

# Introduction to elementary Particle Physics

Emmanuel Olaiya

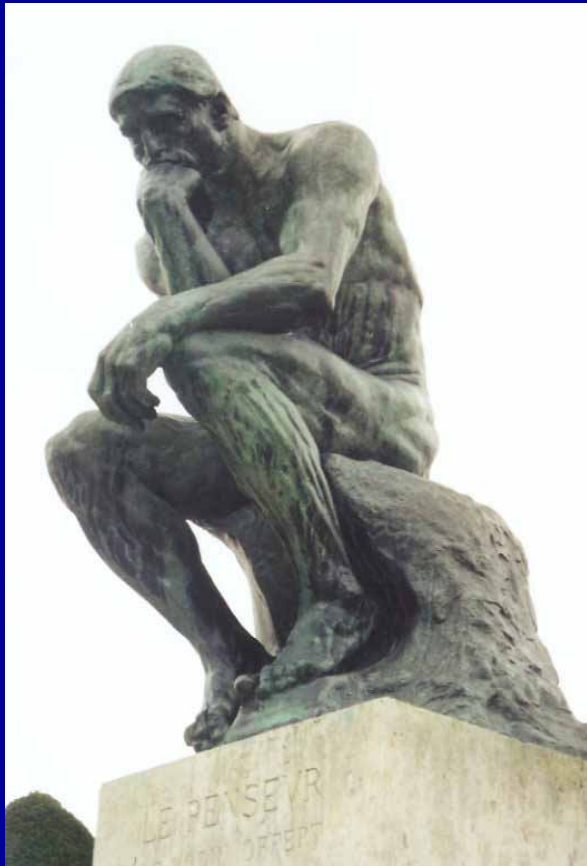
15-17<sup>th</sup> March 2006

# Outline

- Elementary Particles
- Huge machines for tiny particles
- B-mesons and CP violation

# The Thinker

(you and me)

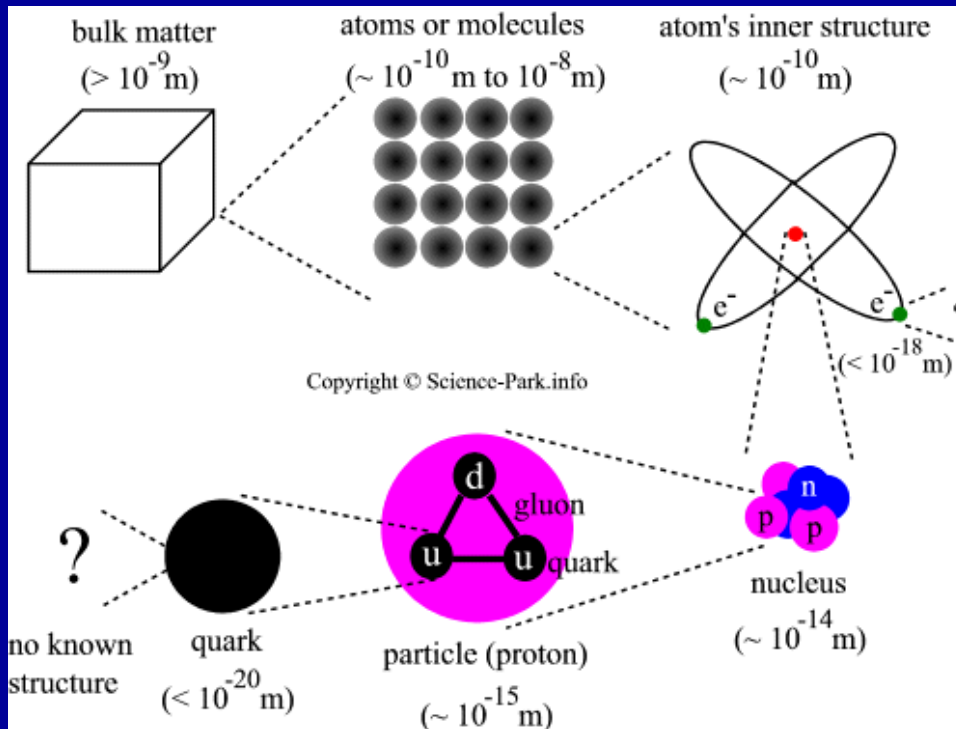


What is the world around us made of?

Can we describe the world in terms of fundamental particles?

It is these questions we try to answer

# Quarks and leptons, the building blocks of the universe



All stable matter around us is can be described using these two quarks and leptons above

We believe these to be the fundamental particles of the universe

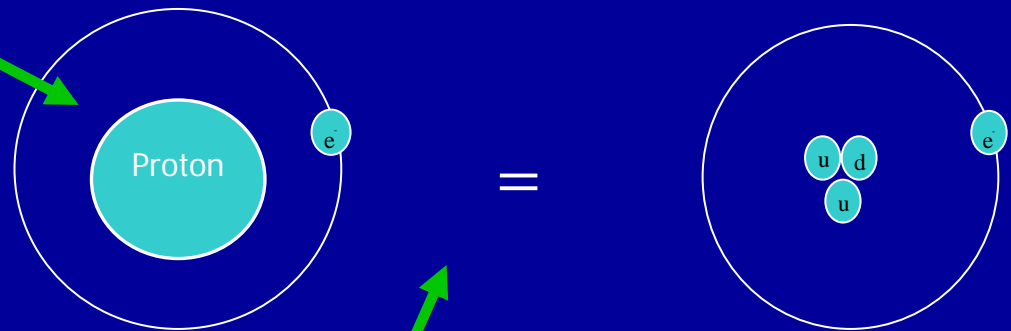
# Hydrogen atom

Periodic Table of the Elements

1	2																	10											
1	H																	He											
2	3	4															10												
	Li	Be															Ne												
3	11	12	13	14	15	16	17	18											18										
	Na	Mg	Al	Si	P	S	Cl	Ar																					
4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36											36
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr											
5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54											54
	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe											
6	55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86											86
	Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn											
7	87	88	89	104	105	106	107	108	109	110											110								
	Fr	Ra	+Ac	Rf	Ha	106	107	108	109	110																			

\* Lanthanide Series  
+ Actinide Series

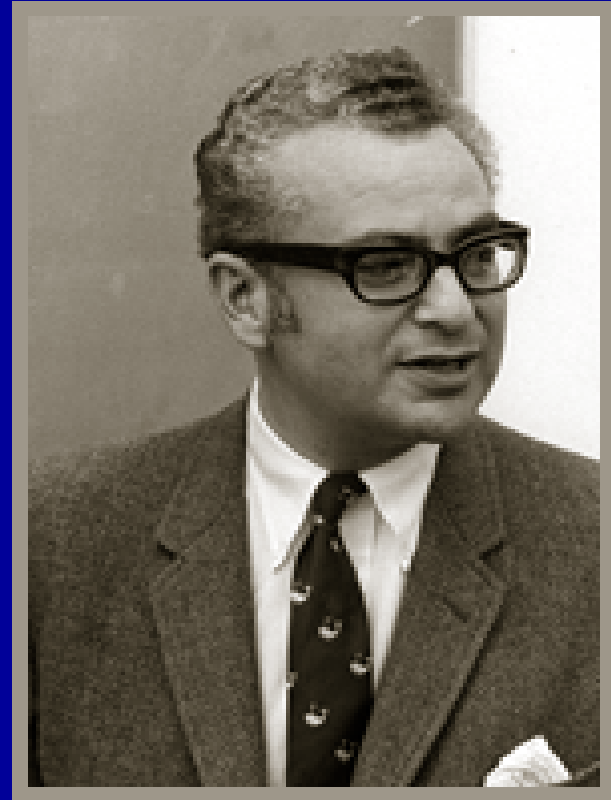
58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
90	91	92	93	94	95	96	97	98	99	100	101	102	103
Tn	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



A proton is not an elementary particle. It can be broken down further into quarks

# Three quarks to muster Mark?

- So far we have been introduced to two quarks, the up (u) and down (d)
- In 1963 Murray Gell-Mann described a previously unexplainable particle ( $\phi$ ) as containing a third type of quark, the s quark. He took the name quark from "three quarks to muster Mark" in James Joyce's book *Finnegans Wake*



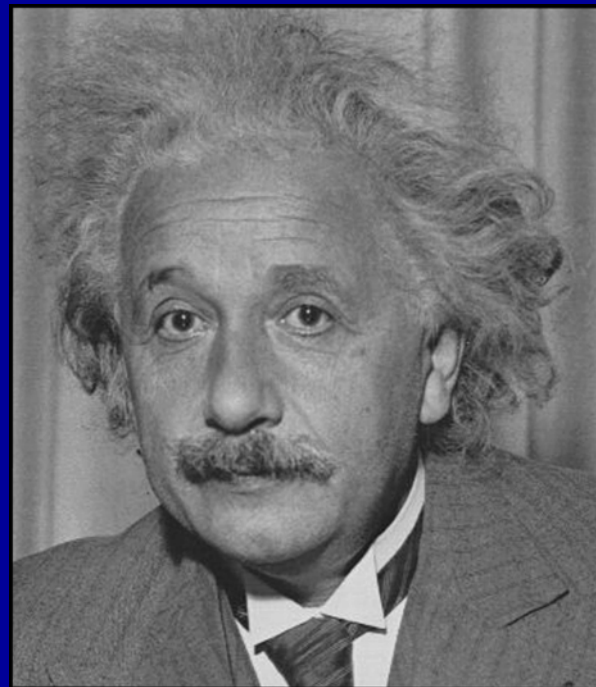
Murray Gell-Mann

# But there's more!

	1st generation	2nd generation	3rd generation	charge
Quarks	<p>mass</p> <p>u ~0.003 GeV</p> <p>d ~0.006 GeV</p>	<p>mass</p> <p>c ~1.2 GeV</p> <p>s ~0.1 GeV</p>	<p>mass</p> <p>t ~175 GeV</p> <p>b ~4.5 GeV</p>	+2/3 -1/3
Leptons	<p>mass</p> <p>e ~ 0.0005 GeV</p> <p><math>\nu_e</math> ~ 0.0 GeV</p>	<p>mass</p> <p><math>\mu</math> ~ 0.105 GeV</p> <p><math>\nu_\mu</math> ~ 0.0 GeV</p>	<p>mass</p> <p><math>\tau</math> ~ 1.8 GeV</p> <p><math>\nu_\tau</math> ~ 0.0 GeV</p>	-1 0

# Matter from Energy

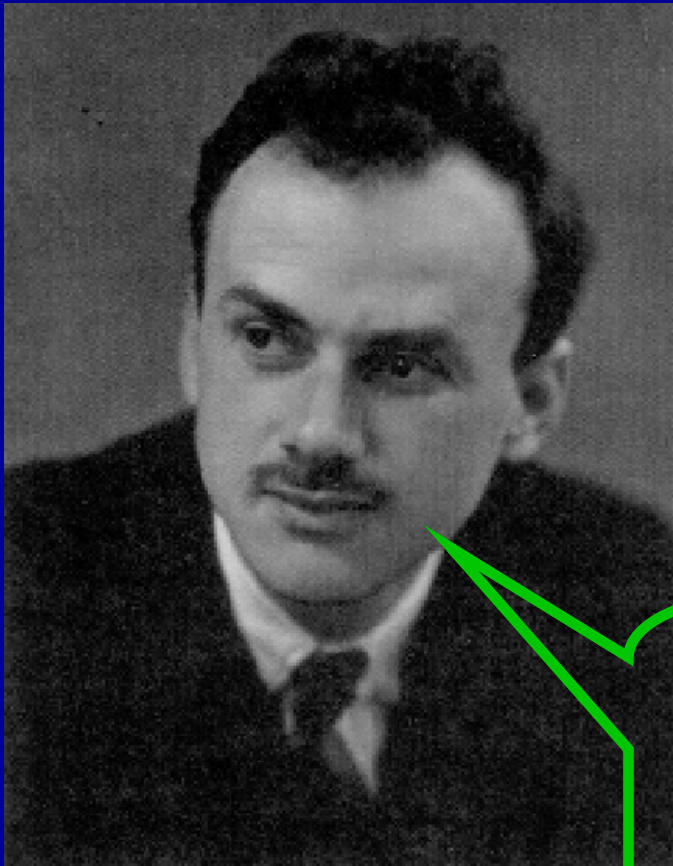
- Einstein derived the relation
  - $E = mc^2$
- Mass is directly related to energy
- Physicists like to refer to particles by their energy when they are at rest rather than their weight (I did this in previous slides)



ALBERT EINSTEIN

# So what's the antimatter

In 1928 Paul Dirac postulated that you can create matter from energy



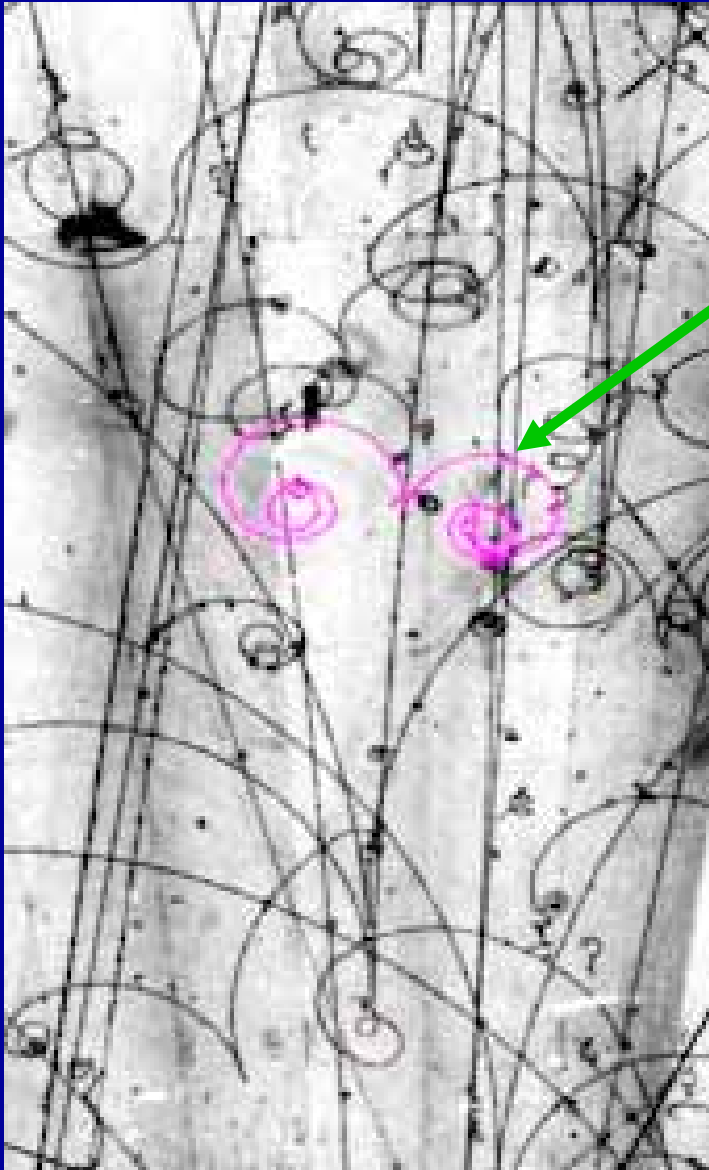
PAUL DIRAC

But I can't just create an electron out of thin air, can I?

It violates conservation of charge and angular momentum

But you could create an electron if you simultaneously created a particle with the opposite charge and angular momentum ..... the positron, Antimatter!





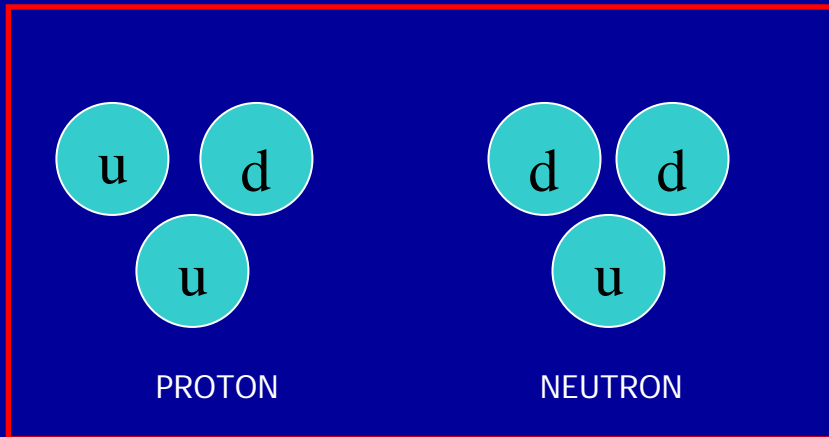
Matter and antimatter particles created in a bubble chamber. The picture shows many bubble tracks created by charged particles passing through a superheated liquid. The tracks highlighted in pink are created by an electron and positron. They spiral in opposite directions in the magnetic field due to their opposite charges

Photons hit atoms in the liquid and the energy released creates particles and antiparticles

- So, all the quarks and leptons introduced earlier have antiparticle partners.
- Antiparticles have the same mass, but opposite charge and angular momentum when generated
- We denote antiparticles with a little hat. The antiparticle of a u-quark is written as  $\bar{u}$

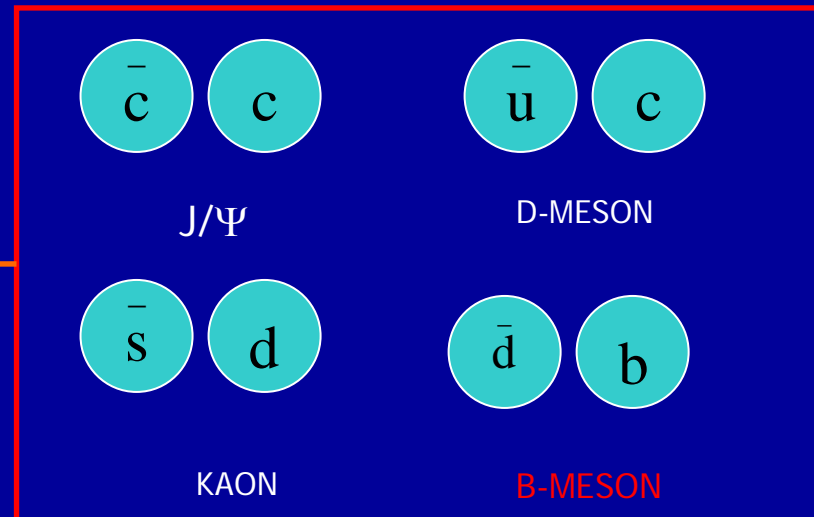
To make life confusing we don't do this with the  $e$ ,  $\mu$ ,  $\tau$  leptons, we just change the sign of the charge in the notation

# Building particles



- Stable particles
- The world around us
- Composed of 1st generation quarks

- Unstable particles
- Need to be created by high energy interactions
- Contain heavy 2nd and 3rd generation quarks. So heavy these particles do not live long. The B-meson lasts one trillionth of a second. Will talk about the B-meson later
- The t-quark is heavier still and so unstable it does not live long enough to join with another quark and form a state with another quark



- $\Delta t = \hbar/\Delta E$

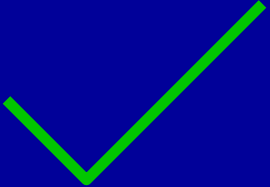
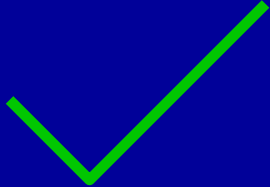
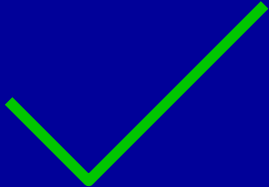
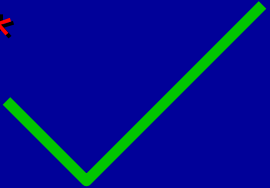
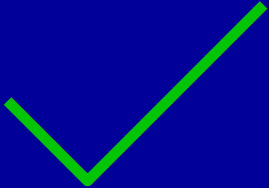
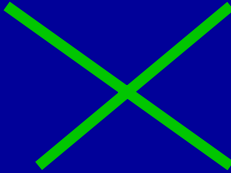
# Particle Interactions

- So what causes the particles to interact with each other?
- Forces, of which we know of four
- These forces are part of the mechanism responsible for generating matter and antimatter (pair production), changing particles from one to another (e.g. beta decay) or even binding particles together
- We call the particles responsible for mediating forces **BOSONS!**

Force	Particle	Where found?
Electromagnetic	$\gamma$	magnets
Strong	gluon	Sun, nuclei
Weak	$W^+, W^-, Z^0$	Beta-decay
Gravity	Graviton (still to be discovered)	Earth

# Particle Interactions

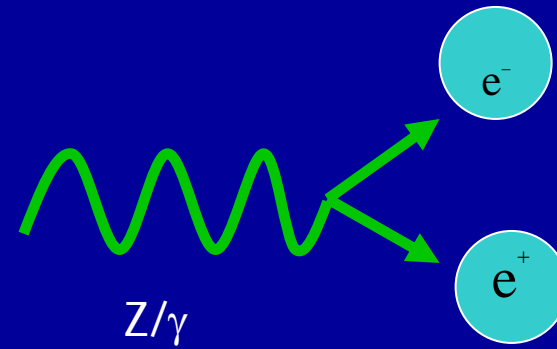
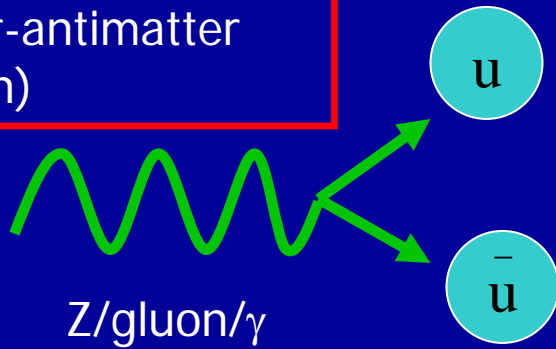
Can quarks and leptons interact with all the forces?

Elementary particle	$\gamma$	$W^+, W^-, Z^0$	Gluons
Quarks			
Leptons	* 		

Leptons do not possess the strong charge we call "colour" so cannot interact with gluons

\* Neutrinos have no electrical charge so only feel the weak force. Consequently they are very hard to detect. So hard to detect they can pass through the earth without interacting

Pair production  
(matter-antimatter  
creation)

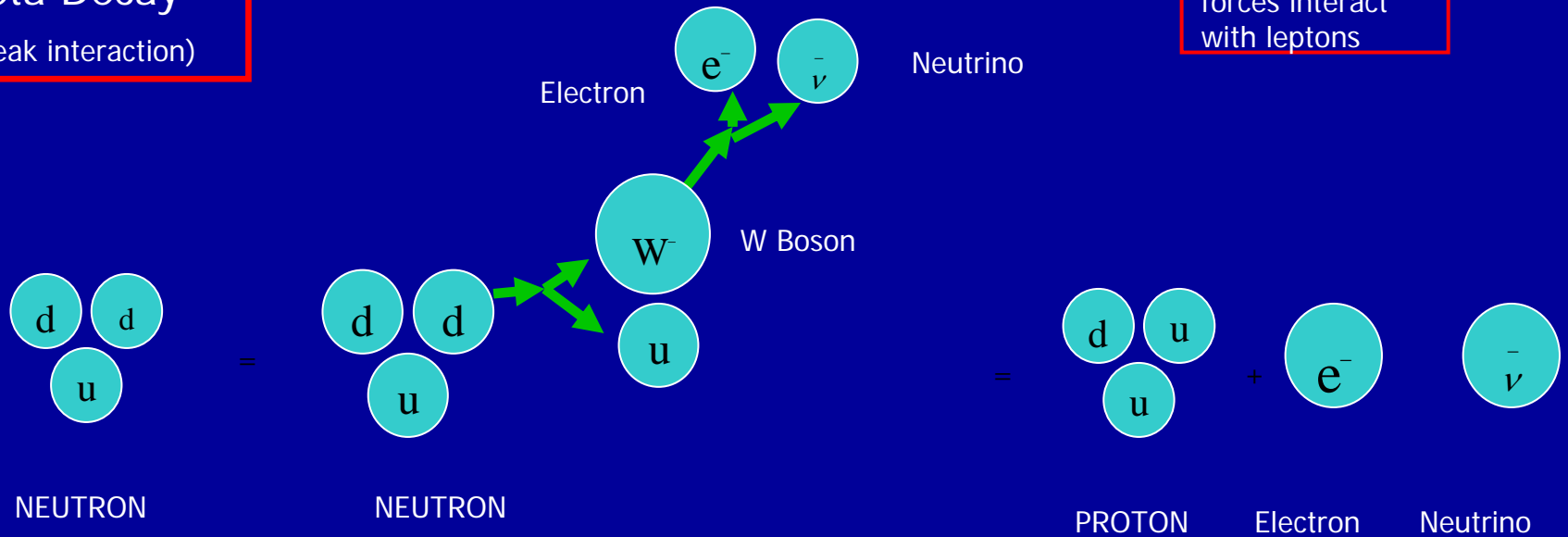


Weak, strong and  
electromagnetic  
forces interact  
with quarks

Only weak and  
electromagnetic  
forces interact  
with leptons

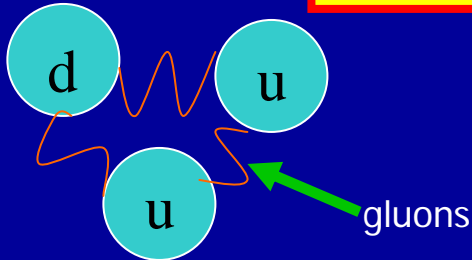
Beta Decay

(weak interaction)



# Particle Interactions

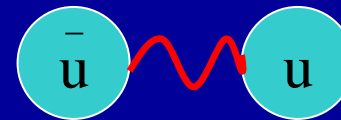
## Quark binding



Quarks in a proton are held together by the exchange of gluons

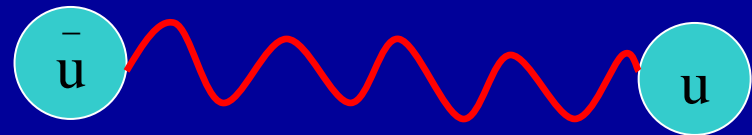
PROTON

## Pair Production

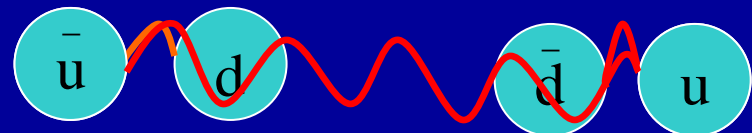


Neutral boson (Z gluon or  $\gamma$ ) changes to a quark and anti quark (pair production)

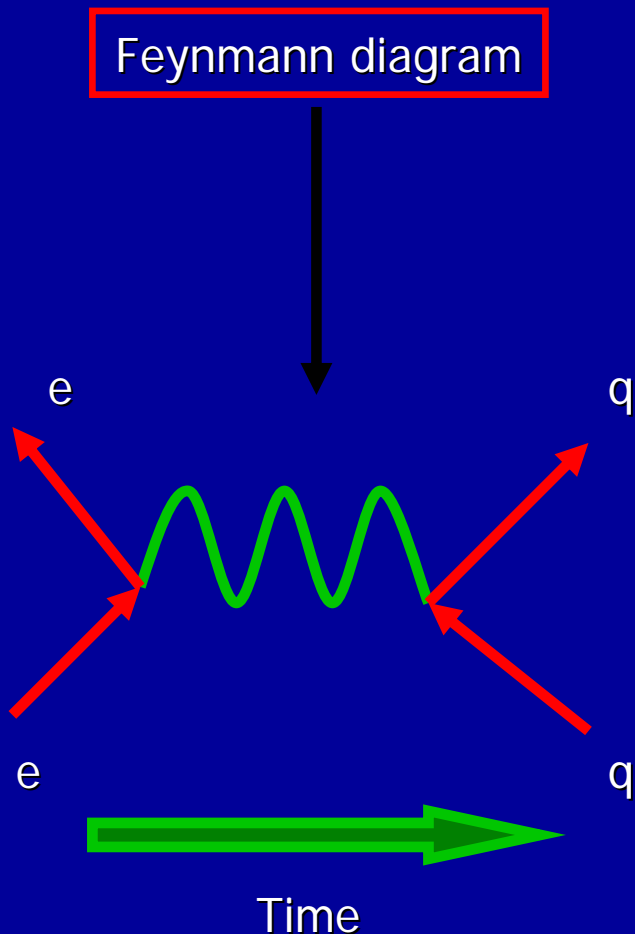
Gluon holds the quarks together as they move further apart



Gluon connection snaps and new quarks appear because quarks cannot exist in isolation



# Particle Interactions



- Forces can be explained as the exchange of particles (bosons) between two points
- The type of particle at the two points determines which force can possibly be mediated
- The calculation of particle interactions via the exchange of discrete bosons (quanta) is known as Quantum Field Theory

# The Standard Model

Quarks	<b>u</b> up	<b>c</b> charm	<b>t</b> top	Force carriers
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	
Leptons	neutrinos			
	$\nu_e$	$\nu_\mu$	$\nu_\tau$	
	<b>e</b> electron	$\mu$ muon	$\tau$ tau	<b>W</b> W boson
				<b>Z</b> Z boson

- We can describe Matter and their interactions using 6, quarks, 6 leptons and 4 force carriers

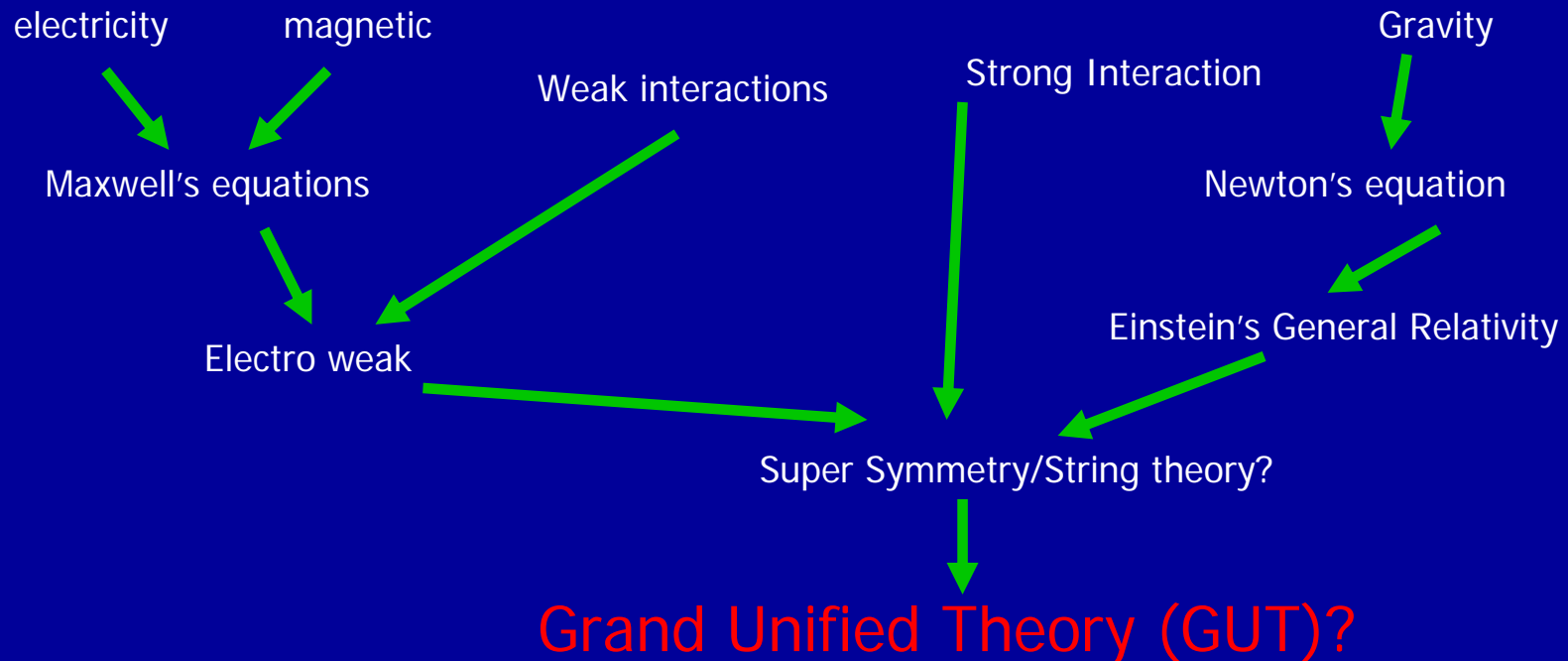
- This framework is part of what we call the standard model

- What about Gravity?

- Experimentally, we have not shown the existence of the graviton so we cannot verify any quantum field theory.

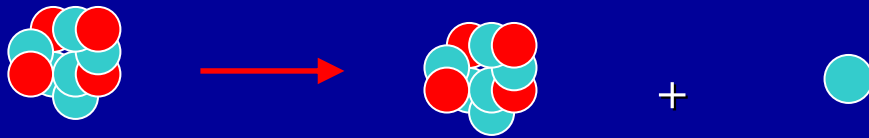
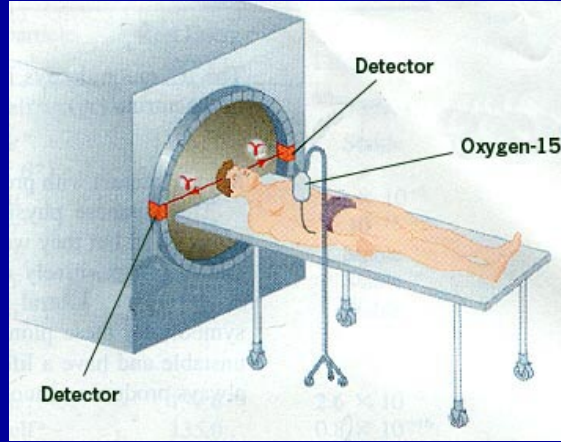
# Beyond The Standard Model

- One big goal is to unite all forces with one theory
- We already see some convergence of the forces



# Particle Physics Applications

- Medicine
  - Positron Emission Tomography scans (PET scans)
  - The oxygen isotope  ${}^8_8\text{O}^{15}$  is administered to a patient and then proceeds to travel throughout the body
  - The isotope  ${}^8_8\text{O}^{15}$  can decay to  ${}^7_7\text{N}^{15} + e^+$  (positron)
  - The positron rapidly interacts with other electrons in the body, annihilating to produce a photon
  - Since the positrons are of low energy they do not travel far. Therefore the photon essentially comes from the source of the isotope decay
  - The photons are detected and used to map the migration of the oxygen isotope in the body



${}^8\text{O}^{15}$  Nucleus

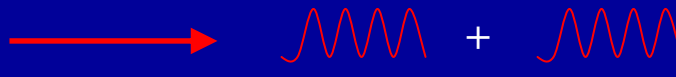
${}^7\text{N}^{15}$  Nucleus

positron



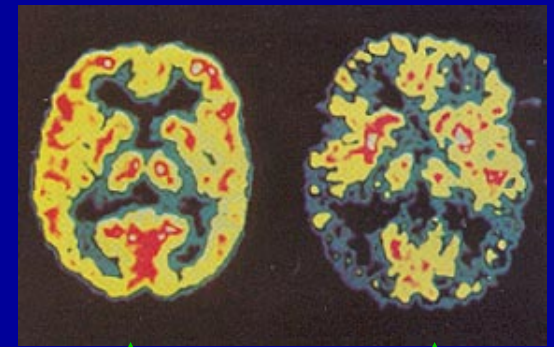
positron

electron



$\gamma$   
2 Photons  
(energy)

Detector readout



Healthy brain

Alzheimer sufferer

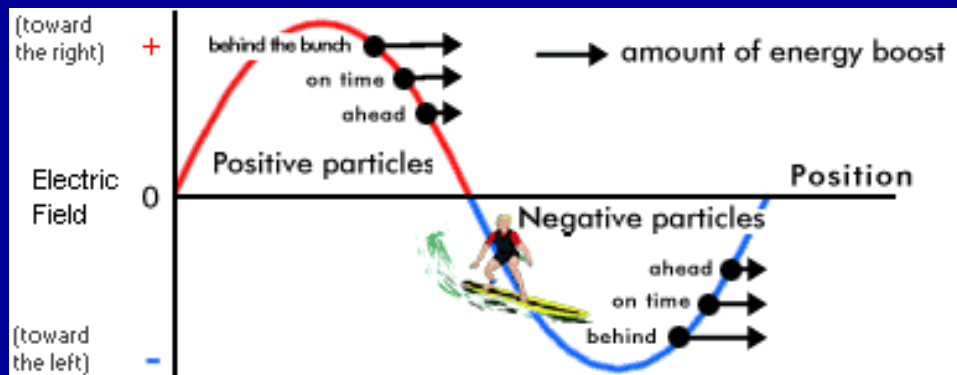
# Huge machines for tiny particles

## Accelerators

- Typically two types of accelerators
  - Linear
  - Circular (synchrotron)

- Bunches of electrons or charged particles are accelerated along in much the same way as surfers are on a wave. In the case of electrons/charged particles, the wave is an electromagnetic wave

- Where the electromagnetic wave is a changing electric and magnetic field



# Accelerators

- Linear
  - Pros
    - Lose less energy than a circular accelerator
  - Cons
    - Longer accelerators are required to push particles up to high energy
    - Particles that fail to collide are not reused
- Circular
  - Pros
    - Less accelerator length is required (particles keep accelerating as they go round and round)
    - Particles can be reused
  - Cons
    - Charged particles lose energy as they go round in circles. Energy loss is proportional to  $(E/m)^4/r$



CERN circular accelerator  
located in Geneva  
Switzerland

26Km circumference

Interactions that take  
place at CERN

$e^+$

$e^-$

$\gamma/Z^0$

matter

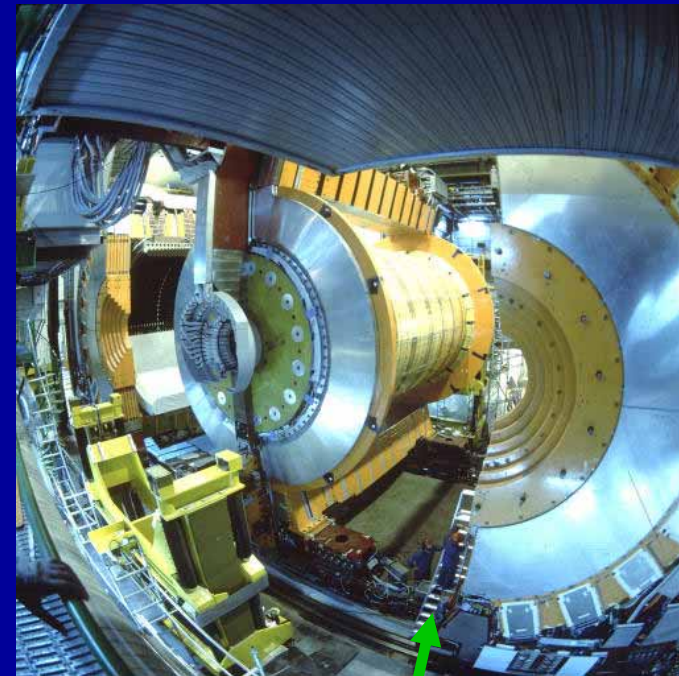
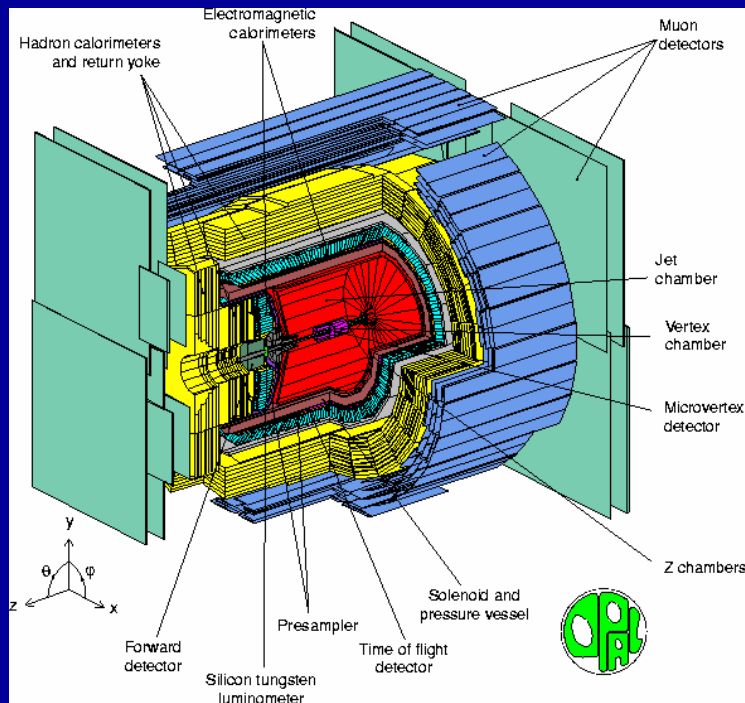
antimatter

Electrons and positron were  
accelerated around and brought into  
collision at **4 interaction regions**  
surrounded by detectors to creating  
new matter and antimatter.

The accelerator is now being  
modified to accelerate protons

# The OPAL Detector

- Omni Purpose Apparatus at Lep



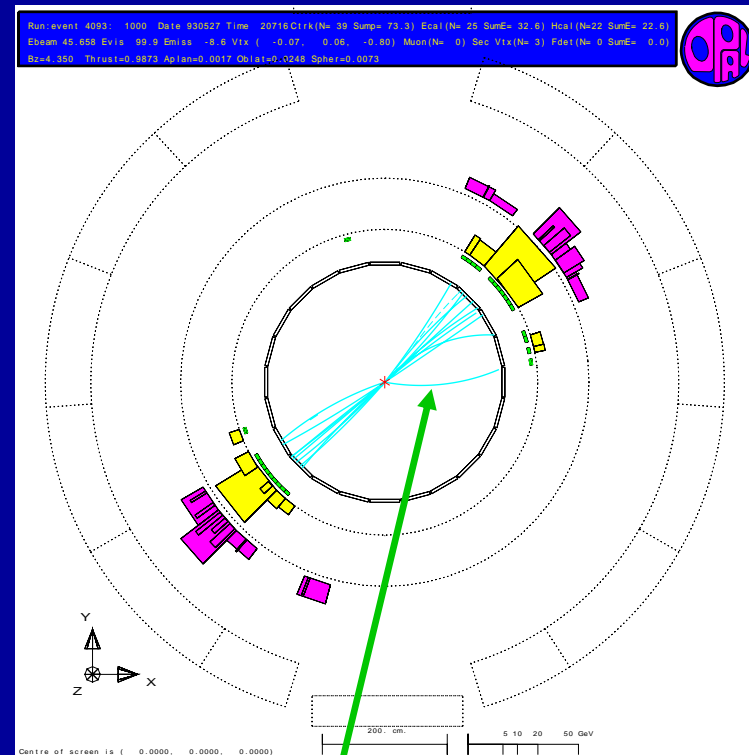
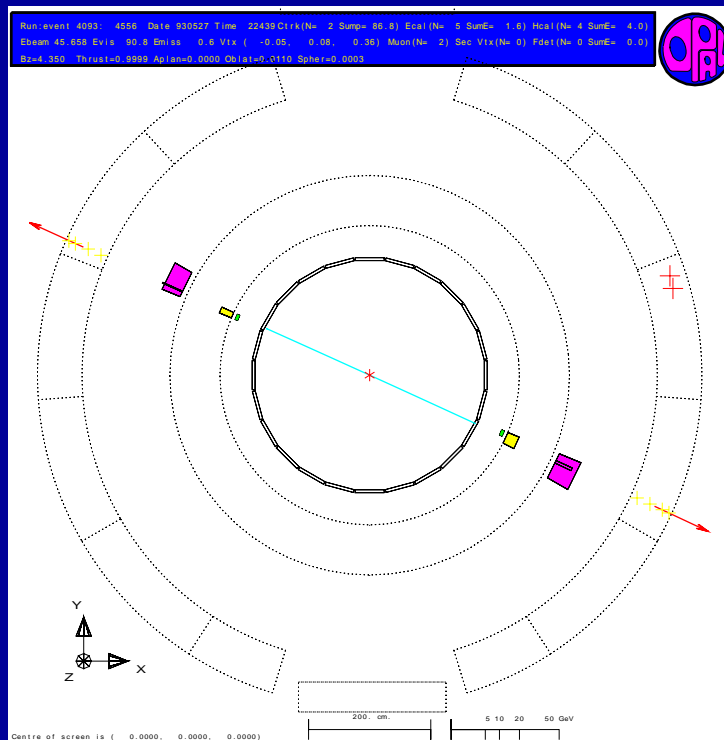
A person helps to show the relative size of the detector

# OPAL reconstructed events

Looking into the accelerator (electrons and positrons move in the z direction)

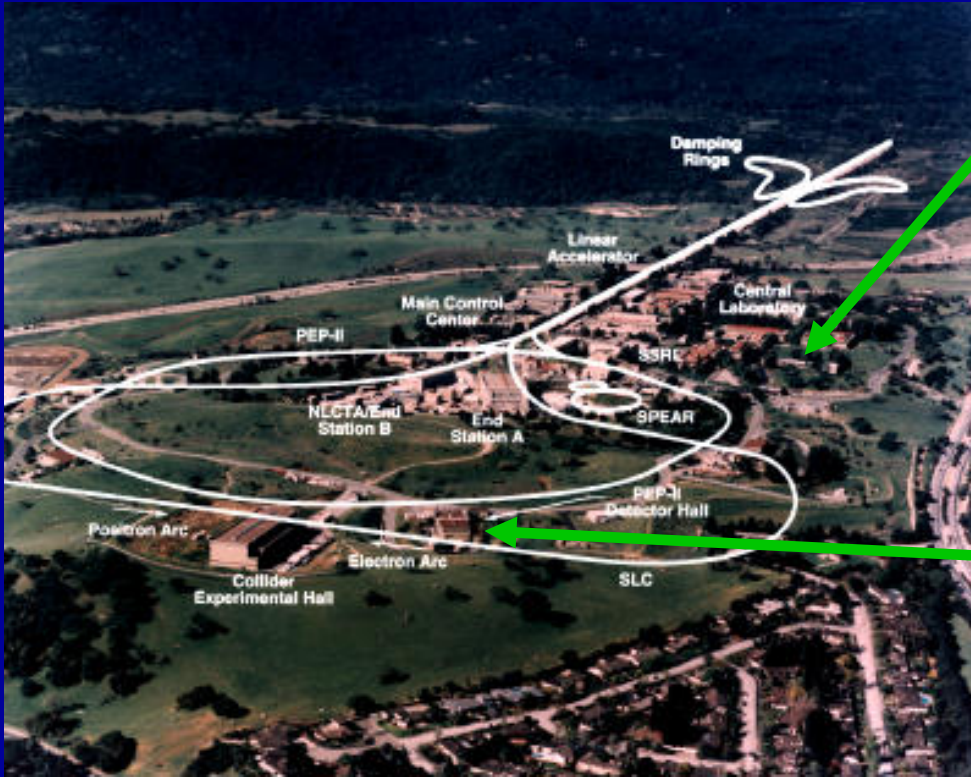
$$e^+e^- \rightarrow Z^0 \rightarrow \mu^+\mu^-$$

$$e^+e^- \rightarrow Z^0 \rightarrow qq$$



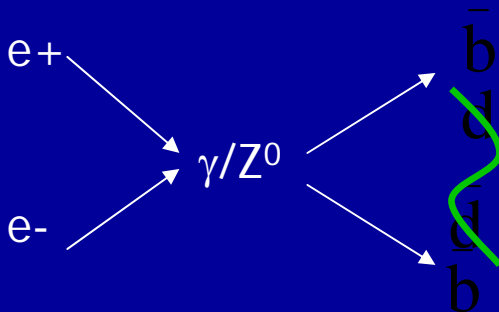
As quarks move apart more quarks are appear, seen as "jets" above

My office at SLAC

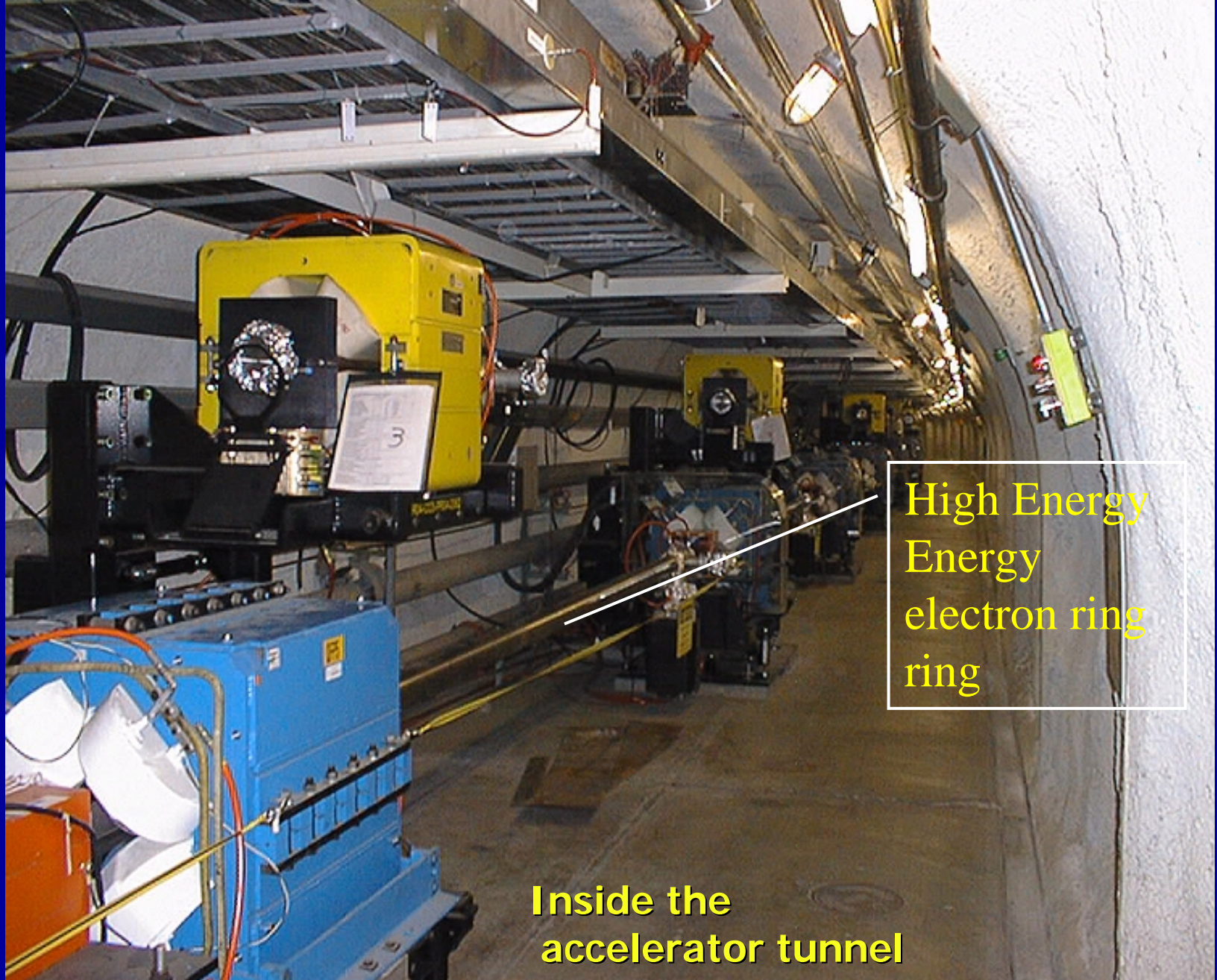


The Stanford Linear Accelerator Center located in Menlo Park, California uses both a linear and circular accelerator for electrons and positrons

There is an interaction point at the BaBar detector. The energy of the electron and positron combined is just enough to generate B and anti-B mesons. That is why we also refer to BaBar as the B-factory



The electron and positron annihilate to energy which in turn forms a b quark and an anti b quark. As the two quarks move further apart their gluonic connection is broken and new d quarks are formed. Quarks cannot exist alone! So we end up with two B-mesons!

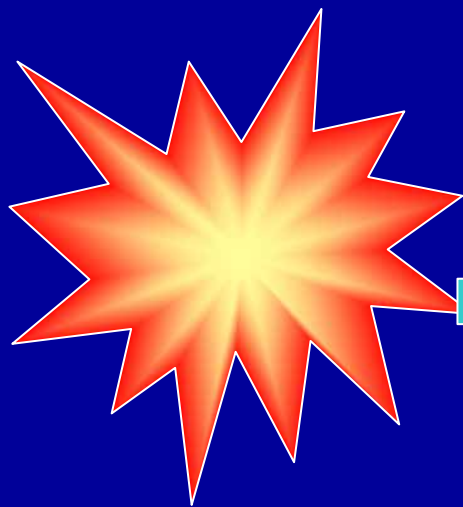


High Energy  
Energy  
electron ring  
ring

Inside the  
accelerator tunnel

# The BaBar experiment

- The experiment generates and studies B and anti-B mesons (B-Bbar) hence the name BaBar and the logo
- The BaBar experiment was built to investigate possible imbalances between matter and antimatter
  - Are the laws of physics the same for matter as anti-matter
    - Previously we suspected that they are not
      - Take the big bang for example



Beginning of  
time, the Big  
Bang (energy)



antimatter

equal amounts

matter

Where has all the  
antimatter gone?

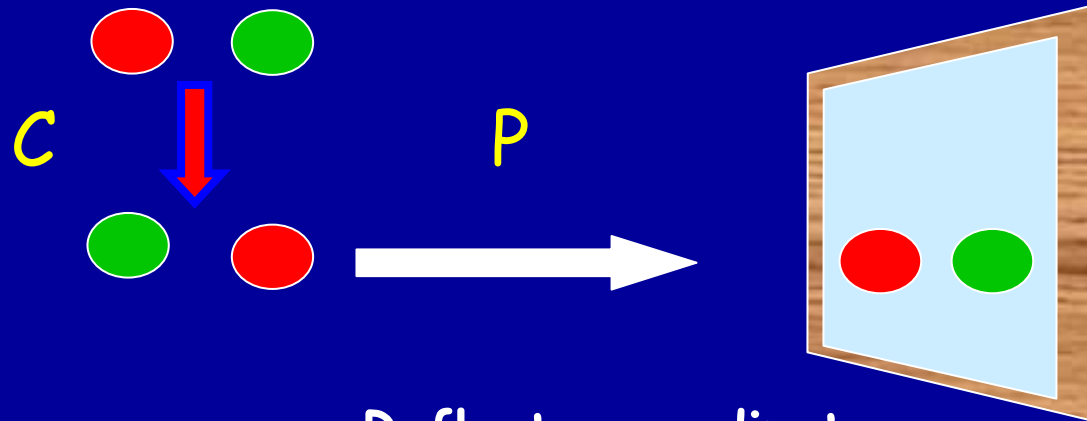
Are the laws of  
physics different  
for antimatter?

Our world

Maybe we can start to answer these  
questions by studying matter and  
antimatter asymmetries

- The BaBar experiment is an experiment which looks at matter antimatter asymmetries
- The BaBar experiment was built to measure Charge Parity (CP) violation in B-mesons
- What is CP?
  - CP is the following operation

Change **particle**  
into **antiparticle**

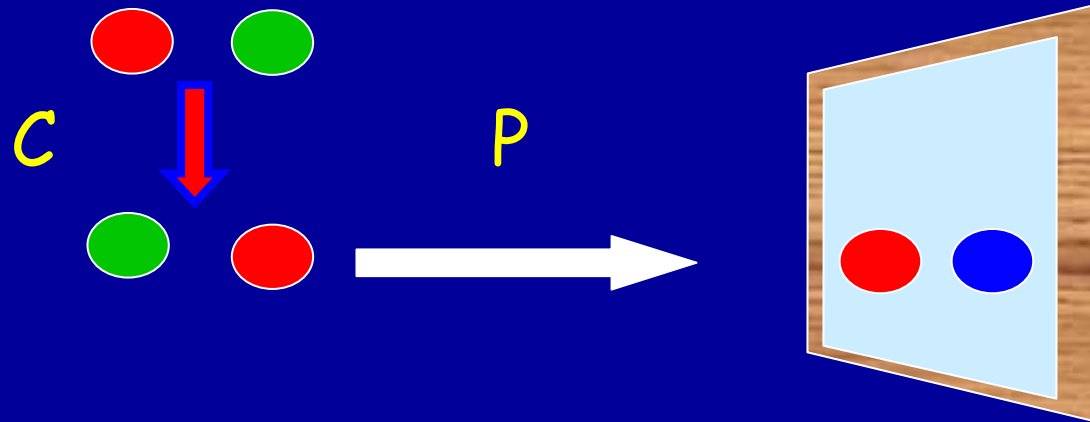


Reflect co-ordinates  
in a mirror

After performing the operations C and P we get  
the same state back.  $CP(\text{red circle green circle}) = (\text{red circle green circle})$

We say the state is symmetric under CP

Change **particle**  
into **antiparticle**



Reflect co-ordinates  
in a mirror

After performing the operations C and P we have a different state?

The symmetry is broken under CP, i.e.

$$CP ( \text{green circle} \text{ red circle} ) \neq ( \text{red circle} \text{ blue circle} )$$

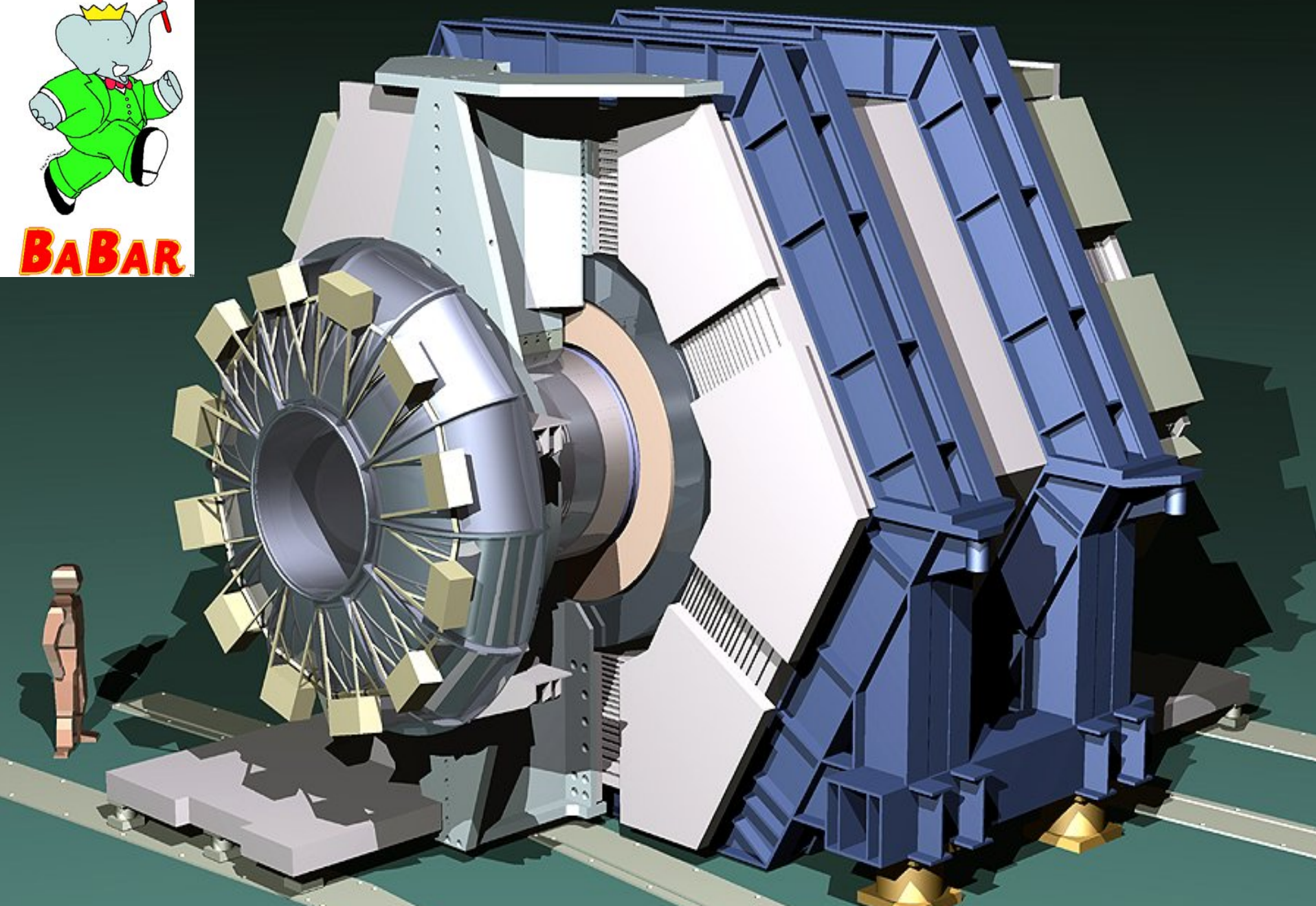
When the CP symmetry is different between initial and final states this is **CP violation**

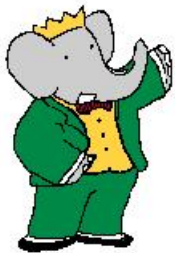
Any difference between particles and anti-particles will result in **CP violation** (~~CP~~)

# BABAR DETECTOR FOR THE PEP-II B FACTORY

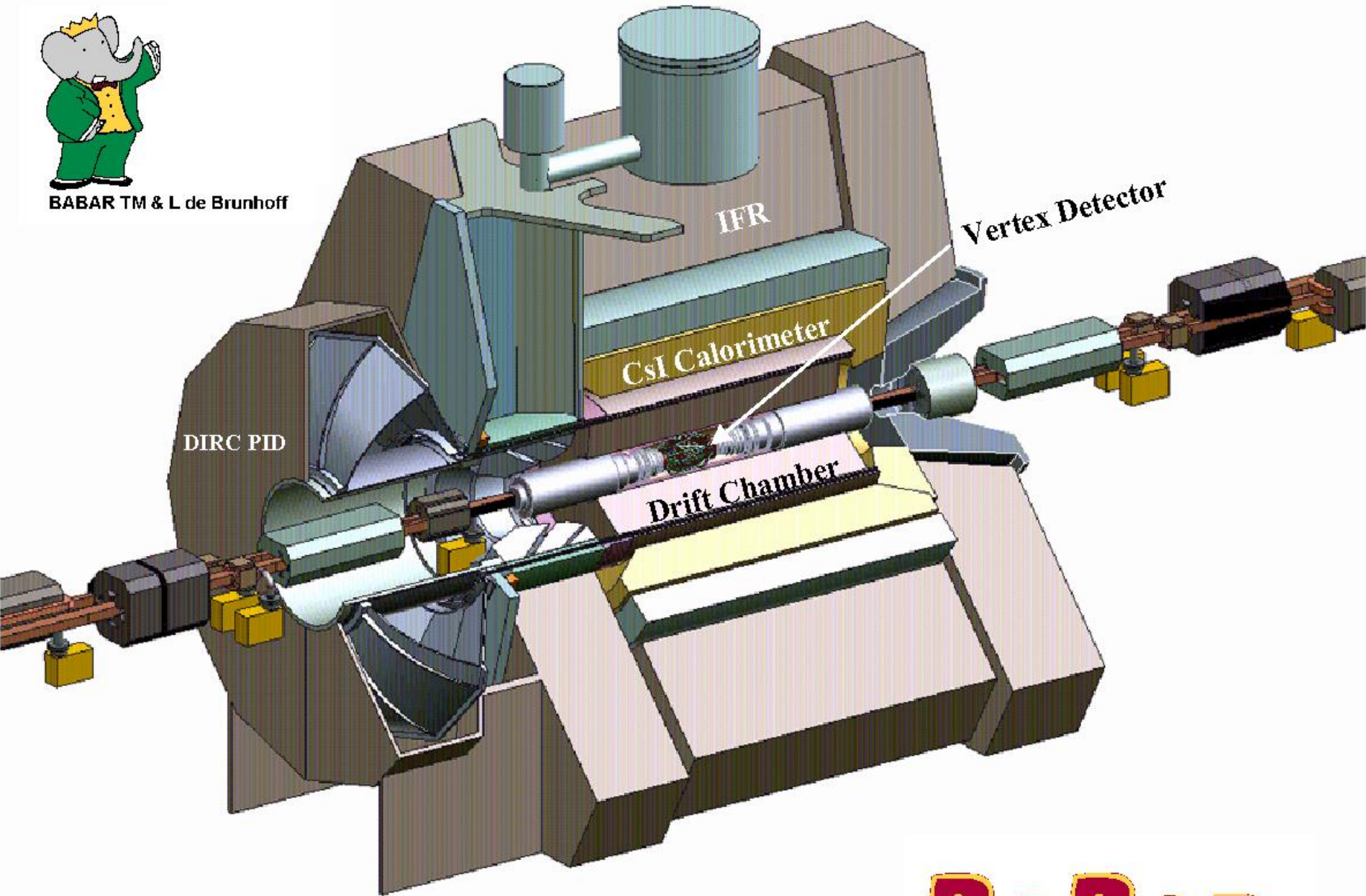


**BABAR**

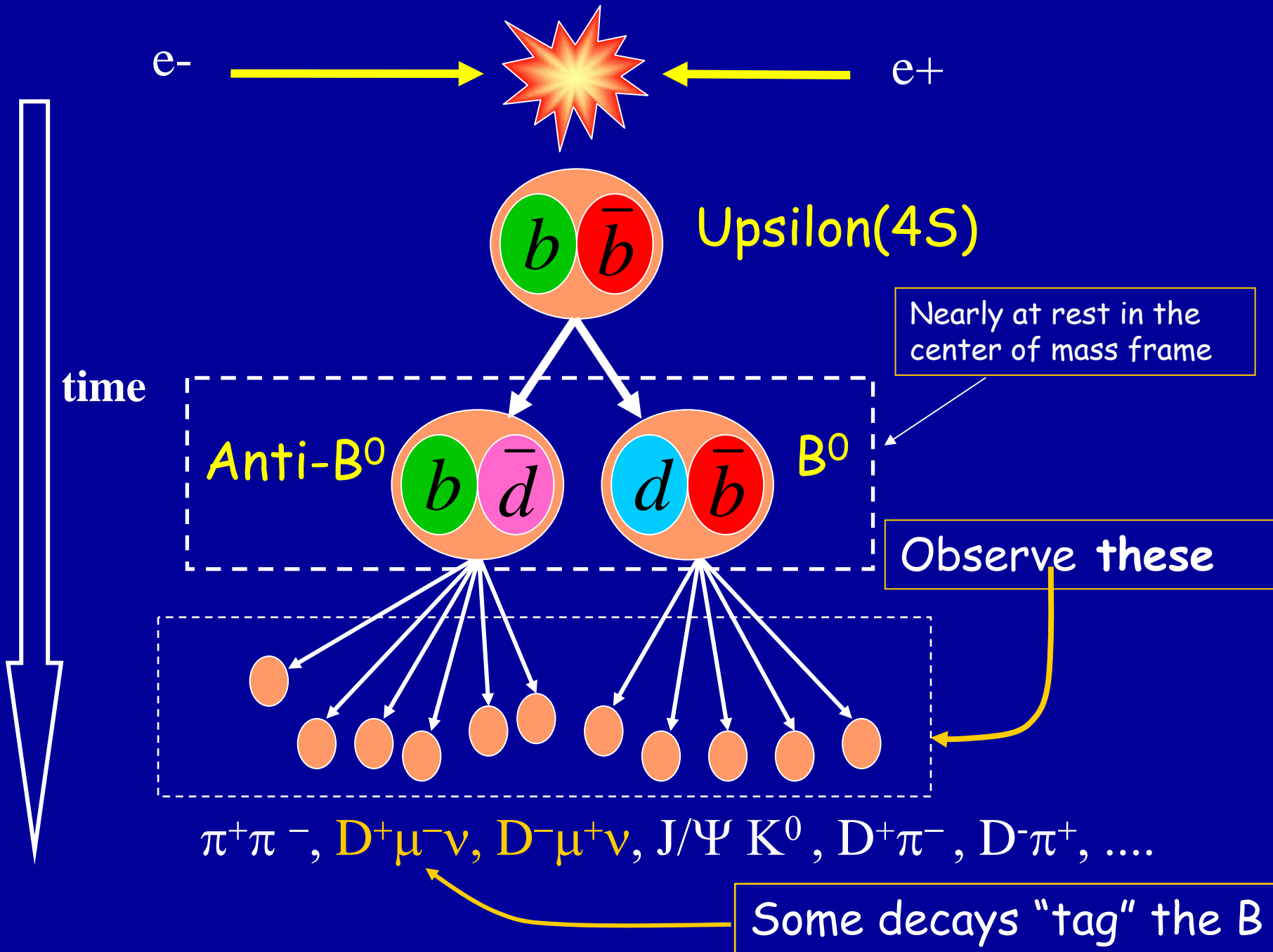




BABAR TM & L de Brunhoff



**BABAR**™

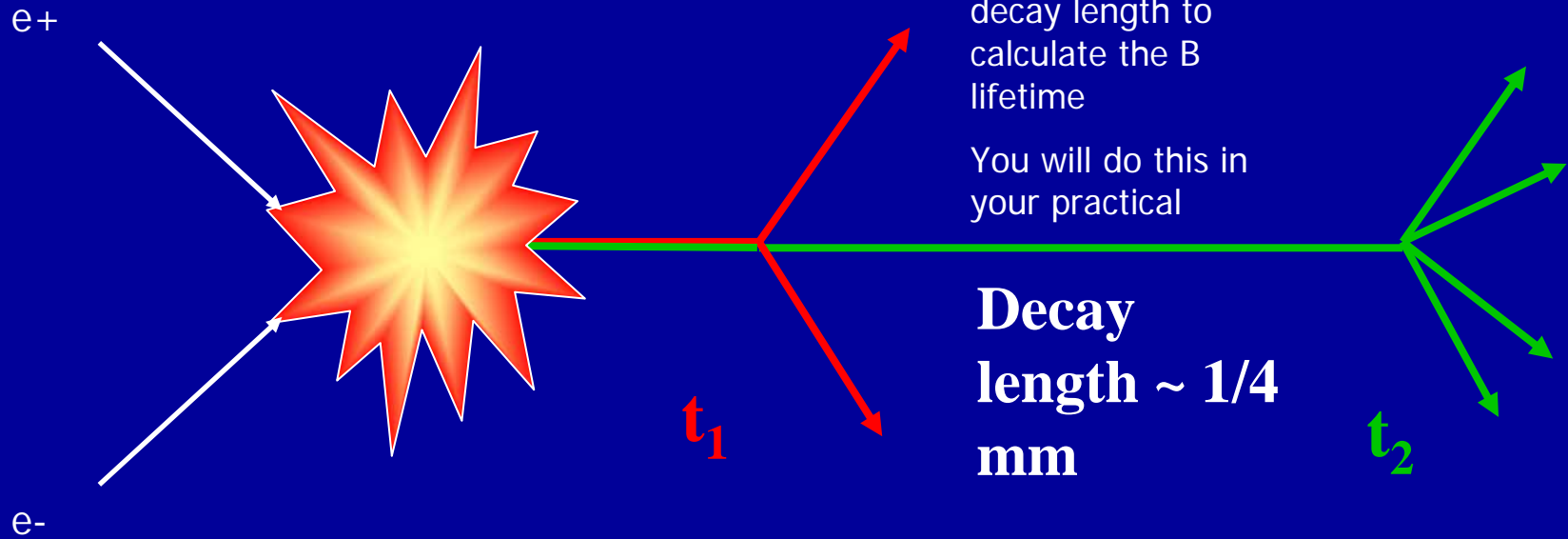


# Search for CP Violation

- We look for CP violation in two ways
  - Does a B-meson decay to a state X the same number of times as a anti-B-meson. If not this is CP violation
  - We measure the decay rate of a state X as a function of time for both the B-meson and anti-B-meson. If the decay distributions are different, this is CP violation
- BaBar started running in 1999 and since then has produced over 300 million B and anti-B meson pairs which have been recorded for analysis

**First B  
decays**

**Second B  
decays**



Use one **B** as a "tag" and count **other decays**

Tests for CP violation

$$A = \frac{N(\overline{B^0} \rightarrow K^+ \pi^-) - N(B^0 \rightarrow K^+ \pi^-)}{N(\overline{B^0} \rightarrow K^+ \pi^-) + N(B^0 \rightarrow K^+ \pi^-)}$$

CP violation if  $A \neq 0$

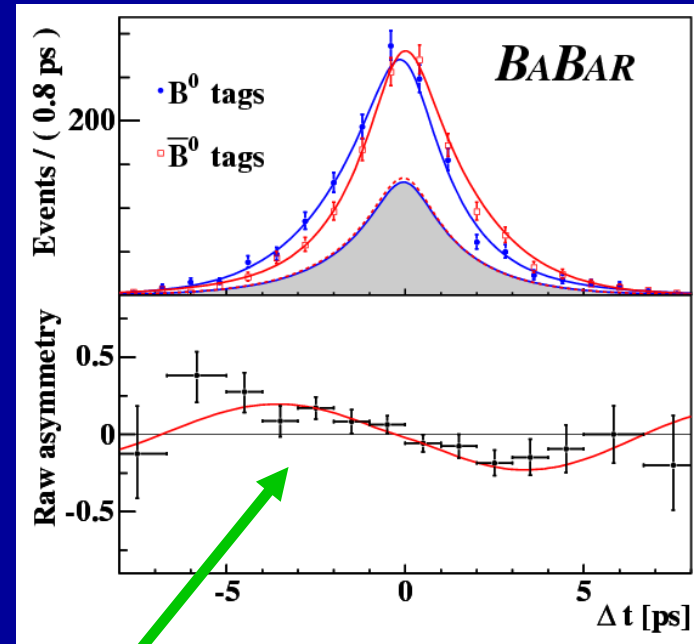
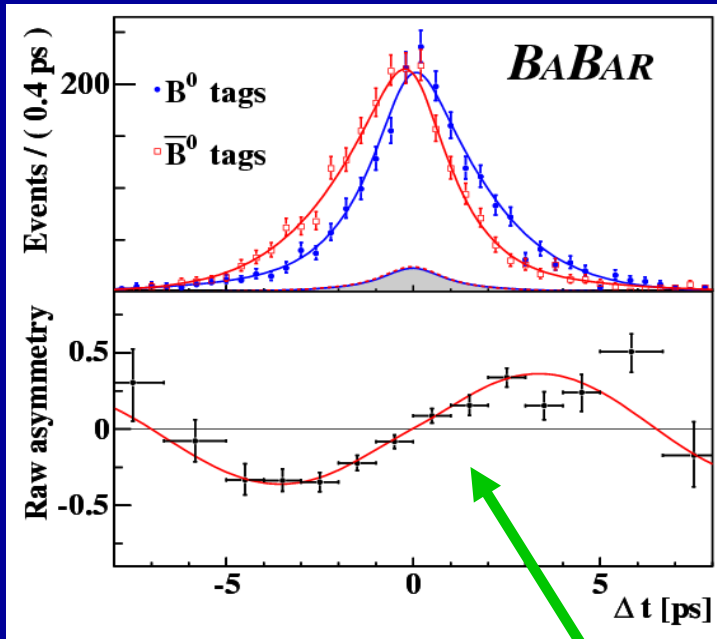
Measure  $\Delta t = t_1 - t_2$  for  $B^0 \rightarrow J/\psi K^0$  and anti  $B^0 \rightarrow J/\psi K^0$

CP violation if distributions are different

# BaBar Results on CP Violation

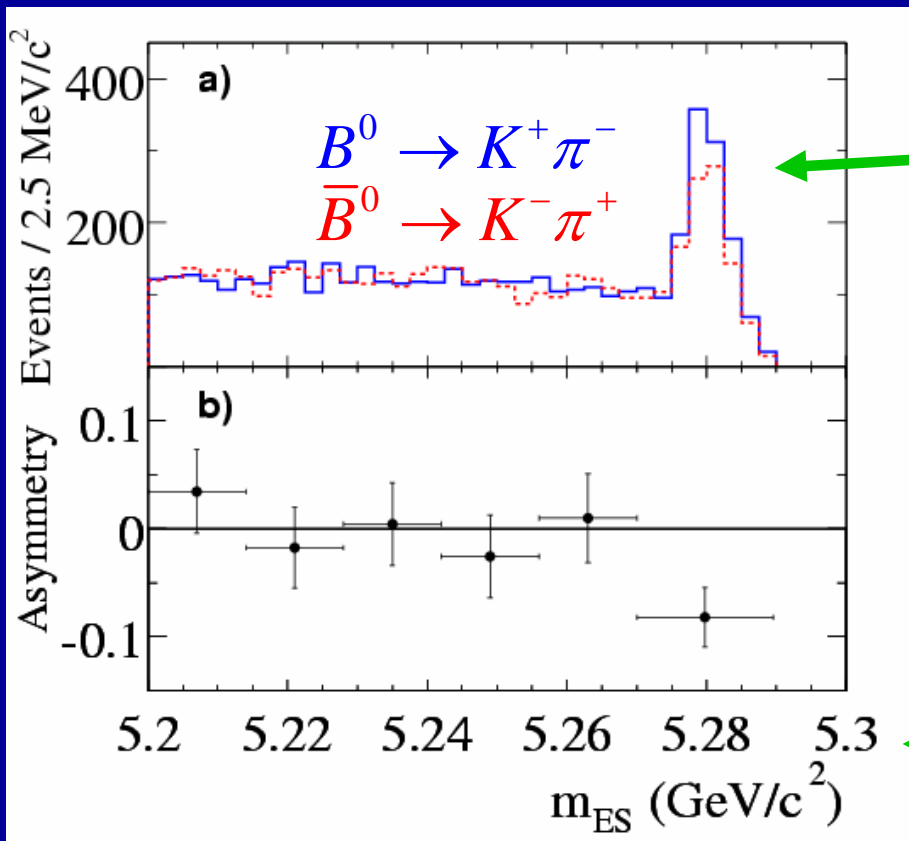
$(c\bar{c})$   $K_S$  (CP odd) modes

$J/\psi K_L$  (CP even) mode



Difference between two B decay distributions is a sine wave.  
A non-zero sine amplitude is a measurement of CP violation.  
The amplitude is given by  $\sin 2\beta$

$$\sin 2\beta = 0.722 \pm 0.040 \text{ (stat)} \pm 0.023 \text{ (sys)}$$



True B events peak at the B mass.

Clearly see different number of reconstructed events for the B and anti-B events

Mass of reconstructed events

$$A_{CP} = -0.133 \pm 0.030 \pm 0.009$$

Non zero asymmetry value is a measurement of direct CP violation

## Some conclusions from the BaBar experiment

- The BaBar experiment has measured CP asymmetries in the B mesons system.
  - The physics of matter and antimatter are not completely symmetric
- The effect does not just occur in one particular decay of the B meson

# Summary

- Elementary particles and their interactions are well understood. Though not perfectly!
  - What about incorporating gravity?
  - Can we come up with a theory to unify all the forces?
  - What about the Higgs Boson (Dr Monika Wieler's talk) ?
- We await more physics results after the switch on of the **L**arge **H**adron **C**ollider at CERN

There is still plenty of physics  
left for you to do!

