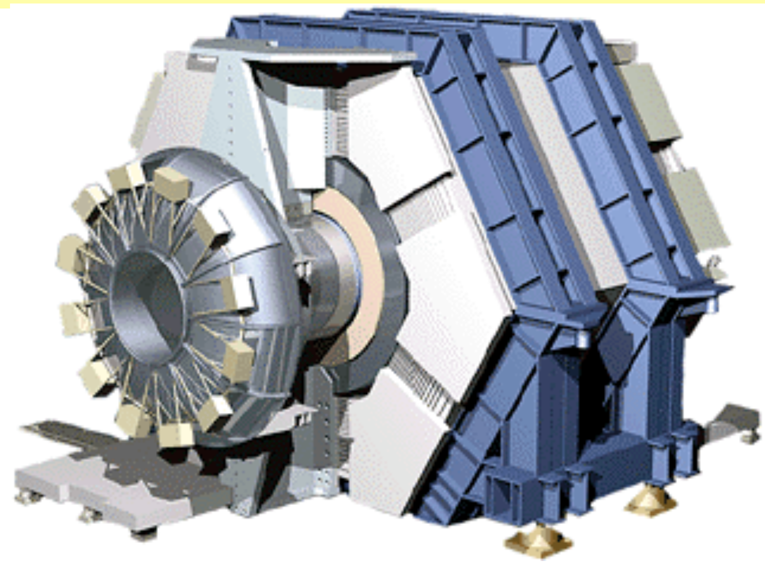
The *BABAR* experiment, *CP* violation, and the search for new physics



Members of the UCR Babar research group:

Faculty: Bill Gary, **Owen Long**

Graduate students: Hulya Atmacan, Gil Vitug, Zafar Yasin

Undergraduate students: Elizabeth Mullin

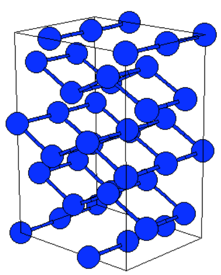
What is matter?

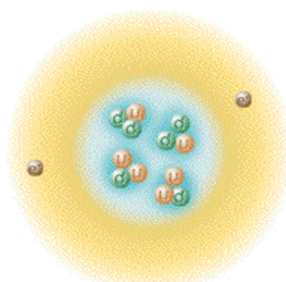
- **Solids** – collections of atoms
- **Atoms** – electrons surrounding a nucleus
- **Nuclei** – collection of protons and neutrons
- **Protons and neutrons** – different combinations of up and down quarks.

Everything is made of electrons and quarks.
These are fundamental particles.

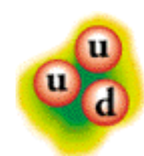
"Large" (10^{-9} m)

Extremely small ($<10^{-18}$ m)
(At least 1 billion times smaller)


Crystal lattice of a solid


Helium atom


Nucleus of a heavy element



A proton is two up quarks and a down quark

electron

Images taken from **http://particleadventure.org**

What is antimatter?

- Almost exactly the same as matter *except* particles and antiparticles have *opposite charge*.
  - Same mass
  - Same lifetime

- It's theoretically possible to have anti-nuclei, anti-atoms, and even anti-solids – *antimatter!*
  - Ok then, ***where is it*** ??? More on this point in a minute…

Why do we need antimatter?

- Seems kind of superfluous, right? Wrong!
- Relativistic quantum mechanics *requires* it.

Why do we need antimatter?

- Seems kind of superfluous, right? Wrong!
- Relativistic quantum mechanics *requires* it.
- What is Quantum Mechanics?
  - The laws of physics *change* as we go from large systems (baseballs flying through the air) to very small systems (electrons orbiting a nucleus).
    - *Classical physics* → *Quantum physics*.
  - Light behaves like a particle (the photon) which is a *quantum* of energy.
  - Relevant for all of atomic physics and high-energy particle interactions.

Why do we need antimatter?

- Seems kind of superfluous, right? Wrong!
- Relativistic quantum mechanics *requires* it.
- What does "relativistic" mean?
  - *Special relativity*: A. Einstein, 1905.
    - *Nothing* can travel faster than light.
    - The speed of light is the same for everyone everywhere.
  - The world's most famous equation:

$$E = m\,c^2$$

Energy ***mass*** ***The speed of light (squared)***


1921

Photos of Nobel laureates from **http://nobelprize.org**

Why do we need antimatter?

- Seems kind of superfluous, right? Wrong!
- Relativistic quantum mechanics *requires* it.
  - P. A. M. Dirac successfully combined special relativity and quantum mechanics for the electron in 1928, but he found the theory predicted strange **negative energy states**.
  - Dirac boldly interpreted these as solutions for *antiparticles* !

e^- **with** $E < 0$

Nonsensical negative-energy electron solution

e^+ **with** $E > 0$

Sensible positive-energy positron solution

1933

Why do we need antimatter?

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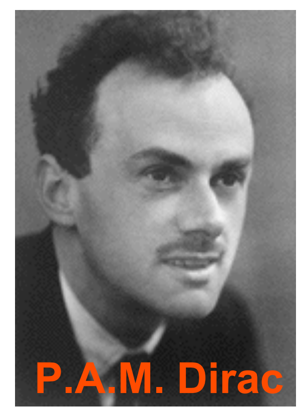
- Relativistic quantum mechanics *requires* it.
  - P. A. M. Dirac successfully combined the two (SR and QM) for the electron in 1928, but he found the theory predicted strange **negative energy states**.
  - Dirac boldly interpreted these as solutions for *antiparticles !*
  - The only problem was that an antiparticle had never been seen! Initially treated with skepticism.

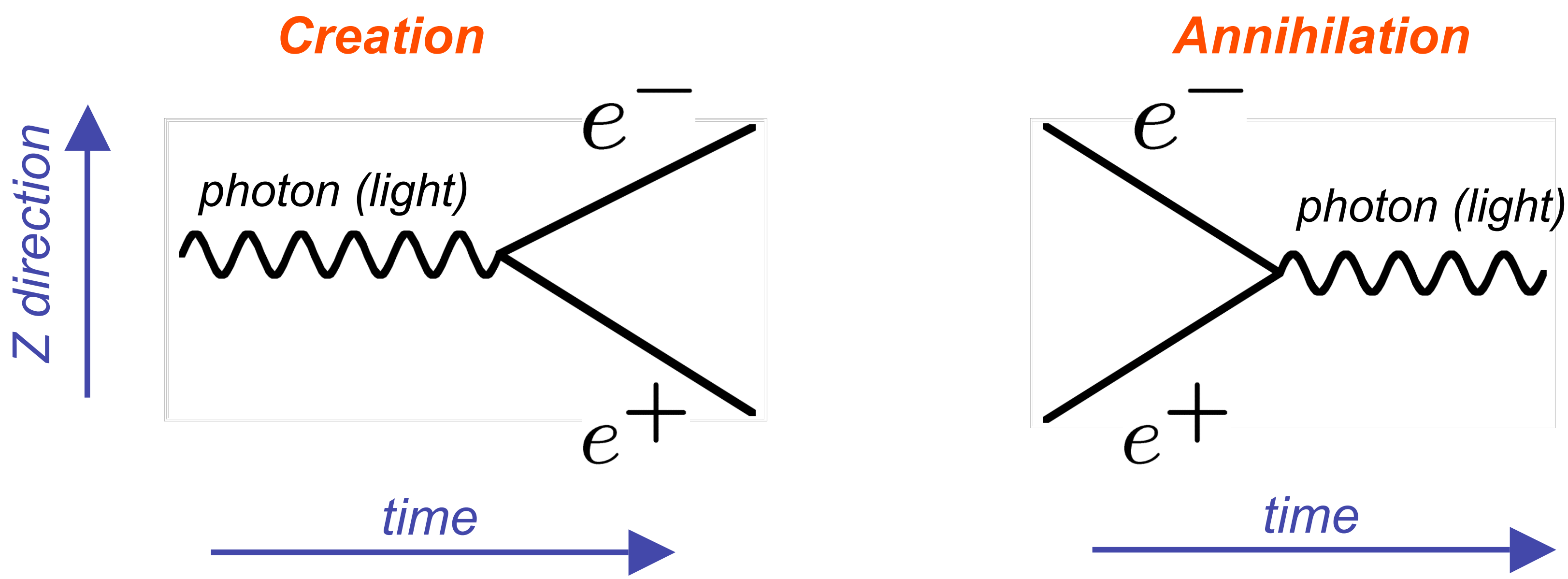



1933

Creation and destruction

- Einstein told us that energy and mass (or matter) are equivalent with his equation. $E = m\,c^2$

- It is never more apparent than the creation and annihilation of particle – antiparticle pairs.



Antimatter is real!

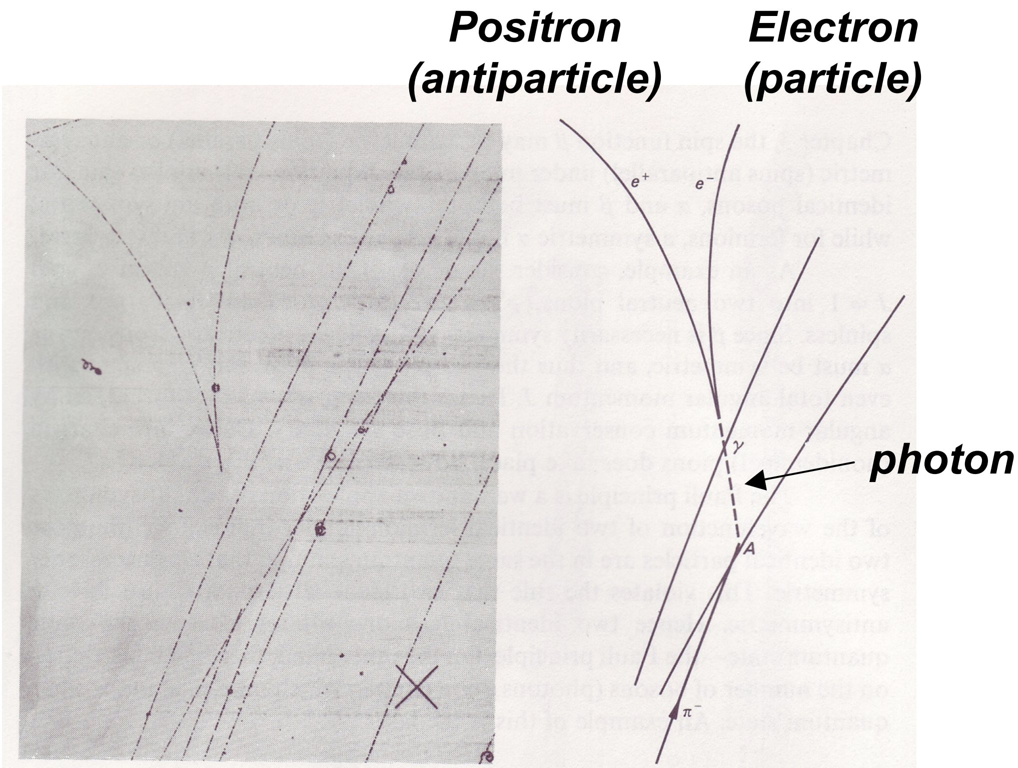


Figure 1.2 Conversion of a photon to an electron-positron pair in a bubble chamber. An incoming negative pion undergoes charge-exchange at point A: $\pi^- + p \rightarrow n + \pi^\circ$, followed by decay of the neutral pion, $\pi^\circ \rightarrow 2\gamma$. Since the π° lifetime is only 10^{-16} s, the pair appears to point straight to the interaction vertex.

Uniform magnetic field going into plane of slide.

The discovery of positrons in the laboratory in 1932 removed all doubt about the reality of antimatter.

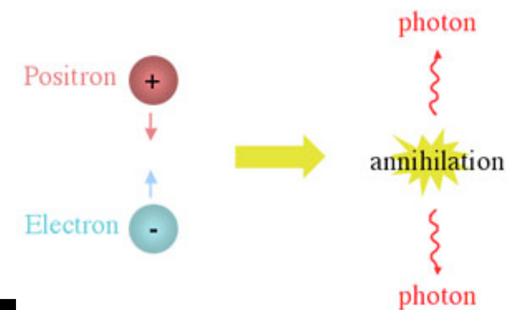
C. Anderson

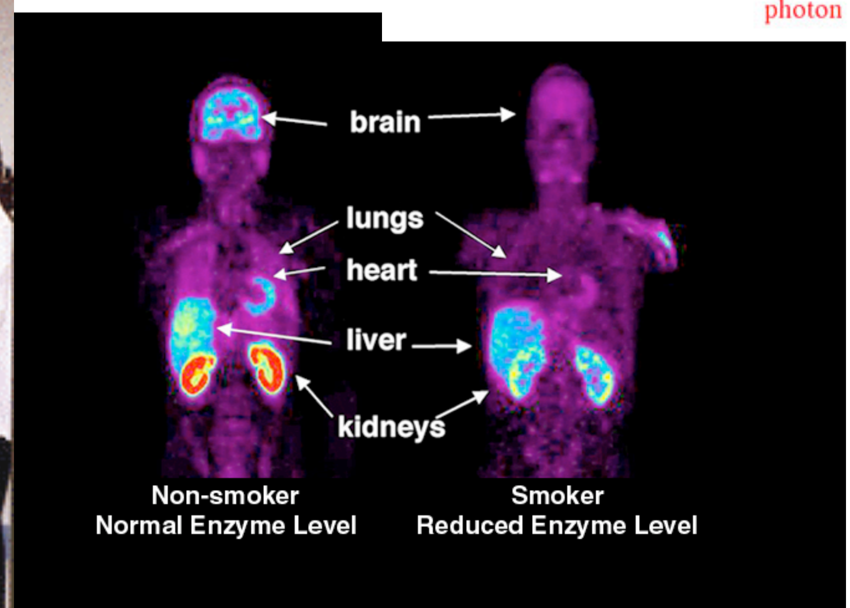
1936

Figure from *"Introduction to High Energy Physics"*, D. Perkins, 3rd edition.

Aside: using antimatter as a tool

- Antimatter is pretty exotic stuff, but it's used routinely in hospitals – PET scans!
  - Positron Emission Tomography



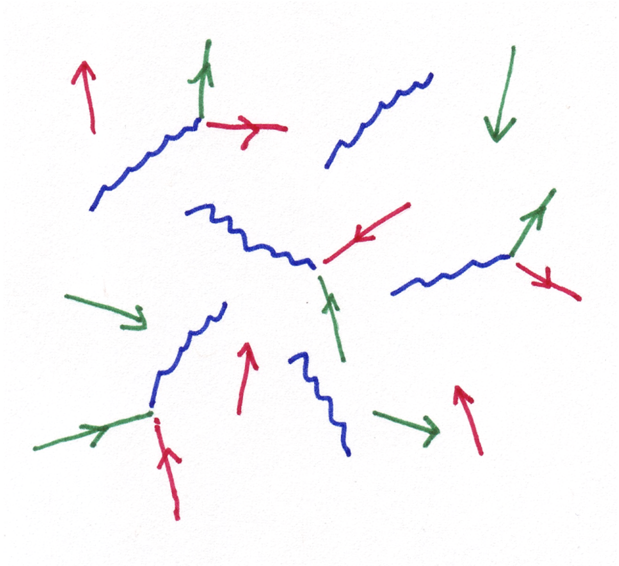


stration shows the concentration of radioactive tracer bound to monoamine oxidase B (MAO B). Red shows
hest concentration. Clearly, lower concentrations are seen in the smoker. In certain areas, such as the lungs
and brain, concentrations are so low as to be virtually absent. This demonstrates decreased amounts of MAO B in
the peripheral organs of smokers compared with nonsmokers.

Proceedings of the National Academy of Sciences, September 8, 2003, "Low Monoamine Oxidase B in Peripheral Organs in Smokers."

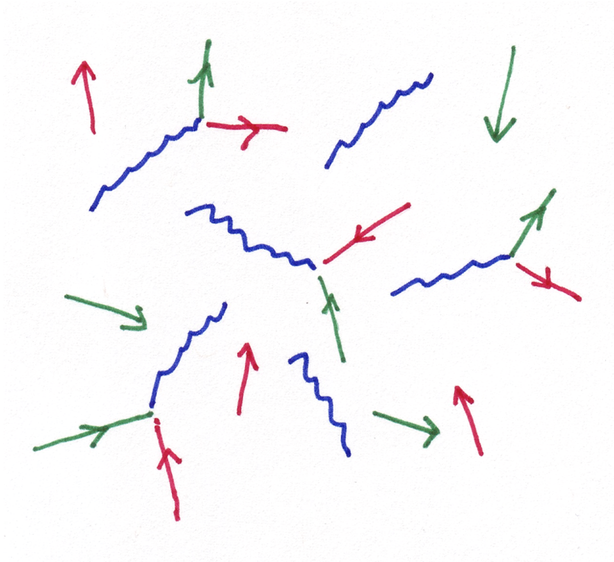
Matter, Antimatter, and the Universe

- At the beginning, the universe was a very *hot*, *dense* place.
  - Heavy exotic particles and high energy photons all over the place interacting with one another.
  - Equal amounts of matter and antimatter.



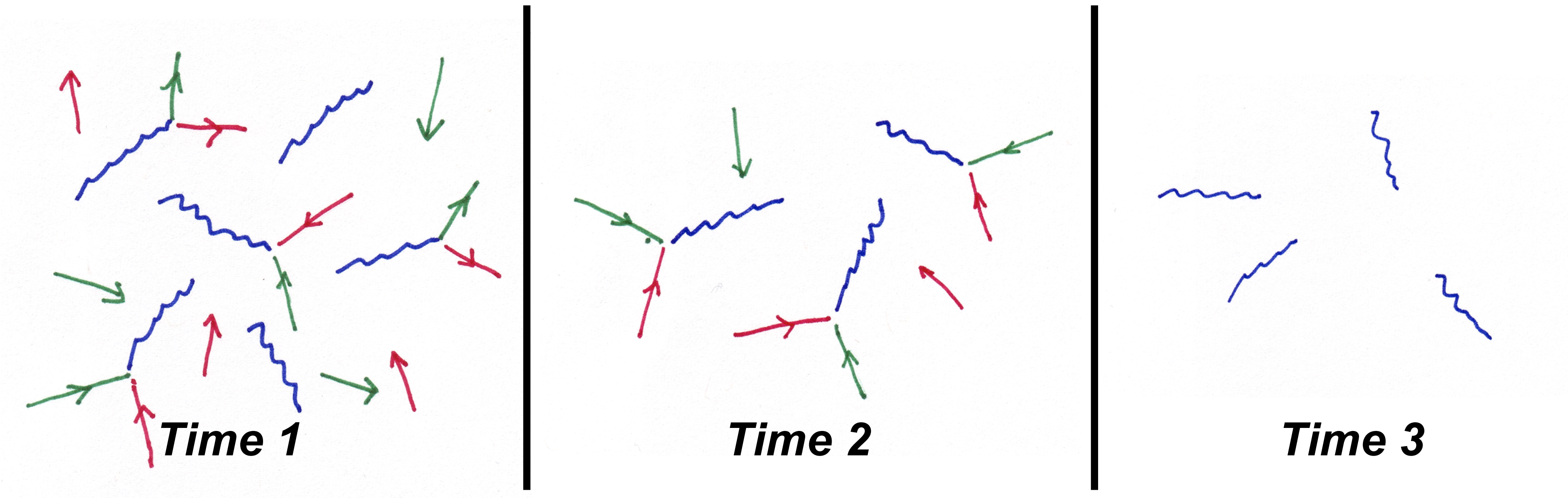
Matter, Antimatter, and the Universe

- One would perhaps guess this would evolve into one of these scenarios:



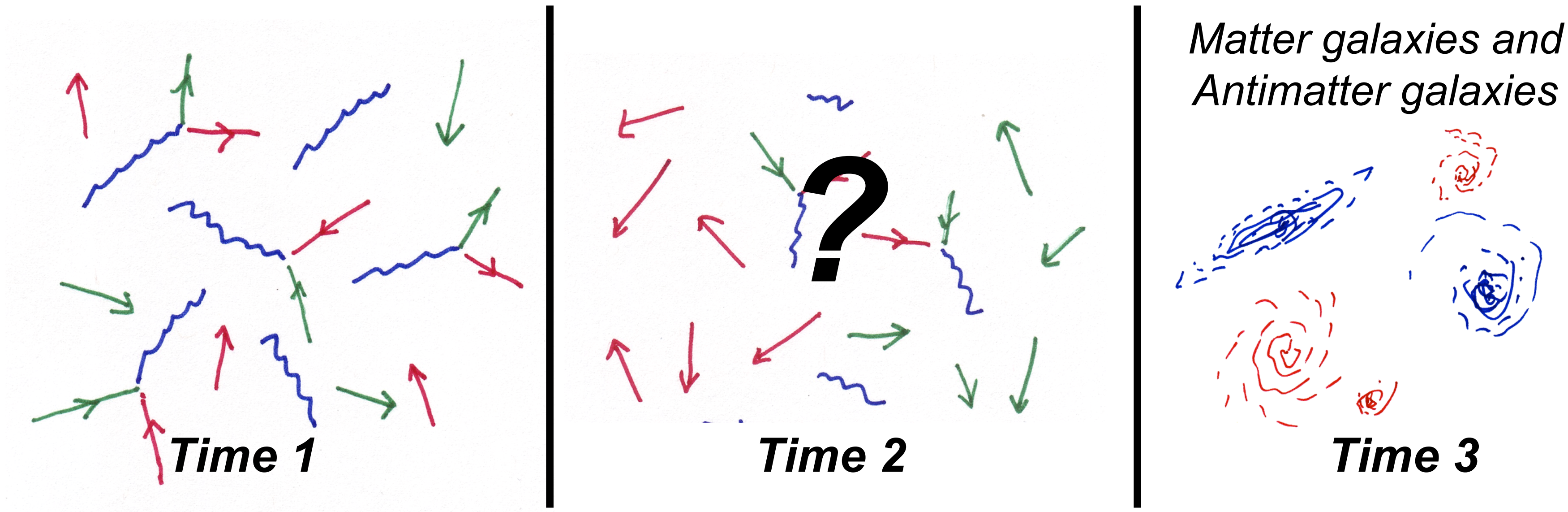
Matter, Antimatter, and the Universe

- One would perhaps guess this would evolve into one of these scenarios:
    1. All matter annihilates with antimatter. Empty universe full of photons (light).



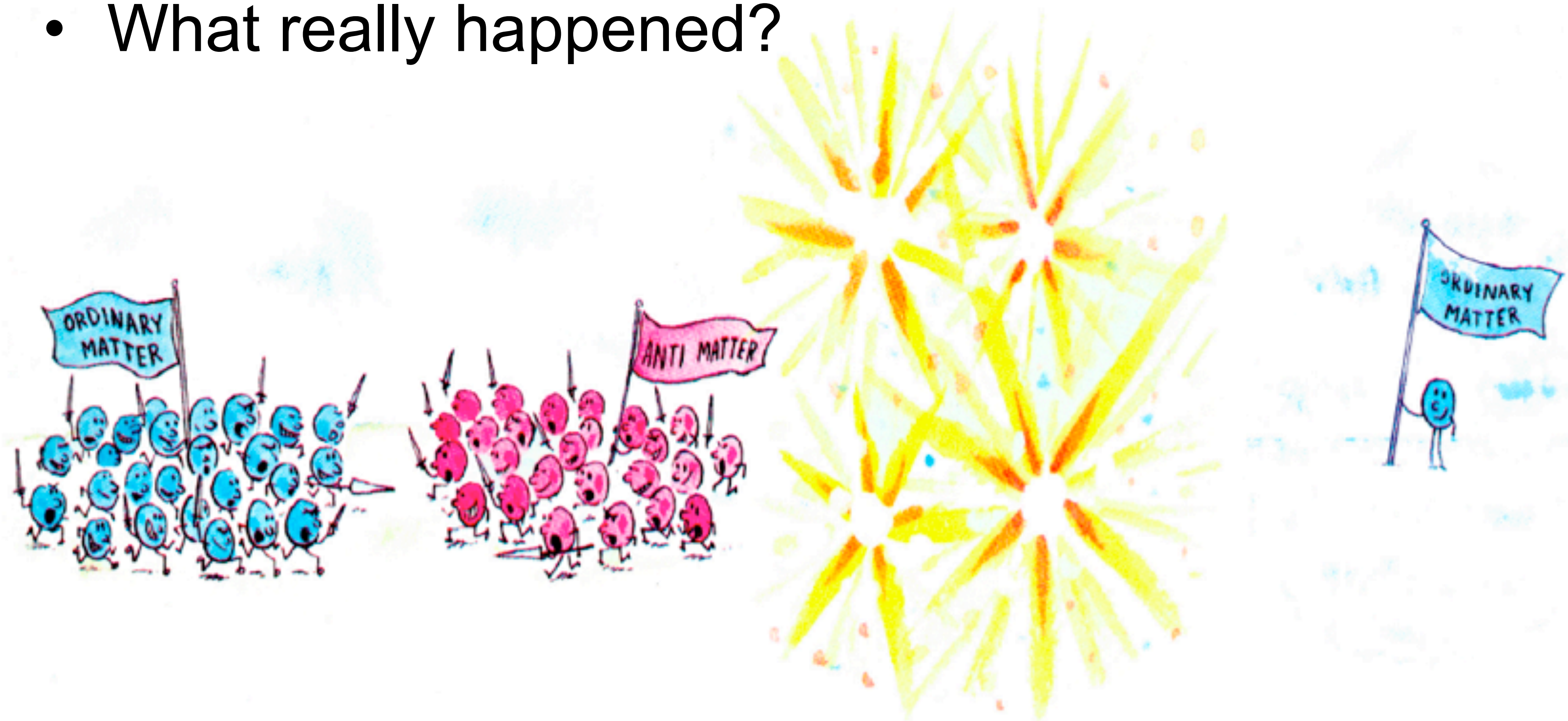
Matter, Antimatter, and the Universe

- One would perhaps guess this would evolve into one of these scenarios:
  1. All matter annihilates with antimatter. Empty universe full of photons (light).
  2. Matter and antimatter separate (somehow). Universe is ½ matter and ½ antimatter.



Matter, Antimatter, and the Universe

- What really happened?



In the early universe, for every billion ordinary particles annihilating with antimatter, one was left standing…

Matter, Antimatter, and the Universe

- What really happened?
  - Most of the matter and antimatter *did* annihilate each other, but we wound up with some matter left over at the end and *no antimatter*.

- How could this happen?
  - The laws of physics are not *exactly* the same for matter and antimatter.
  - The asymmetry is due to a strange phenomenon called **CP violation**.

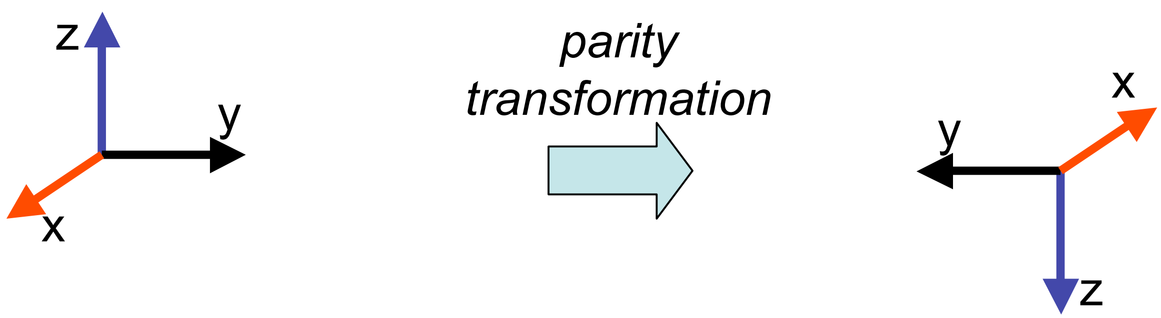
CP Violation

C = charge conjugation (particle to antiparticle)

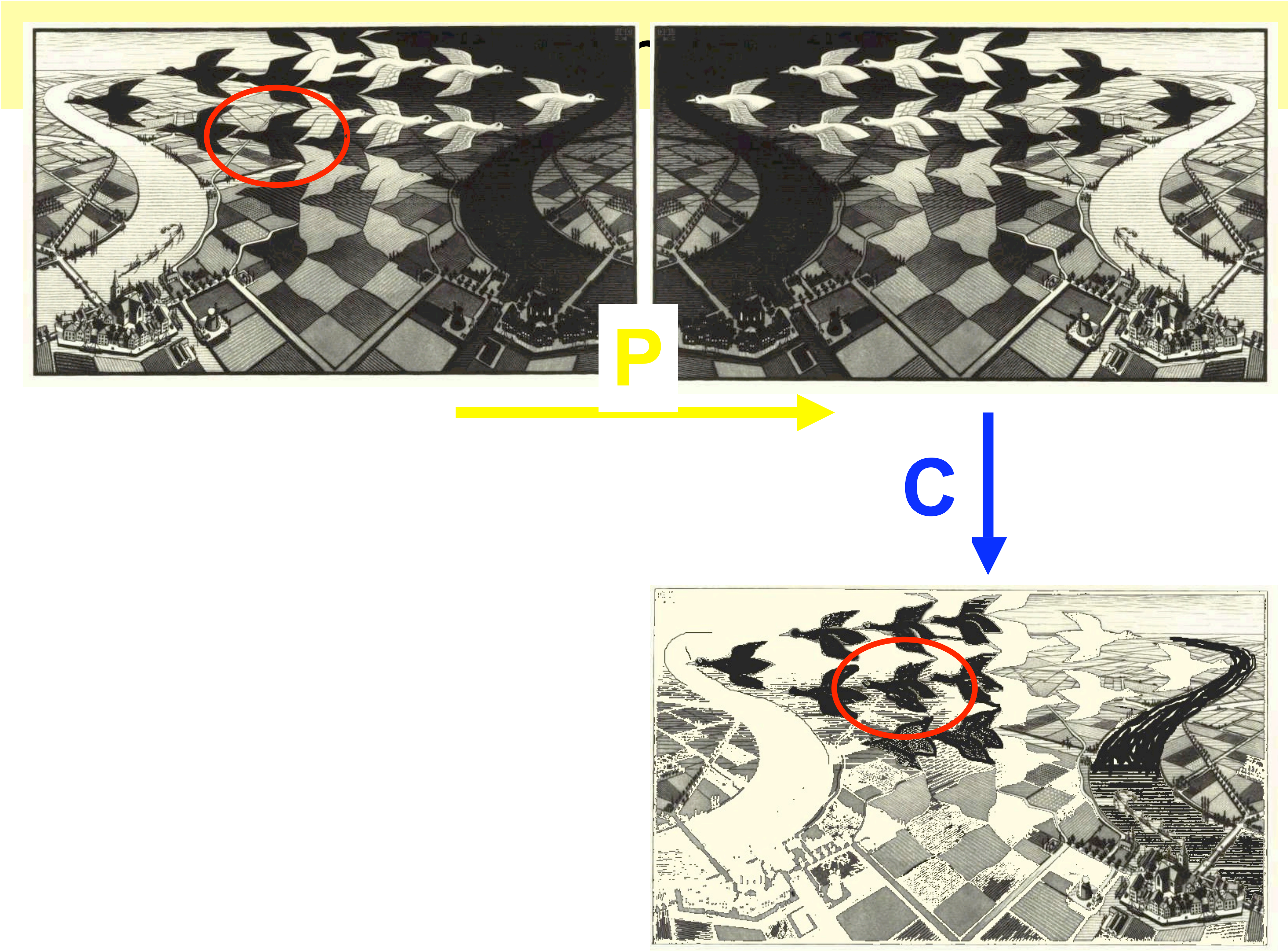
and vice versa

$$e^{-} \xrightarrow{\textit{charge conjugation}} e^{+}$$

P = parity (inversion of spatial directions)



- If the laws of physics were the same after CP transformation, matter and antimatter would behave *exactly* the same. But we know CP symmetry is violated…


P
C

The discovery of CP violation

- In 1964 Cronin and Fitch experimentally observed the CP forbidden decay

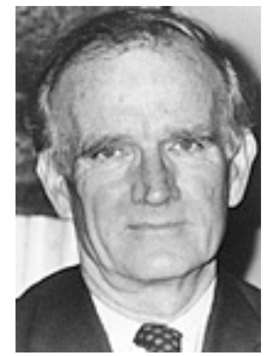
$$K_L \rightarrow \pi^+ \pi^-$$

CP odd particle ***CP even final state***

  - *Total surprise* (at the time).
  - Plausible explanation came years later (1972).
  - Explanation only recently (2002) tested.

J. Cronin

V. Fitch

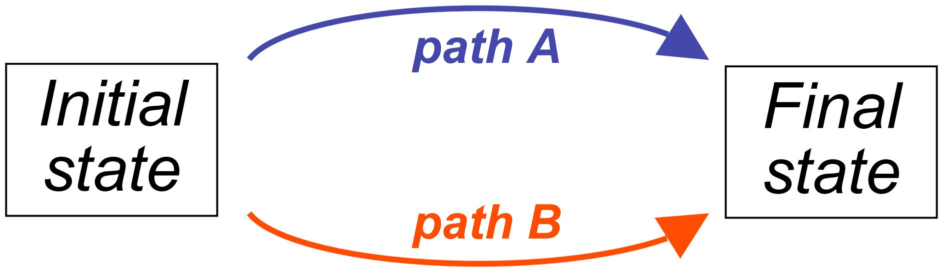


1980

R. Turlay

Quantum interference

- Quantum mechanics tells us that if there's more than one path, you must consider them *all simultaneously*.



Which path did it take?

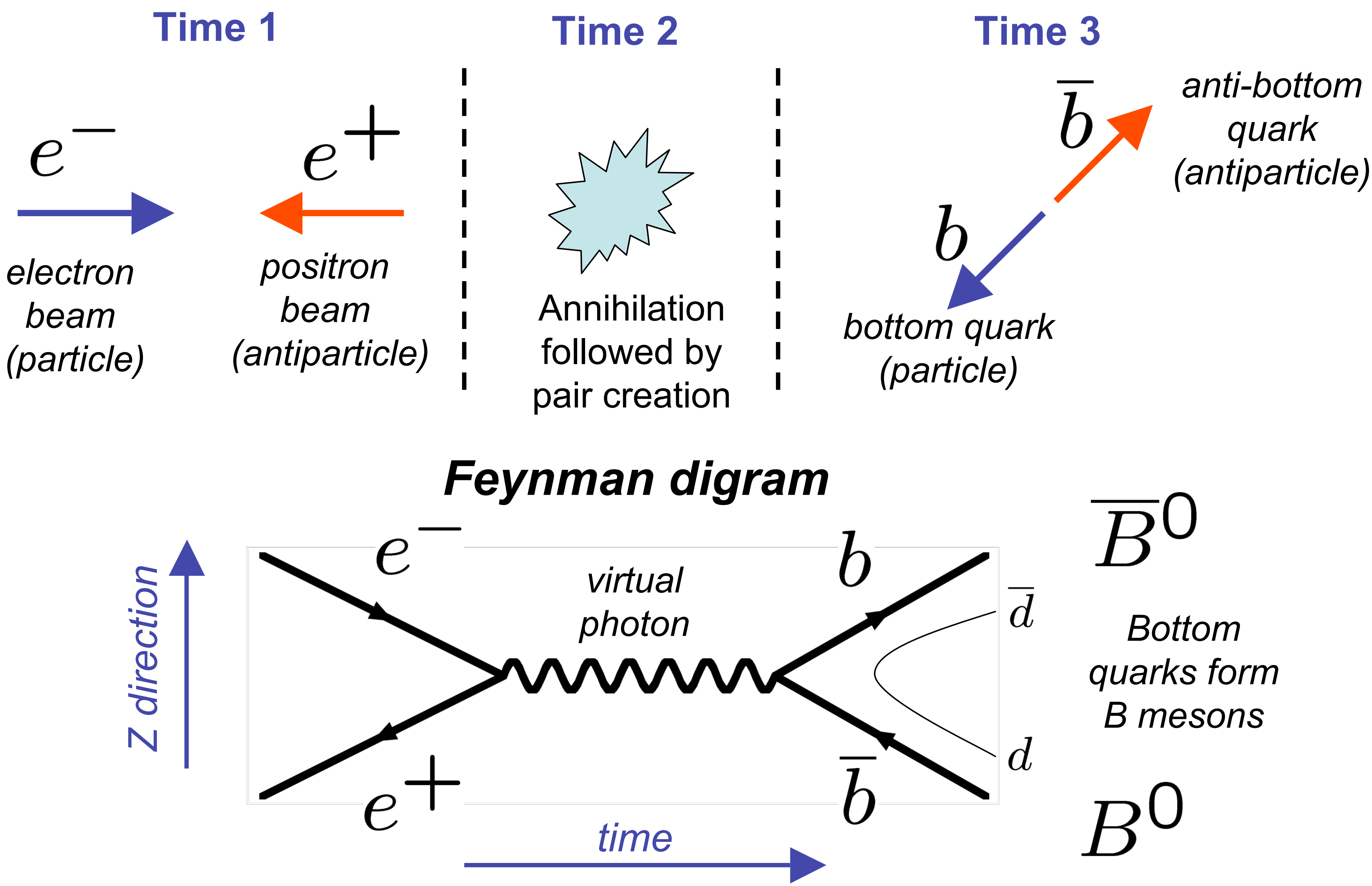
Classical physics: either *A* or *B*.

Quantum physics: *both A and B !*

CP violation experiments

- Ordinary matter (electrons, protons, neutrons) in normal conditions does not violate CP.
- Some Heavy particles (quarks) do violate CP as they quickly decay to more ordinary particles.
- We can study CP violation by making heavy quark-antiquark pairs in the laboratory using accelerators.

A bottom quark factory



Stanford Linear Accelerator Center

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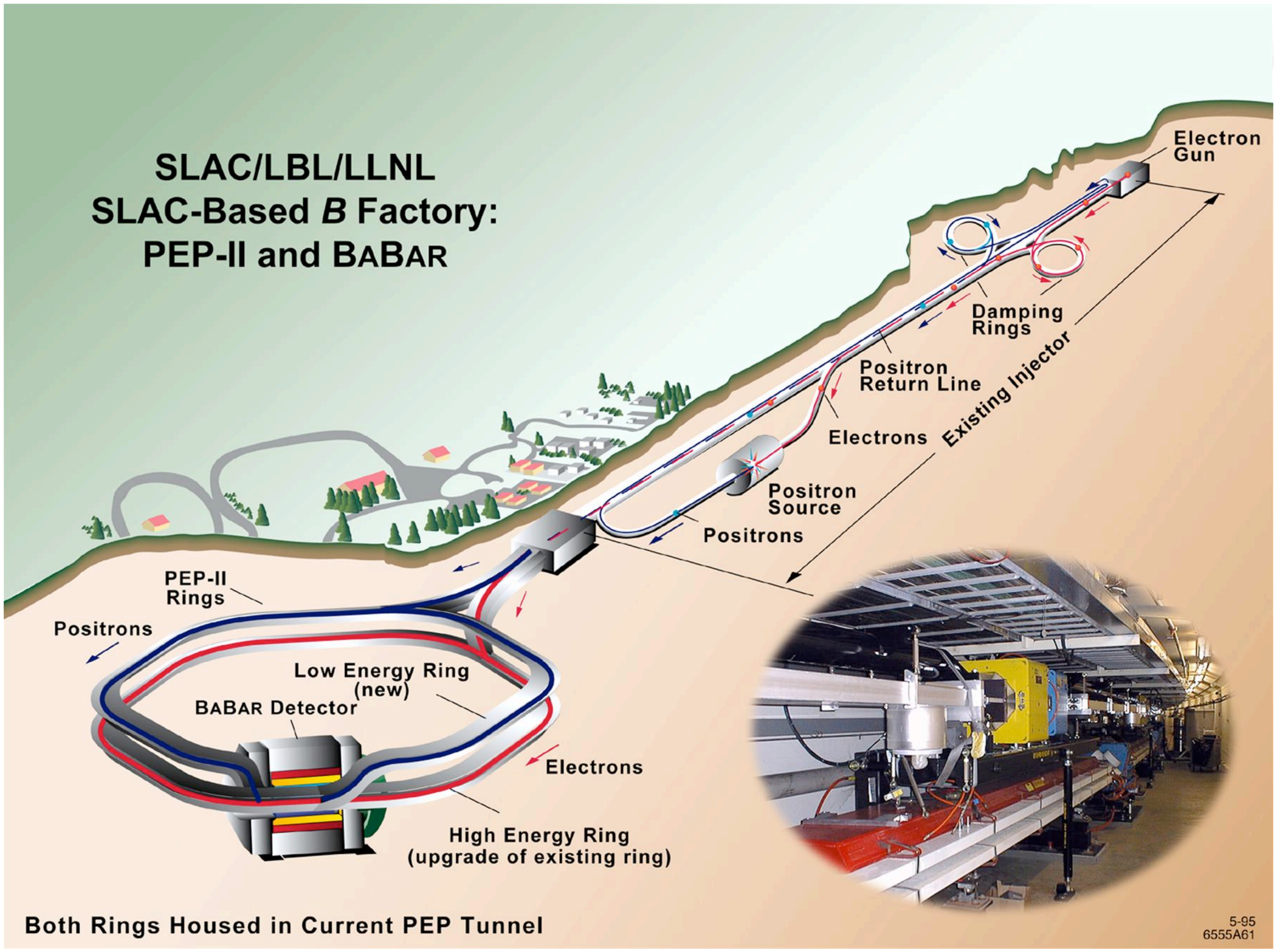
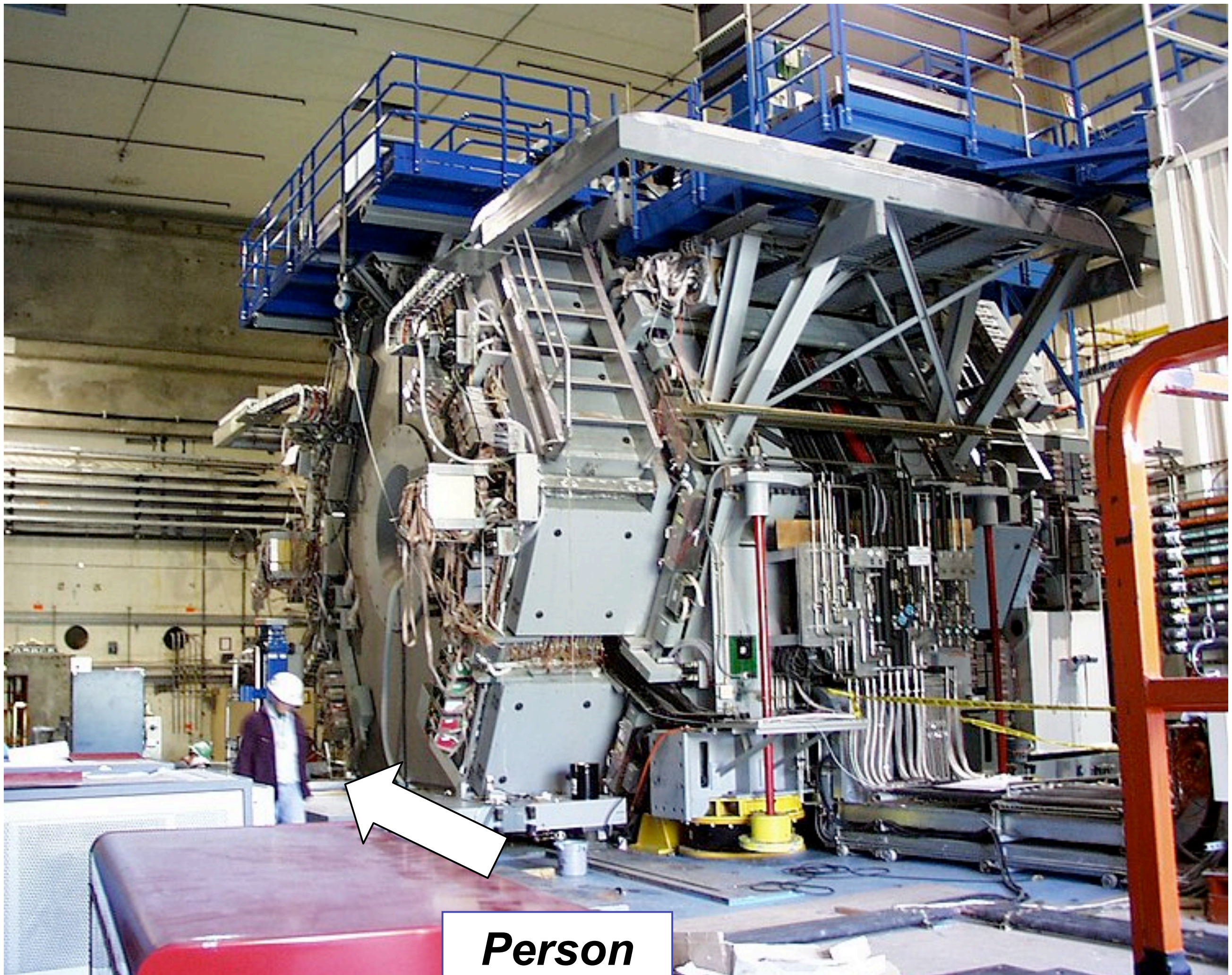


The *BABAR* Experiment

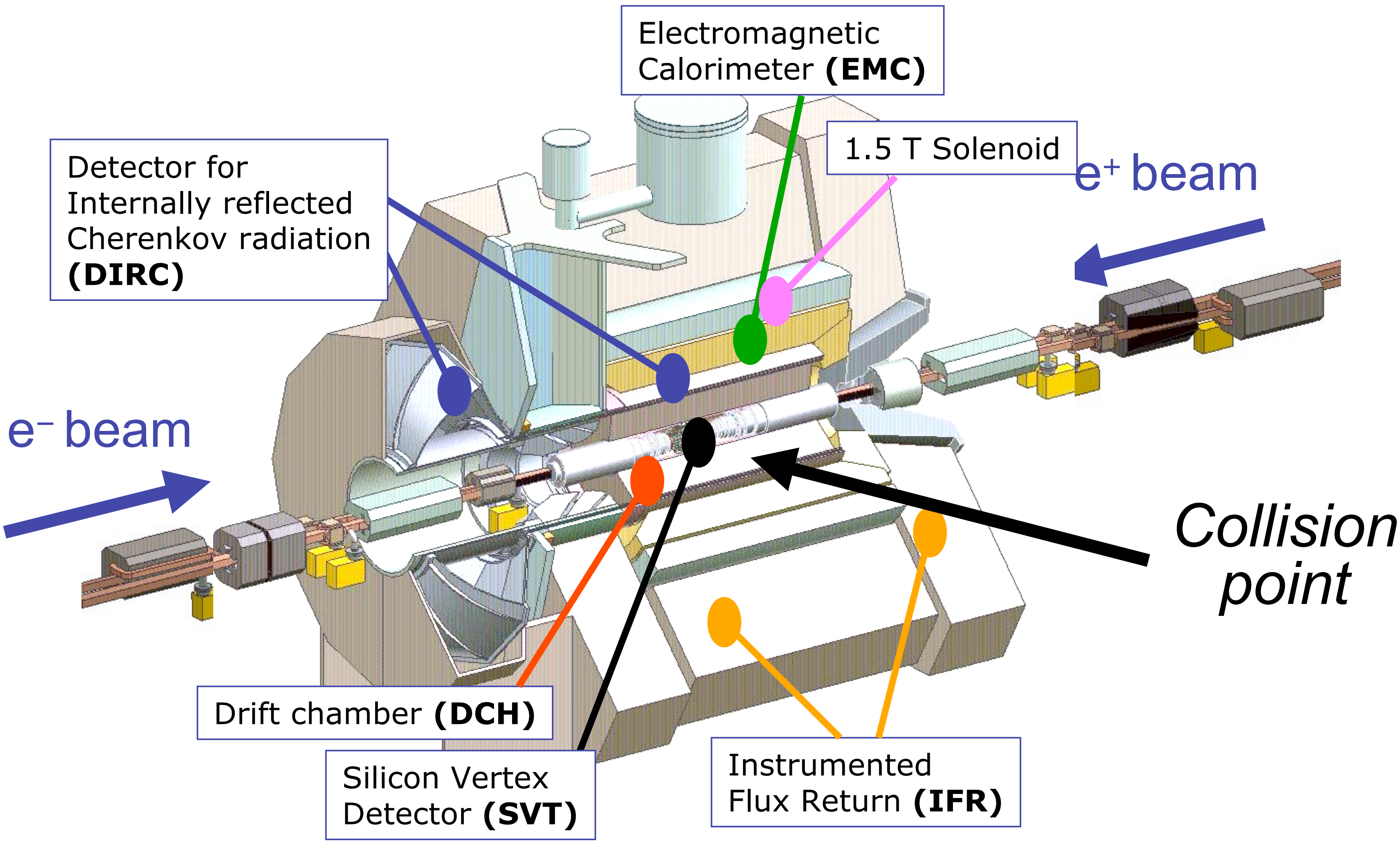


Person for scale

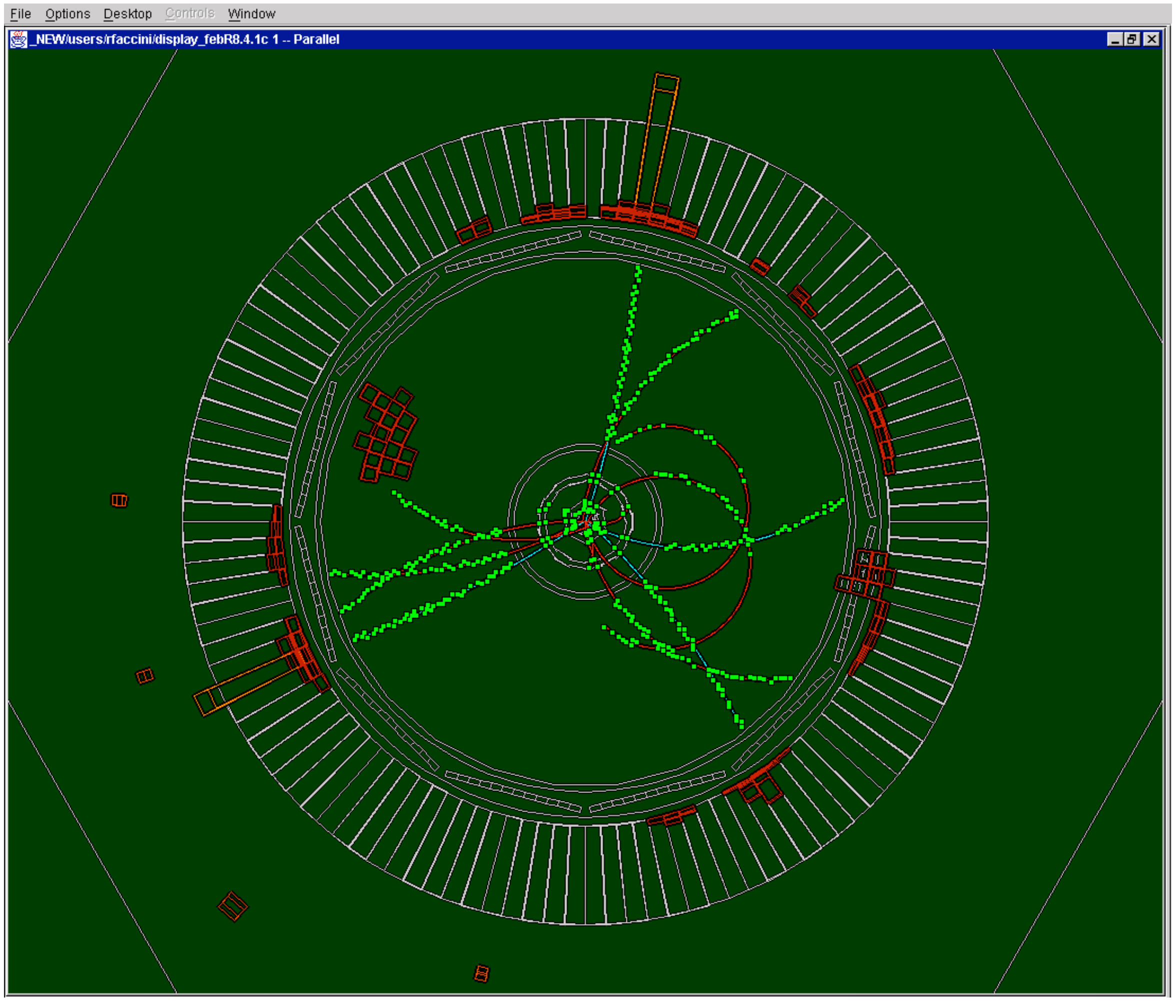
$b\ \overline{b}$

get it? ☺

The *BABAR* Experiment



Reconstructed Event
End View



- Uniform magnetic field going into screen.

$$F = m\frac{v^2}{r} = qvB$$

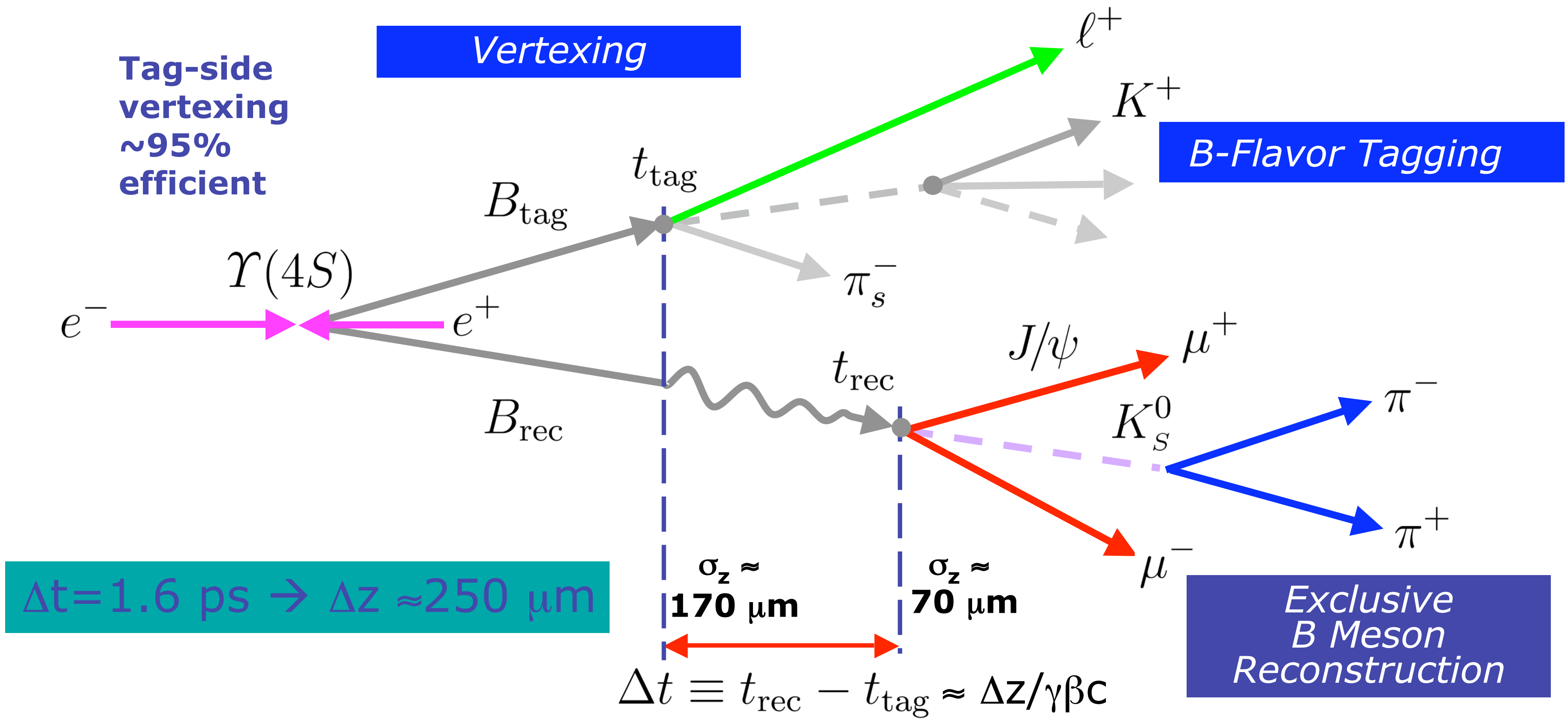
$$p = mv = qBr$$

- Charged particles coming out leave “tracks”.

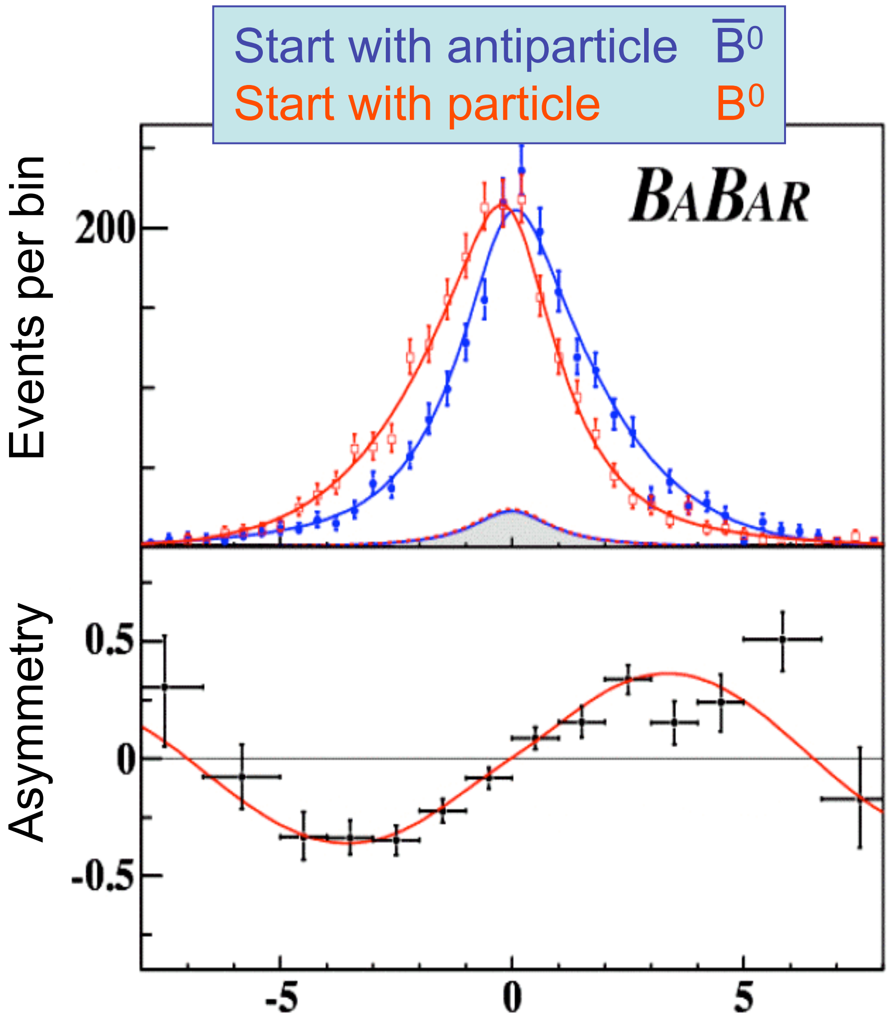
- Energy measured in outer detector.

Measuring (time dependent) CP asymmetries

- $B^0\bar{B}^0$ system from Y(4s) evolves as coherent system
    - Need to explicitly measure time dependence
  - B^0 mesons guaranteed to have opposite flavor at time of 1st decay and we can use 'other B^0' to tag flavor of B^0_{CP} at t=0



A CP Violation Measurement



Measured time difference between two B decays in trillionths of a second (10^{-12} s).

Measures interference of this path…

particle → *Final state*

B^0 decay

…with this possible path

particle → *anti-particle* → *Final state*

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

$\overline{B}^0$ decay

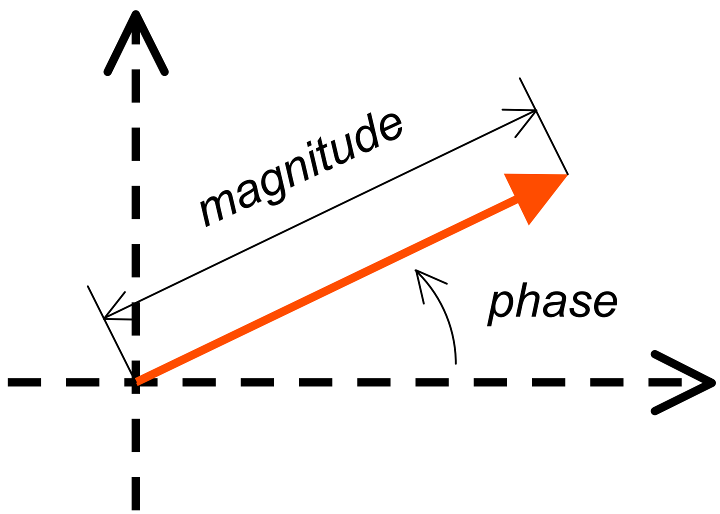
The matter-dominated universe

- We now have a working, tested model for CP violation. Does it explain our universe?
- ***No!*** The CP violation that we understand from experiments gets it totally wrong.
  - Would allow for much more annihilation to occur.
  - No galaxies. Just a few protons rattling around…
- We need *new sources* of CP violation to explain how the universe evolved to its present state from the big bang.

Backup material

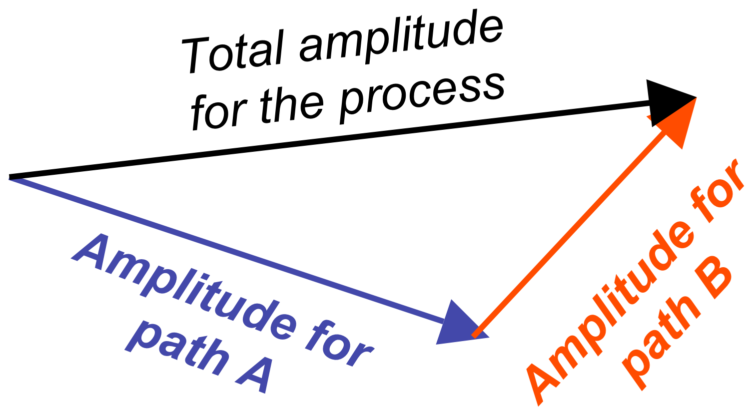
Quantum amplitudes

- Probabilities for paths are expressed as *amplitudes*.
  - Amplitude is described by a magnitude (length) and a phase (angle)



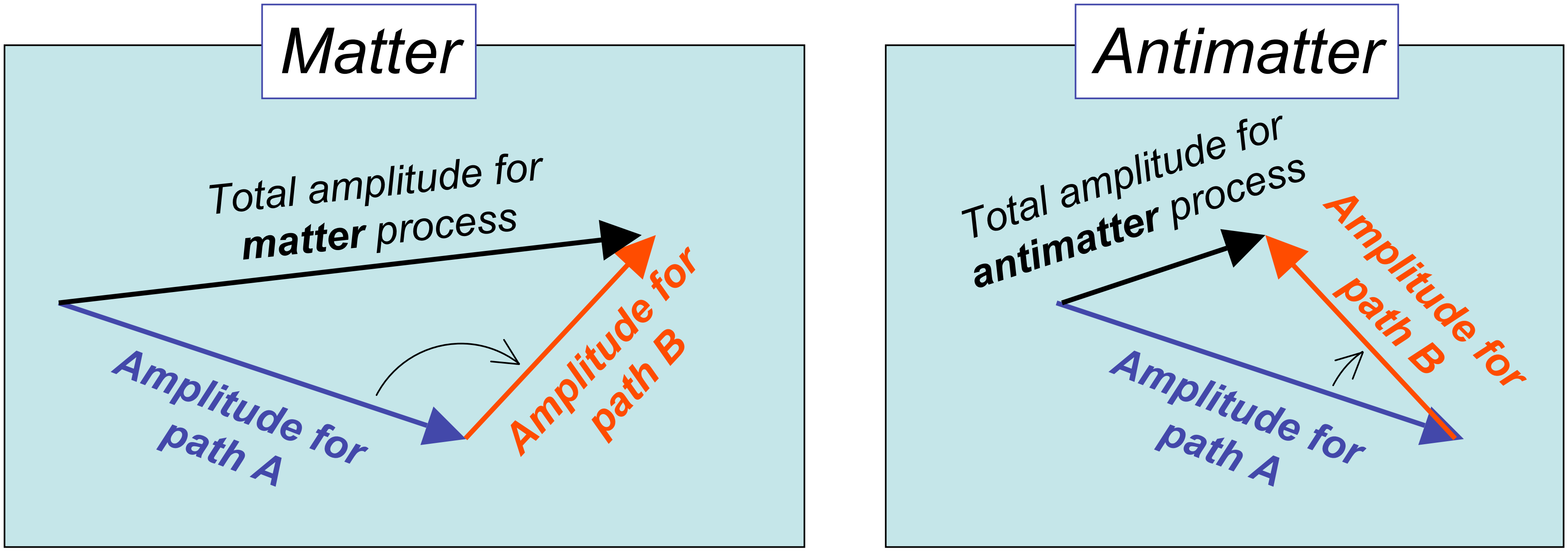
Interfering quantum amplitudes

- Quantum mechanics says that we must consider all paths (or amplitudes) for a process.



- The magnitude of the total amplitude (length of the black arrow) determines the probability that the process will happen.

CP Violation from interfering amplitudes

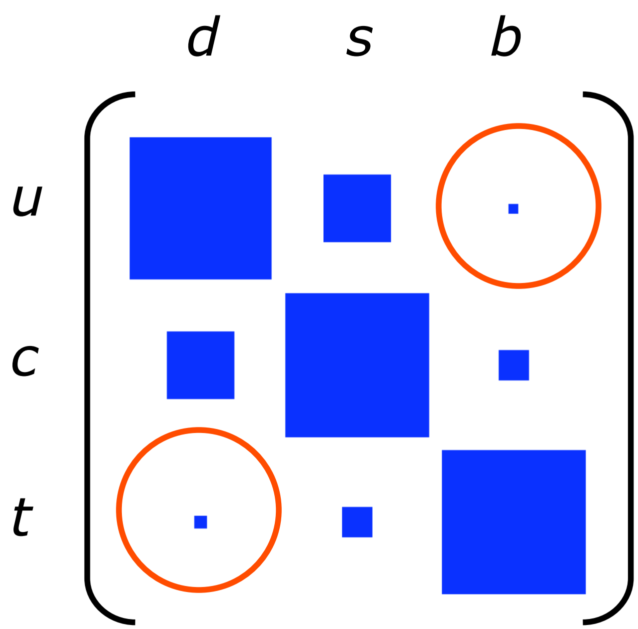


- Only the relative phase (or angle) between *A* and *B* is different, but that is enough to generate CP violation.
- In this example, the antimatter process will be *less likely* because the total amplitude is smaller!

Features of CKM quark mixing matrix

- Off-diagonal elements are small. Couplings that cross generations are *suppressed*.

Relative magnitudes



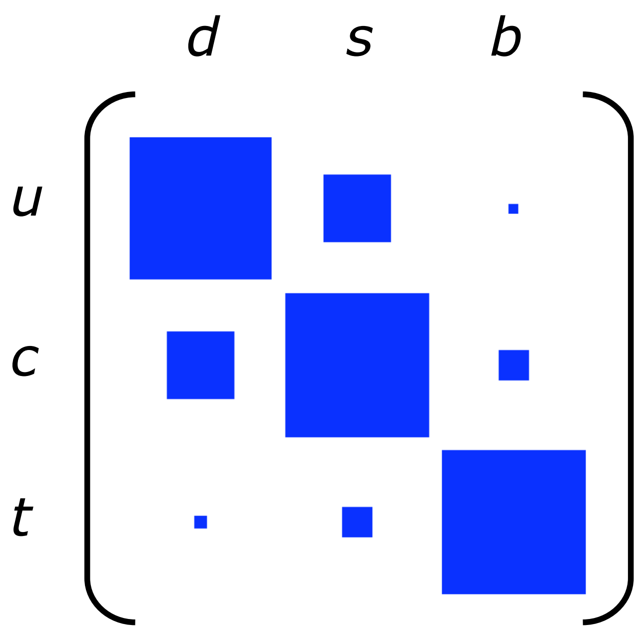
The CP-violating phases

$$\begin{array}{c c} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix} \end{array}$$

Features of CKM quark mixing matrix

- Off-diagonal elements are small. Couplings that cross generations are *suppressed*.
- The CP-violating phases occur in the smallest elements. CP violation is rare. You need to look for it in specific places…
- Mesons (quark-antiquark bound states) that contain a *bottom quark* (or anti-quark) exhibit a variety of *CP* violating effects.

Relative magnitudes



The CP-violating phases

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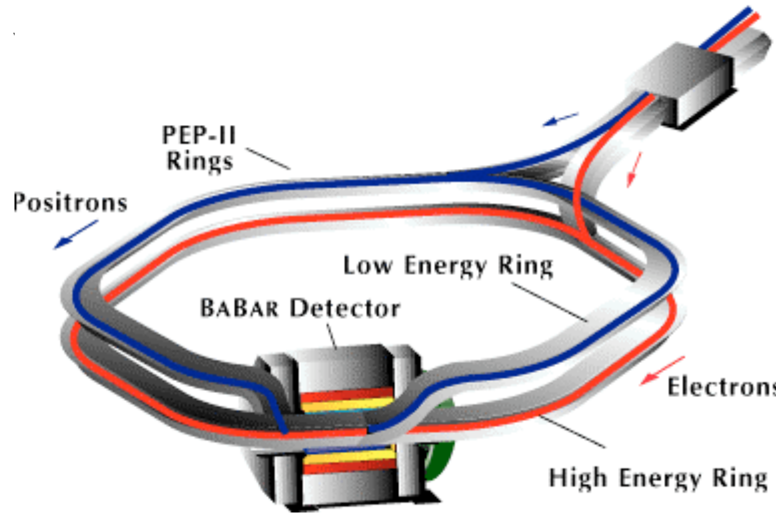
The PEP-II B factory – specifications

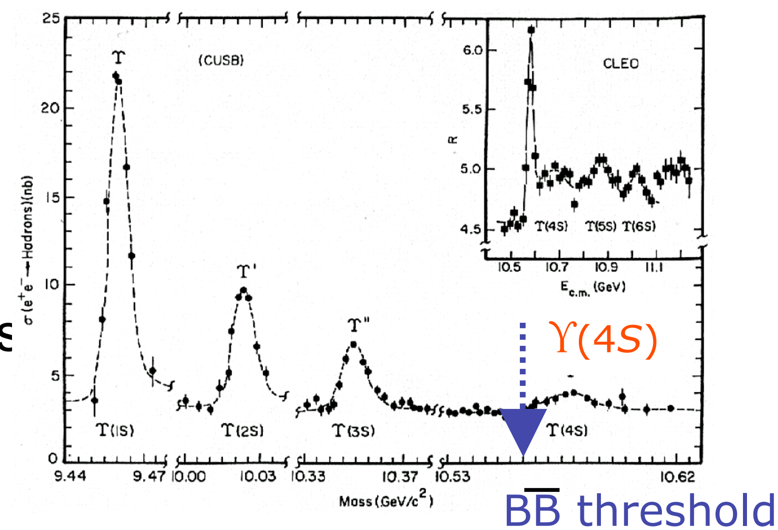
- Produces $B^0\bar{B}^0$ and B^+B^- pairs
  Y(4s) resonance (10.58 GeV)

- Asymmetric beam energies
  - Low energy beam 3.1 GeV
  - High energy beam 9.0 GeV

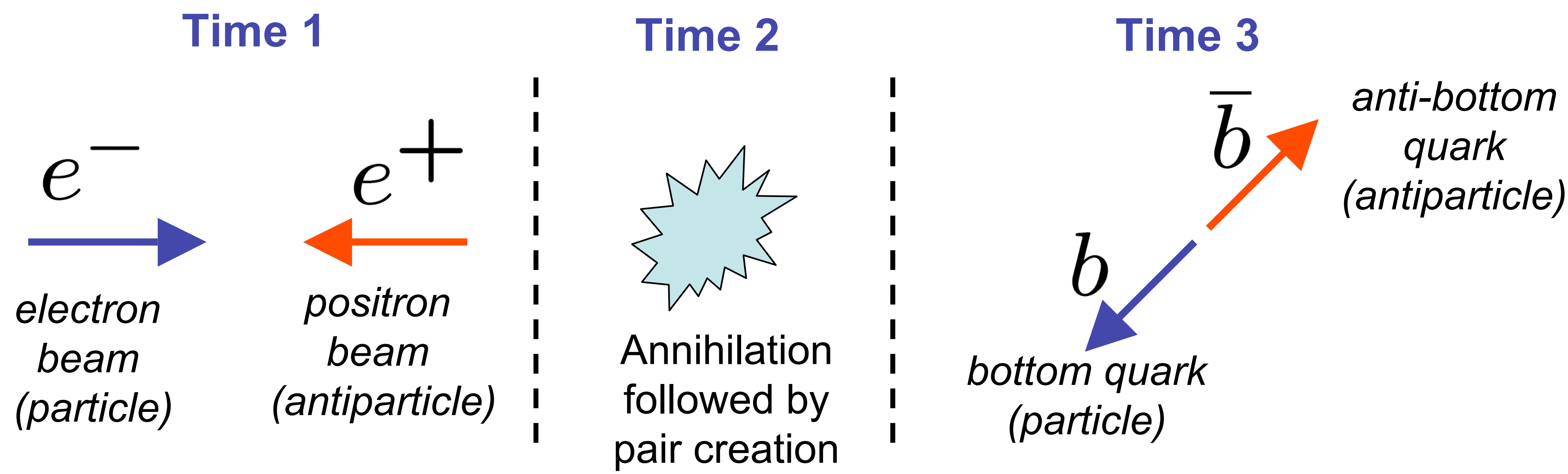
- Boost separates B and $\bar{B}$ and allows measurement of B^0 life times

- Clean environment
  - ~28% of all hadronic interactions is

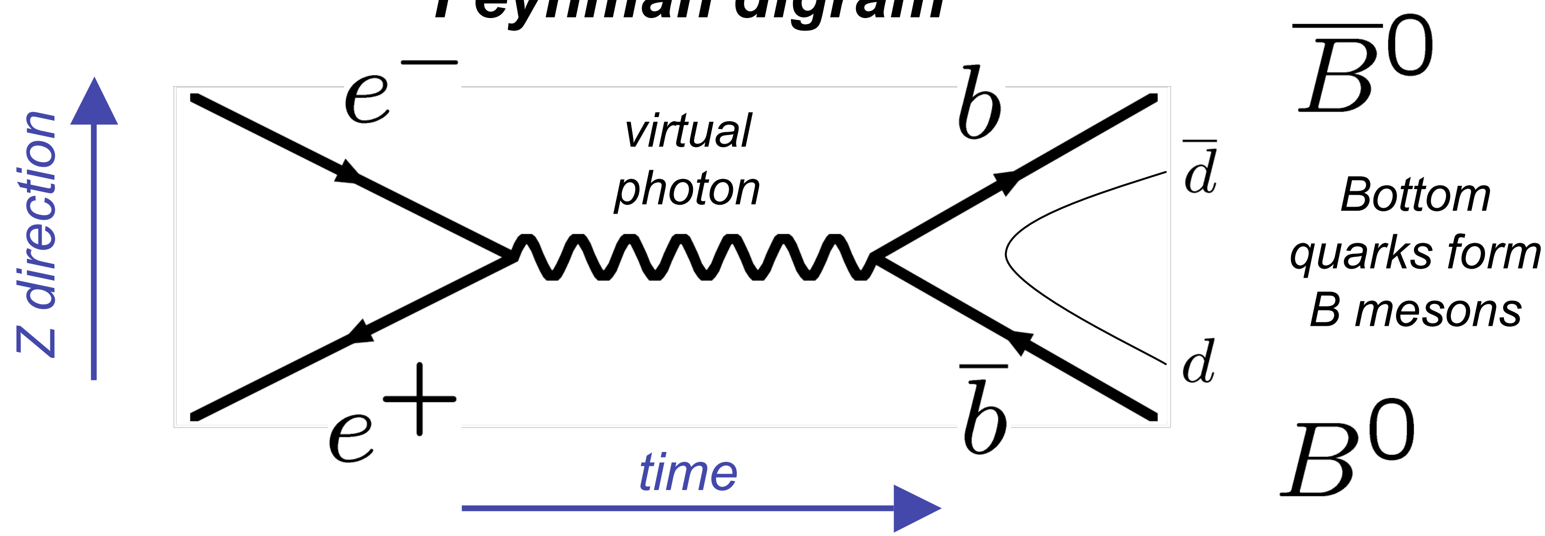




A bottom quark factory



Feynman digram

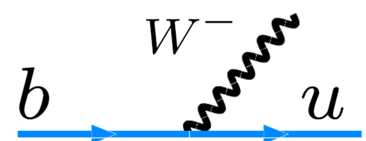


CP violation experiments

- Mesons (quark-antiquark bound states) that contain a *bottom quark* (or anti-quark) exhibit a variety of *CP* violating effects.

CP-violating phases of the CKM matrix

$$\begin{array}{cc} & \begin{array}{ccc} d & s & \boldsymbol{b} \end{array} \\ \begin{array}{c} \boldsymbol{u} \\ c \\ t \end{array} & \begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix} \end{array}$$



$$V_{ub}$$

Rare B decays

$$\overline{B}^0 \to \pi^+ K^-$$

CP violation experiments

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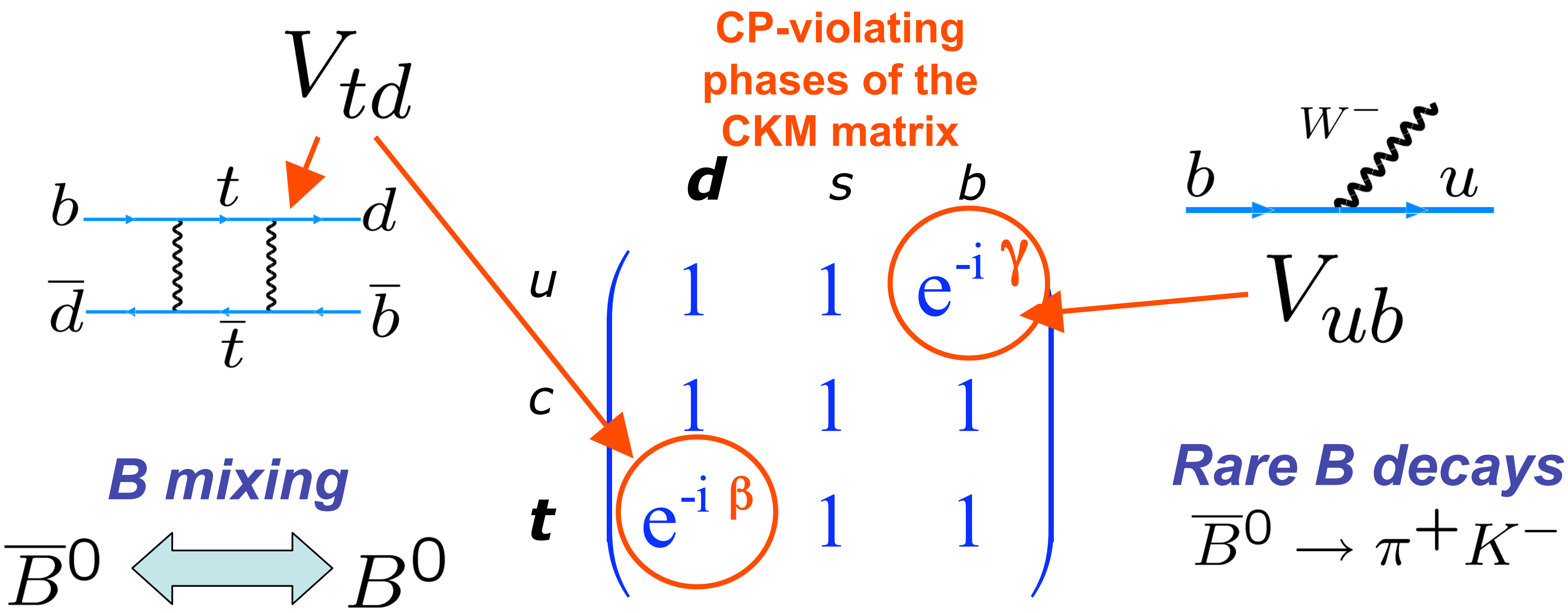
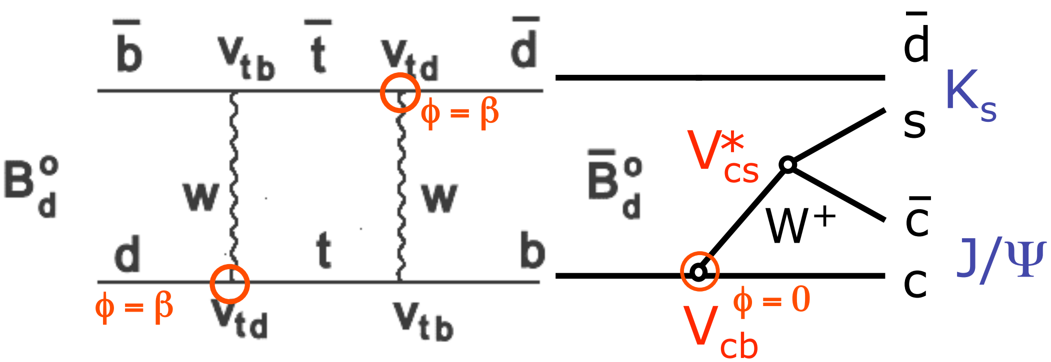


- The ***BABAR* experiment** at the Stanford Linear Accelerator Center (SLAC) is producing and analyzing hundreds of millions of B meson decays.

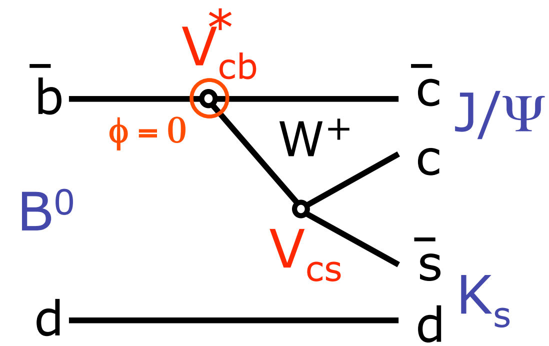
B-factory ‘flagship’ measurement: sin2β from J/ψ K_S

- Interference between **mixing** and **single real decay**

B^0 Mixing……followed by………Decay



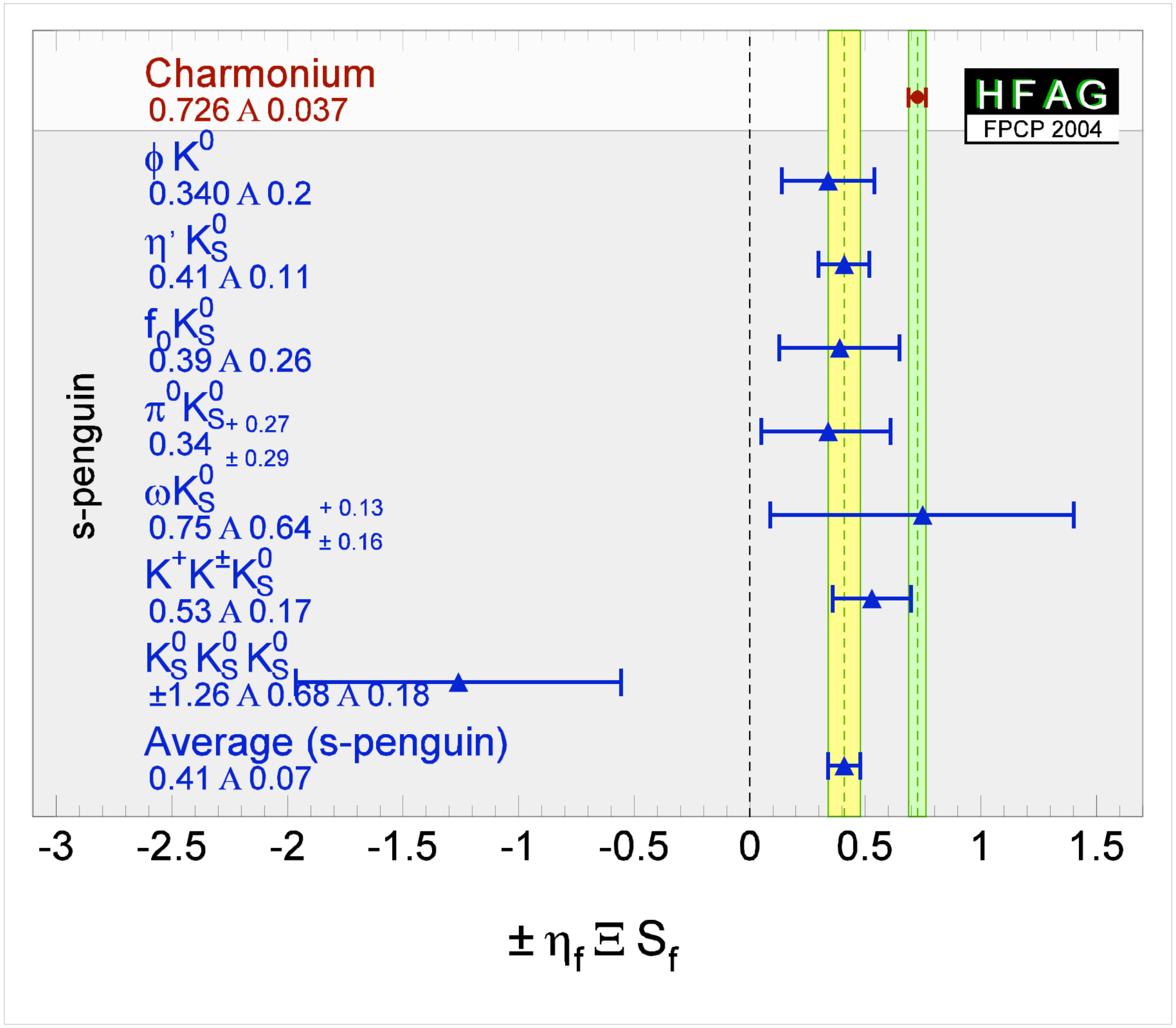
Decay



- *Extraordinarily clean* theory prediction (~1% level)
  - Single real decay amplitude → all hadronic uncertainty cancel
  - $A_{CP}(t)$ = **sin(2β)** $\sin(\Delta m_d\, t)$

- Experimentally easy
  - ‘Large’ branching fraction $O(10^{-4})$
  - Clear signature (J/ψ → l^+l^- and $K_S \rightarrow \pi^+\pi^-$)

Interesting discrepancy…



Blue points should agree with the *red point* at the top.

Could be a sign of something new!