Modern Physics

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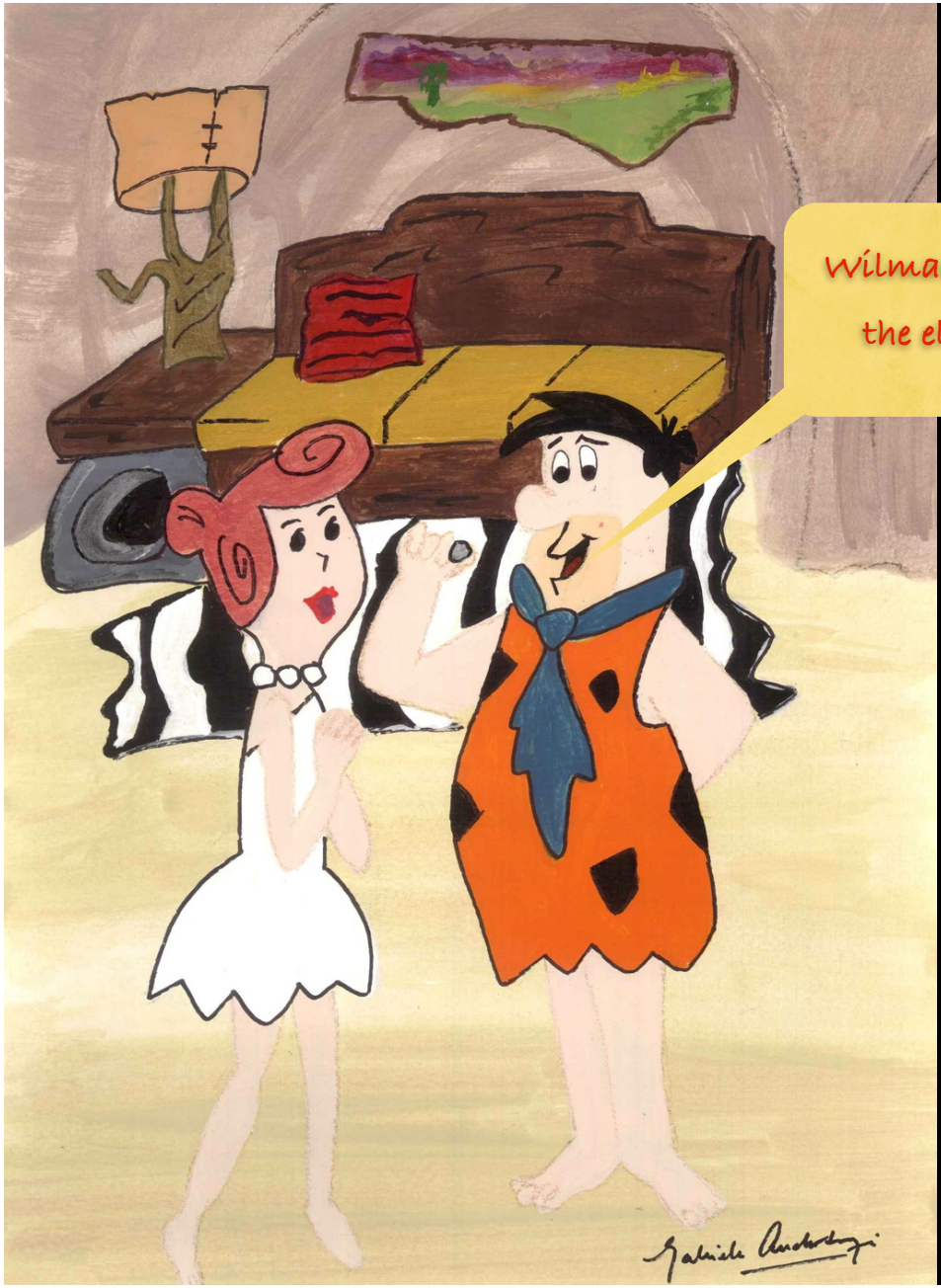
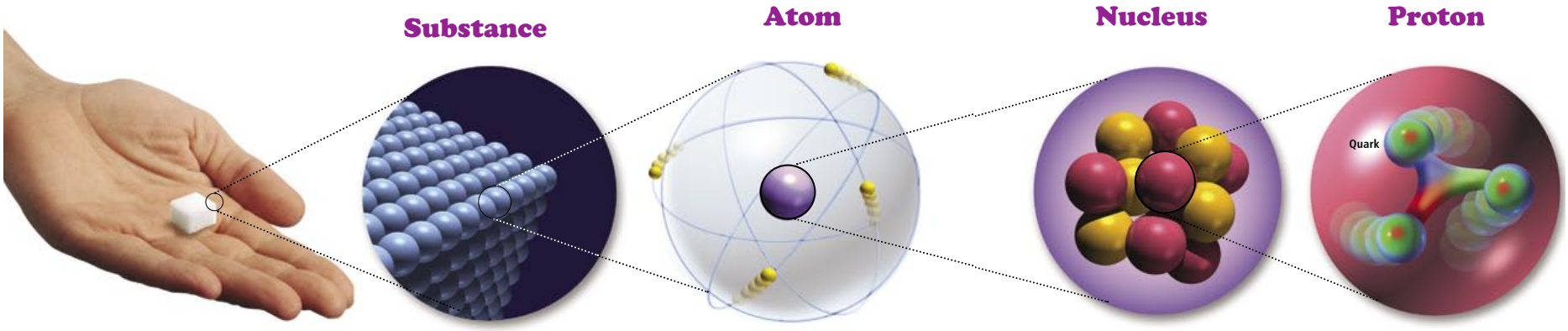
The Standard Model is our most modern attempt to answer two simple questions that have been perplexing (wo)mankind throughout the epochs:

What is the Universe made of? Why is our world the way it is?


Wilmaaaaaa... I've discovered what I believe to be the elementary basic particle: a small stone

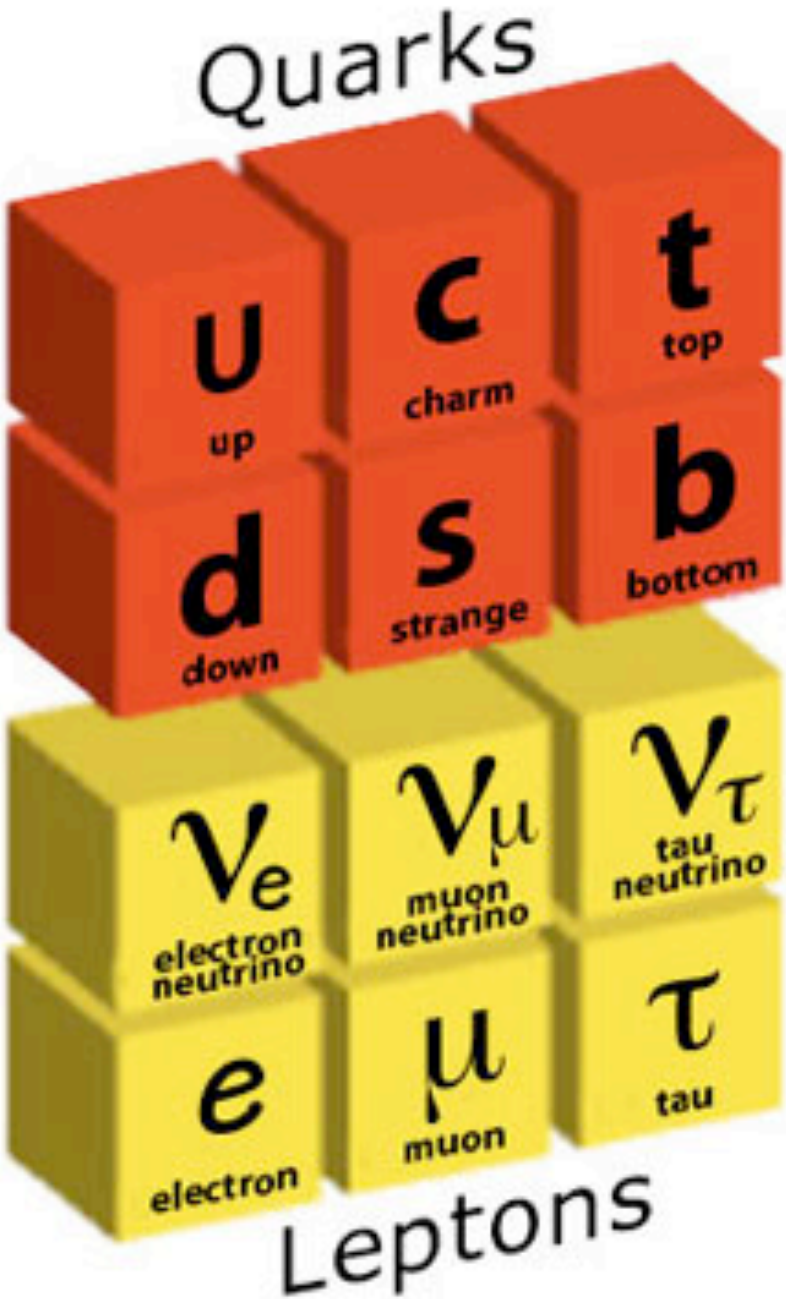
- If we look deep inside Fred's rock ☞ we can see that



it is made up of only a few types of elementary "point-like" particles

- Elementary-particle model accepted today
  views quarks and leptons as basic constituents of ordinary matter

- By "pointlike"
  we understand that quarks and leptons show no evidence
  of internal structure at the current limit of our resolution
  which is about $r \sim 2 \times 10^{-20}$ m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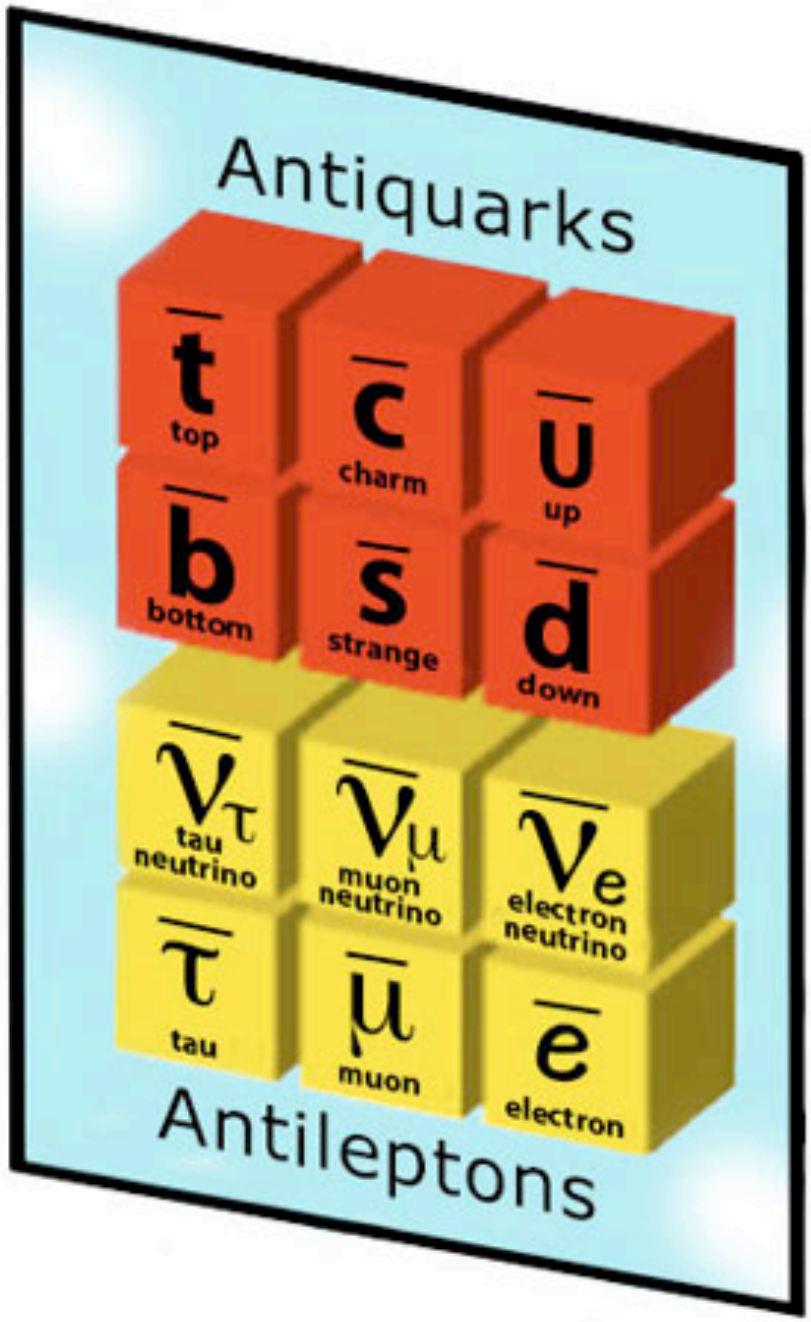
Leptons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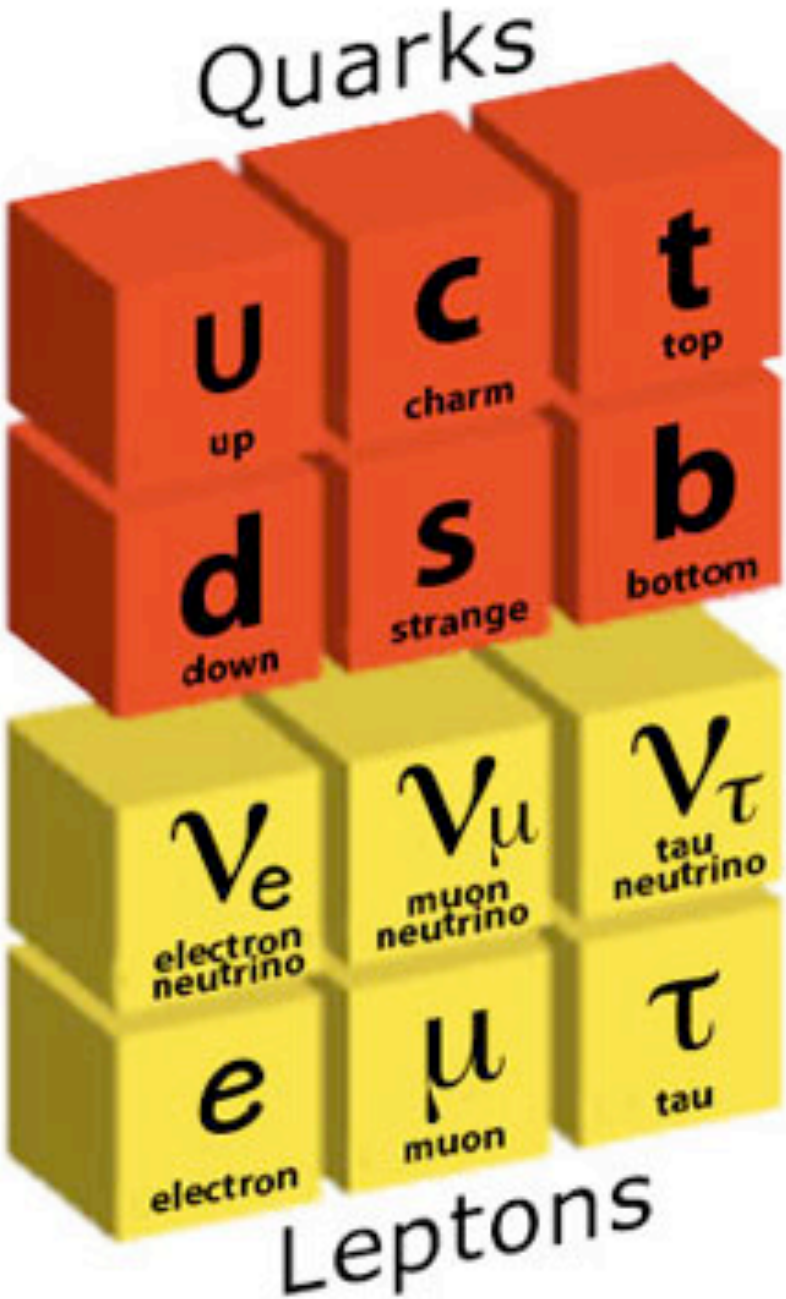
Antileptons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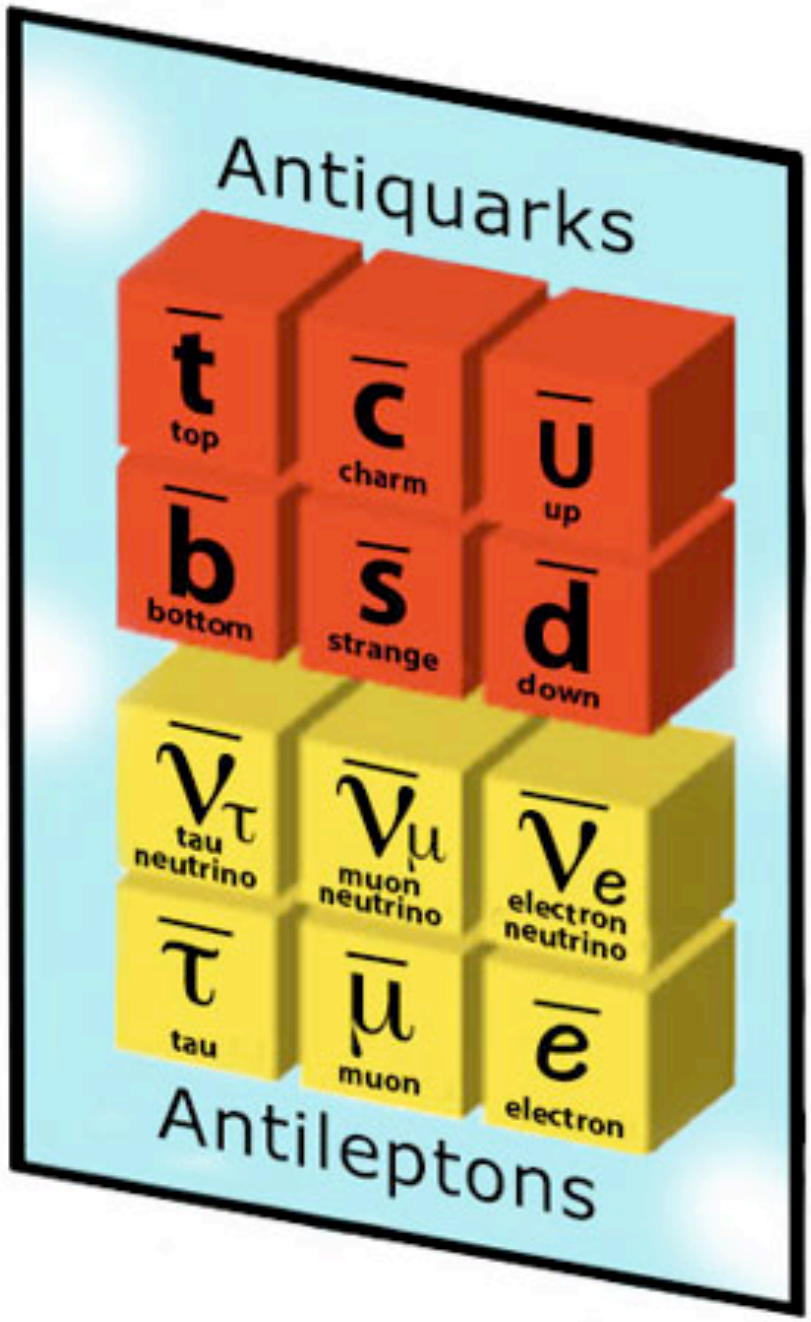
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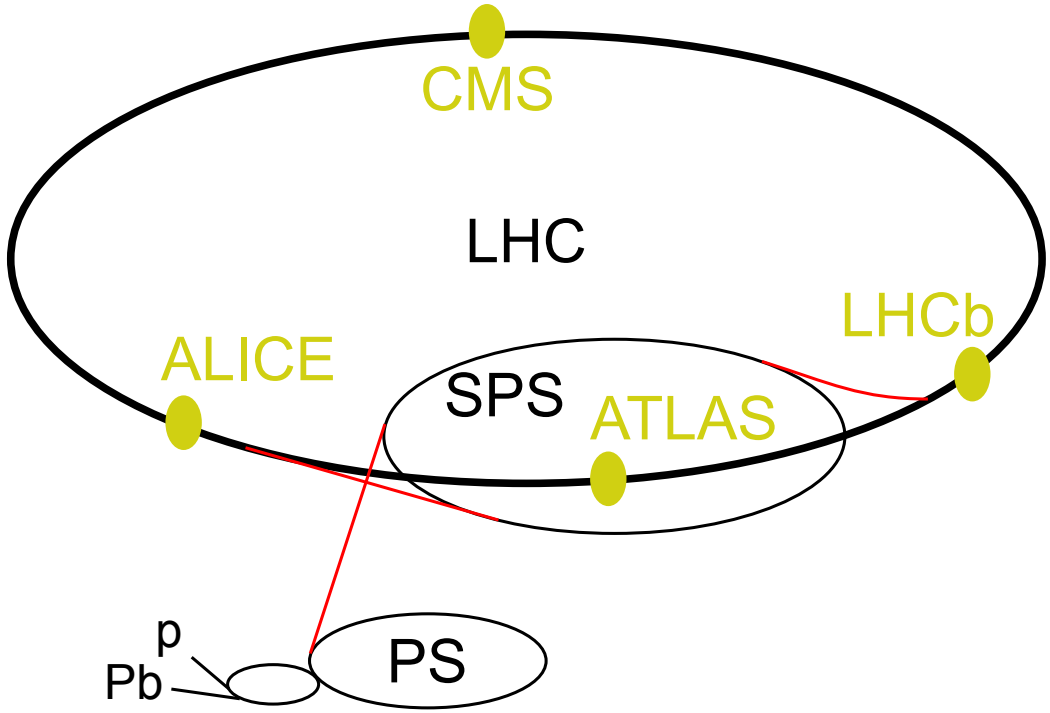
Antileptons

- Colossal microscope attaining such incredble resolution is LHC

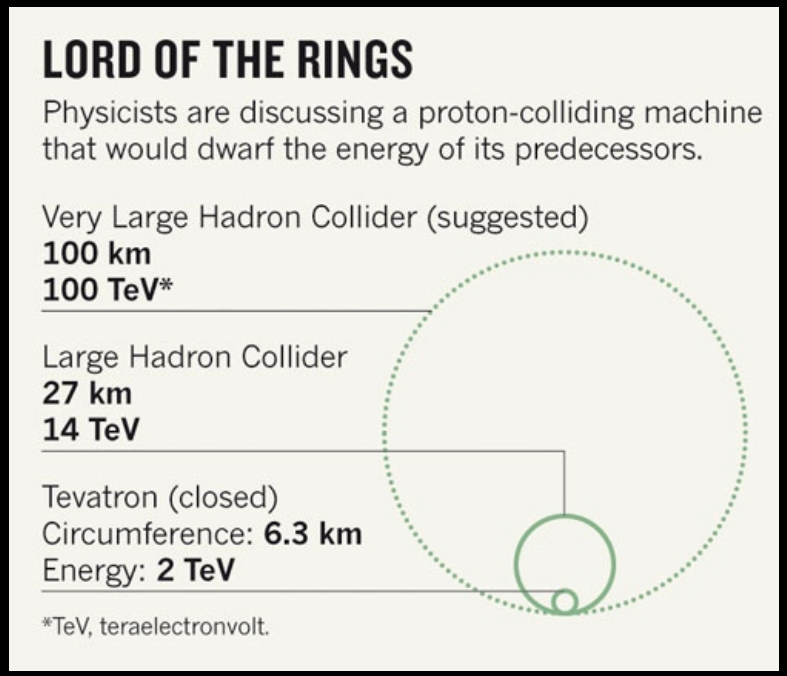


- Remarkably ☞ 70% of energy carried into collision by protons emerges perpendicular to incident beams
- At given transverse energy $E_\perp$ ☞ rough estimate of resolution

$$r \approx \hbar c/E_\perp \approx 2\times 10^{-19}\ \text{TeV}\,\text{m}/E_\perp$$

- For CM collisions of 13 TeV ☞ we obtain resolution of 2×10^{-20} m

The World's Largest Microscope



LHC Roadmap

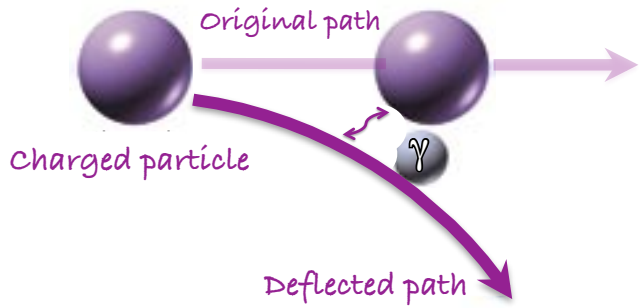
Machine	$\sqrt{s}$	Final Integrated Luminosity
LHC Phase I	14 TeV	300 fb^{-1}
HL – LHC or LHC Phase II	14 TeV	3000 fb^{-1}
HE – LHC	33 TeV	3000 fb^{-1}
VLHC	100 TeV	3000 fb^{-1}


PATRIOTS
12
THE LORD OF THE RINGS

- Now ☞ an understanding of how world is put together
  needs theory of how quarks and leptons interact with one another
- Equivalently ☞ it requires theory of basic forces of nature
- Four such forces have been identified
- Two of the forces ☞ gravitation and electromagnetism
  have an unlimited range
  largely for this reason they are familiar to everyone
- Remaining forces ☞ simply called weak force and strong force
  cannot be perceived directly
  because their influence extends only over a short range
  no larger than the radius of an atomic nucleus

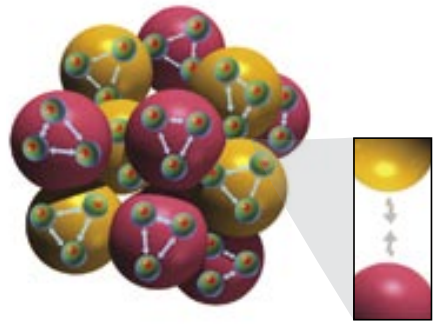
- electromagnetic and gravity force
  can be felt directly as agencies that pull or push

Electromagnetic Interaction



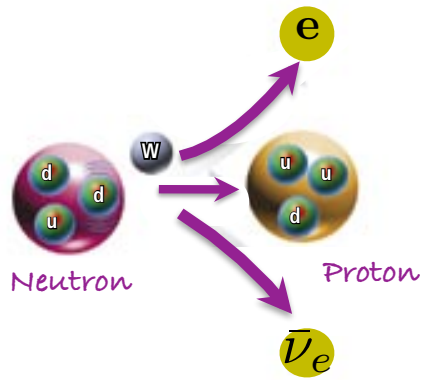
- Strong force binds together quarks inside hadrons
- Indirectly ☞ also binds protons and neutrons
  into atomic nuclei

Strong Interaction



- Weak force
  is mainly responsible for decay of certain particles
- Its best-known effect
  is to transmute a down quark into an up quark
  which causes neutron to become proton
  plus electron and antineutrino

Weak Interaction



Fundamental forces of Nature

Forces can be characterized on basis of 4 criteria

1. types of particles that experience force
2. relative strength of force
3. range over which force is effective
4. nature of particles that mediate force

- electromagnetic force is carried by the photon
- strong force is mediated by gluons
- W and Z bosons transmit weak force
- quantum of gravitational force is called graviton

Relative force strength for protons inside a nucleus

Force	Relative Strength
Strong	1
Electromagnetic	10^{-2}
Weak	10^{-6}
Gravitational	10^{-38}

Though gravity is most obvious force in daily life
on nuclear scale it is weakest of four forces
and its effect at particle level can nearly always be ignored

Standard Model

3 generations of quarks and leptons

	Fermion	Short-hand	Generation	Charge	Mass	Spin
Quarks	up	u	I	$+\frac{2}{3}$	$2.3^{+0.7}_{-0.5}$ MeV	$\frac{1}{2}$
	charm	c	II		1.275 ± 0.025 GeV	
	top	t	III		173.21 ± 0.51 GeV	
	down	d	I	$-\frac{1}{3}$	$4.8^{+0.5}_{-0.3}$ MeV	$\frac{1}{2}$
	strange	s	II		$95^{\pm}5$ MeV	
	bottom	b	III		4.18 ± 0.03 GeV	
Leptons	electron neutrino	ν_e	I	0	< 2 eV 95% CL	$\frac{1}{2}$
	muon neutrino	ν_μ	II		< 0.19 MeV 90% CL	
	tau neutrino	ν_τ	III		< 18.2 MeV 95%CL	
	electron	e	I	-1	0.511 MeV	$\frac{1}{2}$
	muon	μ	II		105.7 MeV	
	tau	τ	III		1.777 GeV	

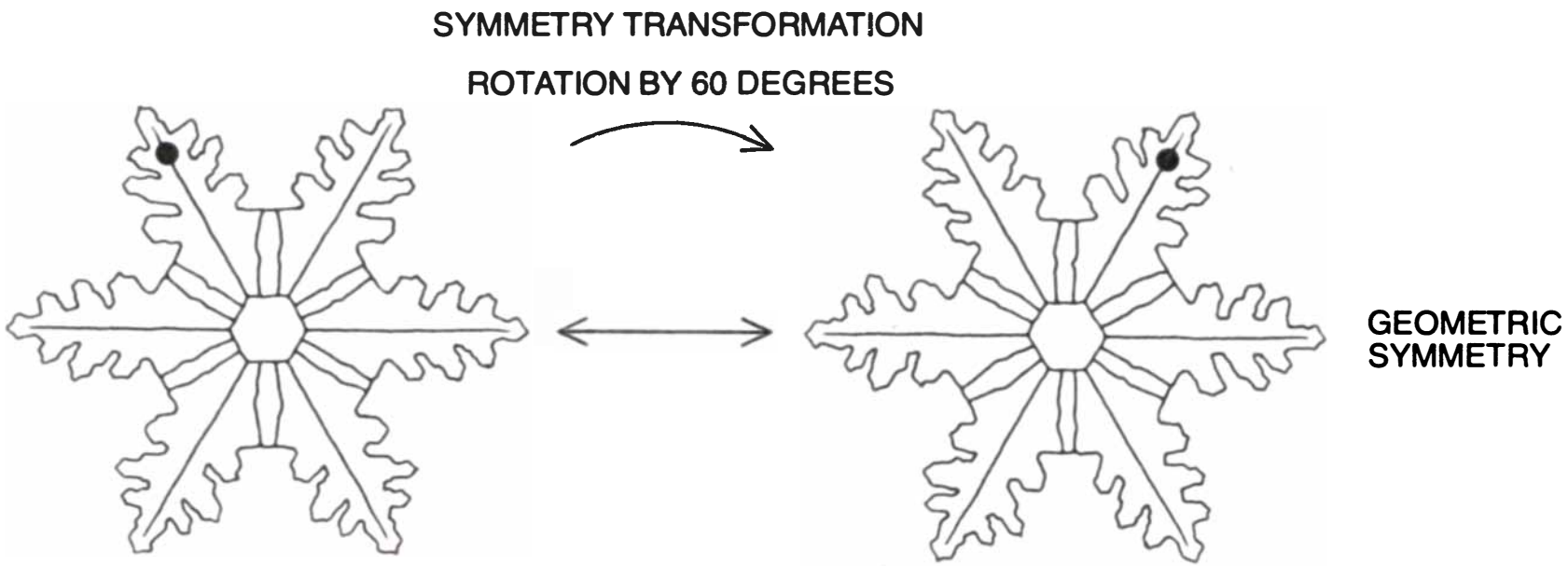
4 force carriers

Force	Boson	Short-hand	Charge	Mass	Spin
Electromagnetic	photon	γ	0	0	1
Weak	W	$W^{\pm}$	± 1	80.385 ± 0.015 GeV	1
Weak	Z	Z^0	0	91.1876 ± 0.0021 GeV	1
Strong	gluon	g	0	0	1

Hadrons

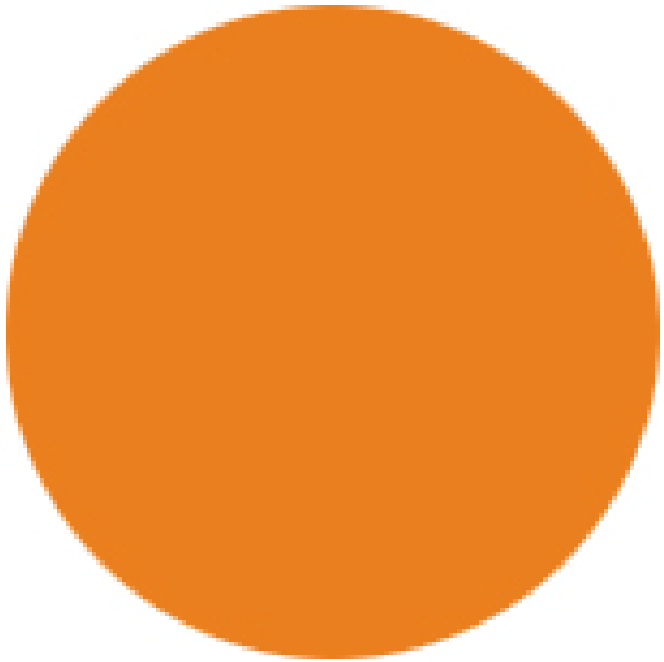
$q\bar{q}$	(quark + antiquark)	mesons	integral spin $\rightarrow$ Bose-Eisntein statistics
qqq	(three quarks)	baryons	half-integral spin $\rightarrow$ Fermi-Dirac statistics

- Symmetries and apparent symmetries in laws of nature
  played major role in development of physical theories
  since time of Galileo and Newton
- Most recognizable symmetries are spatial or geometric ones
- snowflake ☞ existence of symmetrical pattern can be detected at first sight
- Symmetry can be defined as:
  invariance in pattern that is observed when some transformation is enforced to it
- Snowflake is invariant with respect to rotations by $\pi/3$

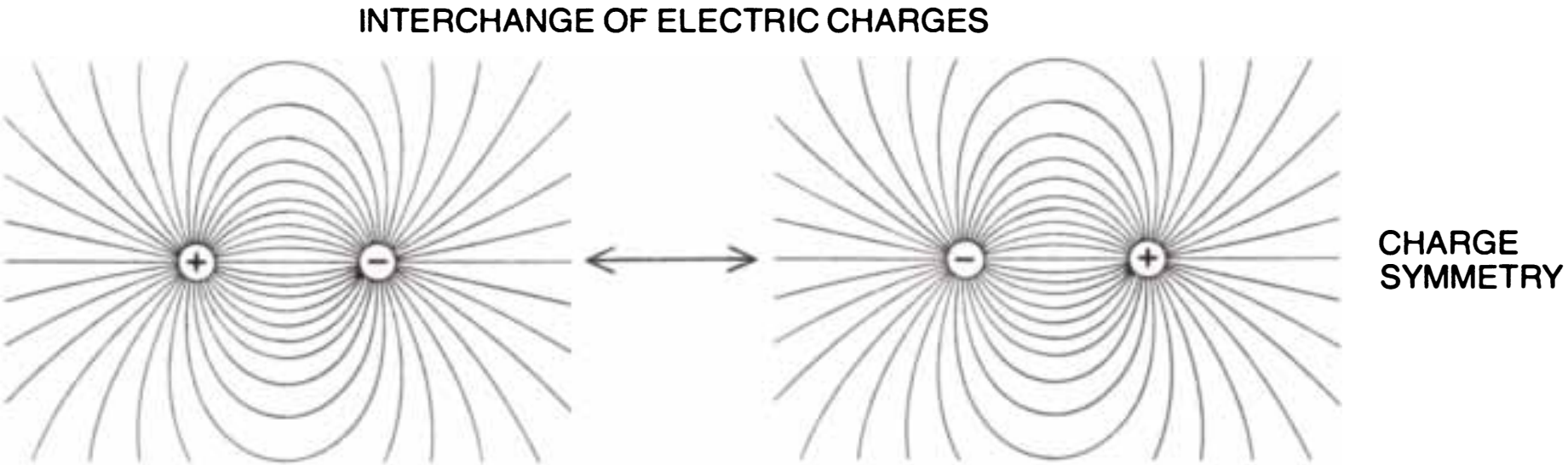


Applying same rule...

- Square is invariant with respect to rotations by $\pi/2$
- Circle is said to have continuous symmetry
  because rotation by any angle leaves it unchanged
- In physics vernacular ☞ circle invariance is known $U(1)$ symmetry



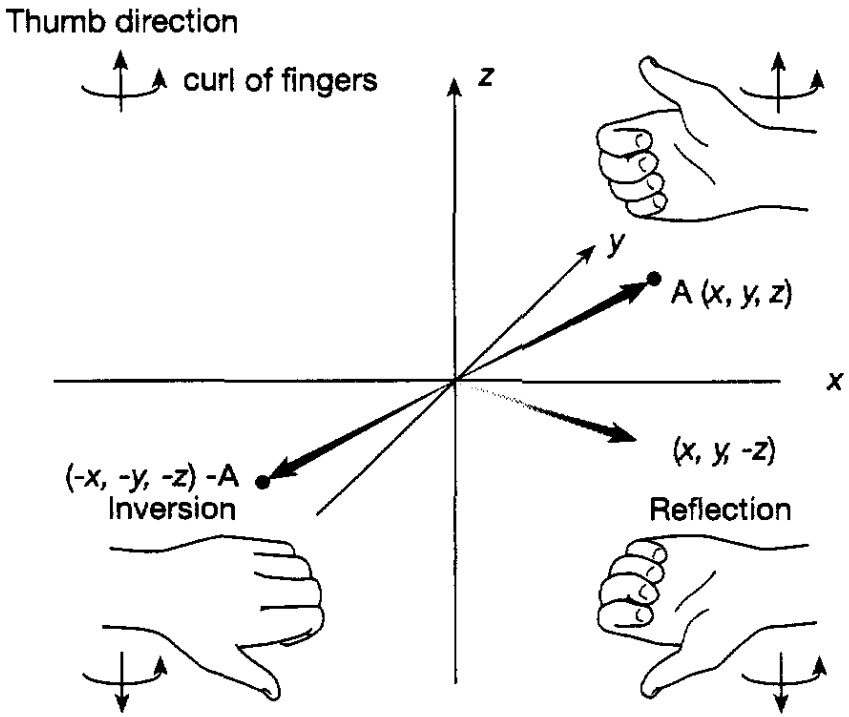
- Although notion of symmetry had its origin in geometry
  it is general enough to encompass invariance
  with respect to transformations of other kinds
- Nongeometric symmetry ☞ charge symmetry of electromagnetism
- Assume definite configuration of electrically charged particles
  measure all forces acting between pairs of particles
  if polarity of all the charges is inverted ☞ forces remain unchanged



- Guiding principle of SM ☞ equations are symmetrical
- Just as sphere looks the same whatever your viewing angle is
  equations remain unchanged
  even when you change the perspective from which they are defined
- Moreover ☞ they remain unchanged even when perspective
  shifts by different amounts at different points in space and time
- Ensuring symmetry of geometric object places very tight constraints on its shape

- Sphere with a bump no longer looks the same from every angle
- Likewise ☞ symmetry of equations places very tight constraints on them
- Symmetries beget forces that are carried by special particles called bosons

- Parity says something about symmetry of system
- Parity operator inverts object completely
  (back to front, side to side, and top to bottom)
  by changing coordinates (x, y, z) to $(-x, -y, -z)$
- This is equivalent to reflection (here in $x - y$ plane)
  together with rotation through $180°$ (here around z axis)
- During inversion
  right-handed system changes to left-handed system



- Vector quantities change sign under parity transformation

$$\mathrm{P} : \vec{p} \rightarrow -\vec{p}$$

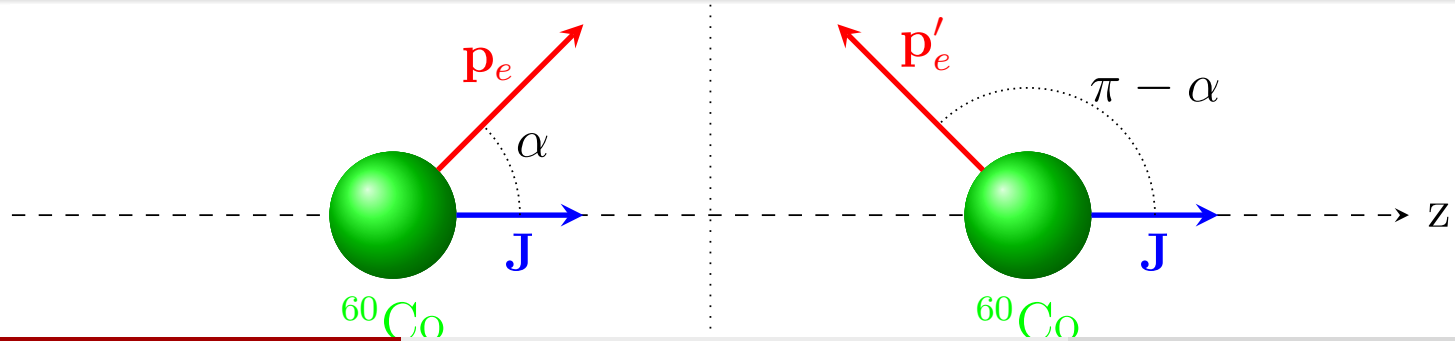
- Axial vectors (like angular momentum) do not switch sign

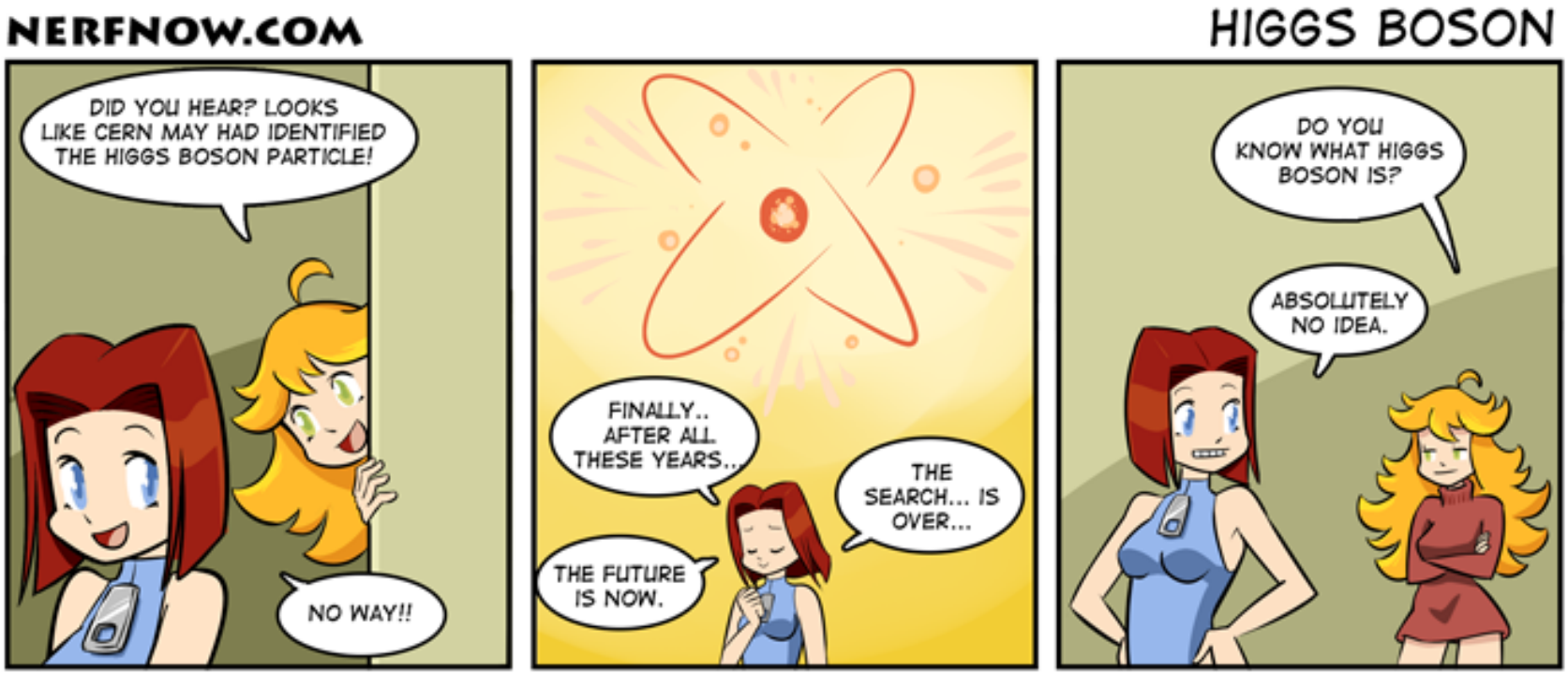
$$\mathrm{P} : \vec{L} = \vec{r} \times \vec{p} \rightarrow \vec{L} = -\vec{r} \times -\vec{p}$$

- Parity of particles depends on spatial symmetry of wavefunction their quantum mechanical description
- In some cases spatial inversion changes sign of wavefunction and parity of system is said to be odd
- In other cases sign doesn't change and parity is said to be even

Wu experiment

- Parity violation was first observed in $^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni}\, e^- \bar{\nu}_e$ by measuring correlation between direction $\hat{p}_e$ of outgoing e^- and spin vector $\vec{J}$ of $^{60}\mathrm{Co}$ nucleus
- Parity leaves the (axial vector) spin unchanged ☞ $\mathrm{P} : \vec{J} \to \vec{J}$ but reverses electron direction $\mathrm{P} : \hat{p}_e \to -\hat{p}_e$
- Accordingly ☞ correlation $\vec{J} \cdot \hat{p}_e$ is manifestly parity violating
- If process obeys reflection symmetry e^- will be as likely to be emitted at angle α as would be at $\pi - \alpha$
- It is found that e^- are more likely to emerge at $\alpha = \pi$ from original Cobalt spin than they are to emerge along the direction of this spin ($\alpha = 0$)





to be continued . . .