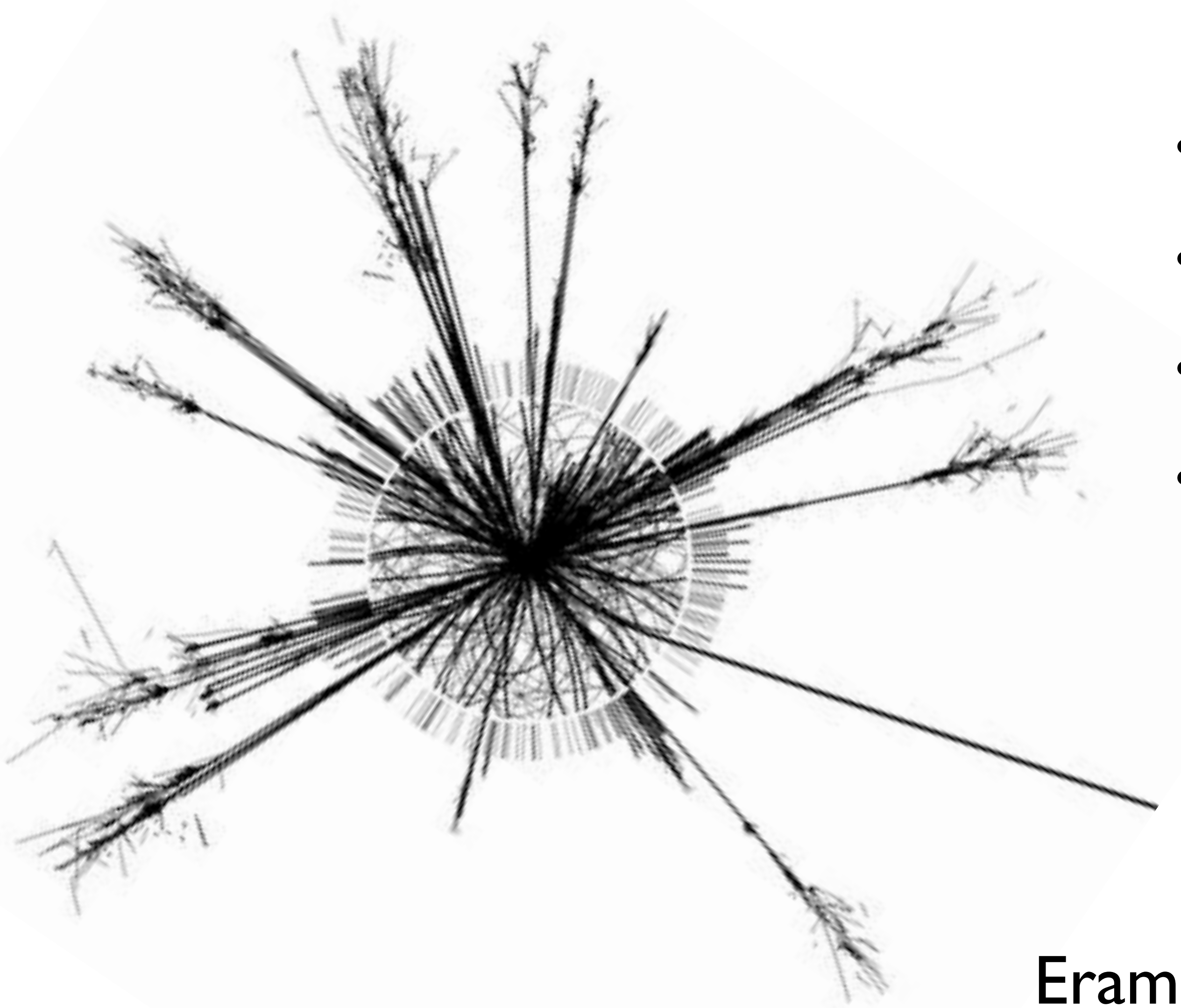
The Standard Model of Particle Physics - I

Lecture 3

- Quantum Numbers and Spin
- Symmetries and Conservation Principles
- Weak Interactions
- Accelerators and Facilities



Eram Rizvi

Queen Mary University of London

Royal Institution - London

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Outline

A Century of Particle Scattering 1911 - 2011
- scales and units
- overview of periodic table → atomic theory
- Rutherford scattering → birth of particle physics
- quantum mechanics - a quick overview
- particle physics and the Big Bang

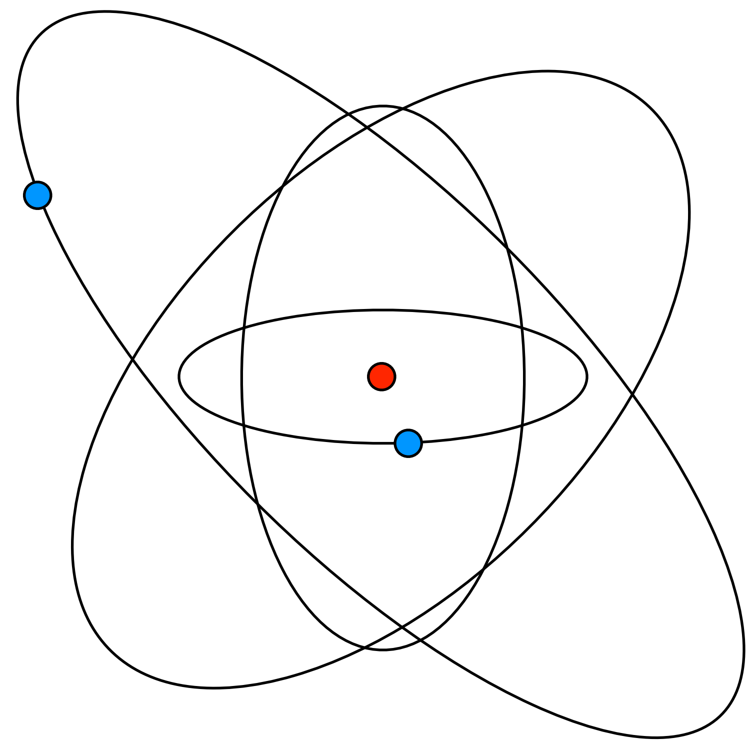
A Particle Physicist's World - The Exchange Model
- quantum particles
- particle detectors
- the exchange model
- Feynman diagrams

The Standard Model of Particle Physics - I
- quantum numbers
- spin statistics
- symmetries and conservation principles
- the weak interaction
- particle accelerators

The Standard Model of Particle Physics - II
- perturbation theory & gauge theory
- QCD and QED successes of the SM
- neutrino sector of the SM

Beyond the Standard Model
- where the SM fails
- the Higgs boson
- the hierarchy problem
- supersymmetry

The Energy Frontier
- large extra dimensions
- selected new results
- future experiments



Why do electrons not fall into lowest energy atomic orbital?

Niels Bohr's atomic model:
angular momentum is quantised ⇒ only discreet orbitals allowed
Why do electrons not collapse into low energy state?

What do we mean by 'electron' ?
charge = -1
spin = ½
mass = 0.511 MeV/c^2

Any object satisfying these conditions is an electron!

Quantum particles possess spin
Measured in units of ħ = h/2π

<u>All</u> particles fall into 2 categories

<u>Fermions</u>:
spin = $^1/_2$, $^3/_2$, $^5/_2$...

<u>Bosons</u>:
spin = 0, 1, 2 ...

True for all particles
A set of <u>quantum numbers</u> specifies the particle type
Quantum numbers are encoded in the wave function
Wave function ψ is related to probability of observing the particle

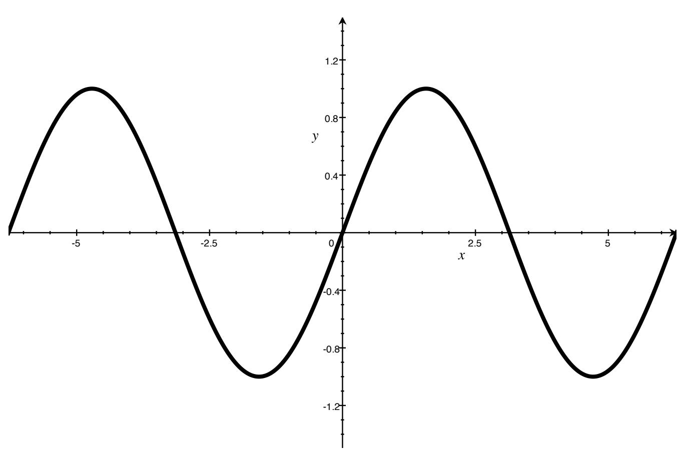
P = Probability of observation
A = some constants of nature

$$P = A\psi^2$$

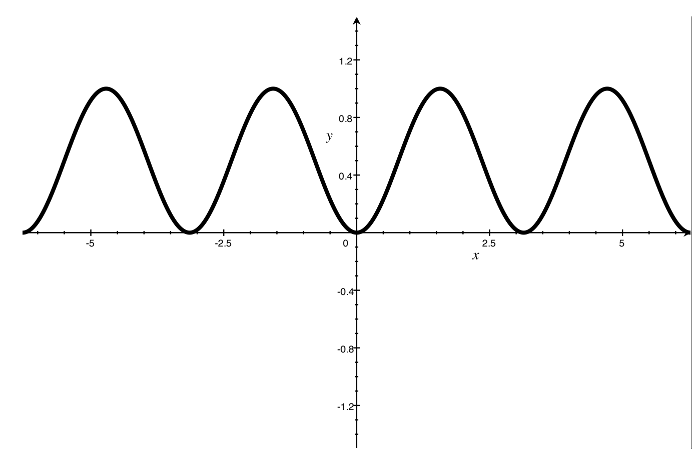
probability can never be negative
probability can never be > 1
Experiment is only sensitive to ψ^2

For example:

ψ =



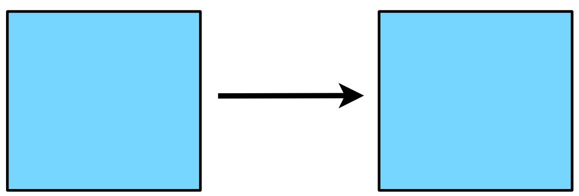
ψ^2 =



Symmetry in Physics

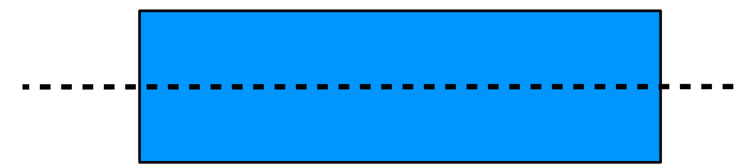
Many forces and phenomena in nature exhibit symmetries
An object has a symmetry if an operation/transformation leaves it invariant (i.e. the same)

Rotational Symmetry



Squares rotated 90° remain unchanged
transformation is $\theta \rightarrow \theta + 90°$

Reflection Symmetry = Parity



Rectangle reflected about axis is invariant
transformation is $x \rightarrow -x$

Mass symmetry

$$F = G\frac{m_1 m_2}{r^2} = G\frac{m_2 m_1}{r^2}$$

Newtons Law is symmetric about
transformations of m_1 and m_2

Time symmetry

Physics remains the same if time runs backwards
Reflections about the t=0 axis are <u>invariant</u>
transformation is $t \rightarrow -t$

Parity

Parity is simply a reflection about a given axis in space

In 3d we reflect object about all three Cartesian axes

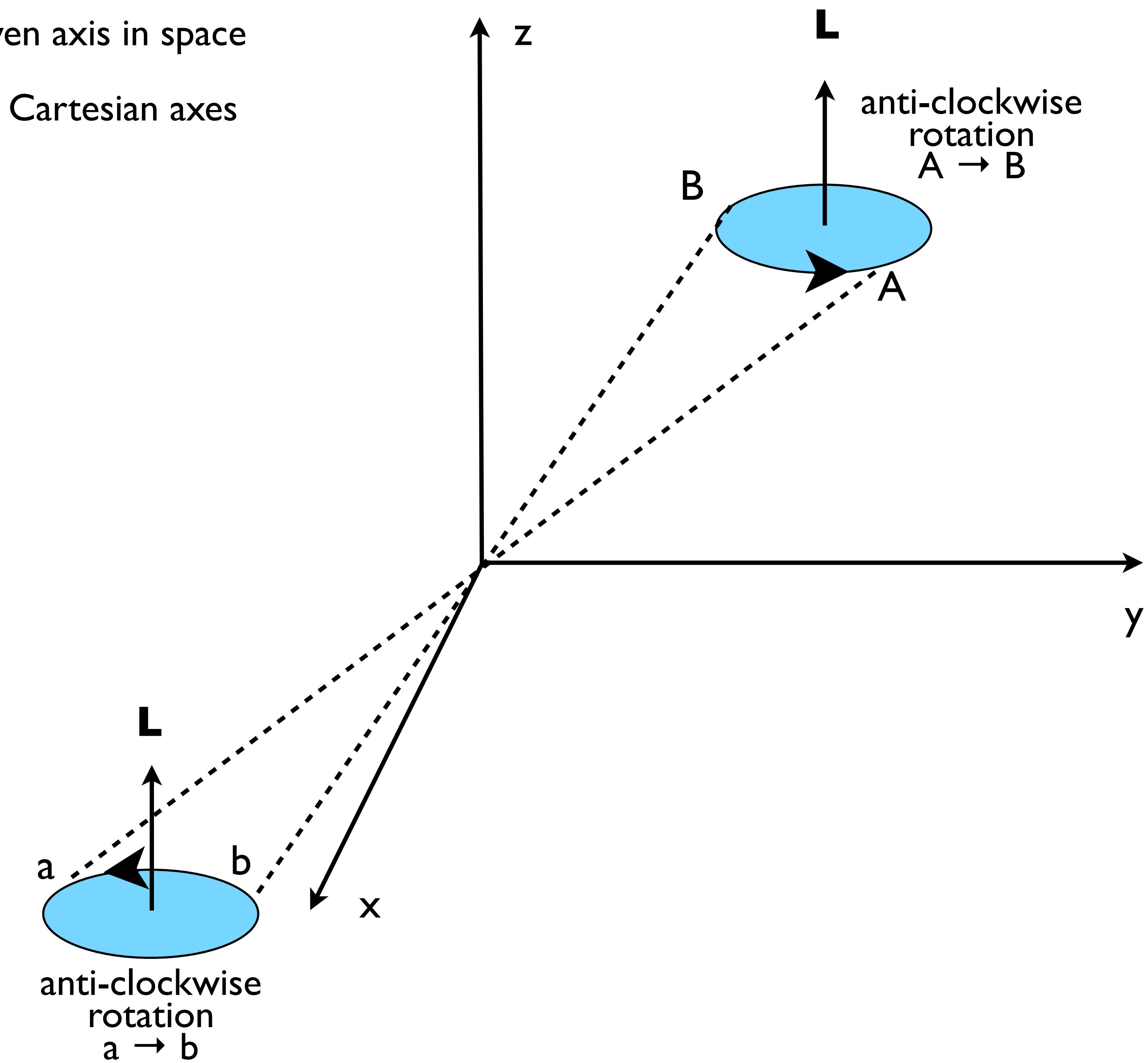
$x \rightarrow -x$

$y \rightarrow -y$

$z \rightarrow -z$

$A \rightarrow a$

$B \rightarrow b$



Some quantities do not flip sign:
L = spin or angular momentum
This remains the same after a parity inversion

Symmetric Wave functions

In terms of wave functions of a particle trapped in a "box" by a potential energy field V
V = 0   inside the box
V =∞ at the walls of the box ⇒ particle is trapped

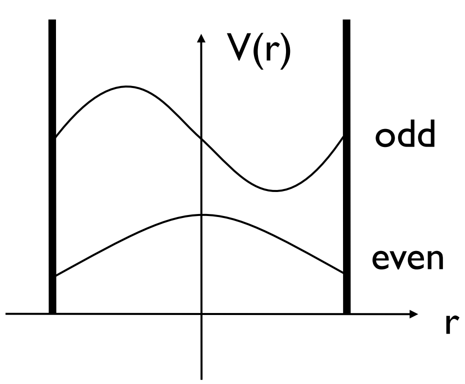
we solve Schrödinger equation to find all allowed states □

$$\frac{-\hbar^2}{2m}\nabla^2\psi + V(r)\psi = i\hbar\frac{\partial}{\partial t}\psi$$

If potential V is symmetric:

$$V(r) = V(-r)$$

then: $|\psi(r)|^2 \equiv |\psi(-r)|^2 \;\rightarrow\; \psi(-r) = \pm\psi(r)$



If V(r) is unchanged then resulting allowed particle states must be even or odd parity

$\psi(-r) = +\psi(r)$ even parity

$\psi(-r) = -\psi(r)$ odd parity

$V(r) \neq V(-r)$ then $|\psi(r)|^2 \neq |\psi(-r)|^2$

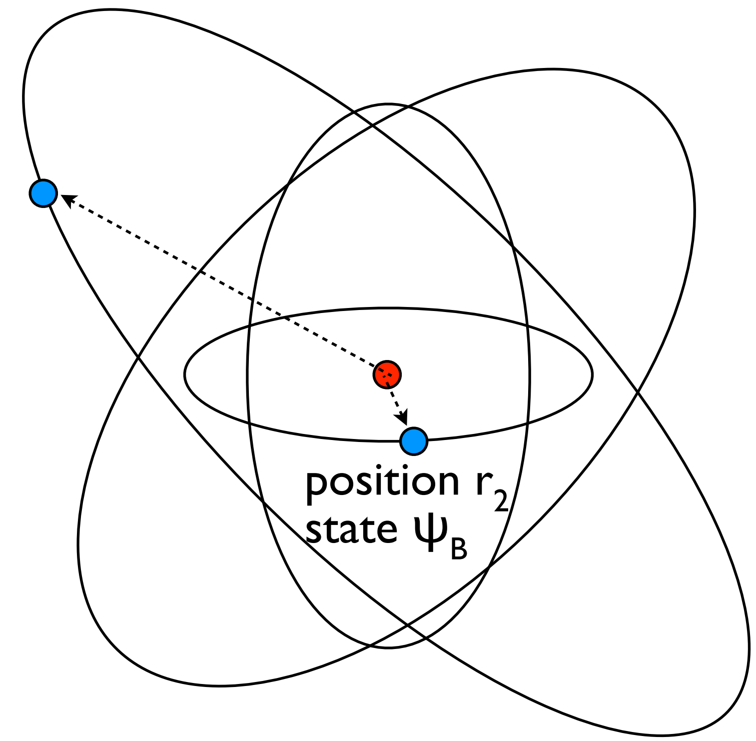
Two-particle Wave functions

Consider 2 electrons in Helium atom at positions r_1 and r_2 and in different states ψ_A and ψ_B

What is the combined two-particle wave function ?

We try:

$$\psi_{AB} = \psi_A(r_1) \cdot \psi_B(r_2)$$



Interchanging the two electrons we get:

$$\psi_{BA} = \psi_B(r_1) \cdot \psi_A(r_2)$$

Electrons are indistinguishable - they do not carry labels to identify one from another

All electrons are the same

So measurement cannot distinguish if two electrons swapped position

But, if a measurement could detect the interchange then they are not indistinguishable

Therefore this 2-particle combined wave function is no good!

For indistinguishable particles, probability densities <u>must</u> be invariant to exchange i.e. ψ_{AB} can differ only by sign from ψ_{BA}

Wave-functions are symmetric if $\psi_{AB} = +\psi_{BA}$

Wave-functions are anti-symmetric if $\psi_{AB} = -\psi_{BA}$

Experiments show:

particles with integer spin (0,1,2...) have symmetric wave-functions

particles with half integer spin ($^1/_2$, $^3/_2$, $^5/_2$) have anti-symmetric wave-functions

Wolfgang Pauli

Nobel Laureate 1945

For two particle systems take wave function of the form:

$$\psi_{AB} \simeq [\psi_A(r_1)\psi_B(r_2) \pm \psi_B(r_1)\psi_A(r_2)]$$

bosons : integer spin +
fermions: half integer spin –

What happens for two identical particles in same quantum state? $\psi_A = \psi_B$

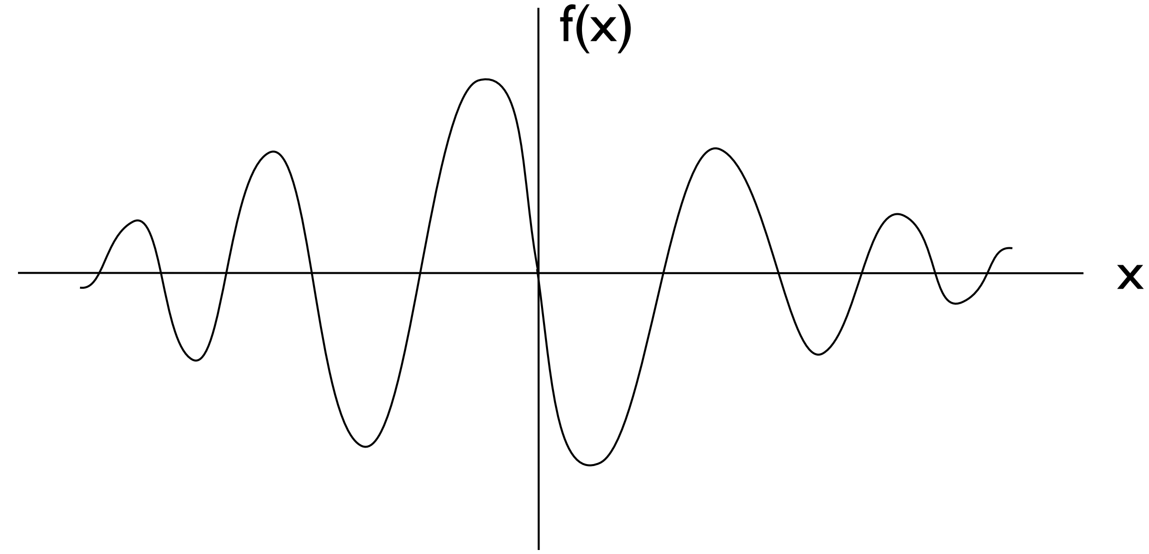
$\psi_{AB} \to 0$ for identical fermions (half integer spin particles)

Pauli Exclusion Principle: Identical fermions cannot occupy the same quantum state!

This stops the atom from collapse!

Consider this function f(x):
exact functional form is unknown

What do we know about it?
it is odd i.e. $f(-x) = -f(x)$
Fourier transform will have no cos terms
sum from -n to +n is 0



So symmetries can provide useful information
Particularly dynamical symmetries of motion
Greeks believed stars moved in circles since they were most symmetrical orbits
Newton realised fundamental symmetries revealed **not** in motions of individual objects...
...but in **set of all possible motions**
Symmetries are manifest in equations of motion - not particular solutions to those equations
Gravity is spherically symmetric, but planets have elliptical orbits
In 1917 role of symmetries in physics was understood: Emmy Noether's Theorem:

Every symmetry of nature yields a conservation law (and vice versa!)

Translation in time	Energy conservation
Translation in space	Momentum conservation
Rotations	Angular Momentum conservation
Gauge Transformation	Charge conservation

Laws of physics are symmetric with respect to translations in time:
they are the same today as they were yesterday

Analysing the set of transformations of a system uses Group Theory

Imagine swapping all numbers +ve and -ve e.g. my bank account
Doing this does not break the laws of mathematics
I suddenly become very rich indeed...

...but if the entire world did this simultaneously we would notice no difference at all!
The banking world is symmetric under sign inversion of real numbers
The total amount of money is conserved !!

A symmetry principle has yielded a law of conservation

Universal Symmetries

In forming theories physicists look for symmetries to help explain phenomena
In particle physics such symmetries tell us of the nature of space-time & particles themselves
Consider charge symmetry: replace all particles with anti-particles

- Our universe is composed of matter
- We **happen** to call it "matter"
- We **could** have called it "anti-matter"
- But, we **do know** that we are made of the same type (either all matter or not)
- Fundamental laws of nature do not tell us if we are made of matter or anti-matter
- There is no difference!

Same is true of parity inversion:

- Parity inversion turns left-handed co-ordinate system into a right-handed one
- There is no fundamental distinction between "left" and "right"
- OK, humans have hearts on left side of body...
- But we concern ourselves with laws of nature, not accidental arrangement of objects

Similarly for time reversal symmetry:

- If we replace t with -t in all equations
- If we did turn time backwards - laws of physics are expected to be the same
- In this universe time <u>does</u> run forwards...
- ...if we changed this, we don't expect Newton's laws to fail

At least, we expect universe to behave this way...

Universal Symmetries

Charge, Parity & Time are 3 fundamental symmetries:

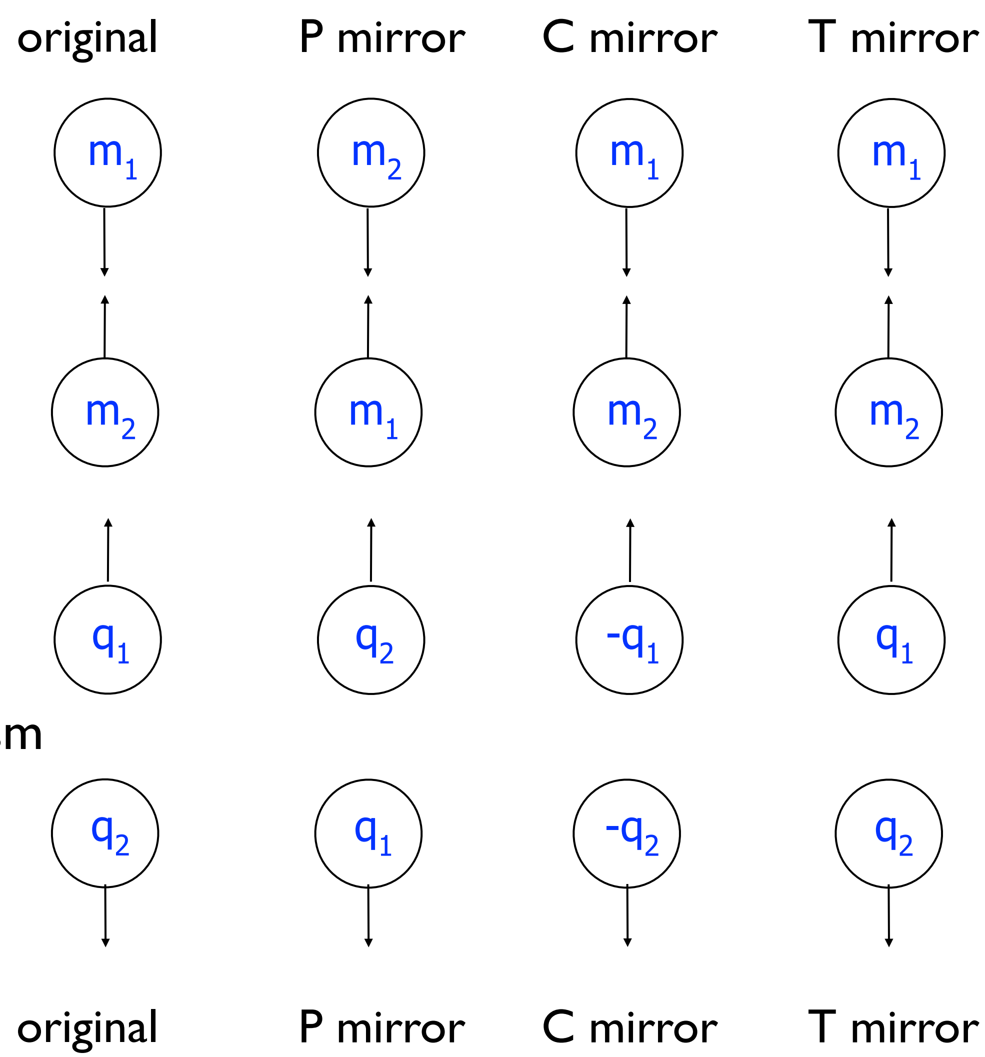
C	Charge conjugation	swap all particles with anti-particles
P	Parity inversion	reflect system about origin: $P\psi(r) = \psi(-r)$
T	Time reversal	time is reversed in direction: $T\psi(t) = \psi(-t)$

Gravity, & electromagnetism are both invariant to C, P and T inversions

8 experiments of two particles with masses m_1 and m_2 and electric charge q_1 and q_2

Gravity

Electromagnetism



Time reversal:
Planetary orbits are reversed
Masses decelerate as they move apart
Force between masses remains same

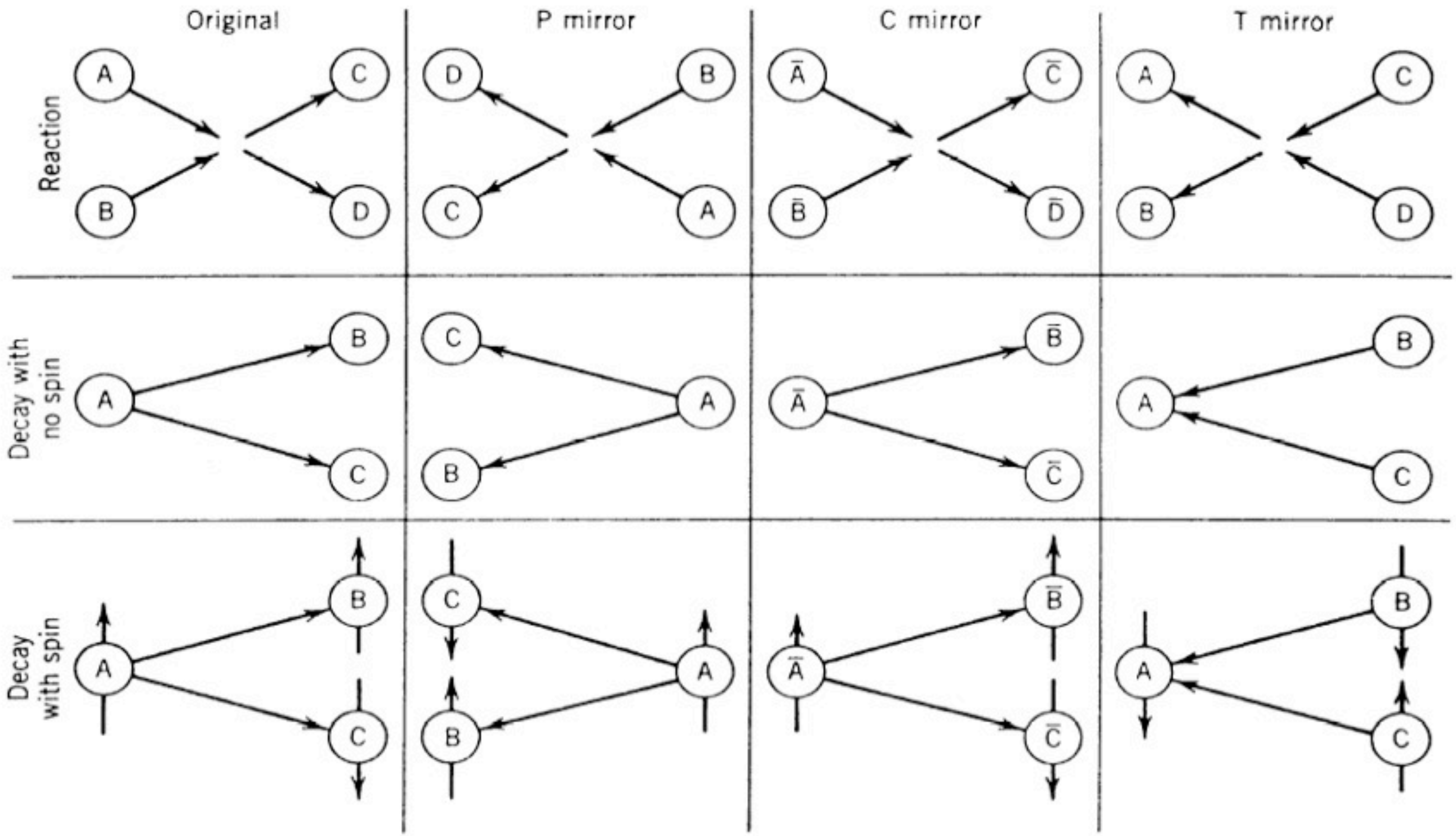
Time reversal:
Charges decelerate as they move together
Force between charges remains same

Can test C, P, and T symmetries in a series of experiments: A+B → C+D

Test P: swap positions of A and B (i.e. projectile A and target B, instead of vice versa)

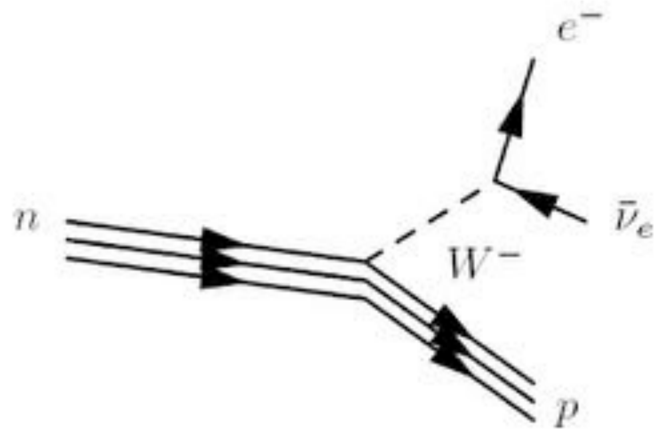
Test C: exchange A and B for anti-particles

Test T: collide C and D to produce A and B



Wolfgang Pauli wrote: *"I do not believe that the Lord is a weak left-hander, and I am ready to bet a very large sum that the experiments will give symmetric results"*

Richard Feynman bet $50 that experiment would confirm parity as a valid symmetry



Beta decay is a weak process
Mediated by W exchange

Madame Wu

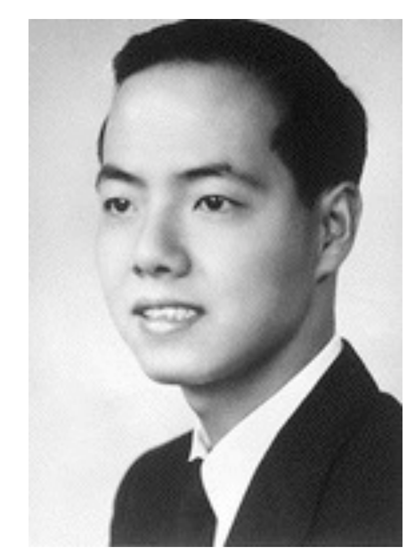
In 1956 Chien-Shiung Wu showed parity is violated in radioactive beta decay
Weak force does not conserve parity!

	Conserves Charge?	Conserves Parity?
Electromagnetism	yes	yes
Strong	yes	yes
Weak	yes	no!

Laws of physics are different for real-world and mirror experiments!

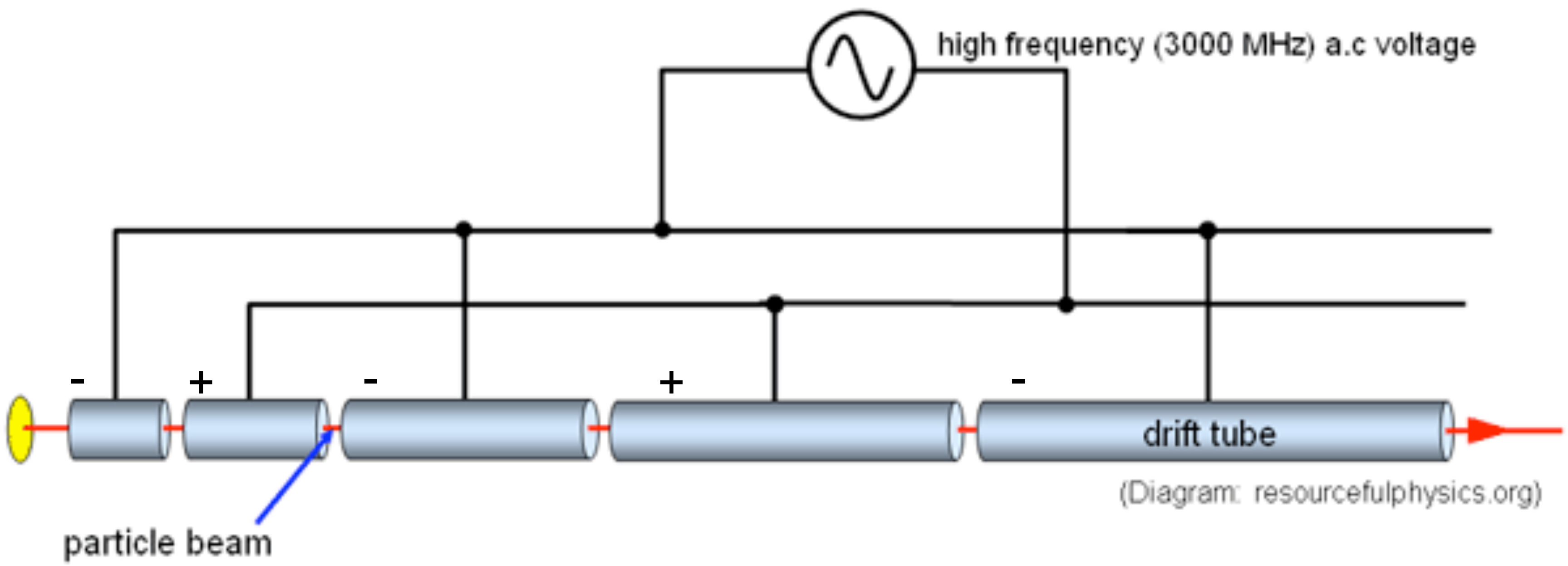
Nobel Laureates 1957

C.N. Yang



T.D. Lee

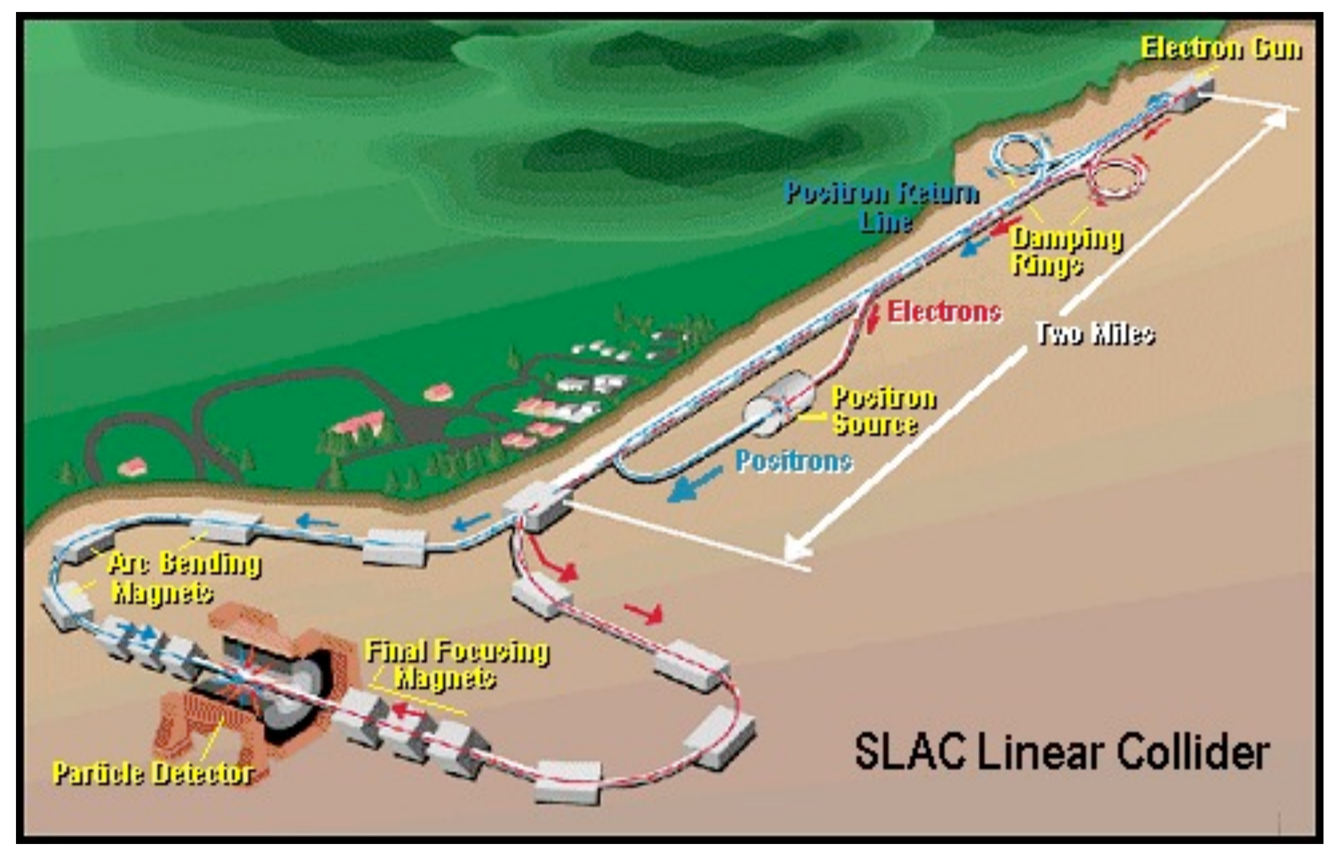
Lee & Yang predicted parity violation in 1956
Awarded Nobel prize in 1957 after Wu's validation



No electric field inside drift tubes

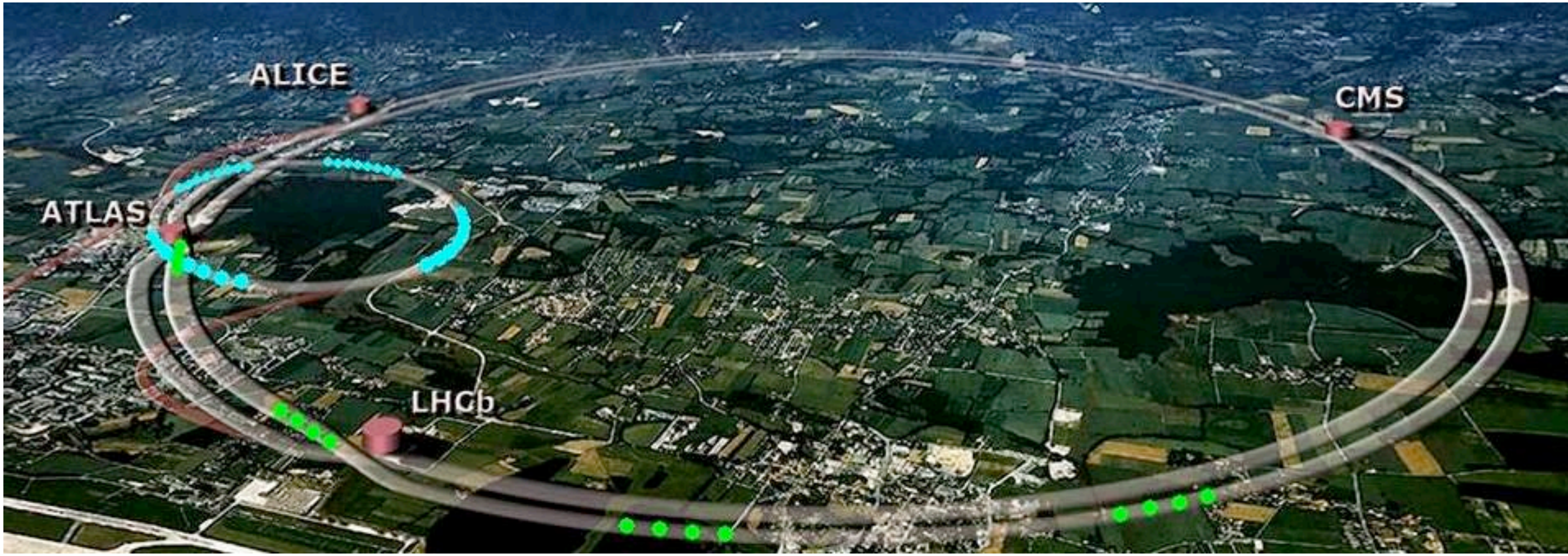
Electric field non-zero between tubes

Adjust tube gap as particle accelerates

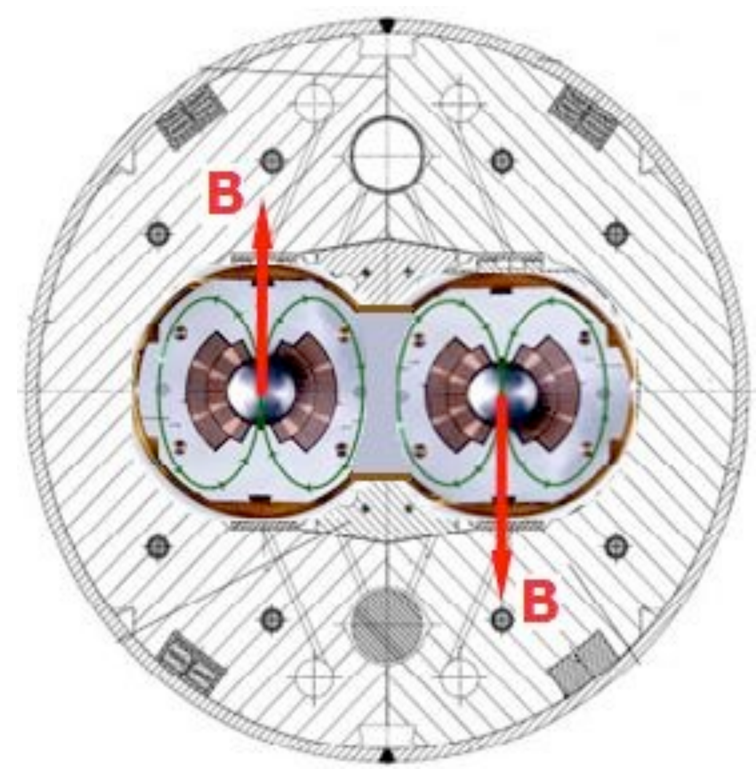


The LHC

The Large Hadron Collider

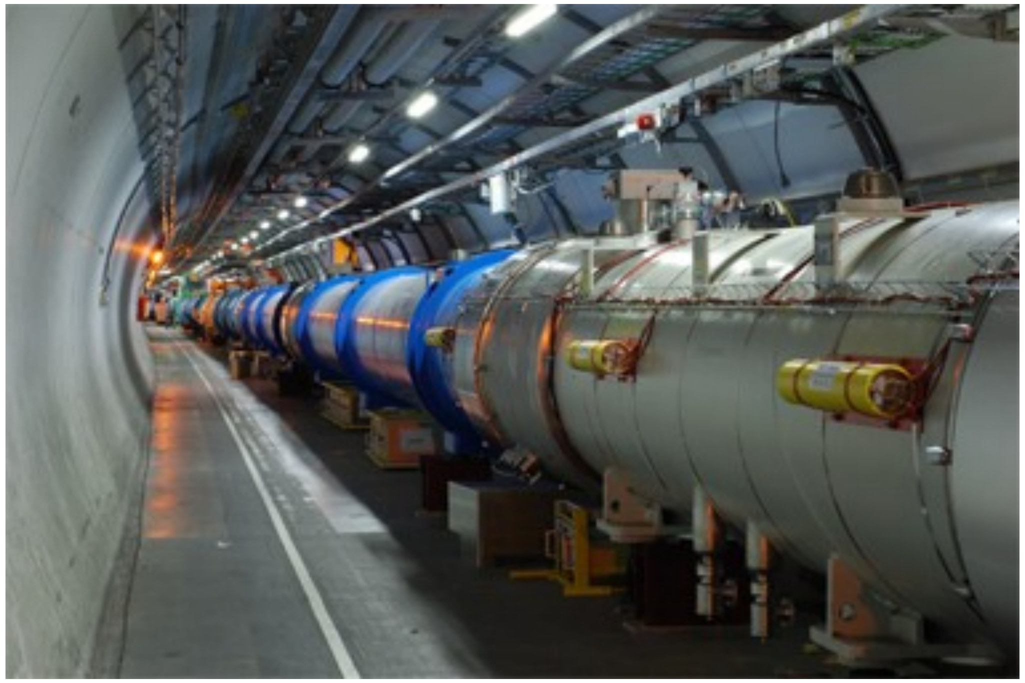


- 27 km circumference tunnel in France / Switzerland - near Geneva
- Highest energy accelerator in the world
- Protons accelerated to 7,000 GeV = 99.9999991% speed of light
- High vacuum
- Super cold superconducting magnets to achieve strong magnetic fields
- 17,000 A current in magnets
- Four experiments:
  - Atlas
  - CMS
  - LHCb
  - Alice



The LHC

Operating temperature: -271°C One of the coldest places in universe
High energy collisions equivalent to temperatures 100,000 times hotter than sun's core
High vacuum needed to avoid unwanted collisions with air molecules - less dense than solar system
1200 dipole magnets to bend the protons
Protons circulate 11,000 times per second
Generates up to 600 million collisions per second
LHC costs for material, construction, personnel (excluding experiments) = € 3, 000 , 000 , 000



The LHC breaks record for 'luminosity'