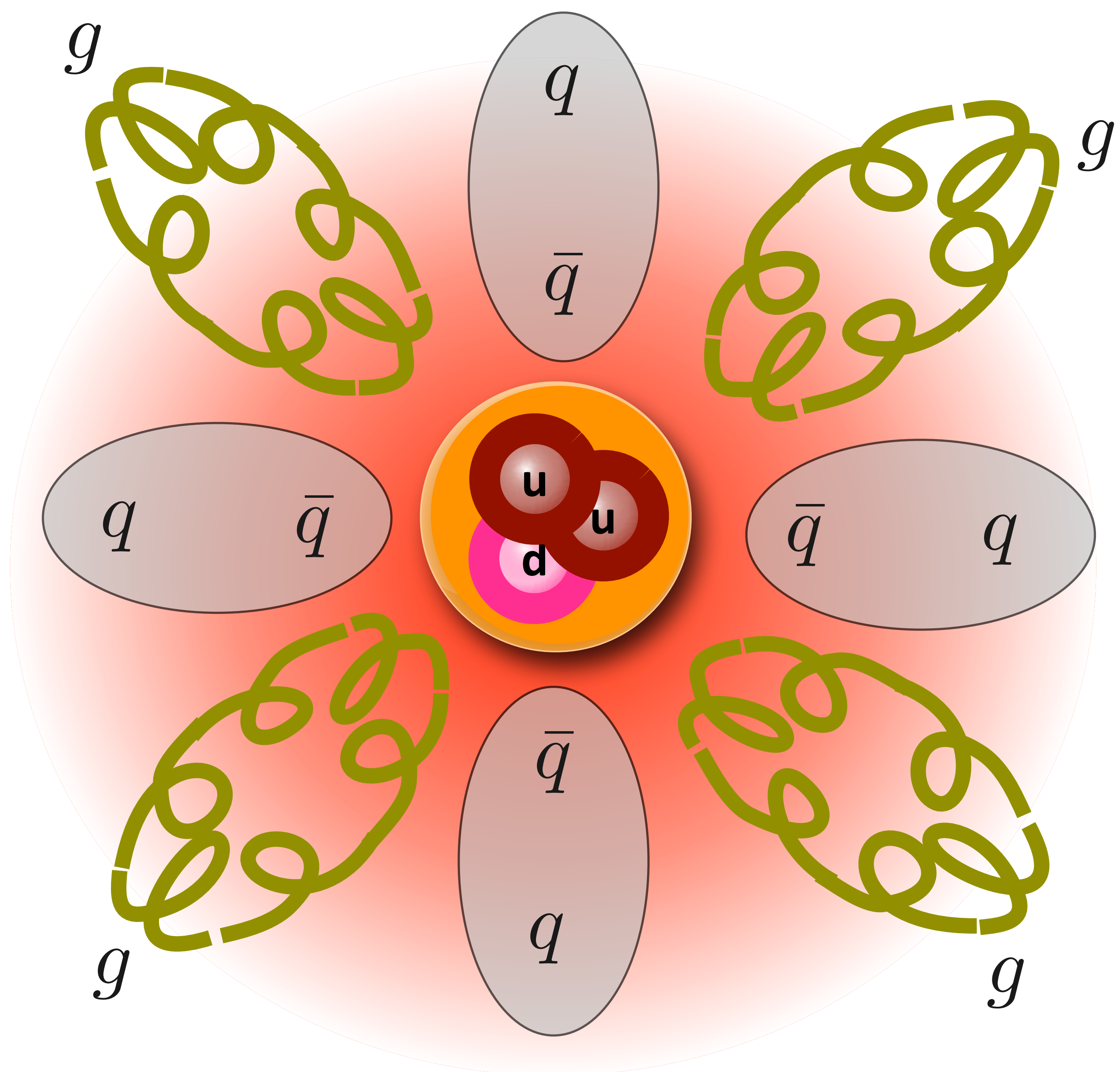
thing 2

their force field is the opposite of electromagnetism, or gravity

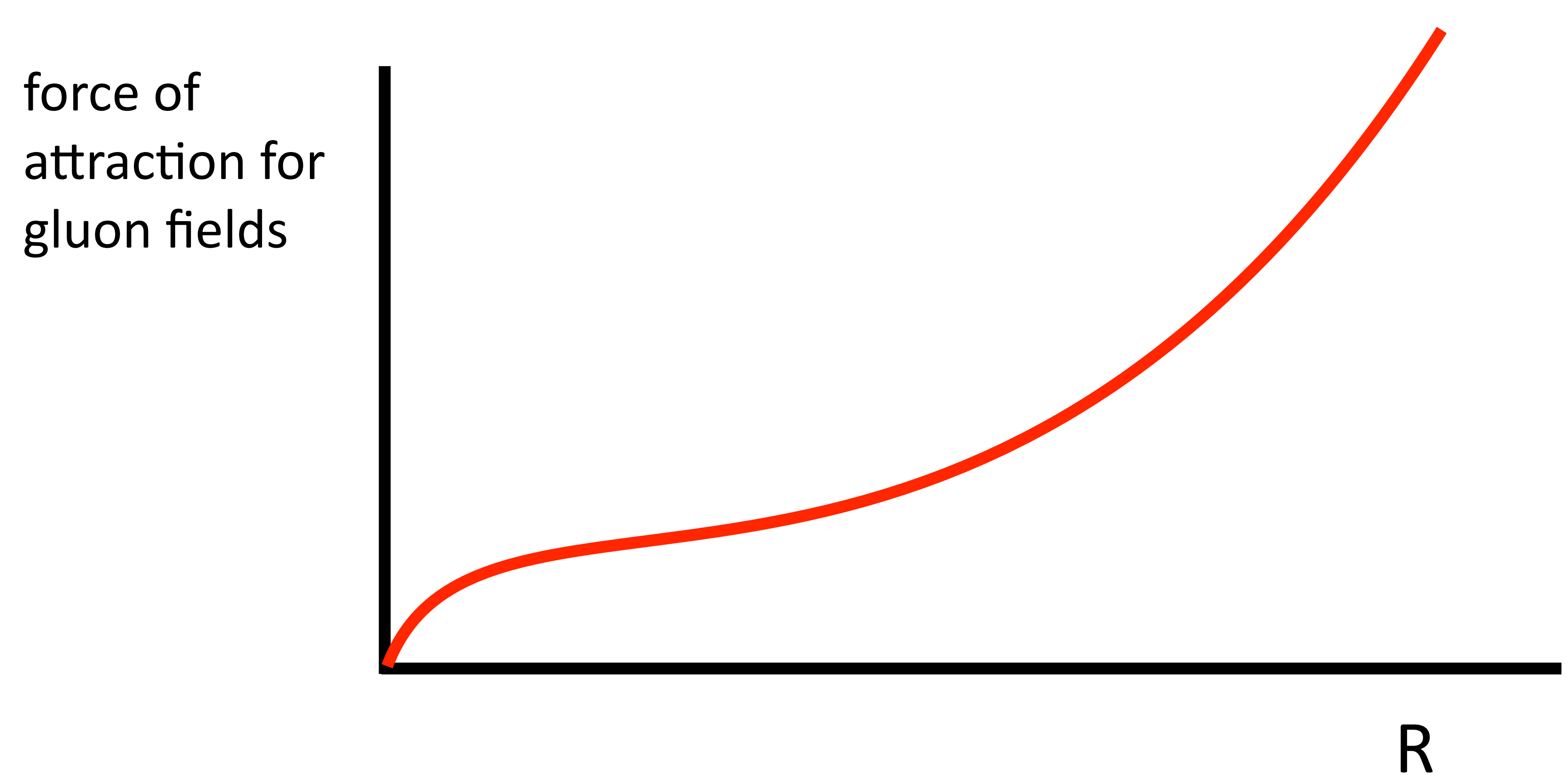




ah, but the gluon is odd



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

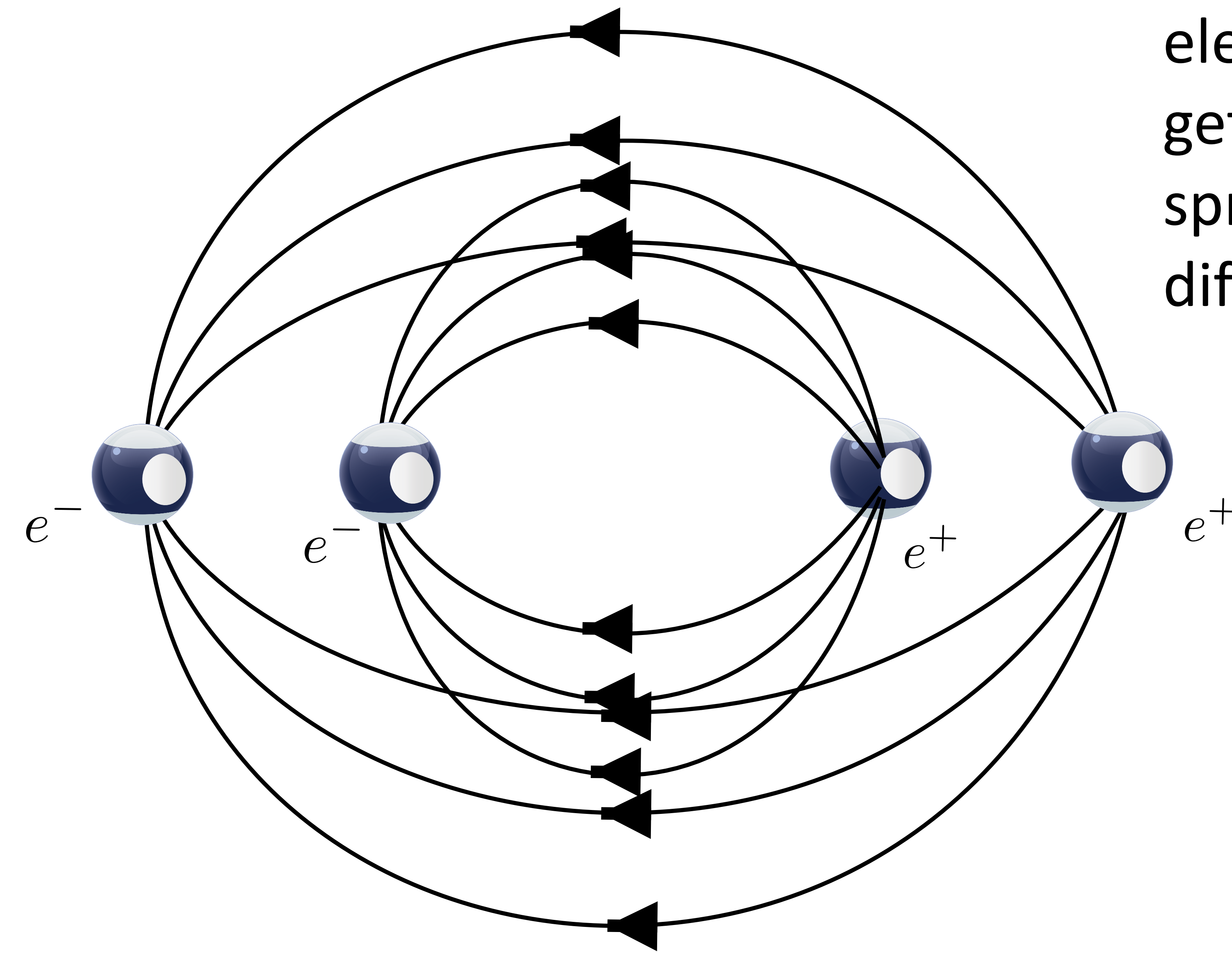


pull 'em apart

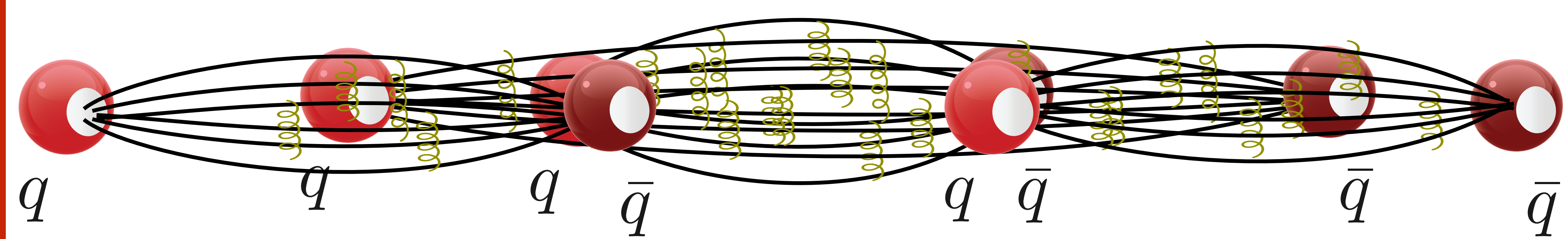
called

quark confinement

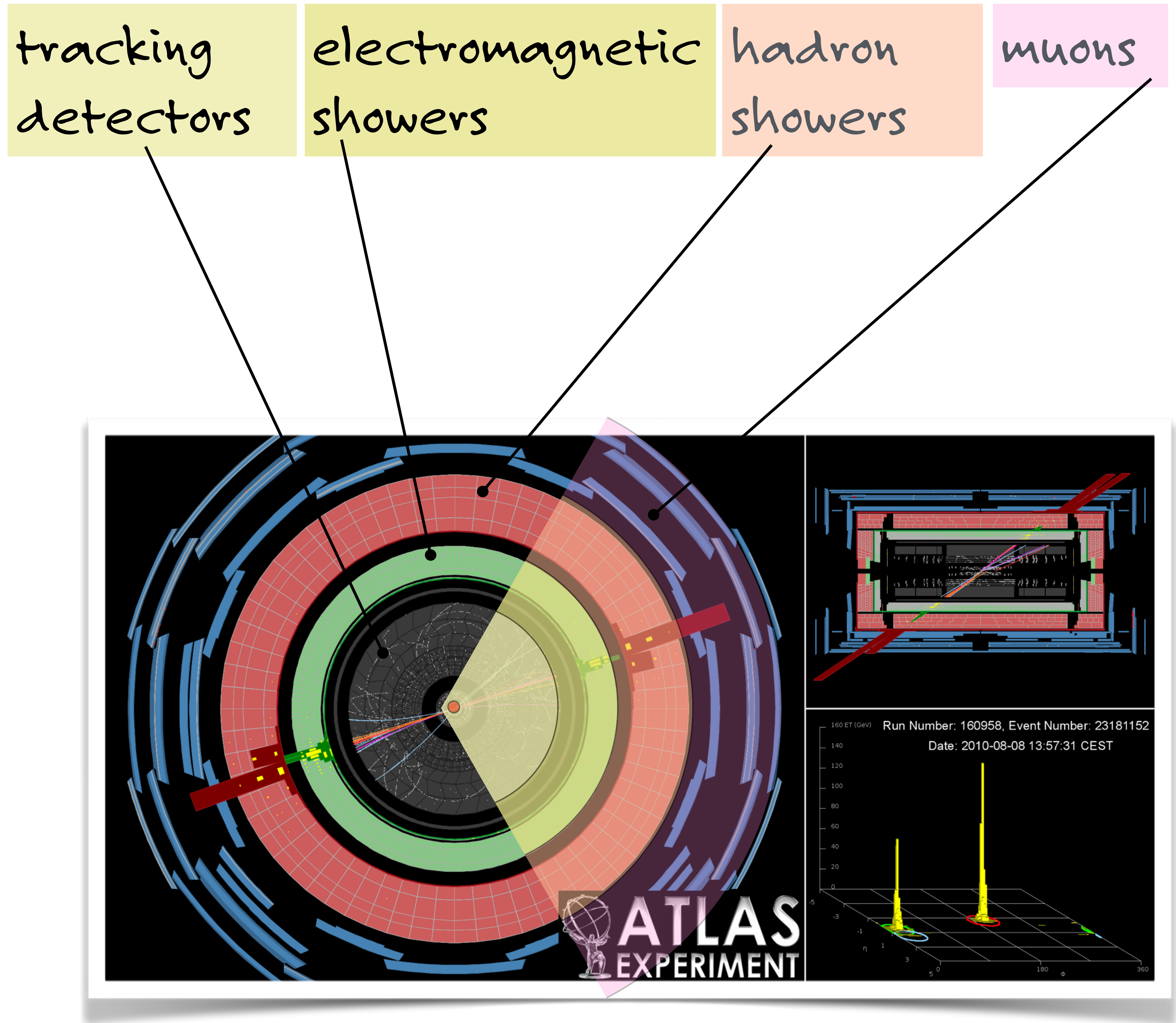
quarks cannot be "free"



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.

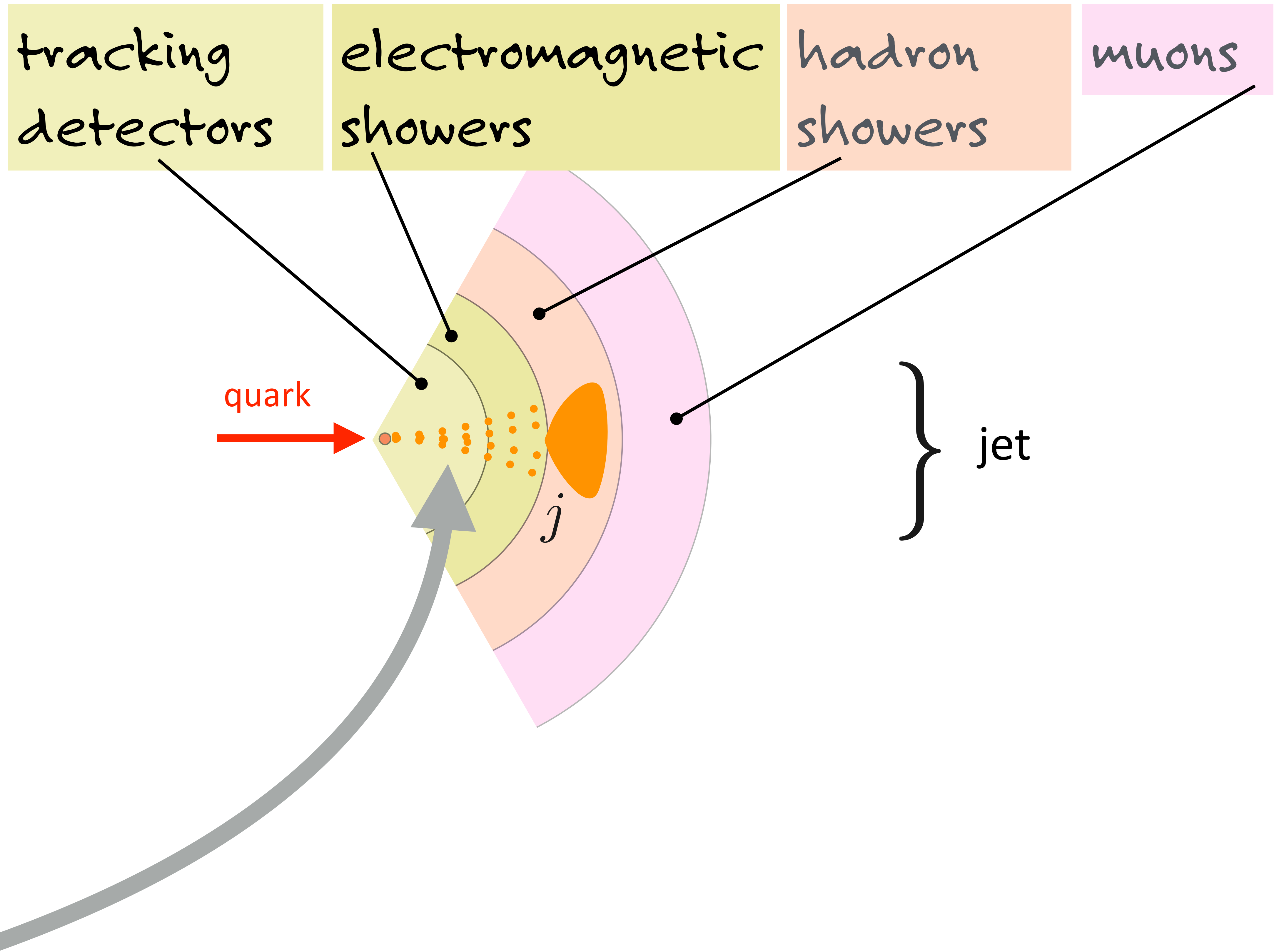

tracking detectors
electromagnetic showers
hadron showers
muons
Run Number: 160958, Event Number: 23181152
Date: 2010-08-08 13:57:31 CEST
ATLAS
EXPERIMENT

We don't see individual quarks or gluons

they make more quarks and gluons

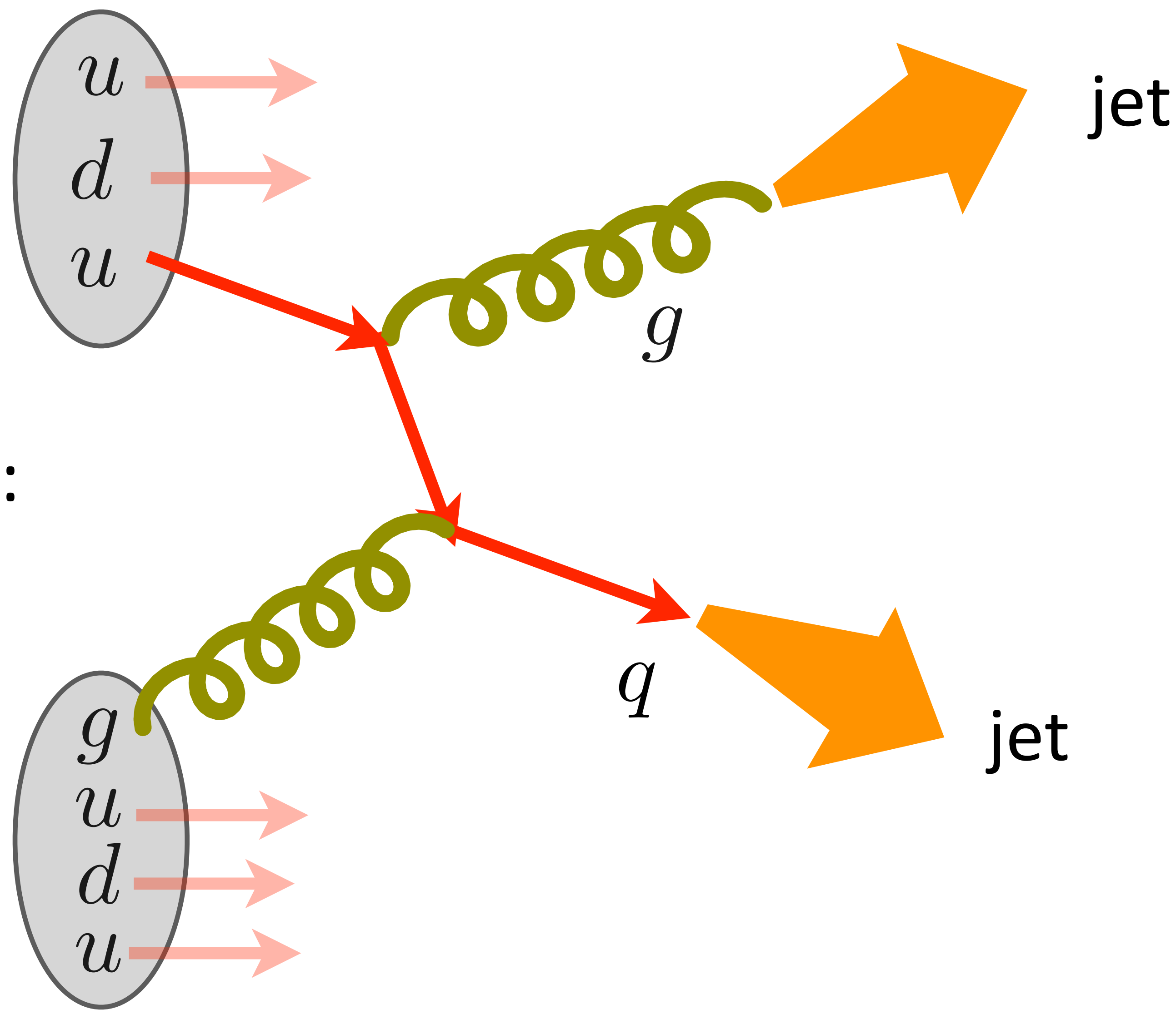
and interact very quickly into a cascade of particles

"quark-gluon **jets**"

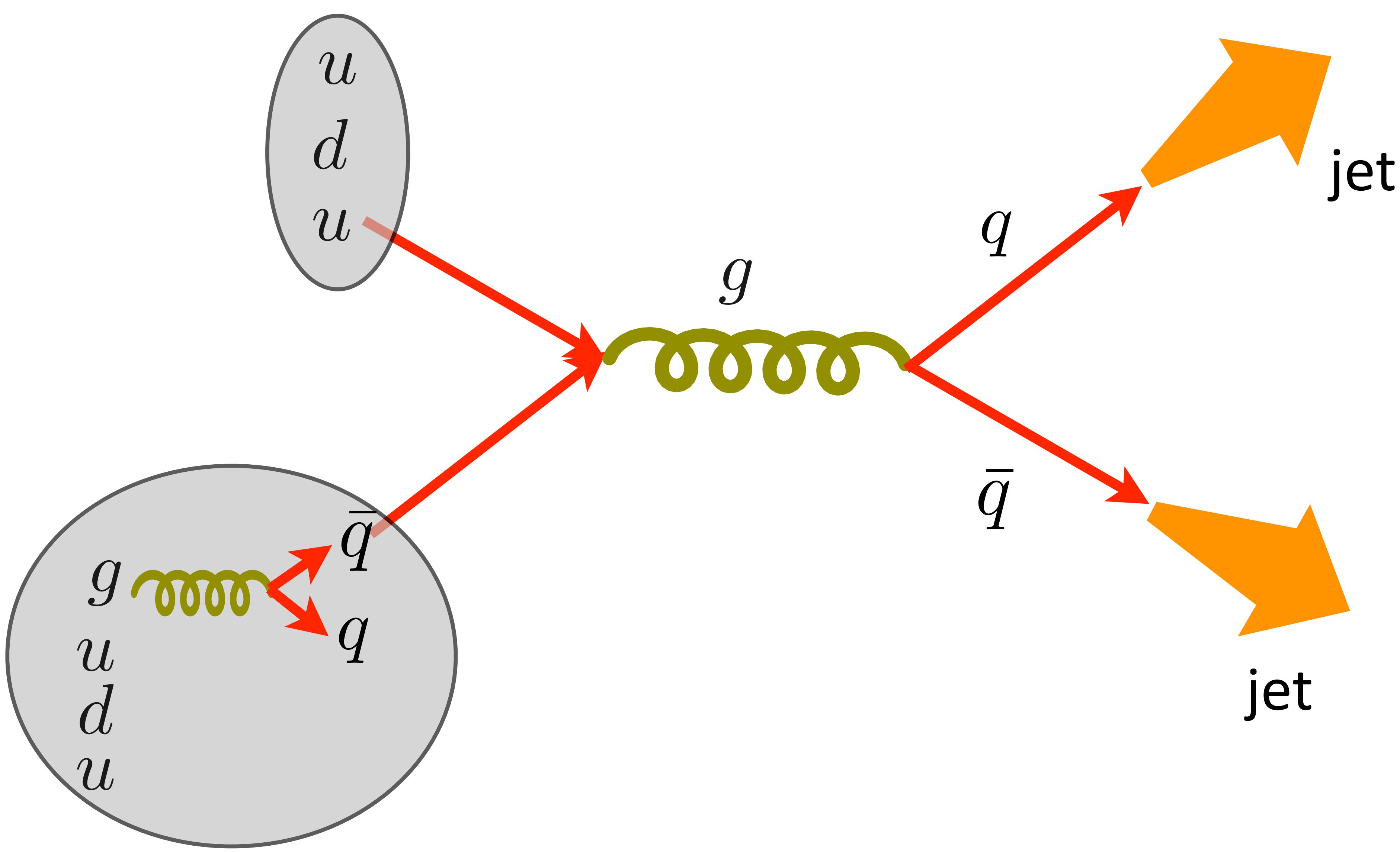


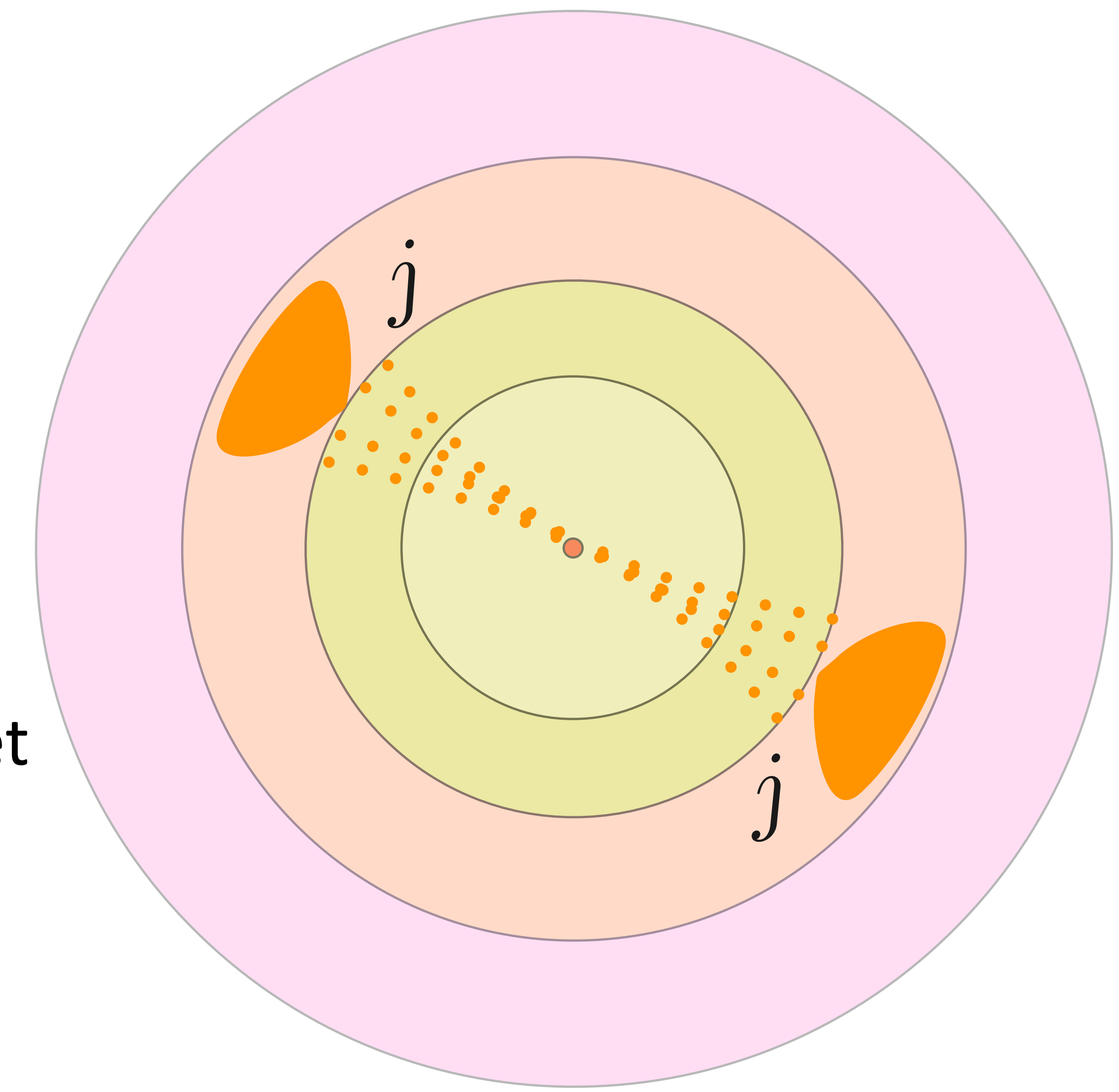
in ATLAS

maybe:

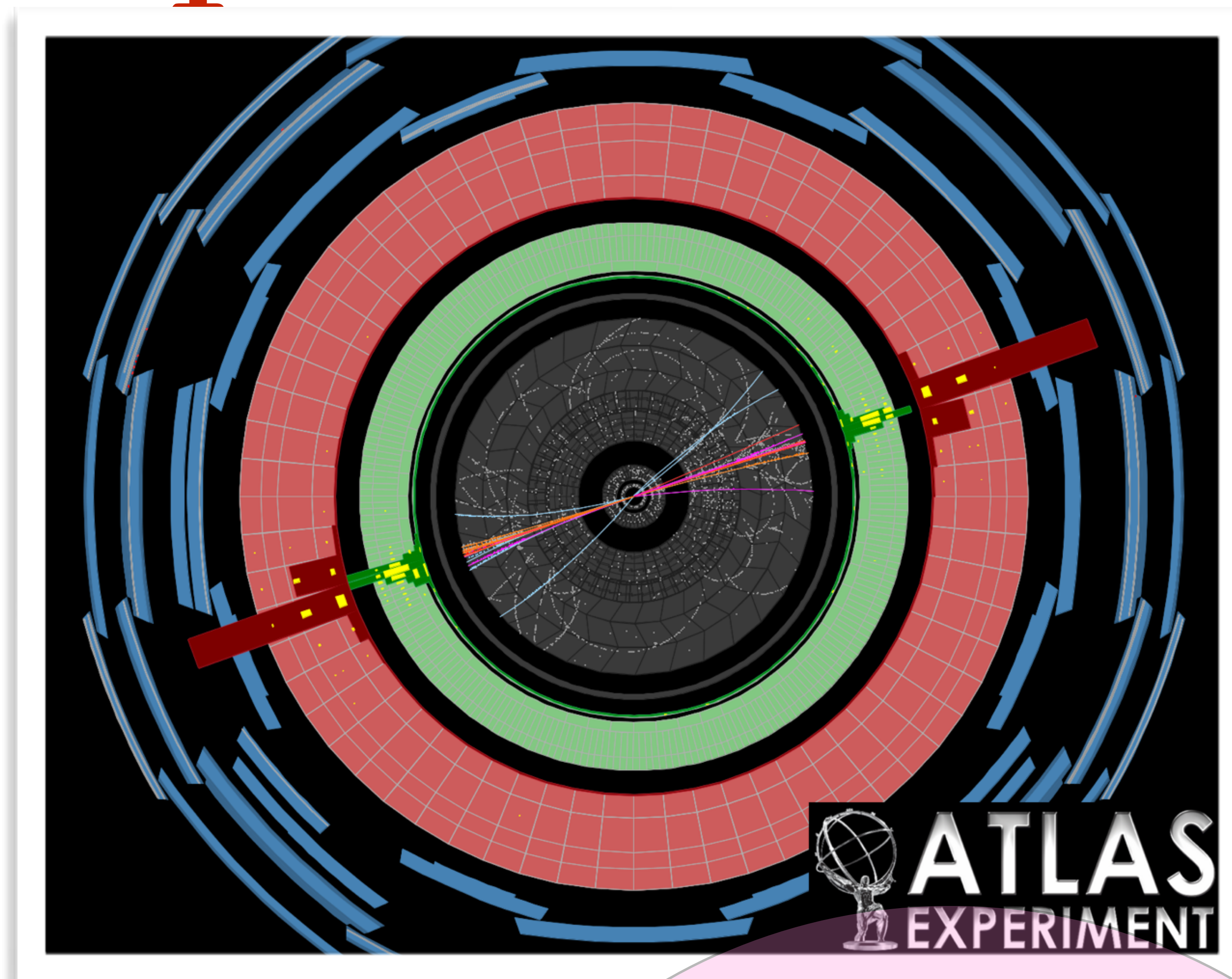


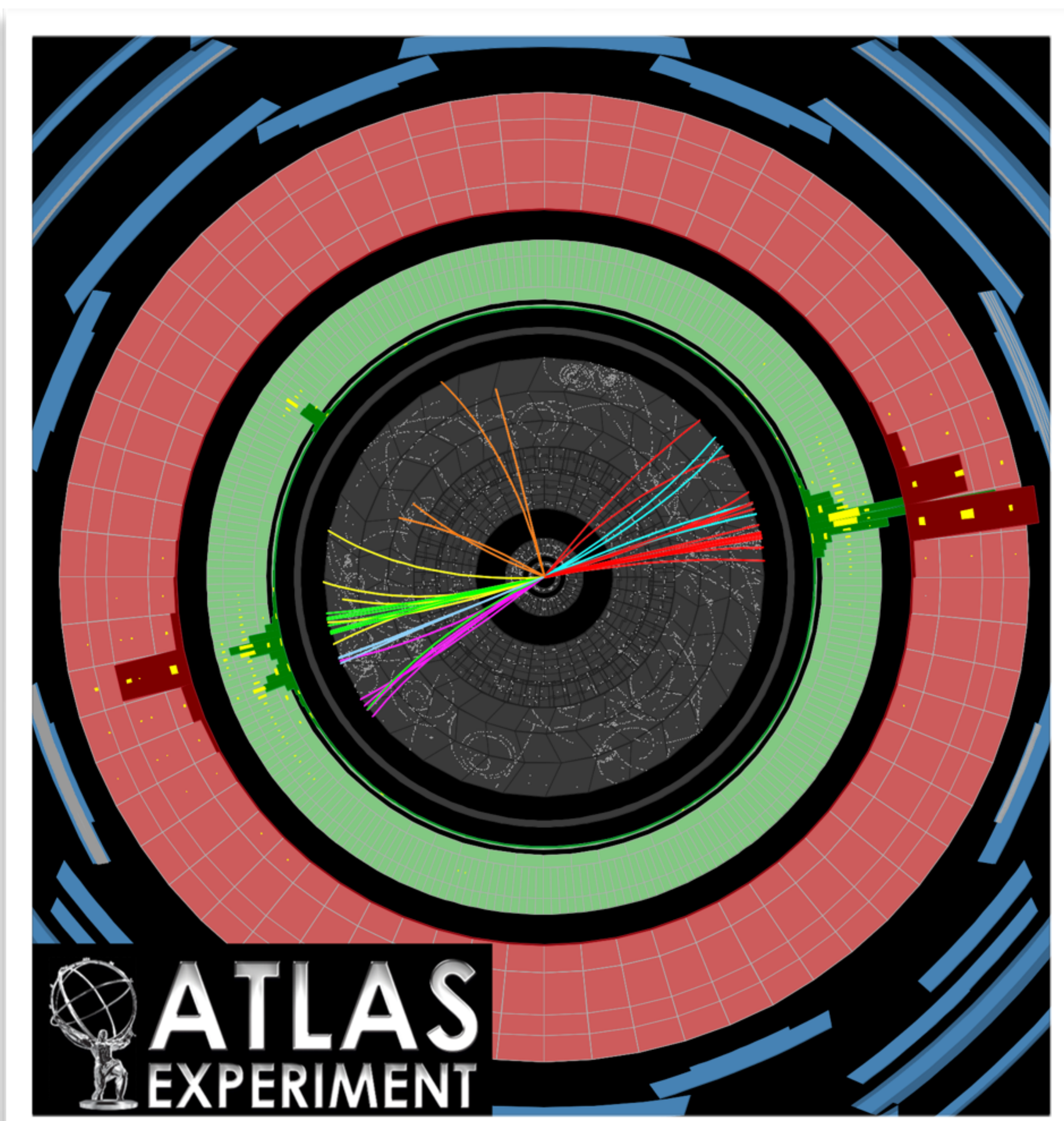
or:

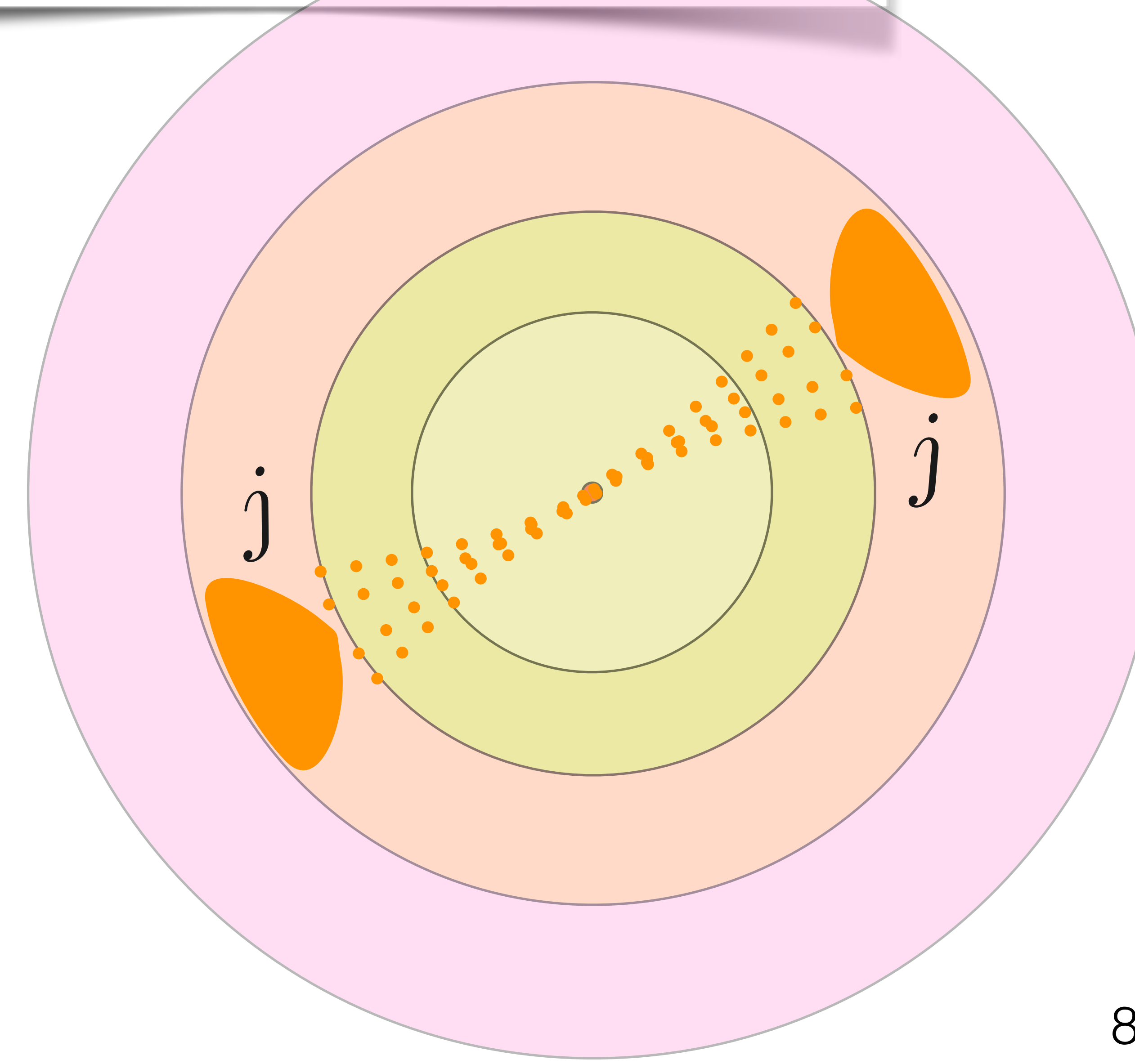




“‘hard’’ quark production





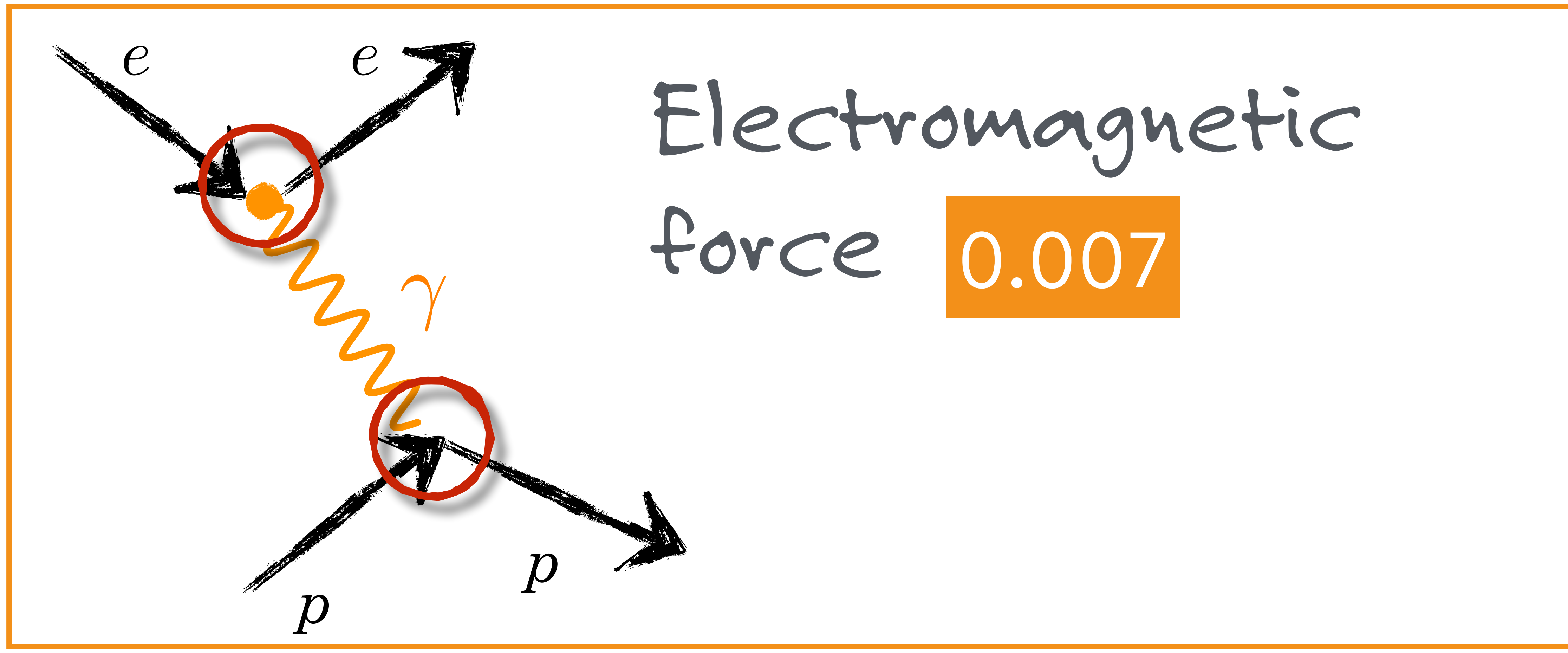


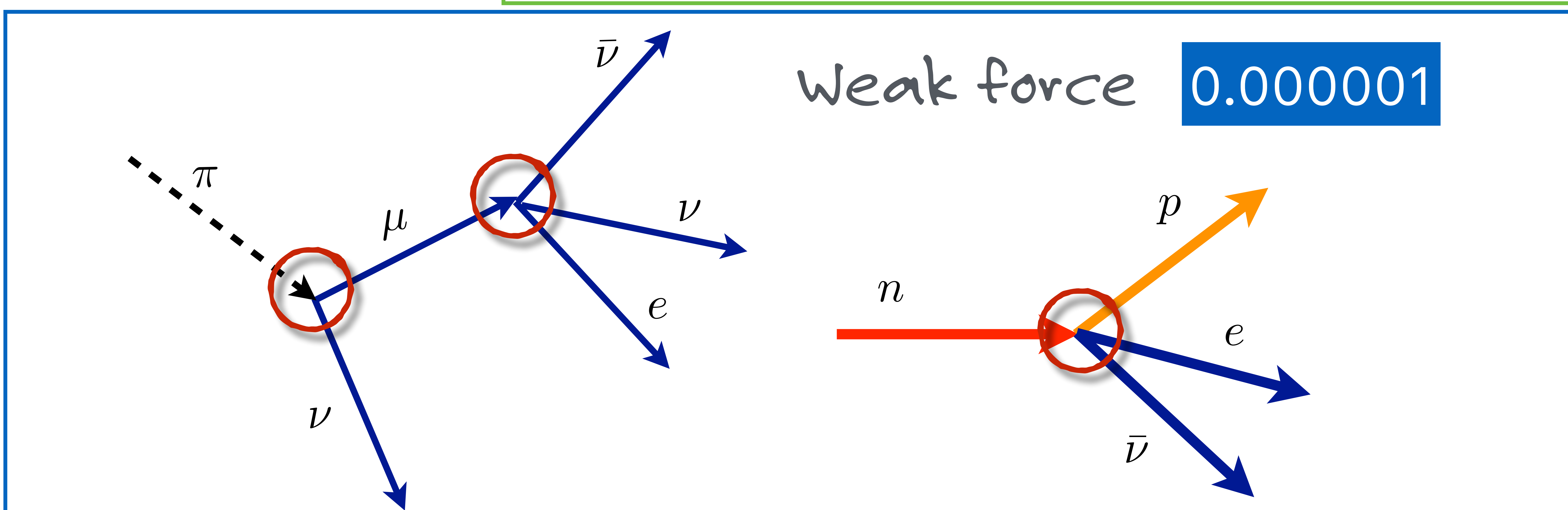
particle: **gluon**

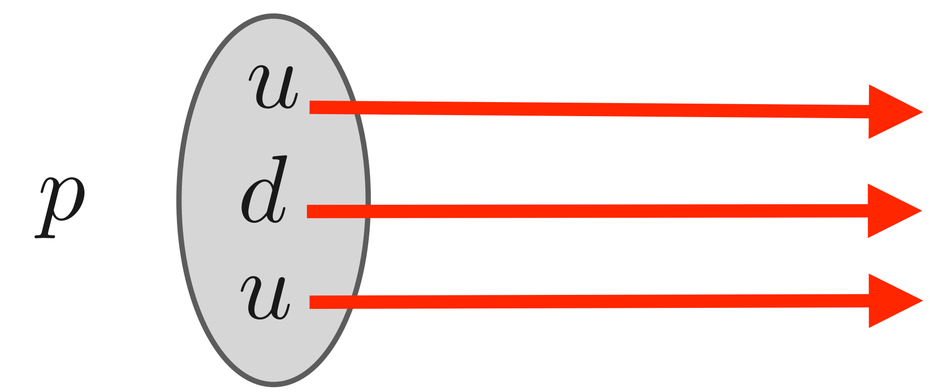
symbol:	*g*
charge:	0
mass:	0
spin:	1
category:	Strong Vector Boson

three forces now

of vastly different strengths







particle: **proton**

symbol: *p*

charge: +1*e*

mass: 1.6726 x 10^{-2} 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

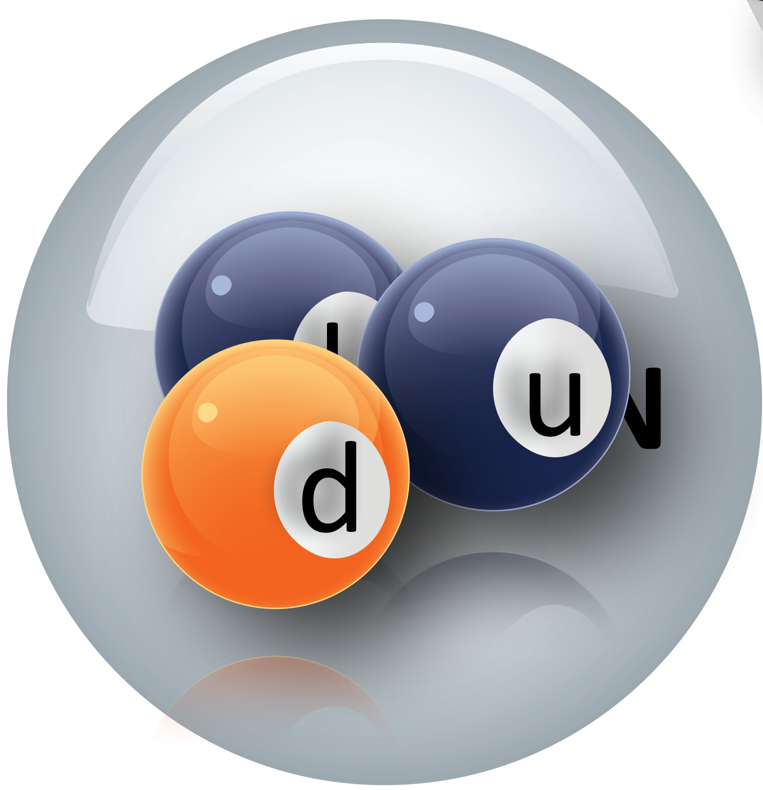
mass: 1.7 to 3.3 MeV/c^2

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

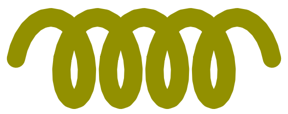
circa 1980

the photon

“propagates the electromagnetic force”

the W Boson

“propagates the weak force”



the gluon

“propagates the strong force”

say tuned.

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

particle: **bottom quark**

symbol: *b*

charge: -1/3 e

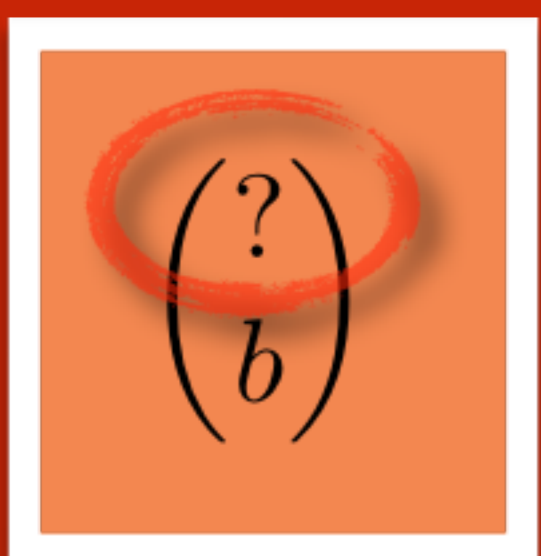
mass: 4.5 GeV/c² = 4.5 p

spin: 1/2

category: Fermion, quark

1977 at Fermilab

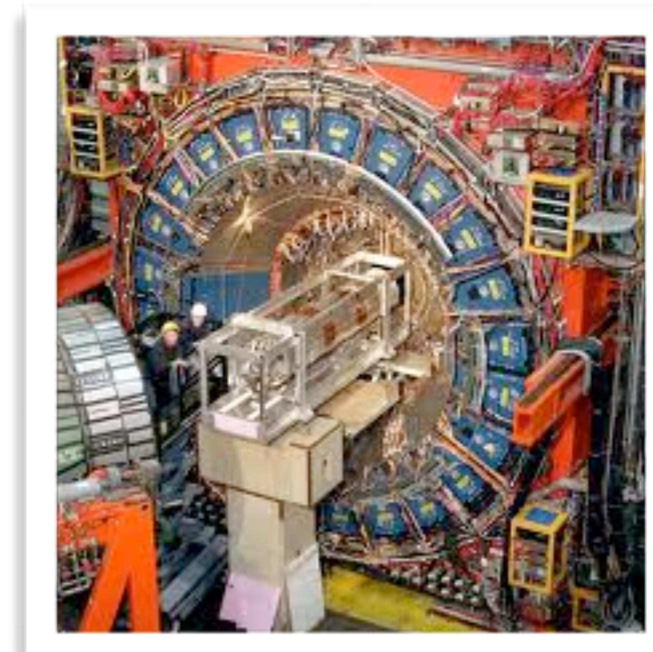
1995: Discovery of the top quark



The two experiments at the Fermilab collider frantically searched

- We collected data for three straight years of running, 24/7

An intense analysis effort actually kept up with the data-collection...



DØ, our experiment, found a single event and published it in 1992...

- suspicious, but one event is not definitive

CDF, the other experiment, thought they had "evidence" in spring of 1994

- published it, cautiously - the rate of production was too high, according to expectations by x2

discovery

In the winter of 1994-95 we began to think we had it

led by Harry Weerts, an MSU professor

We thought we were on to something and wanted to be first, but we needed to be sure

that meant 2 months of furious argument, calculations, writing, and yelling

“Was it background?” “How significant was the signal?”

Things fell apart, and came together over and over.

finally: "top quark" discovered in 1995

by our 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

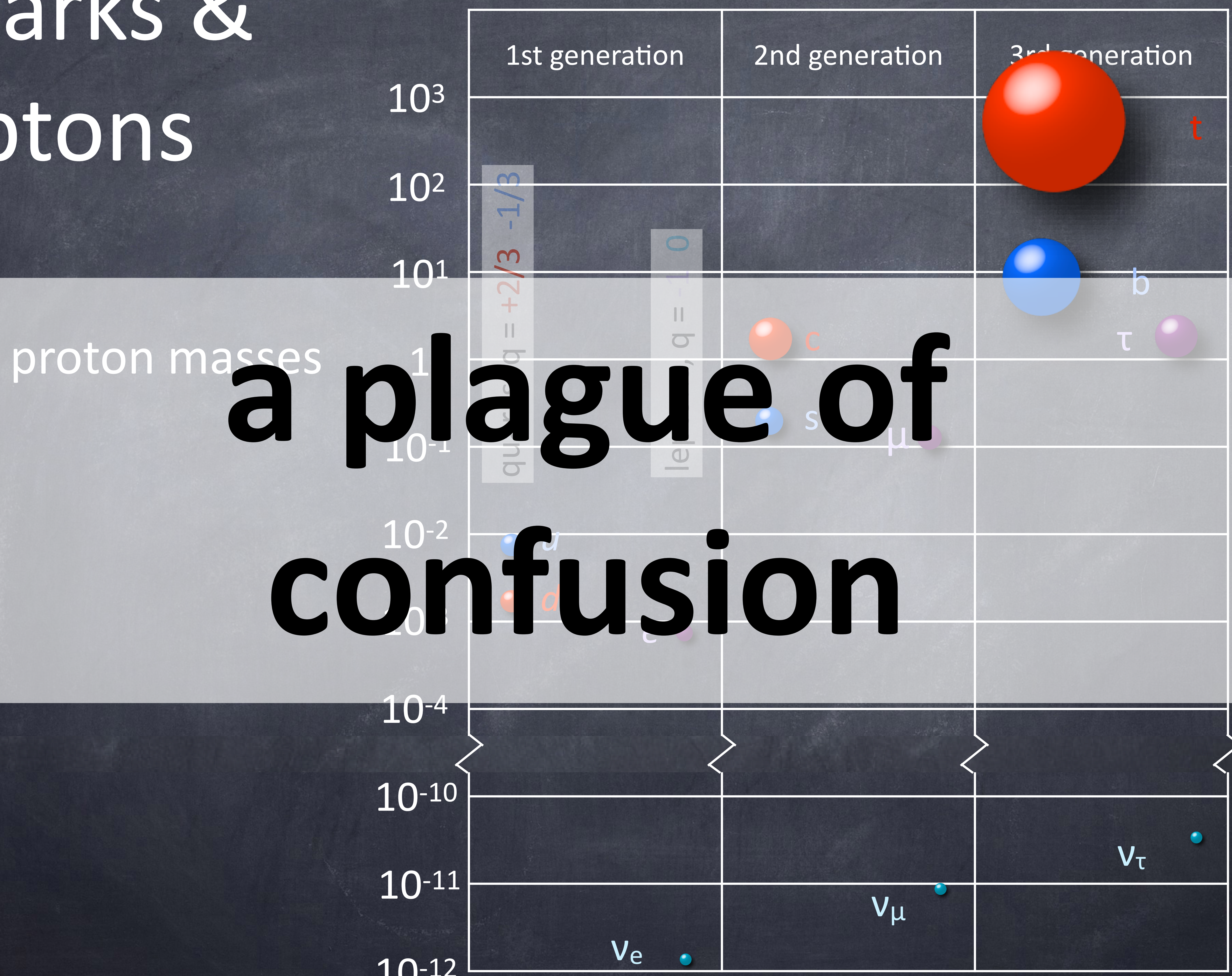
March 2, 1995 the announcement was made at Fermilab


Cultura e Spettacoli
Dove vai, cacciatore di quark?
Alles Quark, oder was?
predatori del quark perduto
Truth by Consensus
Nation
RICERCA ITALIANA
EPPUR SI MUOVE
AUJOURD'HUI
The Quark Is a Porker
Ora la fisica è al Top
LES BRICOLAGES DE LA VIE
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

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

0
-1

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

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

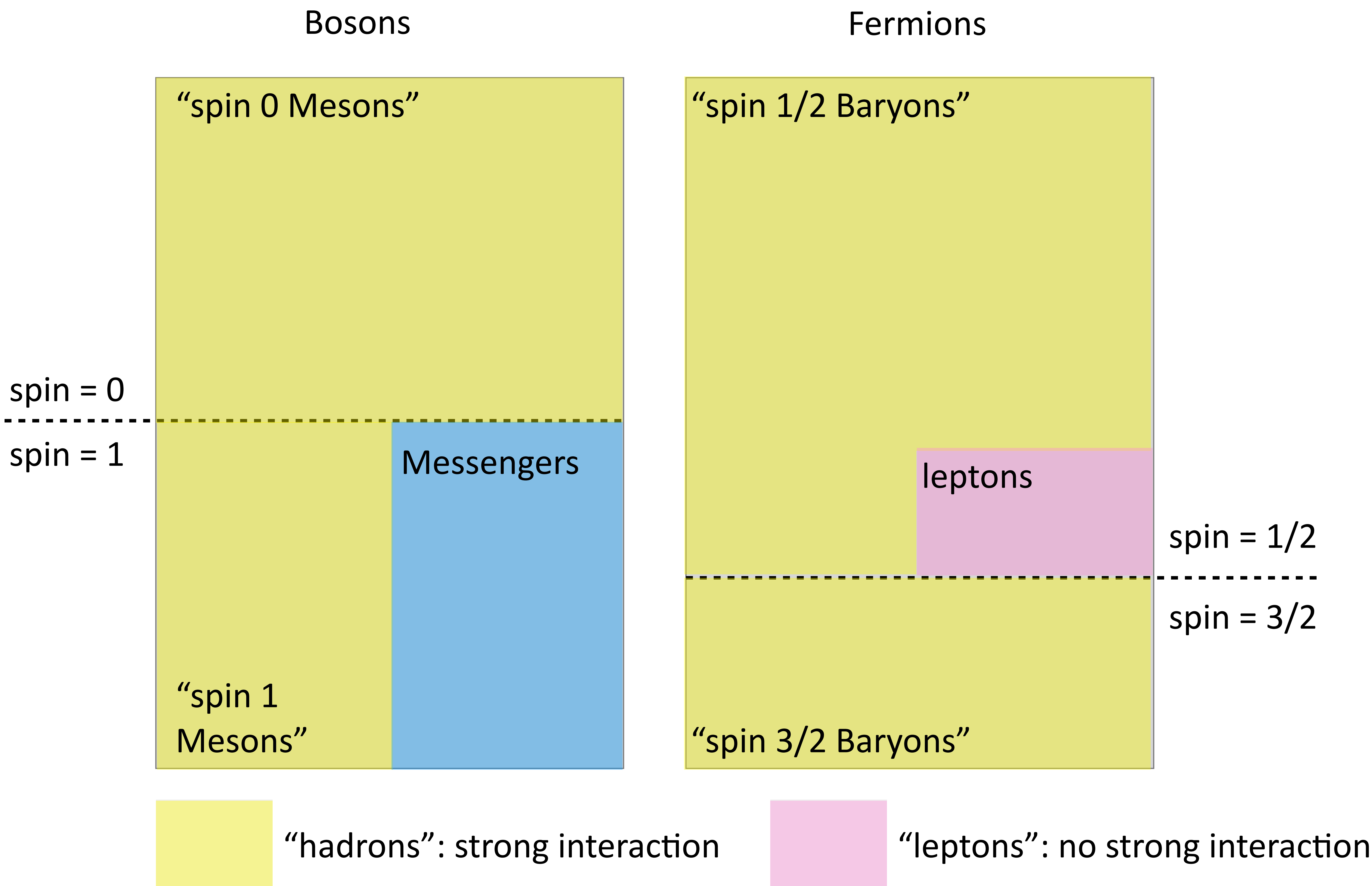
the quark families...quark "doublets"

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

and their interactions: ✗ no, ✔ yes.

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

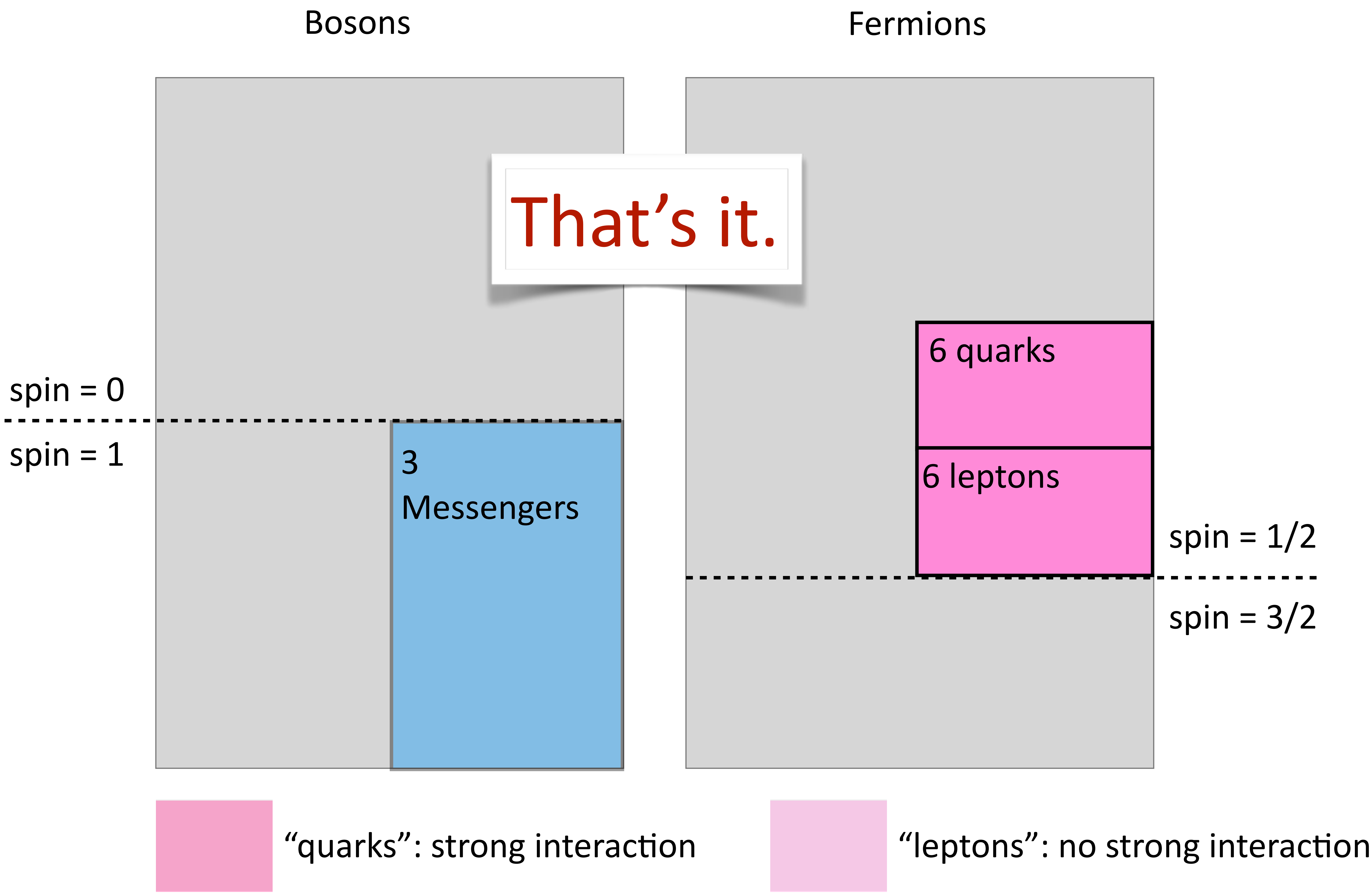
The Particle Zoo?



instead of the Municipal zoo of particles

we have a petting zoo of quarks and leptons

The Particle Zoo? *tamed*.



shifting gears

the weak and electromagnetic forces are one.

“phase transitions”

not a subject of Particle Physics

we thought

but we stole a theory from materials scientists

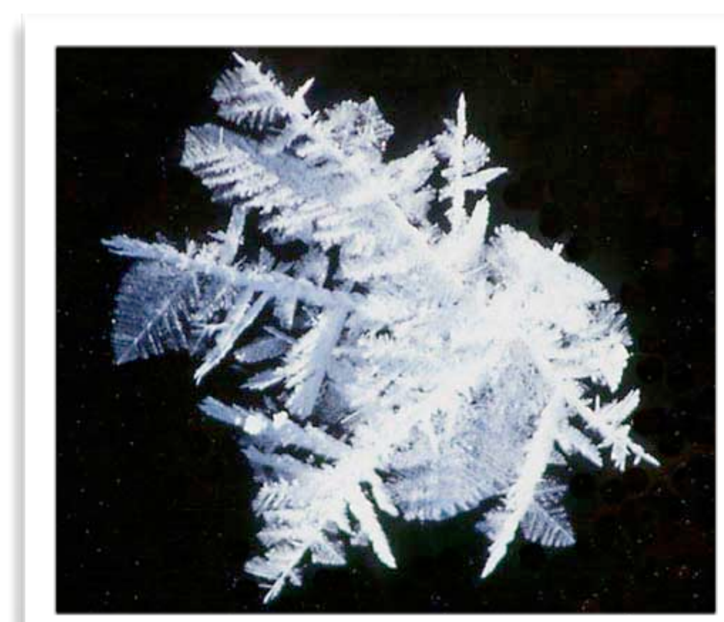
think about a phase transition

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



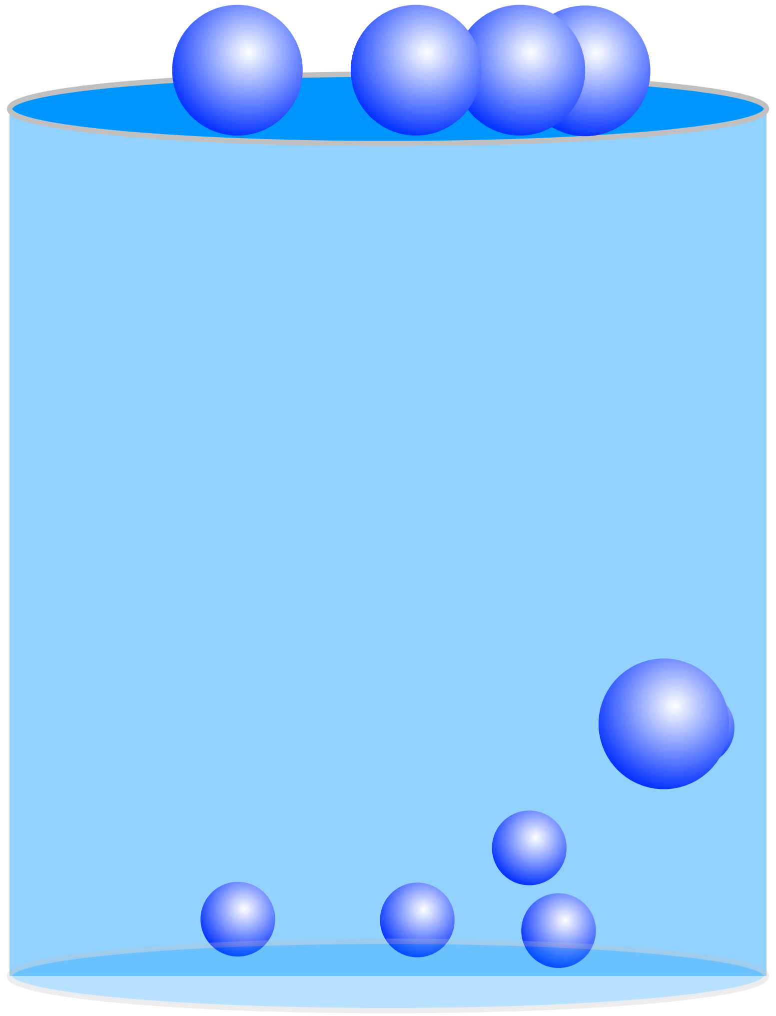
after: now there are special directions

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

there are basically 2 kinds of boiling

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

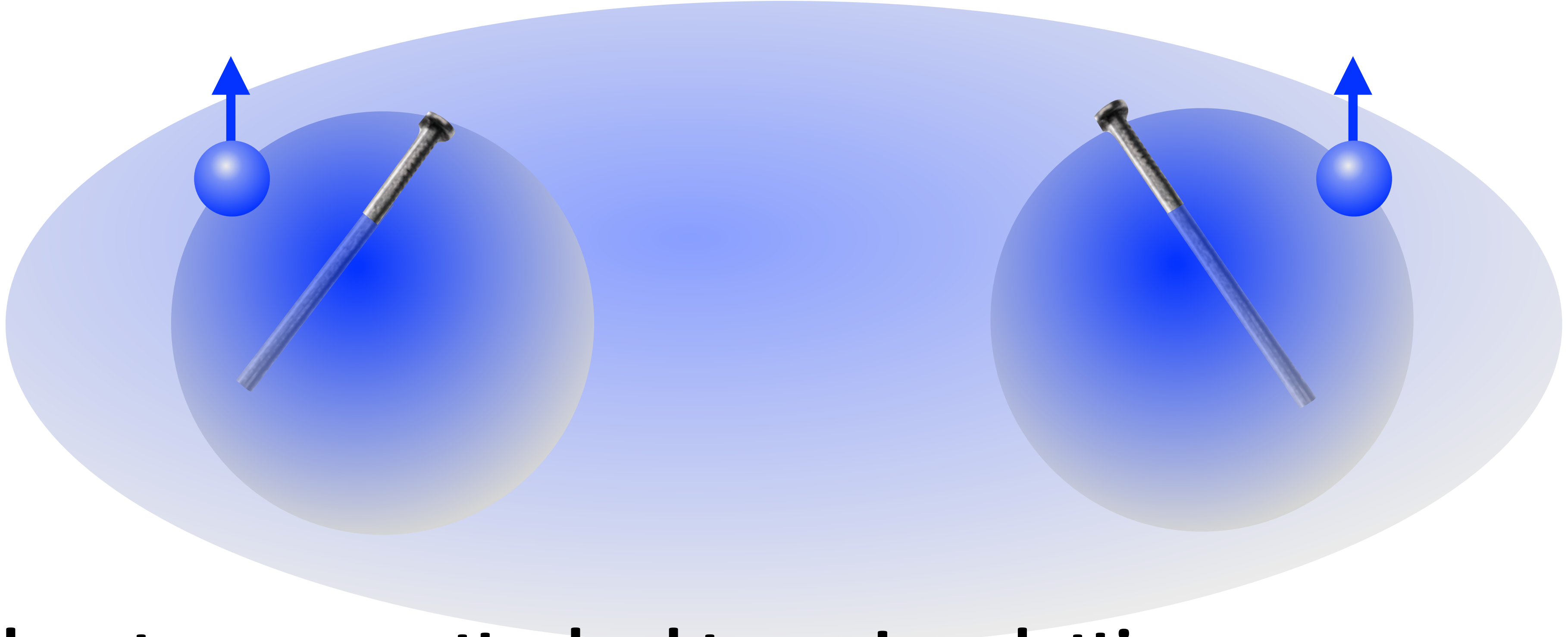
most familiarly:

iron

also:Co, Ni, Li gas

many compounds

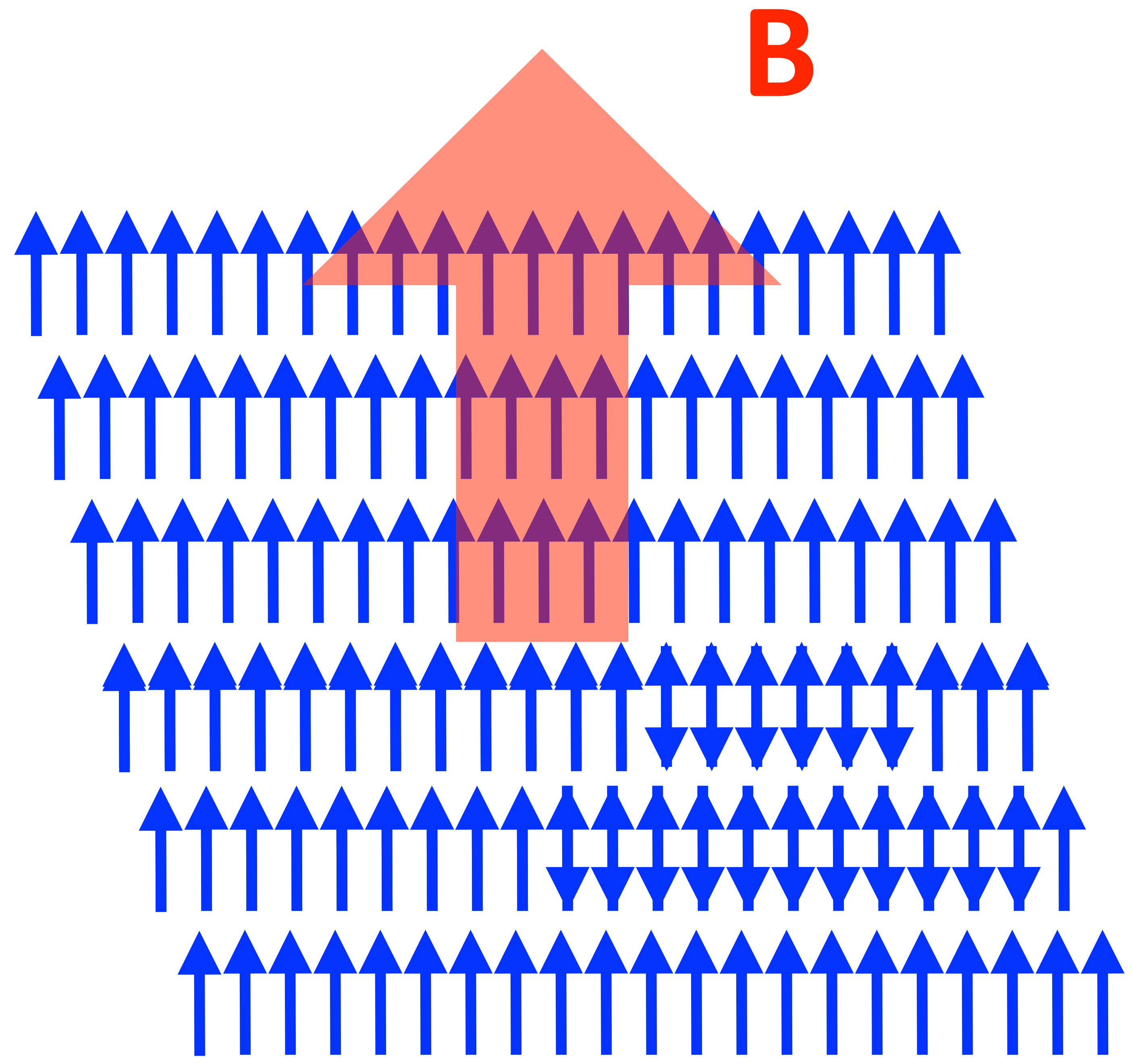
If atoms are far apart...a quantum mechanical effect keeps the outer electron spins aligned, minimizing the electrostatic energy



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

that's a permanent ferromagnet

in 2 - dimensions



why

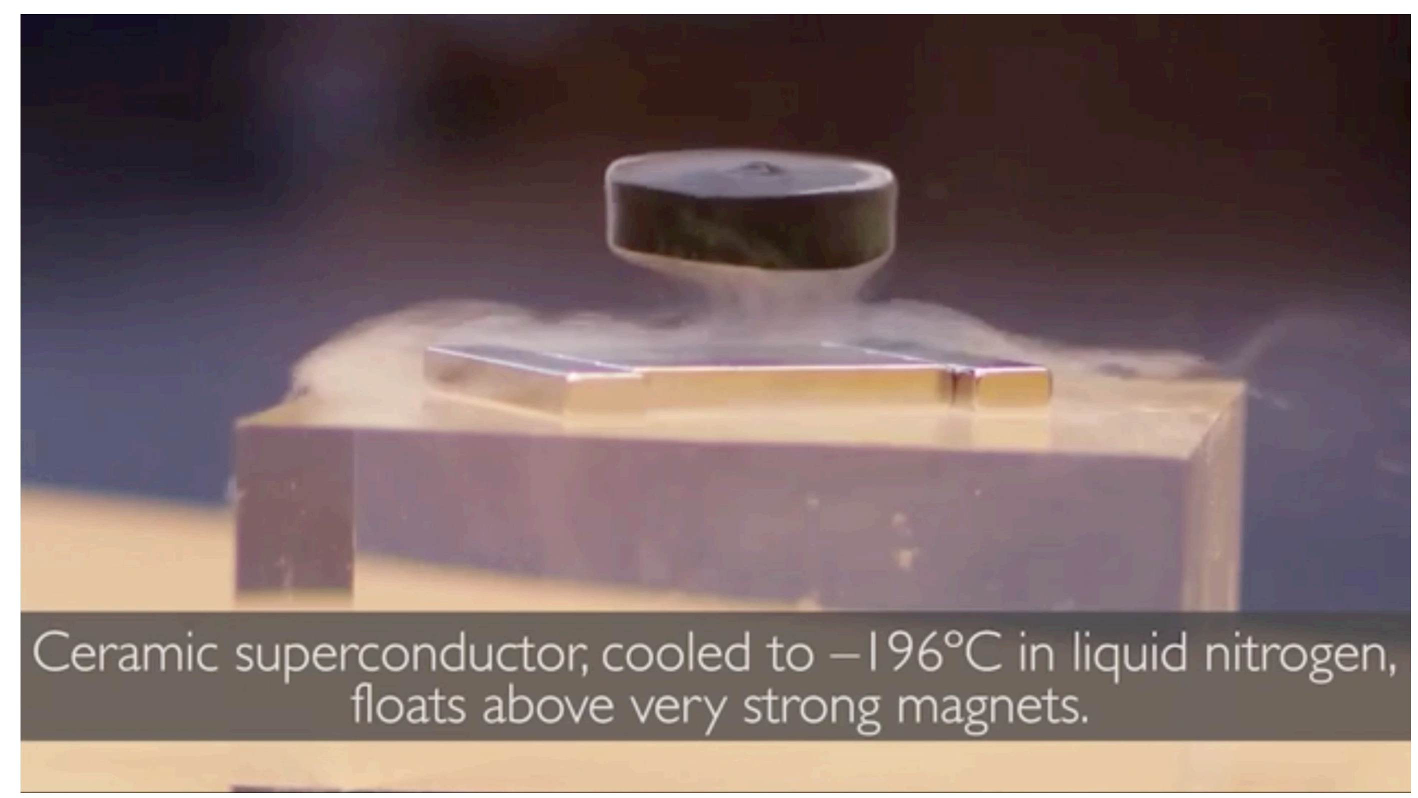
is he talking about phase transitions you're asking yourself?

Superconductivity

room temperature, insulator

below 1.9 K - superconducting

LHC magnets, NSCL cyclotron



Superfluidity

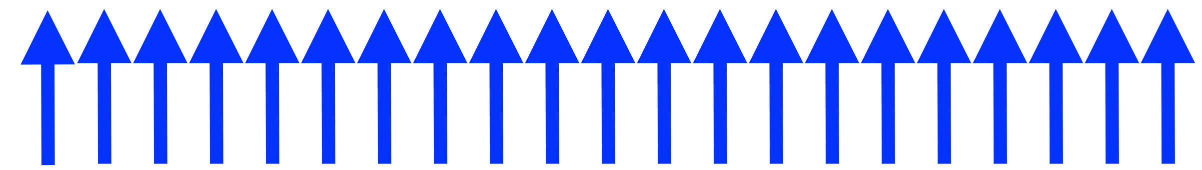
4.2 K - liquifies

2.17 K - superfluid

a little model of an *ideal* ferromagnet

in one - dimension

At a low temperature – like room temperature:



M is maximum

M, "magnetization": a measure of how magnetized

"ground state" – state of lowest energy –

when all electronic magnets are aligned

There is a high temperature – the "Curie Point":

then the "ground state" – state of lowest energy –

when all electronic magnets are random

M becomes zero