Matter and Antimatter

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NOTATION

M = matter

$\overline{M}$ = antimatter

OUTLINE

- What is Antimatter ?
- Energy and mass ($E=mc^2$)
- Sources of Antimatter
- Antimatter Applications
- Big Bang M-$\overline{\text{M}}$ Annihilation ✷
- Theory of M-$\overline{\text{M}}$ asymmetry

- Kaon experiments: Overview
- The “KTEV” experiment at Fermilab
- The Concept of Uncertainty
- Results of K-$\overline{\text{K}}$ decay asymmetry
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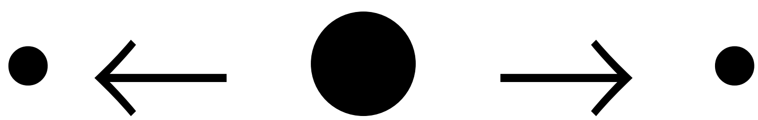
WHAT IS MATTER ?

Matter is anything with "mass."

Most types of matter-particles decay into less massive particles.
(very few particle are stable)



"Lifetime" =
average time before decay.

"Decay Rate" =
number of decays per second.

WHAT IS ANTIMATTER ?

Every "particle" has a partner called an "anti-particle" .
The two have the same mass and the same lifetime (if it decays).

The main difference is that they have OPPOSITE electric charge.

EXAMPLES: (year of discovery)

• electron e^-		(1897)
• positron e^+		(1932)
● proton	$p^+ = u\,u\,d$	(1919)
❍ anti-proton	$p^- = \bar{u}\,\bar{u}\,\bar{d}$	(1955)
● neutron	$n = u\,d\,d$	(1932)
❍ anti-neutron	$\bar{n} = \bar{u}\,\bar{d}\,\bar{d}$	(1956)

Experimental Tests

Define

$$\frac{\text{mass(particle)}}{\text{mass(anti-particle)}} - 1$$

= 0 (perfect M/$\overline{\text{M}}$ symmetry)

≠ 0 (broken M/$\overline{\text{M}}$ symmetry)

Experimental Tests

$$\frac{\text{mass(electron)}}{\text{mass(positron)}} - 1 < 0.000\,000\,008$$

(8 ppb)

$$\frac{\text{mass(proton)}}{\text{mass(antiprot)}} - 1 < 0.000\,000\,06$$

(60 ppb)

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WHAT IS ENERGY ?

Something that can do "work"
(push, pull, heating, etc ...)

Some examples:

- **Gravitational**
- **Nuclear**
- **Photons**
  (light, radio signals, dental X-rays)

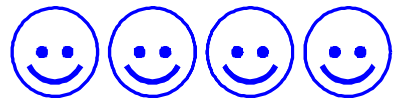
$$E=mc^2$$

(matter)

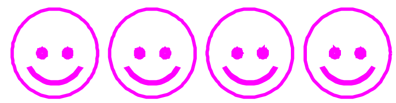
$$E=\overline{m}c^2$$

(antimatter)

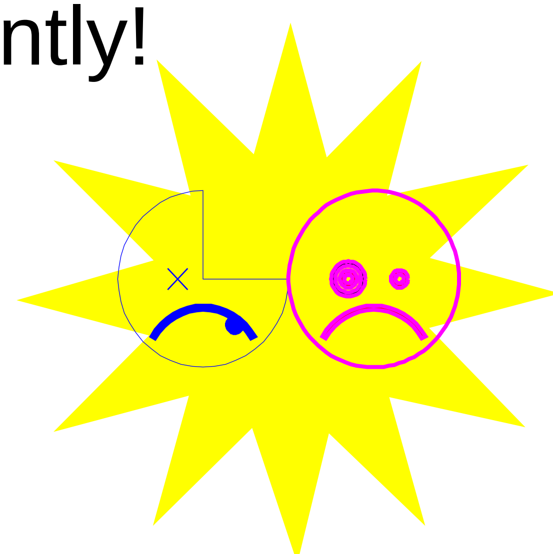
Matter particles
are happy together



Antimatter particles
are happy together



Matter and antimatter
react violently!



Matter (●) and antimatter (❍) annihilate into photons (~), and vice-versa.

PAIR ANNIHILATION:

●❍ ➣ ~~

M $\bar{\text{M}}$ → photons (energy)

PAIR CREATION :

~~ ➣ ●❍

photons → M $\bar{\text{M}}$

(● and ❍ ALWAYS created in pairs)

The energy from:

1 kg of antimatter +
1 kg matter

could supply all US electricity for 1 week.

This is equivalent to:

- ☞ **1.5 kilo-tons of natural Uranium†.**
- ☞ **30,000 kilo-tons of coal.**

†**This must be reduced to 0.2 kilo-tons of 3.5% purity U-235 needed for reactors. Just 0.008 kilo-tons (8 tons) of weapons-grade 90% U-235 would do the same job.**

Particle Energy = Rest Energy (mc^2)

+ kinetic energy

$$E = \gamma mc^2$$

γ = “Boost” or ”time-dilation” factor

$\gamma = [1 - (v/c)^2]^{-1/2}$

$$E = \gamma mc^2$$

at rest	γ=1
55 MPH in a car	γ=1.000000000000000034 (1 sec per 10 million yrs)
Jet Plane 	γ=1.0000000000000034 (1 sec per 100 thousand yrs)
Space Craft ➢	γ=1.0000000028 (1 sec per 10 yrs)
Fermilab proton accelerator	γ=860
CERN electron-positron collider	γ=200,000
Most energetic cosmic proton	γ=1 trillion (10^{12})

If cosmic protons with γ=trillion originated from the Big Bang, their current rest-frame age is

$$\text{age} = \frac{\text{age of universe}}{\gamma = 1 \text{ trillion}}$$

$$= 3 \text{ days !!!}$$

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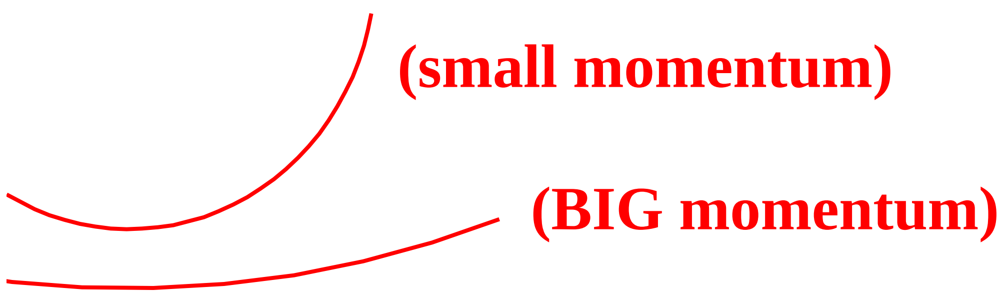
What is MOMENTUM ?

Momentum =
Mass x Velocity x γ

Charged particles curve in magnetic field.



Measured curvature gives momentum

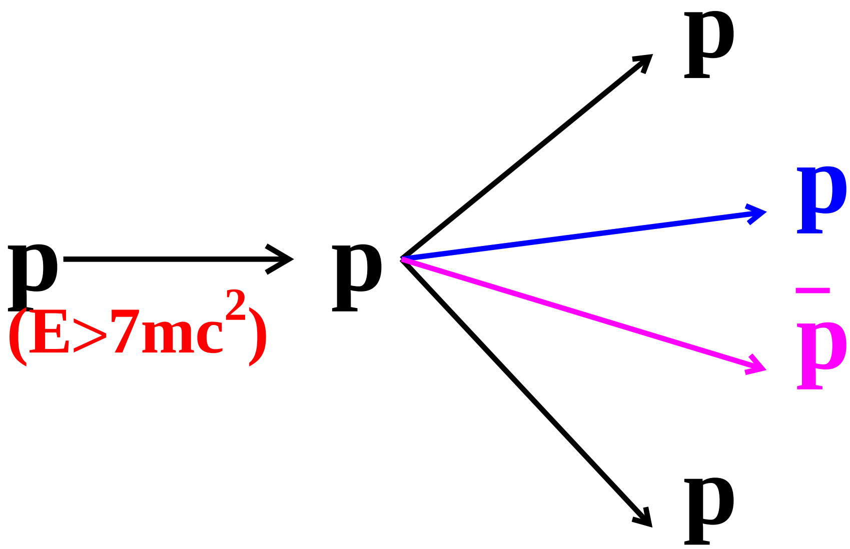
In 1932, the anti-electron (positron) was the first anti-particle ever observed.

See

http://archives.caltech.edu/photoNet.html

and then click "Carl Anderson." Figure 1.2-7 shows a famous positron track.

Anti Proton Production



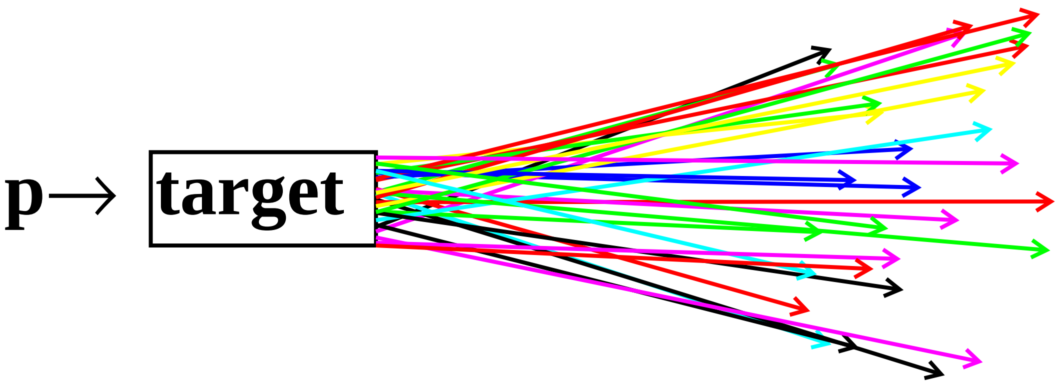
This process occurs in:

- Outer space
- Particle accelerators,
  Berkeley, 1955

(dominant known source of "natural" antimatter)

Antiproton Discovery at the U.C. Berkeley Bevatron (1955)

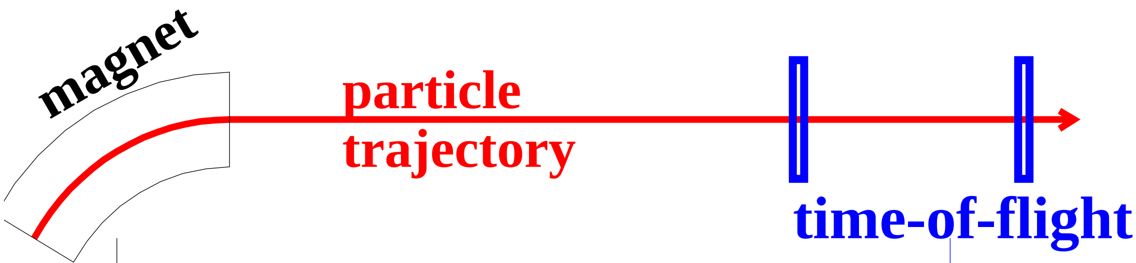
Used new 6 billion electron-Volt proton beam ($E=7m_p$)



Only 1 in 100,000 is an antiproton ...

how did they find it ?

Antiproton Discovery at the U.C. Berkeley Bevatron (1955)

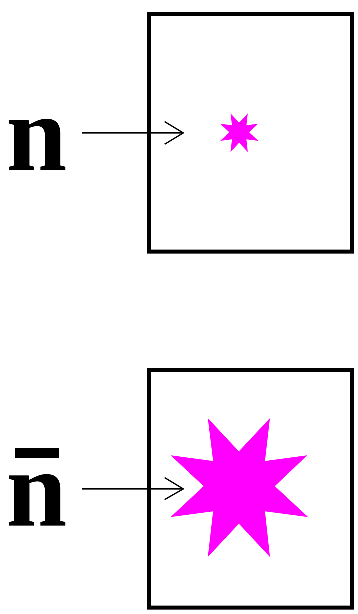


Momentum = Mass x Velocity

Charge is NEGATIVE

= proton mass within 5%

Antineutron Discovery at the U.C. Berkeley Bevatron (1956)



anti-neutron annihilation releases more energy

Total Human-Made AntiMatter

$p\,\bar{p}$ Colliders: $10^{16}\ \bar{p}$

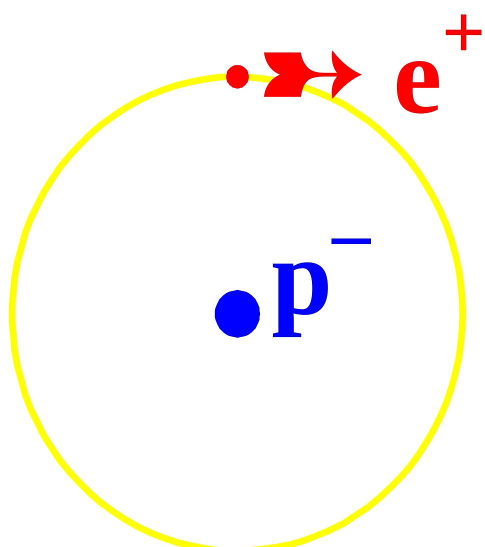
mass = 0.000 000 01 grams (10^{-8} g)

$e^{-}\,e^{+}$ Colliders: $10^{17}\ e^{+}$

mass = 0.000 000 000 1 grams (10^{-10} g)

Anti-Hydrogen is the ONLY anti-atom ever seen.

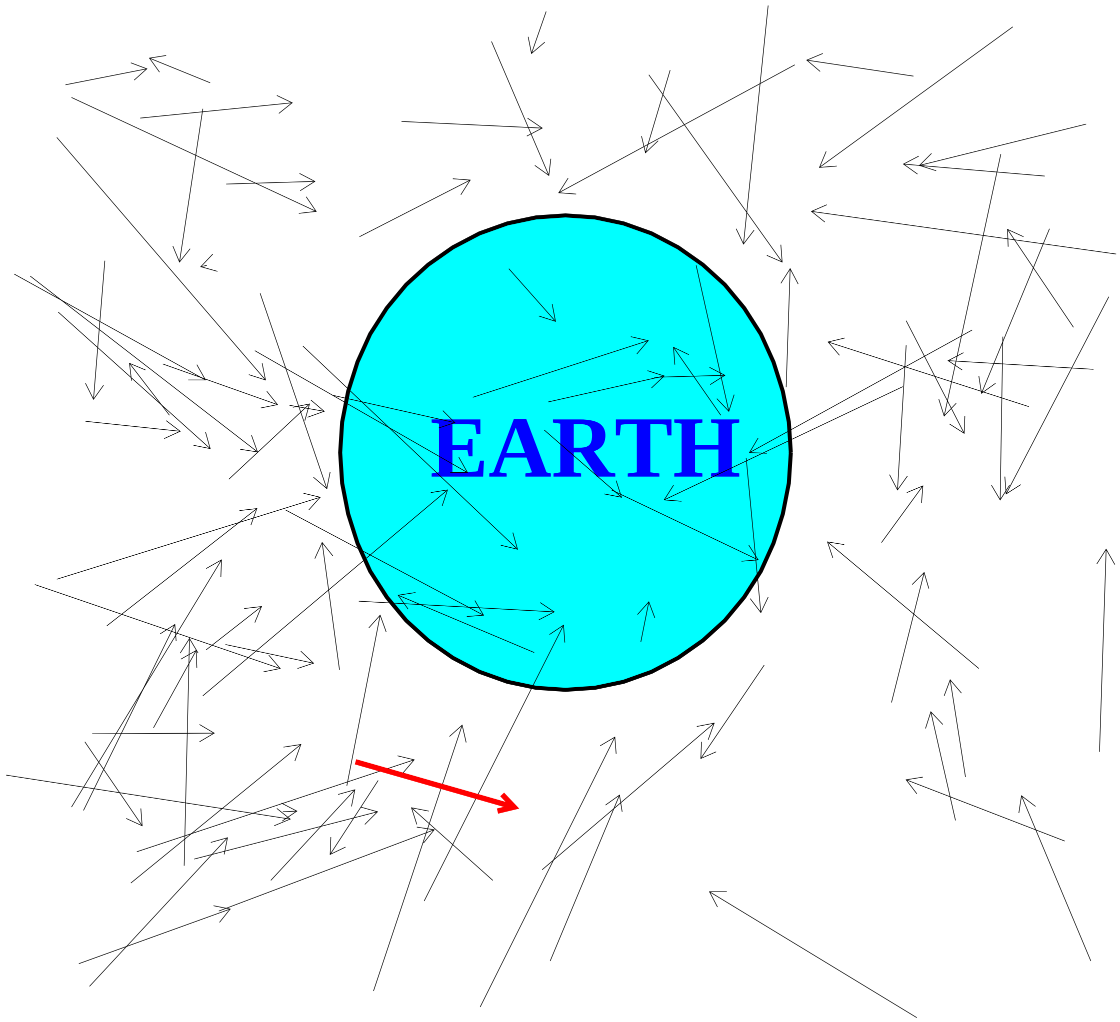
(few events at CERN)
(57 events at Fermilab)



No anti-atom has ever been observed in cosmic rays

Cosmic Protons Hitting Earth

$p/\bar{p} = 10{,}000$



Cosmic Antiprotons ($\overline{P}$) as Energy Source ?

Assume 100% cosmic $\overline{P}$ collection above the USA atmosphere (before the $\overline{P}$ annihilate) and 100% conversion to energy.

⇓

The total power could only boil one cup of coffee in a minute.

⇓

Cosmic $\overline{P}$ is NOT a practical energy source ! (try solar power)

What about anti-stars and anti-galaxies ?

NO EVIDENCE!

❖❖❖❖❖❖❖❖❖

☛ **anti-supernovae should leave anti-nuclei ...**
Not found.

☛ **anti gas clouds should annihilate with gas clouds to make photons ...**
Not found.

CAVEAT: Experiments cannot rule out anti galaxy clusters that are very far away. But this is difficult to accommodate in the Big Bang model of the universe.

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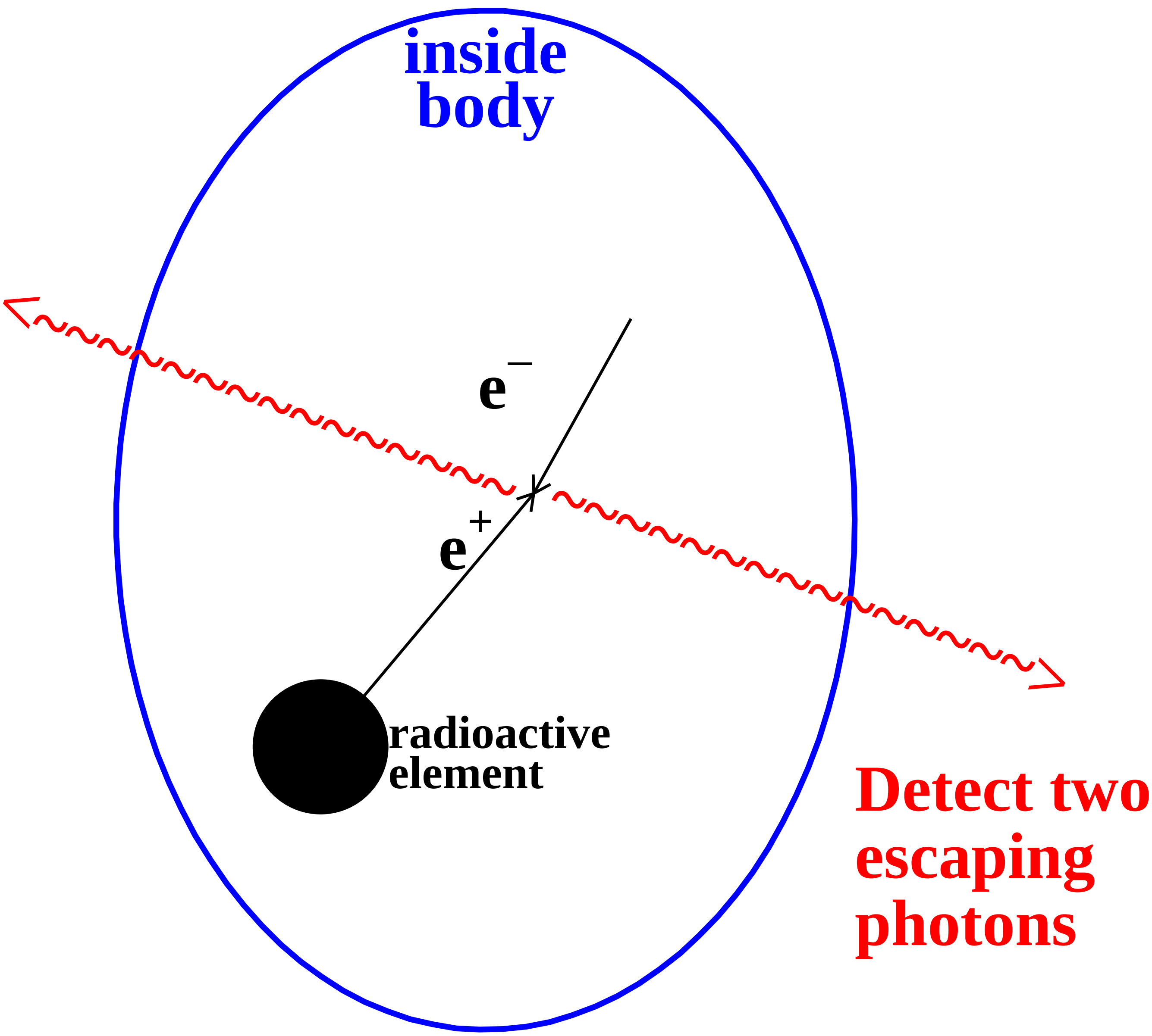
Antimatter in Medicine: Positron Emission Tomography (PET)



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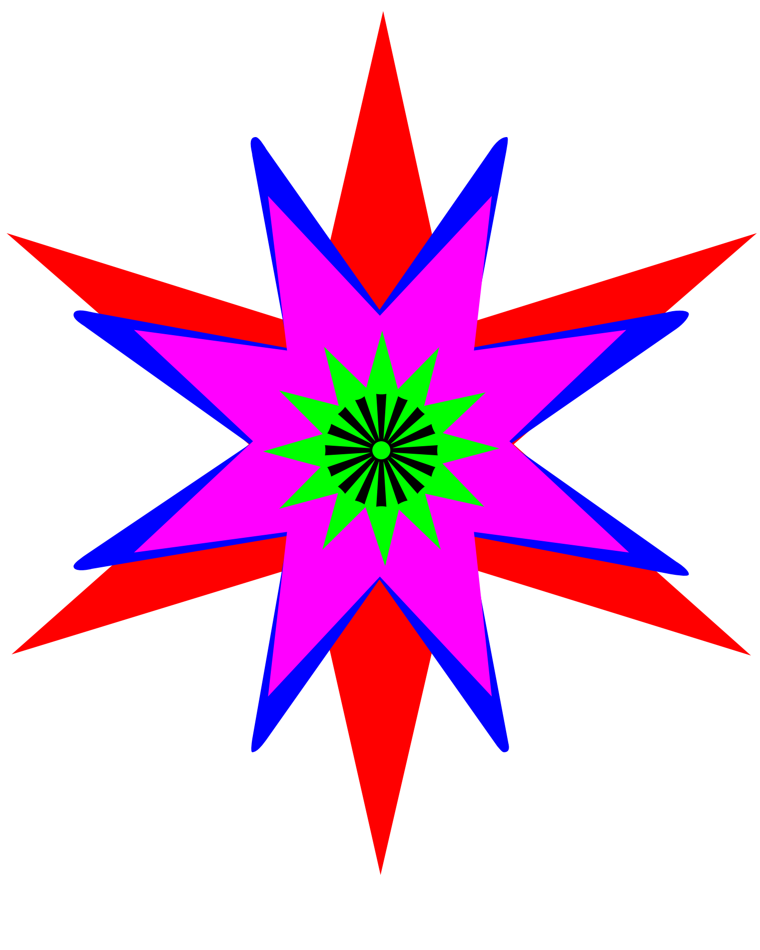
The expanding universe suggests a
BIG BANG
at the origin of time



The Basic Picture

- Equal number of M, $\bar{M}$ and photons. M-$\bar{M}$ annihilation and photon-photon pair creation maintain balance.

- A tiny asymmetry develops between M and $\bar{M}$ (origin unknown).

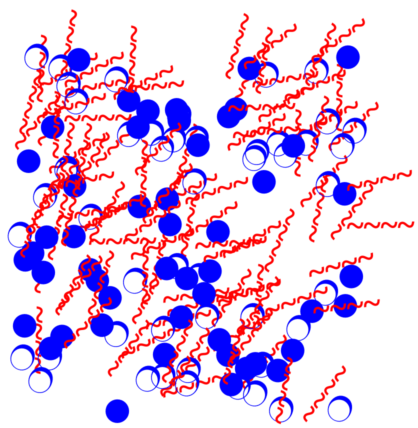
- As the universe expands and cools, the photon energy drops below MC^2 and pair creation stops. M-$\bar{M}$ annihilations continue until $\bar{M}$ is depleted.

- The tiny amount of left-over matter made all the stars and galaxies that we see today.

Age=10^{-41} second   T=10^{30} deg K

● particle   ○ anti-particle

~~~~ photon



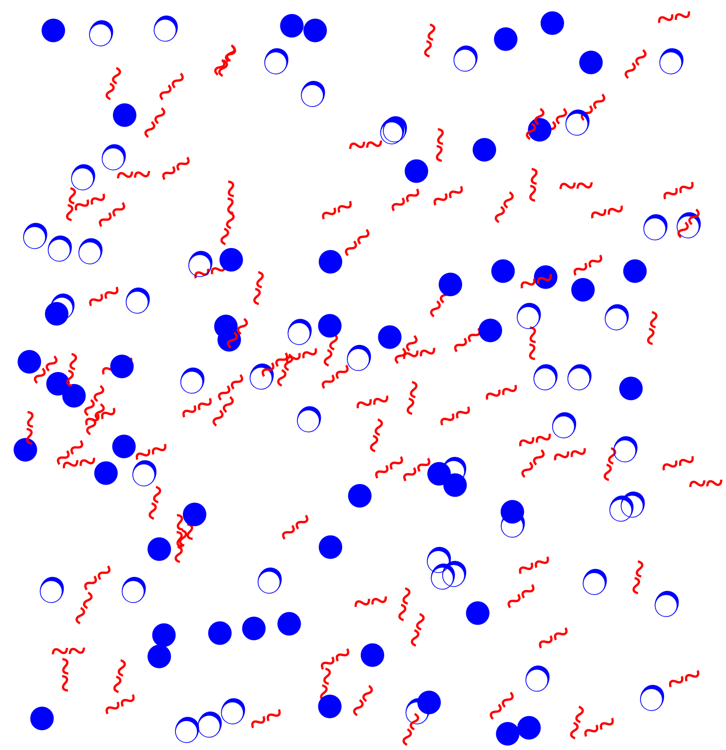
$$N_{\bullet} = N_{\circ} \approx N_{\sim\sim\sim\sim}$$

Age=10^{-34} second   T=10^{26} deg K

● particle   ❍ anti-particle

~~ photon

origin of matter-antimatter asymmetry

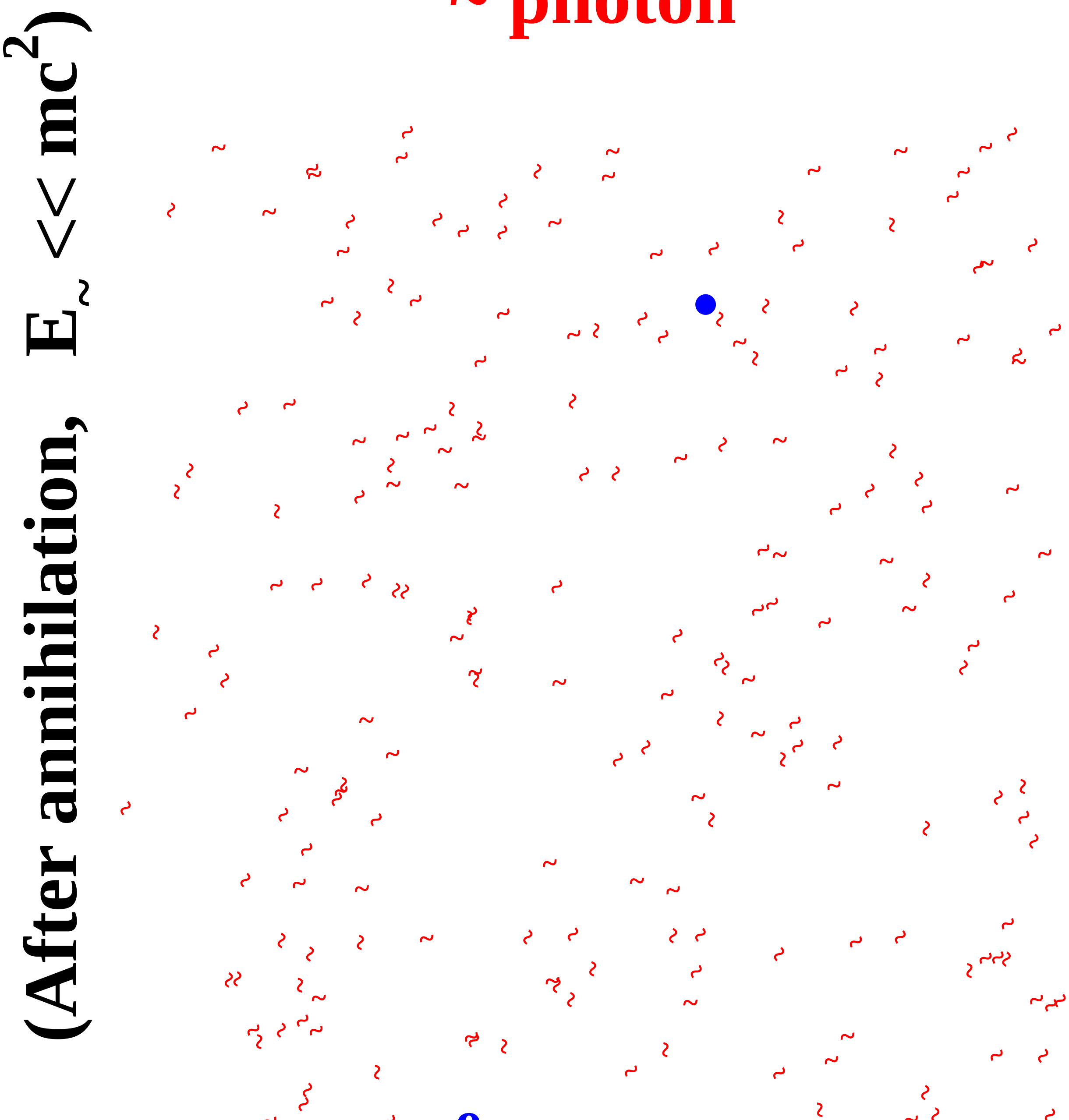


$$N_{\bullet} = 1.000000001 \times N_{\circ} \approx N_{\sim\sim}$$

Age=1 second T=10^{10} K

● particle ○ anti-particle

~ photon



$N_{\bullet}/N_{\sim} \approx 10^{-9}$ and $N_{\bigcirc} \approx 0$

SUMMARY OF MATTER and ANTIMATTER

- **For every 1,000,000,000 anti-particles there were 1,000,000,001 particles.**

- **The origin of this SYMMETRY BREAKING is still not understood**

- **After ANNIHILATION, there are roughly 1,000,000,000 photons for each particle.**

- **Today these photons have cooled to 3^0 K, and are known as COSMIC MICROWAVE BACKGROUND RADIATION (CMBR).**

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Special Relativity +
Quantum Mechanics

$\Downarrow$

Anti Particles must exist

(predicted by P.Dirac, 1929)

The first anti-particle was discovered in 1932 (3 years after prediction)

It was the anti-electron, now called as a POSITRON.

Q. Does current particle theory allow for a matter-antimatter asymmetry ?

Theory REQUIRES:

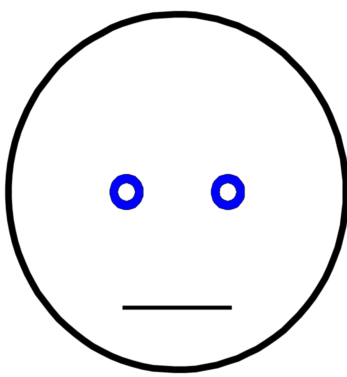
- ☛ **same mass for M and $\overline{M}$**
- ☛ **same life-time for M and $\overline{M}$**

A. YES !

There is an important loophole.

“Partial decay” LOOPHOLE:

Partial decay rates for matter and antimatter can be different without contradicting any theory.



say what ??????

Example of Partial Decay LOOPHOLE:

Imagine a very heavy (hypothetical) particle called "X"

DECAY CHANNEL	DECAY RATE
$X \rightarrow p\ e^{-}$	0.500000000
$X \rightarrow e^{+}\ e^{-}$	0.500000000
$X \rightarrow$ all	1.000000000
$\bar{X} \rightarrow \bar{p}\ e^{+}$	0.499999999
$\bar{X} \rightarrow e^{-}\ e^{+}$	0.500000001
$\bar{X} \rightarrow$ all	1.000000000

Discussion of the Hypothetical X Decay

Note that X and $\bar{X}$ have exactly the same total decay rate*. Next define a partial decay ASYMMETRY (A)

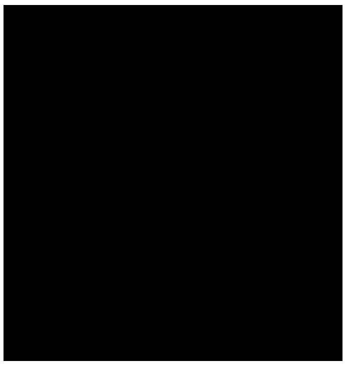
$$= \left[\frac{\text{Rate}(X \to p\, e^-) - \text{Rate}(\bar{X} \to \bar{p}\, e^+)}{\text{Rate}(X \to \text{all})} \right]$$

$$= \left[\frac{0.500000000 - 0.499999999}{1.000000000} \right]$$

$$= 0.000000001 \; (10^{-9})$$

* the lifetime = 1/(total decay rate) so that equal decay rates imply equal life-times.

Antimatter and SYMMETRIES



Imagine a cube of empty, boring space (i.e., NOTHING!!!)

Properties:

- distance
- time evolves
- speed of light
- isotropy
- forces

There are 3 very important SYMMETRY operations:

C: **Charge reversal (-e $\rightarrow$ +e)**

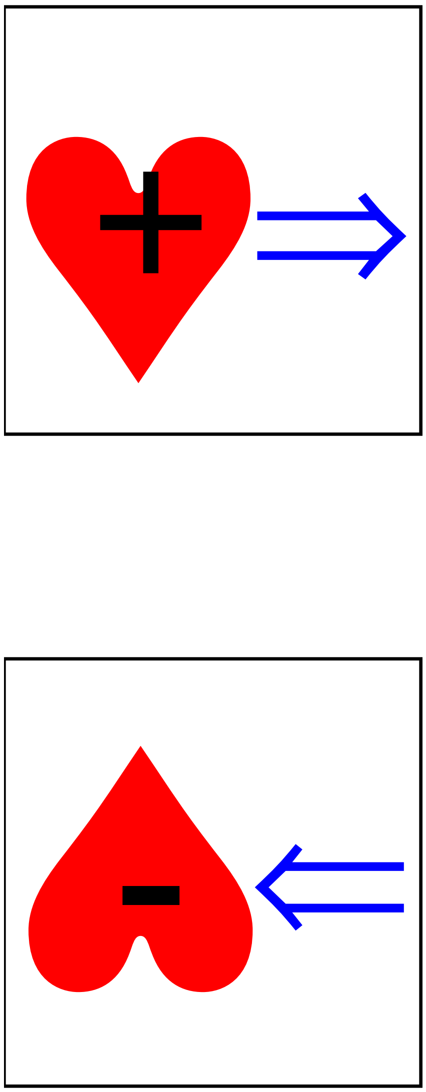
P: **Parity flip (-x $\rightarrow$ +x)**

T: **Time reversal**
(playing movie backward)

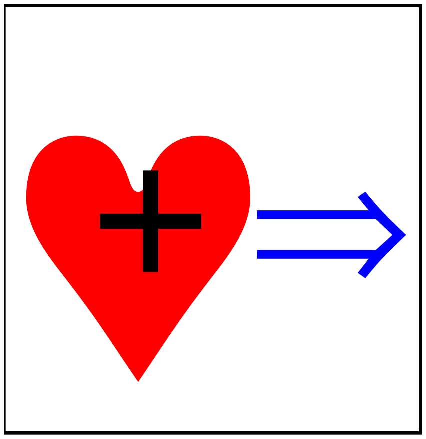
The ULTIMATE Symmetry of Relativistic Quantum Mechanics is:

The laws of Physics are the same if C, P and T are all applied.

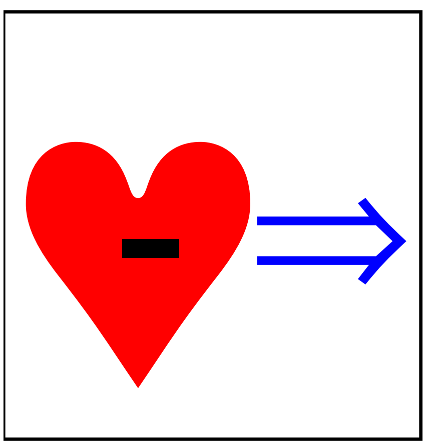
(aka: CPT theorem)



CPT-mirror systems can NEVER be distinguished



C-mirror systems $(M \rightarrow \bar{M})$ ’’ might ’’ be distinguished



Early universe and *kaons* CAN distinguish !!

Consequences of CPT Theorem

Particles and antiparticles have:

- → **EQUAL MASS**
- → **EQUAL LIFE-TIME**

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The antimatter deficit in the universe and the partial decay Loophole motivate the experimental search for a particle and its anti-particle with different partial decay rates.

THE PARTICLES

- electron
- proton
- neutron

- positron
- antiproton
- antineutron

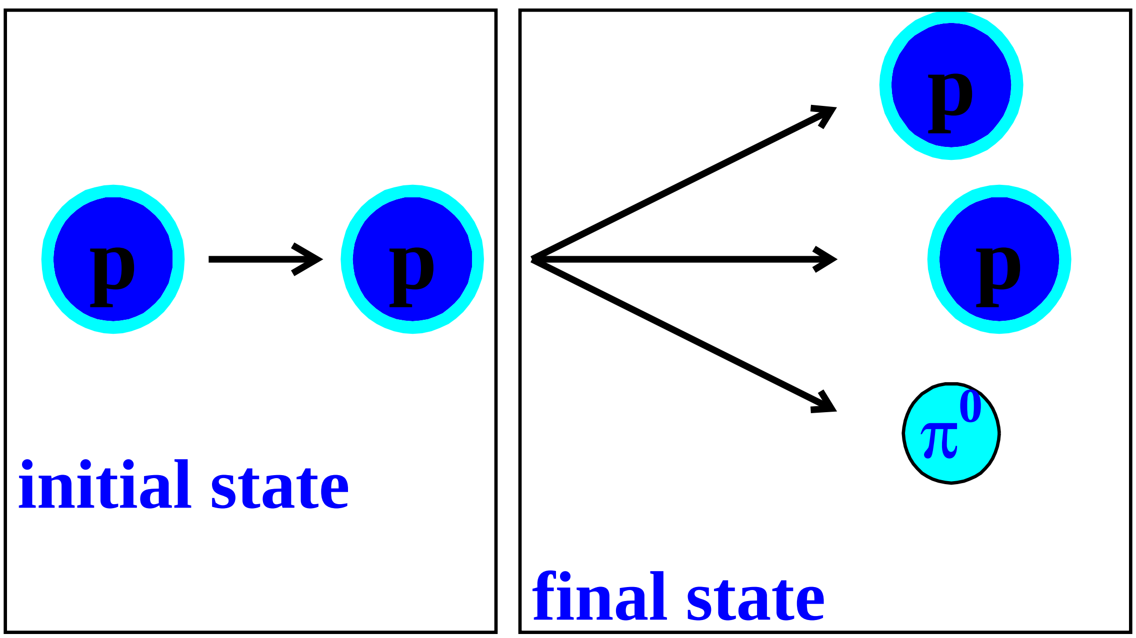
kaons, K^0, $\overline{K}^0$
(1/2 proton mass)

pions, π^+, π^-, π^0
(1/6 proton mass)

compare
$K^0 \rightarrow \pi\pi$
to
$\overline{K}^0 \rightarrow \pi\pi$

(How do we make pions and kaons?)

A hard hit proton can shake off a pion.

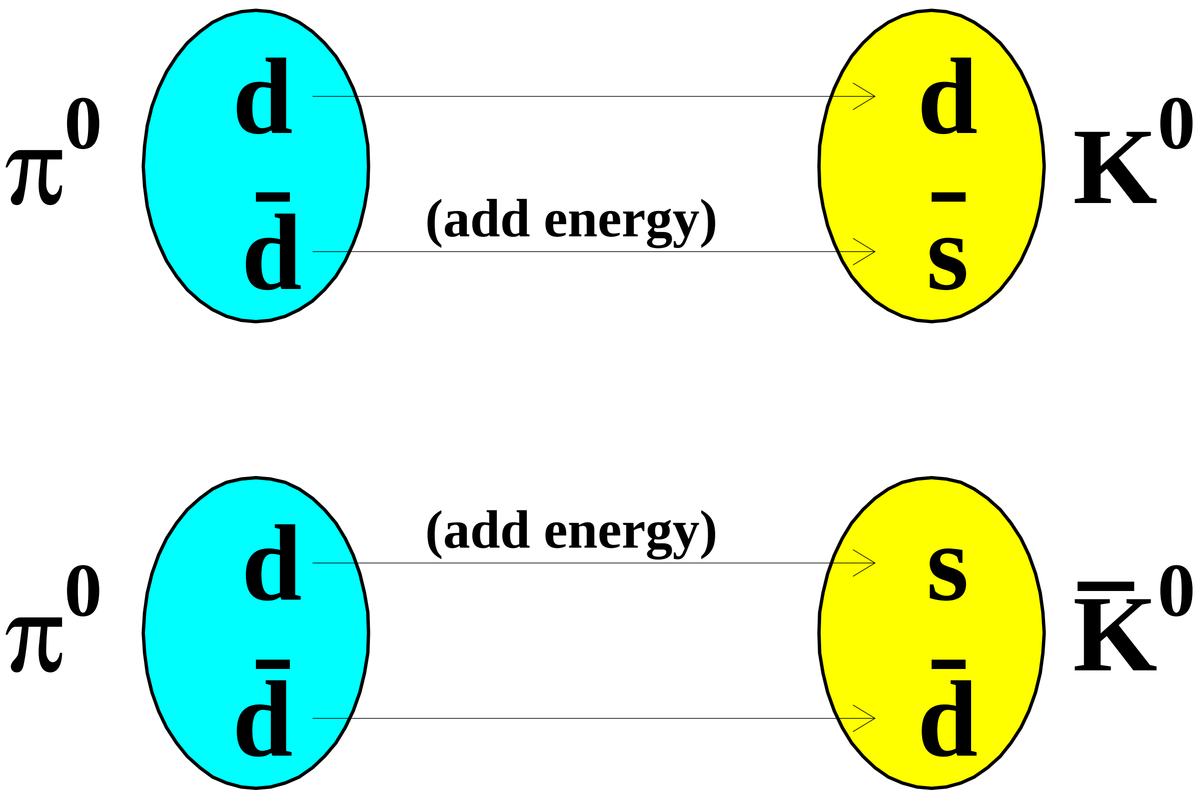


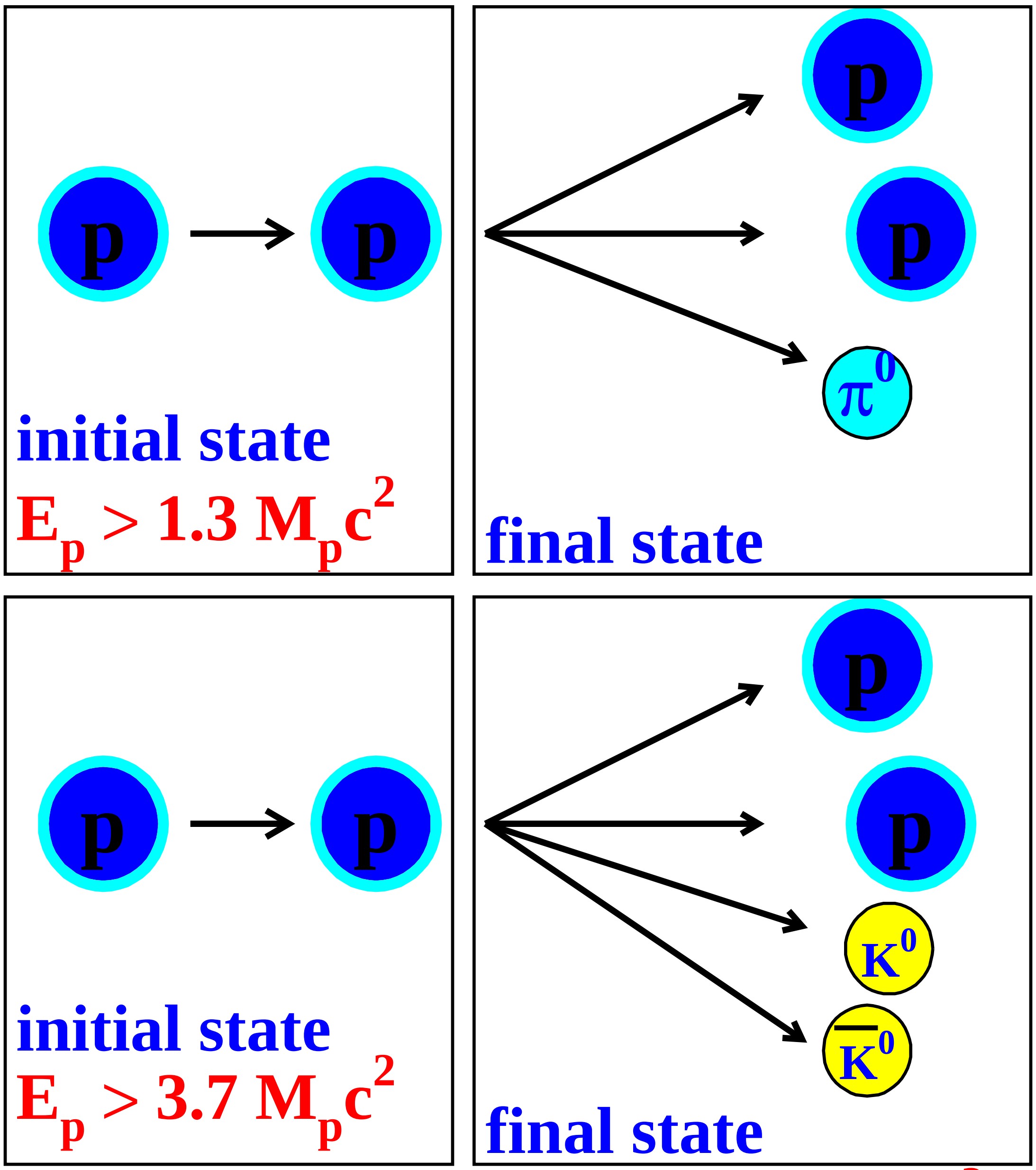
Where is the anti-π^0 ?

$\pi^0 = d\,\bar{d}$ is its own anti-particle.

Recall $\pi^0 = d\,\bar{d}$.

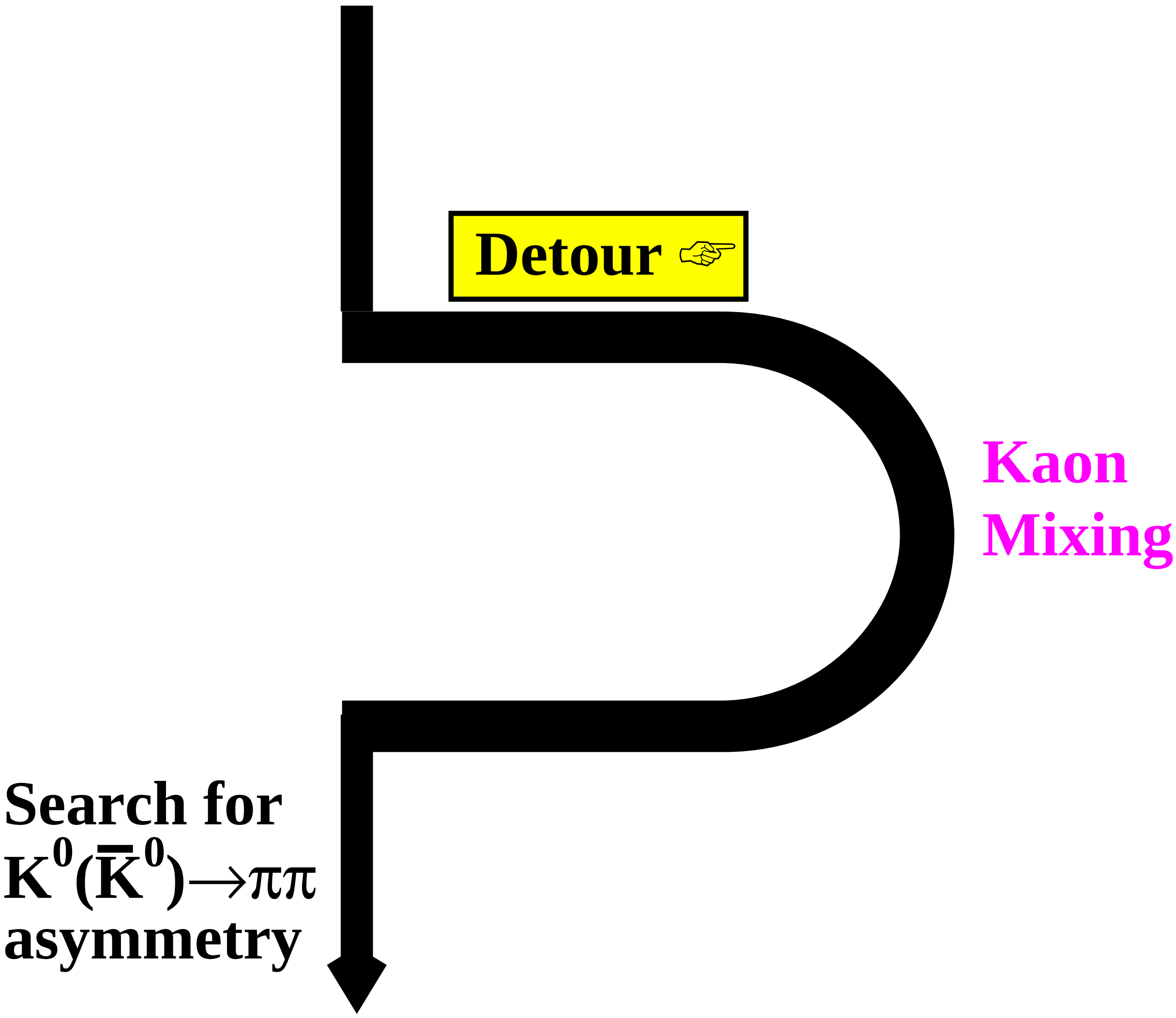
With more energy, replace the light “d”-quark with a heavier “s”-quark





Fermilab proton energy = $860M_pc^2$!

Now that we can make kaons, we can watch them decay. BUT WAIT! Detour ahead.



KAON MIXING

Kaons and anti-kaons "oscillate" back and forth, 5 billion times per second.

$\mathbf{K^0 \rightarrow \overline{K}^0 \rightarrow K^0 \rightarrow \overline{K}^0 \rightarrow K^0 \rightarrow \overline{K}^0 \rightarrow}$

(pendulum demo)

Matter-antimatter symmetry demands equal number of K^0 and $\overline{K}^0$ decays.

1964: found 0.23% difference !!!

$\bar{K}^0 \to K^0$ is preferred over $K^0 \to \bar{K}^0$ by 0.23%

☺ **The asymmetry in K^0-$\bar{K}^0$ mixing was the first experiment to distinguish between matter and antimatter.**

☹ **Does not involve decays.**
(recall partial decay loophole to account for antimatter deficit)

The quest began to compare $K^0 \to \pi\pi$ to $\bar{K}^0 \to \pi\pi$.

Partial Decay LOOPHOLE for kaons ??

Many experiments and theory suggest the following:

DECAY CHANNEL	DECAY RATE
$K^0 \rightarrow \pi^+\pi^-$	2/3
$K^0 \rightarrow \pi^0\pi^0$	1/3
$K^0 \rightarrow$ all	1
$\bar{K}^0 \rightarrow \pi^+\pi^-$	2/3 + asymmetry
$\bar{K}^0 \rightarrow \pi^0\pi^0$	1/3 – asymmetry
$\bar{K}^0 \rightarrow$ all	1

Some History ...

- Almost 30 years would pass before the first experimental hint of the partial decay asymmetry in kaon decays.

- In the early 1990s, both CERN and Fermilab began large new experiments to look for this asymmetry.

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Fermilab uses a high energy proton beam ($E=860mc^2$). There is plenty of energy to produce kaons.

The experiment is called

KTEV

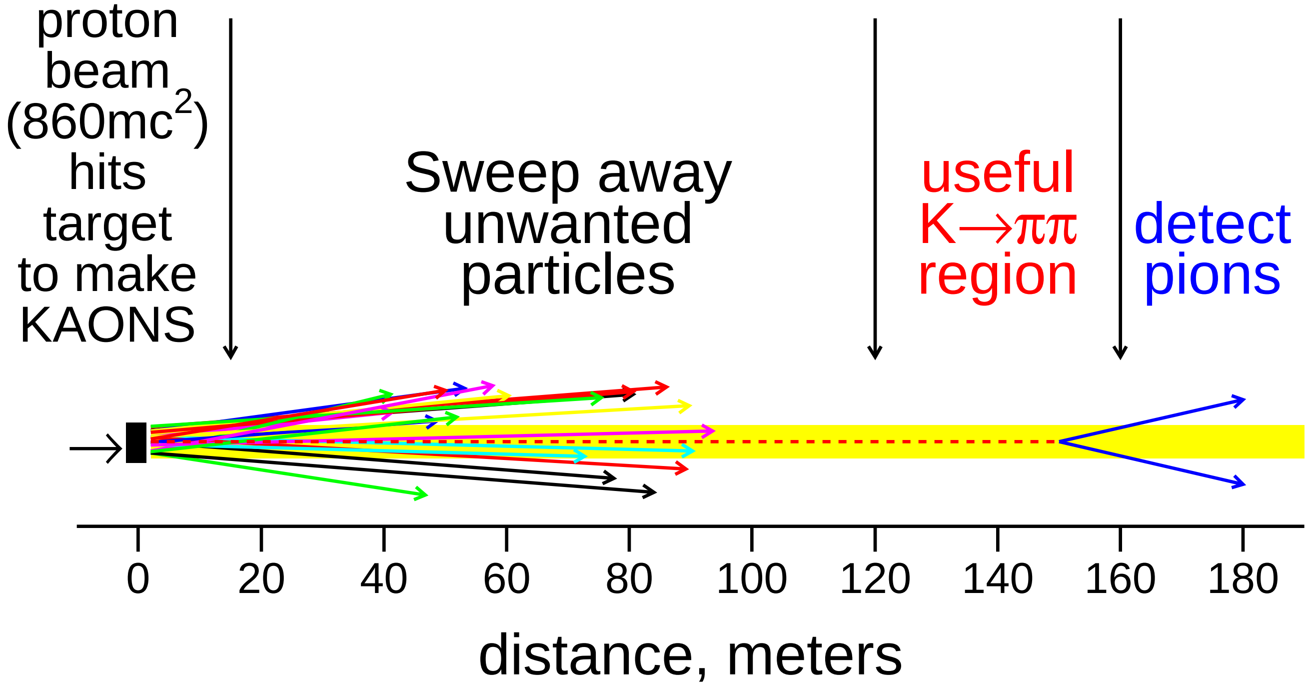
"Kaons at the Tevatron"

TEV = 1 trillion electron volts (10^{12} eV)
Tevatron = name of accelerator (highest energy in the world)

About 80 physicists from 12 institutions work on KTEV.

Elmhurst College
Fermi National Accelerator Laboratory
Osaka University, Japan
Rice University
Rutgers University
University of Arizona
University of California, Los Angeles
University of California, San Diego
University of Chicago
University of Colorado, Boulder
University of Virginia, Charlottesville
University of Wisconsin, Madison

The KTEV experiment is nearly 200 meters long!

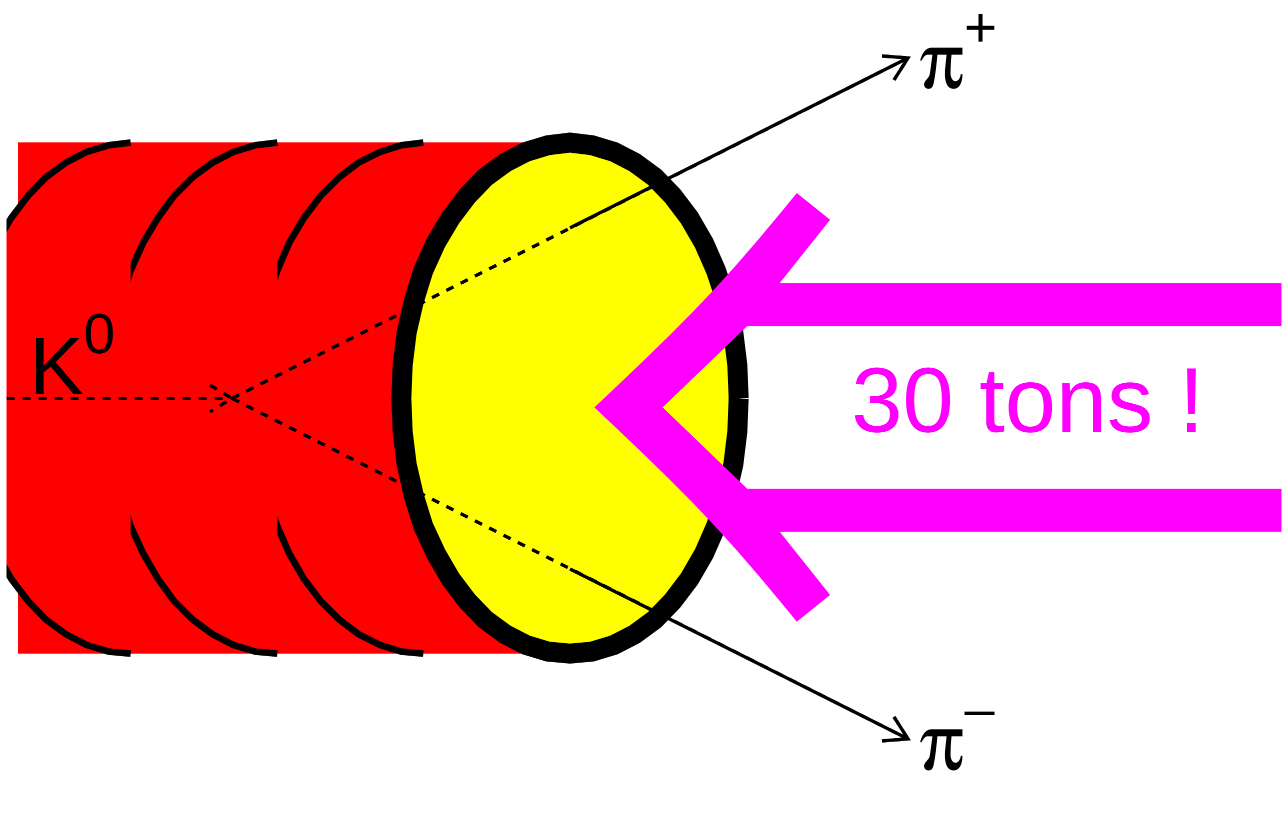


KTEV Kaons ...

- **typical velocity is 99.997% the speed of light.**
- **Boost factor γ = 140 !!**
  $\rightarrow$ travels 2 km (on average), instead of 15m, before it decays
- **kaons traverse our 40 meter long decays region in 0.13 x 10^{-6} seconds.**

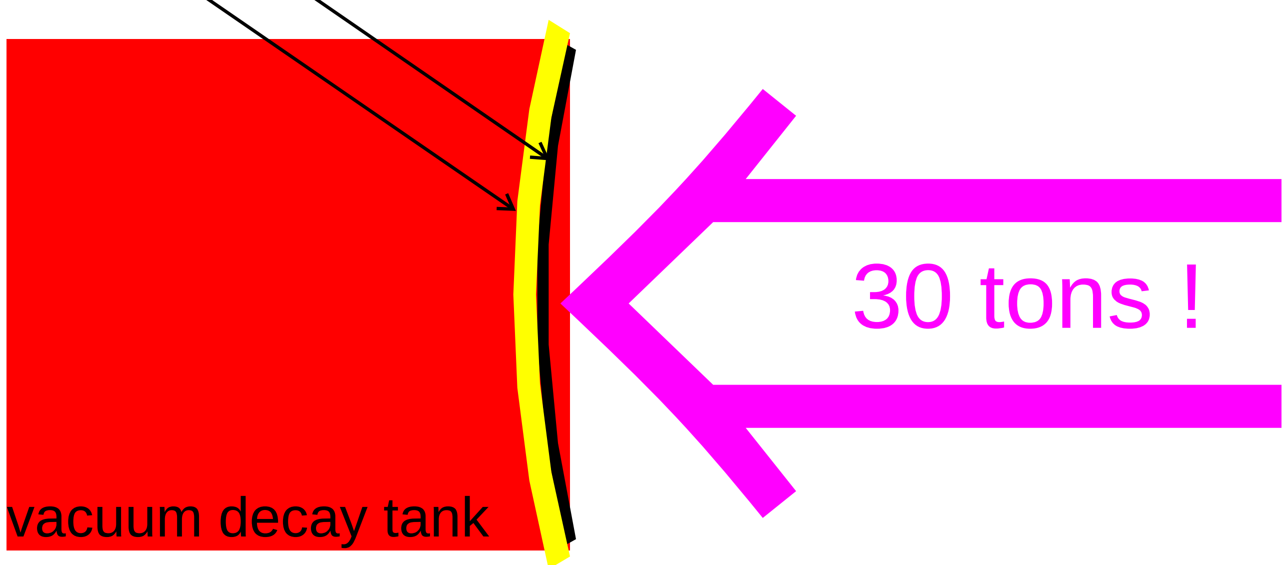
To avoid kaon collisions with air molecules, the kaons decay in a VACUUM tank at 1/billionth (10^{-9}) of an atmosphere of pressure.

CHALLENGE: design 2m vacuum window strong enough to support 30 tons of pressure, but thin enough to let the pions (π) escape.



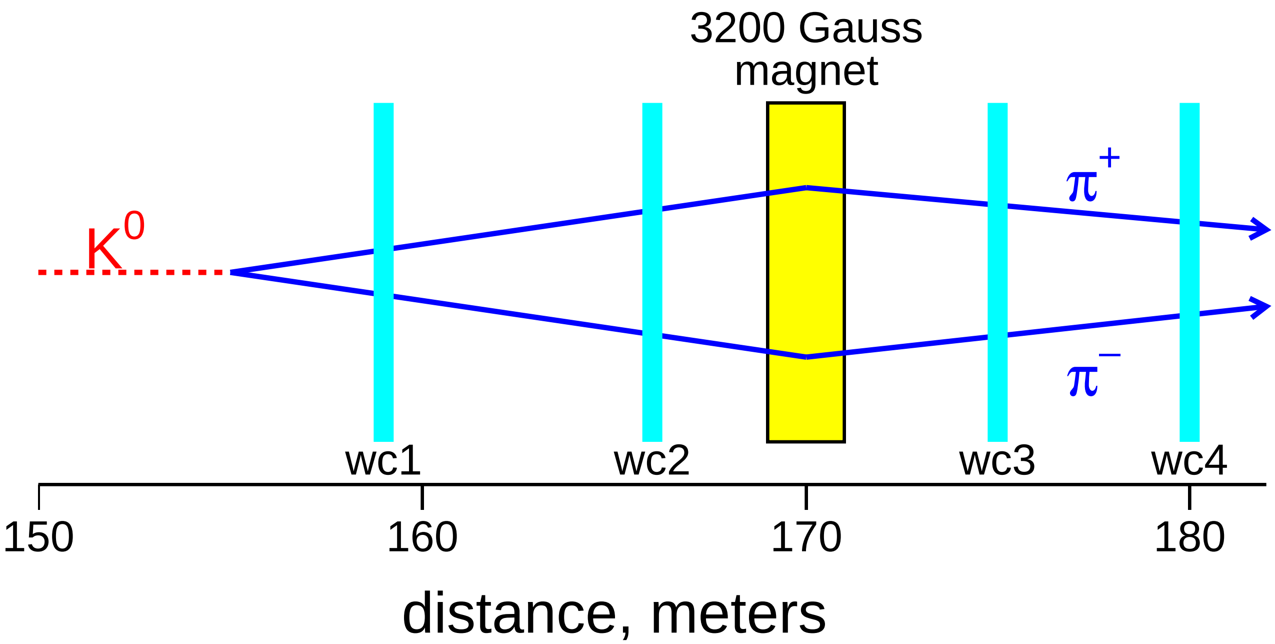
SOLUTION:

use kevlar for strength, and
use mylar for vacuum seal.



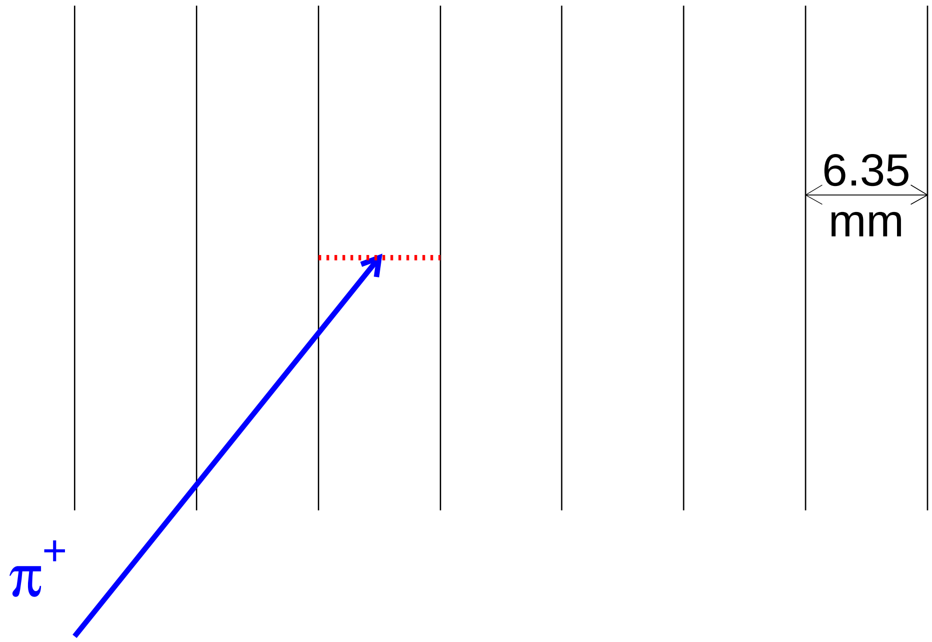
The window thickness is 0.5 mm and the 3 m^2 area weighs just over 1 kg. Air pressure deflects the window by 10 cm ! The outgoing pions scatter by only 0.001^0 (1 cm deflection per km).

The π^+ and π^- momenta are measured from the bend-angle through a strong magnet.



wc1-4 are “wire chambers”

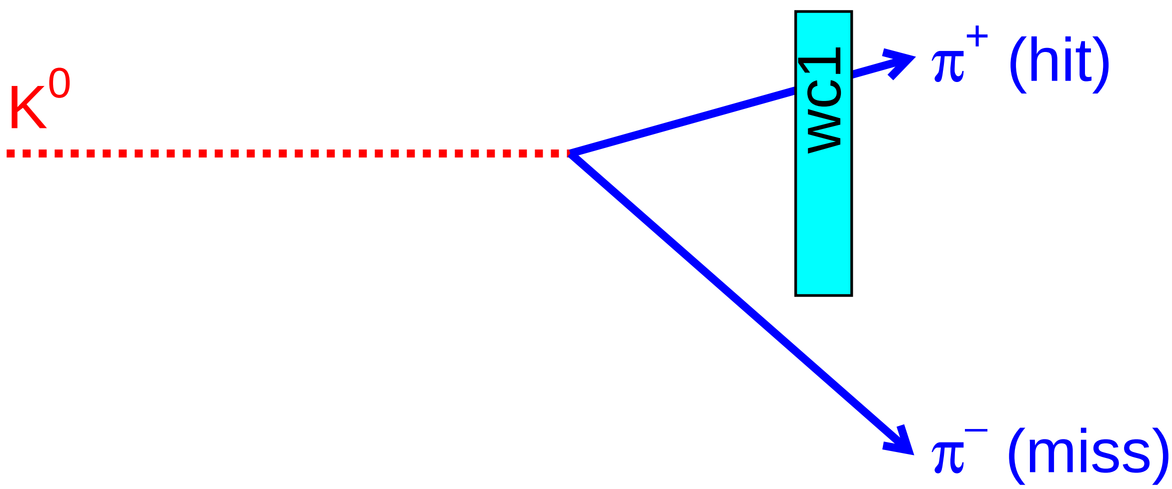
Wire Chambers for π^+ and π^-



- charged tracks leave tiny electric signals on nearby wires (10^{-8} Amp)
- The time difference gives accurate position to within 0.1 mm (note 6.25 mm wire spacing)
- There are 4 horizontal and 4 vertical views ⇨ 2000 total wires!
- Wire thickness is just 0.025 mm

COMPUTER SIMULATIONS

When kaons decay into two pions, at least one pion misses our detector for about half of the decays, and are NOT counted.
See example below.



A detailed computer simulation was used to predict the exact fraction of decays that missed our detector. The calculation took a few CPU-months!

ON-LINE COMPUTING

- ☛ 24 parallel processors
  (200 MHz each ≈ 1/2 pentium)
- ☛ 70 Tera-bytes of data storage
  (70 million Mega-bytes)
- ☛ 2 GB of memory

DATA COLLECTION

Despite our enormous computing power,
we would need 100 times more computing
to process all of the particle interactions
in our detectors.

To get around this problem we use a
custom-built ELECTRONIC TRIGGER
to do most of the selection.
It makes a decision 53 million times per second.
The time per decision is less than
0.000,000,020 seconds (2×10^{-8} s)!

DATA COLLECTION

This is what happens in 1 second during the experiment:

☛ 200 billion protons hit the target.

☛ 1/2 million kaons decay in the 50 meter long vacuum tank.

☛ The electronic trigger selects 10,000 for on-line computer processing.

☛ The on-line farm of 24 processors selects 2,000 for permanent data storage (10 MB).

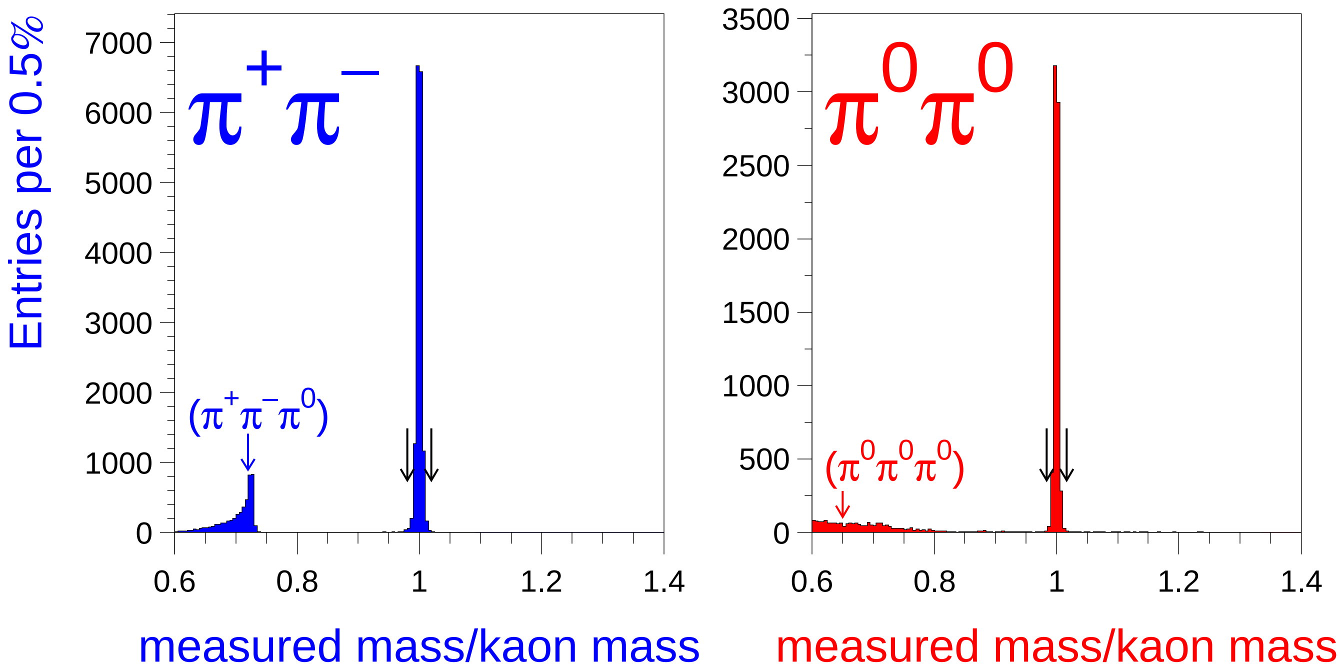
☛ After off-line analysis, about 10 events are cleanly identified as $K \to \pi\pi$.

STATISTICS

To measure a tiny asymmetry we need to count alot of decays:

- ☛ 100 million K^0 ($\overline{K}^0$) $\rightarrow \pi\pi$ decays
- ☛ 2 billion other kaon decays for systematic error studies.

KTEV DATA



The ratio of the measured mass to known kaon mass is shown for both the $\pi^+\pi^-$ and $\pi^0\pi^0$ decays. The peaks centered at one are the signals and they both have a width of 0.3%. The vertical arrows show the events selected for analysis.

The events at the left of each plot are due to background from decays into 3 pions in which a π^0 escapes detection.

Note: less than 1% of the data are shown here.

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- Energy and mass ($E=mc^2$)
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- Theory of M-$\overline{M}$ asymmetry
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The Concept of Uncertainty

Flip a coin 100 times.
(expect 50 heads, 50 tails).

You get 40 heads, 60 tails ...
Is it "loaded" ?

A standard deviation is 5 flips.

50± 5 heads (45-55) happens 67%

50±10 heads (40-60) happens 95%

50±15 heads (35-65) happens 99%

The above experiment would report 40±5 heads. What do you conclude ?

The Concept of Uncertainty

The result 40±5 heads is "two standard deviations" from the expected value. The chance of observing such a fluctuation is 5%.

CONCLUSION:

this result by itself cannot distinguish a random fluctu-ation from a loaded coin. Need more coinflips!

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Partial Decay LOOPHOLE for kaons ??

Many experiments and theory suggest the following:

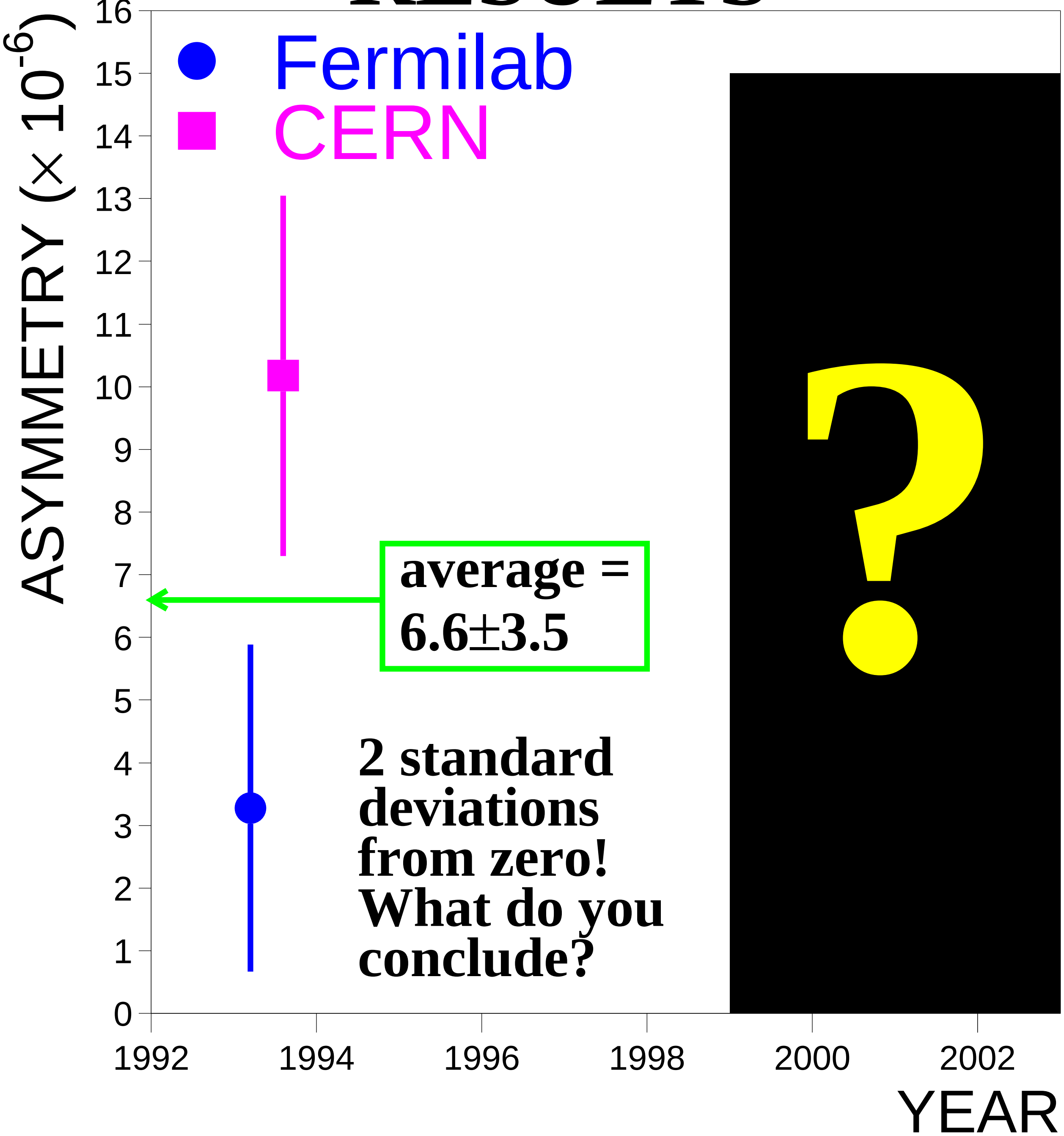
DECAY CHANNEL	DECAY RATE
$K^0 \to \pi^+\pi^-$	2/3
$K^0 \to \pi^0\pi^0$	1/3
$K^0 \to$ all	1
$\bar{K}^0 \to \pi^+\pi^-$	2/3 + asymmetry
$\bar{K}^0 \to \pi^0\pi^0$	1/3 – asymmetry
$\bar{K}^0 \to$ all	1

Define partial decay ASYMMETRY =

$$\frac{\text{Rate}(K^0 \rightarrow \pi\pi) - \text{Rate}(\bar{K}^0 \rightarrow \pi\pi)}{\text{Rate}(K^0 \rightarrow \text{all})}$$

Is it zero or non-zero ?

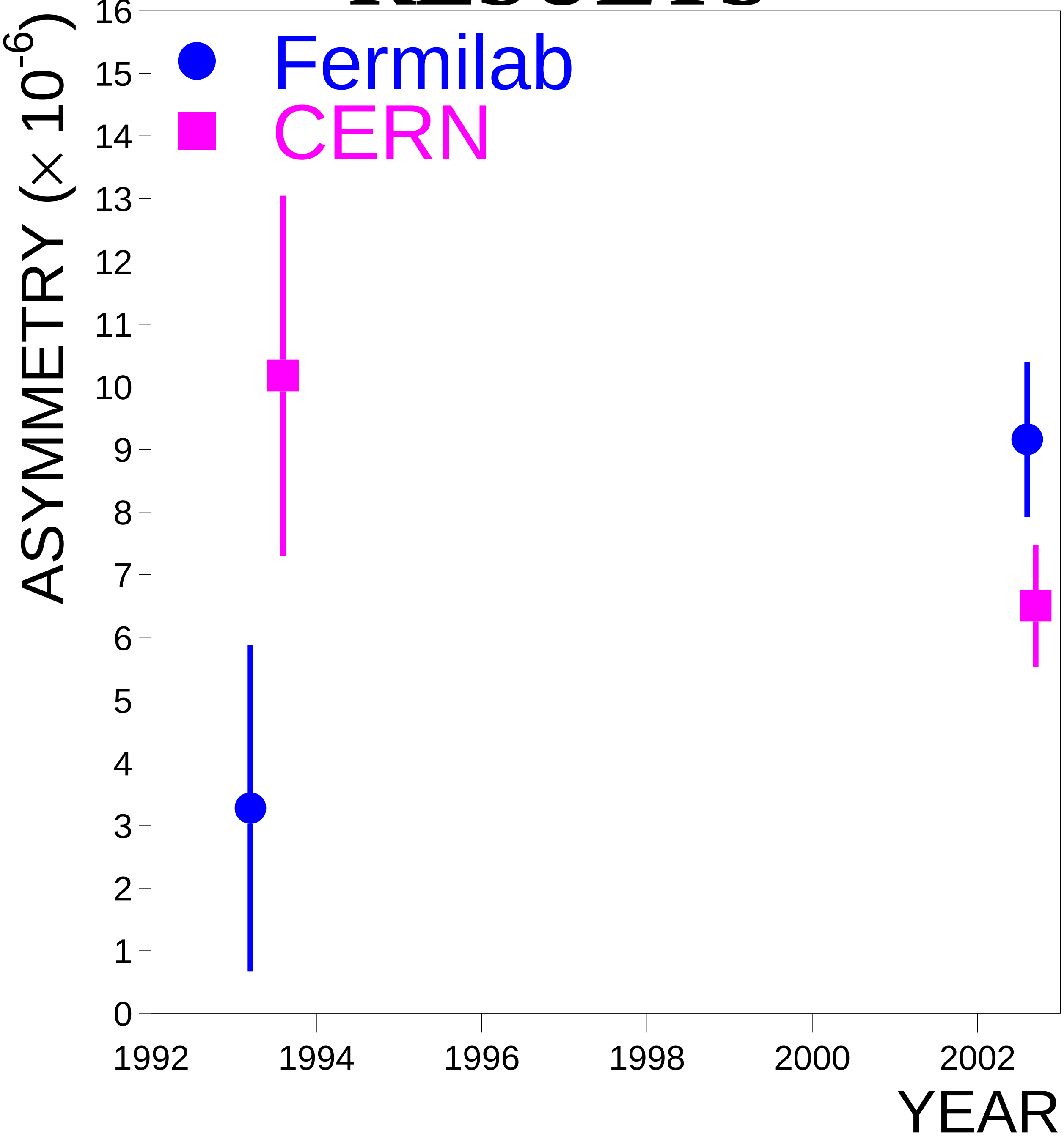
RESULTS


Fermilab
CERN
average = 6.6±3.5
2 standard deviations from zero! What do you conclude?
?
ASYMMETRY (× 10^-6)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
1992
1994
1996
1998
2000
2002
YEAR

In 1993 the partial decay asymmetry for $K^0(\bar{K}^0)\rightarrow\pi\pi$ was 6.6±3.5 parts per million. This had about the same statistical significance as 100 coin flips with 40±5 heads.

Need more data!

RESULTS



Fermilab
CERN
ASYMMETRY (× 10^-6)
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
1992
1994
1996
1998
2000
2002
YEAR

Experimental Summary (Oct, 2002)

☛ **Average of four experiments gives a decay asymmetry of $(7.4 \pm 0.7) \times 10^{-6}$**

(10^{-6} = parts per million)

☛ **The effect is ten standard deviations from zero**
$\Rightarrow$ VERY SIGNIFICANT !

(more data still to process ...)

Significance of Kaon Experiments

☛ The observed $K^0(\bar{K}^0)\rightarrow\pi\pi$ asymmetry cannot explain the $\bar{M}$ deficit in our universe (no protons in kaon decays). ☹

☛ **This is a "proof of principle" for the partial decay asymmetry between a particle and its anti-particle. This fundamental principle could be responsible for the antimatter deficit in the universe.** ☺

Are Aliens Made of Matter or Antimatter ?

An interesting puzzle is to use our knowledge of kaons to figure out if aliens are made of matter or antimatter. After all, we would want to be sure that aliens are made of matter before arranging a visit. A possible communication is given below.

Since the Fermilab beam and target are made of matter, we produce slightly more K^0 than $\overline{K}^0$. For example,

$$p + p \rightarrow p\, K^0 \Lambda \quad \text{is allowed}$$

$$p + p \rightarrow p\, \overline{K}^0\, \overline{\Lambda} \quad \text{is forbidden}$$

The same experiment in an antimatter world would have an excess of $\overline{K}^0$. The K^0 and $\overline{K}^0$ excesses are:

$$p + \text{target} \rightarrow 7\, K^0 \text{ per } 6\, \overline{K}^0 \quad \text{(matter world)}$$

$$\overline{p} + \overline{\text{target}} \rightarrow 7\, \overline{K}^0 \text{ per } 6\, K^0 \quad \text{(antimatter world)}$$

- **Earth message:**
  "Matter kaons (K^0) have bigger decay rate into $\pi^+\pi^-$, "
  $$\text{Rate}(K^0 \rightarrow \pi^+\pi^-) > \text{Rate}(\overline{K}^0 \rightarrow \pi^+\pi^-)$$

- **Alien message if made of matter: Same as earth message.**

❍ **Alien message if made of antimatter:**
"Antimatter kaons ($\overline{K}^0$) have bigger decay rate into $\pi^+\pi^-$ "

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For more than three decades, the K^0 and $\overline{K}^0$ were the only particles to demonstrate a matter-antimatter difference.

In 2001, a matter-antimatter asymmetry was observed in another type of particle, known as B^0 and $\overline{B}^0$.

http://www.slac.stanford.edu/slac/media-info/20020723/sine2b.html

What is a B^0 ?

π^0 $d\bar{d}$ (1/6 proton mass)

K^0 $d\bar{s}$ (1/2 proton mass)

B^0 $d\bar{b}$ (x5 proton mass)

B^0 - $\overline{B}^0$ MIXING

B^0 and $\overline{B}^0$ "oscillate" back and forth, 5 trillion times per second,

$$B^0 \rightarrow \overline{B}^0 \rightarrow B^0 \rightarrow \overline{B}^0 \rightarrow B^0 \rightarrow \overline{B}^0 \rightarrow$$

Matter-antimatter symmetry demands equal number of B^0 and $\overline{B}^0$ decays.

2001: Belle (Japan) and BaBar (SLAC) find large difference !!!