The Physics of BABAR:
The Weak Force and Antimatter

QuarkNet Associate Teacher's Institute

D. Kirkby, 19 August 2002

What is BABAR ??

- A particle physics experiment
- An international collaboration of physicists
- An asymmetric-energy B-factory detector
- An acronym: “B Anti-B Asymmetric Rings”
- An elephant

The "Standard Model" of Particle Physics

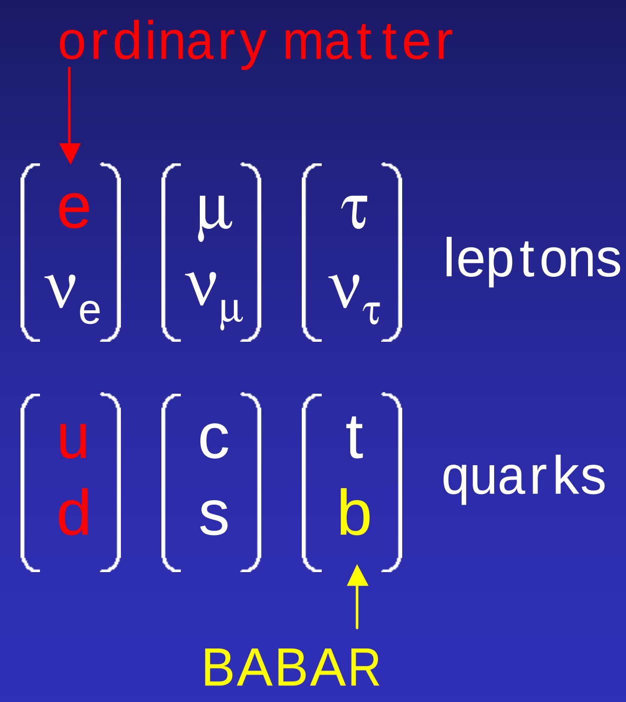
We have developed a very successful model that agrees with all observations (but does not yet include gravity).

Matter is made from 12 different fundamental "fermions":

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3



More info -> http://particleadventure.org/particleadventure/

Interactions

The interactions between fundamental particles reflect the underlying symmetries of nature.

The “Standard Model” describes Weak, EM, and Strong interactions.

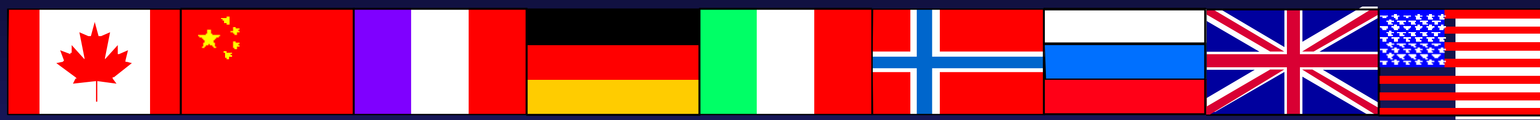
PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Astronomy (↑ Gravitational) BABAR (↑ Weak) Chemistry, biology (↑ Electromagnetic)

The BABAR Collaboration

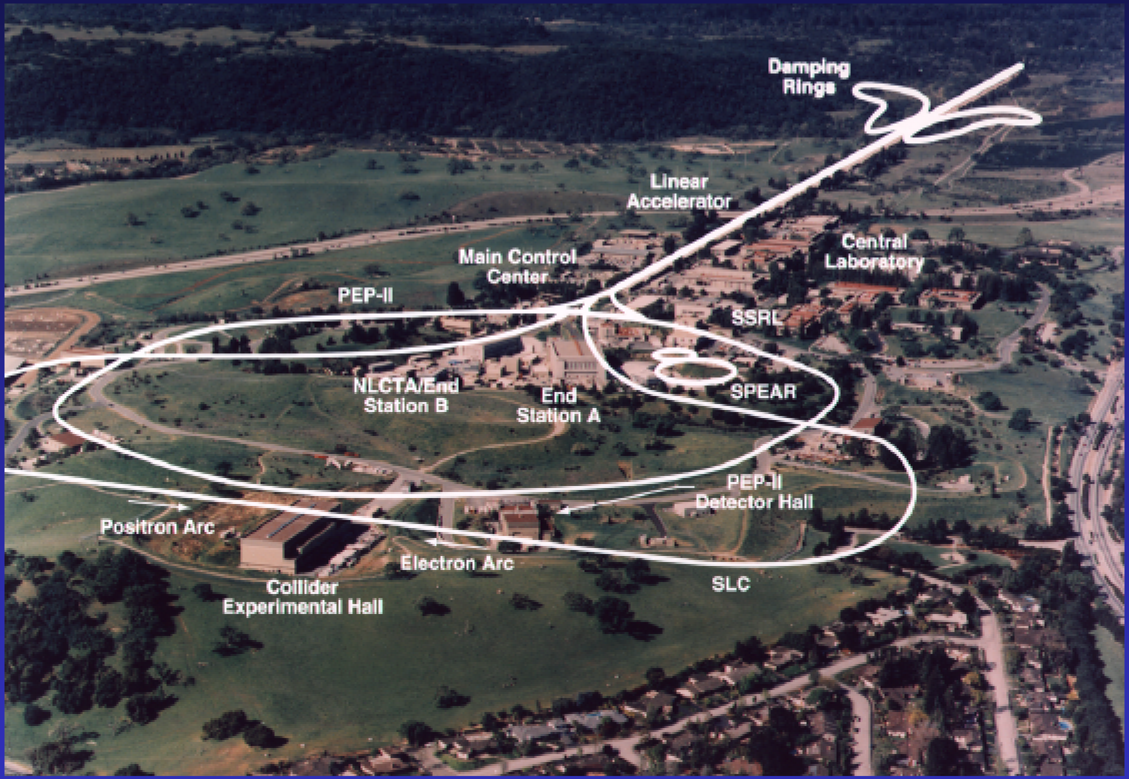
BABAR is an international collaboration of ~530 physicists from 74 institutions in 9 countries!



The BABAR Experiment at SLAC

BABAR is a large particle-physics detector located at the Stanford Linear Accelerator Center (SLAC).

BABAR records e+e- collisions produced by the PEP-II collider.



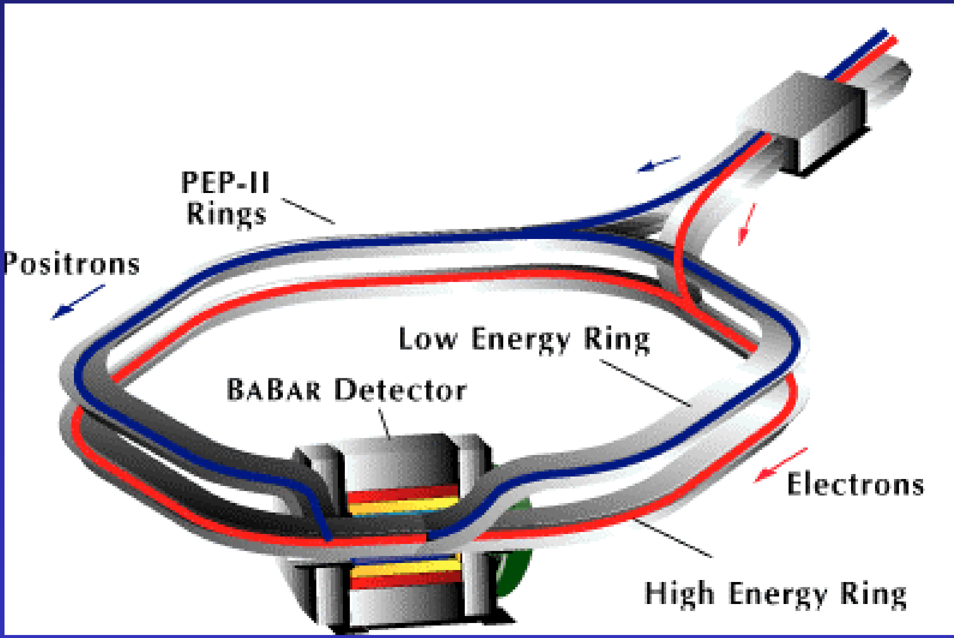
More info -> http://www.slac.stanford.edu/BFROOT

The PEP-II Asymmetric Energy B Factory

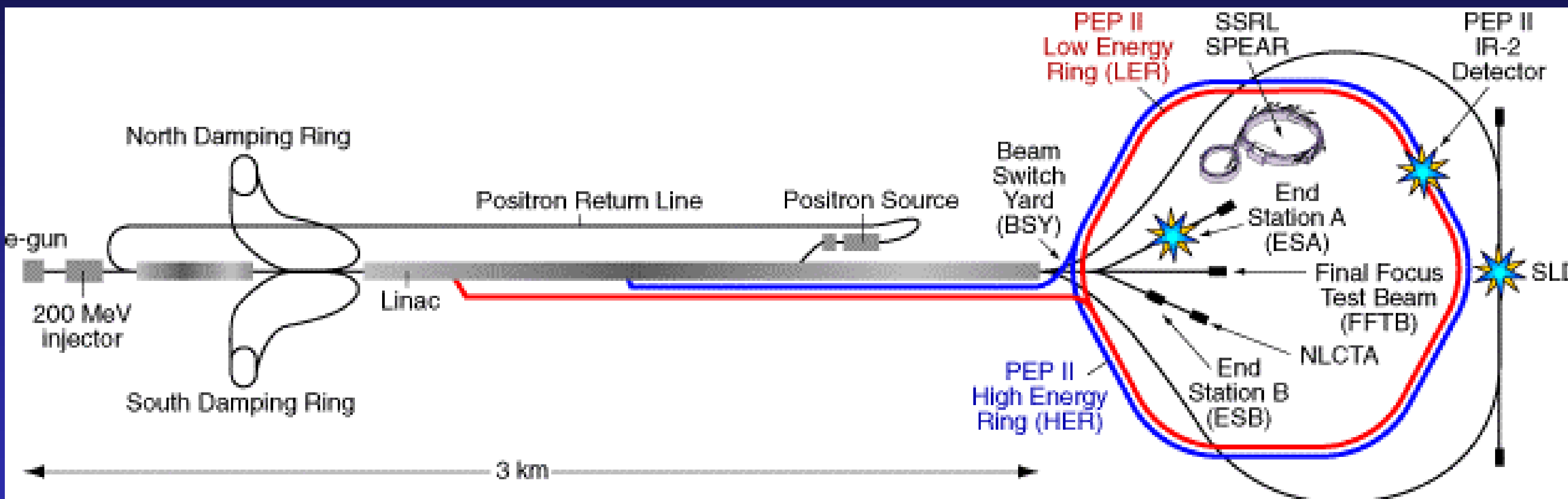
PEP-II collides circulating beams of electrons and positrons.

PEP-II is an unusual collider since the particles in each beam have different (asymmetric) energies.

PEP-II is a “B Factory” since the energies of the 2 beams are tuned so that their collisions produce new particles containing b quarks.

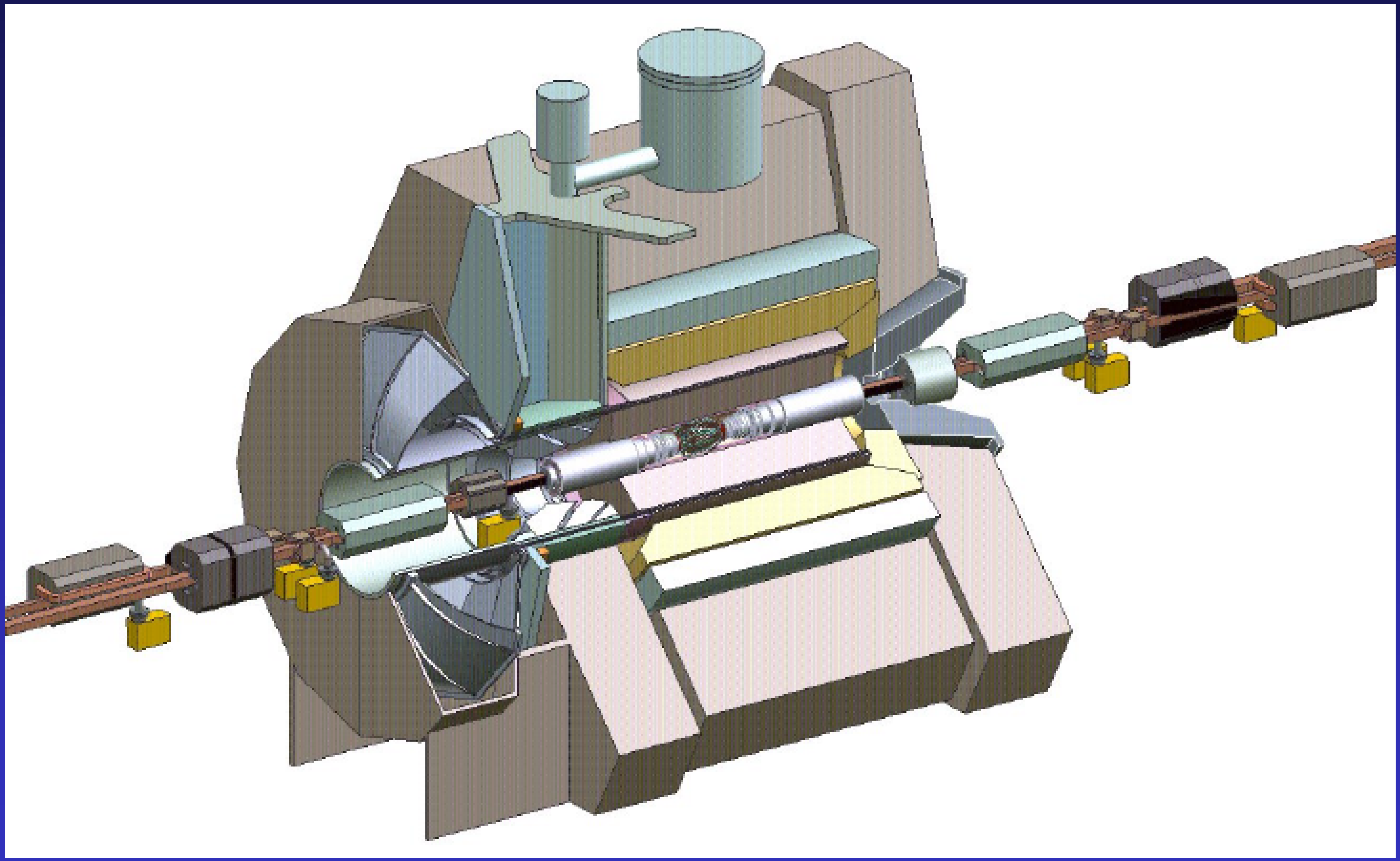


Electrons & positrons are accelerated to their final energies in a linear accelerator and then “injected” into the PEP-II storage rings:



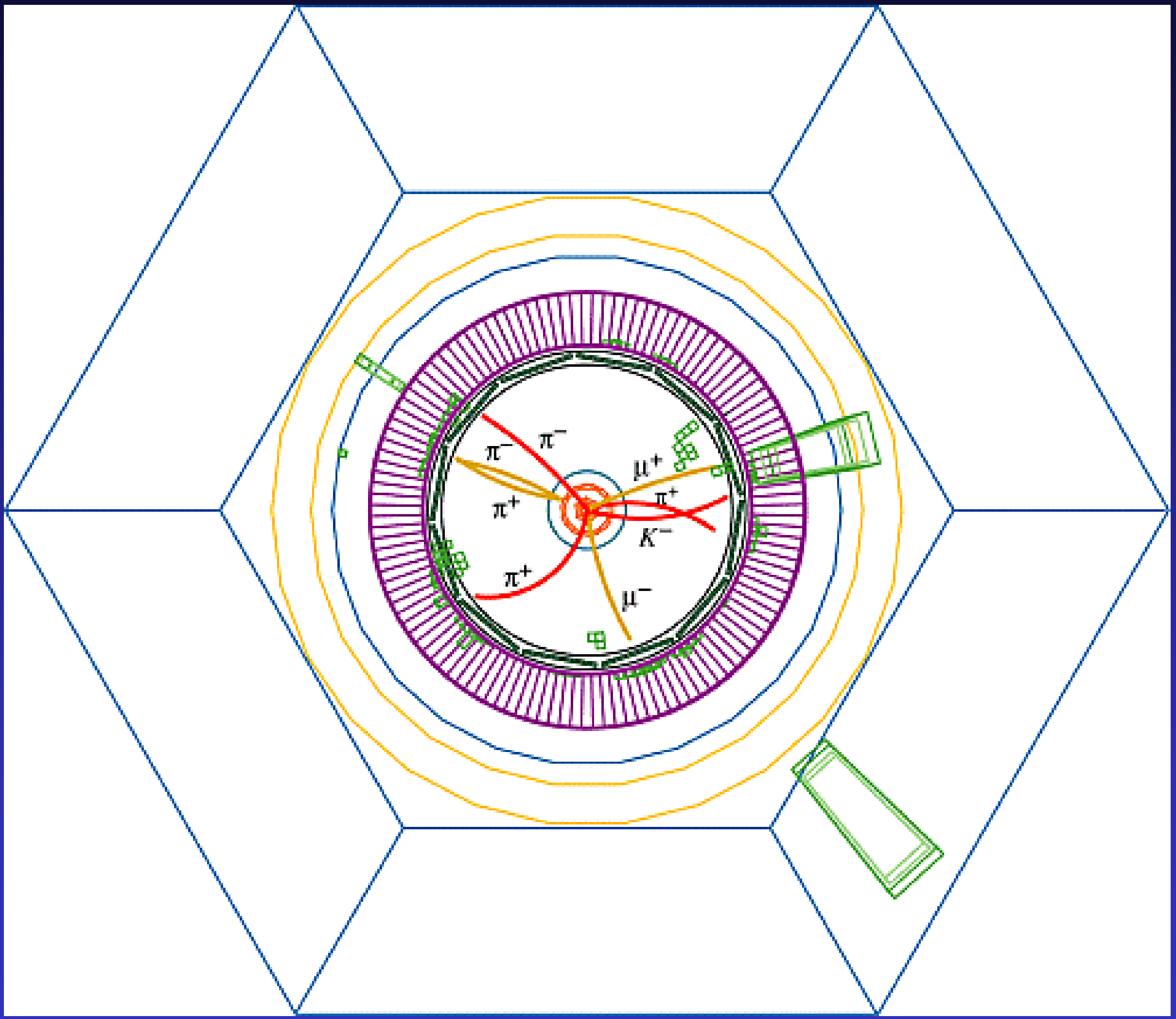
The BABAR Detector

Particle physics detectors for collider experiments are built like an onion. Each layer is specialized to perform a particular type of measurement.



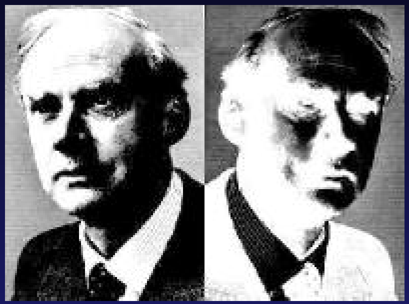
The purpose of the detector is to make an electronic record ("event") of the particles produced in a collision.

Reconstruction software analyzes each event to determine the energy, momentum, and type of each particle produced.



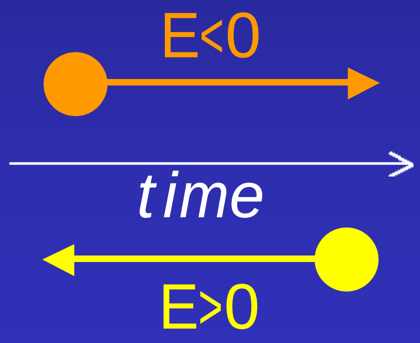
BABAR Physics: Matter & Antimatter

The equations of motion for charged particles moving close to the speed of light (QED) were first worked out in 1931 by Paul Dirac.



The equations have 2 possible solutions, both of which are mathematically equally valid (just like $x^2 = 1 \Rightarrow x = \pm 1$). But only one solution makes sense for ordinary matter (ie, positive energy moving forwards in time)!

The other solution describes particles with negative energy moving forwards in time, or equivalently, positive energy moving backwards in time…

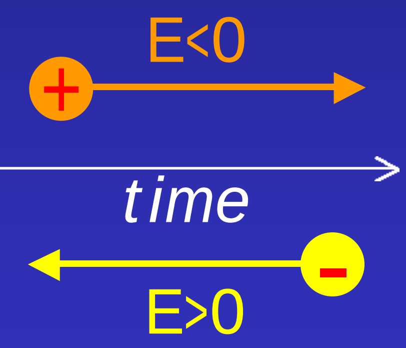


What are the Properties of Antimatter?

Every fundamental particle has its own antiparticle (although some particles are their own antiparticles, e.g. the photon).

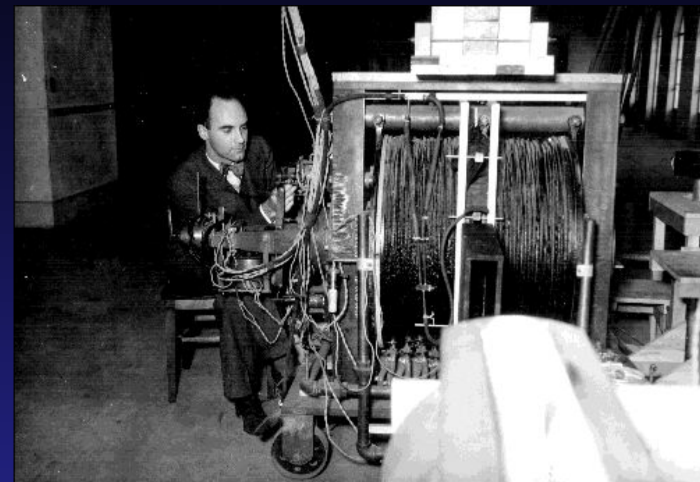
Most intrinsic properties of a particle and its antiparticle are the same (mass, spin, ...). The exceptions are properties that depend on the direction of time such as charge. Therefore, a particle that is its own antiparticle must be neutral (but not vice-versa: ν?)

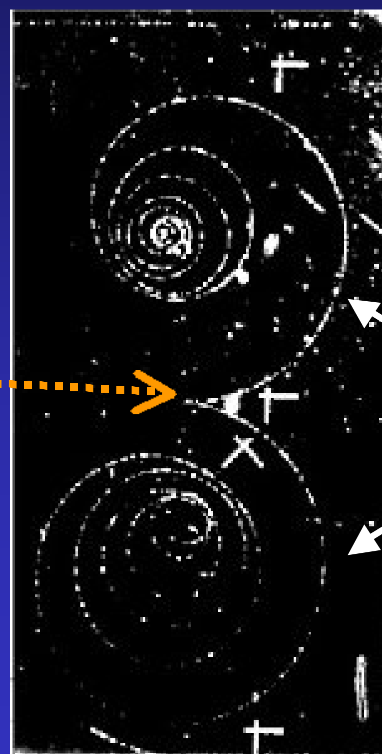
We usually use a bar to indicate an antiparticle ($d \leftrightarrow d$), except for charged fermions (e,μ,τ) where we just flip the charge label ($\mu^- \leftrightarrow \mu^+$)



Antimatter is Discovered!

Antimatter did not remain a mathematical curiosity for long. In 1932, Anderson discovered anti-electrons ("positrons") produced in a cloud chamber by cosmic rays.





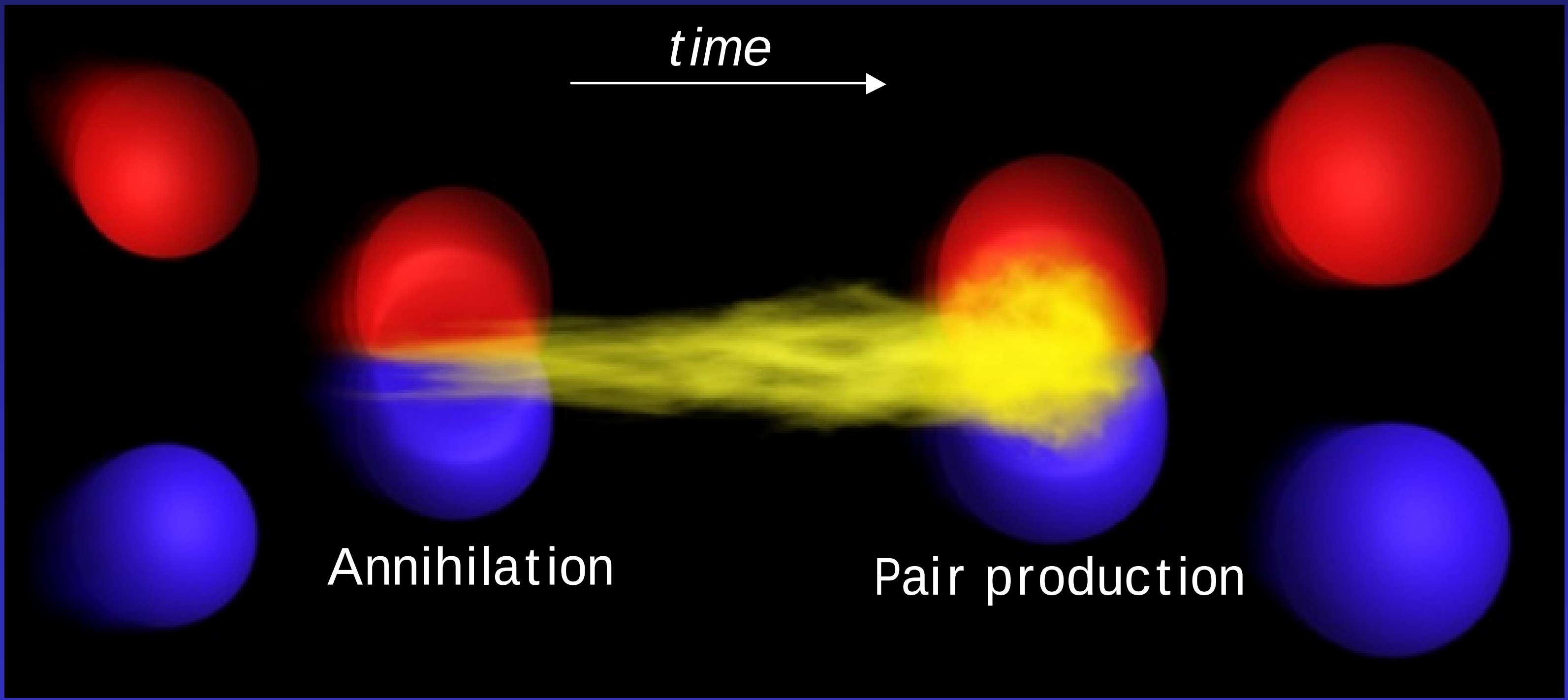
neutral particle

The produced particles have same mass but opposite charge (trajectories are bent in a transverse B field)

Annihilation & Pair-Production

A striking signature for the presence of antimatter is that when a particle & antiparticle meet, they will annihilate to form an energy state (photons, etc).

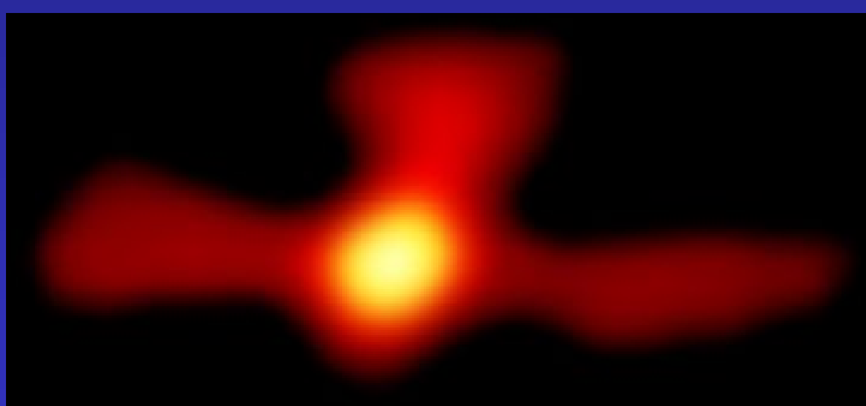
Similarly, an energy state can spontaneously transform into a particle & antiparticle (“pair production”).

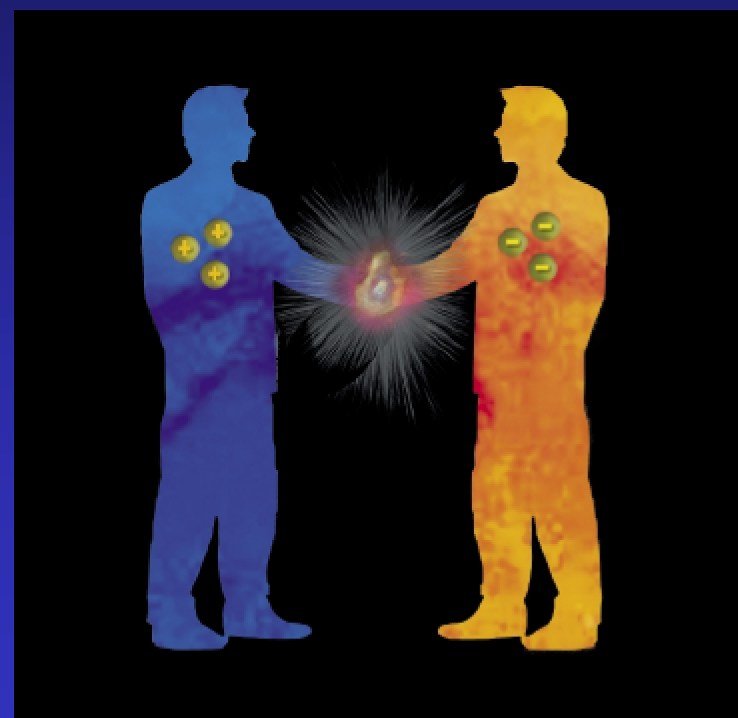


Anti-people in Anti-worlds

Antimatter is not restricted to the domain of fundamental particles. Anti-quarks can be combined to make an anti-proton. An anti-proton can be combined with an anti-electron ("positron") to make anti-hydrogen (this has actually been done at CERN), etc…

There is no physics reason why anti-people should not be living in an anti-world somewhere!

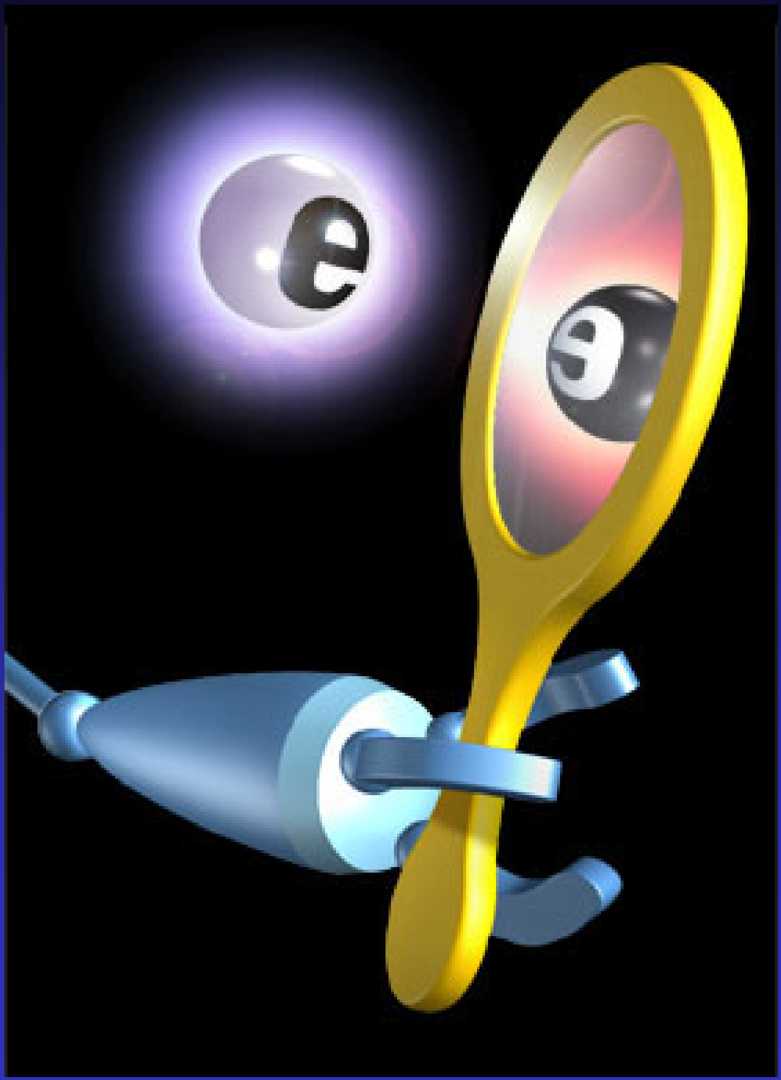




Antimatter is the Mirror Partner of Matter

The mathematical transformation that turns a particle into its antiparticle (and vice versa) is like a mirror.

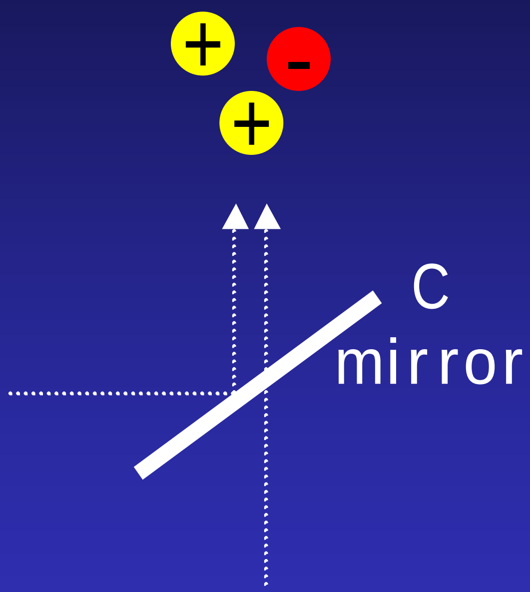
We call this transformation "charge conjugation" or just C.



Charge Conjugation is a Symmetry

Suppose you did an experiment to determine the equations of motion from a system of particles. Could you tell from your results whether you were looking at particles directly, or through a C mirror?

We believe that you can (almost) never tell the difference. In other words, C is a symmetry of nature.



Note: C is a discrete transformation, rather than a continuous one (like time translation or rotation). So there is not necessarily a conservation law associated with C symmetry.

Parity is also a Symmetry

Parity (P) is a mathematical transformation that only affects vectors (or quantities derived from vectors):

scalar: $s \rightarrow s$, e.g. $3 \rightarrow 3$
vector: $\vec{v} \rightarrow -\vec{v}$, e.g. $(4,-1,3) \rightarrow (-4, 1,-3)$

Parity is a mirror transformation (like C).

Although it does not behave exactly like an optical mirror, we use the terminology “left-handed” and “right-handed” to distinguish between particles and their reflections.

We believe that parity is (almost) a symmetry of nature.

C and P are Almost Symmetries

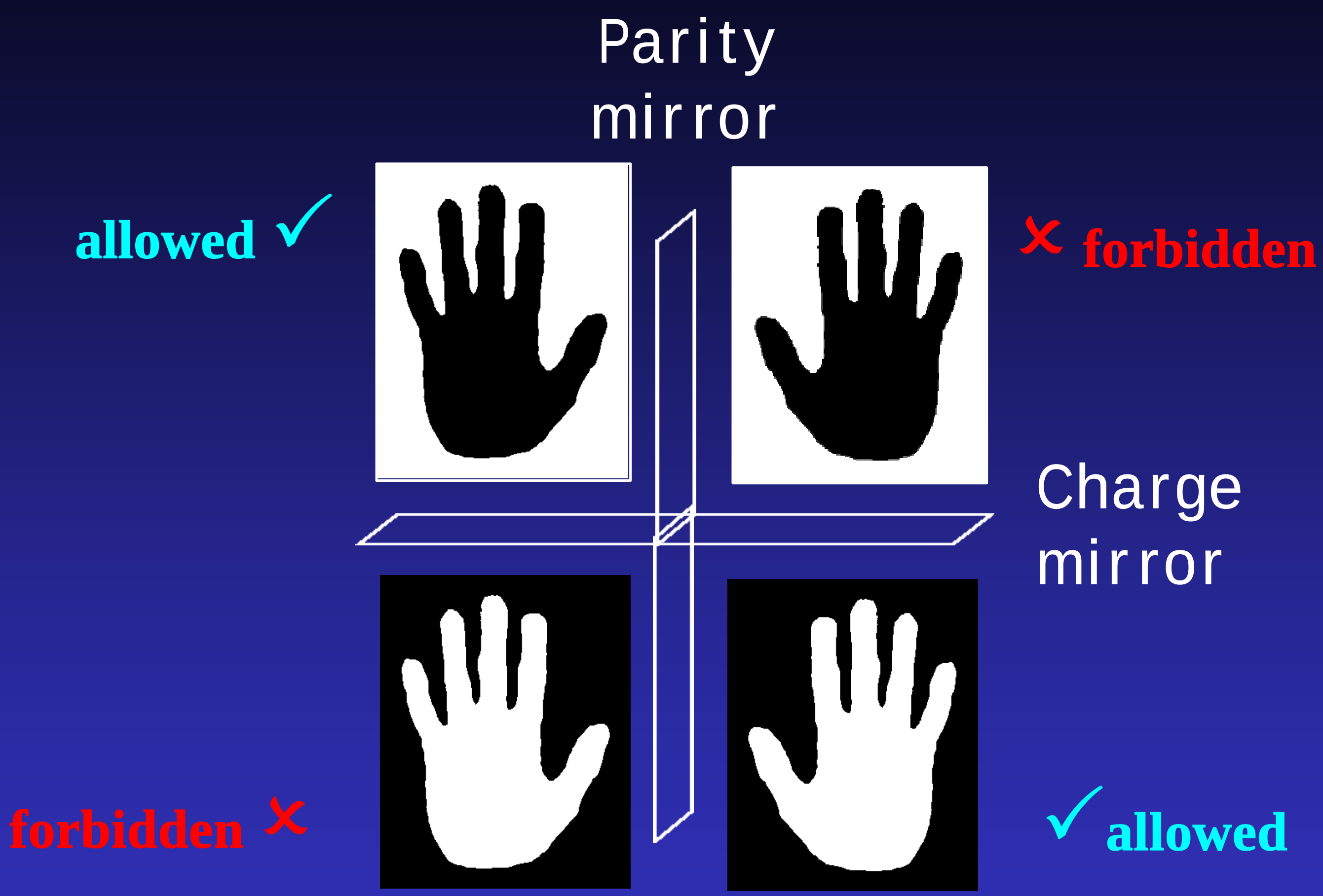
We believe that the only exceptions to the rule that C and P are perfect symmetries occur for the <u>weak interactions</u> of charged particles (which are mediated by $W^{\pm}$ bosons).

These are precisely the processes that BABAR studies!

In 1956, Yang & Lee proposed that the laws of physics are different when viewed through a Parity mirror.

This idea was confirmed experimentally in 1957 (by Wu and others) and led to a theory of charged weak interactions in which the C and P symmetries are both "maximally violated"...

Weak Interactions of Charged Particles



In this theory, nature is symmetric under combined action of the C and P transformations ("CP") in either order.

CP Symmetry is Violated

In 1964, Cronin, Fitch & others made the unexpected discovery that even the combined CP transformation is not an exact symmetry in the weak decays of exotic “Kaon” particles (which contain s-quarks).

The effect was small (about 1 part in 1000) but non-zero!

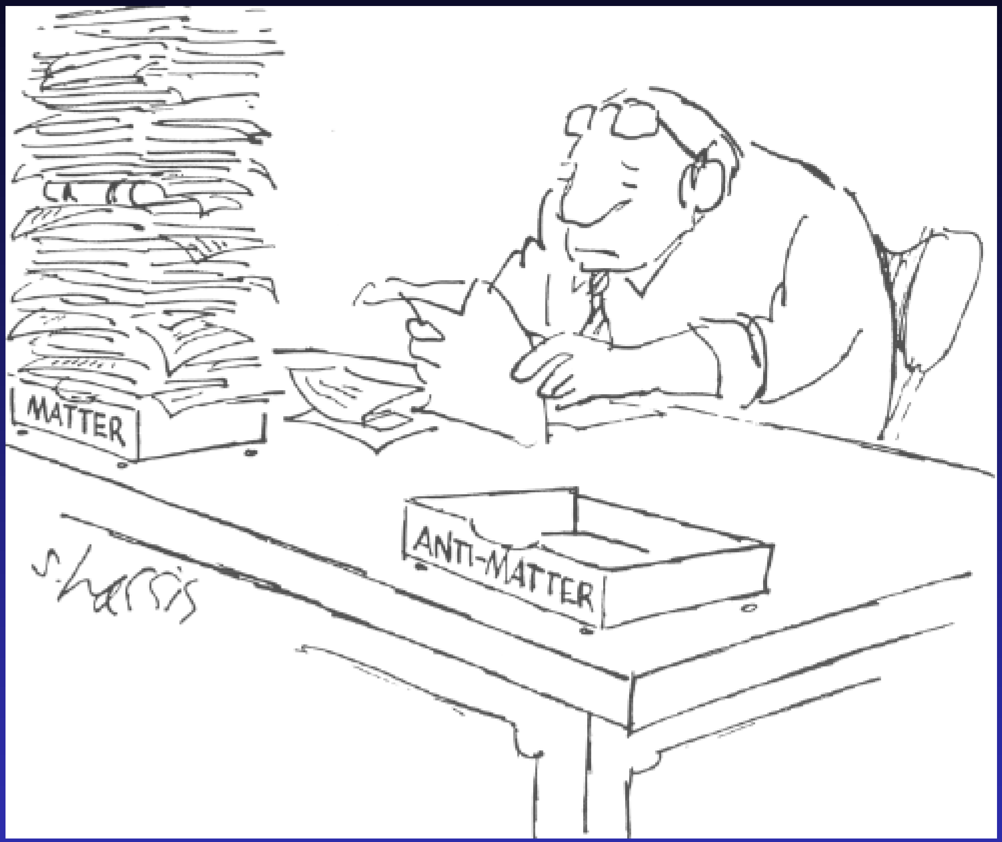
Nobel Prize!

So what! Why do I care about 0.1% discrepancies for W bosons and strange quarks?

BABAR Physics: The Big Picture

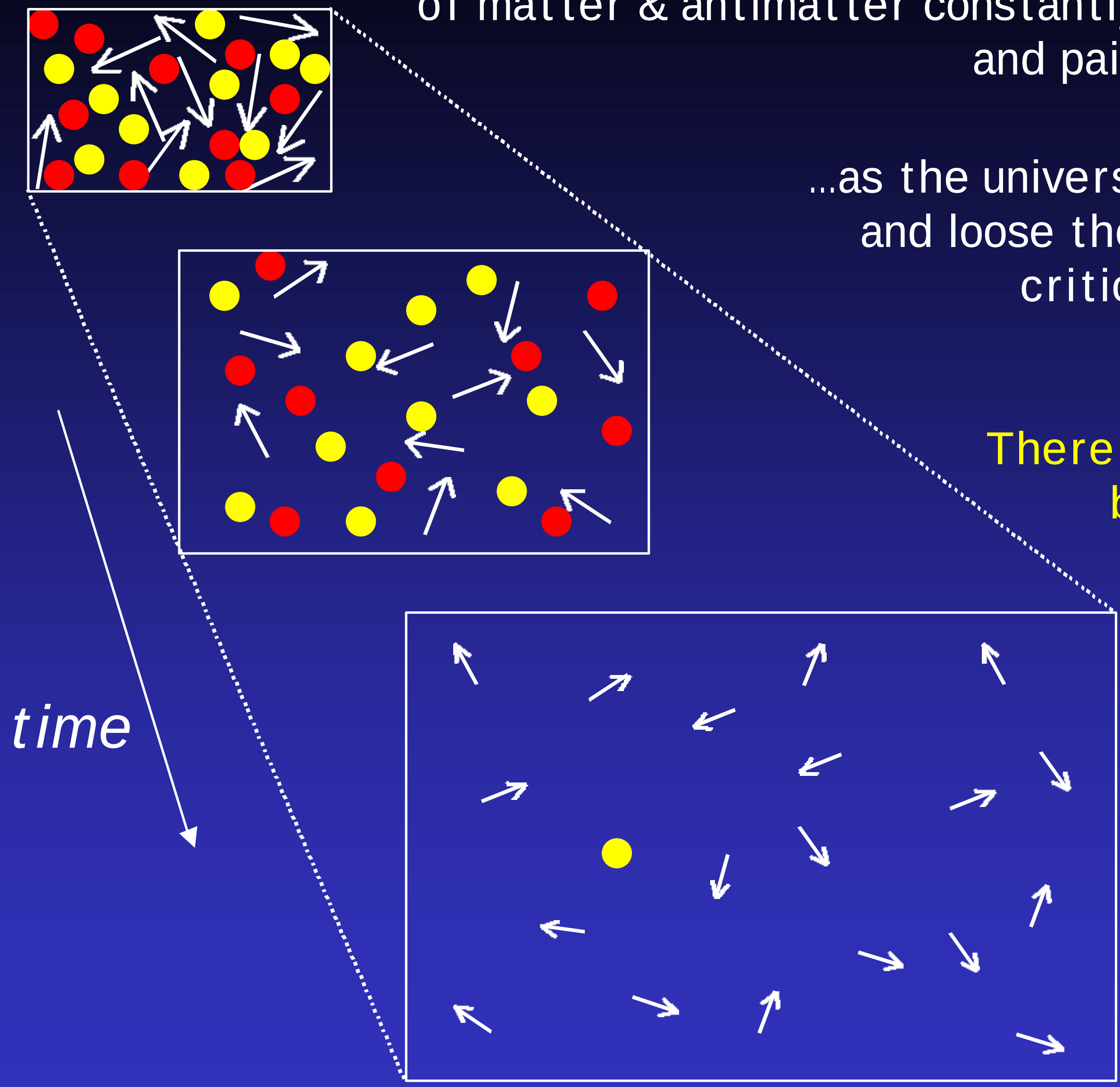
Why are we here??

Observations tell us that the visible universe is almost entirely made of matter…



…however, our theories of cosmology tell us that the universe would be completely empty of both matter (stars, planets, people) and antimatter if CP were an exact symmetry of nature!

Just after the Big Bang. There are equal amounts of matter & antimatter constantly annihilating and pair-producing...



...as the universe expands, the photons cool and loose their energy until they reach a critical temperature below which pair-production is forbidden but annihilation continues...
There is 1 extra particle for every billion particles at this point!

The universe today: all of the antimatter has been annihilated and we are left with that tiny 1 part per billion matter excess (planets, stars, people...) and lots of photons (the cosmic microwave background).

BABAR Physics: CP Violation

One of the conditions needed to explain the different evolution of matter and antimatter in the early universe is that…

> The laws of physics are different when viewed through a "CP mirror".

The BABAR experiment compares the behavior of B mesons (containing an anti-b quark) with that of anti-B mesons (containing a b quark). Any differences are due to CP violation.

Do we have a Theory for CP Violation?

Yes and no...

We can explain our observations of CP violating processes quite simply by just replacing the weak coupling constants (analog of α for the EM force) with complex numbers and assuming that they are complex-conjugated in a CP mirror.

But we really don't know why these couplings should be complex!

One useful prediction of our theory is that there is just one (real) number that describes all possible CP-violating phenomena.

Why do we use B instead of K mesons?

Why do we use mesons containing a b quark instead of a c quark (as was first done 35 years ago)?

The theoretical interpretation of B / anti-B meson differences is much more straightforward than the corresponding differences for K / anti-K mesons.

This was recognized a long time ago, but the technological advances needed to study B mesons kept us busy until a few years ago.

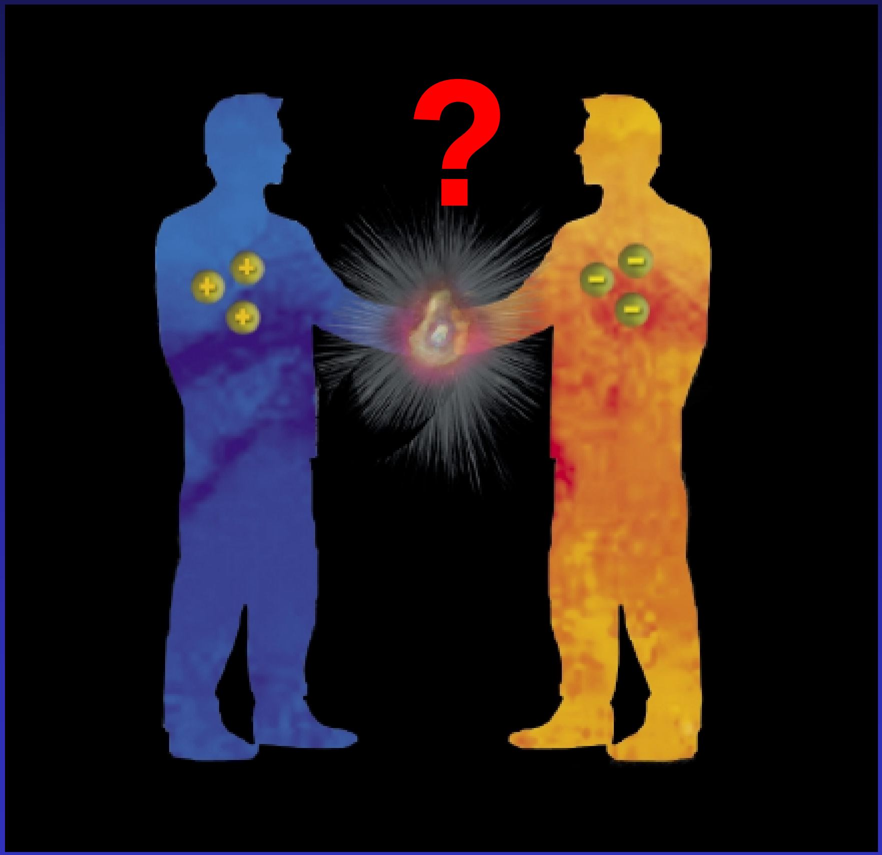
The study of CP violation with B mesons is so important that 2 experiments (BABAR, BELLE) were built to study it, and several others are in the works.

A "Practical" Application of CP Violation

Suppose we contacted a remote civilization (via radio waves) and arranged a meeting.

How could we be sure that the initial handshake would not be disastrous?

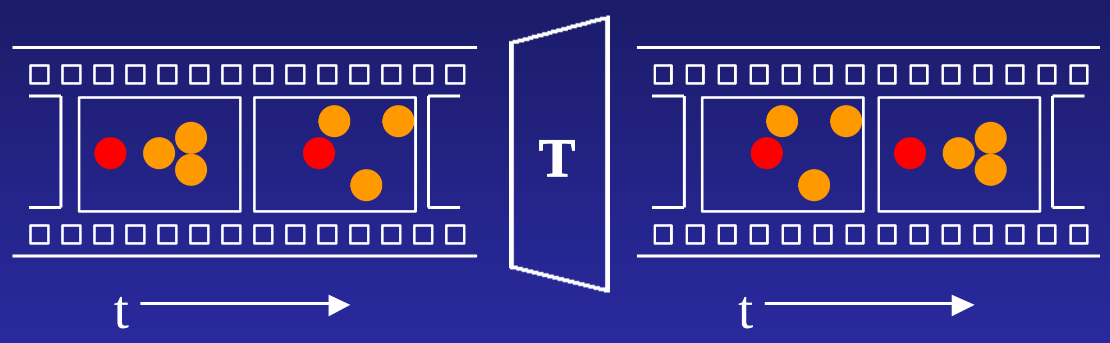
By comparing results for an experiment with B mesons, we could unambiguously agree on whether we are made of the same stuff or not!



Time Reversal and the CP Transformation

The CP transformation is related to a 3rd mirror transformation by the “CPT theorem” : CP = T

The “T” transformation reverses the direction of time:



The laws of nature are different for left-handed matter & right-handed antimatter (“CP violation”). Using the CPT theorem, we therefore expect that the laws of nature are different when the direction of time is reversed!

BABAR Results: sin2β

The parameter that we actually measure in BABAR is called sin2β. A non-zero value establishes that B mesons and anti-B mesons behave differently.

Our most recent result using 88 million B decays is:

$\sin 2\beta$ = 0.741 +- 0.067 (statistical) +- 0.033 (systematic)