hi

Day 27, 19.04.2018

Particle Physics 2

housekeeping

The end game: next slide

Particle Physics:

Readings: Oerter and Hobson

Hobson_PP.pdf is chapter 17 out of Hobson

Homework #12 is all from MasteringPhysics - normal due date

Feynman Diagram rules

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

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

last 2 weeks & final

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

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

will cover material since midterm plus the last week of class

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

only the shadow knows when

Remember when I was sick?

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

Final Exam day:

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

I'm willing to rethink this

honors project began

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

contains:

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

dates:

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

the data

should have been in zipped format

rather, somehow they were unzipped in some process

fixed: now

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

Index of /storage/Homework_Projects/honors_project_2018

Name	Last modified	Size	Description
Parent Directory		-	
ISP220_inspirationaltalk.pdf	2018-03-01 07:10	4.3M	Portable Document Format file
MinervaInstructions1_2018.pdf	2018-03-01 07:10	2.3M	Portable Document Format file
MinervaInstructions2_2018_2.pdf	2018-04-09 22:11	112K	Portable Document Format file
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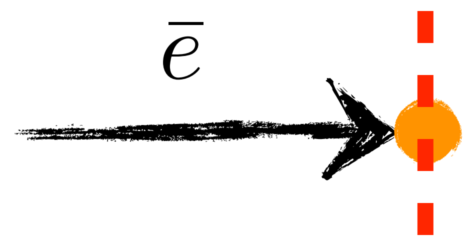
I need a Section 2

to test the Z-path uploading machinery and instructions

particles in time

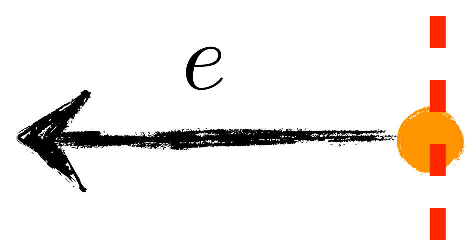
An anti-electron...coming **into** an **initial** state to a node:



Yes, this makes sense

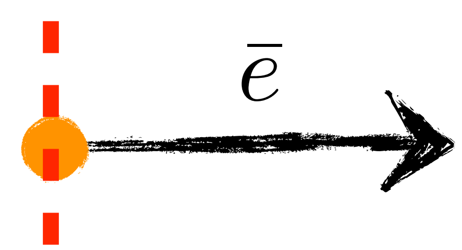
is the same thing as

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

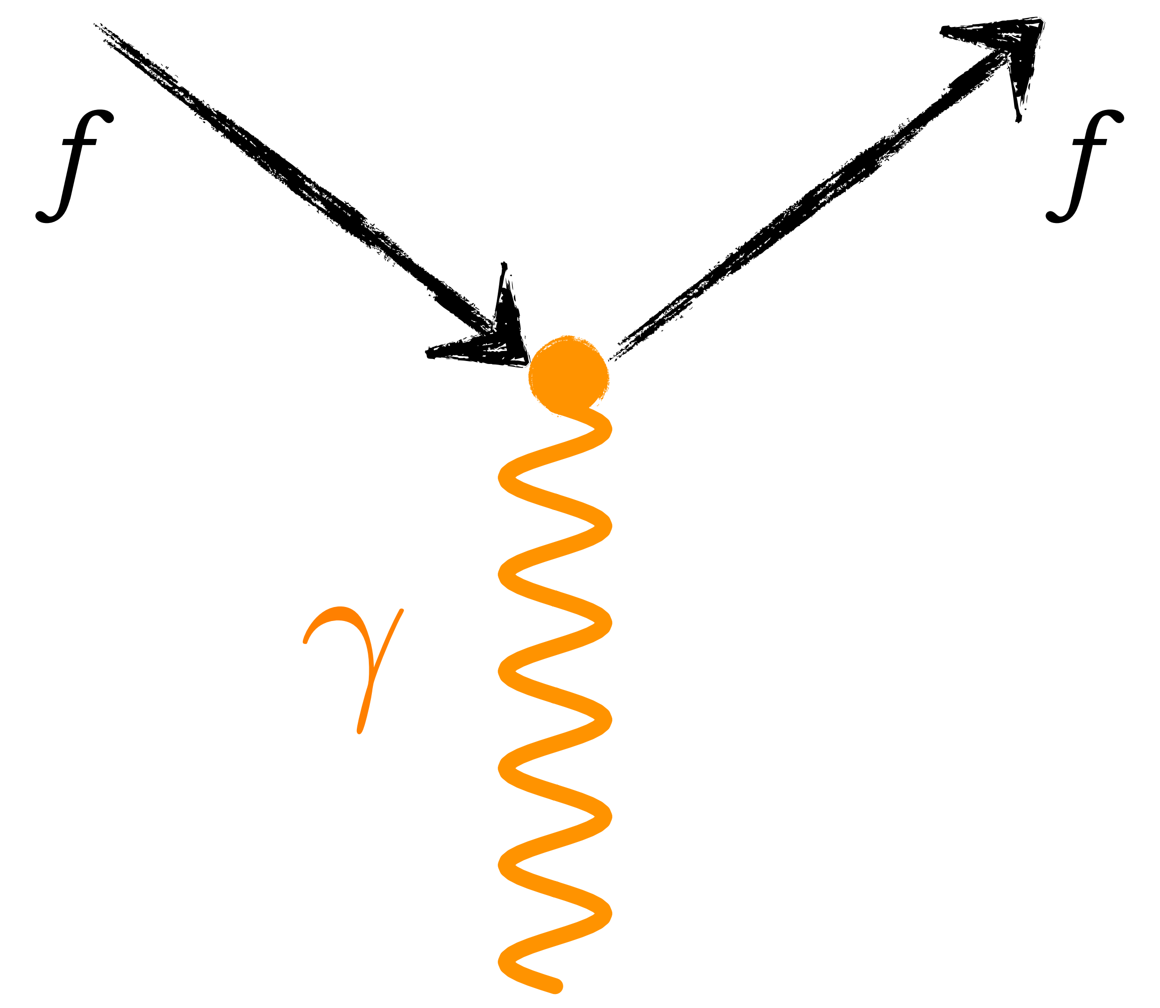
An electron coming **into** a **final** state (?)

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

primitive diagrams

are general

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

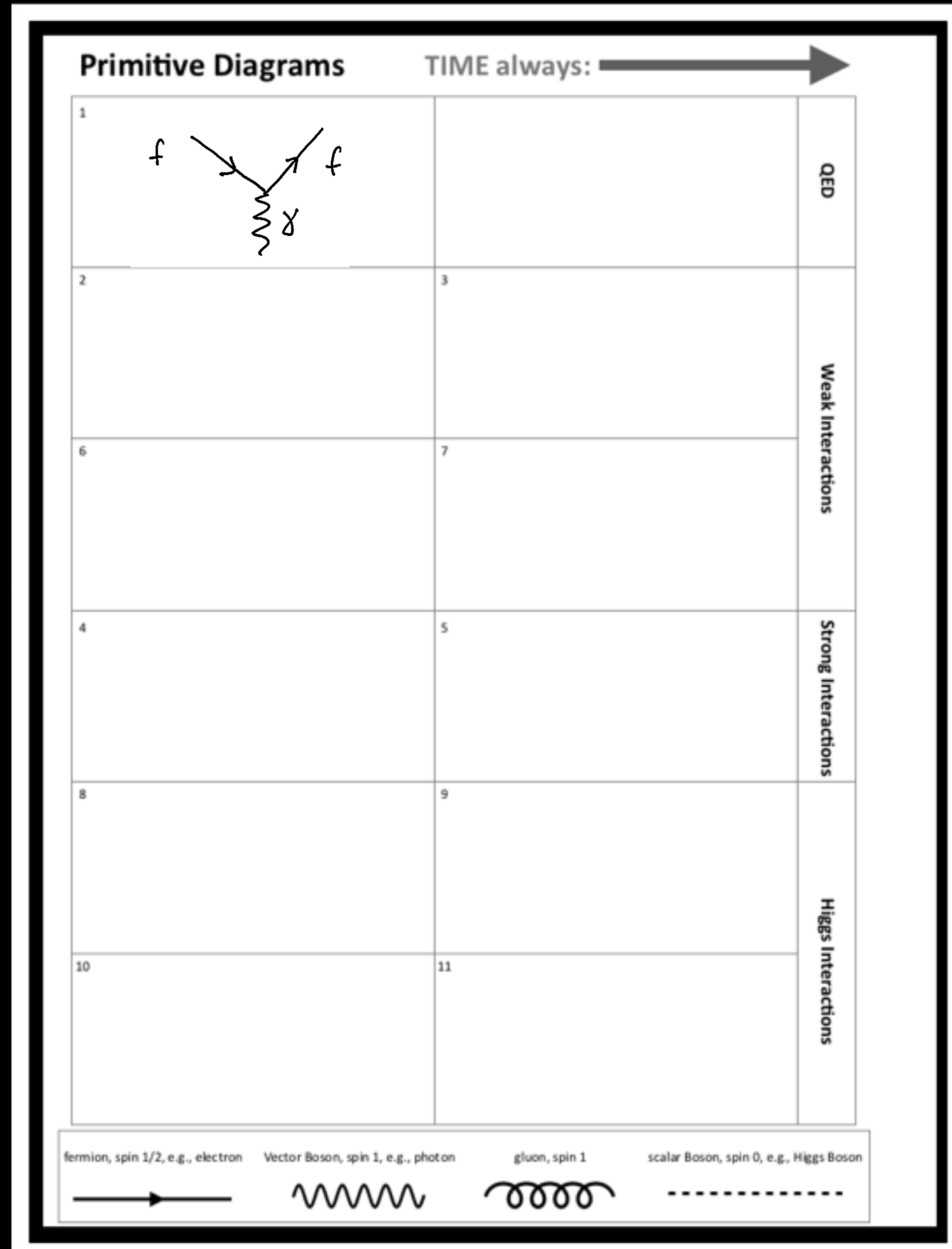


f could be electron, positron, proton, antiproton...and more – any electrically charged **f**ermion.

Their diagrams are identical.

Primitive Diagram Scorecard

your first entry



beta decay

the inaugural non-QED interaction

Weak Force

Fermi Theory of Beta Decay

uses the Dirac ideas of quantum electrodynamics

particle creation and annihilation

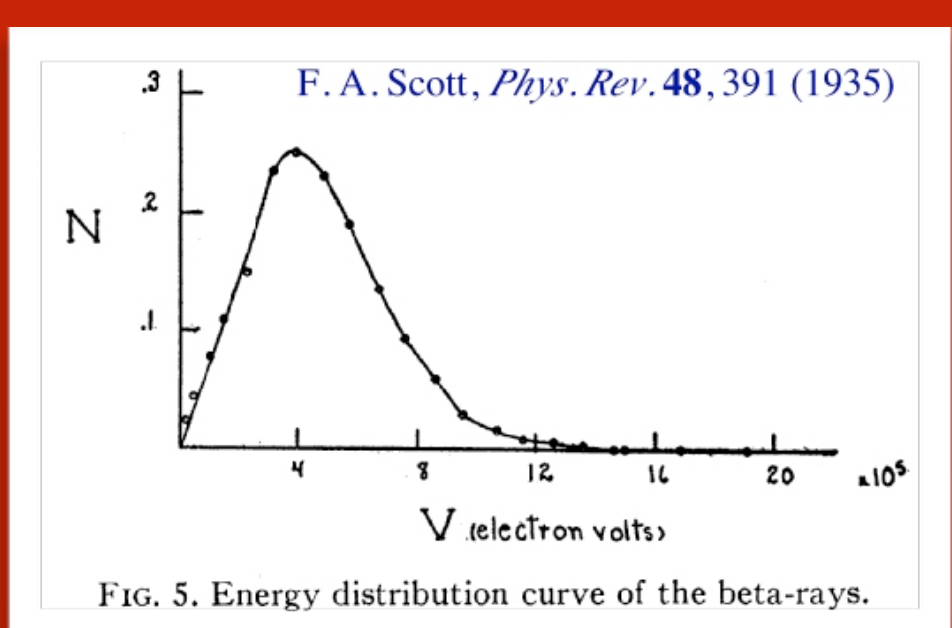
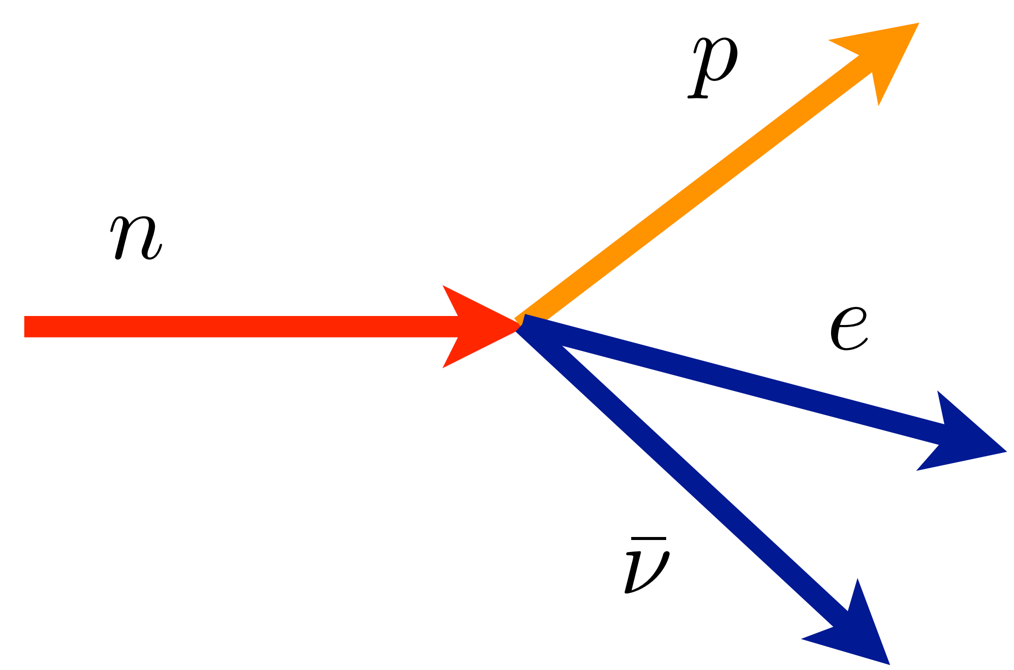


FIG. 5. Energy distribution curve of the beta-rays.

$m_{neutron} > m_{proton}$

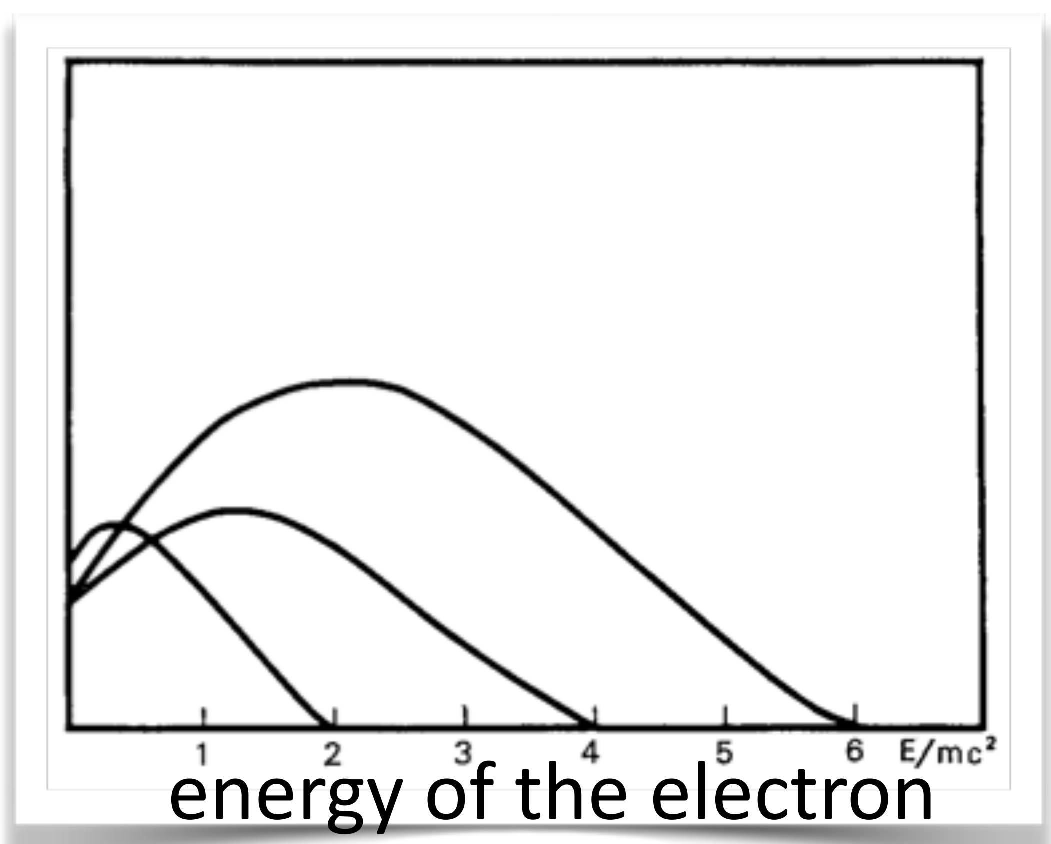
a smidgen.



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…so far

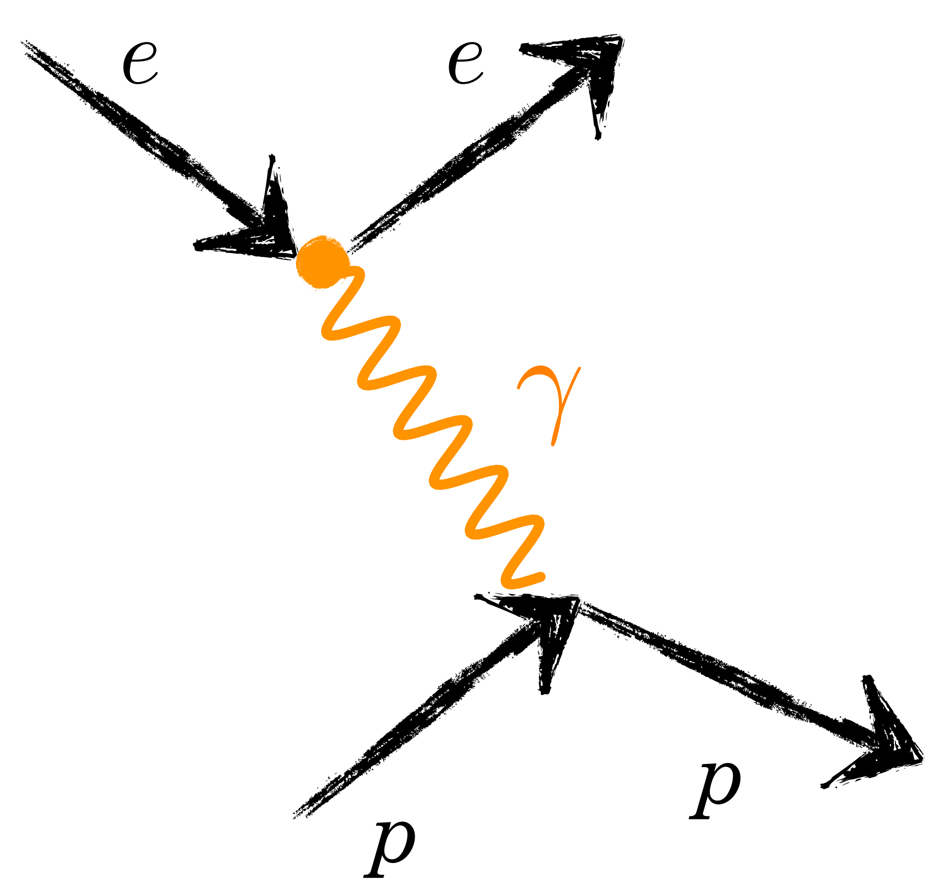
electromagnetism

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

the force that holds the protons and neutrons together

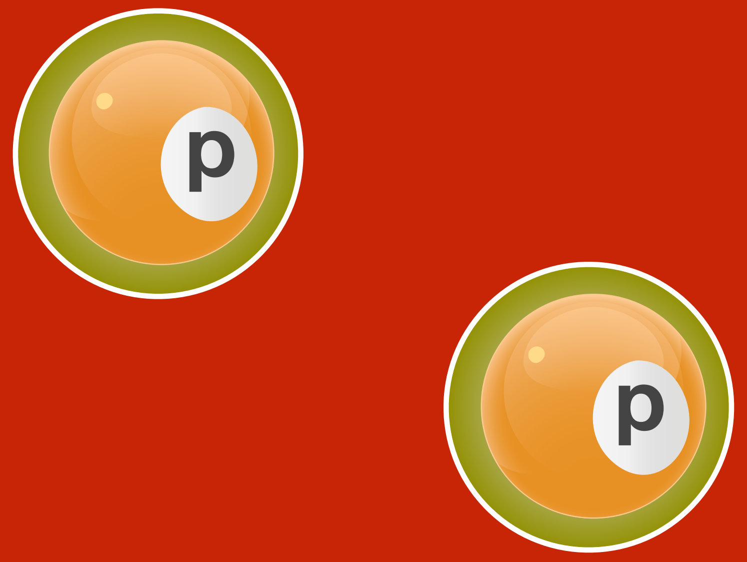
is the same between n-n, p-p, n-p

Strong Force

but only over a very short range...

the STRONG force

overwhelms the electromagnetic force



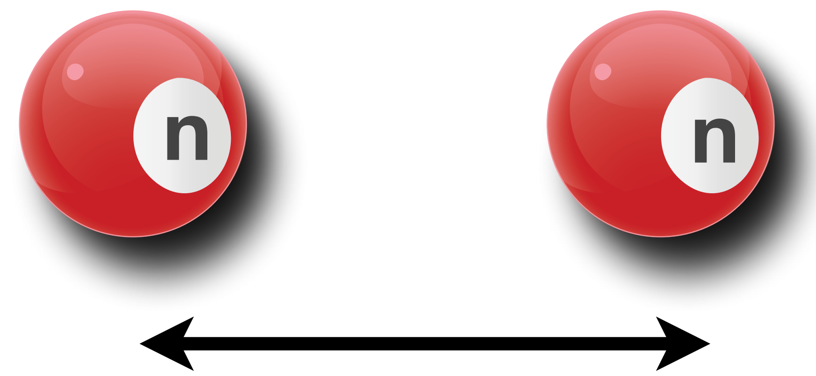
uncertainty certainly to the rescue

brilliant observation by Yukawa

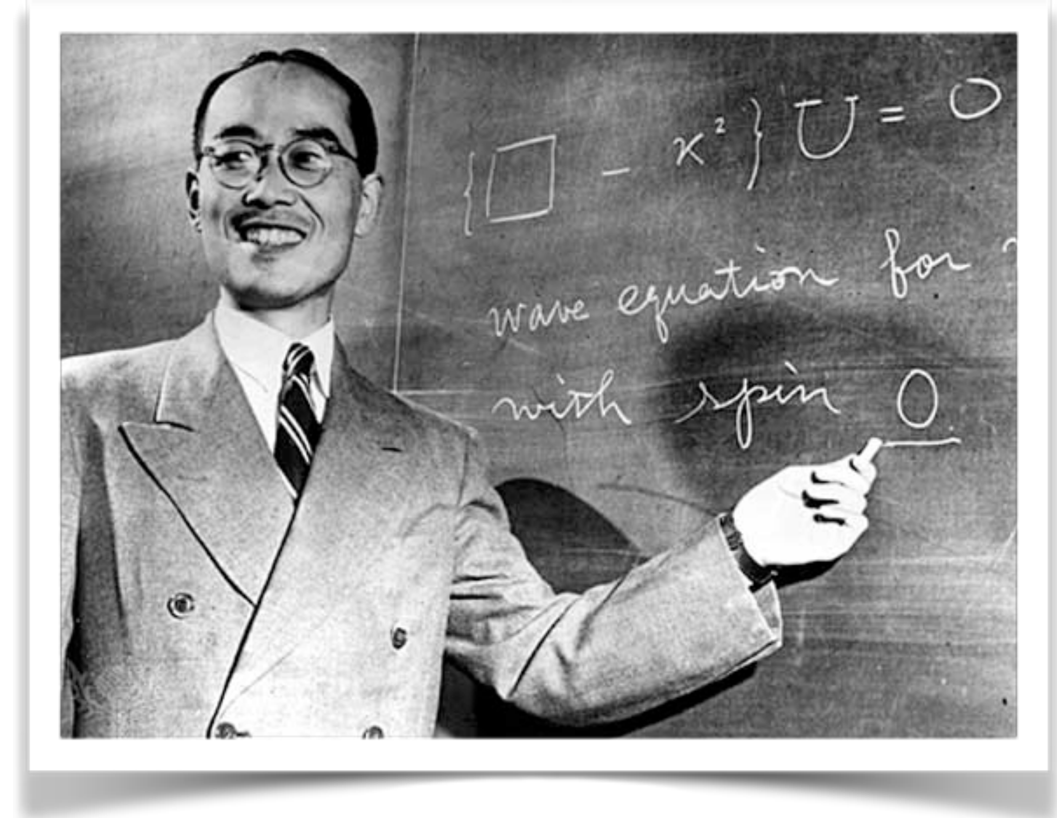
maybe there's a quantum that is active only over the size of a nucleus: "U"

another exchange force/particle?

So: $p \rightarrow n + U$?



$\Delta x = 10^{-15}$ m



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

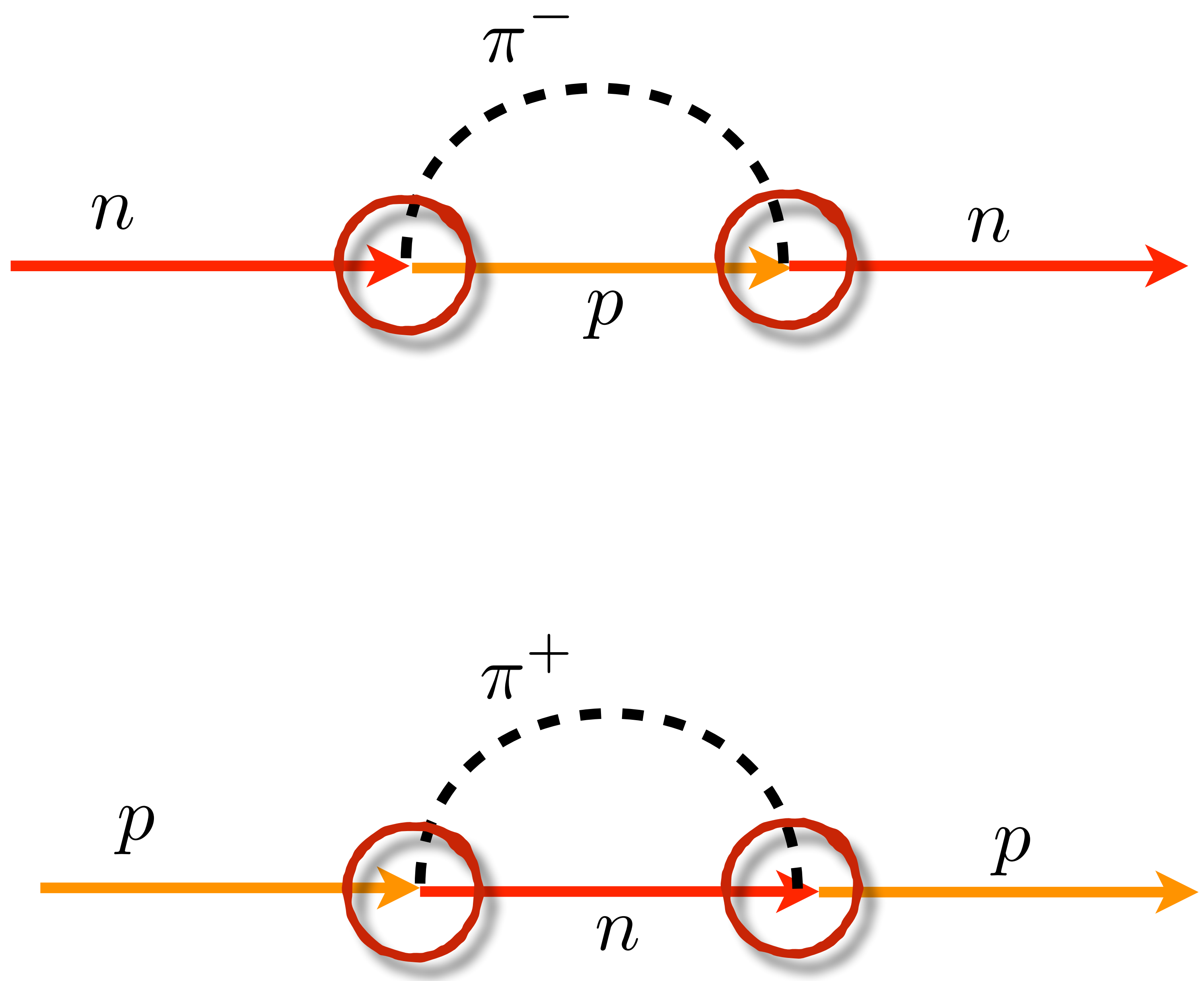
Then Uncertainty could estimate U's mass... $\Delta E \Delta t = h/4\pi$

$$m_U = \Delta E / c^2$$

$$m_U \overset{?}{\approx} 100 \times 10^6 eV = 100 MeV$$

the Yukawa particle

is the pion



These coupling strengths are large - strong.

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

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**

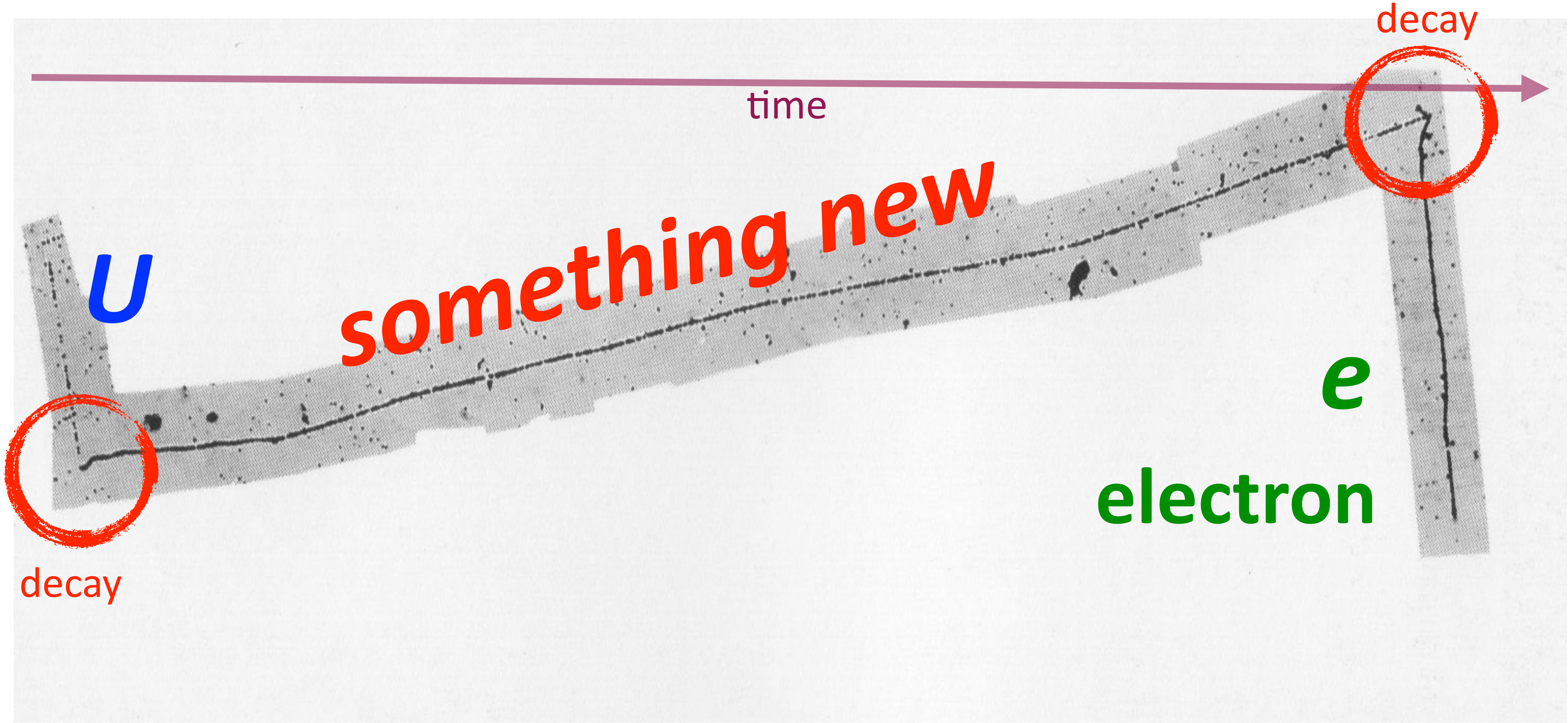
refers to: either a proton or a neutron

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

example: “nucleon force”

strange things in cosmic rays

thick photographic substrates



by 1950 the forces were identified

"strong"

as evidenced by the pion (refined later)

"electromagnetic"

as evidenced by the exchange of photons among electrically charged particles

"weak"

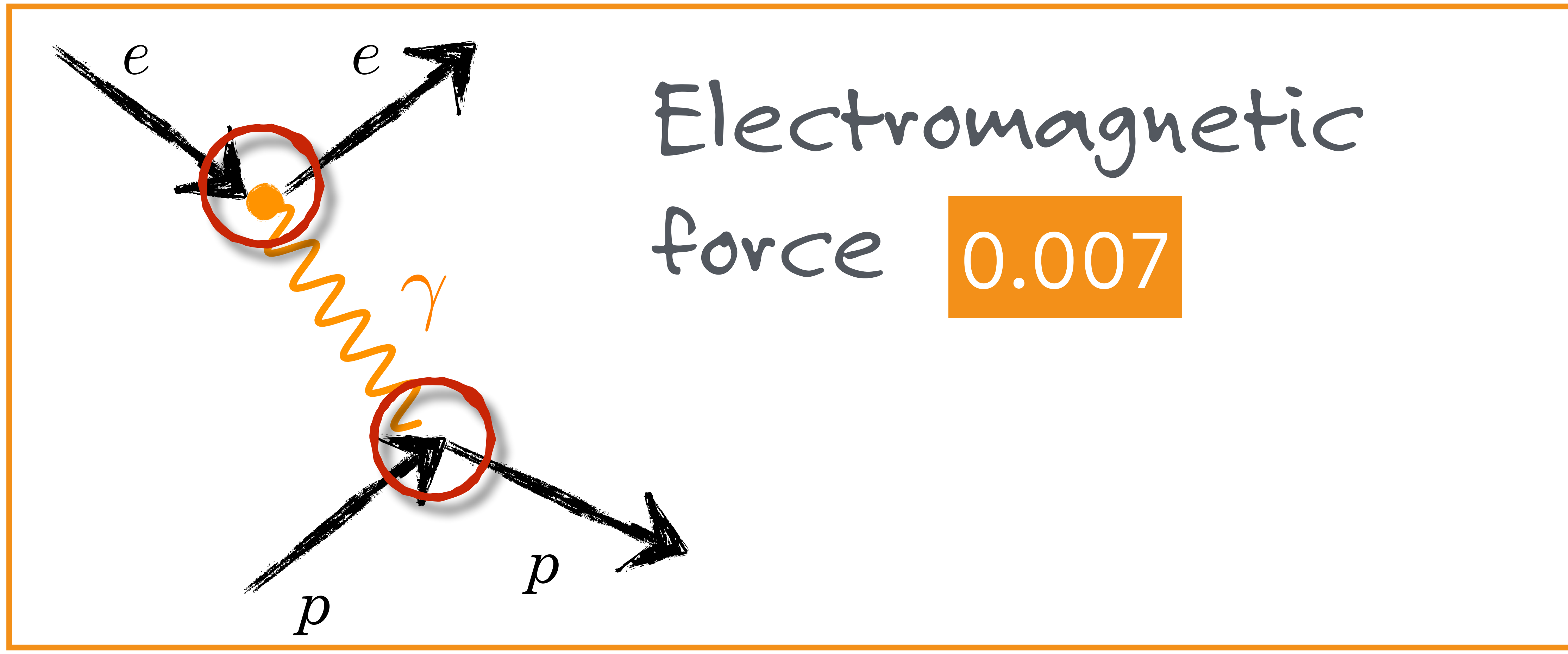
as originally evidenced by neutron beta decay, and subsequently pion, muon, and other hadronic decays

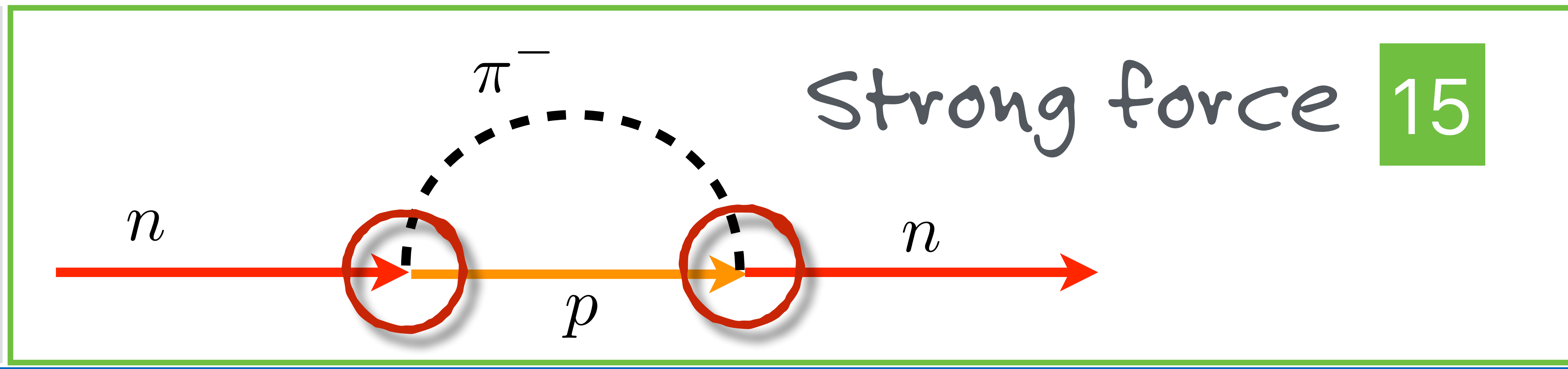
"gravitational"

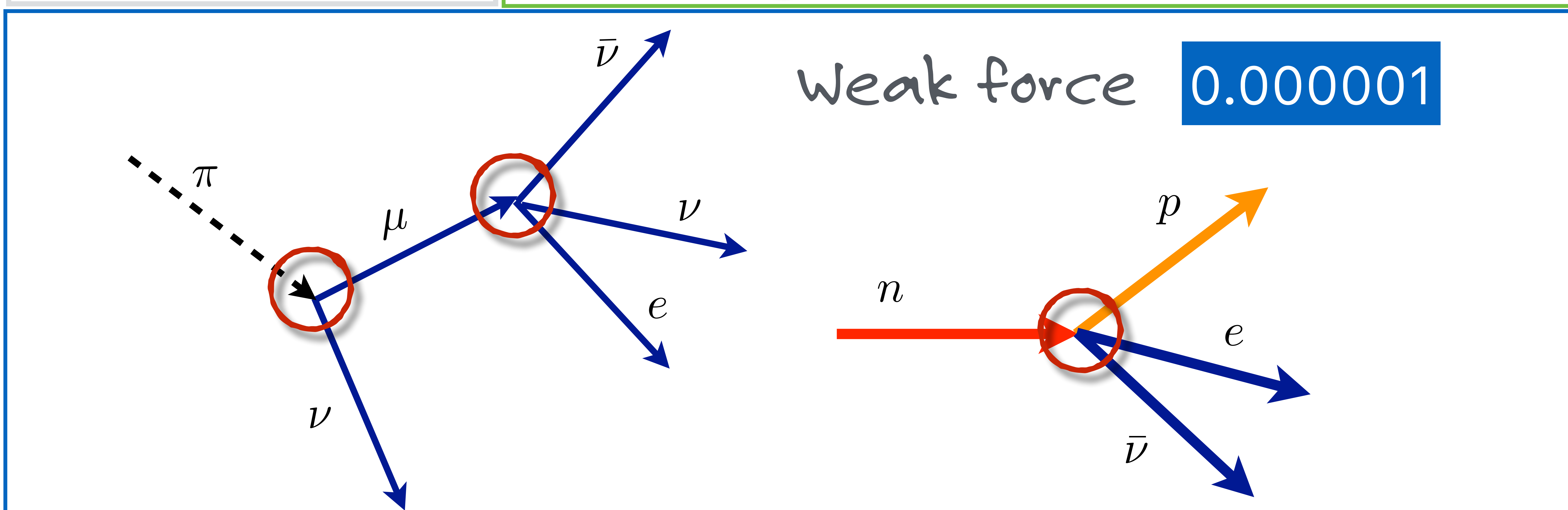
the weakest of all…quantum theory of gravity still a mystery

three forces now

of vastly different strengths







FAMILIES

Nature prefers

like-particles

Lepton Families

electrons and a neutrino

muons and a neutrino

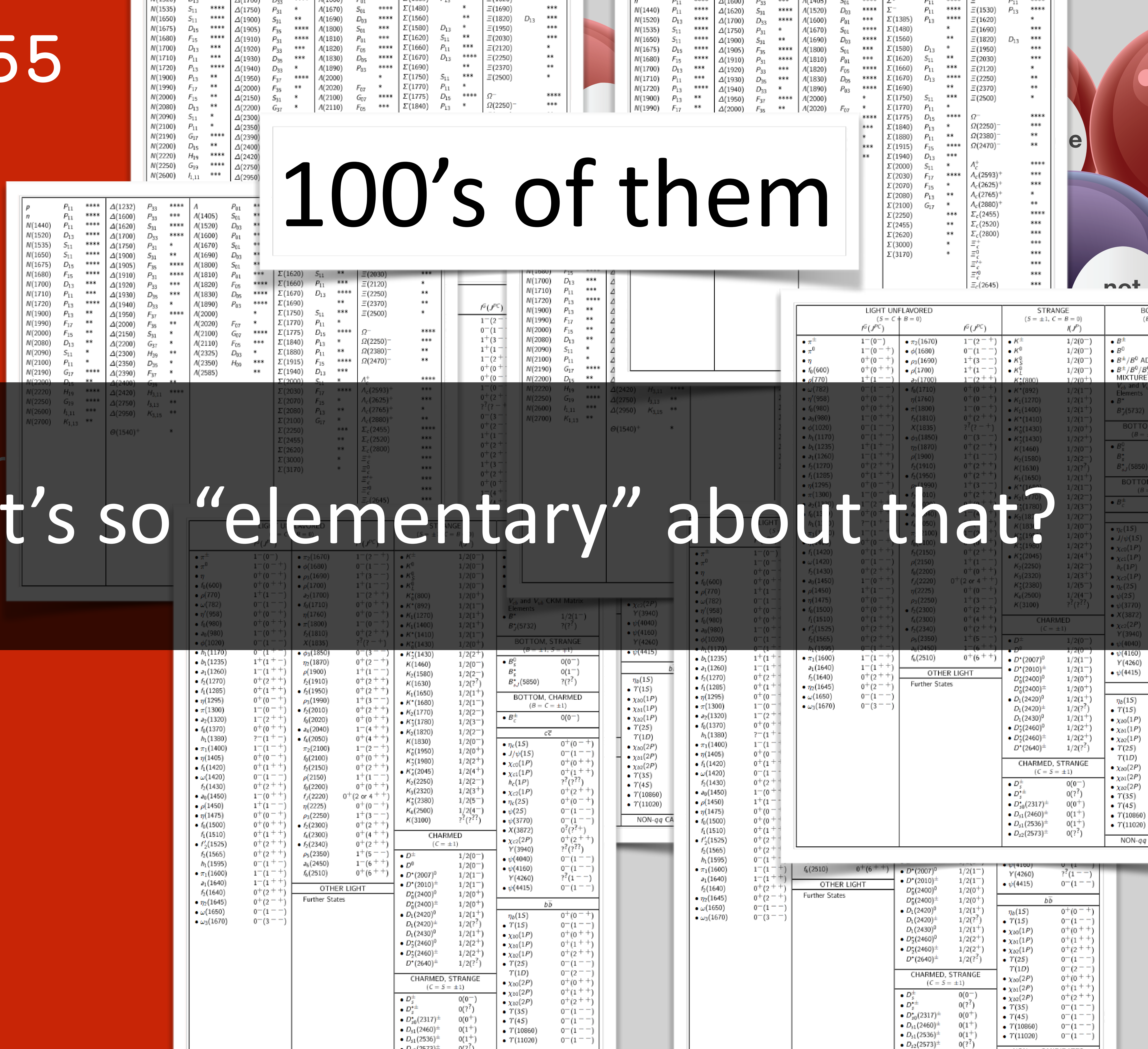
taus and a neutrino

These sorts of patterns are a huge deal.

Q			
0	ν_e	ν_μ	ν_τ
−1	e	μ	τ

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

by 1955



100's of them

things were
mess

what's so "elementary" about that?

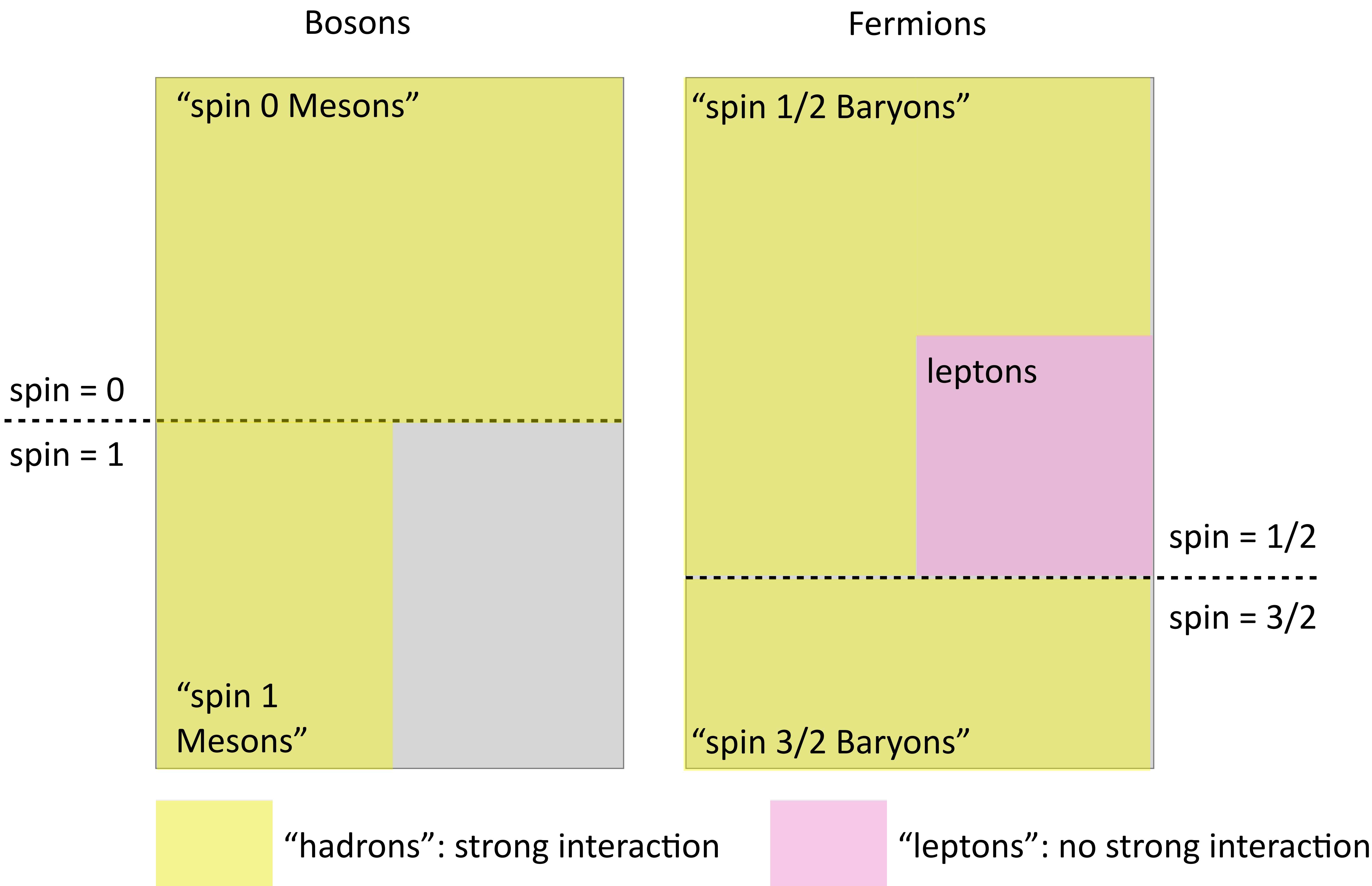
jargon alert: **hadron**

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!

The Particle Zoo?



jargon alert:

particle quantum numbers

refers to:	quantities that are inherently a part of particles, which are conserved in interactions or decays
entomology:	historical to Bohr and Schroedinger
example:	electric charge, baryon number, lepton number, isospin

something like these will never happen:

so, you'll always see:

$$A^+ \rightarrow B^+ + C^+$$

Q: +1 +1 +1

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

Q: +1 +1 +1 -1

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

Strangeness, S

strangeness seems to come in pairs

assign "strangeness" empirically.

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

S: 0 0 −1 +1

Strong interaction

~~$\pi^- + p \to \Lambda^0 + n$~~ ?

S: 0 0 −1 0

and yet you *do* see:

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

S: −1 0 0

Weak interaction

Production of a subset of all baryons seems to require them to come in pairs.
Strong interactions conserve Strangeness

Decay of those same baryons...notsomuch
Weak interactions change Strangeness by 1 unit

the dominant Baryons

Particle	Symbol	Rest Mass MeV/c²	spin	Q	B	S	Lifetime	dominant decay modes
proton	p	938.3	1/2	+1	+1	0	> 10^{31} y	
neutron	n	939.6	1/2	0	+1	0	920	$pe^-\bar{\nu}_e$
Lambda	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	Ξ^-	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}	$\Xi^0\pi^-,\ \Lambda^0K^-$

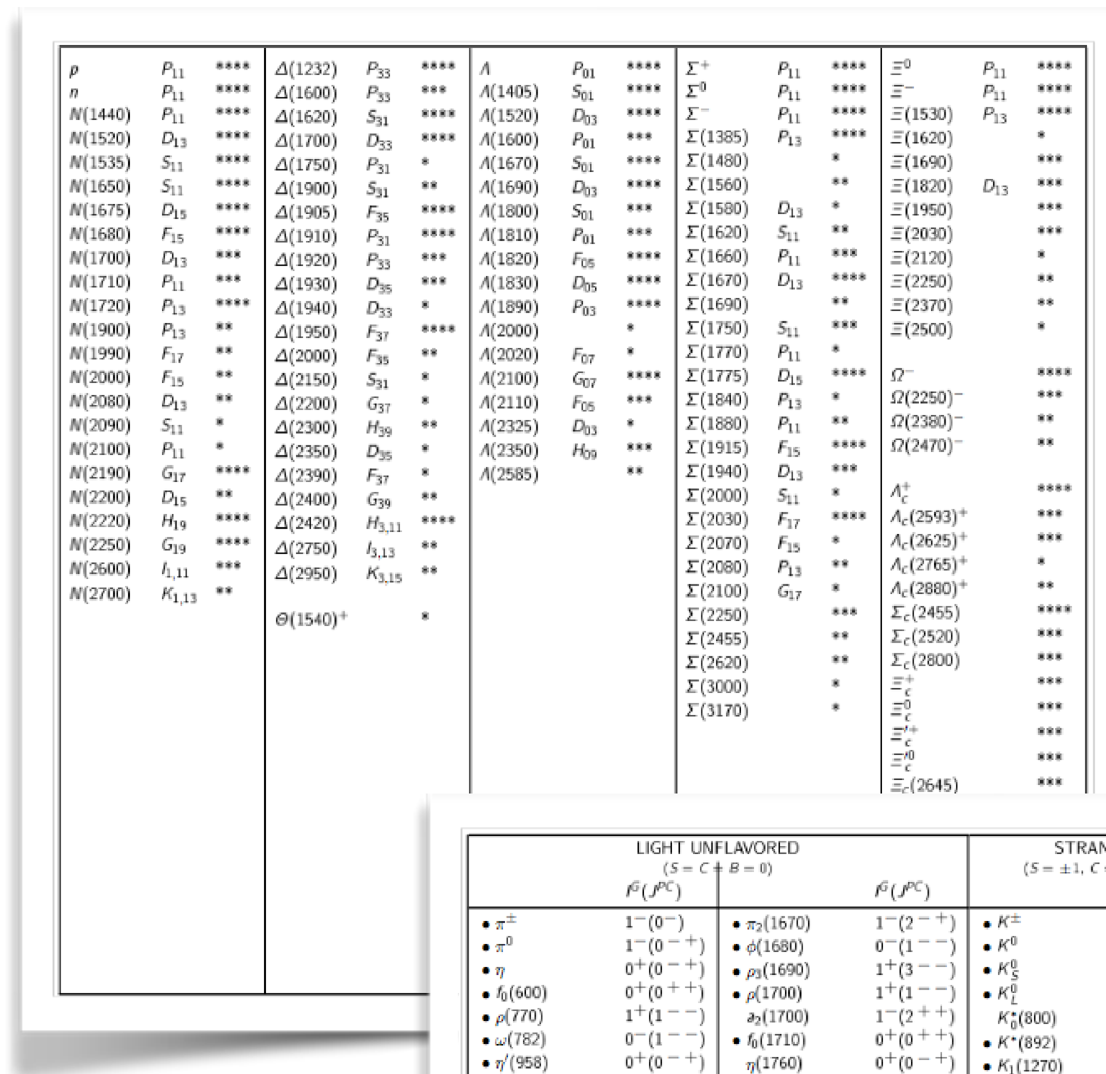
the dominant Mesons

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

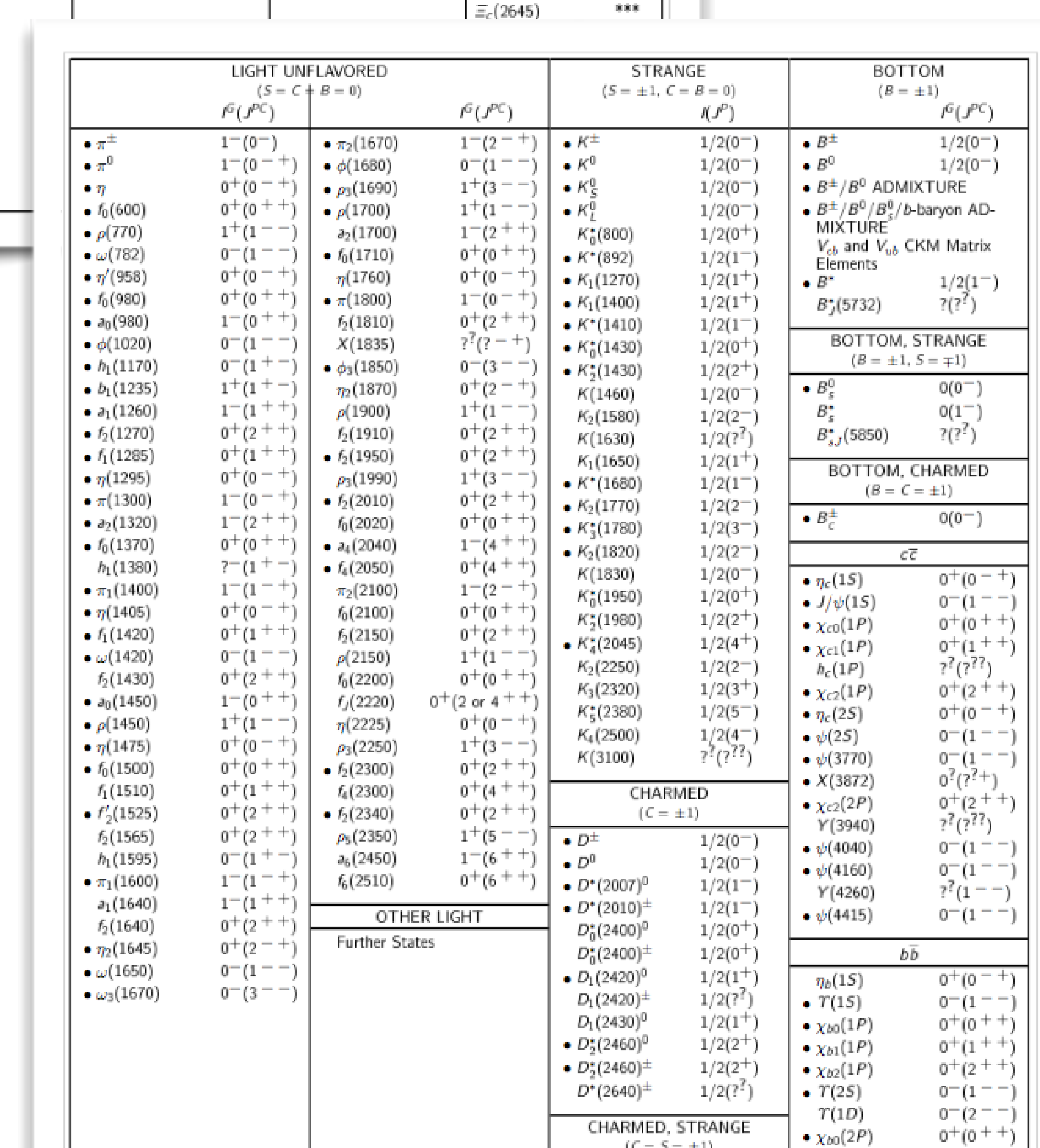
patterns emerged

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

Δ^0 Ξ^- Δ^-
Σ^- Λ^0 $\Xi^* p$
Δ^+ Σ^0 Σ^{*-}
Σ^{*+} Δ^{++} n
Ξ^0 Ξ^{*0} Σ^+ Σ^{*0}



p	P_{11}	****	$\Delta(1232)$	P_{33}	****	Λ	P_{01}	****	Σ^+	P_{11}	****	Ξ^0	P_{11}	****
n	P_{11}	****	$\Delta(1600)$	P_{33}	***	$\Lambda(1405)$	S_{01}	****	Σ^0	P_{11}	****	Ξ^-	P_{11}	****
$N(1440)$	P_{11}	****	$\Delta(1620)$	S_{31}	****	$\Lambda(1520)$	D_{03}	****	Σ^-	P_{11}	****	$\Xi(1530)$	P_{13}	****
$N(1520)$	D_{13}	****	$\Delta(1700)$	D_{33}	****	$\Lambda(1600)$	P_{01}	***	$\Sigma(1385)$	P_{13}	****	$\Xi(1620)$		*
$N(1535)$	S_{11}	****	$\Delta(1750)$	P_{31}	*	$\Lambda(1670)$	S_{01}	****	$\Sigma(1480)$		*	$\Xi(1690)$		***
$N(1650)$	S_{11}	****	$\Delta(1900)$	S_{31}	**	$\Lambda(1690)$	D_{03}	****	$\Sigma(1560)$		**	$\Xi(1820)$	D_{13}	***
$N(1675)$	D_{15}	****	$\Delta(1905)$	F_{35}	****	$\Lambda(1800)$	S_{01}	***	$\Sigma(1580)$	D_{13}	*	$\Xi(1950)$		***
$N(1680)$	F_{15}	****	$\Delta(1910)$	P_{31}	****	$\Lambda(1810)$	P_{01}	***	$\Sigma(1620)$	S_{11}	**	$\Xi(2030)$		***
$N(1700)$	D_{13}	***	$\Delta(1920)$	P_{33}	***	$\Lambda(1820)$	F_{05}	****	$\Sigma(1660)$	P_{11}	***	$\Xi(2120)$		*
$N(1710)$	P_{11}	***	$\Delta(1930)$	D_{35}	***	$\Lambda(1830)$	D_{05}	****	$\Sigma(1670)$	D_{13}	****	$\Xi(2250)$		**
$N(1720)$	P_{13}	****	$\Delta(1940)$	D_{33}	*	$\Lambda(1890)$	P_{03}	****	$\Sigma(1690)$		**	$\Xi(2370)$		**
$N(1900)$	P_{13}	**	$\Delta(1950)$	F_{37}	****	$\Lambda(2000)$		*	$\Sigma(1750)$	S_{11}	***	$\Xi(2500)$		*
$N(1990)$	F_{17}	**	$\Delta(2000)$	F_{35}	**	$\Lambda(2020)$	F_{07}	*	$\Sigma(1770)$	P_{11}	*			
$N(2000)$	F_{15}	**	$\Delta(2150)$	S_{31}	*	$\Lambda(2100)$	G_{07}	****	$\Sigma(1775)$	D_{15}	****	Ω^-		****
$N(2080)$	D_{13}	**	$\Delta(2200)$	G_{37}	*	$\Lambda(2110)$	F_{05}	***	$\Sigma(1840)$	P_{13}	*	$\Omega(2250)^-$		***
$N(2090)$	S_{11}	*	$\Delta(2300)$	H_{39}	**	$\Lambda(2325)$	D_{03}	*	$\Sigma(1880)$	P_{11}	**	$\Omega(2380)^-$		**
$N(2100)$	P_{11}	*	$\Delta(2350)$	D_{35}	*	$\Lambda(2350)$	H_{09}	***	$\Sigma(1915)$	F_{15}	****	$\Omega(2470)^-$		**
$N(2190)$	G_{17}	****	$\Delta(2390)$	F_{37}	*	$\Lambda(2585)$		**	$\Sigma(1940)$	D_{13}	***			
$N(2200)$	D_{15}	**	$\Delta(2400)$	G_{39}	**				$\Sigma(2000)$	S_{11}	*	Λ_c^+		****
$N(2220)$	H_{19}	****	$\Delta(2420)$	$H_{3,11}$	****				$\Sigma(2030)$	F_{17}	****	$\Lambda_c(2593)^+$		***
$N(2250)$	G_{19}	****	$\Delta(2750)$	$I_{3,13}$	**				$\Sigma(2070)$	F_{15}	*	$\Lambda_c(2625)^+$		***
$N(2600)$	$I_{1,11}$	***	$\Delta(2950)$	$K_{3,15}$	**				$\Sigma(2080)$	P_{13}	**	$\Lambda_c(2765)^+$		*
$N(2700)$	$K_{1,13}$	**							$\Sigma(2100)$	G_{17}	*	$\Lambda_c(2880)^+$		**
			$\Theta(1540)^+$		*				$\Sigma(2250)$		***	$\Sigma_c(2455)$		****
									$\Sigma(2455)$		**	$\Sigma_c(2520)$		***
									$\Sigma(2620)$		**	$\Sigma_c(2800)$		***
									$\Sigma(3000)$		*	Ξ_c^+		***
									$\Sigma(3170)$		*	Ξ_c^0		***
												$\Xi_c'^+$		***
												$\Xi_c'^0$		***
												$\Xi_c(2645)$		***



LIGHT UNFLAVORED ($S = C = B = 0$)	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_2(1270)$	$0^+(2^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$	• $f_2(1950)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $\pi(1300)$	$1^-(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $a_2(1320)$	$1^-(2^{++})$	$f_0(2020)$	$0^+(0^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $a_4(2040)$	$1^-(4^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $f_4(2050)$	$0^+(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$	$f_0(2100)$	$0^+(0^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$f_2(2150)$	$0^+(2^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$\rho(2150)$	$1^+(1^{--})$
$f_2(1430)$	$0^+(2^{++})$	$f_0(2200)$	$0^+(0^{++})$
• $a_0(1450)$	$1^-(0^{++})$	$f_J(2220)$	$0^+(2 \text{ or } 4^{++})$
• $\rho(1450)$	$1^+(1^{--})$	$\eta(2225)$	$0^+(0^{-+})$
• $\eta(1475)$	$0^+(0^{-+})$	$\rho_3(2250)$	$1^+(3^{--})$
• $f_0(1500)$	$0^+(0^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_1(1510)$	$0^+(1^{++})$	$f_4(2300)$	$0^+(4^{++})$
• $f_2'(1525)$	$0^+(2^{++})$	• $f_2(2340)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$h_1(1595)$	$0^-(1^{+-})$	$a_6(2450)$	$1^-(6^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	$f_6(2510)$	$0^+(6^{++})$
$a_1(1640)$	$1^-(1^{++})$	OTHER LIGHT	
$f_2(1640)$	$0^+(2^{++})$	Further States	
• $\eta_2(1645)$	$0^+(2^{-+})$		
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

STRANGE ($S = \pm1, C = B = 0$)	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$
CHARMED ($C = \pm1$)	
• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
$D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D^*(2640)^\pm$	$1/2(?^?)$
CHARMED, STRANGE	

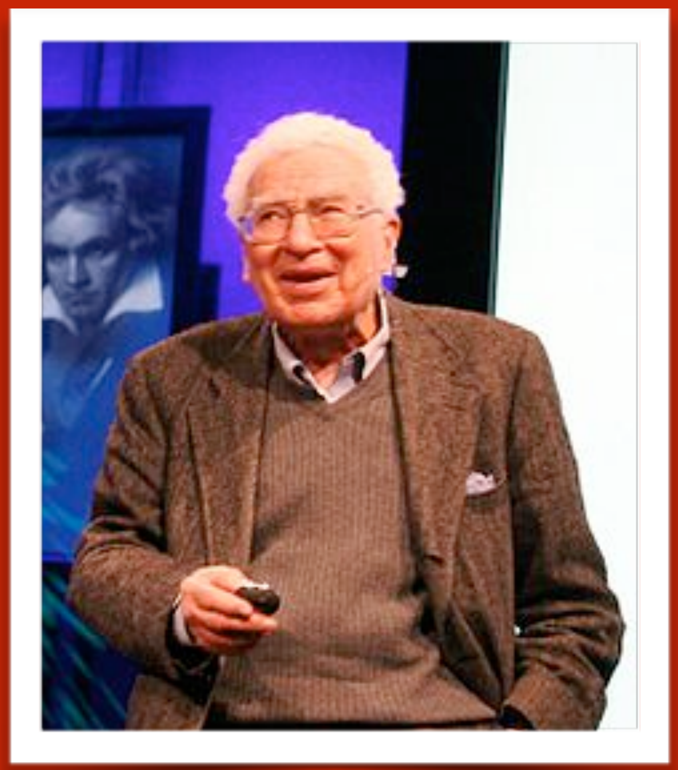
BOTTOM ($B = \pm1$)	$I^G(J^{PC})$
• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$
BOTTOM, STRANGE ($B = \pm1, S = \mp1$)	
• B^0_s	$0(0^-)$
B^*_s	$0(1^-)$
$B^*_{sJ}(5850)$	$?(?^?)$
BOTTOM, CHARMED ($B = C = \pm1$)	
• $B^\pm_c$	$0(0^-)$
$c\bar c$	
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
$h_c(1P)$	$?^?(?^{??})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^?(?^{?+})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$Y(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
$Y(4260)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$b\bar b$	
$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
$\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$

family arrangements

quarks

the mathematical description of such patterns

1964



Murray Gell-Mann

1929 -

theoretician

Nobel Laureate 1969

genius

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

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

Unraveled many of the organization puzzles of the particle zoo:

- strangeness
- an empirical mass formula relating them

Worries a lot now about the nature of physical law.

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

Not known for his humility.

http://www.ted.com/talks/murray_gell_mann_on_beauty_and_truth_in_physics.html

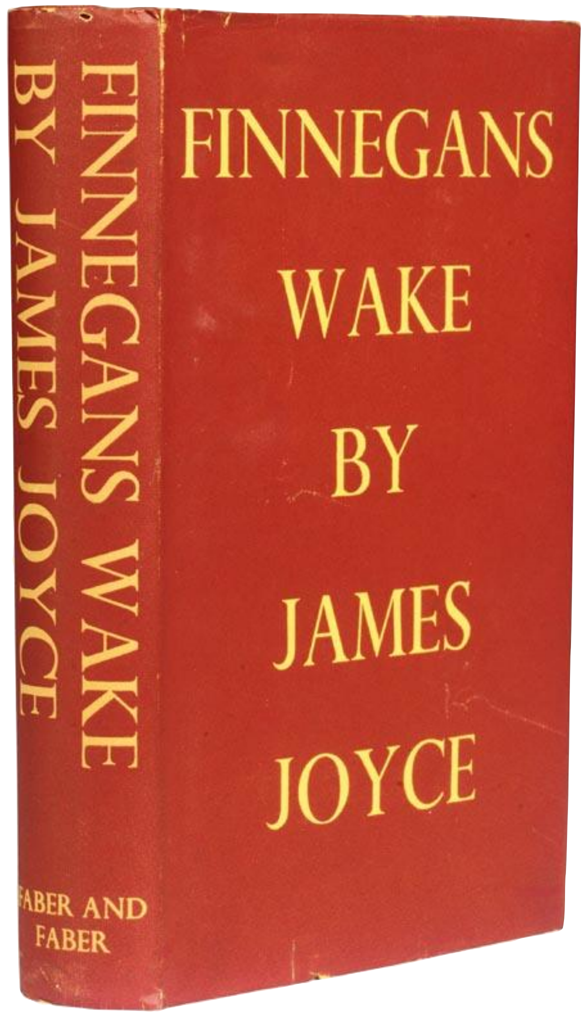
Gell-Mann found that the patterns work

if every particle is composed of smaller bits

up
down
strange

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

"Quarks"



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

with fractional electric charge:

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

fundamental particles, circa…now

quarks and leptons

hadrons are composite: made of quarks

electrons and cousins are fundamental on their own

Baryons & Mesons differ by quark-content

Baryons are made of 3 quarks

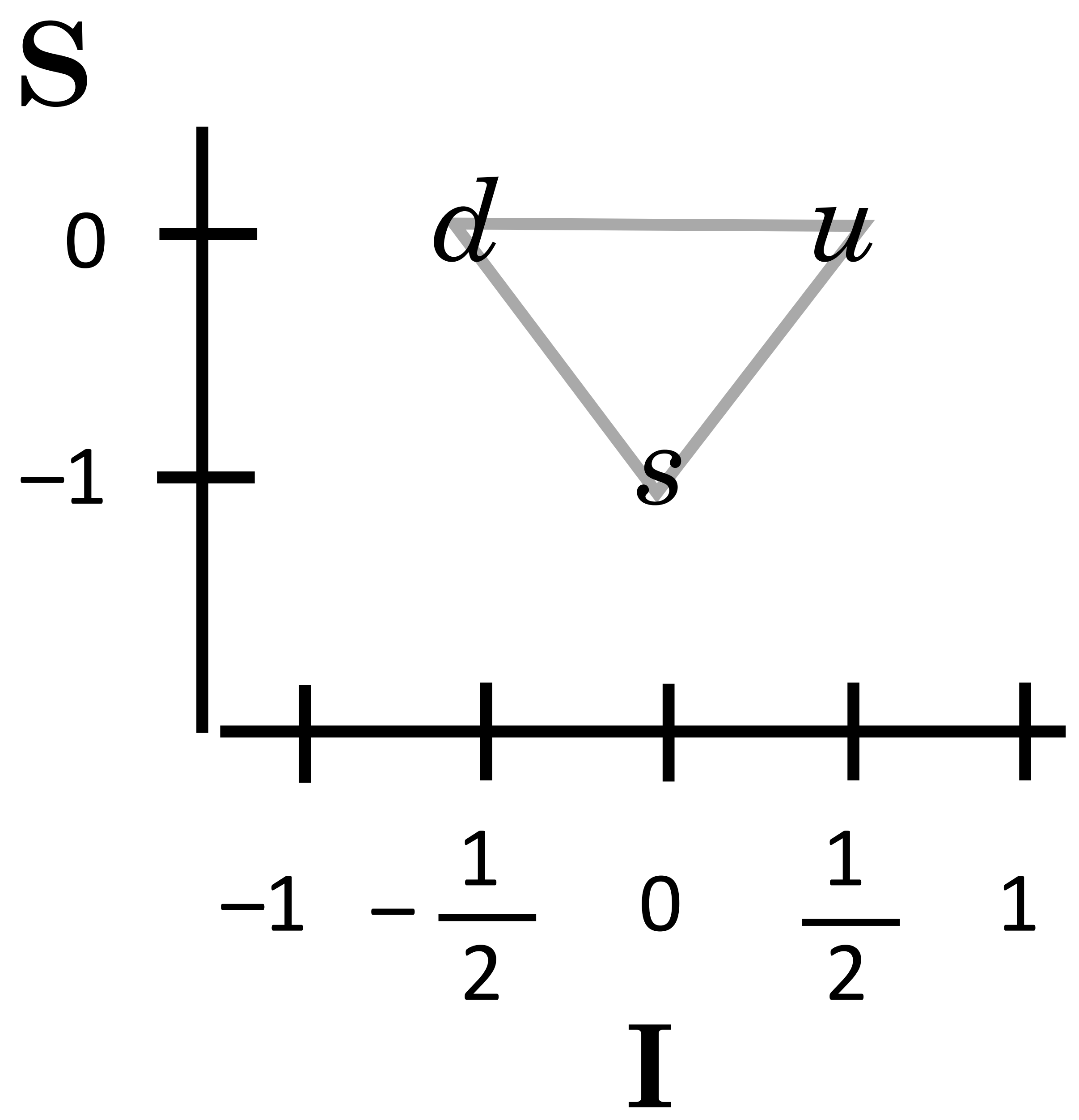
Mesons are made of 1 quark and 1 antiquark

Quarks

1964 version

fundamental fermions

in same league as electrons and neutrinos

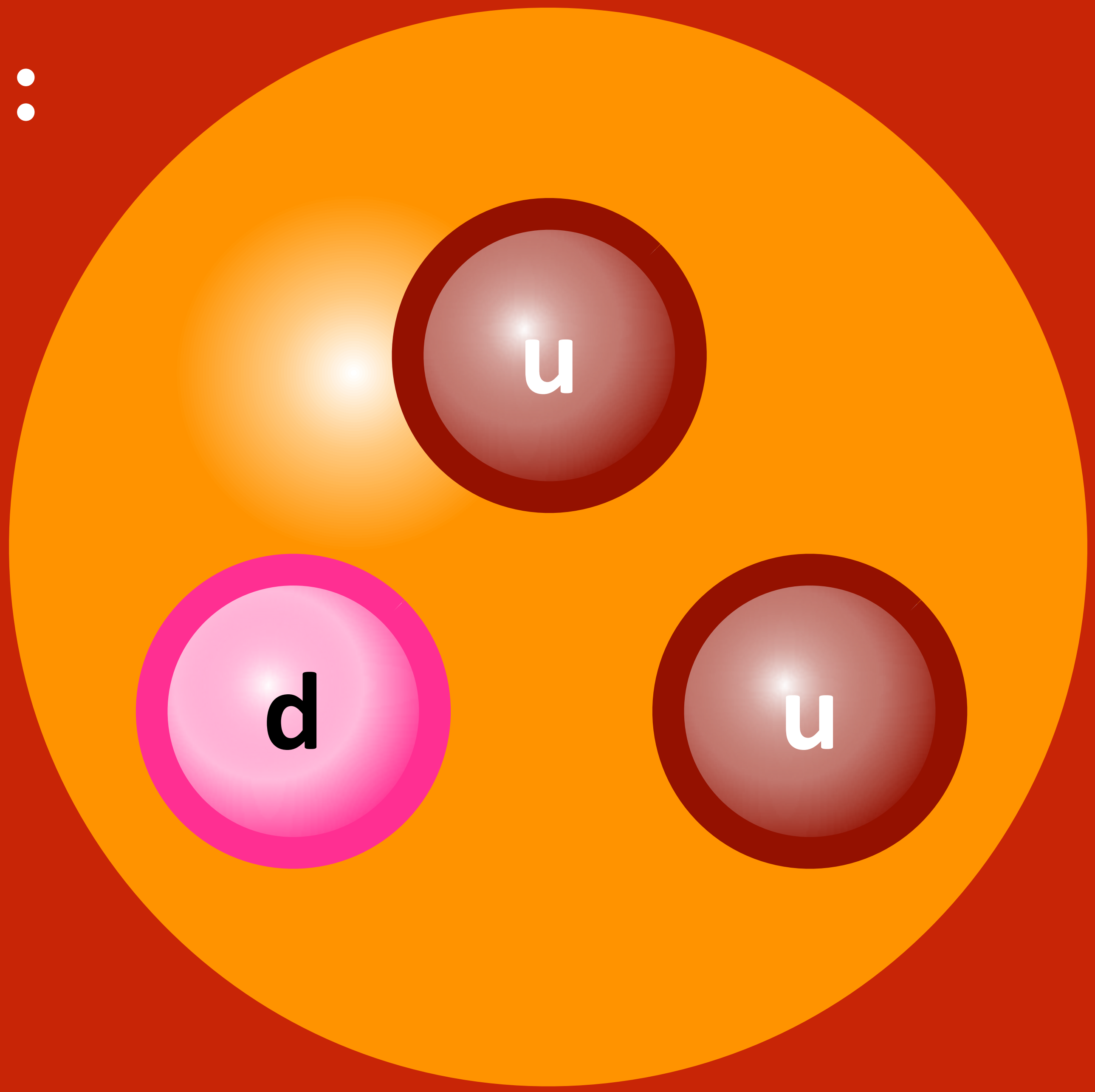


Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece 'em together:

proton

electric charge = +1

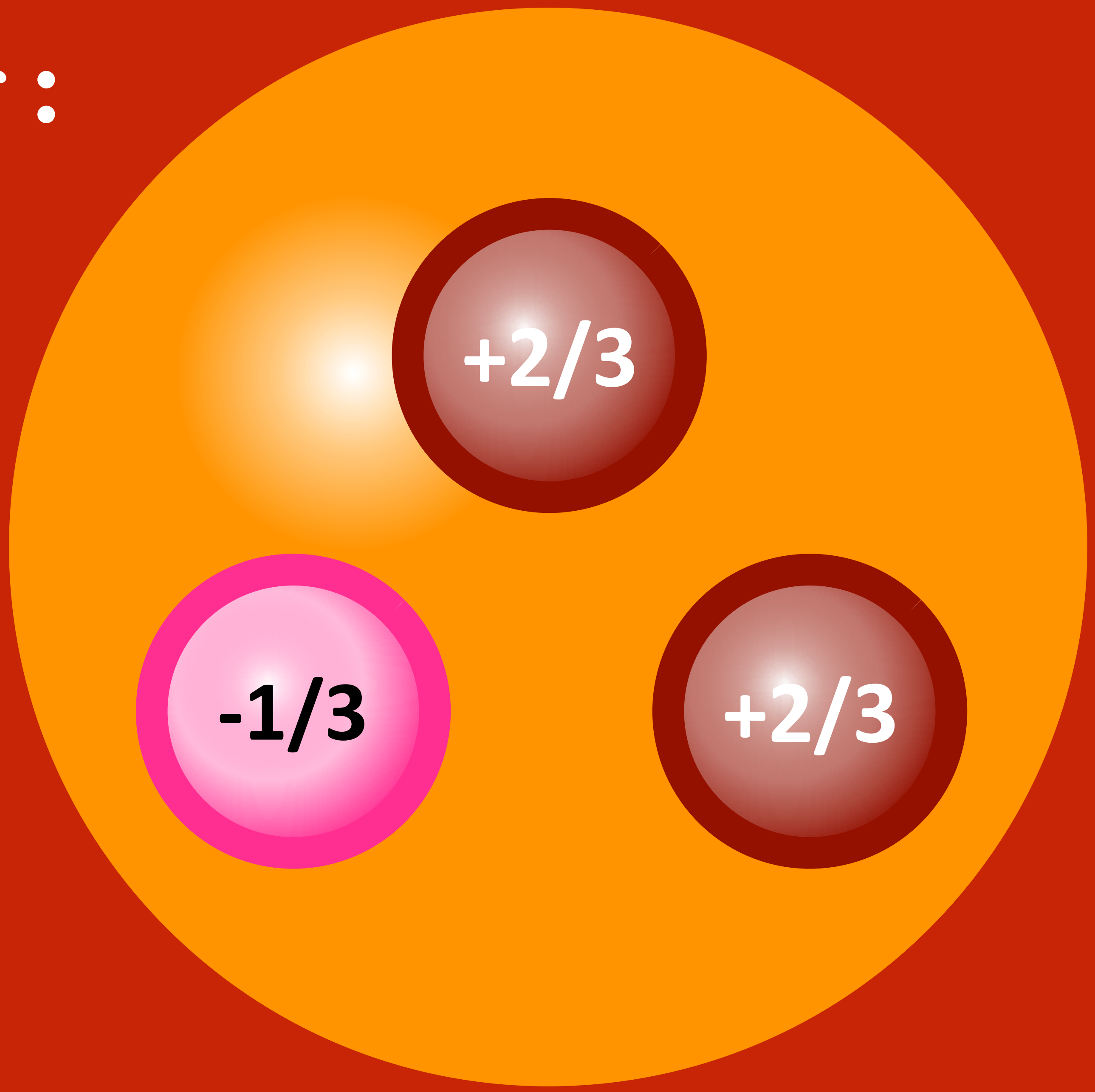


Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece 'em together:

proton

electric charge = +1

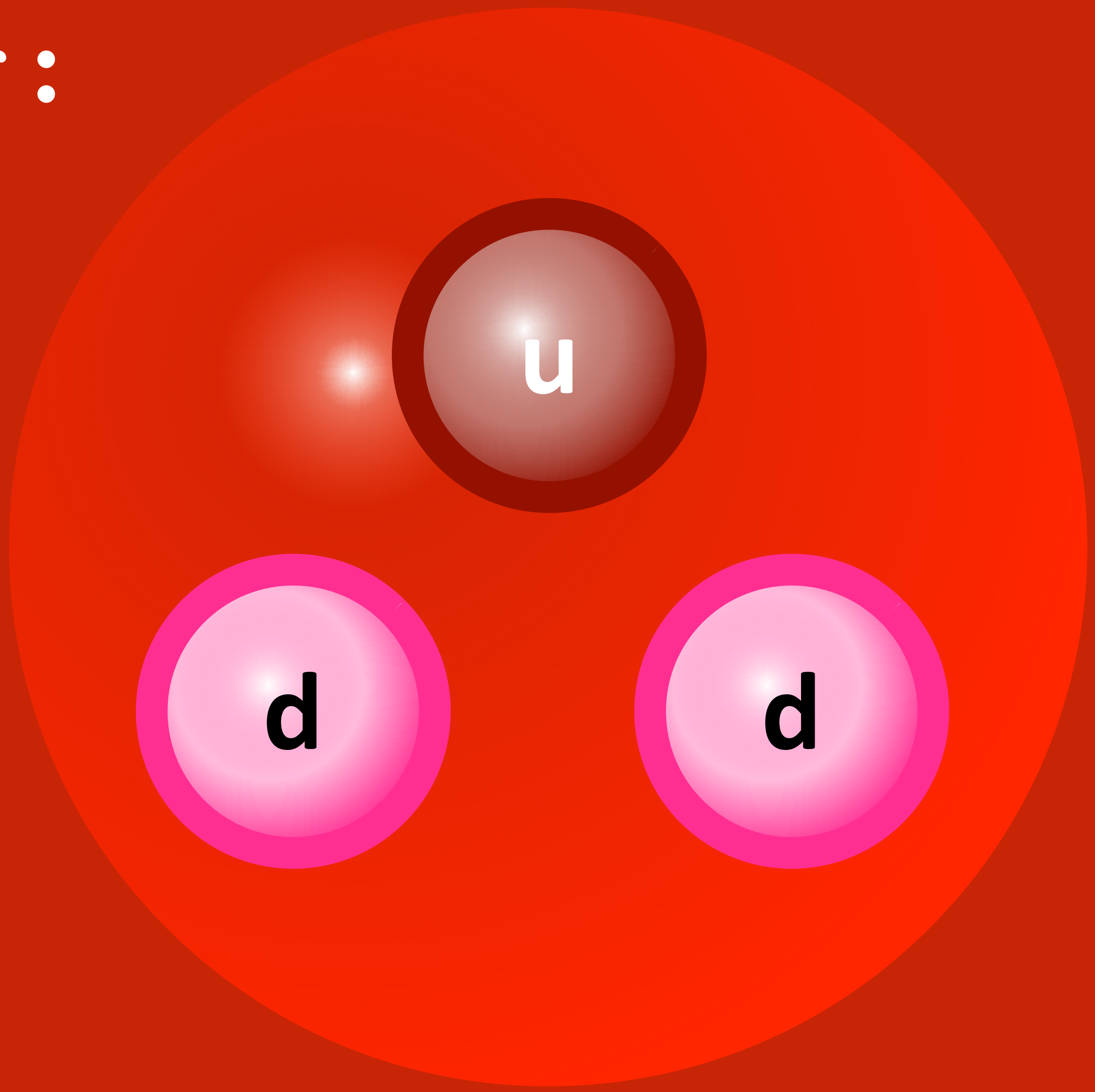


Quark	Symbol	Rest Mass MeV/c^2	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece ‘em together:

neutron

electric charge = 0

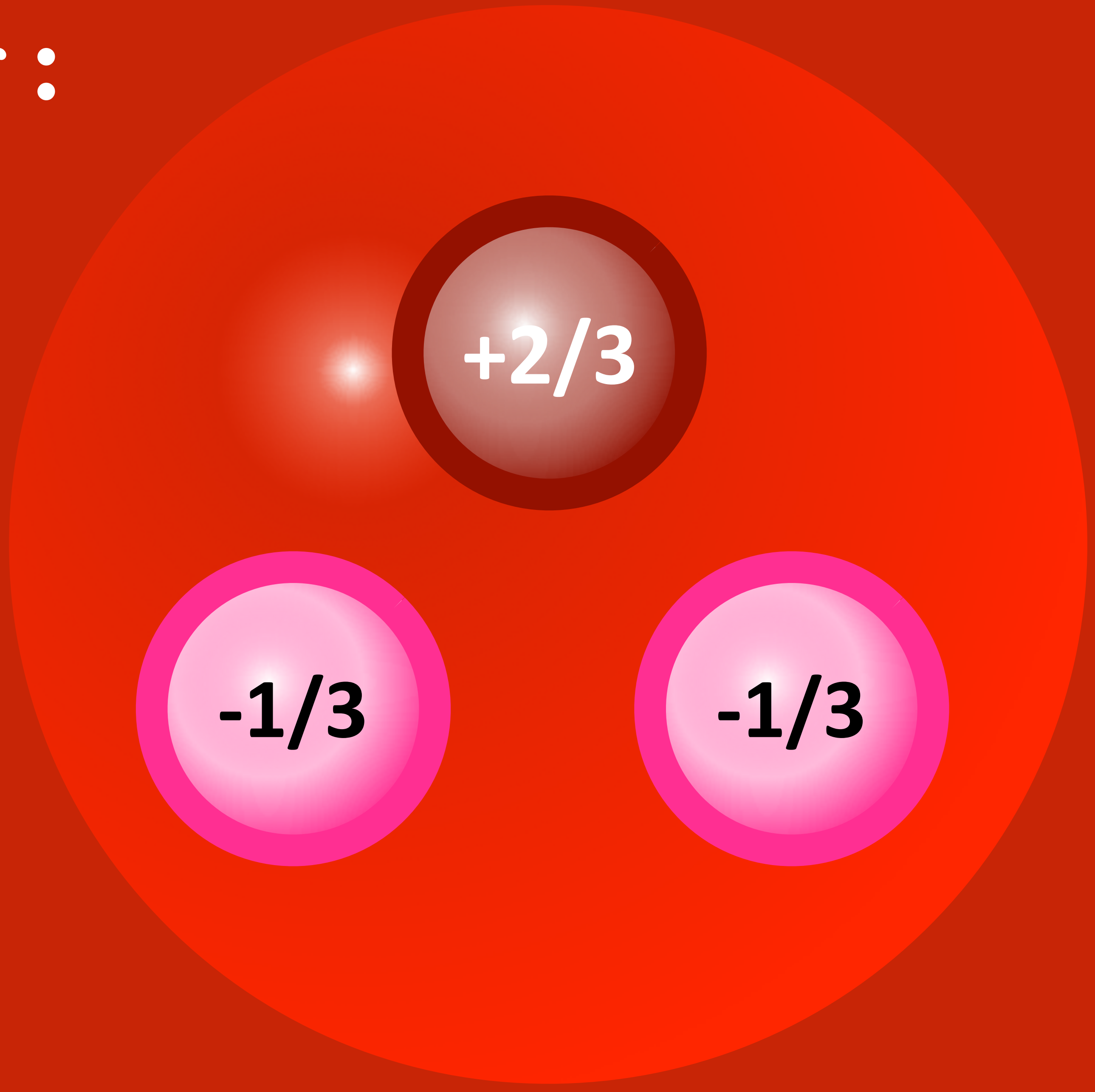


Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

piece 'em together:

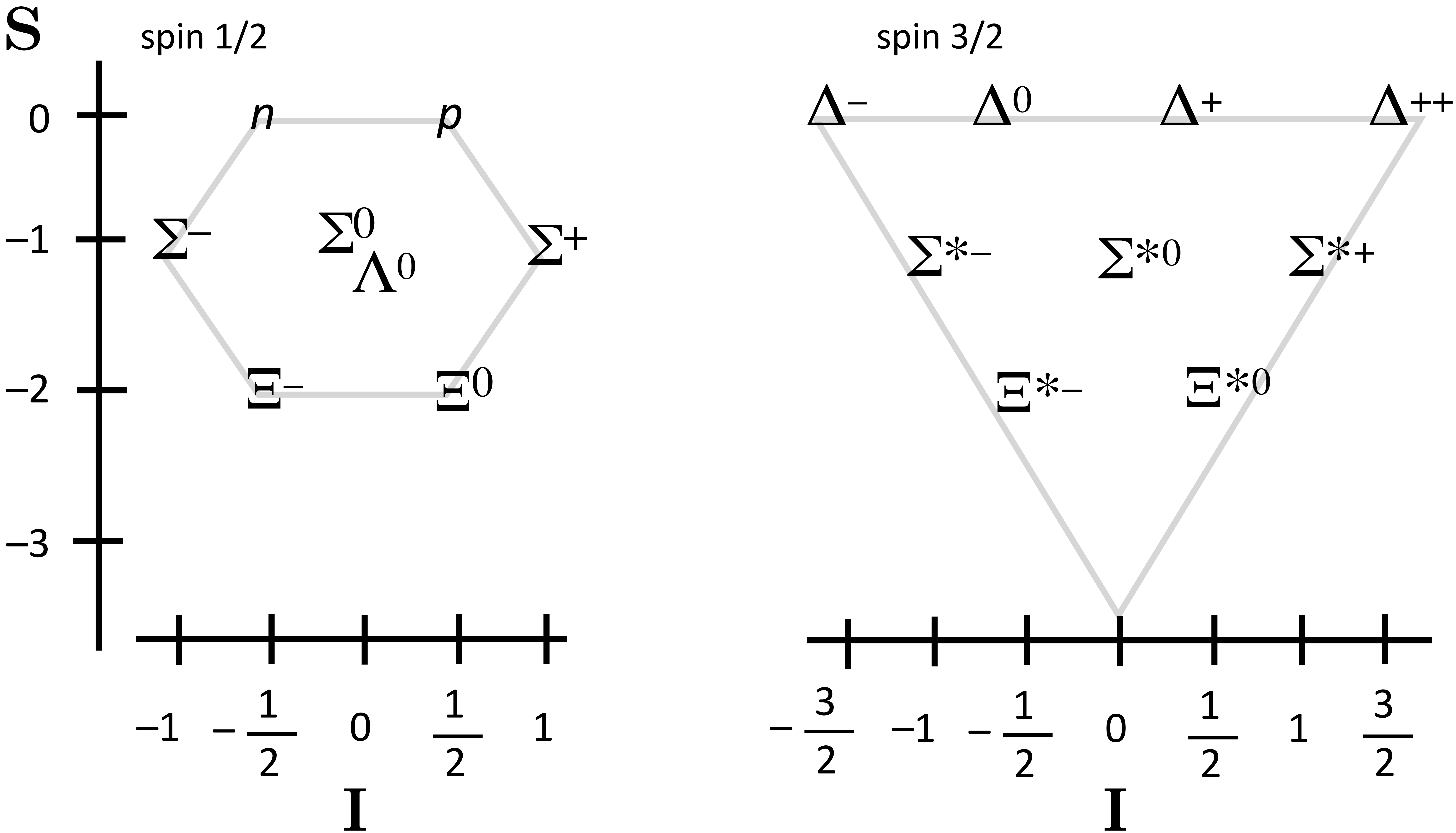
neutron

electric charge = 0

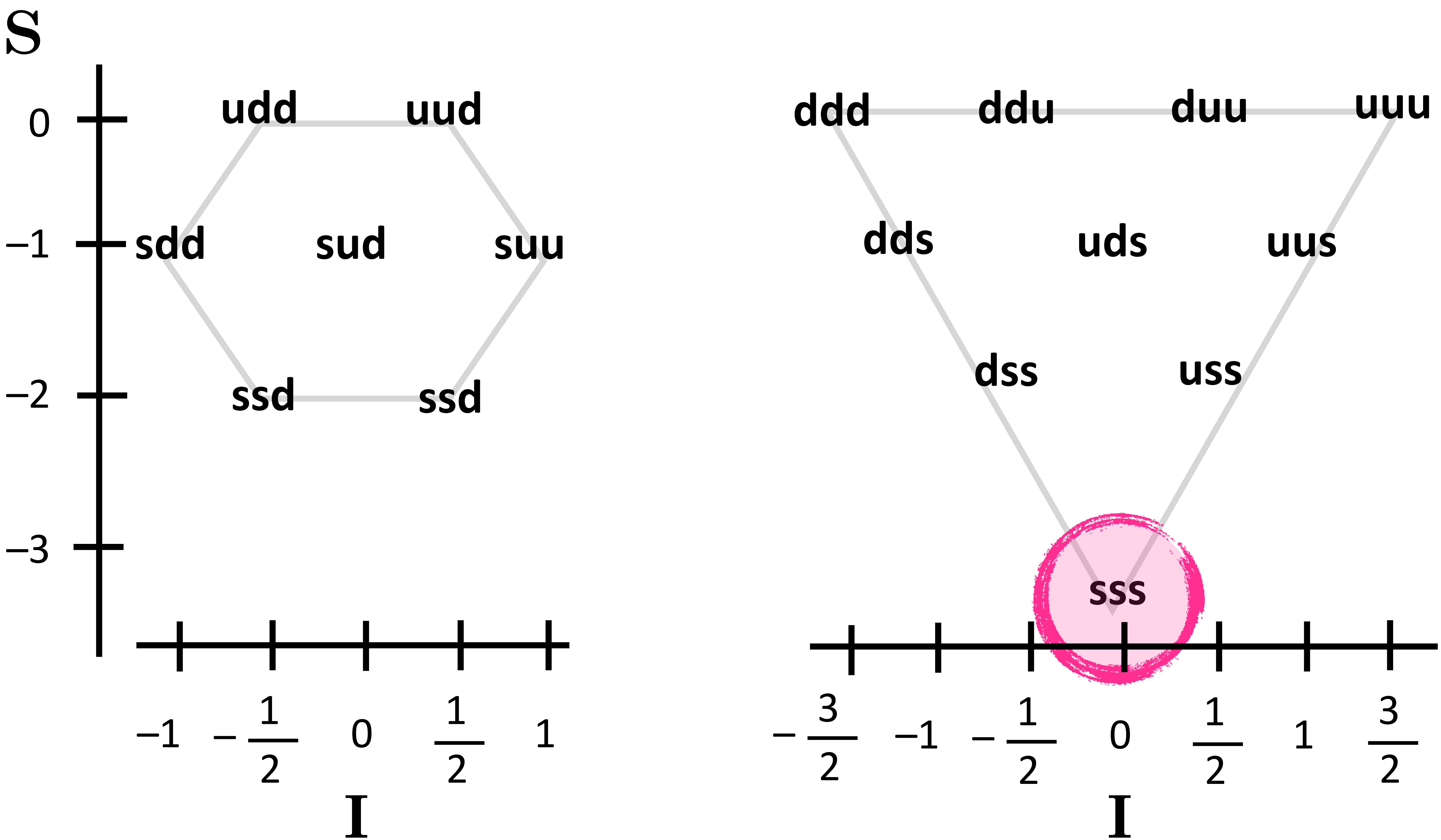


Quark	Symbol	Rest Mass MeV/c²	spin	Q	B	S
up	u	1.7 - 3.3	1/2	+2/3	1/3	0
down	d	4.1 - 5.8	1/2	−1/3	1/3	0
strange	s	101	1/2	−1/3	1/3	−1

they all fit

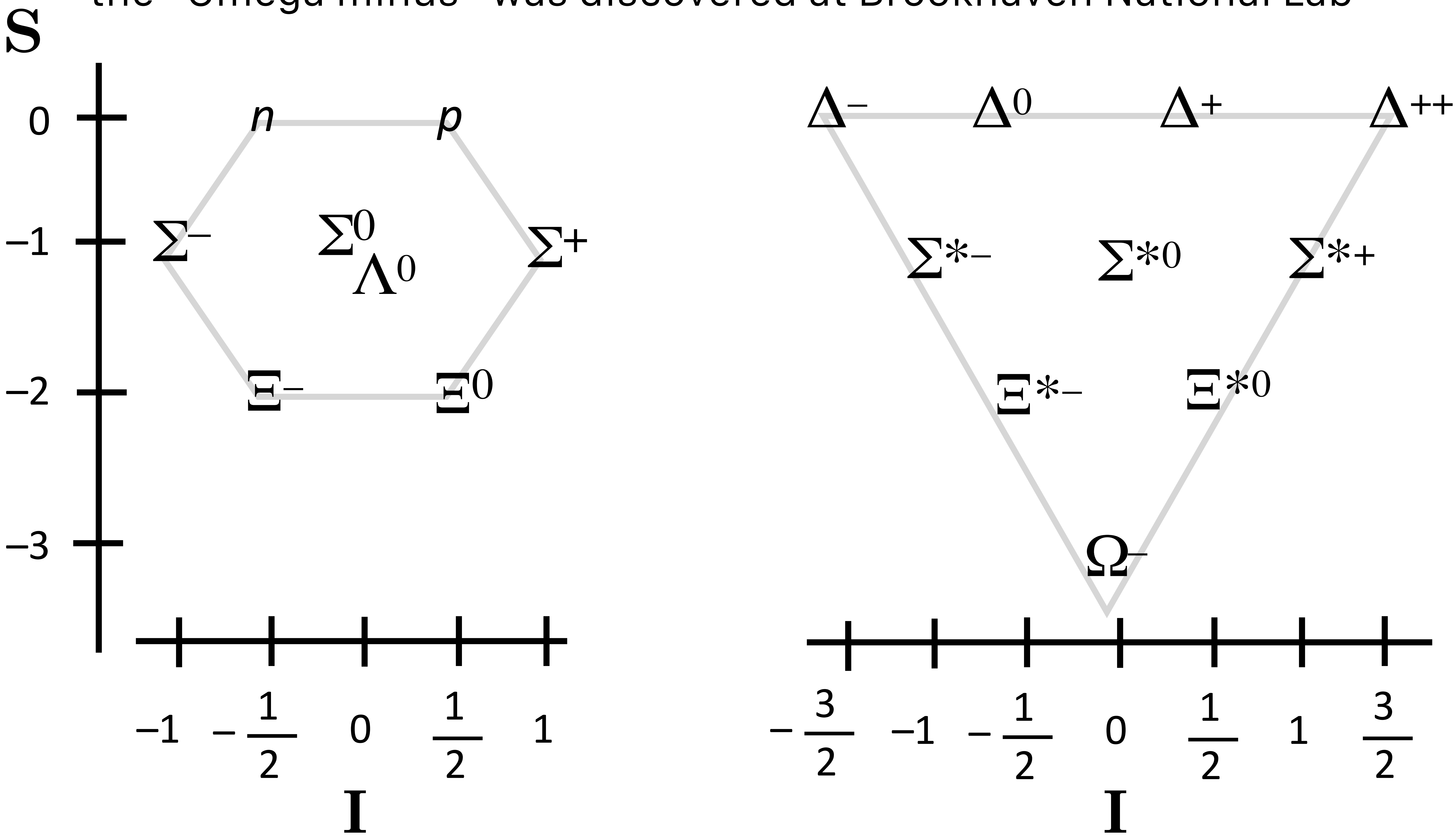

S
spin 1/2
0
−1
−2
−3
n
p
Σ−
Σ0
Λ0
Σ+
Ξ−
Ξ0
−1
−1/2
0
1/2
1
I
spin 3/2
Δ−
Δ0
Δ+
Δ++
Σ*−
Σ*0
Σ*+
Ξ*−
Ξ*0
−3/2
−1
−1/2
0
1/2
1
3/2
I

like a glove


S
0
−1
−2
−3
udd
uud
sdd
sud
suu
ssd
ssd
−1
− 1/2
0
1/2
1
I
ddd
ddu
duu
uuu
dds
uds
uus
dss
uss
sss
− 3/2
−1
− 1/2
0
1/2
1
3/2
I

discovered at Brookhaven within a year

the “Omega minus” was discovered at Brookhaven National Lab



most famous bubble chamber picture in history, 1964

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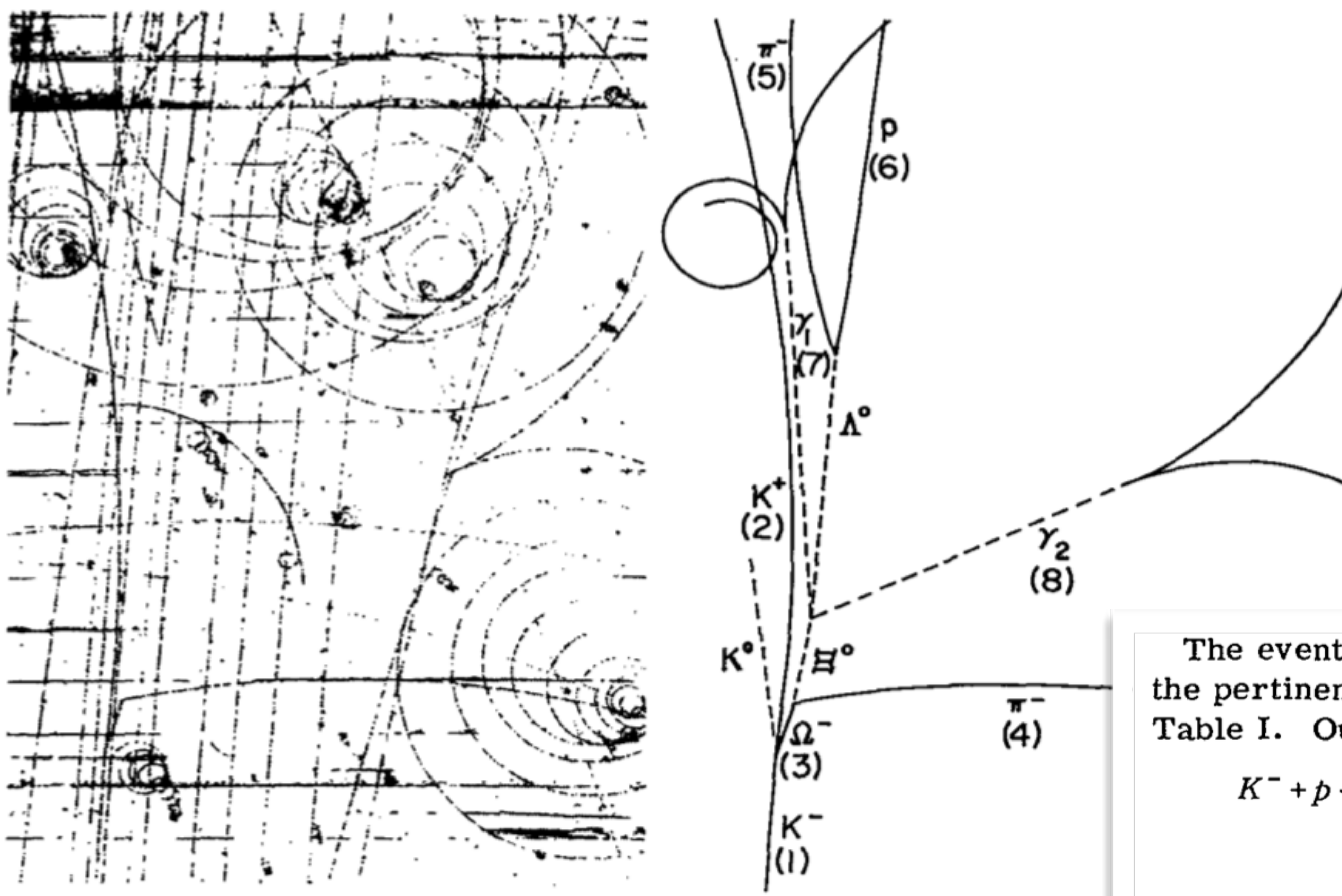


FIG. 2. Photograph and line diagram of event showing dec

The event in question is shown in Fig. 2, and the pertinent measured quantities are given in Table I. Our interpretation of this event is

$$
\begin{array}{l}
K^- + p \to \Omega^- + K^+ + K^0 \\
\quad \Omega^- \to \Xi^0 + \pi^- \\
\quad\quad \Xi^0 \to \Lambda^0 + \pi^0 \\
\quad\quad\quad \pi^0 \to \gamma_1 + \gamma_2 \\
\quad\quad\quad\quad \gamma_2 \to e^+ + e^- \\
\quad\quad\quad\quad \gamma_1 \to e^+ + e^- \\
\quad\quad\quad \Lambda^0 \to \pi^- + p.
\end{array}
\qquad (1)
$$

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/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	2.6×10^{-10}	$p\pi^-,\ n\pi^0$	uds
Sigma	Σ^+	1189.4	1/2	+1	+1	−1	0.8×10^{-10}	$p\pi^0,\ n\pi^+$	uus
Sigma	Σ^0	1192.5	1/2	0	+1	−1	6×10^{-20}	$\Lambda^0\gamma$	uds
Sigma	Σ^-	1197.3	1/2	−1	+1	−1	1.5×10^{-10}	$n\pi^-$	dds
Delta	Δ^{++}	1232	3/2	+2	+1	0	0.6×10^{-23}	$p\pi^+$	uuu
Delta	Δ^+	1232	3/2	+1	+1	0	0.6×10^{-23}	$n\pi^+,\ p\pi^0$	uud
Delta	Δ^0	1232	3/2	0	+1	0	0.6×10^{-23}	$n\pi^0$	udd
Delta	Δ^-	1232	3/2	−1	+1	0	0.6×10^{-23}	$n\pi^-$	ddd
Xi	Ξ^0	1315	1/2	0	+1	−2	2.9×10^{-10}	$\Lambda^0\pi^0$	uss
Xi	Ξ^-	1321	1/2	−1	+1	−2	1.64×10^{-10}	$\Lambda^0\pi^-$	dss
Omega	Ω^-	1672	3/2	−1	+1	−3	0.82×10^{-10}	$\Xi^0\pi^-,\ \Lambda^0K^-$	sss

mesons

a little different

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

The pion:

Particle	Symbol	anti-particle	Rest Mass MeV/c²	spin	Q	B	S
Pion	π^+	π^-	139.6	0	+1	0	0

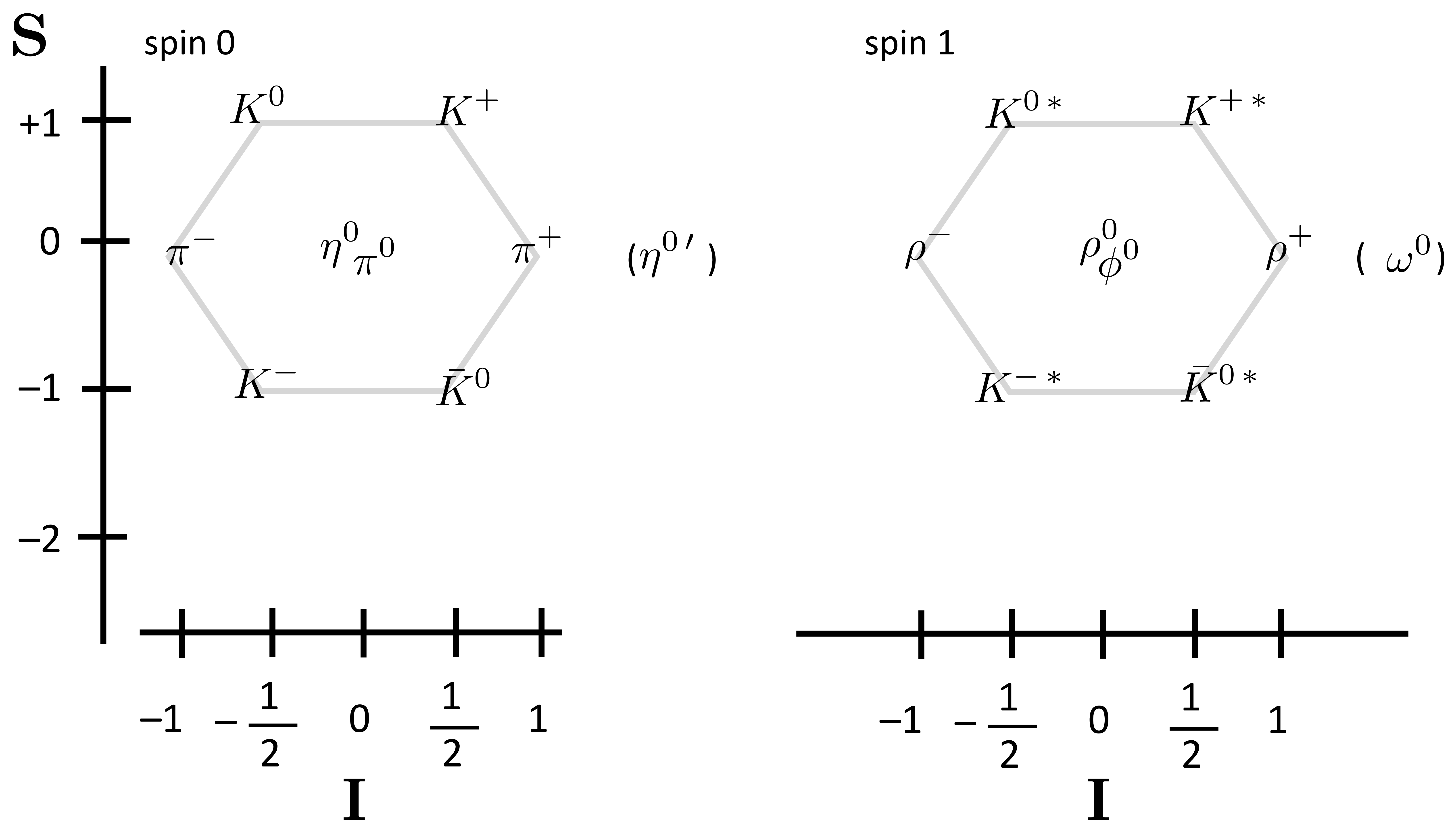
$$\pi^+ = (u \quad \& \quad \bar{d})$$

has the right stuff.

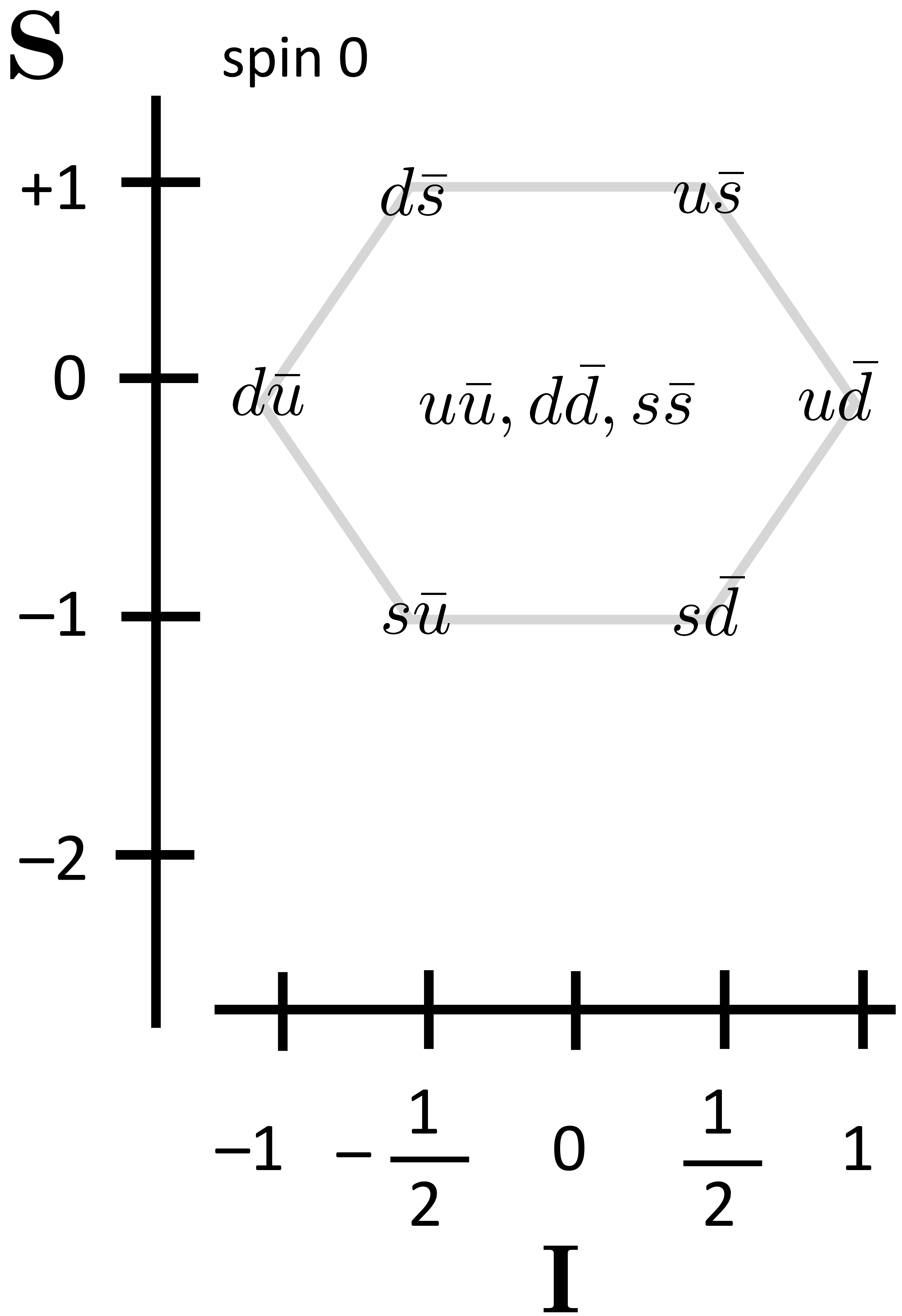
Q:	+1	+2/3 + −(−1/3)	
B:	0	1/3 + −(1/3)	
S:	0	0	0

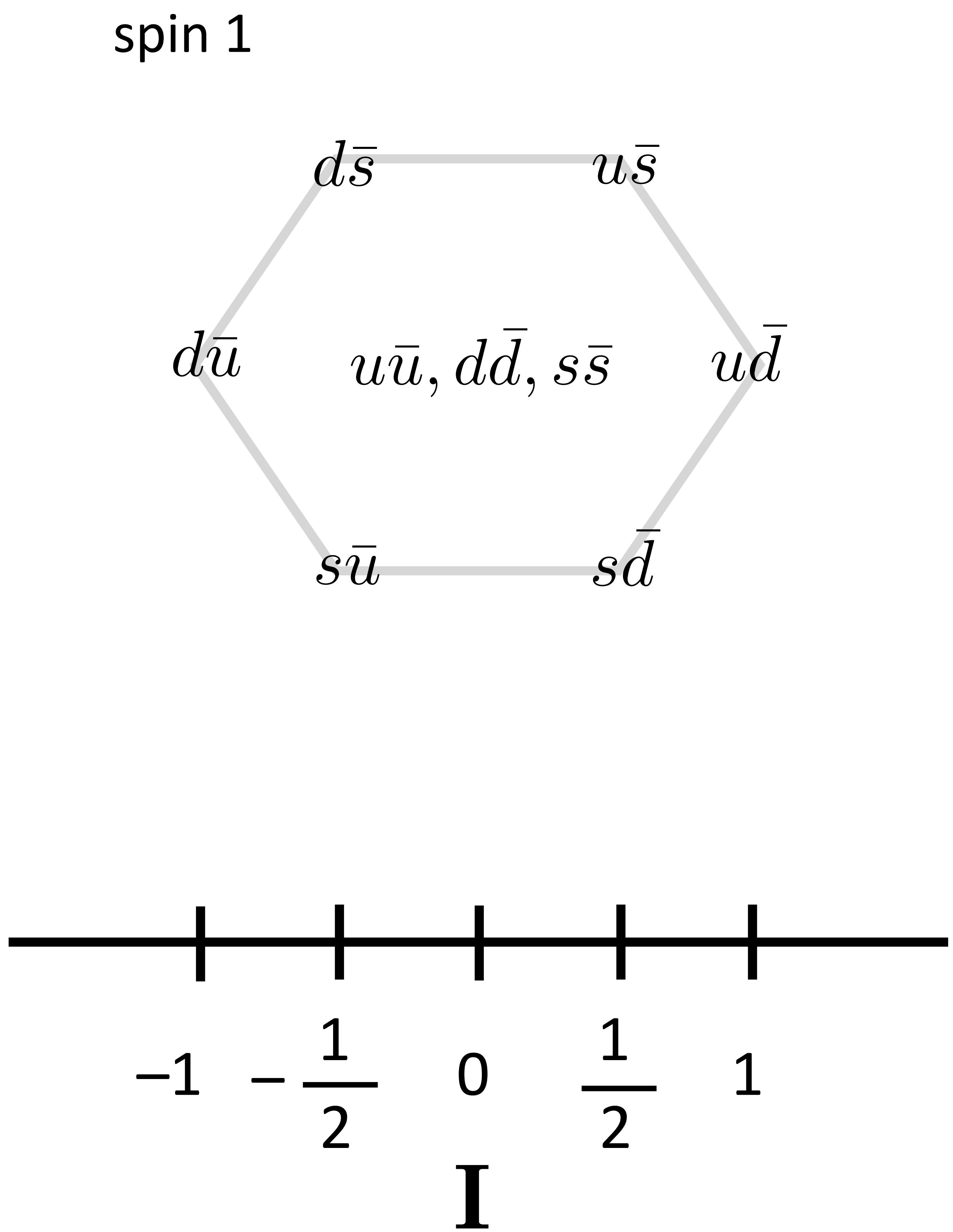
$$\pi^+ = u\bar{d}$$

a similar thing happens for the mesons



meson quark content





the dominant Mesons

Particle	Symbol	anti-particle	Rest Mass MeV/c^2	spin	Q	B	S	Lifetime	dominant decay modes	quark content
Pion	π^+	π^-	139.6	0	+1	0	0	2.6×10^{-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	1.24×10^{-8}	$\mu^+\nu_\mu, \pi^+\pi^0$	$u\bar{s}$
K-short	K_S^0	K_S^0	497.7	0	0	0	+1	0.89×10^{-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	5.2×10^{-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	$0.4 \times 10^{--23}$	$\pi^+\pi^-, 2\pi^0$	$u\bar{d}$
Rho-naught	ρ^0	ρ^0	770	1	0	0	0	$0.4 \times 10^{--23}$	$\pi^+\pi^-$	$u\bar{u}, d\bar{d}$
Omega	ω^0	ω^0	782	1	0	0	0	$0.8 \times 10^{--22}$	$\pi^+\pi^-\pi^0$	$u\bar{u}, d\bar{d}$
Phi	ϕ	ϕ	1020	1	0	0	0	20×10^{-23}	$K^+K^-, K^0\bar{K}^0$	$s\bar{s}$

spins work out

add up the spins

Keep track of quark spins: spin +1/2 $q\uparrow$

spin –1/2 $q\downarrow$

for example, a couple of baryons:

p	$u\uparrow u\downarrow d\uparrow$	total spin: 1/2
Δ^+	$u\uparrow u\uparrow d\uparrow$	total spin: 3/2

for example, a couple of mesons:

π^+	$u\uparrow \bar{d}\downarrow$	total spin: 0
ρ^+	$u\uparrow \bar{d}\uparrow$	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.

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

d u u

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

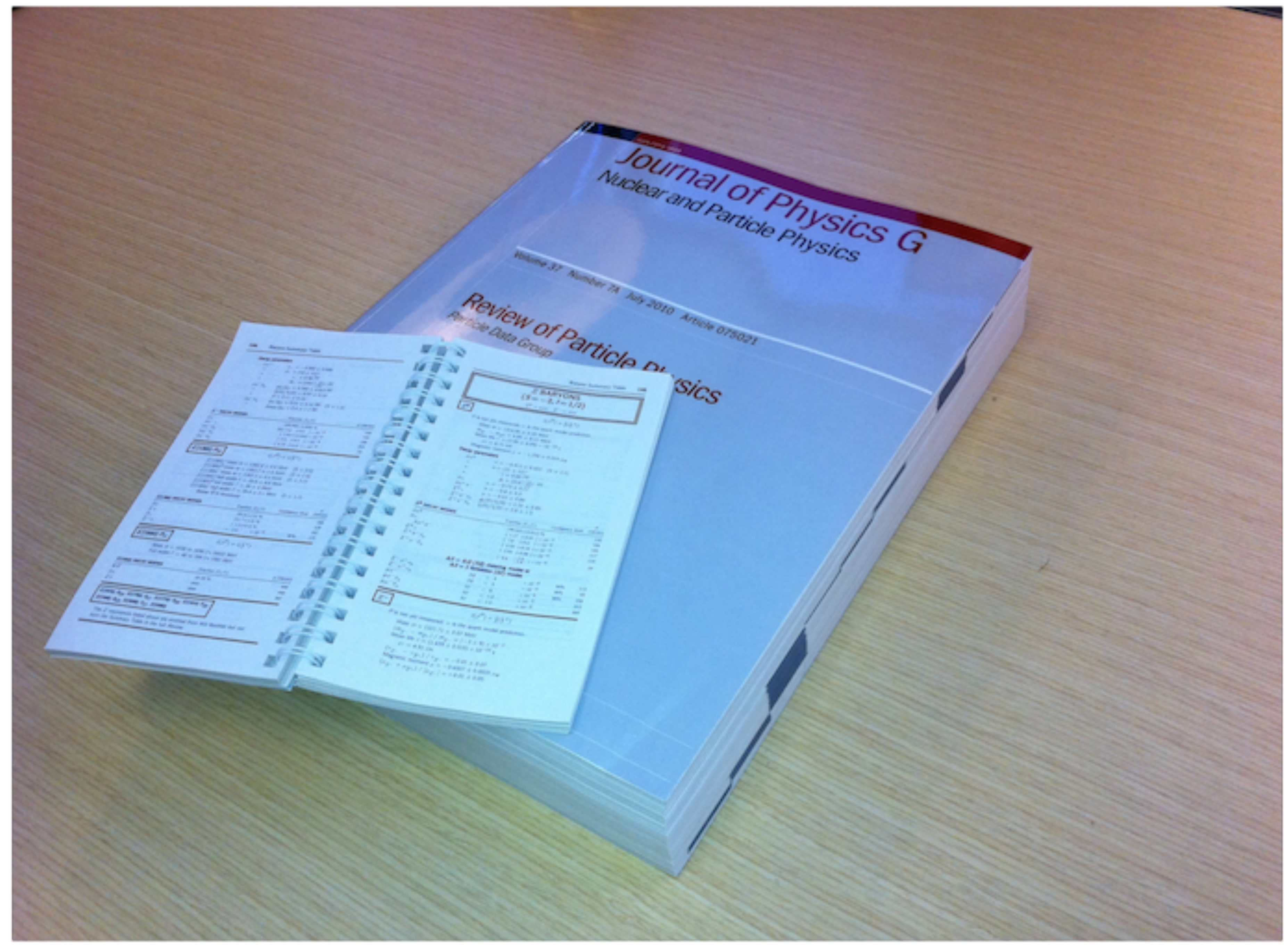
d

u u

you can tell a particle physicist

by the books that we carry

"I laughed, I cried"



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

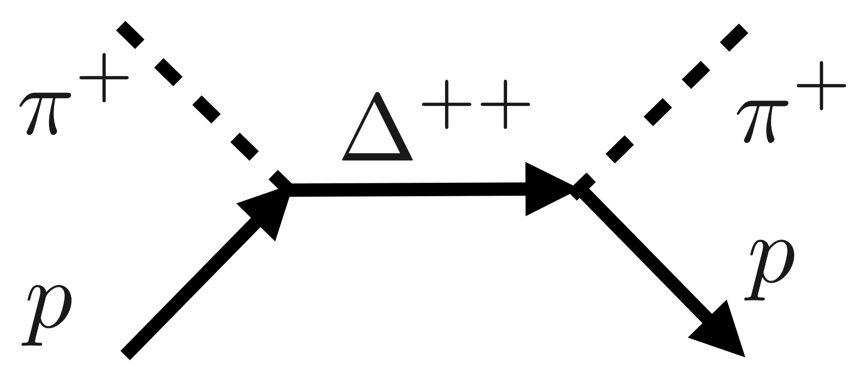
became apparent

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

$$\pi^+ + p \to \pi^+ + p$$

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

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



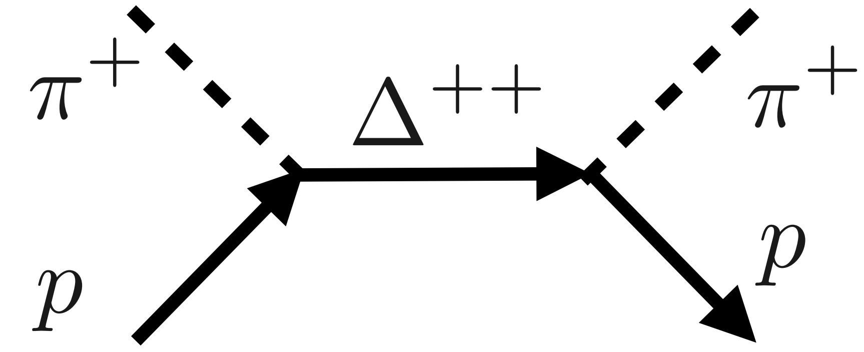
* I call them “pseudo” as doing real calculations with them are kind of ad-hoc

scatterings now are thought of diferently

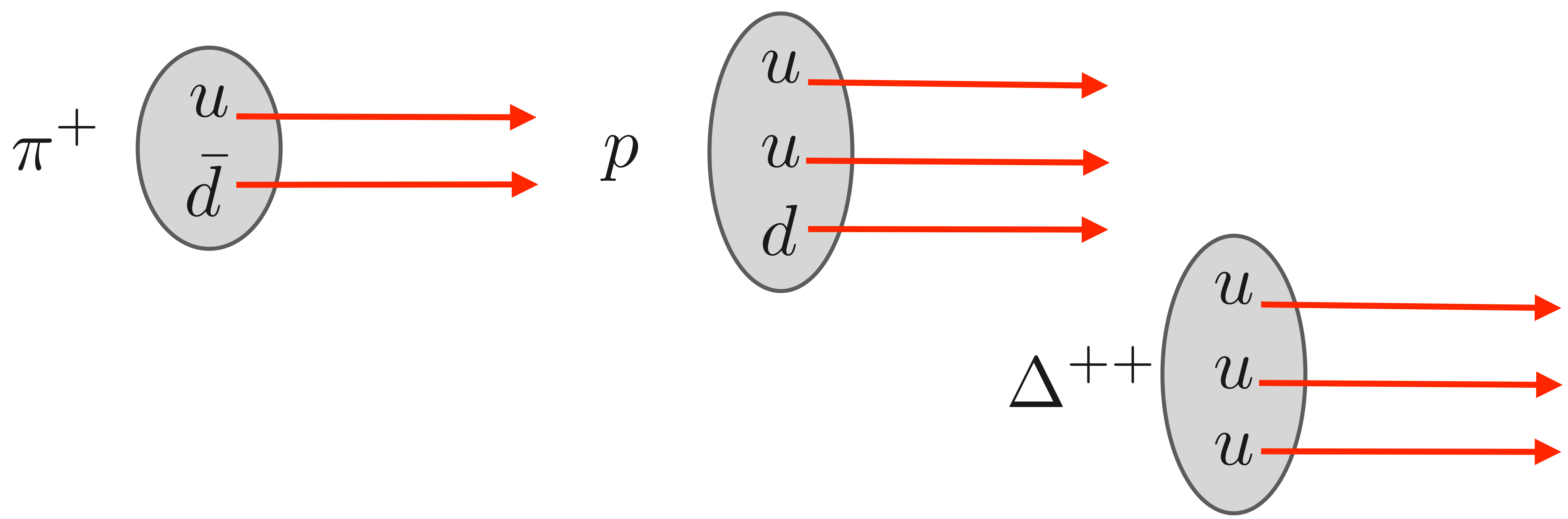
by following the lines...

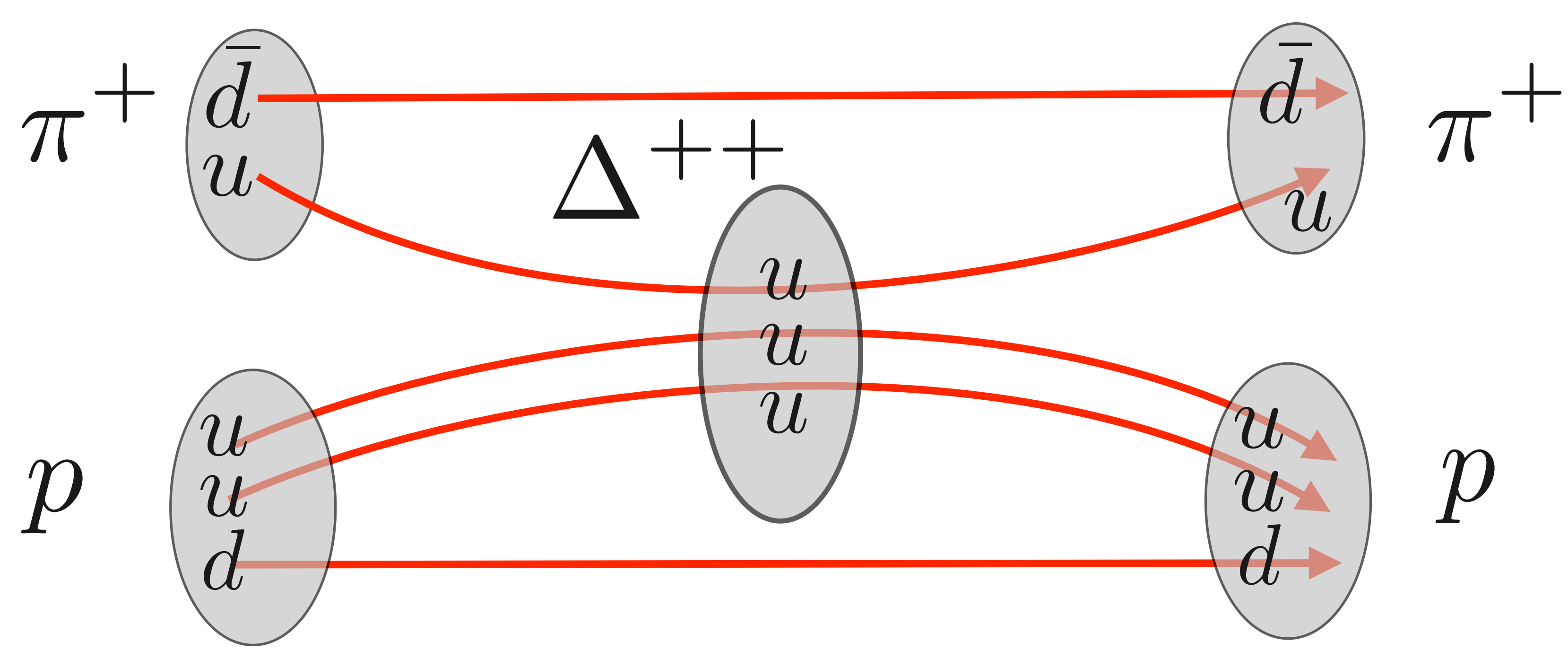
$$\pi^+ + p \to \Delta^{++} \to \pi^+ + p$$

Feynman Diagram, pre-1964:



in quark language:



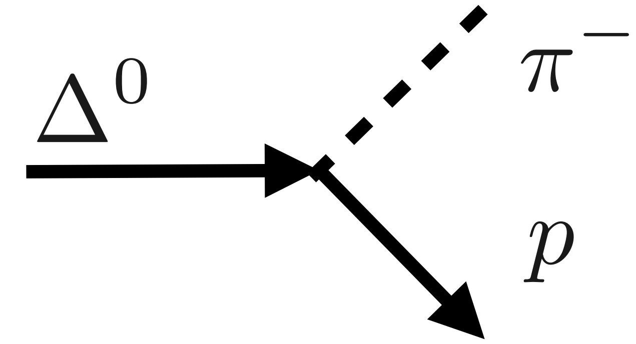


how about a strong interaction decay?

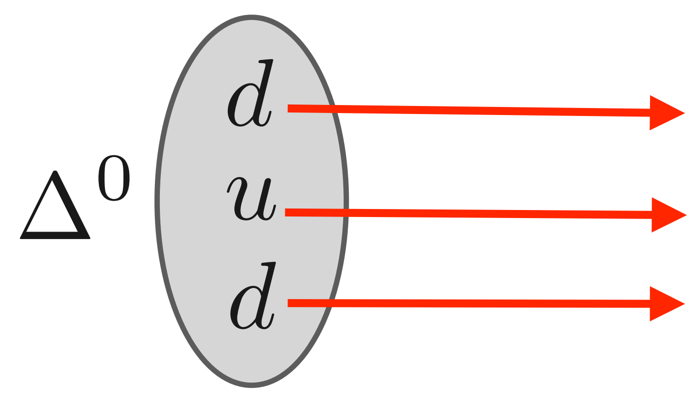
a little non-intuitive.

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

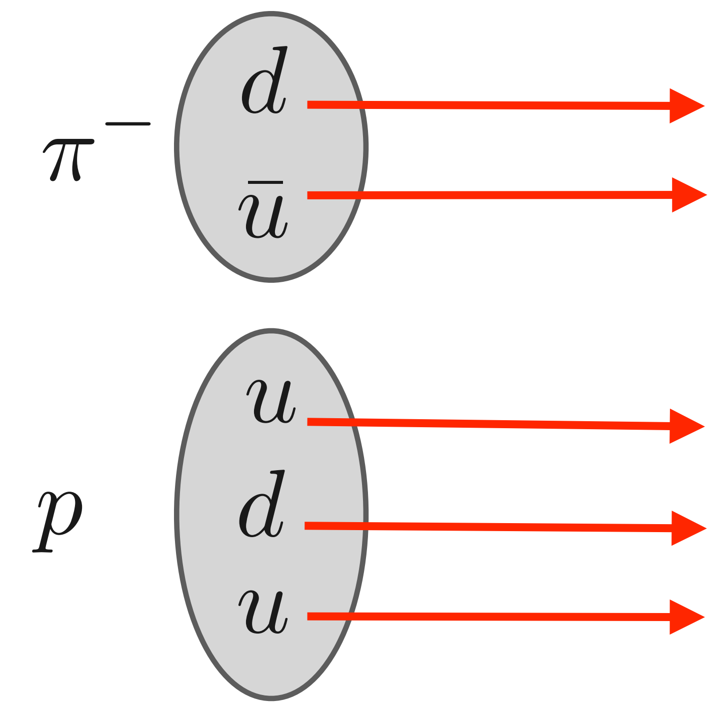
the old way:



the quark way:

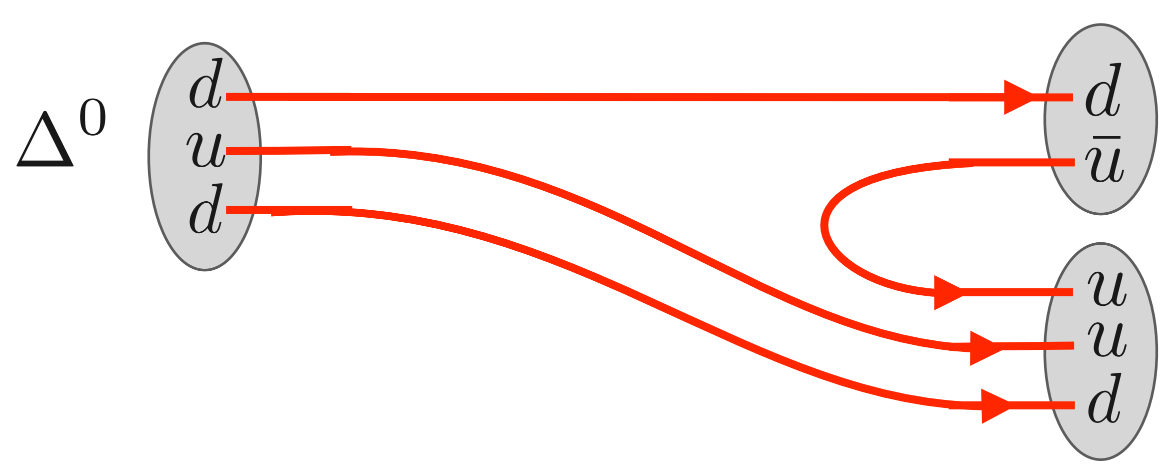


3 quarks



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?

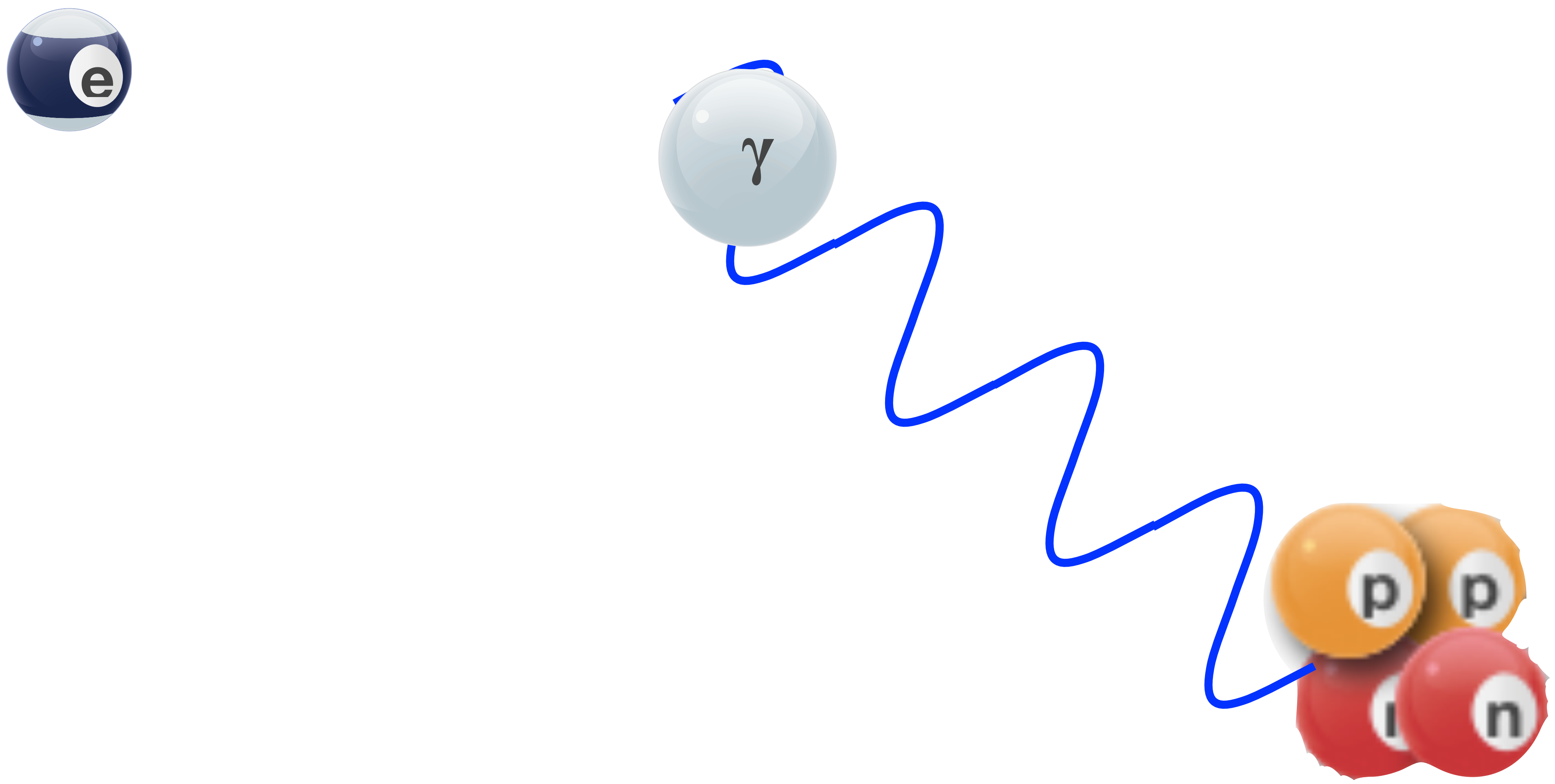
wavelength has to be about the size of the object

larger the momentum

the smaller the spatial resolving capability

scattering of an electron from a nucleus

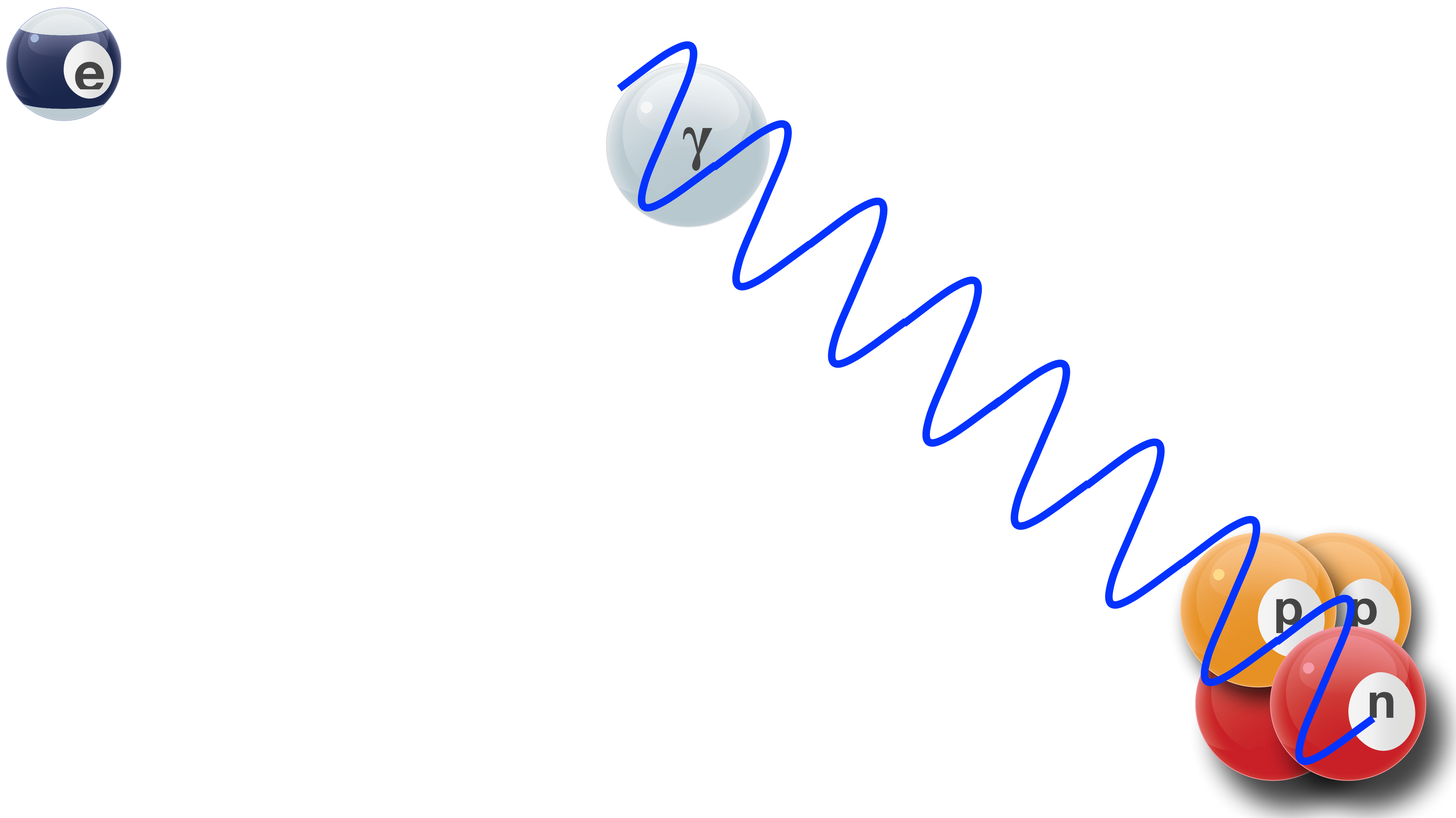
slow electron, long wavelength photon



“sees” the whole nucleus

scattering of an electron from a nucleus

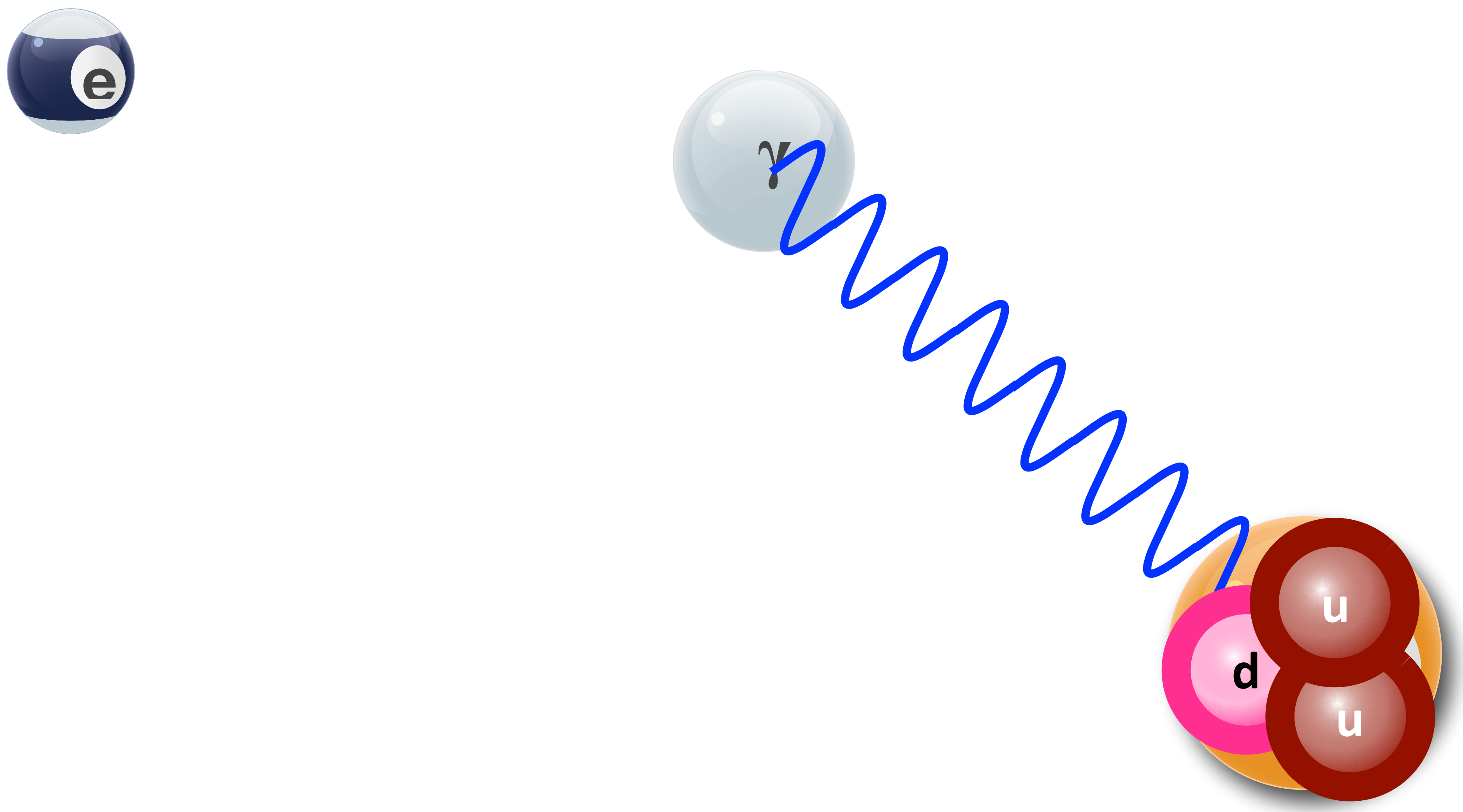
fast electron, **medium-short** wavelength photon



“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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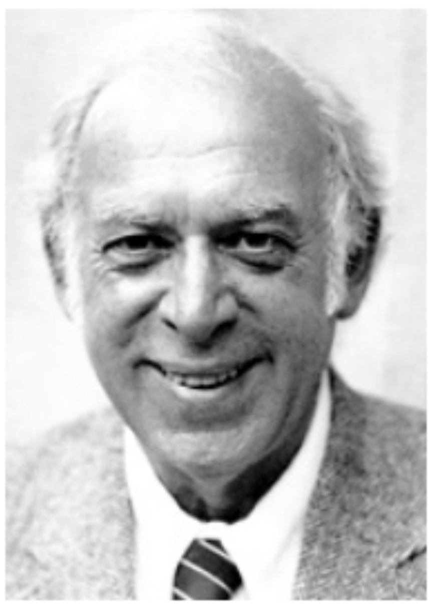
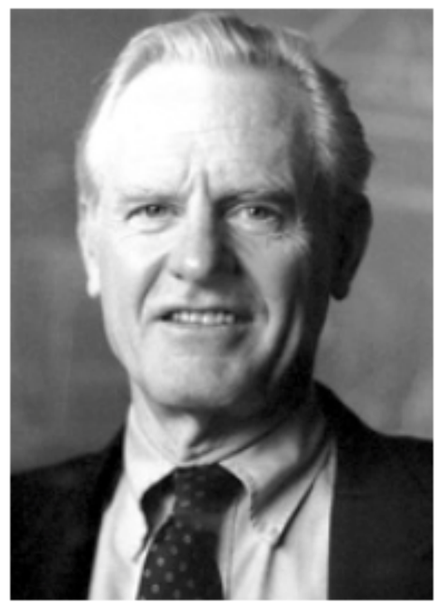
The Nobel Prize in Physics 1990



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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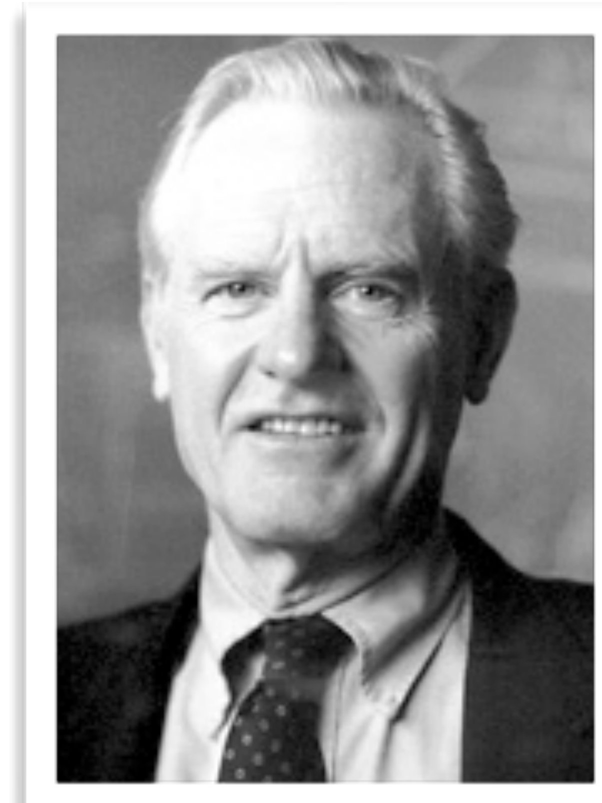
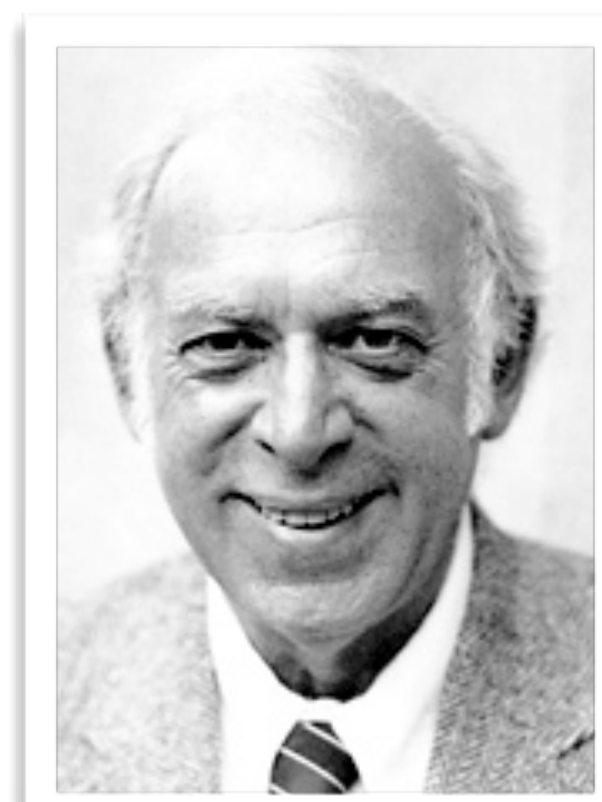




particle: **up quark**

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**

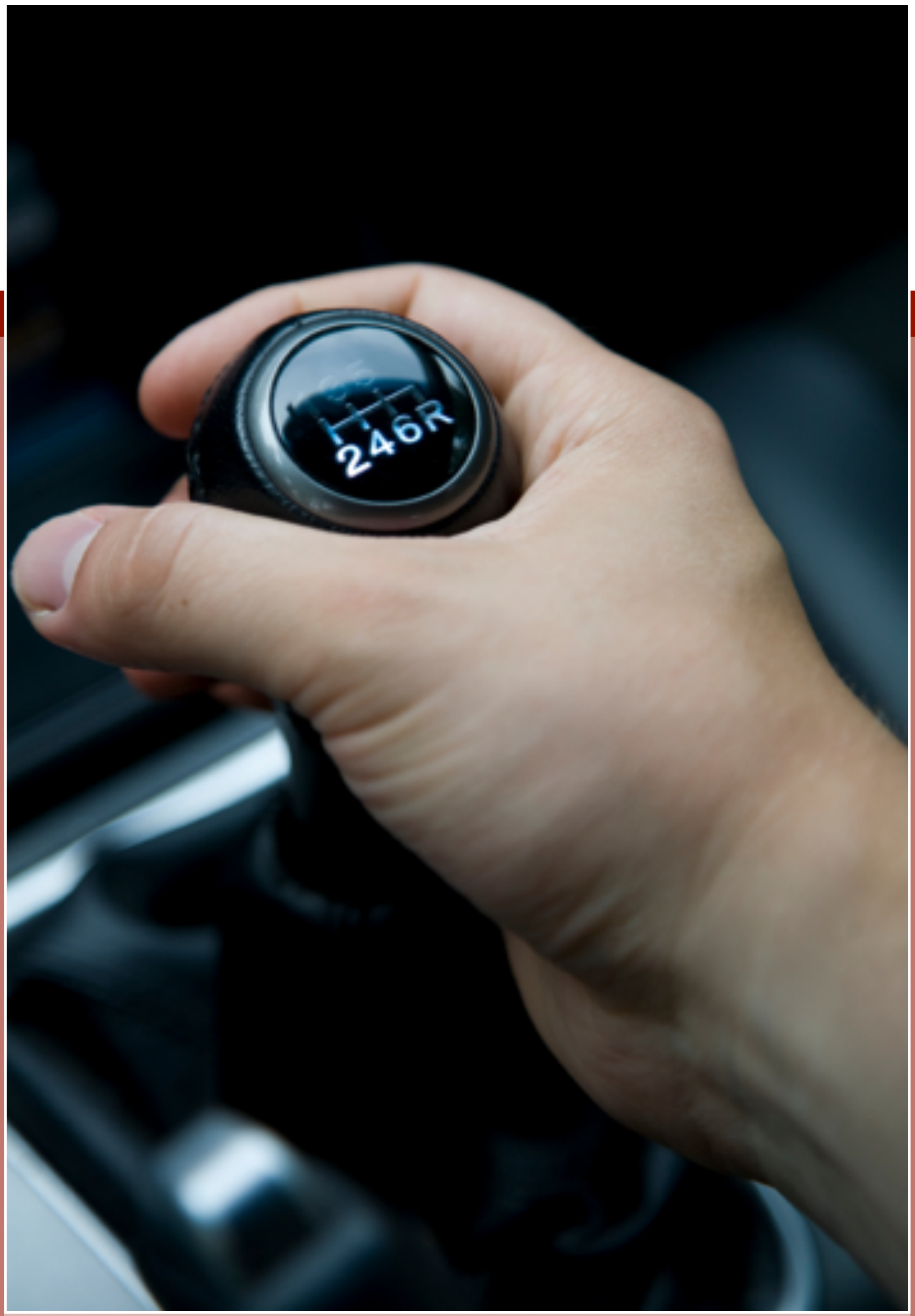
symbol:	*d*
charge:	–1/3
mass:	4.1 to 5.8 MeV/c^2
spin:	1/2
category:	Fermion, I=–1/2, B=1/3, S=0

particle: **strange quark**

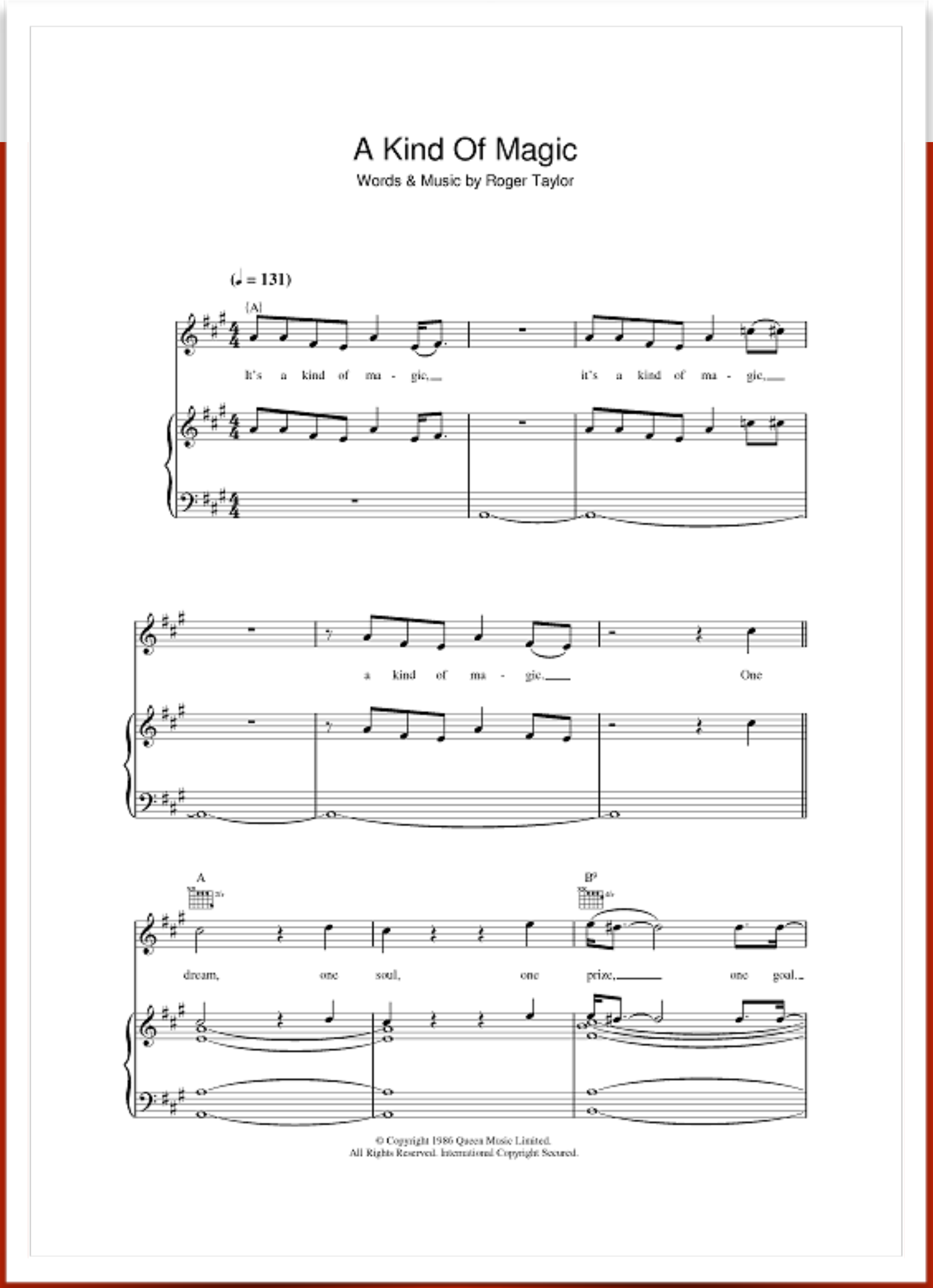
symbol:	*s*
charge:	–1/3
mass:	101 MeV/c^2
spin:	1/2
category:	Fermion, I=–1/2, B=1/3, S=–1

shifting gears

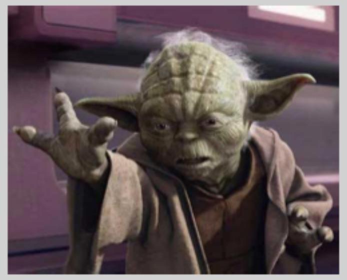
the weak interaction needs a boson



the quantum relativistic field theory

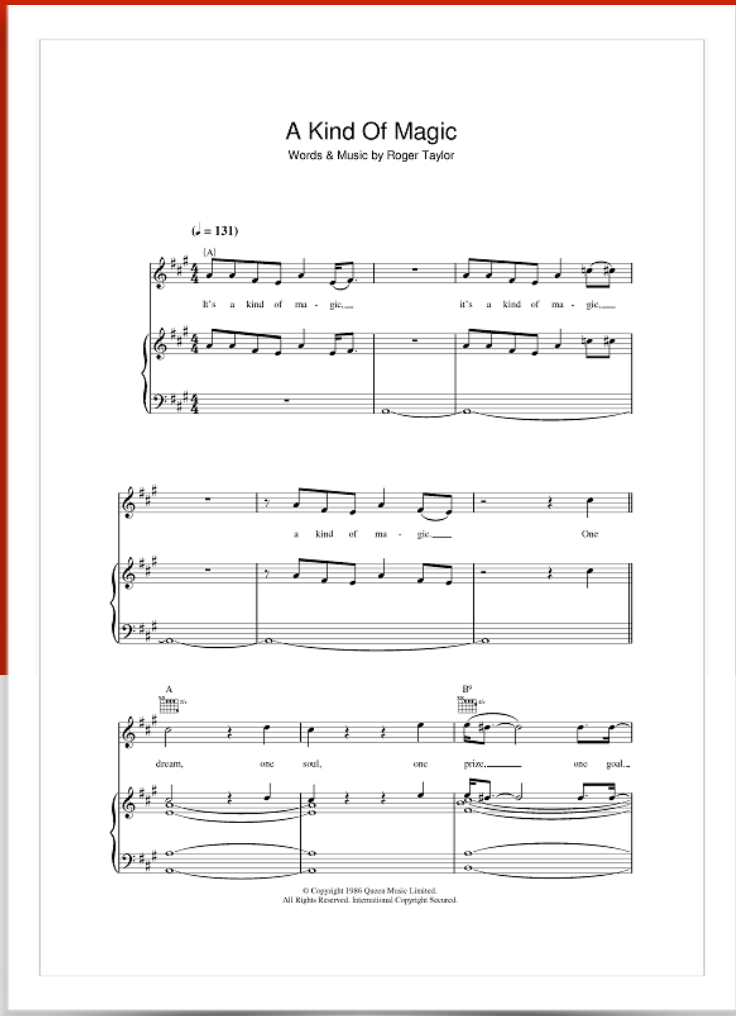
theme song:

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.



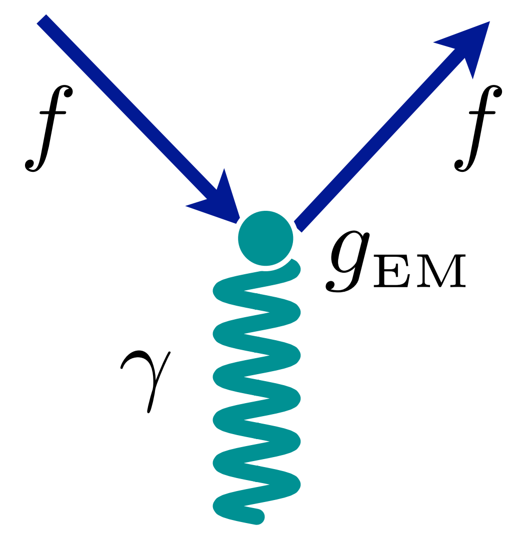
for the electromagnetic interaction:

the force is the electromagnetic force

the field is E & B

the clumpiness – the quantum – is:

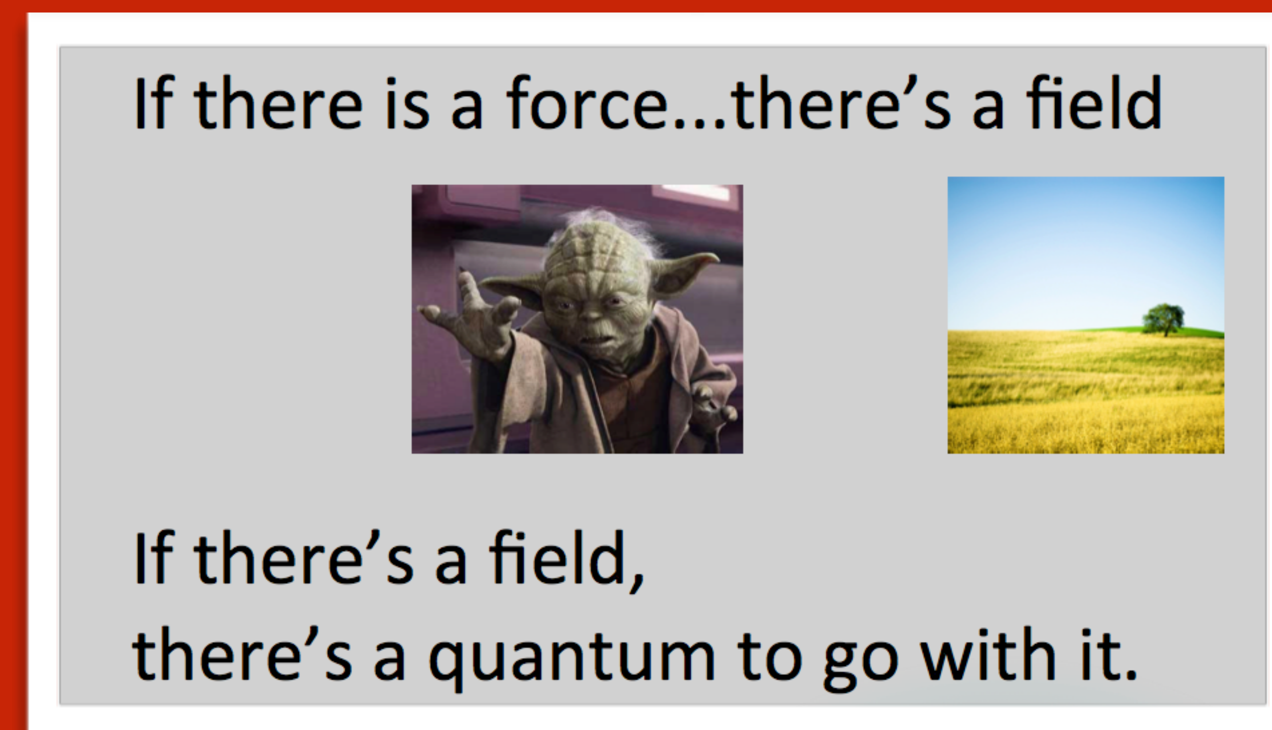
The photon: γ



Well, the Weak Force

must have a field

…yadda yadda yadda



Because Nature is Clumpy.

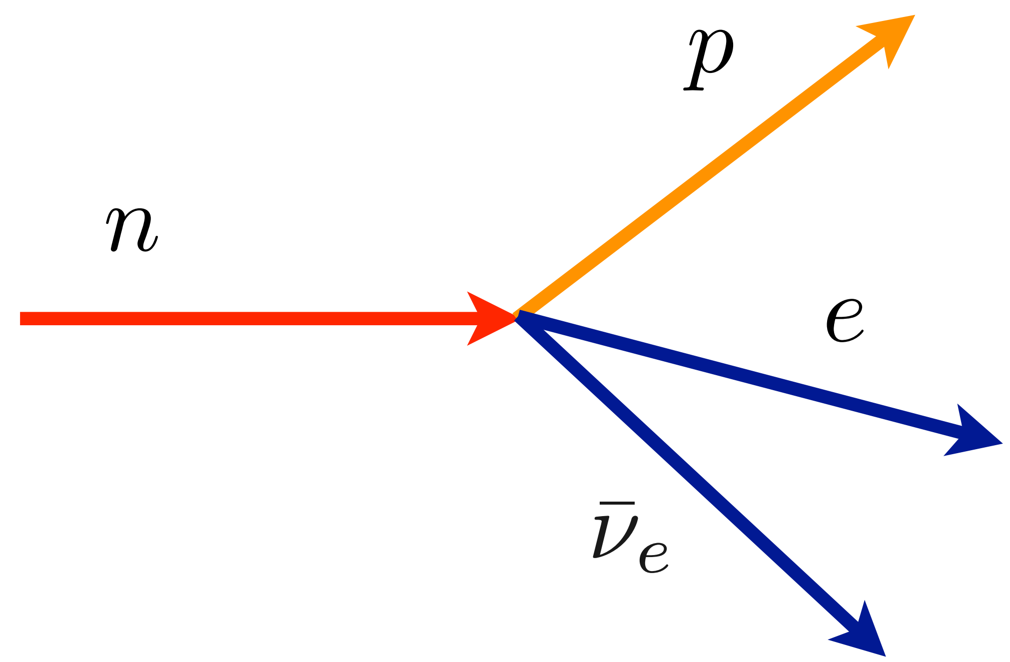
for weak interaction:

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

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

here's a weak interaction

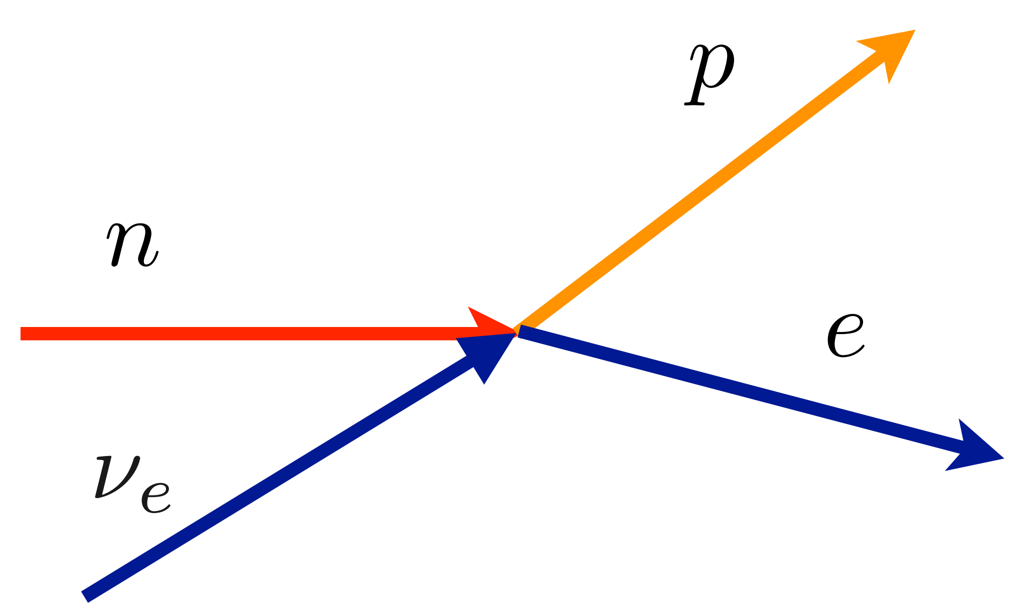
neutron beta decay



changes electric charge

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

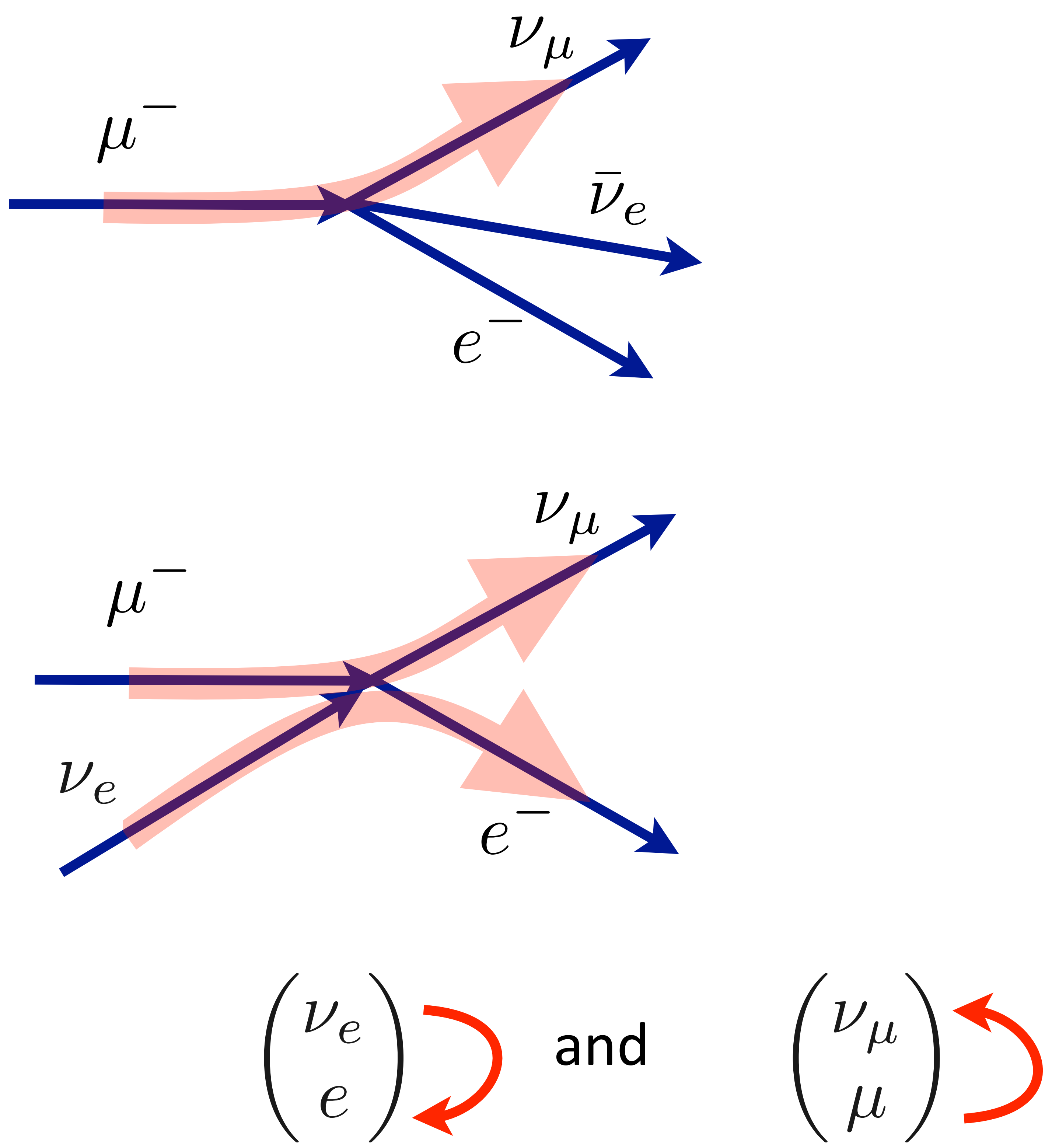
Manipulate the graph in the now familiar way:



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

the muon decay is the same sort of

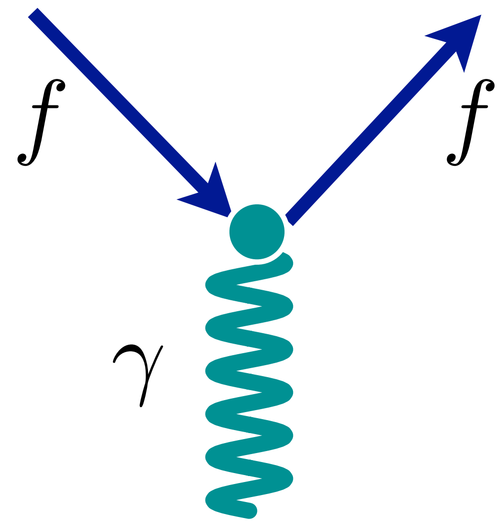
in that second way of looking at it:



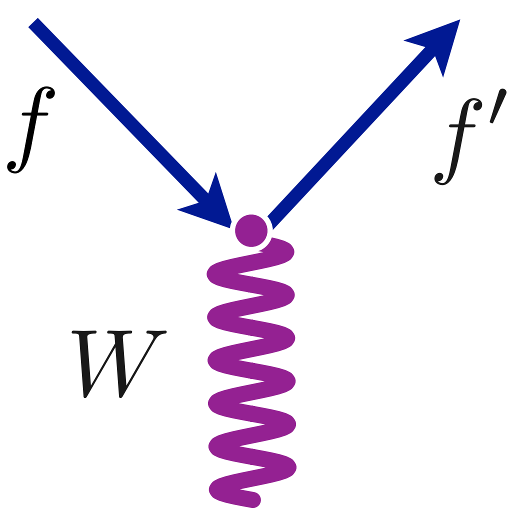
do it again?

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.



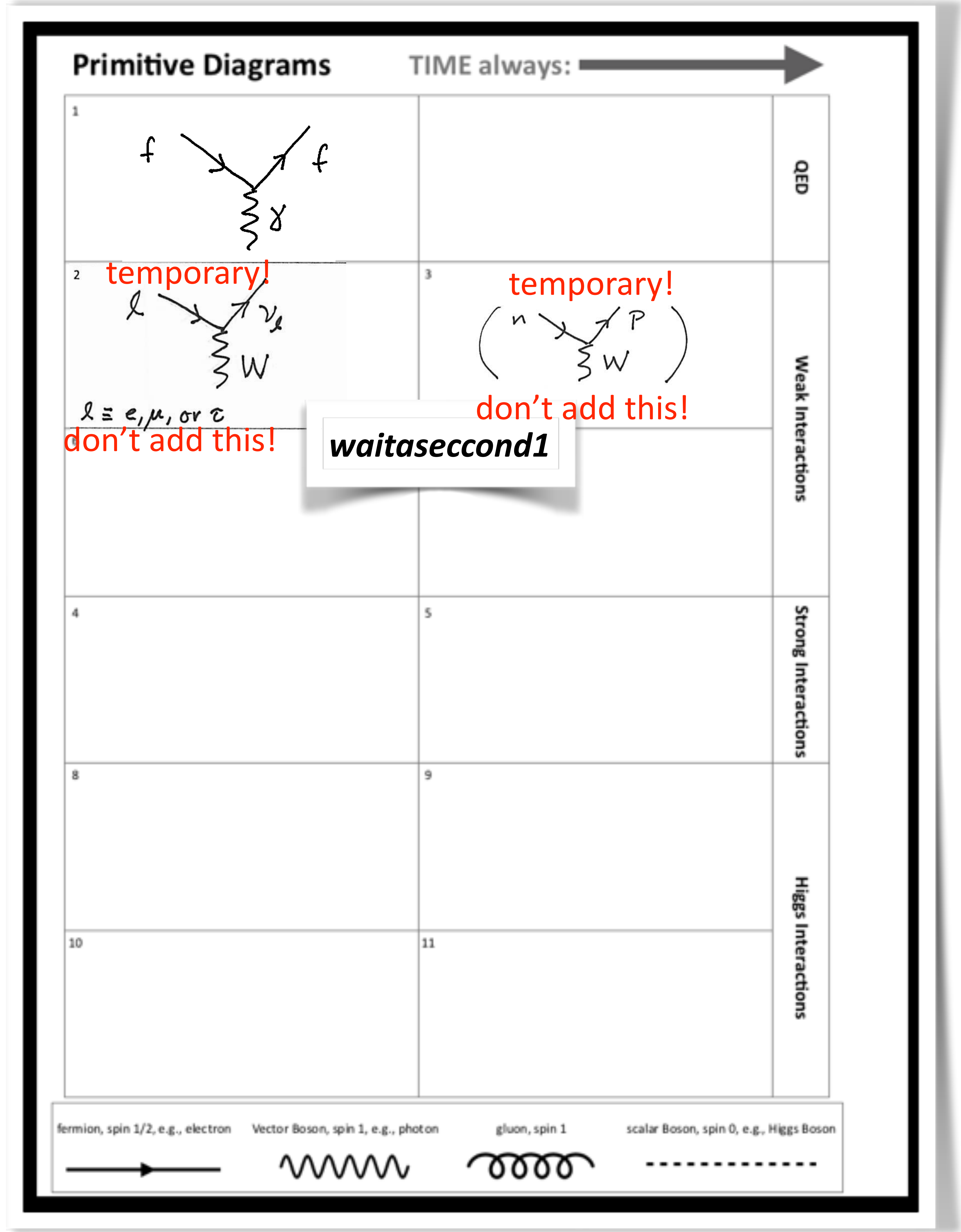
Feynman and Murray Gell-Mann worked out a consistent theory based on the idea of a “heavy” photon with electric charge.

“W” for “Weak”

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

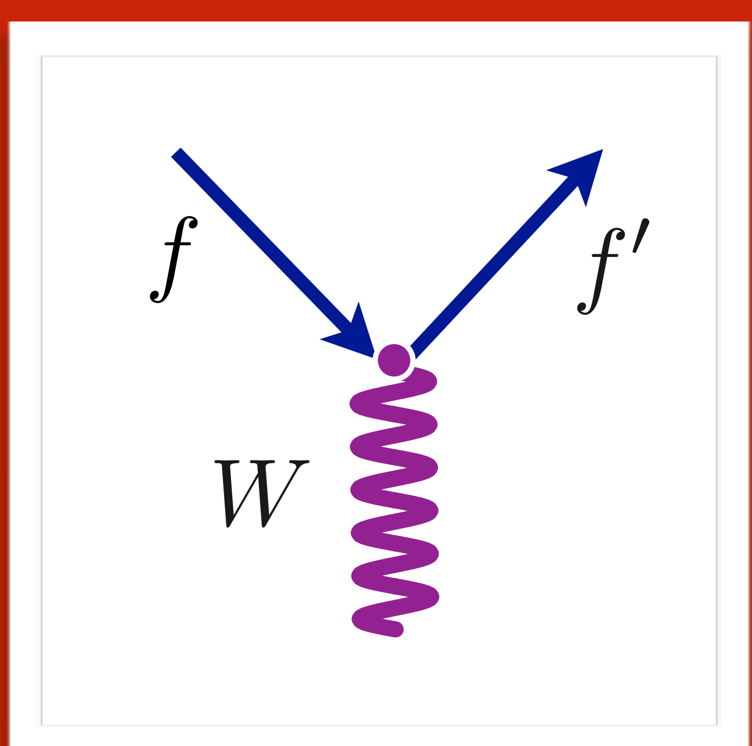
temporary entries into your

table of primitive diagrams



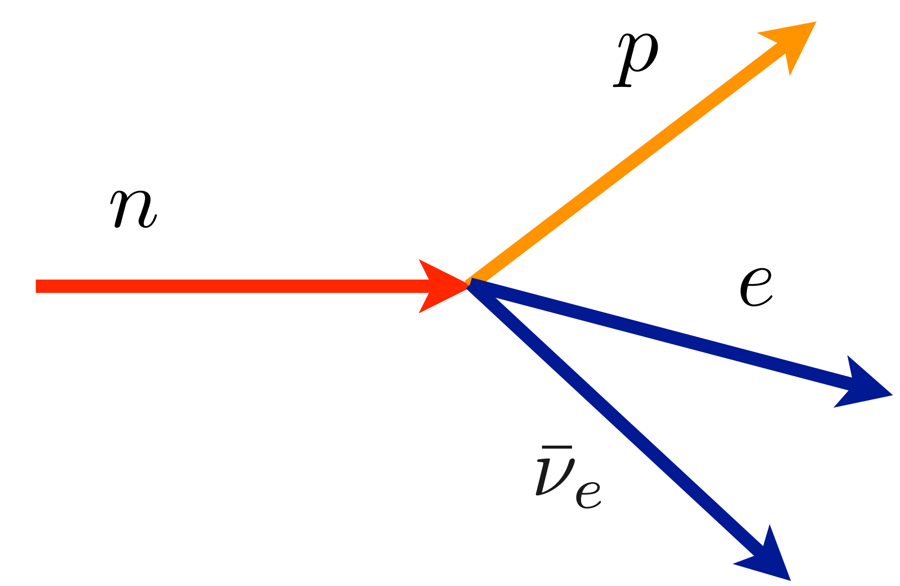
so, a new primitive diagram

for the Weak Interaction

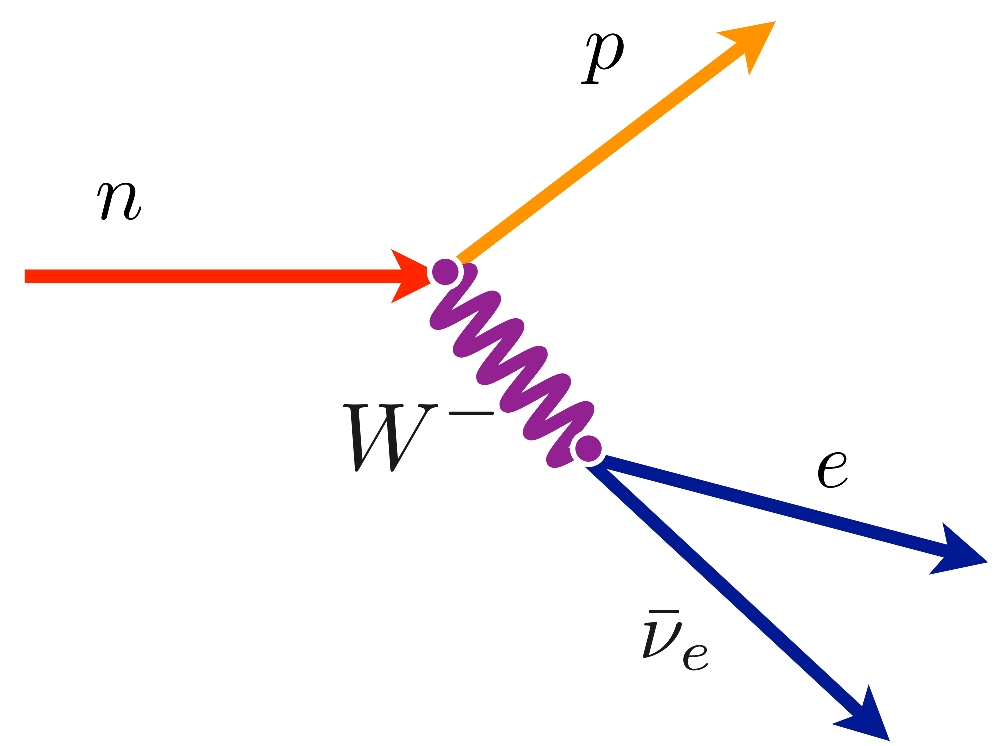


pretend this is primitive for a moment.

Neutron beta decay:

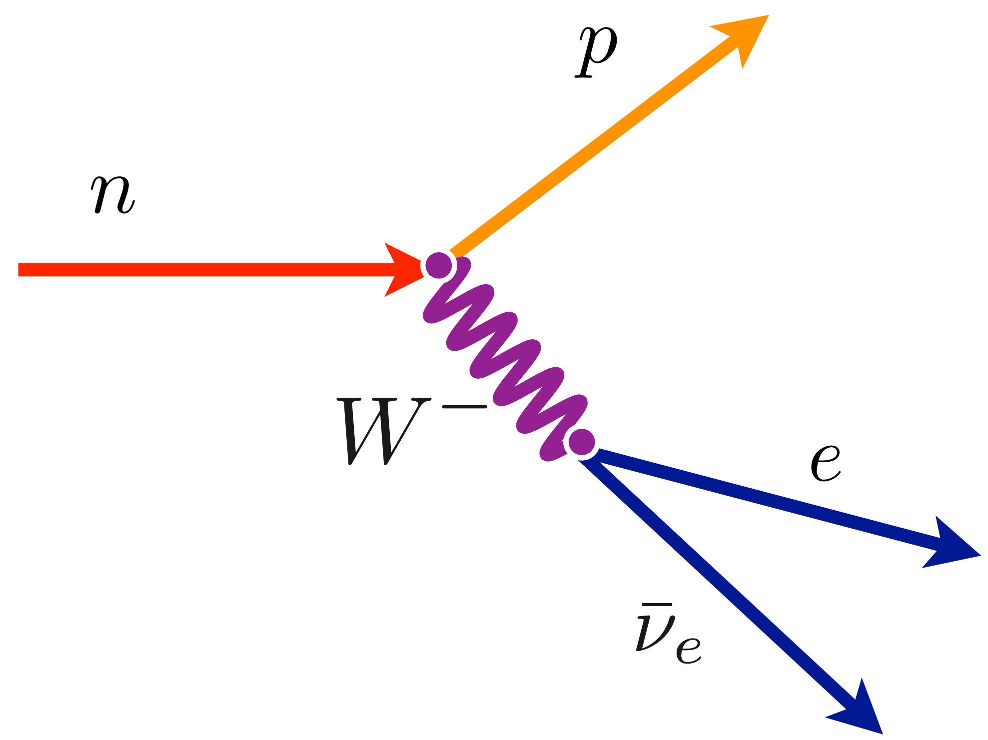


becomes:



keep track of the charge flow

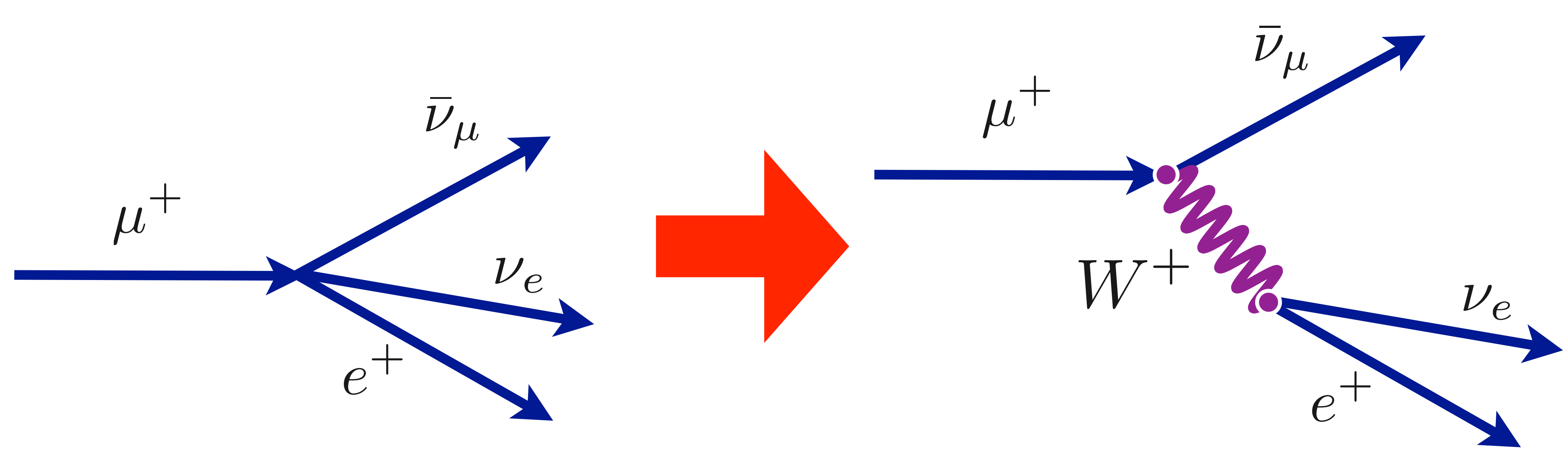
there are 2 W charged states



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

Q: 0 = +1 + −1 = +1 + −1 + 0 = 0

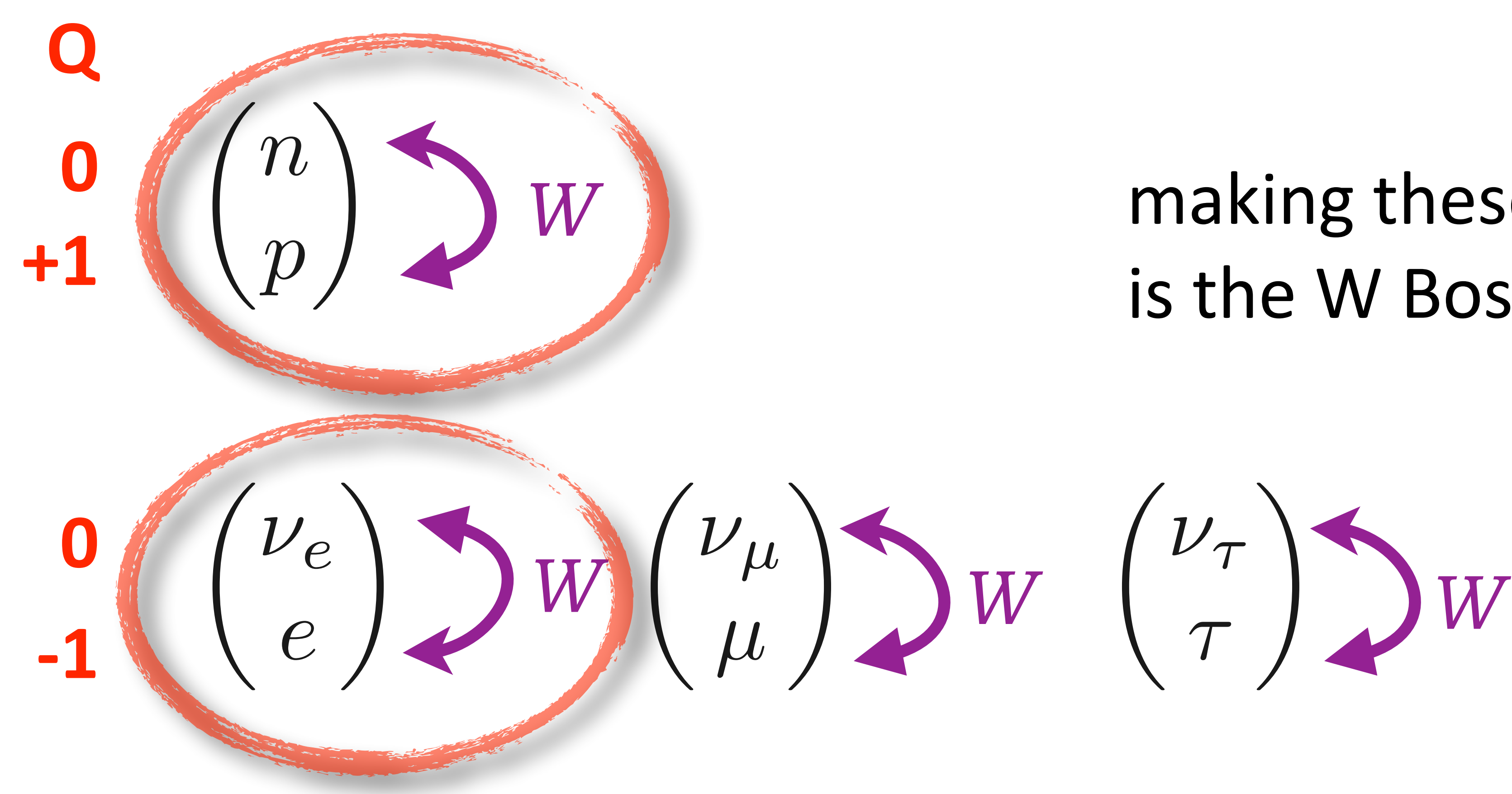
So: W^- lowers the electrical charge by 1
W^+ raises the electrical charge by 1



here is where those weak "doublets" come in

the Weak Interaction connects them

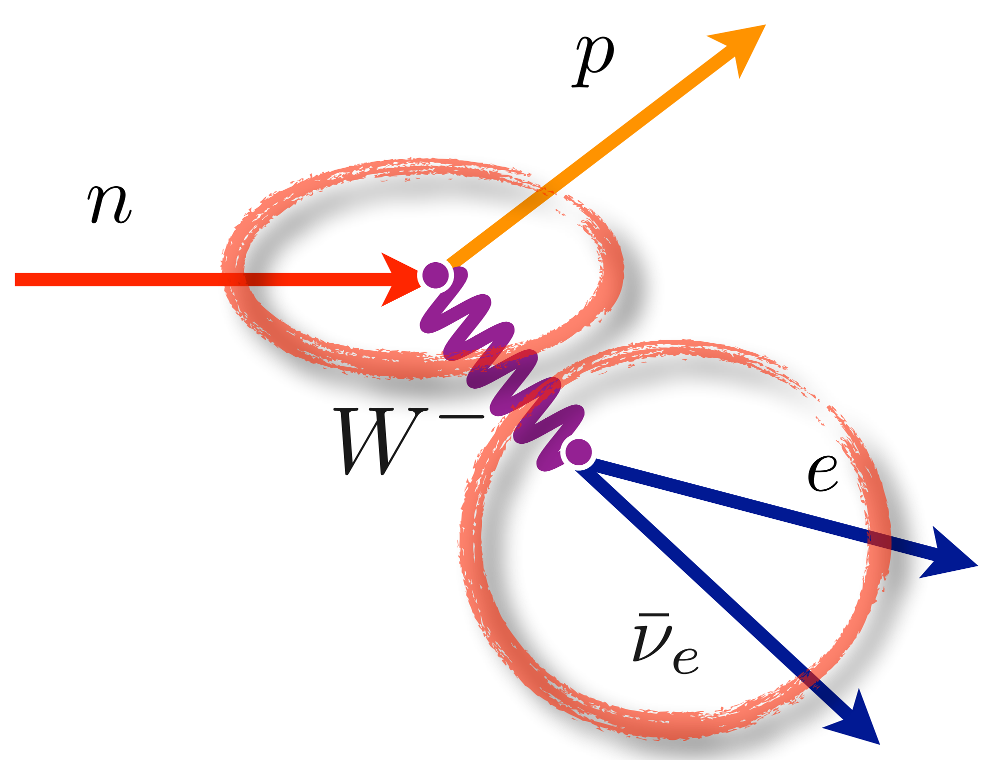
The particle doublets that we know so far:



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

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"

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

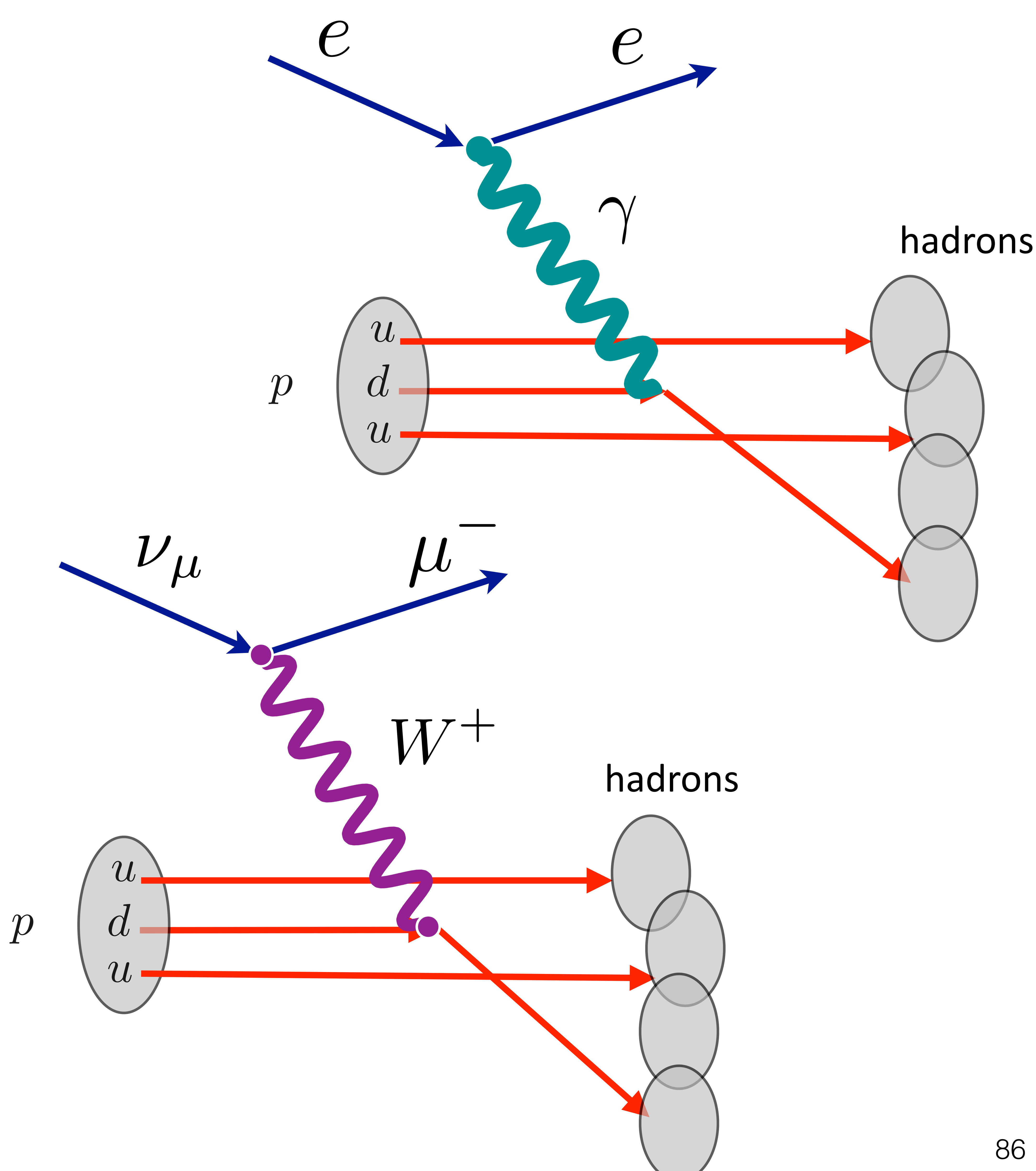
$$\ell = e, \mu, \tau$$

“deep inelastic scattering”

hitting quarks individually

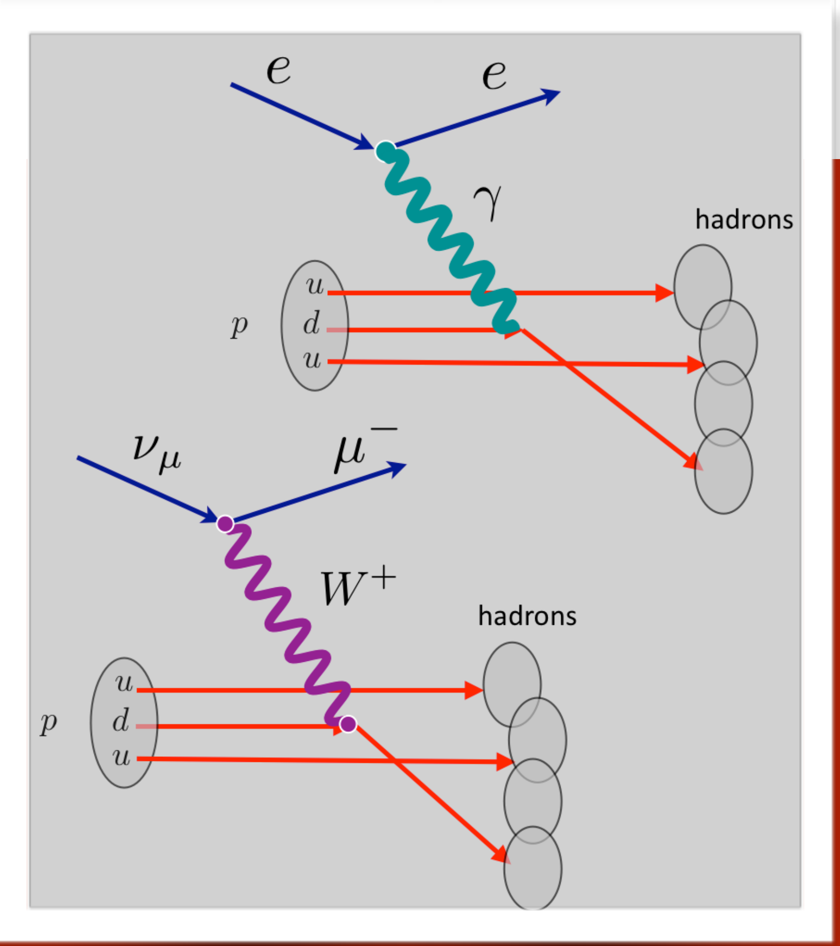
of course in a statistical fashion

neutrinos do it too…



analyses of these reactions,

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



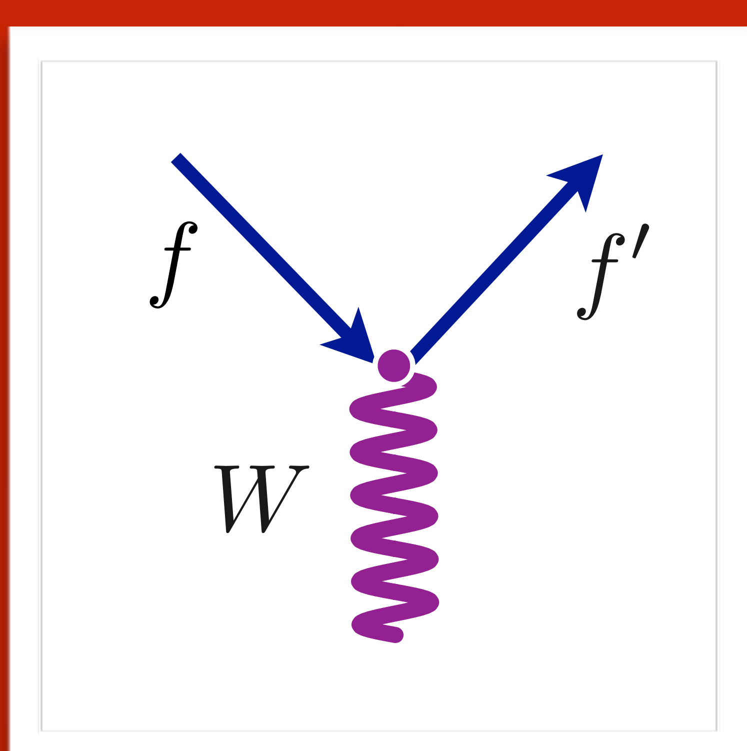
confirm the point-like (?) nature of quarks

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

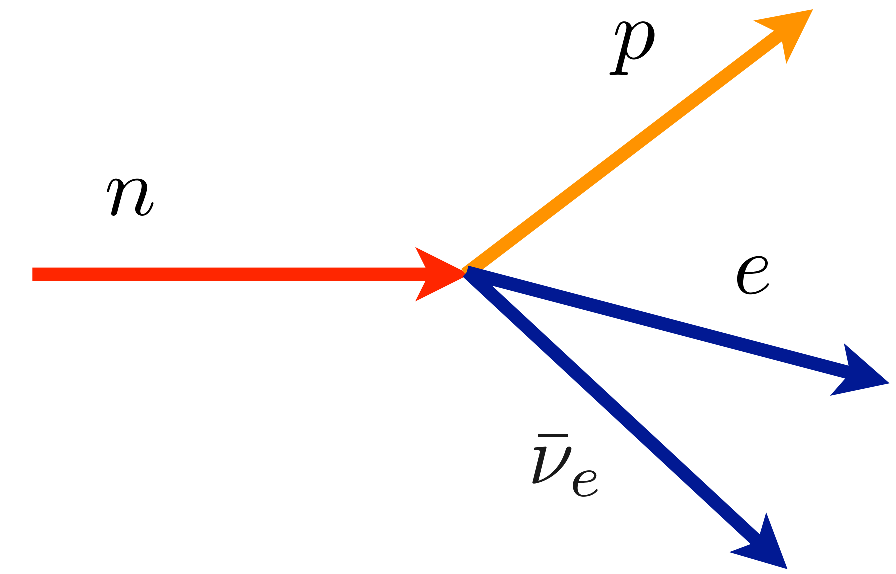
confirm their fractional electric charges!

so, a new primitive diagram

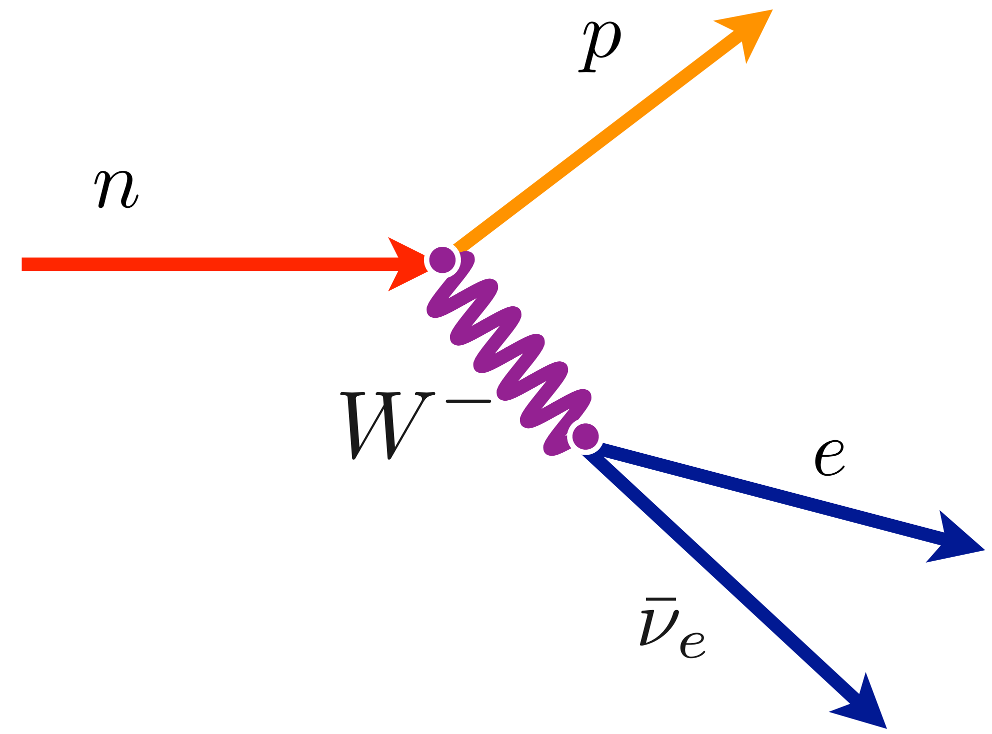
for the Weak Interaction with quarks, to go with the leptons



Neutron beta decay:

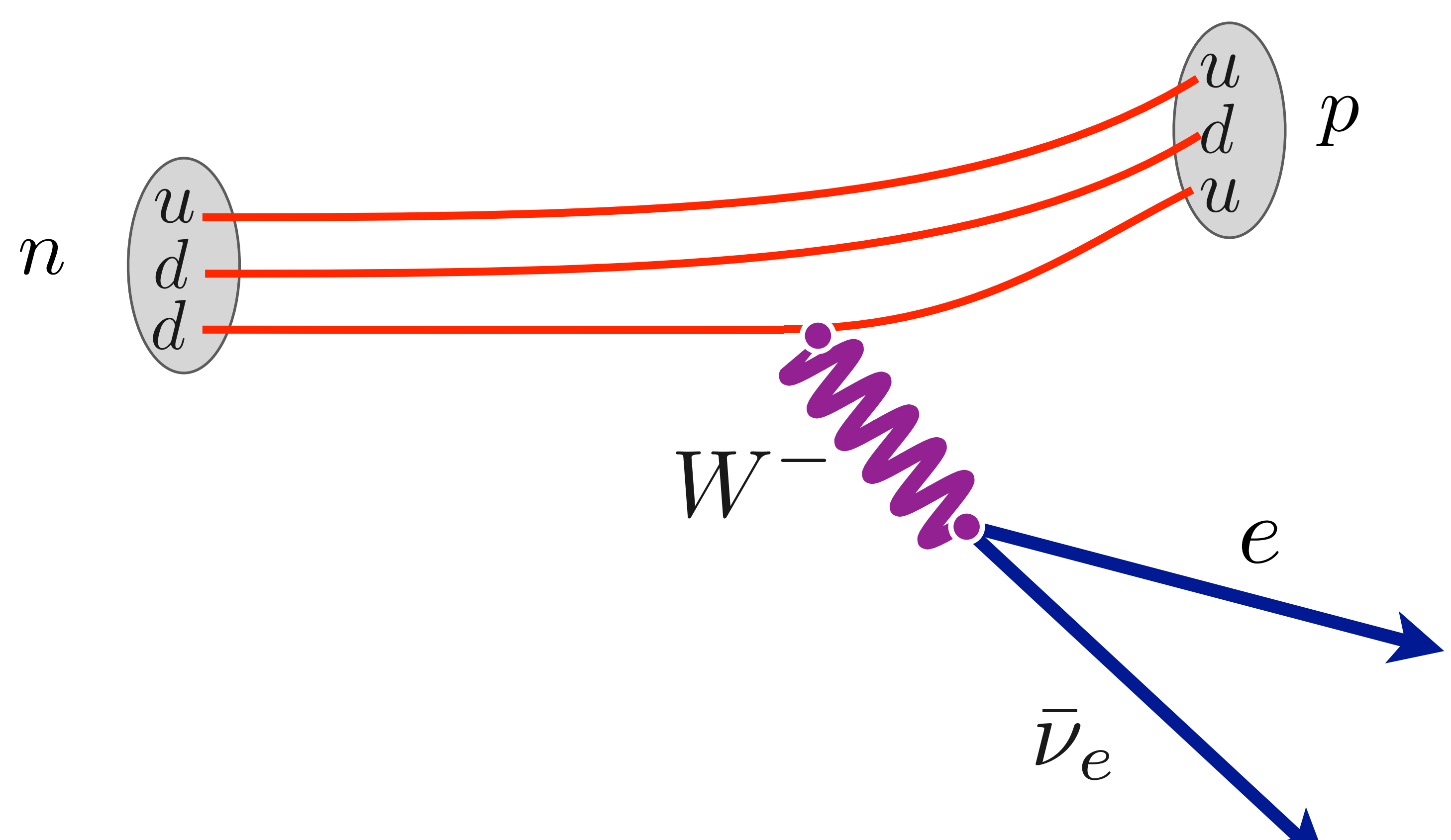


becomes:



and in the quark interpretation:

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

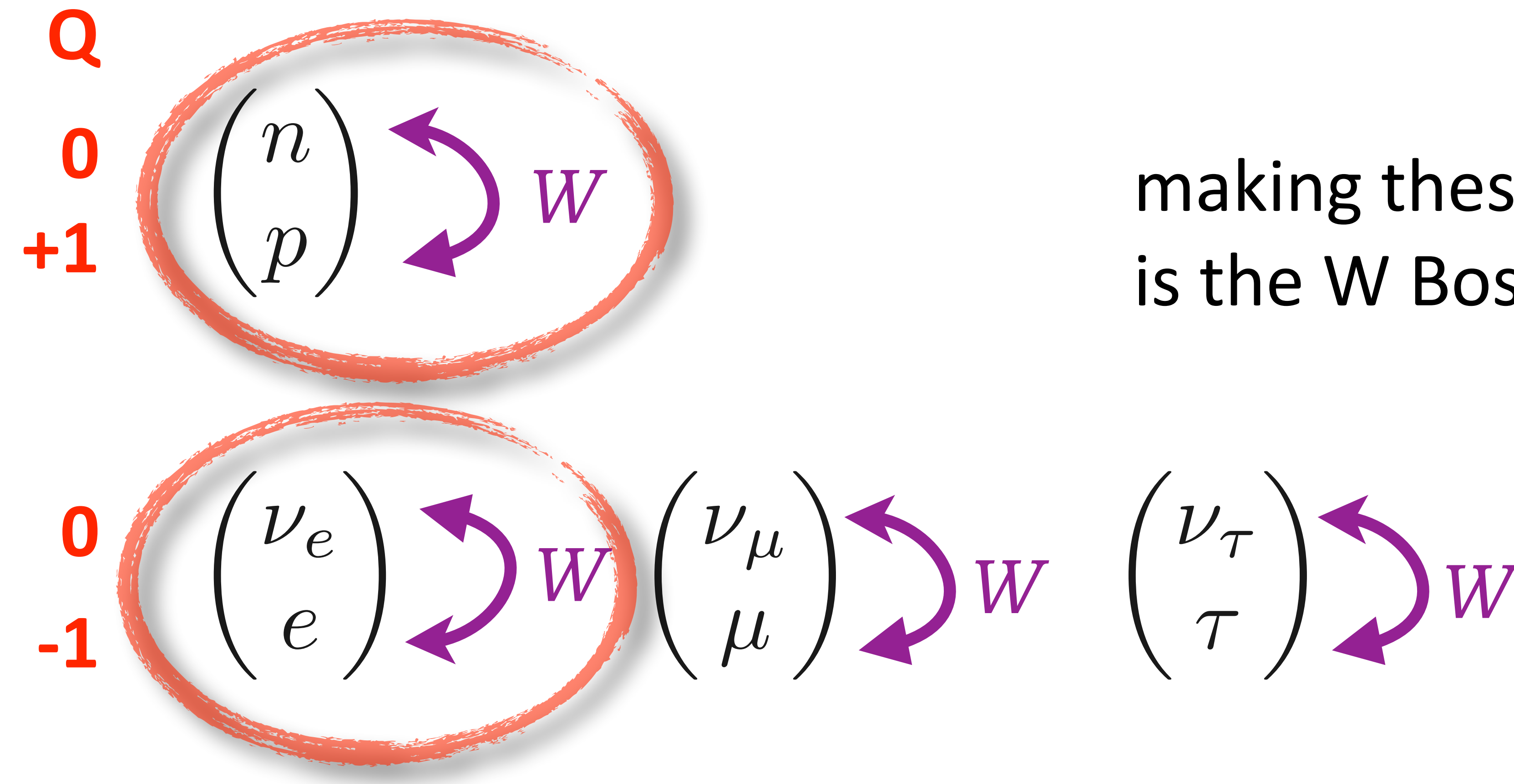


instead of what I had before:

there are still weak interactions

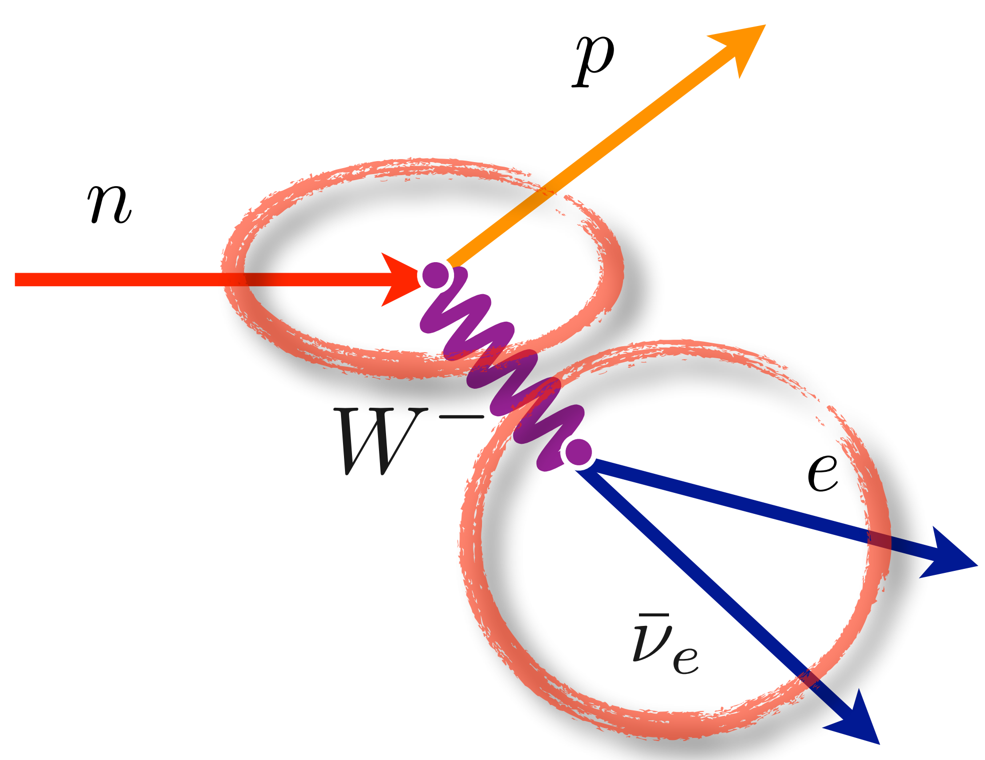
including transitions among quarks

The particle doublets that we know so far:

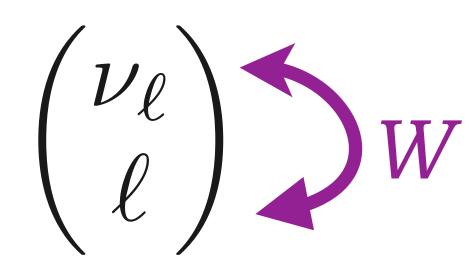


making these transitions is the W Boson's job.

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



call a generic lepton, "ℓ"



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

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

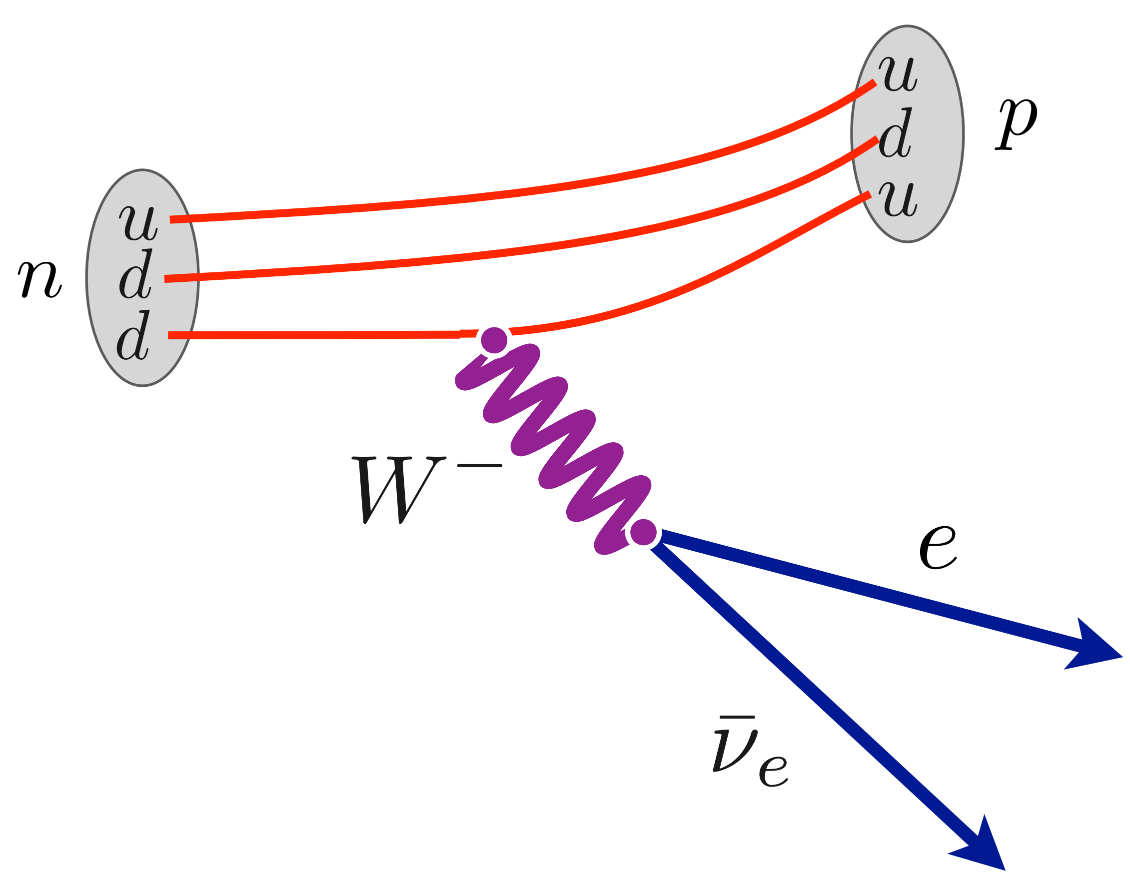
making these transitions is *still* the W Boson's job.

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"

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

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



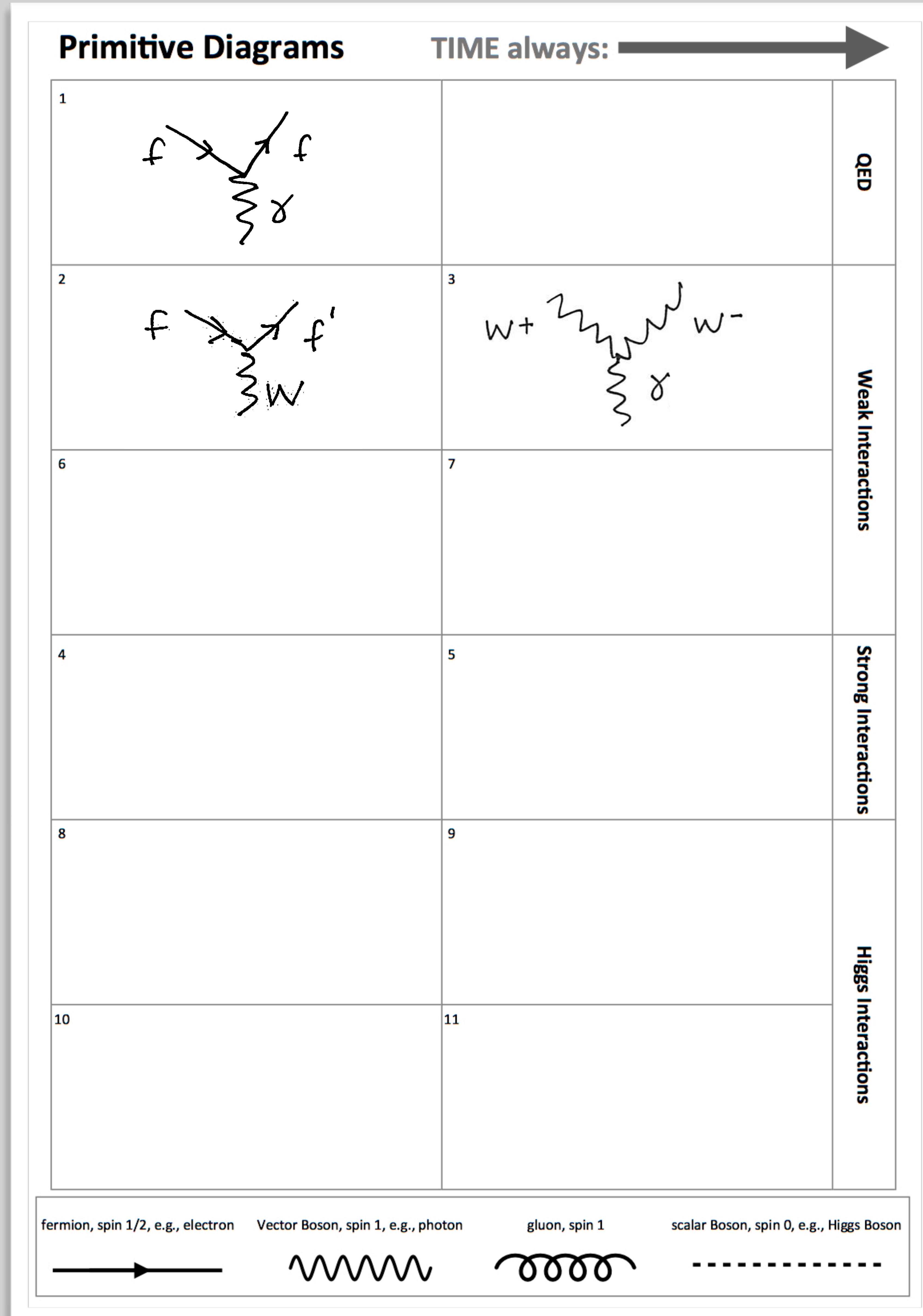
or:
call a generic fermion, "f"

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

$$f = \ell, q$$

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

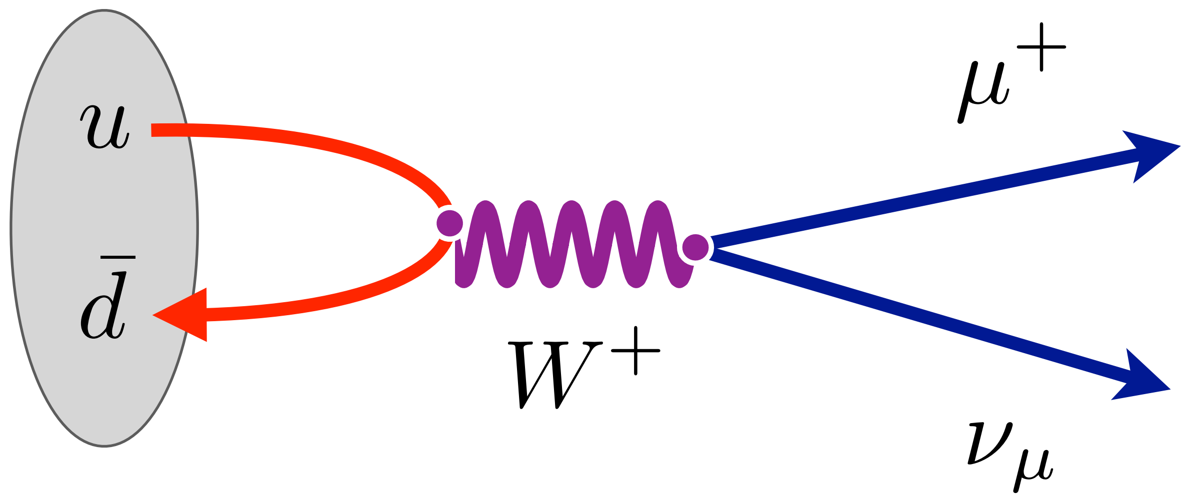
so, decays we've seen

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...

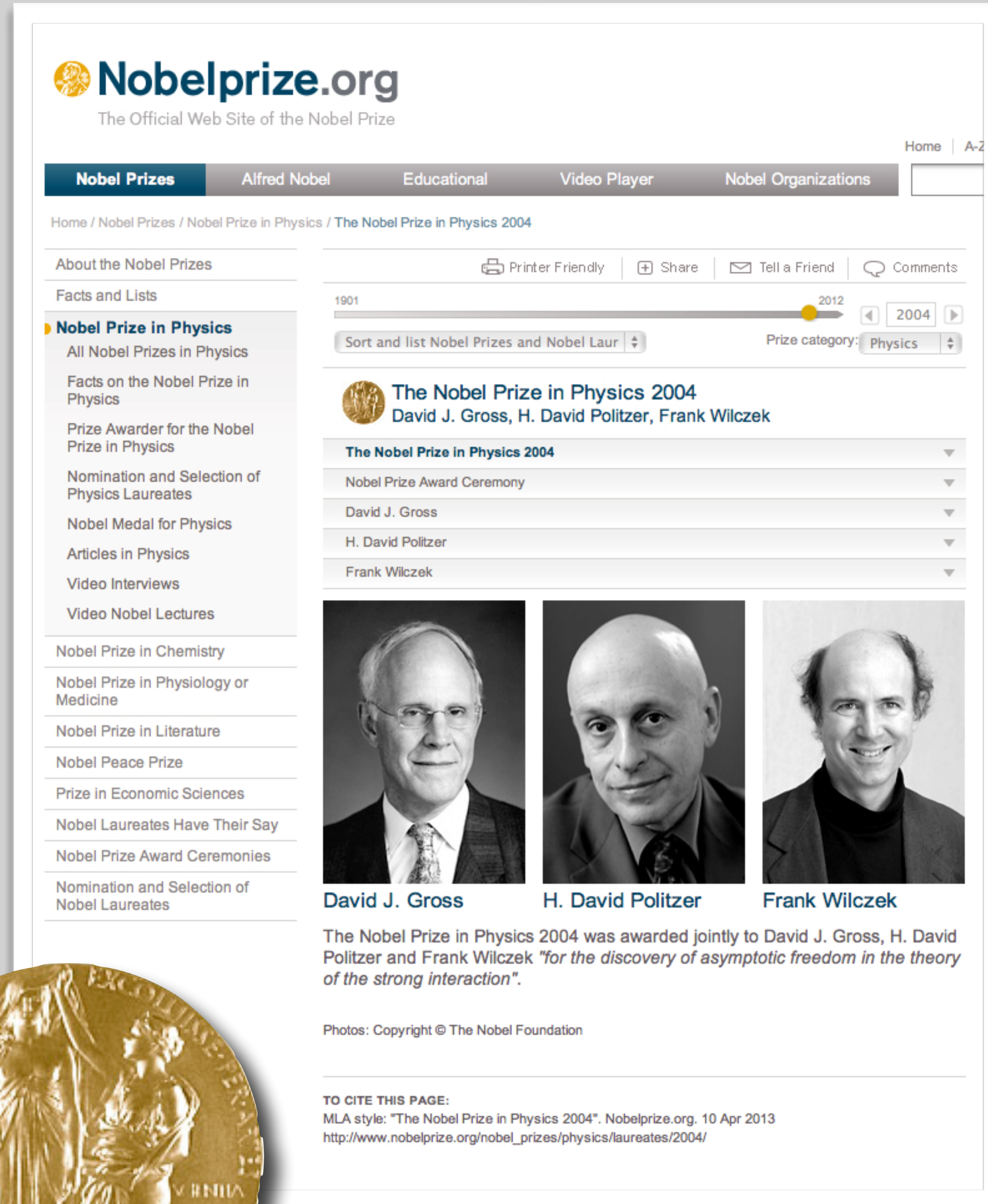
now in play for quarks:

what holds the quarks inside of the baryons and mesons?

Gross, Politzer, and Wilczek

2004

"asymptotic freedom" in strong interactions



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The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

- **The Nobel Prize in Physics 2004**
- Nobel Prize Award Ceremony
- David J. Gross
- H. David Politzer
- Frank Wilczek

David J. Gross | H. David Politzer | Frank Wilczek

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.

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http://www.nobelprize.org/nobel_prizes/physics/laureates/2004/

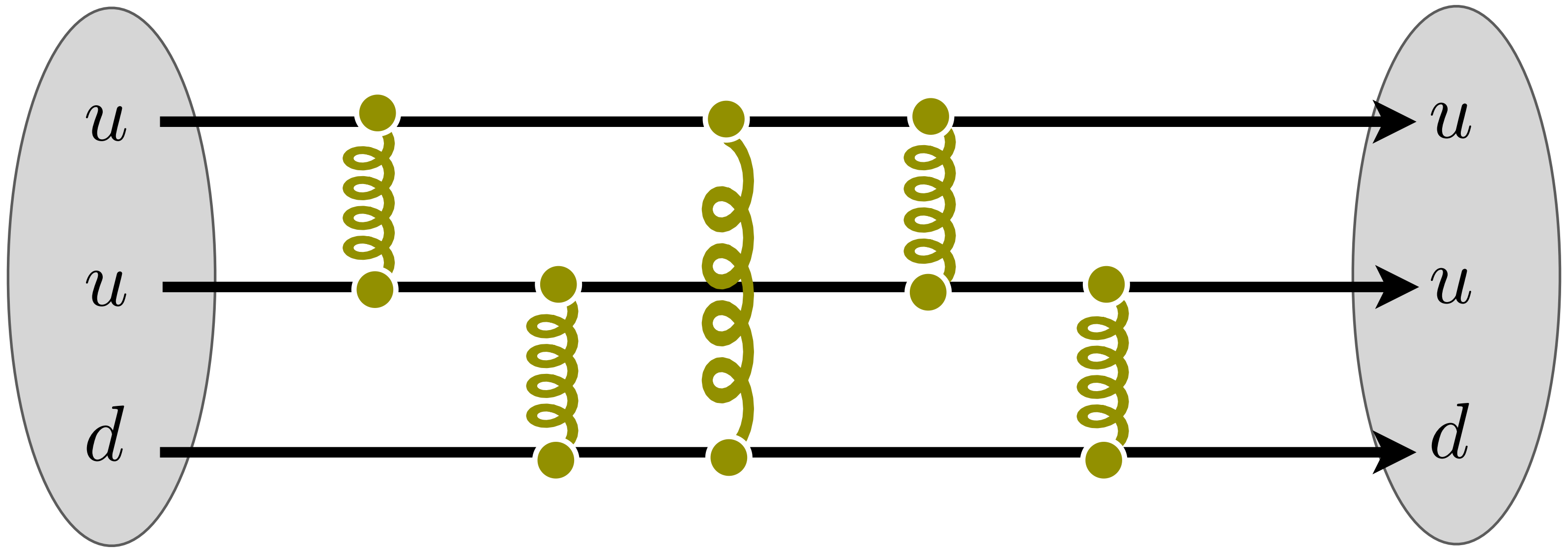
it's the glue that holds everything together

virtually

Predicted the existence of the Strong Messenger Particle:

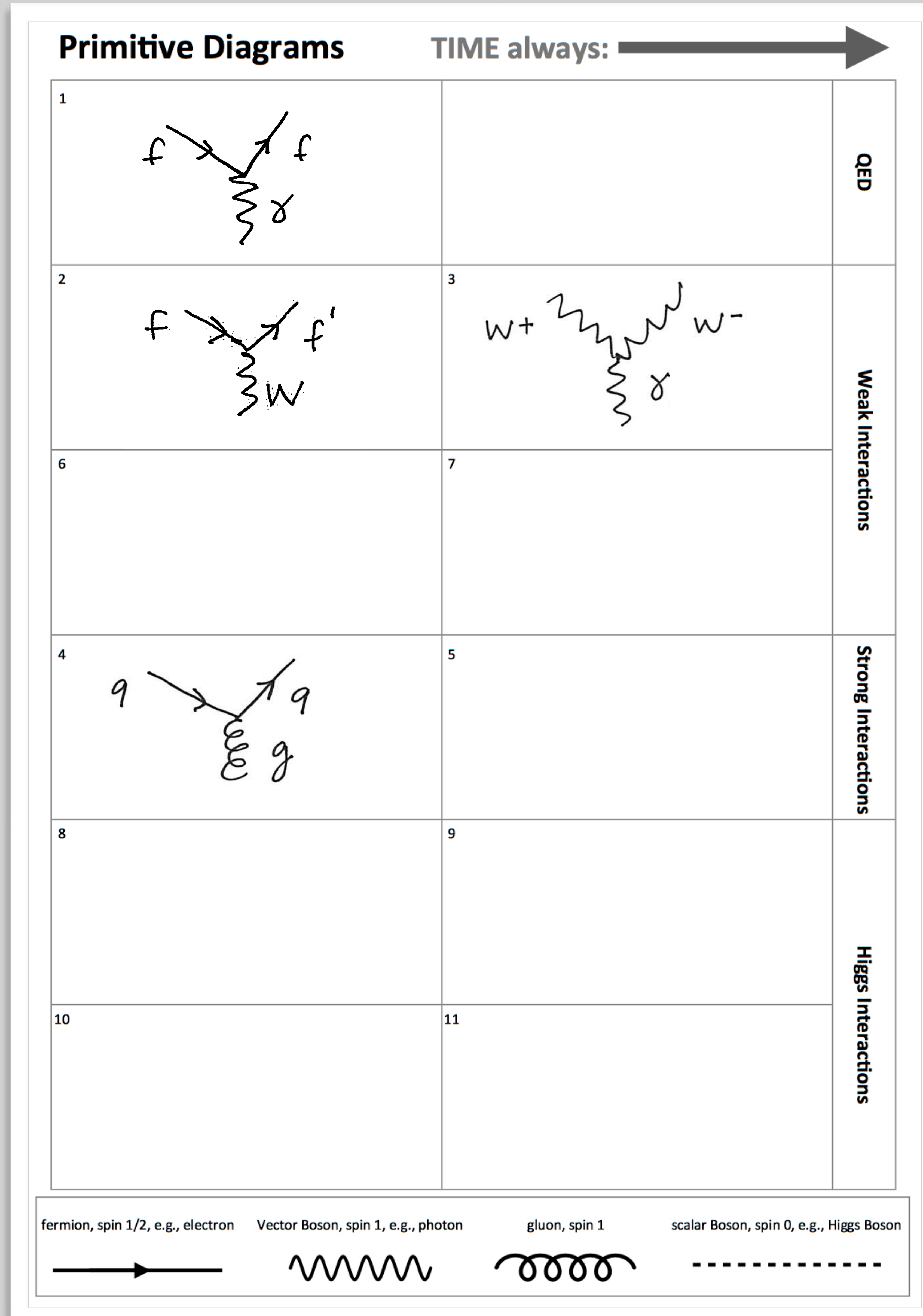
the Gluon

my gluon



third entry into your

table of primitive diagrams

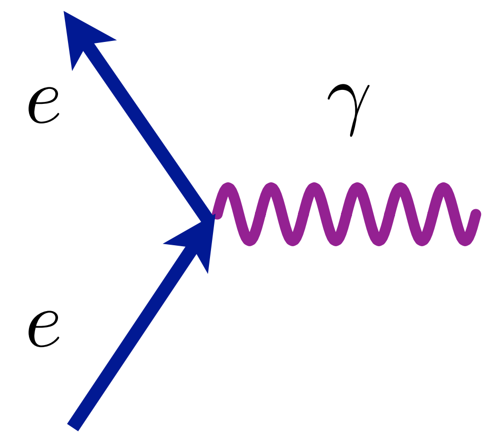


there are two amazing things

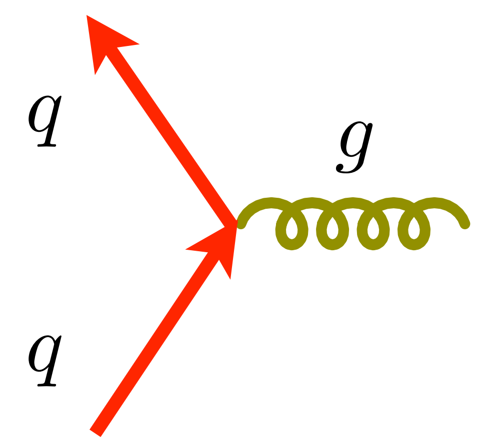
about gluons

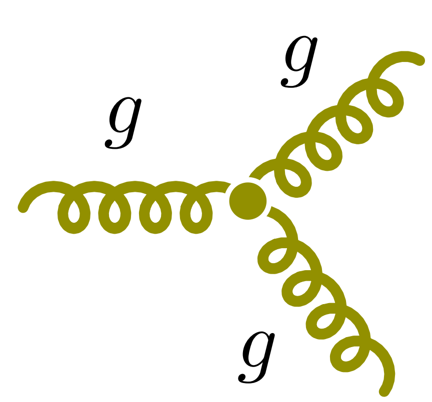
thing 1

they self-interact

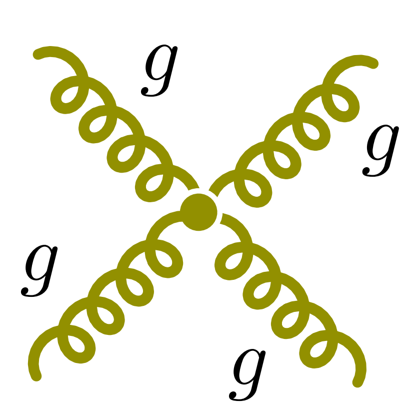


a photon propagates the electromagnetic force...but it does not have an electric charge



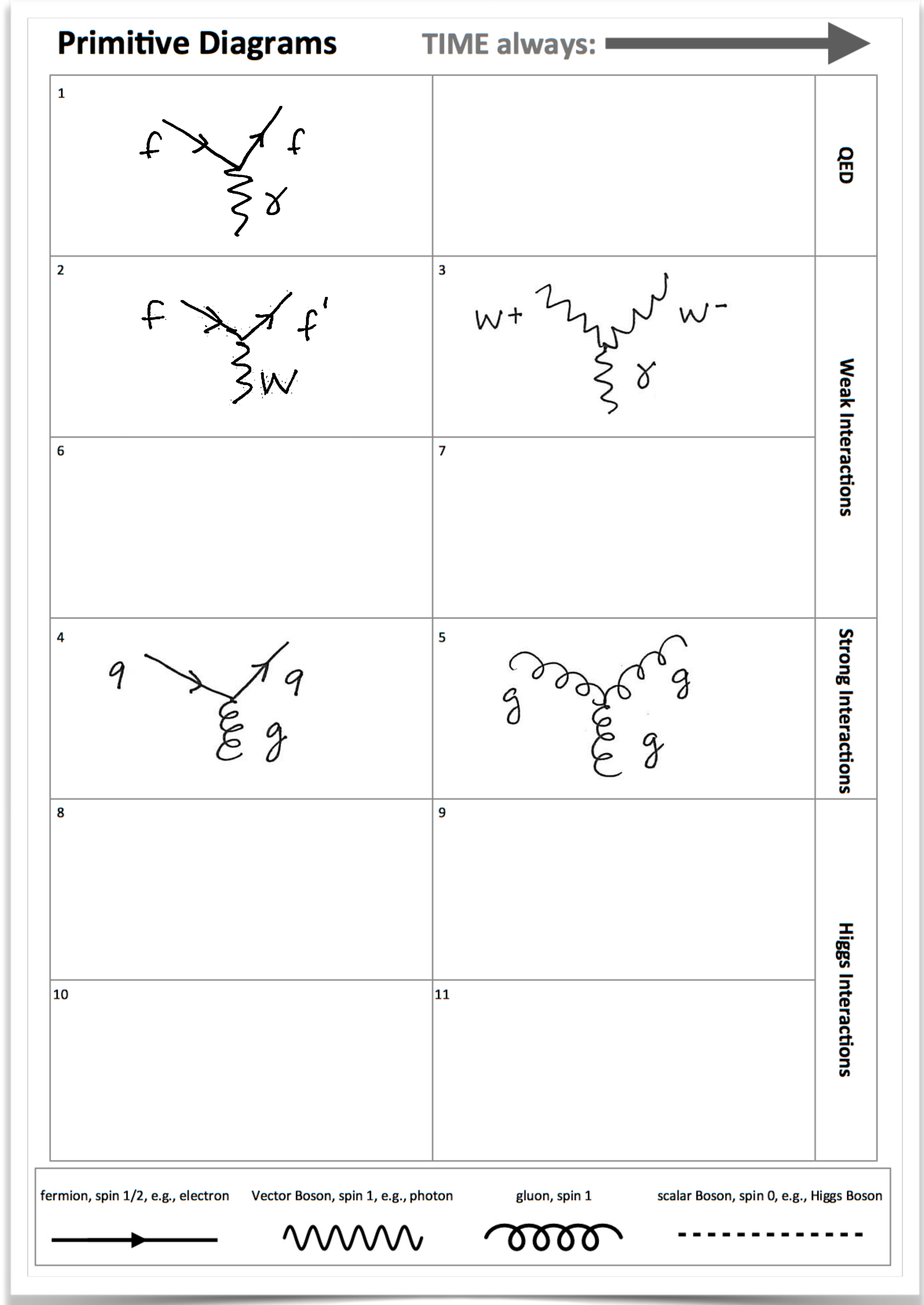


the gluon propagates the strong force...and it DOES have a “strong charge”



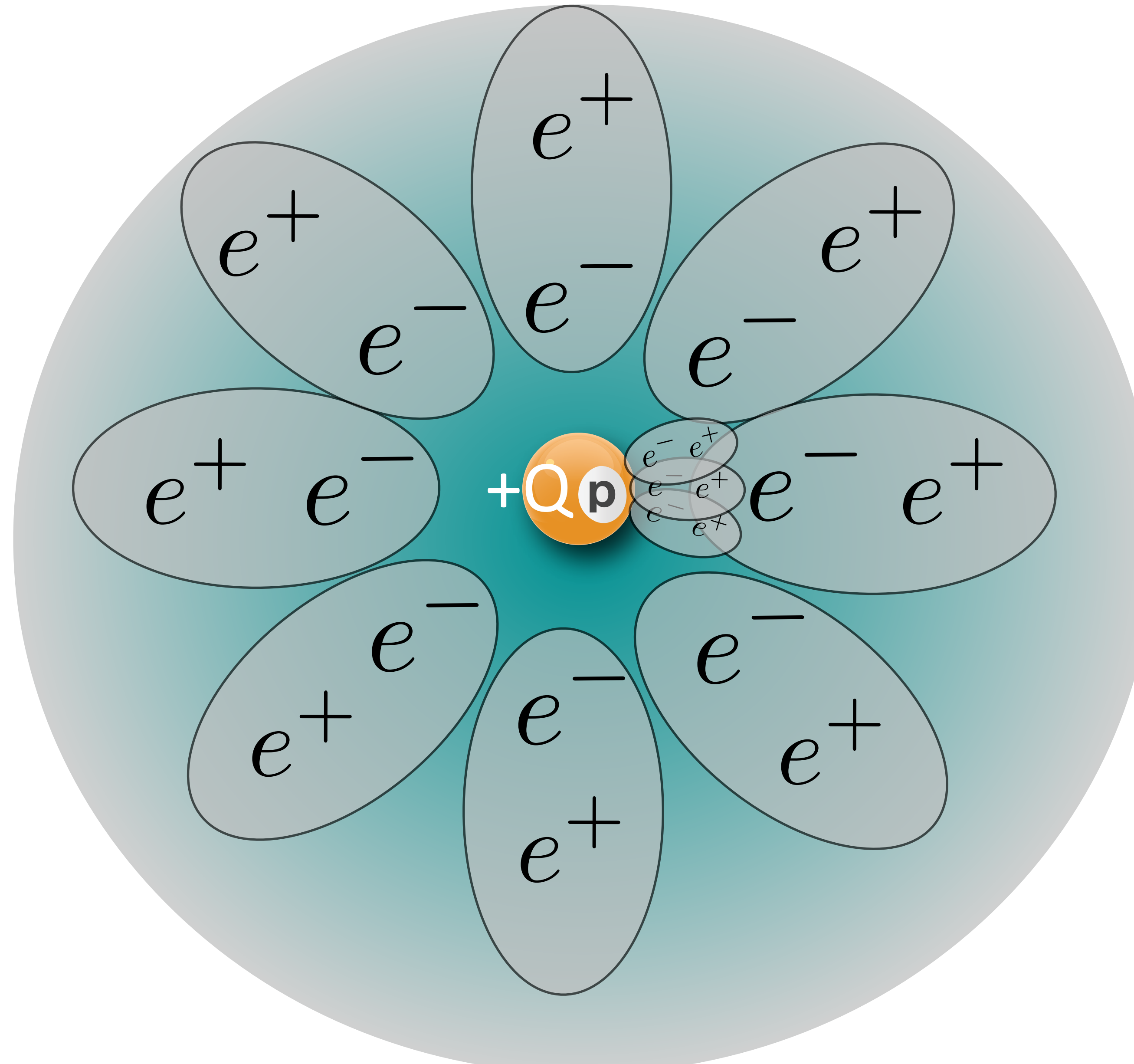
This has significant consequences...almost magical fourth and fifth entries into your

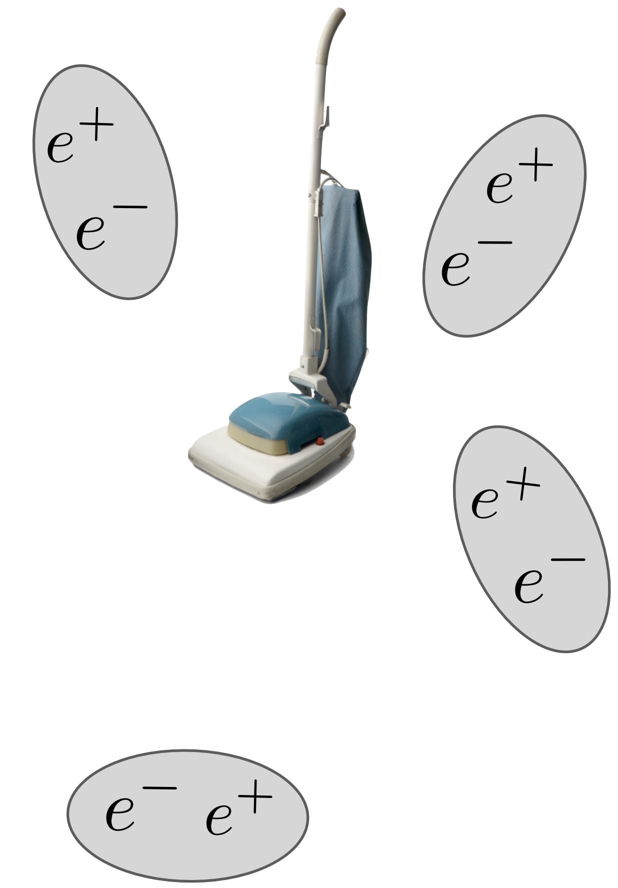
table of primitive diagrams

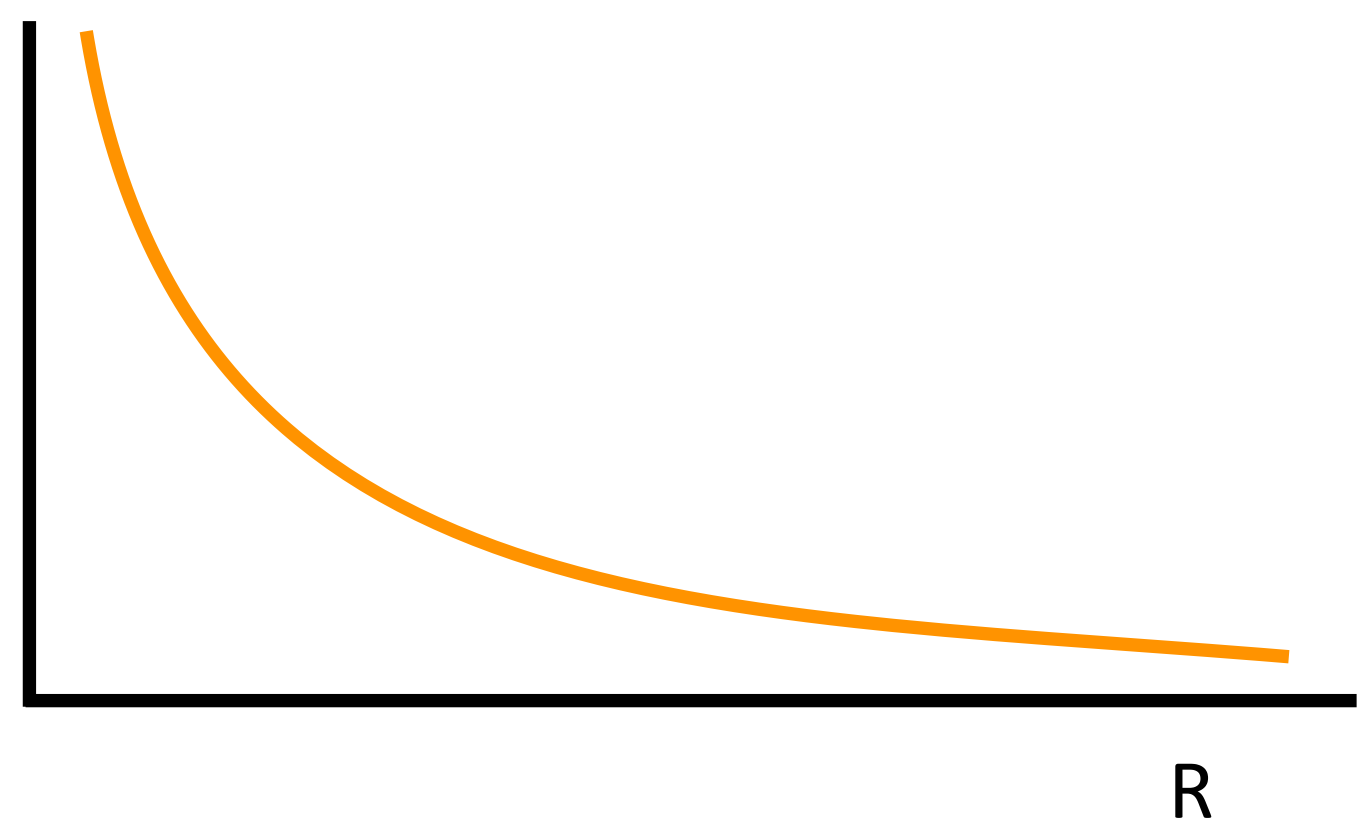


thing 2

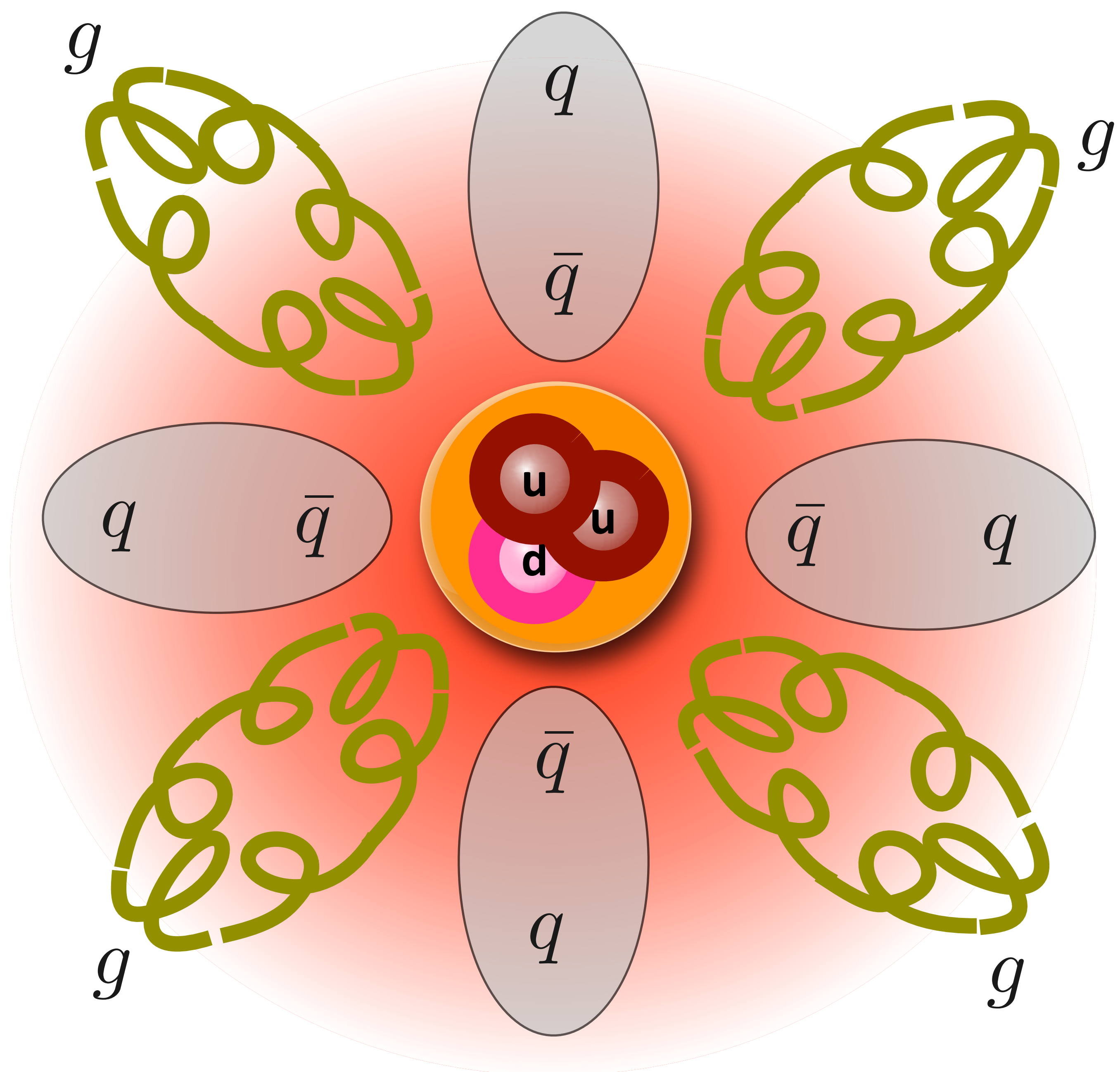
their force field is the opposite of electromagnetism, or gravity



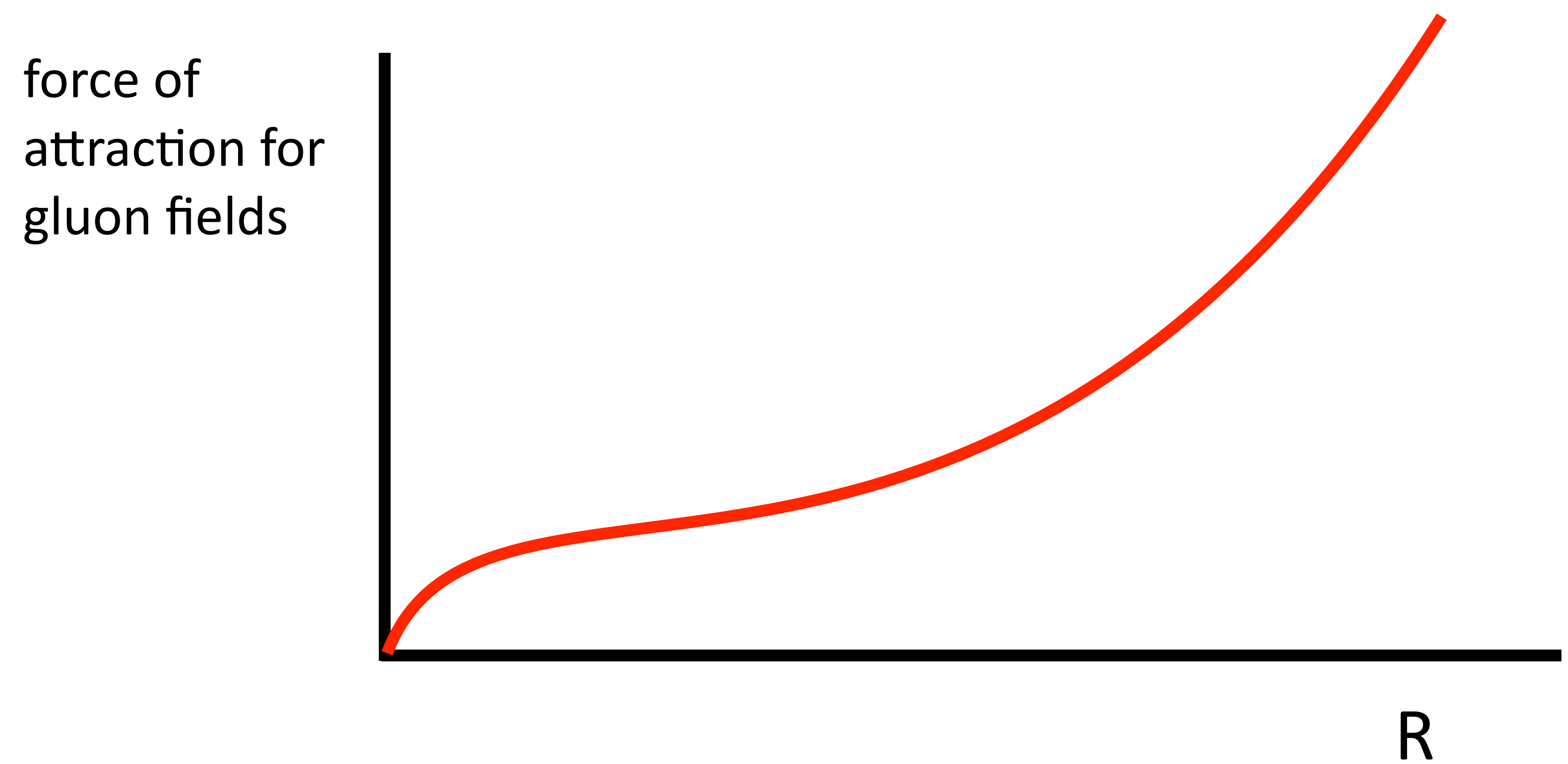




ah, but the gluon is odd



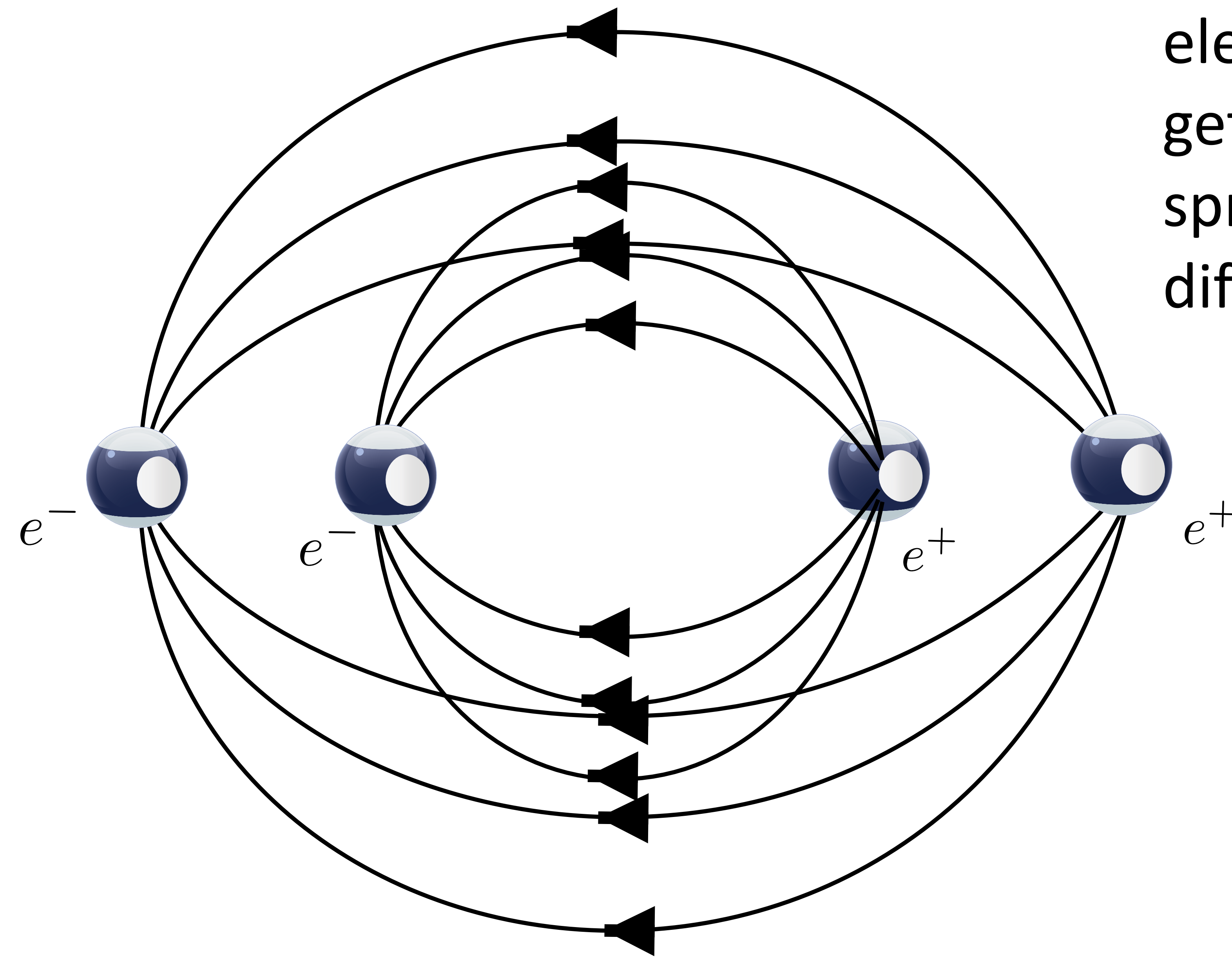
the further away you get, the **STRONGER** the quark-quark attraction is!



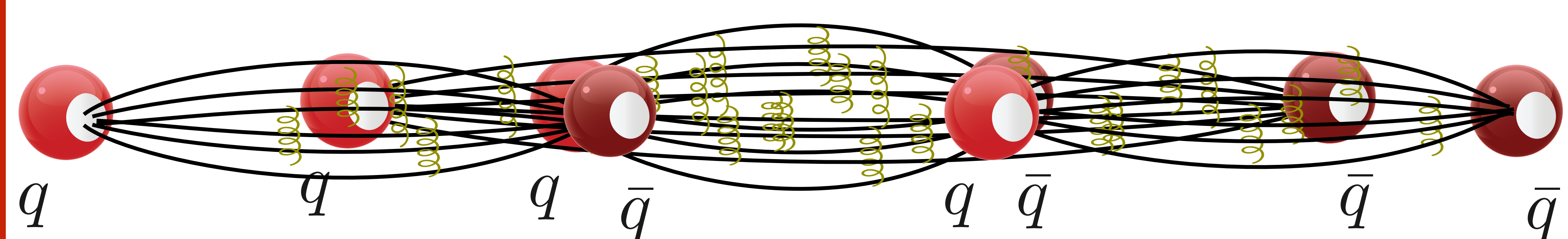
pull ‘em apart

called

quark confinement



electric fields get more spread out – diffuse



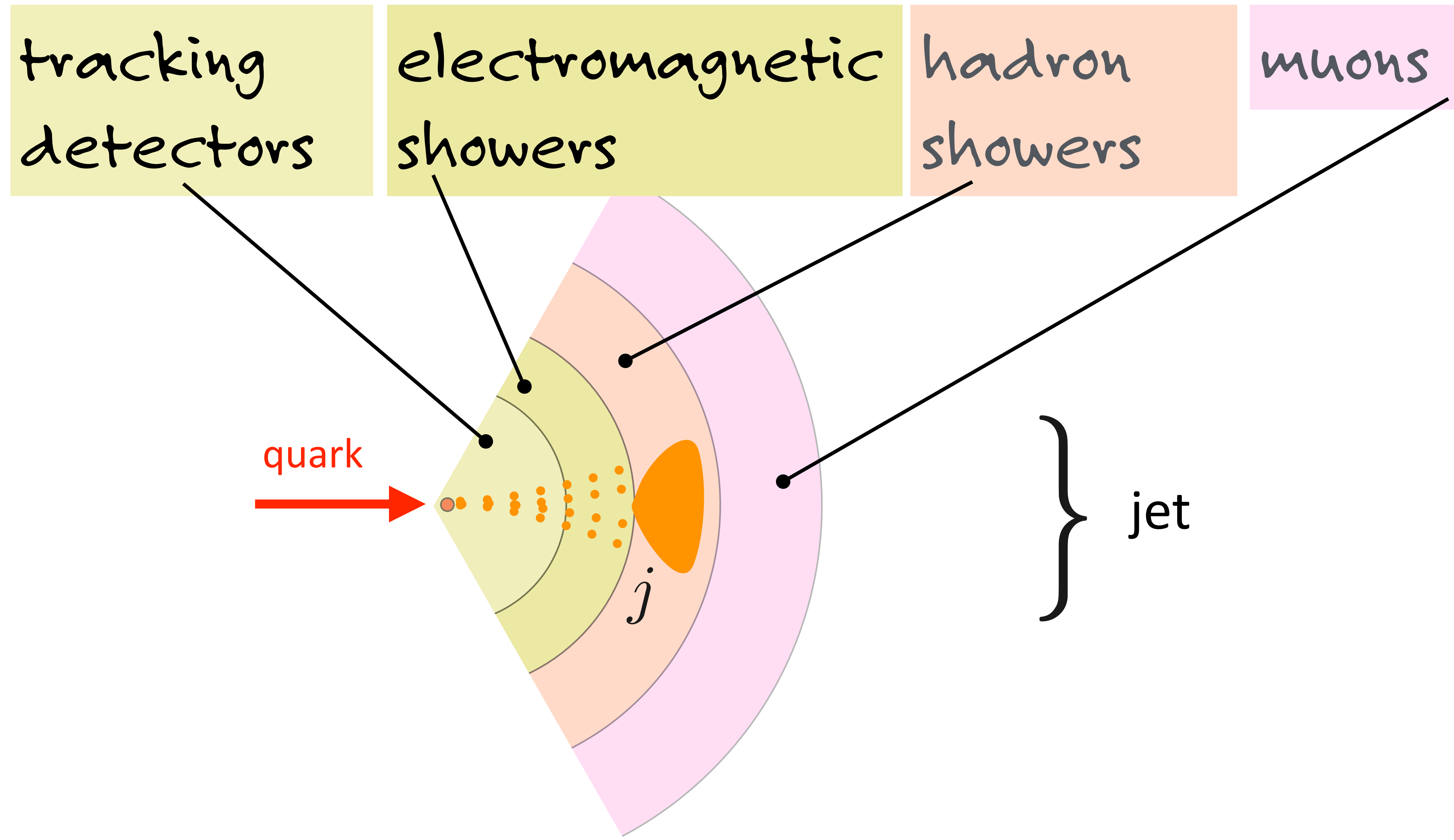
The energy in the field is so high...that it pops a new quark-antiquark pair out of the vacuum.

We don't see individual quarks or gluons

they make more quarks and gluons

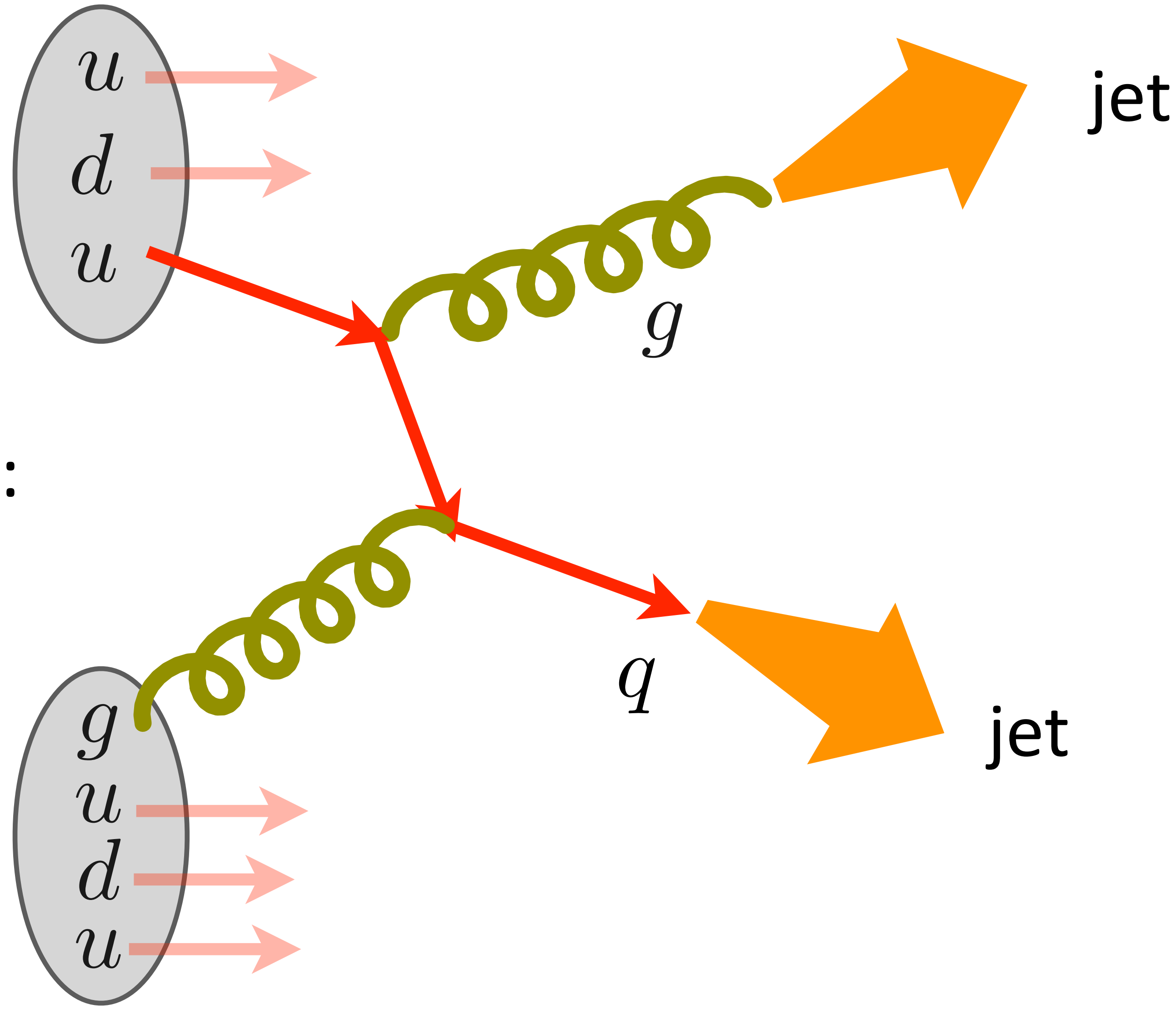
and interact very quickly into a cascade of particles

"quark-gluon **jets**"

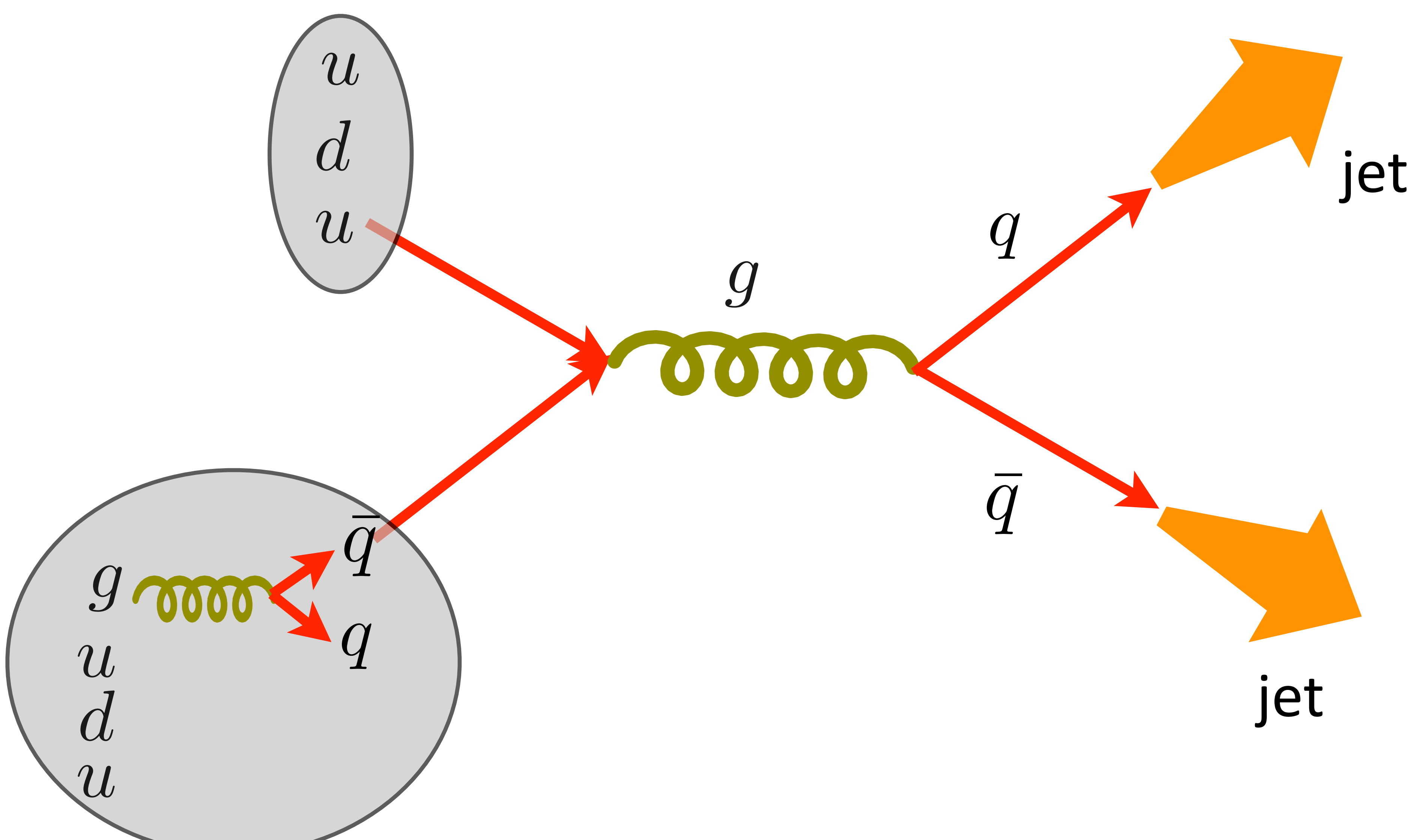


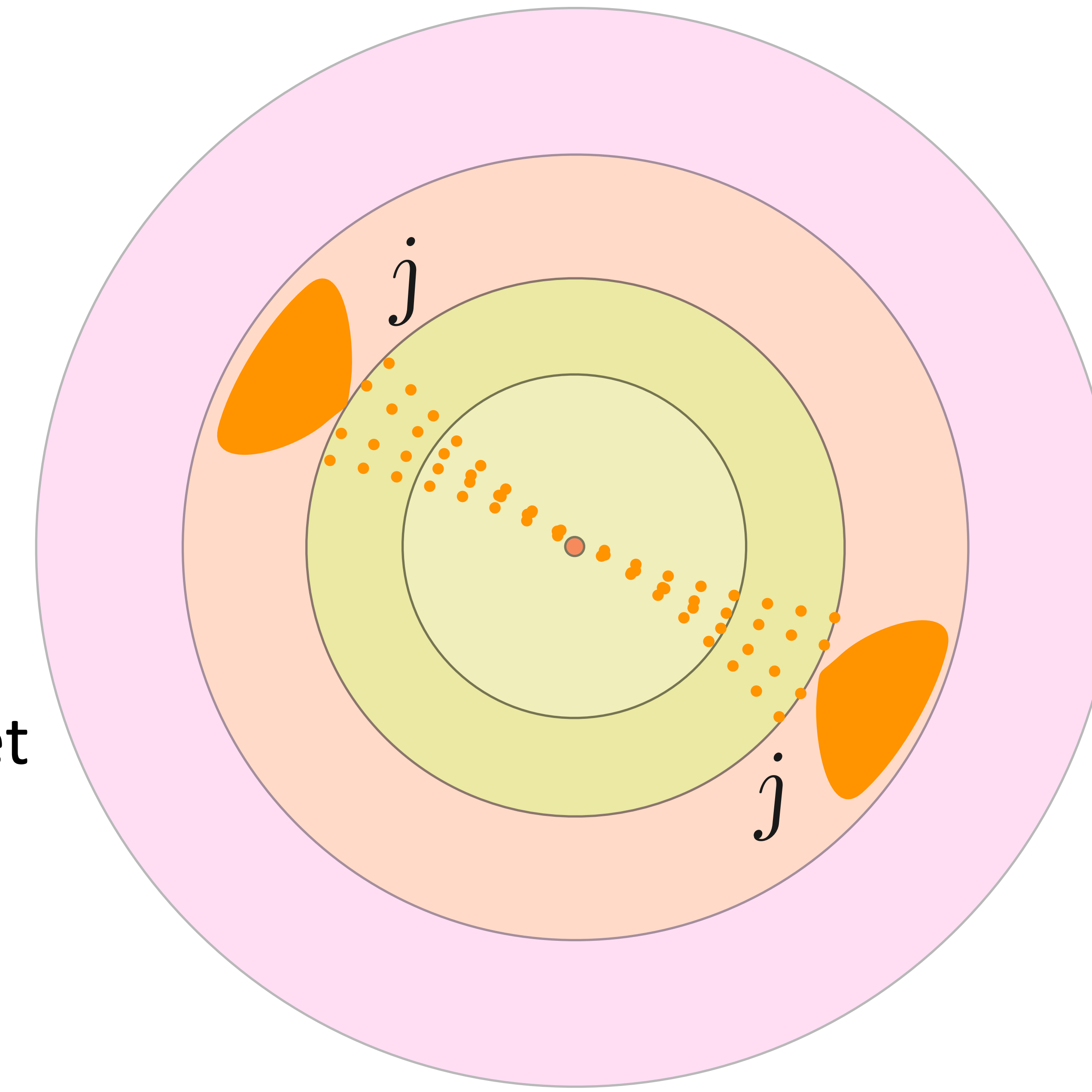
in ATLAS

maybe:

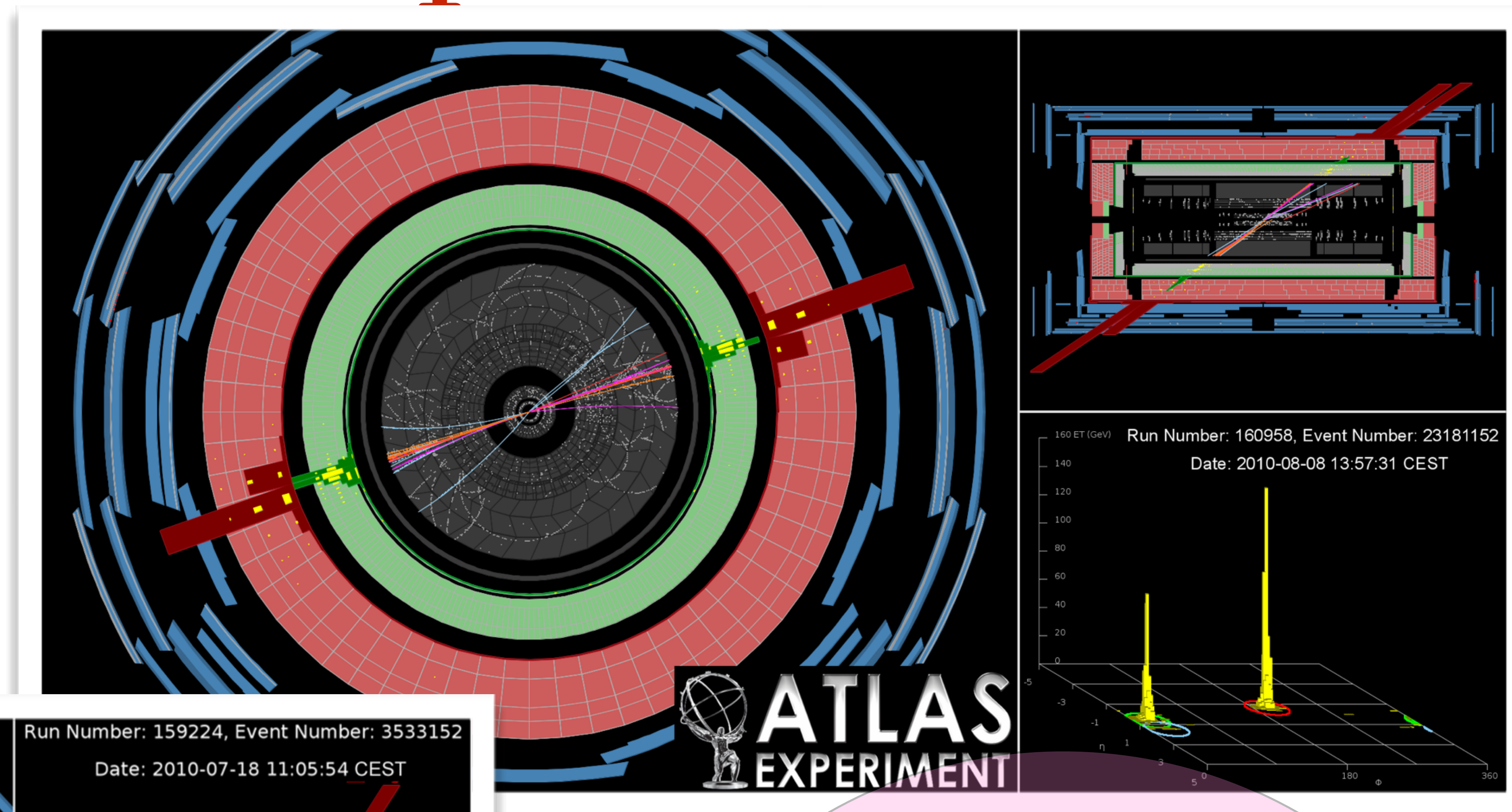


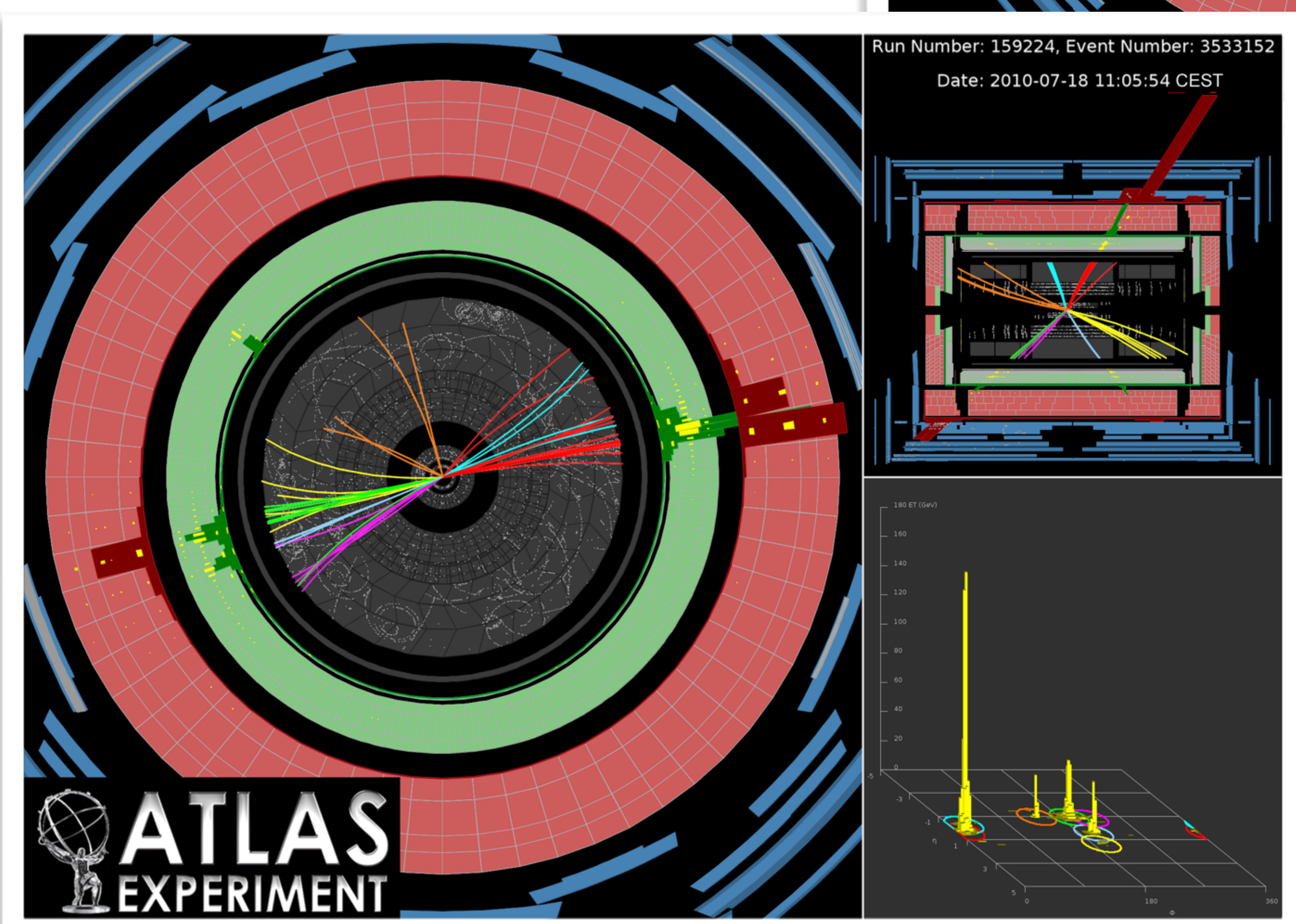
or:

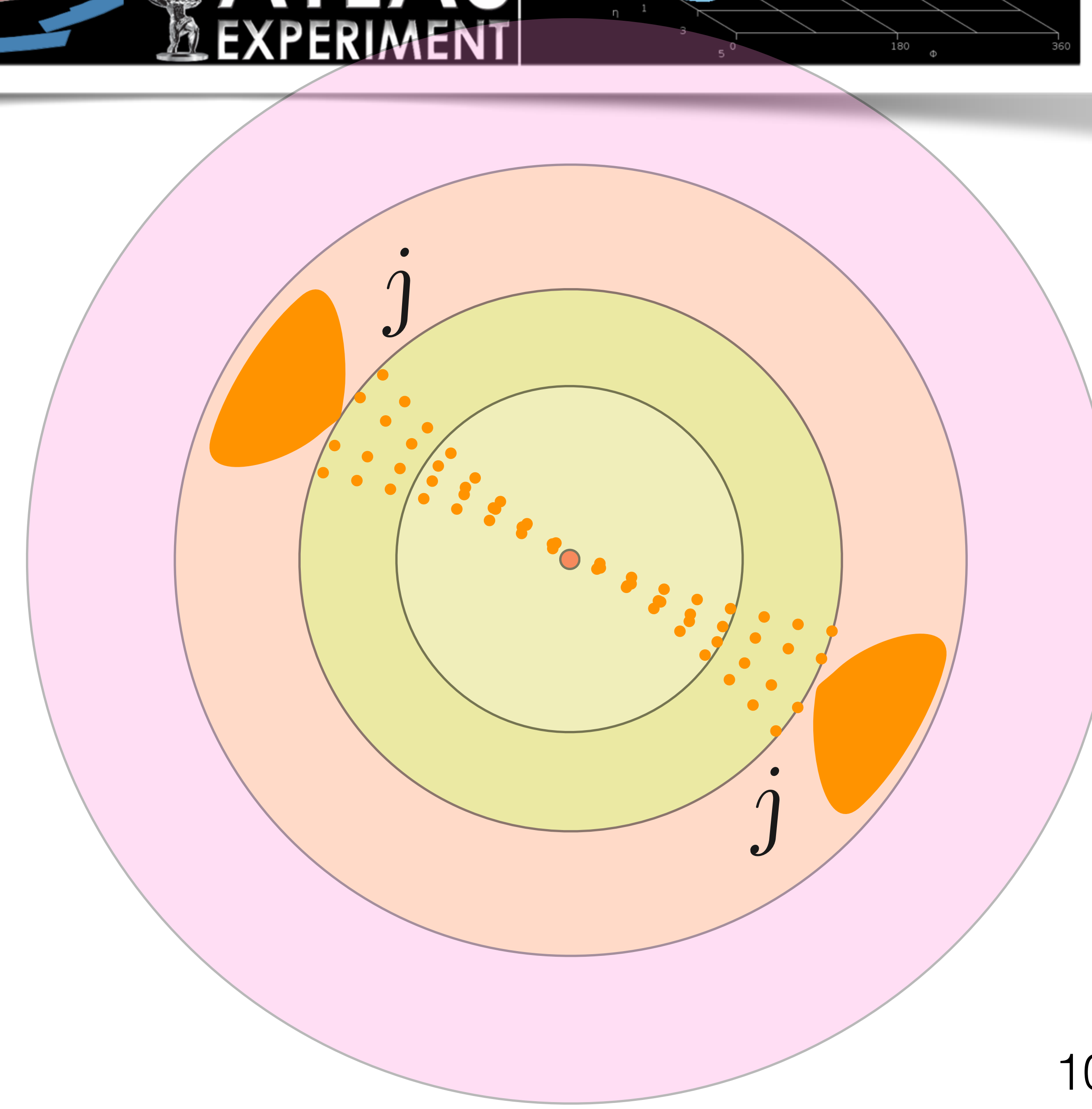




‘‘hard’’ quark production





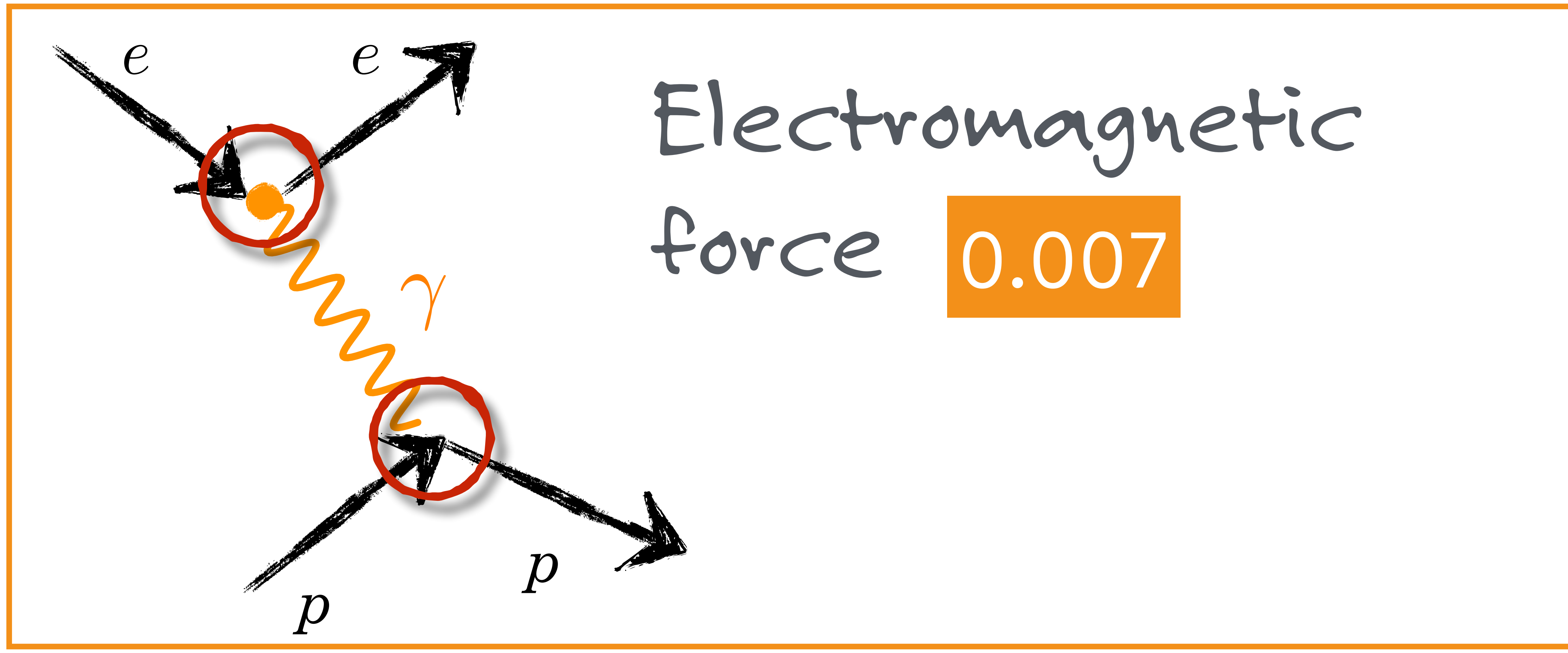


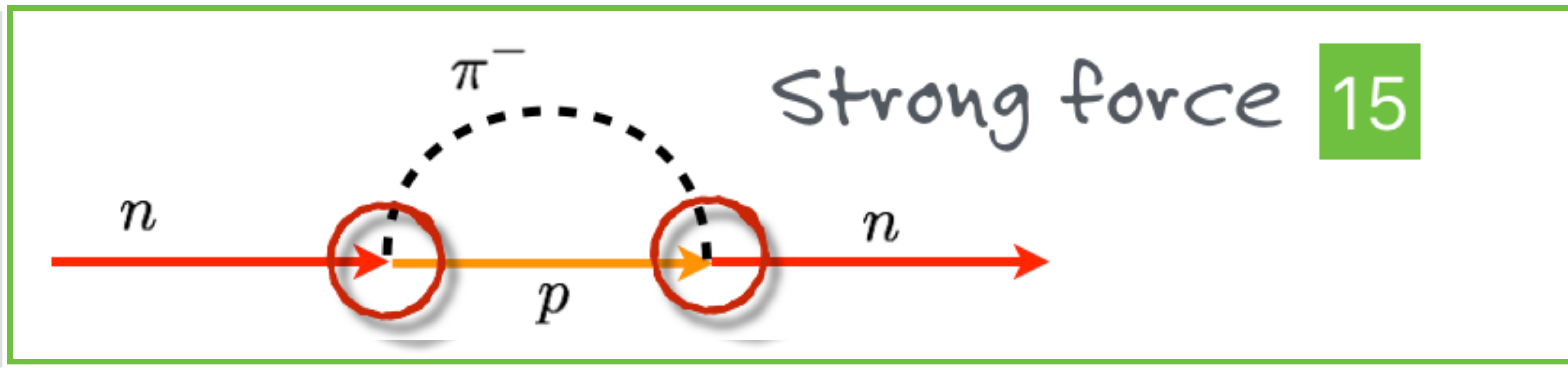
particle: **gluon**

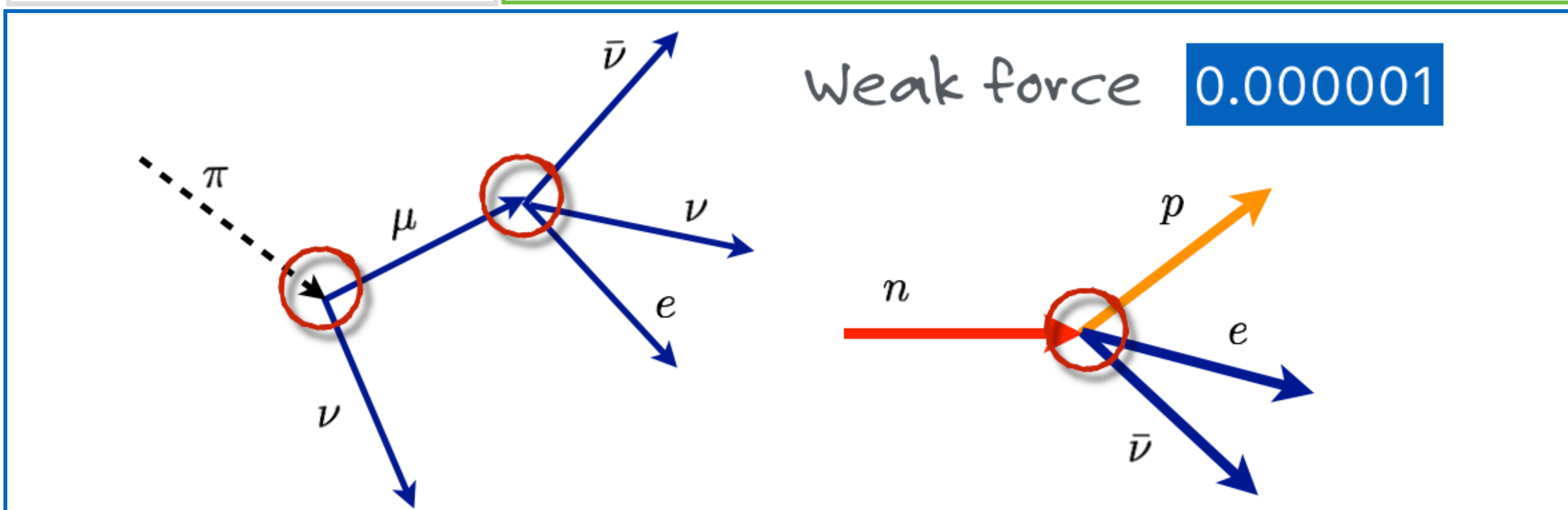
symbol:	g
charge:	0
mass:	0
spin:	1
category:	Strong Vector Boson

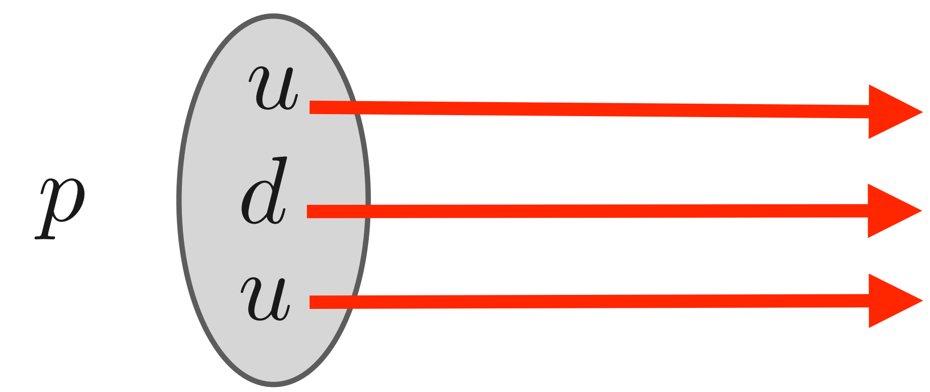
three forces now

of vastly different strengths









particle: **proton**

symbol: p

charge: $+1e$

mass: 1.6726×10^{-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**

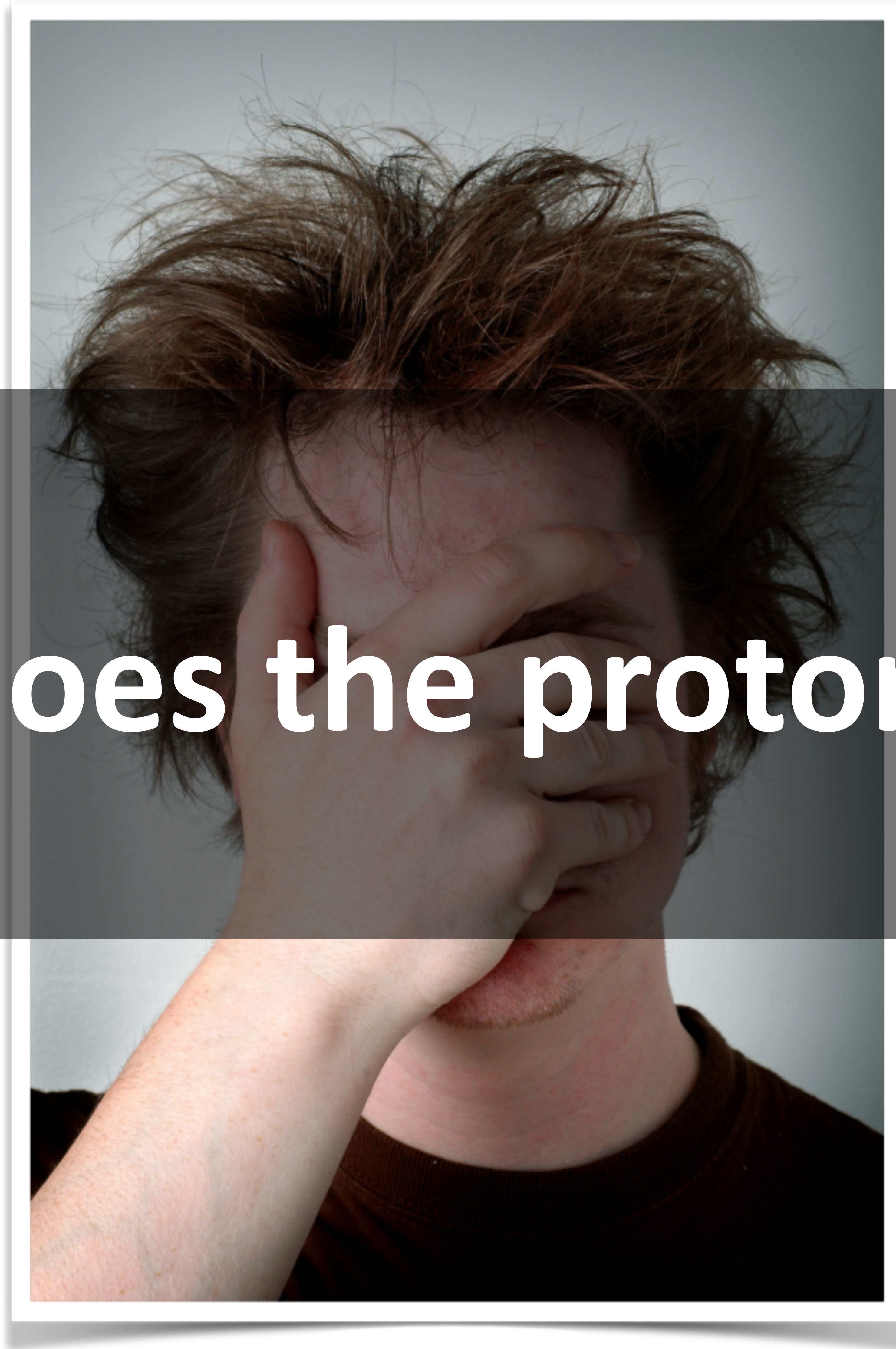
symbol: u

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:

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

when you step on the scale

you measure the earth's attraction

to the gluons' mass-energy in your protons and neutrons

and you use the non-quantum Newton's theory to do it

your "weight" is a quantum relativistic
field theoretic thing

here's the elementary particles story

circa 1975

the messengers

spin 1 Bosons

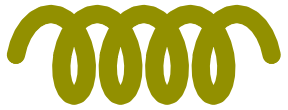
circa 1980

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

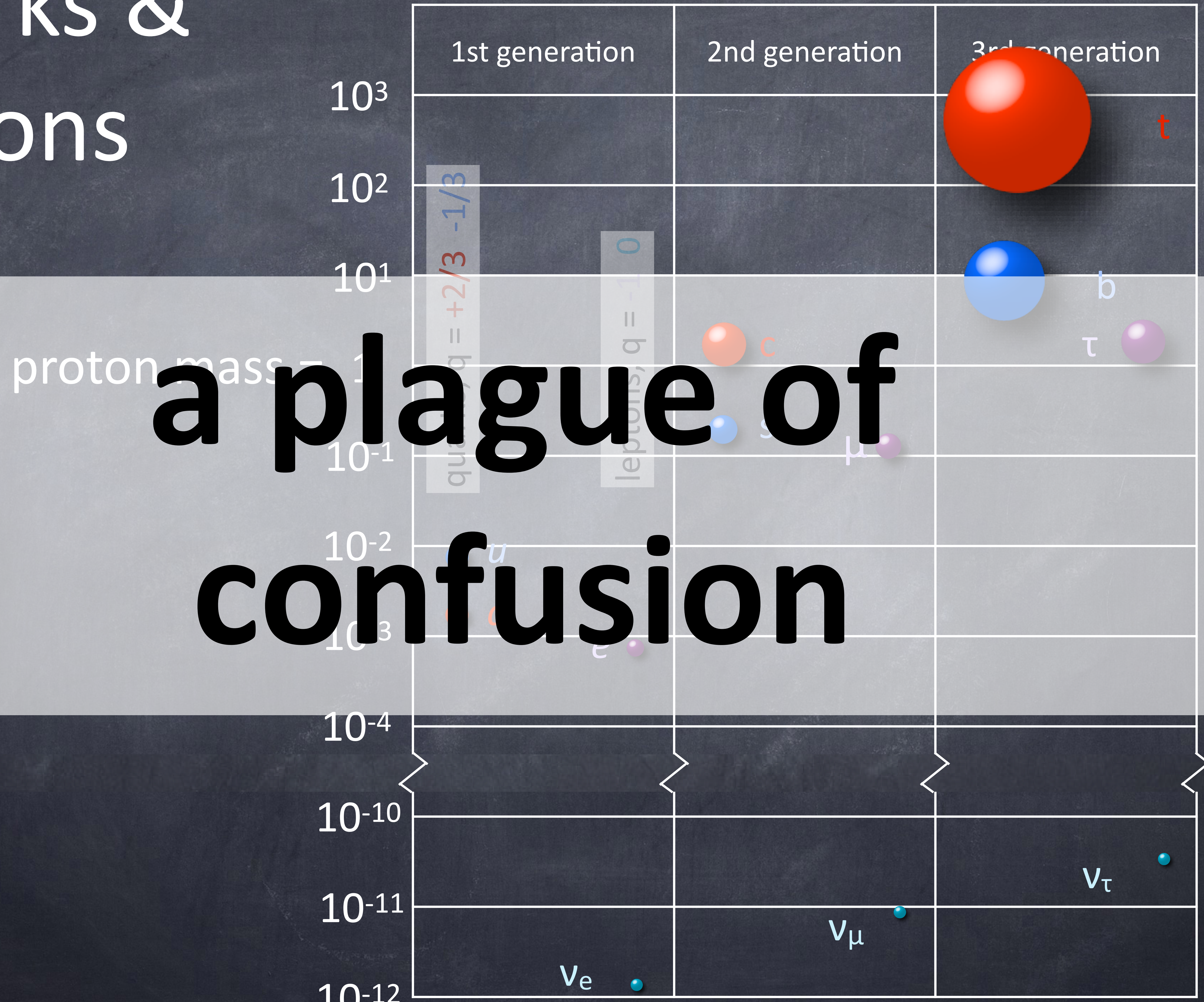
March 2, 1995 the announcement was made at Fermilab


Cultura e Spettacoli
Dove vai, cacciatore di quark?
Alles Quark, oder was?
predatori del quark perduto
Nation
For physicists, last piece of a
RICERCA ITALIANA
EPPUR SI MUOVE
Truth by Consensus
AUJOURD'HUI
Quand les particules livrent leur dernier secret
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	$\begin{pmatrix} u \\ d \end{pmatrix} \circlearrowright W$	$\begin{pmatrix} c \\ s \end{pmatrix} \circlearrowright W$	$\begin{pmatrix} t \\ b \end{pmatrix} \circlearrowright W$
0 -1	$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \circlearrowright W$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \circlearrowright W$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \circlearrowright W$

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

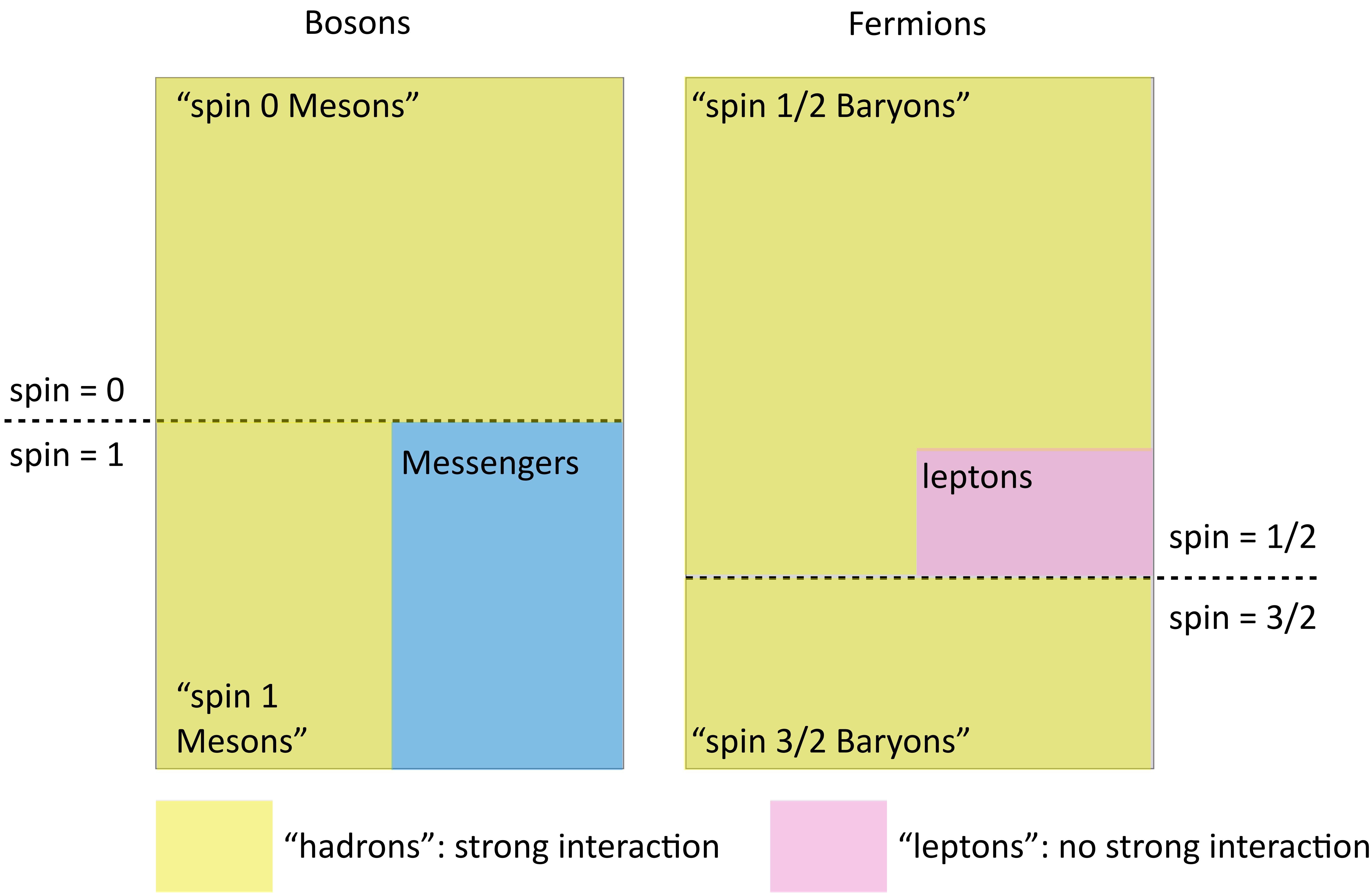
the quark families...quark "doublets"

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

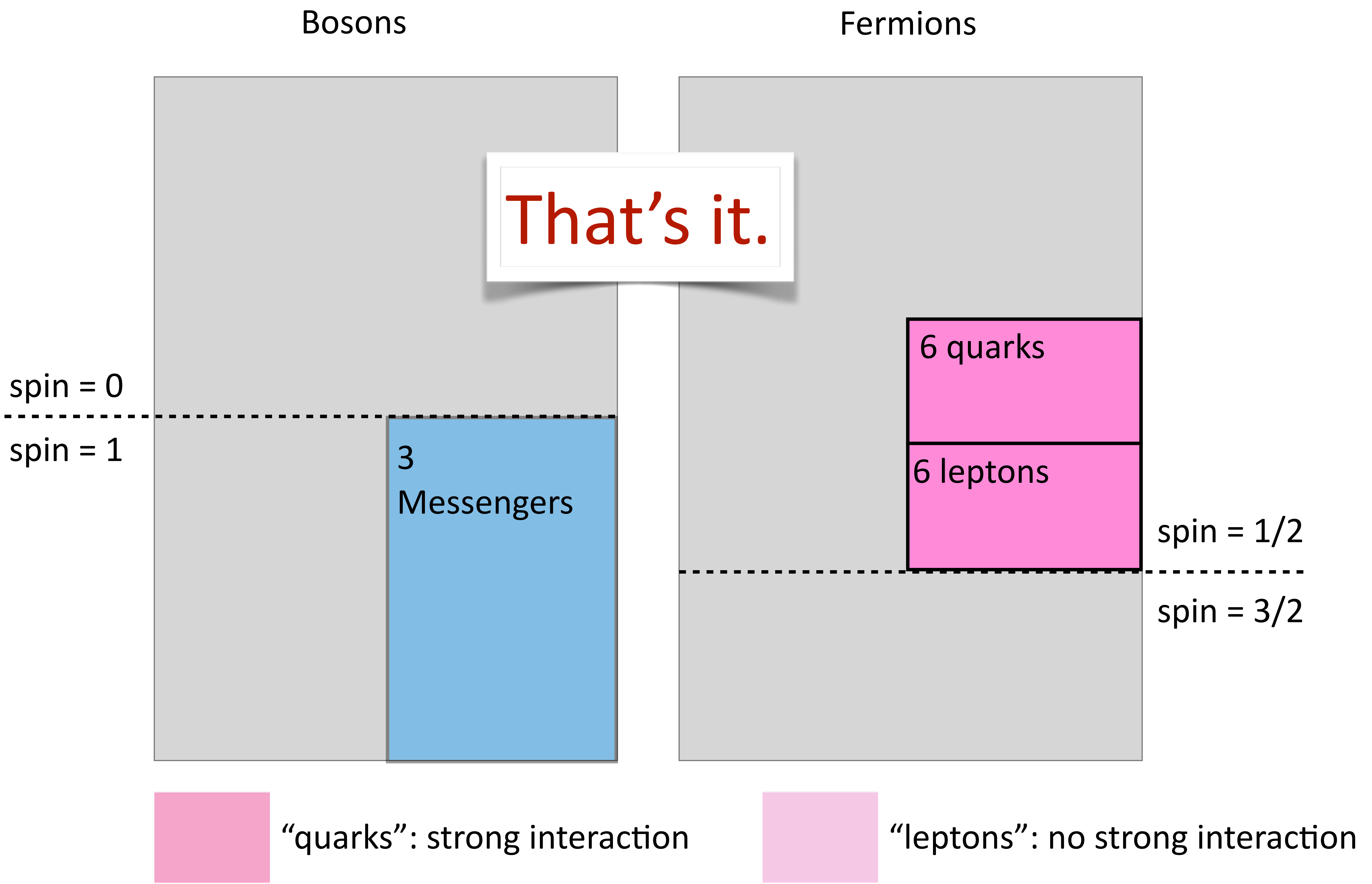
and their interactions: ✗ no, ✔ yes.

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

The Particle Zoo?

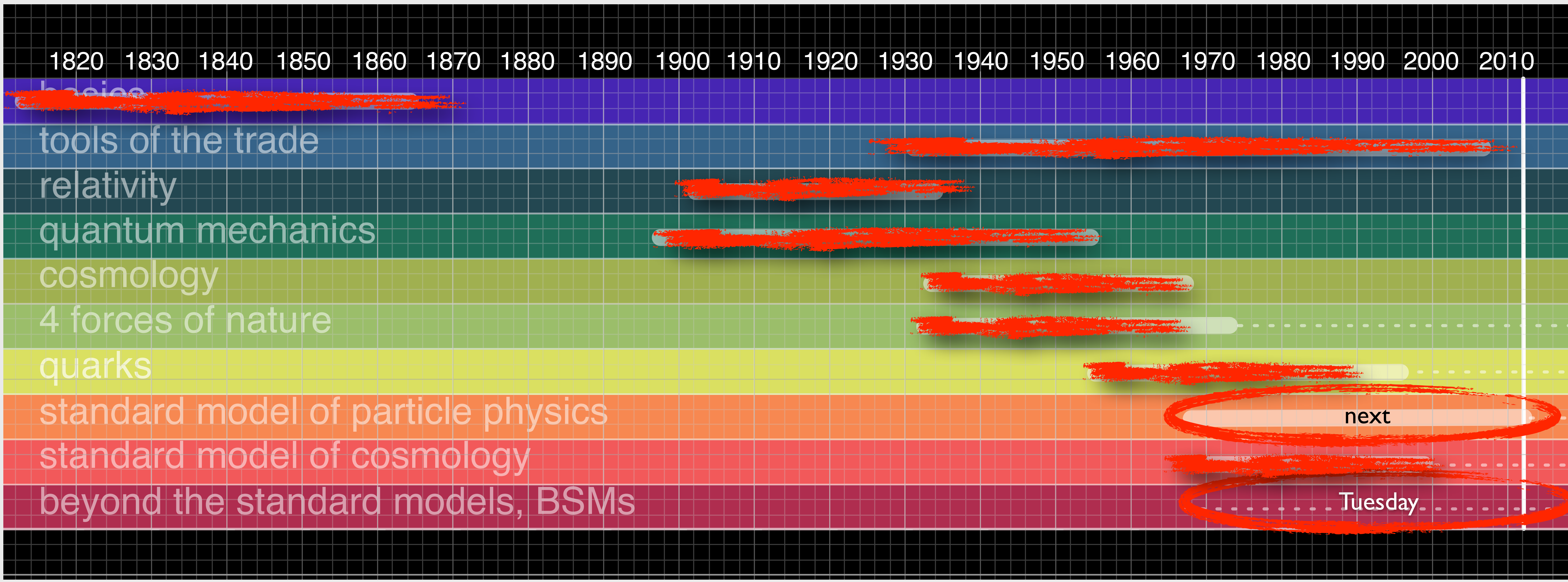


The Particle Zoo? *tamed*.



shifting gears

the weak and electromagnetic forces are one.



1820 1830 1840 1850 1860 1870 1880 1890 1900 1910 1920 1930 1940 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

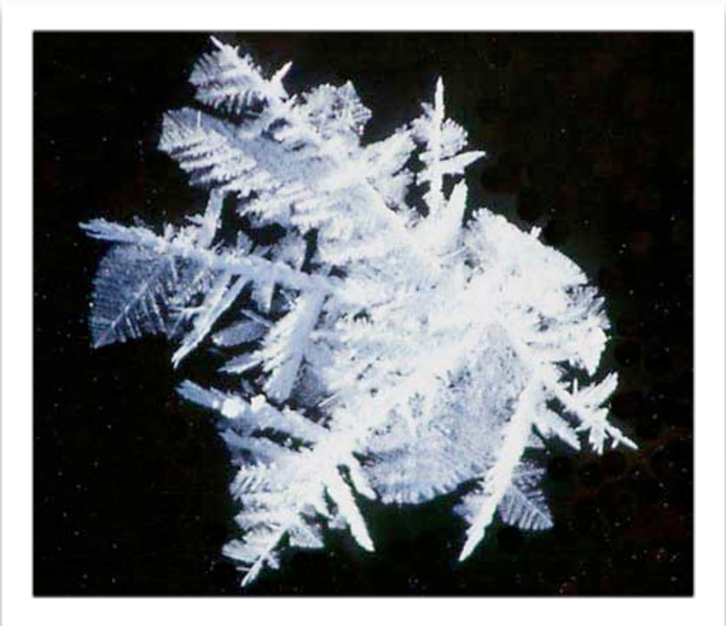
think about a phase transition

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



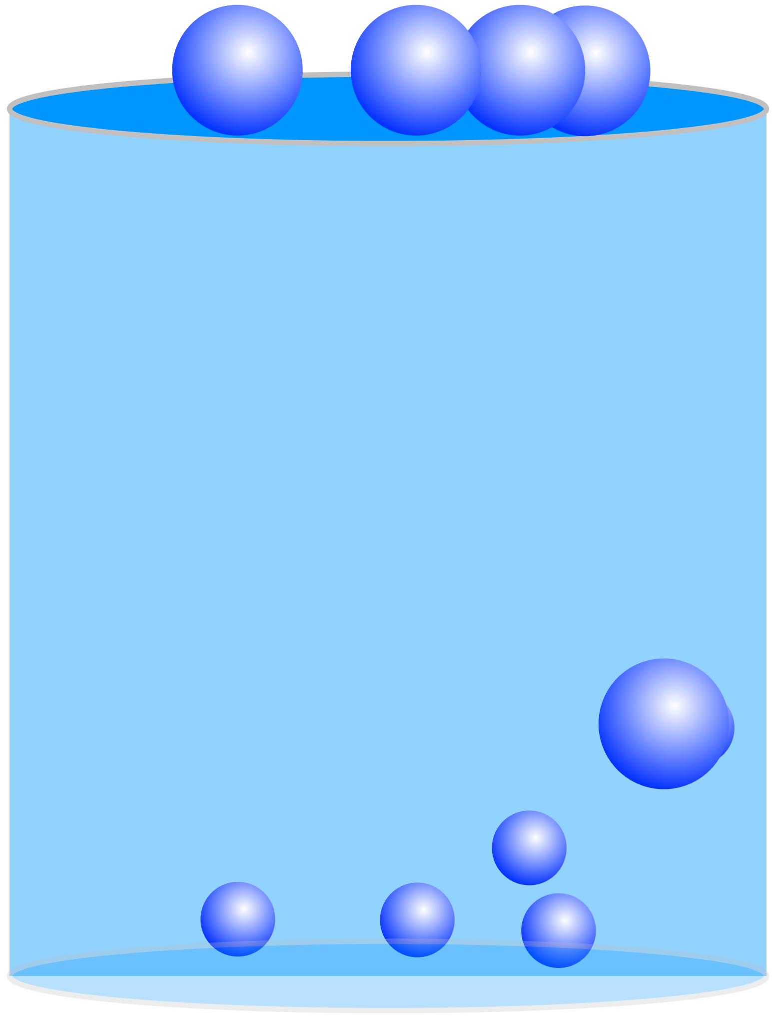
after: now there are special directions

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