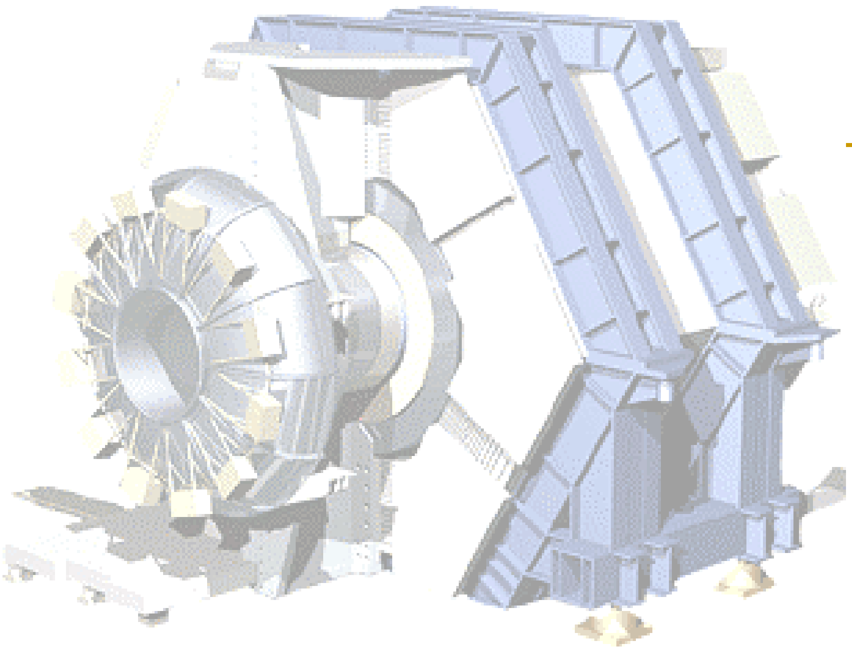
How to Measure a Triangle: Probing the Matter/Antimatter Asymmetry in the Universe

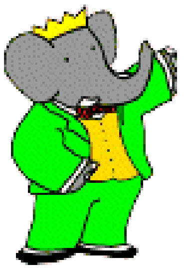
2002 Sambamurti Lecture

Brookhaven National Laboratory



James D. Olsen

Princeton University



Overview

- A little background
  - A brief history and the Standard Model
  - The Big Bang, and a Big Question
  - Matter and antimatter
  - Symmetries
  - Parity and CP violation
- The triangle and the elephant
  - CP violation in the Standard Model
  - Why B's are better than K's
  - The BaBar experiment
  - Discovery of CP violation in B decays
- A final thought from my favorite politician…

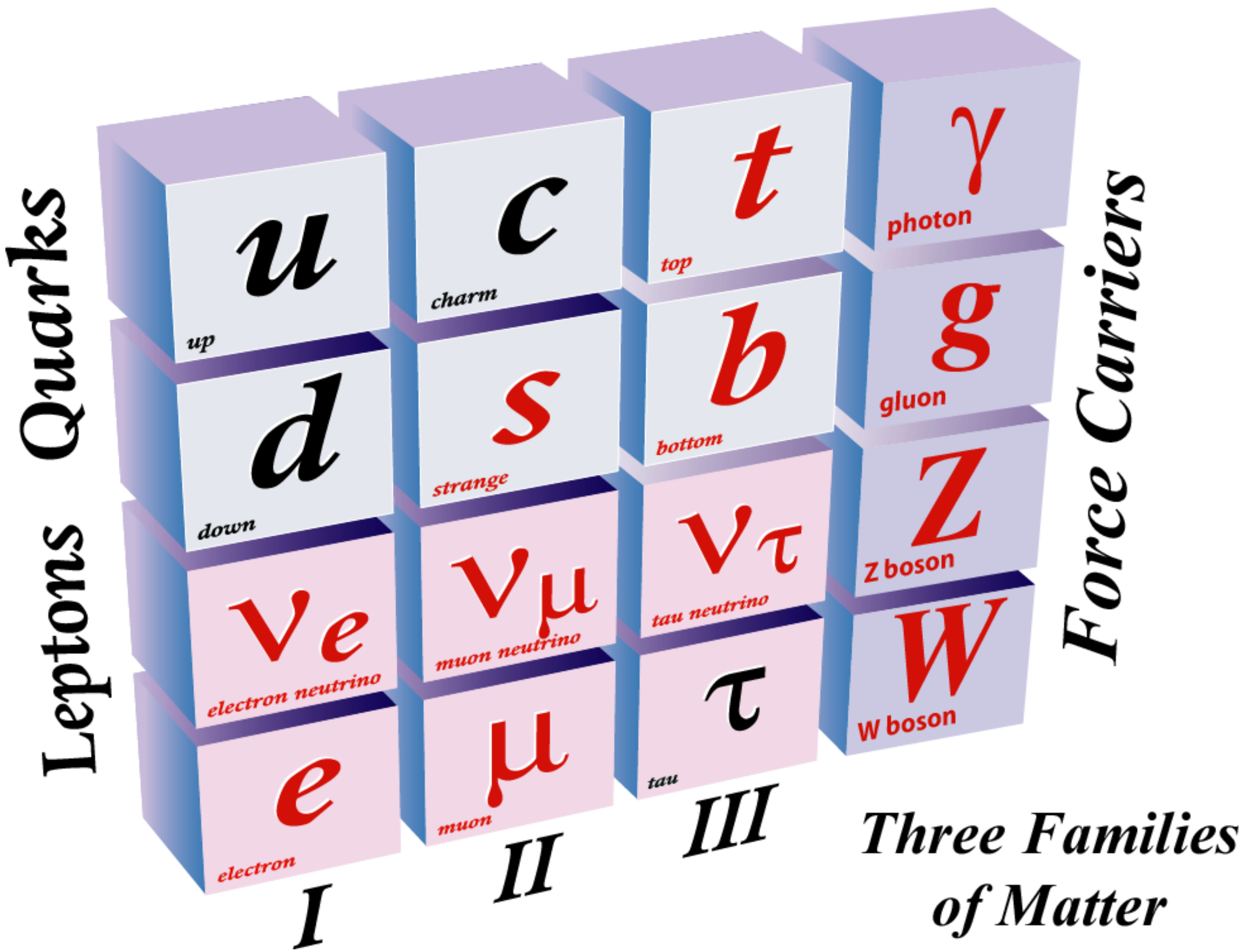
A Brief History of the 20th Century…

- 1900-1950:
  - Relativity and quantum mechanics emerge as the pillars of 20th century physics
  - Antimatter predicted (1928) and positron discovered (1933)
  - Quantum Electrodynamics sets the template for particle theories
- 1950-1983: If you build it, they will come
  - 100's of new particles and "resonances" are discovered in new accelerators at Berkely, Brookhaven, and elsewhere
  - Quark model (1964) brings order from chaos
  - Electroweak theory postulated by Glashow, Weinberg, and Salam
    - Dramatically confirmed with the discovery of the W and Z bosons (1983)
- 1983-present:
  - The Standard Model is established as the most likely theory of particle interactions. But there are still some loose ends…

The Standard Model of Particle Physics

- The modern theory of particle physics is called the "Standard Model"
- The underlying principle is that Nature can be described in the context of forces acting on particles
  - Quantum Field Theory is the official language
- The Fundamental Forces:
  - Electromagnetism (light, atomic and molecular binding)
  - Weak (beta, and other, decays)
  - Strong (binds quarks inside protons, neutrons, etc…)
  - Unification of all forces (including gravity)? Not in this talk!
- The Fundamental Particles:
  - Quarks (nuclear building blocks)
  - Leptons (the "light" particles: electrons, neutrinos, etc…)

The Particle Rubik's Cube

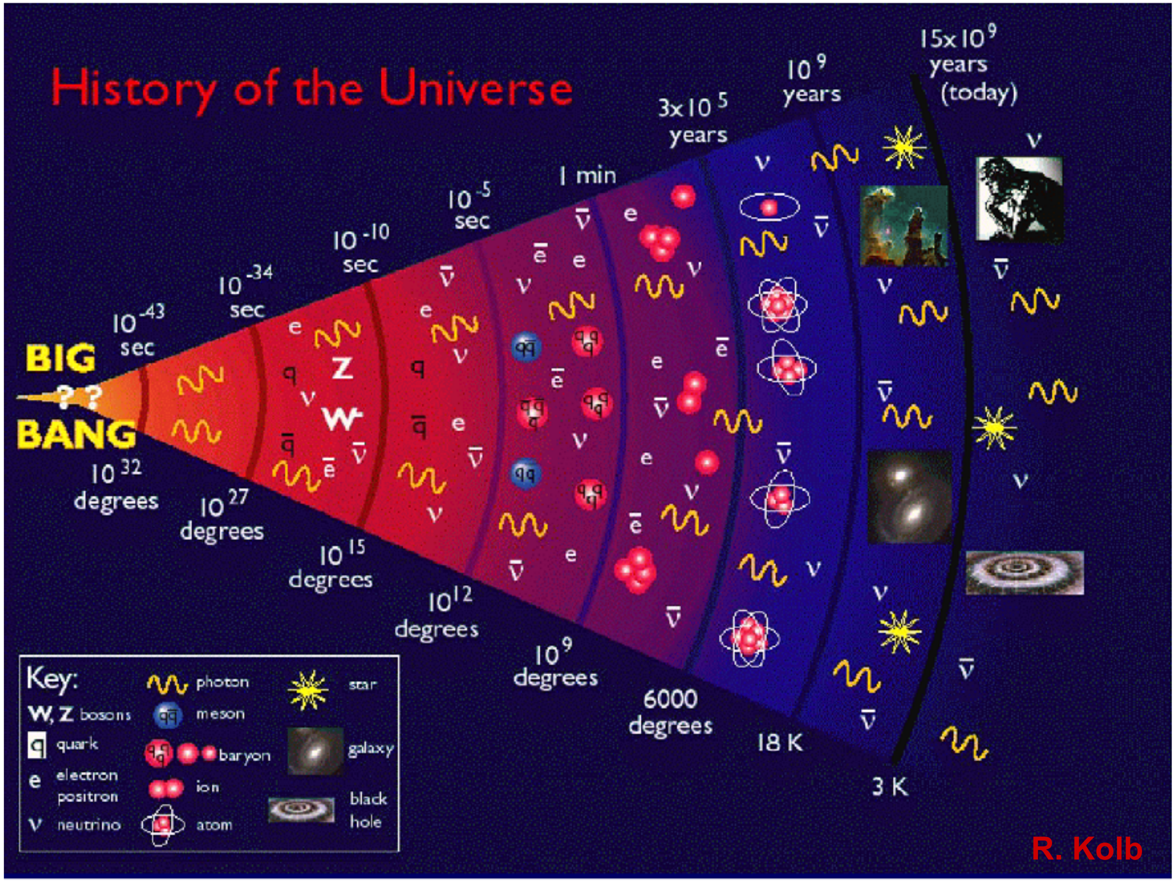


Big Bang: From Particles to People…

- Pre-heat oven to 10^{32} degrees, add quarks/leptons/forces
- Reduce temperature and stuff "hadrons" with quarks using a strong glue
  - Mesons – quark/antiquark pairs
    - K^0 meson = down + antistrange
    - B^0 meson = down + antibottom
  - Baryons – three quarks or three antiquarks
    - Proton = up + up + down
    - Neutron = up + down + down
- Continue reducing temperature, electrons will bind to the protons → atoms (watch out for clumping galaxies)
- Slowly cool atoms to form molecules, proteins, cells, and, after 15 billion years in the kitchen, people!

Big Question: Where is the Antimatter?

Added equal amounts matter and antimatter…



Only matter comes out

In fact, all matter should have annihilated; lucky for us it didn’t!

Mom: “So what is antimatter anyway?”

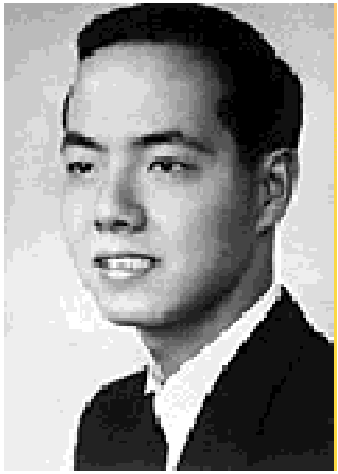
- The marriage of relativity and quantum mechanics embodied in the Dirac equation predicts that for every particle there is an antiparticle with opposite charge and magnetic moment
  - All other attributes are identical: mass, lifetime, etc…
  - Neutral (fundamental) particles are their own antiparticles
- The discovery of the positron in 1933 confirmed the prediction, but does *every* particle have an antiparticle?
  - Antiproton and antineutron were discovered in 1955-6
- The laws of physics at that time treated particle and antiparticle equally, so how could an imbalance arise in the early universe?

Symmetry and Conservation Laws

- Symmetry is a deep and fundamental concept in physics
- Nöether's theorem states that for every symmetry in Nature there is a conserved quantity
  - Conservation laws separate the theory wheat from the chafe by requiring the fundamental interactions to obey the corresponding symmetries
- Some well-known examples:
  - Lorentz invariance → conservation of energy-momentum
  - Rotational invariance → conservation of angular momentum (spin)
- These dynamical symmetries refer to the fundamental structure of space-time itself. What about discrete symmetries related to sub-atomic particles?

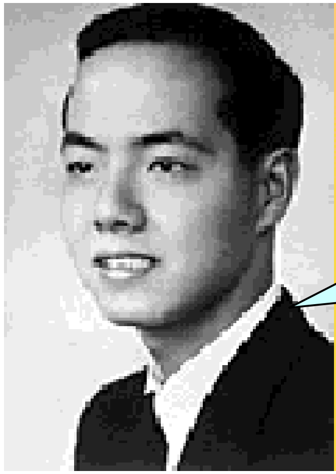
Discrete Symmetries: C, P, and T

- Three very important discrete symmetries:
  - Charge conjugation (C): particle ⟺ antiparticle
  - Parity (P): $x \rightarrow -x$, $y \rightarrow -y$, $z \rightarrow -z$
    - The mirror image of any physical process should be possible
  - Time reversal (T): $t \rightarrow -t$
- Before 1956, all interactions were assumed to obey all three symmetries independently
- In practical terms, it means that we cannot tell particle from antiparticle, left-handed from right-handed, or the direction in time; they are relative, not absolute concepts
- To distinguish these characteristics you need to break the symmetry! So what happened in 1956?



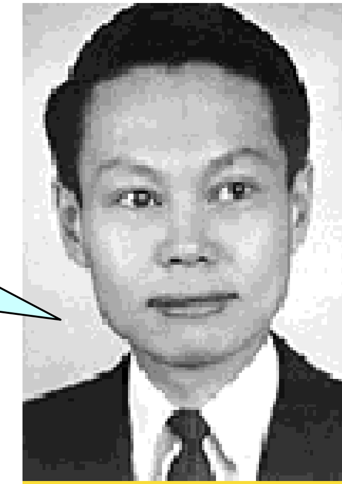
T. D. Lee (Columbia)

C.N. Yang (IAS)



T. D. Lee (Columbia)

Is Parity Conserved in Weak Interactions?



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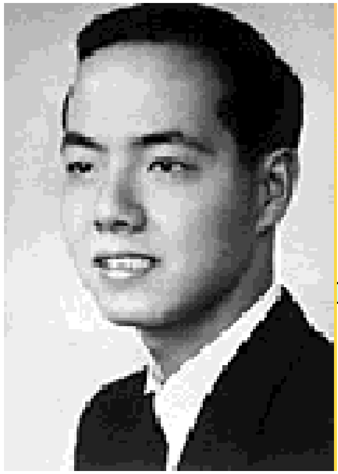

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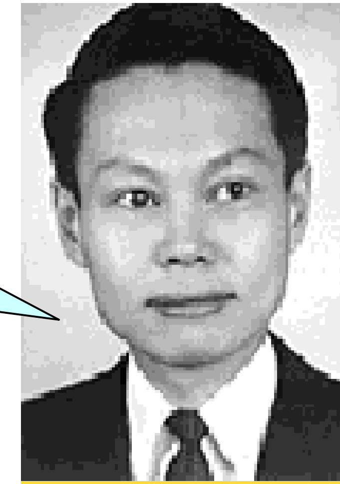
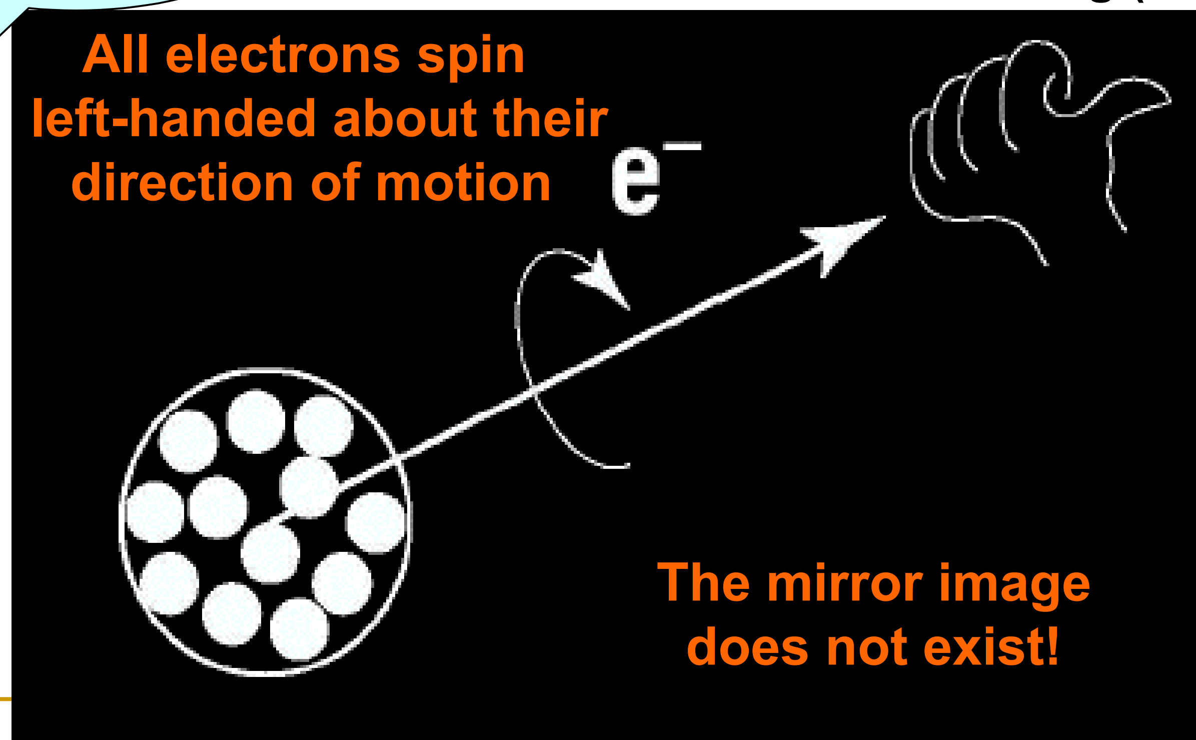


C.N. Yang (IAS)

NO!

C. S. Wu (Columbia)



C and P Bad, CP Good?

- Wu and others found that left-handed positrons do not exist either, so C and P are maximally violated!
- However, the combined operation (CP) of swapping particle/antiparticle and left-handed/right-handed restores the symmetry:

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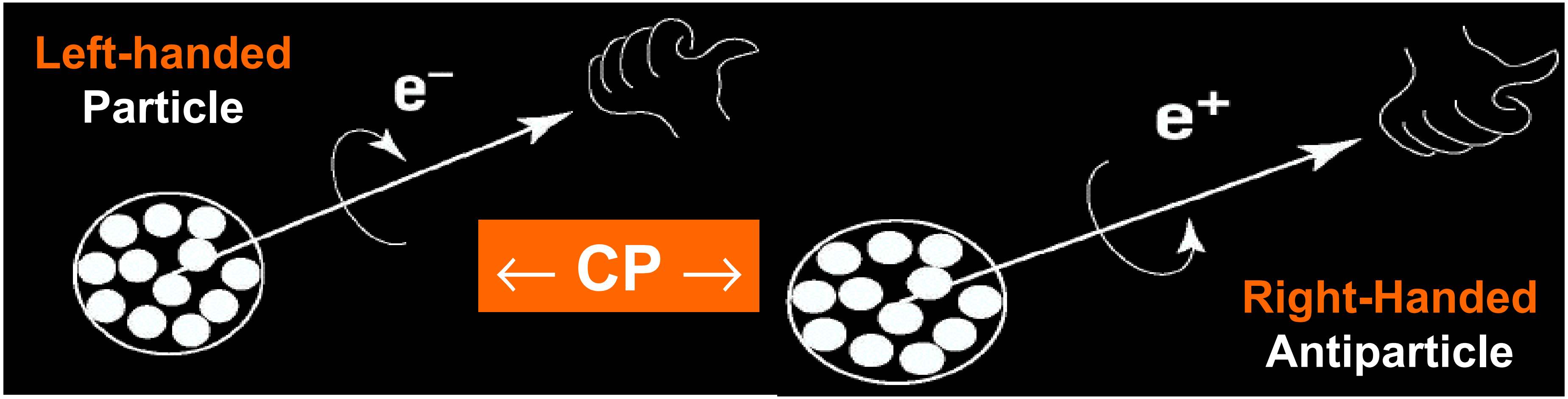

CP Violation

- In 1964, Princeton researchers (Cronin and Fitch) working at the Brookhaven AGS observed the CP-violating decay $K_L \to \pi^+\pi^-$
- Completely unexpected!
- Unlike parity violation, CP violation did not fit into existing models
- Fundamentally altered our understanding of the weak force

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EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in.$\times$48-in. collimator at an average distance of 14.5 ft. from the internal target. This collimator was followed by a sweeping magnet of 512 kG-in. at ~20 ft. and a 6-in.$\times$6-in.$\times$48-in. collimator at 55 ft. A $1\frac{1}{2}$-in. thickness of Pb was placed in front of the first collimator to attenuate the gamma rays in the beam.

The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay products consisted of two spectrometers each composed of two spark chambers for track delineation separated by a magnetic field of 178 kG-in. The axis of each spectrometer was in the horizontal plane and each subtended an average solid angle of 0.7×10^{-2} steradians. The spark chambers were triggered on a coincidence between water Cherenkov and scintillation counters positioned immediately behind the spectrometers. When coherent K_1^0 regeneration in solid materials was being studied, an anticoincidence counter was placed immediately behind the regenerator. To minimize interactions K_2^0 decays were observed from a volume of He gas at nearly STP.

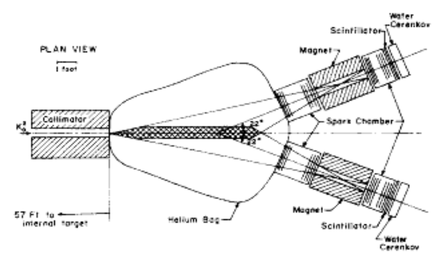


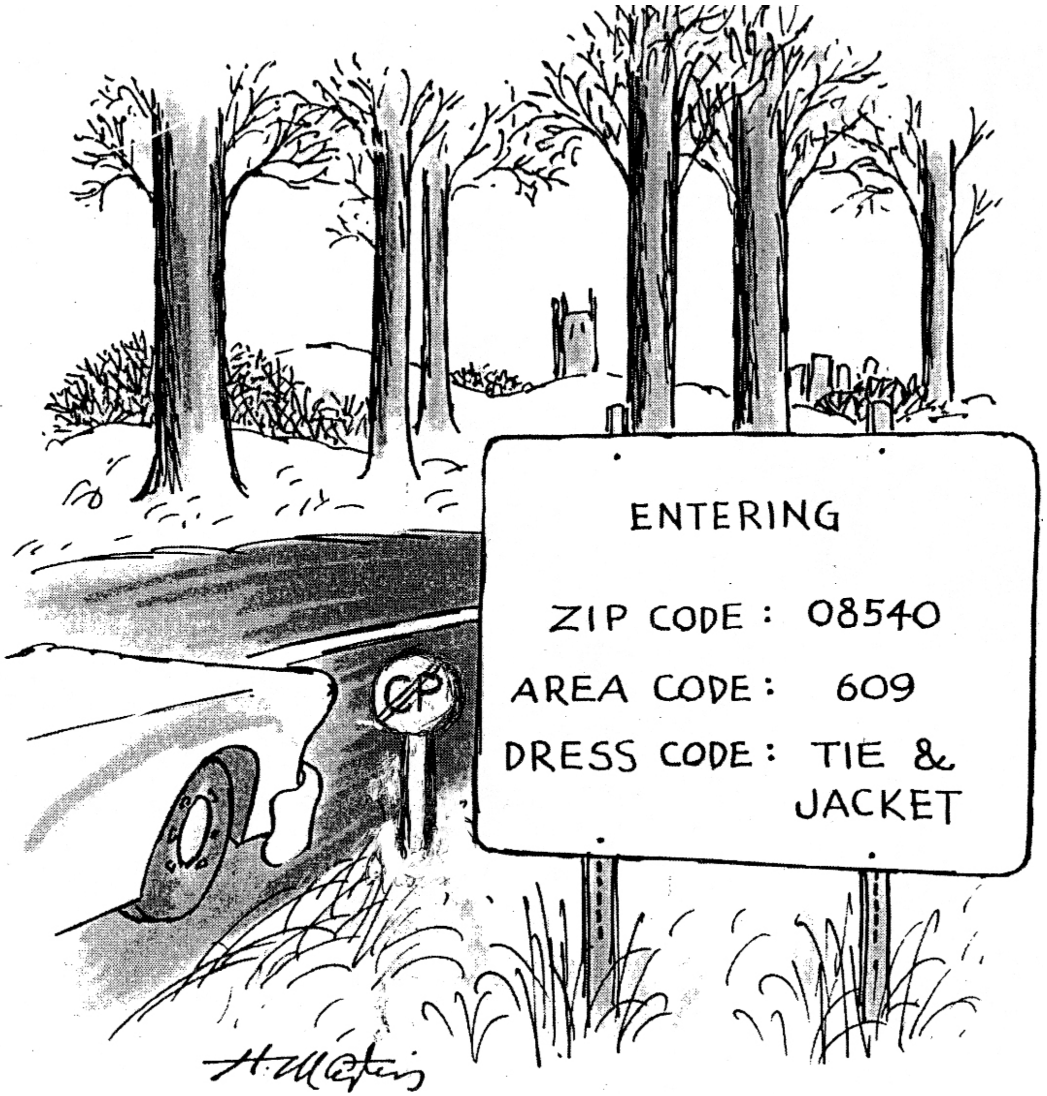
FIG. 1. Plan view of the detector arrangement.

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This angle should be zero for two-body decay and is, in general, different from zero for three-body decays.

An important calibration of the apparatus and data reduction system was afforded by observing the decays of K_1^0 mesons produced by coherent regeneration in 43 gm/cm² of tungsten. Since the K_1^0 mesons produced by coherent regeneration have the same momentum and direction as the K_2^0 beam, the K_1^0 decay simulates the direct decay of the K_2^0 into two pions. The regenerator was successively placed at intervals of 11 in. along the region of the beam sensed by the detector to approximate the spatial distribution of the K_2^0's. The K_1^0 vector momenta peaked about the forward direction with a standard deviation of 3.4 ± 0.3 milliradians. The mass distribution of these events was fitted to a Gaussian with an average mass 498.1 ± 0.4 MeV and standard deviation of 3.6 ± 0.2 MeV. The mean momentum of the K_1^0 decays was found to be 1100 MeV/c. At this momentum the beam region sensed by the detector was 300 K_1^0 decay lengths from the target.

For the K_2^0 decays in He gas, the experimental distribution in m^* is shown in Fig. 2(a). It is compared in the figure with the results of a Monte Carlo calculation which takes into account the nature of the interaction and the form factors involved in the decay, coupled with the detection efficiency of the apparatus. The computed curve shown in Fig. 2(a) is for a vector interaction, form-factor ratio $f^-/f^+ = 0.5$, and relative abundance 0.47, 0.37, and 0.16 for the K_{e3}, $K_{\mu 3}$, and $K_{\pi 3}$, respectively.[3] The scalar interaction has been computed as well as the vector interaction

A Nobel Prize, and a Cartoon!



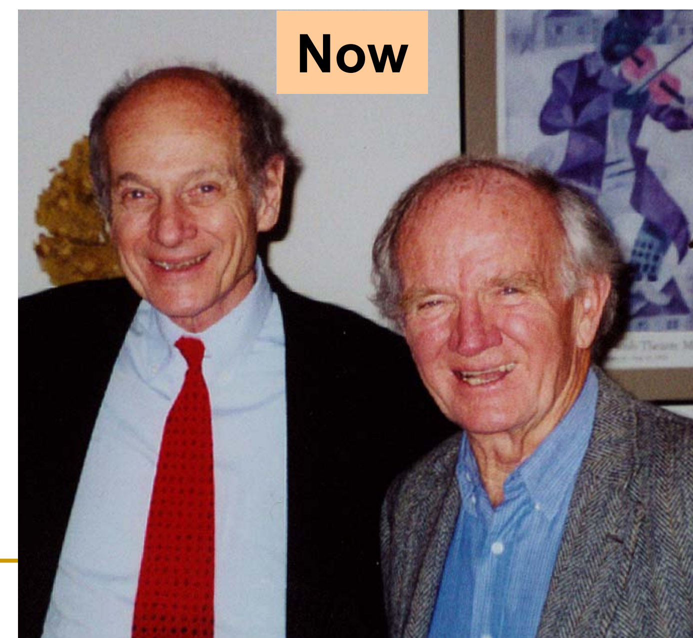
(Hank Martin, New Yorker)

Jim Cronin

Val Fitch

Then

Now

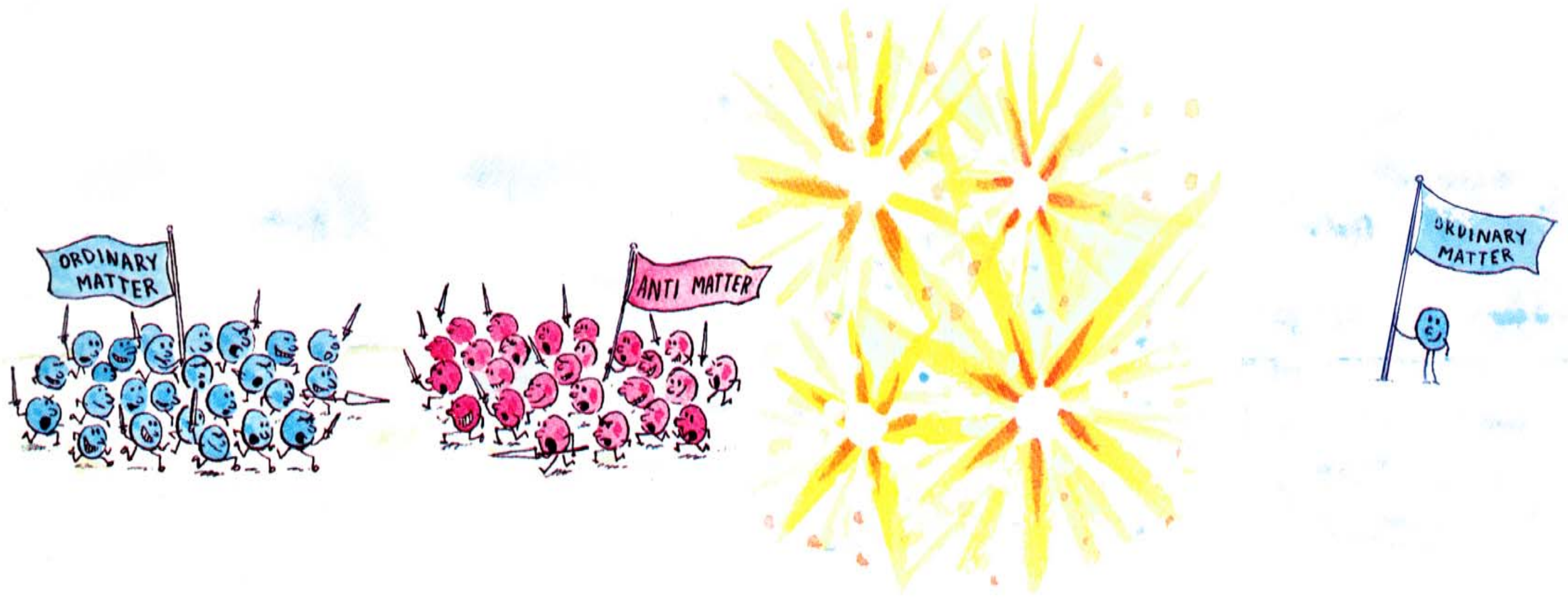


from A. J. Smith

So What?

CP violation is one of the necessary ingredients to produce a matter/antimatter asymmetry in the early universe!

A Cosmological Fight to the Death…



For every billion ordinary particles annihilating with antimatter in the early Universe, one extra was left "standing."

-- The Smithsonian

Intermission

- Calculations showed that the level of CP violation observed in the Cronin-Fitch experiment failed, by billions, to explain the matter/antimatter asymmetry in the universe. Hmmm…..
- Meanwhile, a mechanism to describe CP violation in the Standard Model was developed by Kobayashi and Maskawa (1973), with inspiration from Cabibbo (1963)
- Despite tireless efforts by experimentalist, for 37 years the question of whether the CKM mechanism was the source of CP violation in the K-meson system remained unanswered…

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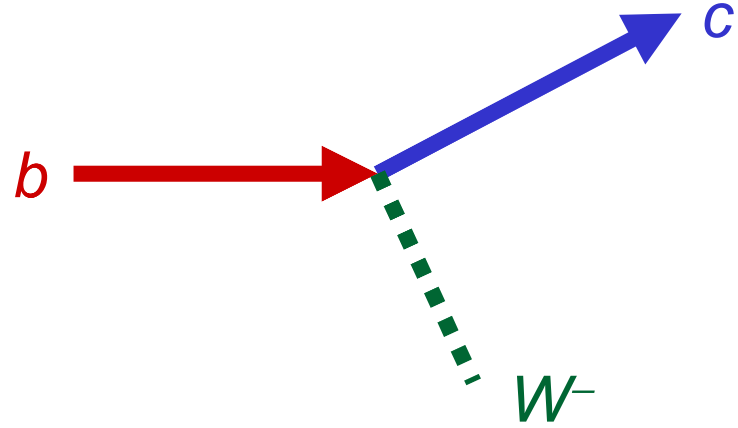
Enter the B Factories!

Beauty is Better than Strangeness

- B mesons have several advantages over K mesons when it comes to studying CP violation:
  - CP-violating observables are much larger (0.5 vs 0.002)
  - Many more decays modes → can cross-check measurements in several decay modes to look for (in)consistencies
  - Less theoretical uncertainty → tighter constraints on theory
- The B's allow for direct confrontation of the Standard Model with experiment, and the possibility to distinguish between competing models of CP violation
- In 1999, two dedicated CP violation experiments using B mesons began taking data: BaBar at Stanford, and Belle at Tsukuba, Japan

Finally, the Triangles!

- Weak interactions can change one quark flavor to another



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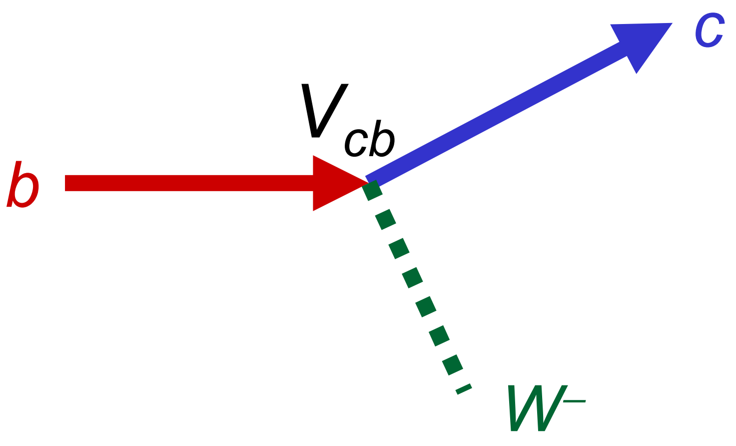
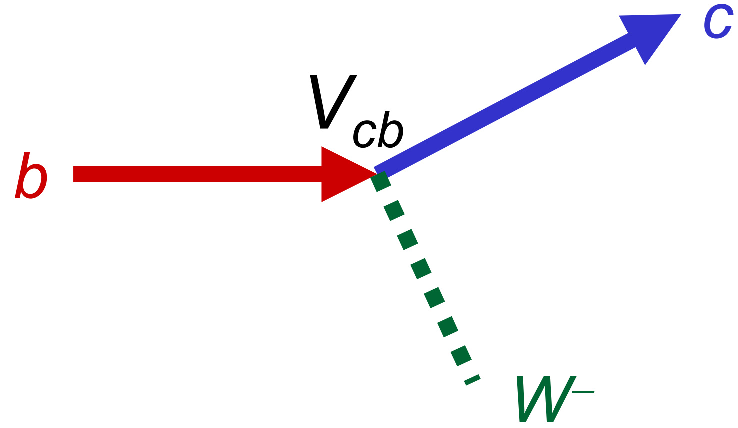


- Weak interactions can change one quark flavor to another
- The strength of the interaction is proportional to one of the elements of the “CKM matrix”

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Finally, the Triangles!



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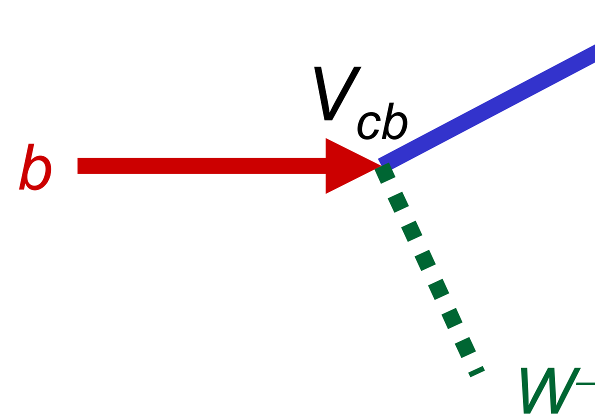
- Unitarity ($V^*V = 1$): "something has to happen!"
  - Leads to "triangles" in the complex plane

CP violation is proportional to the area!

Finally, the Triangles!



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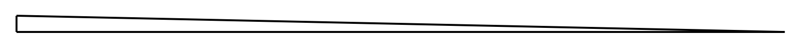
K mesons: $V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} = 0$



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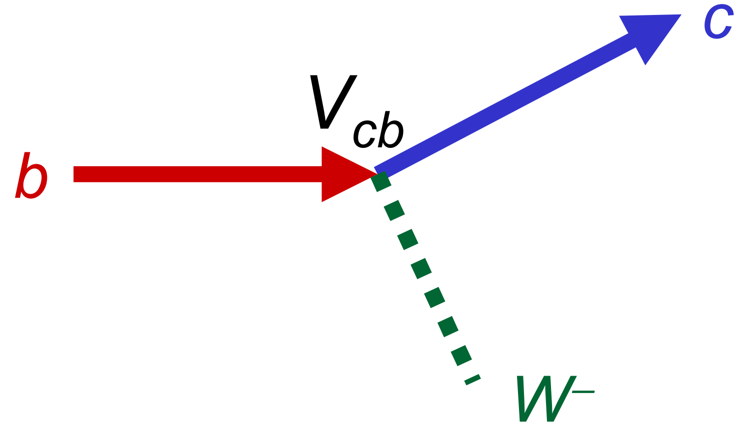

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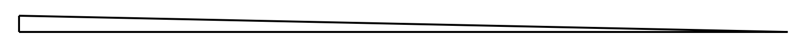
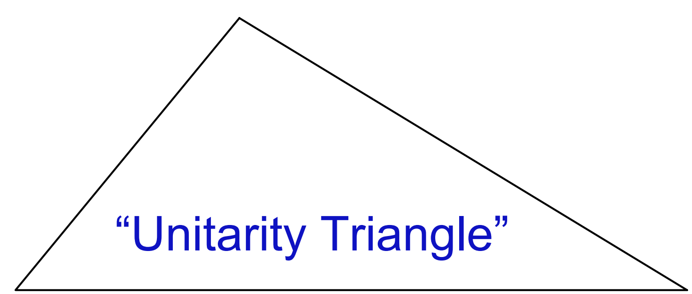
- The strength of the interaction is proportional to one of the elements of the “CKM matrix”

$$V = \begin{pmatrix} \boxed{\begin{matrix} V_{ud} \\ V_{cd} \\ V_{td} \end{matrix}} & \begin{matrix} V_{us} \\ V_{cs} \\ V_{ts} \end{matrix} & \boxed{\begin{matrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{matrix}} \end{pmatrix}$$

K mesons: $V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} = 0$



B mesons: $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$



- Unitarity (V*V = 1): “something has to happen!”
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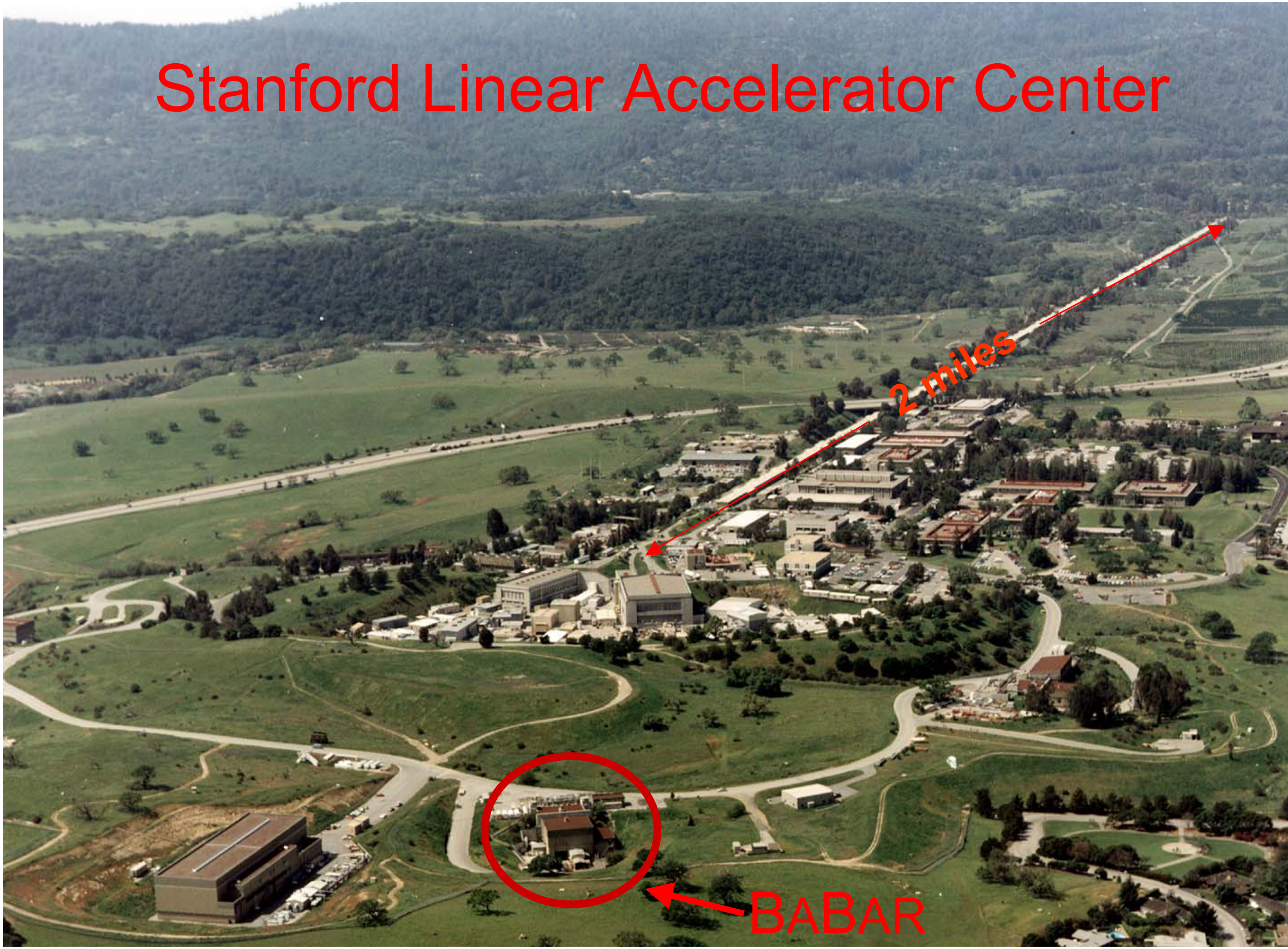
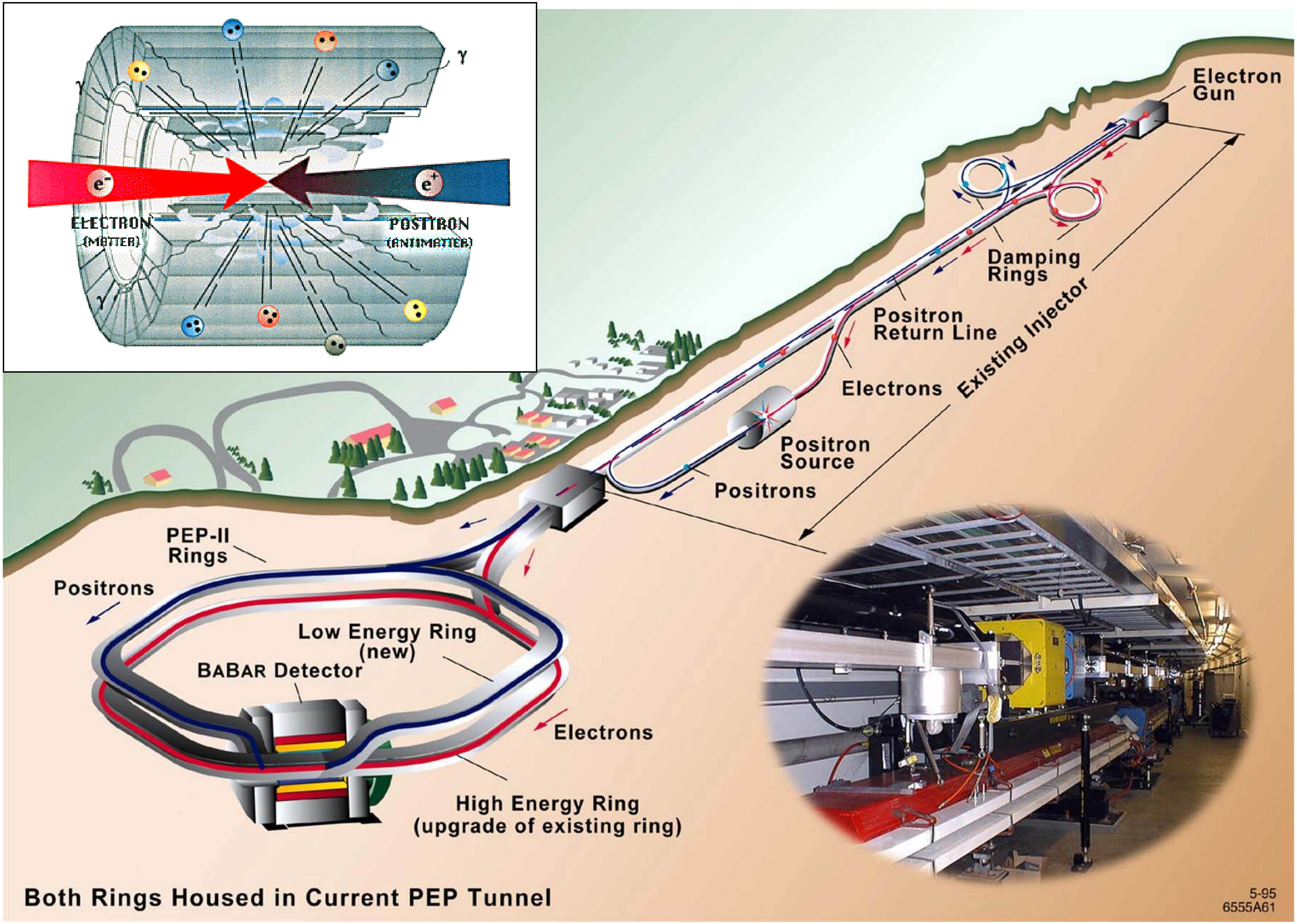
CP violation is proportional to the area!

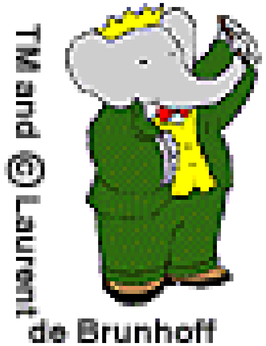
It's easy, and not so easy…

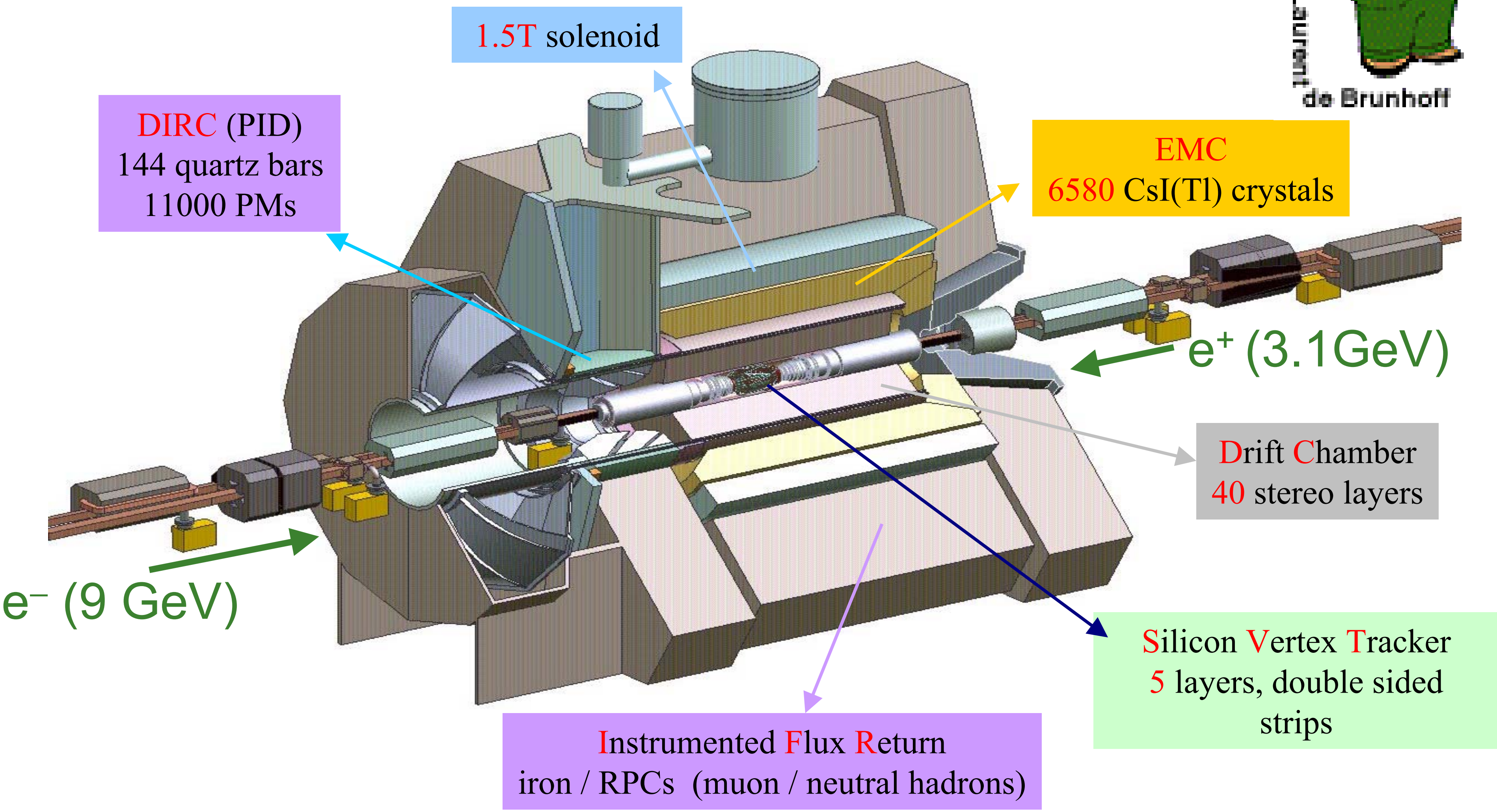
- The angles of the Unitarity Triangle are observable as CP-violating asymmetries in the time spectra of B^0 and anti-B^0 decays to well-defined states of CP symmetry
  - CP violation demonstrated if any angle is different from 0 or 180!
- Task of the B Factories is to measure the angles and sides of the Unitarity Triangle with unprecedented precision
- But, the relevant decays are rare (1 in 10,000), and the B meson lives for only 1.5 *trillionths* of a second
  - Need lots of B's → B Factories!!!
  - Even at B Factories, the B flies on average only .25 millimeters before decay → precision detectors needed to "see" the B decay


Stanford Linear Accelerator Center
2 miles
BABAR

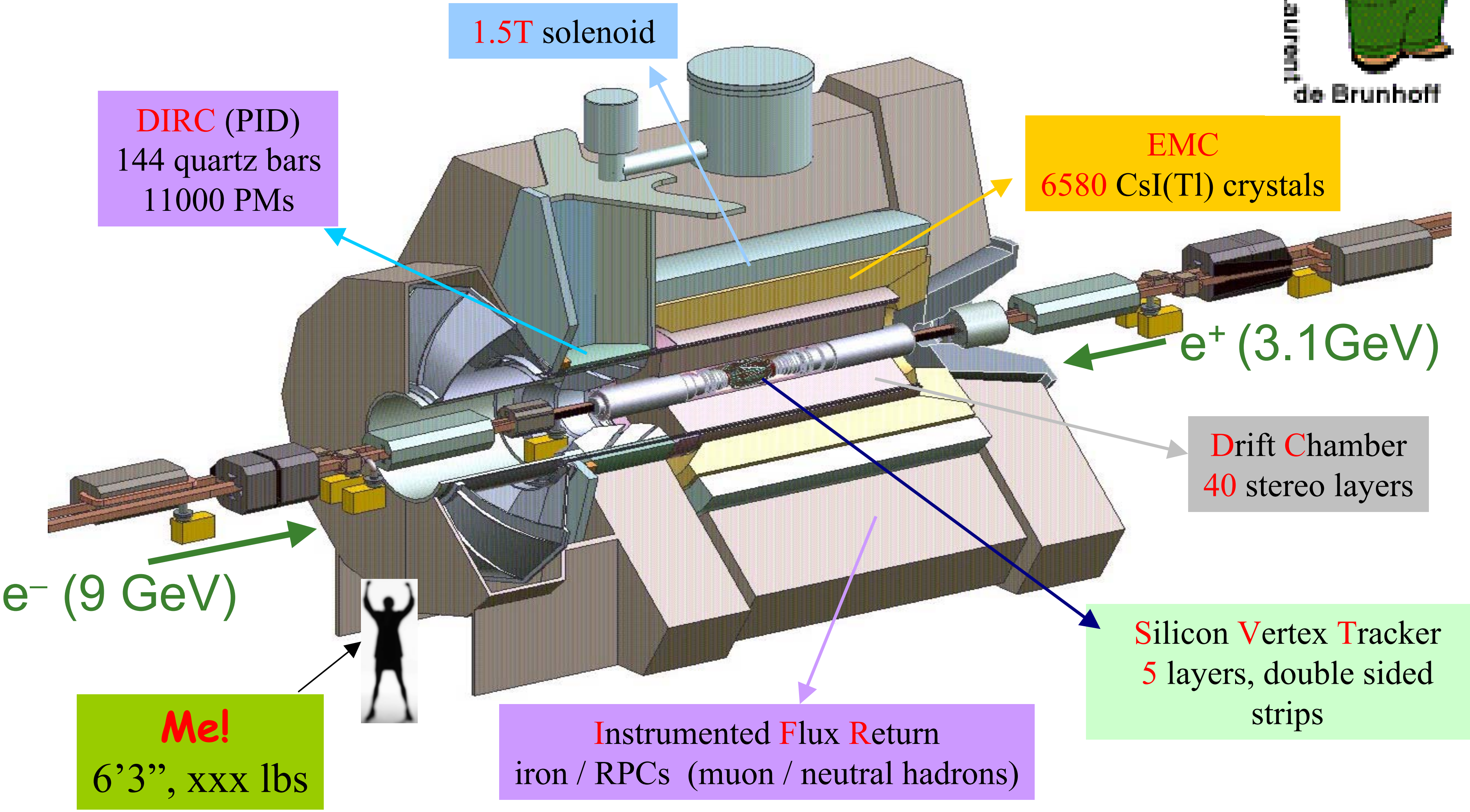

γ
γ
γ
e-
e+
ELECTRON
(MATTER)
POSITRON
(ANTIMATTER)
Electron
Gun
Damping
Rings
Positron
Return Line
Existing Injector
Electrons
Positron
Source
Positrons
PEP-II
Rings
Positrons
Low Energy Ring
(new)
BABAR Detector
Electrons
High Energy Ring
(upgrade of existing ring)
Both Rings Housed in Current PEP Tunnel
5-95
6555A61

BaBar Detector: Peel the Onion





BaBar Detector: Peel the Onion



How many physicists does it take to herd an elephant?

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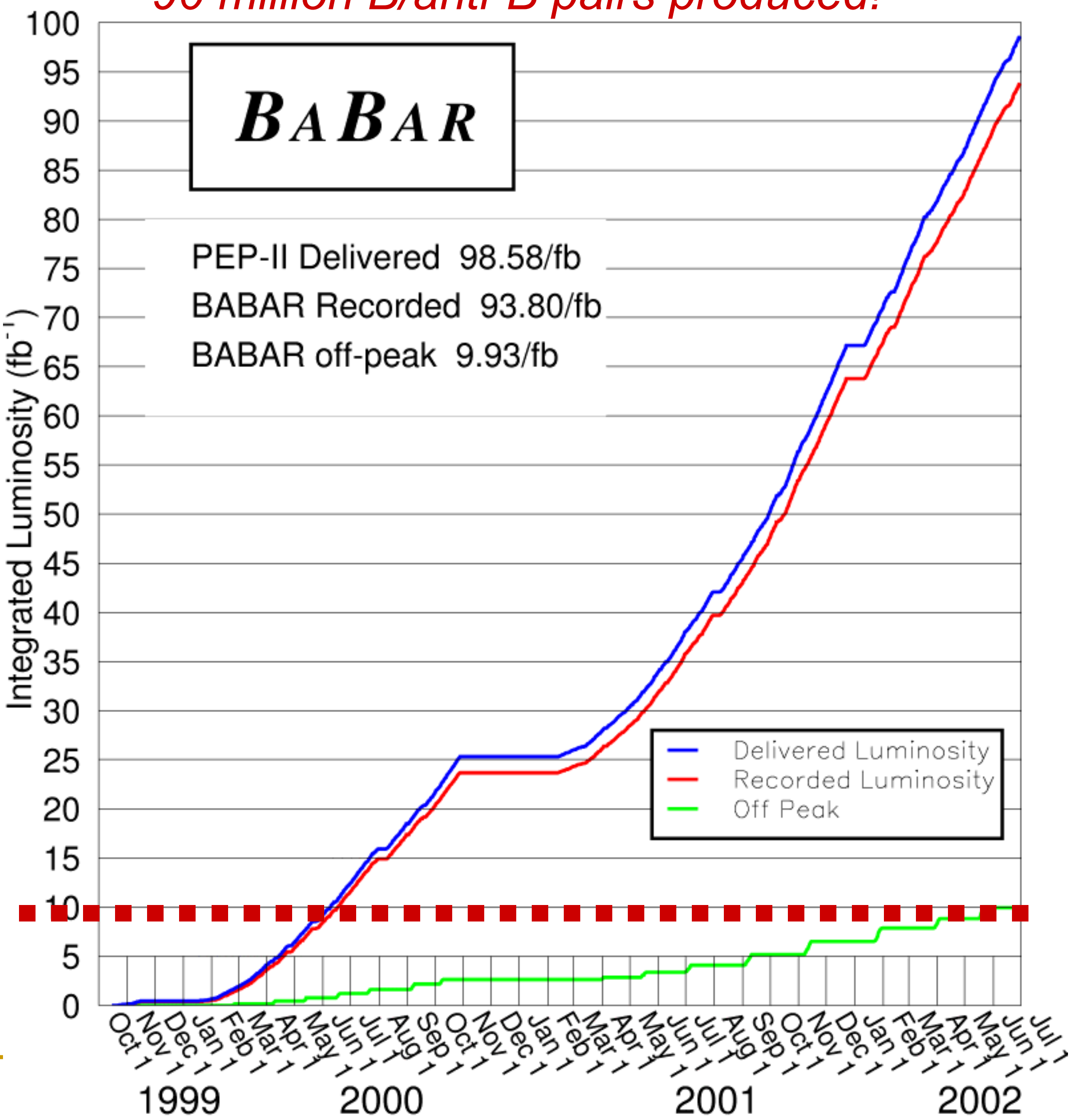
~600!

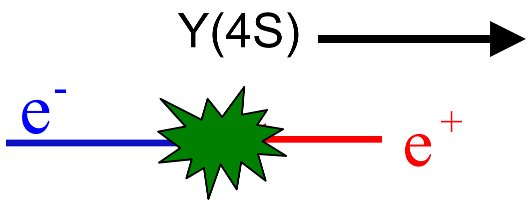
It's Really a B Factory!

90 million B/anti-B pairs produced!



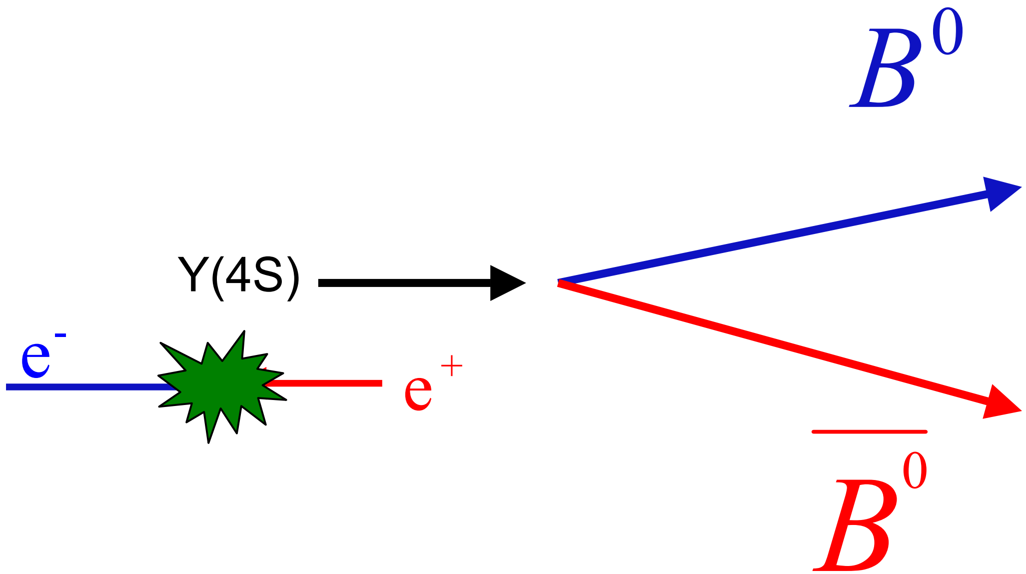
All previous B data recorded since the Big Bang

Experimental Setup



Electron and positron collide producing an Upsilon meson boosted in the lab frame

Experimental Setup

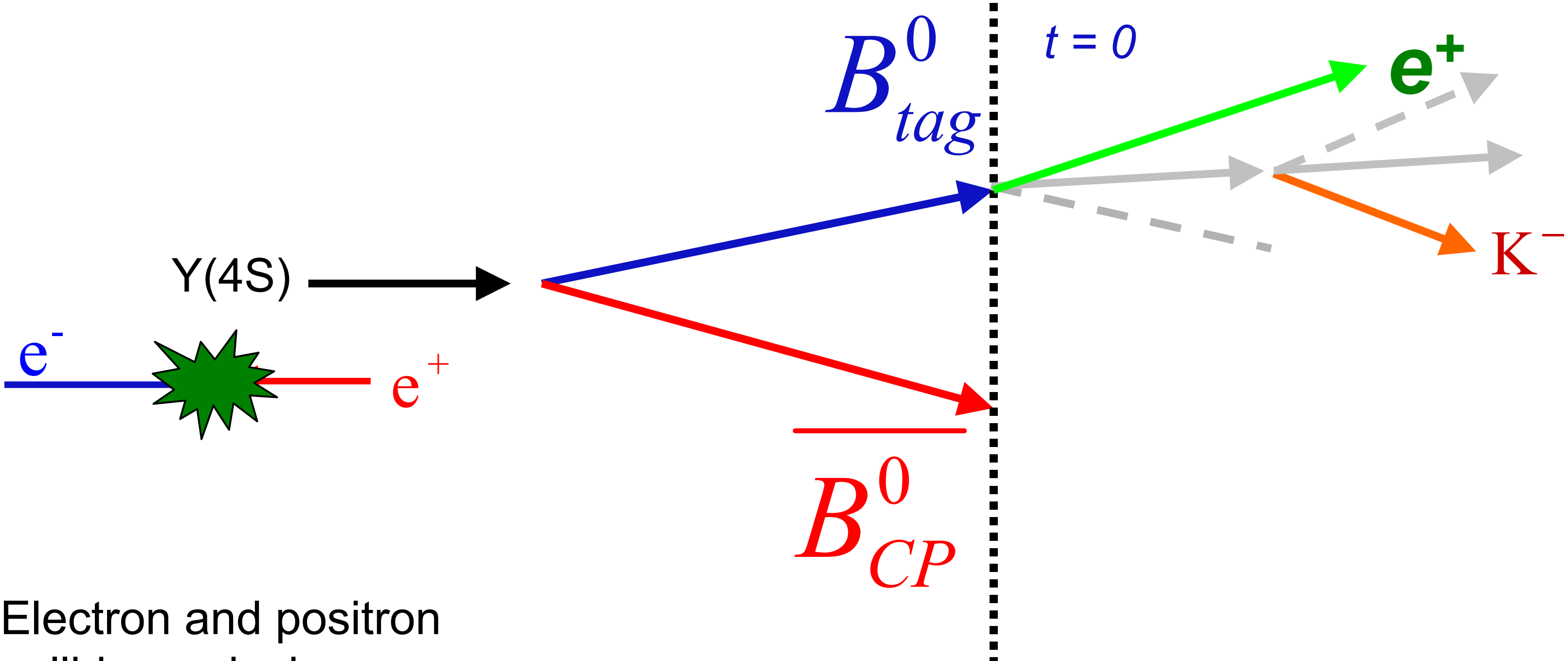


Electron and positron collide producing an Upsilon meson boosted in the lab frame

Upsilon decays to B/anti-B pair in coherent angular momentum state

Experimental Setup

Start the clock when one B (call it B_{tag}) decays, “tag” it’s flavor



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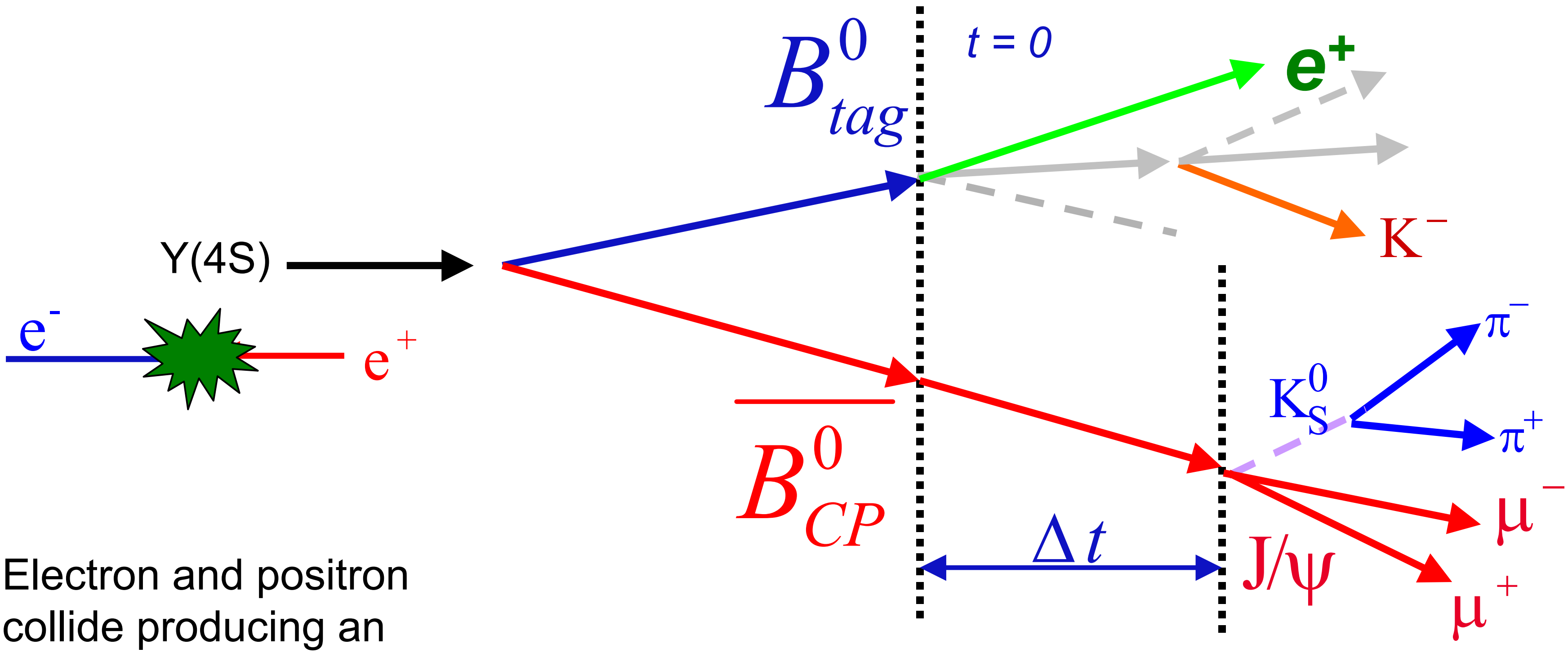

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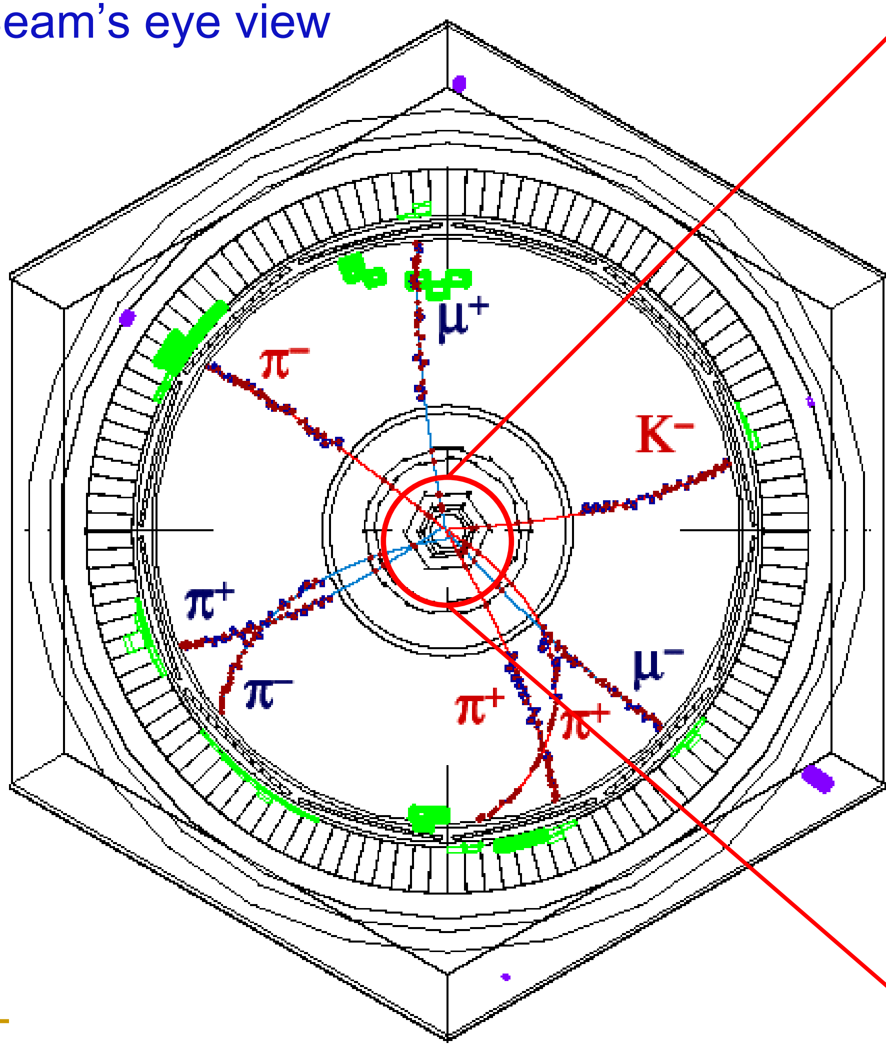
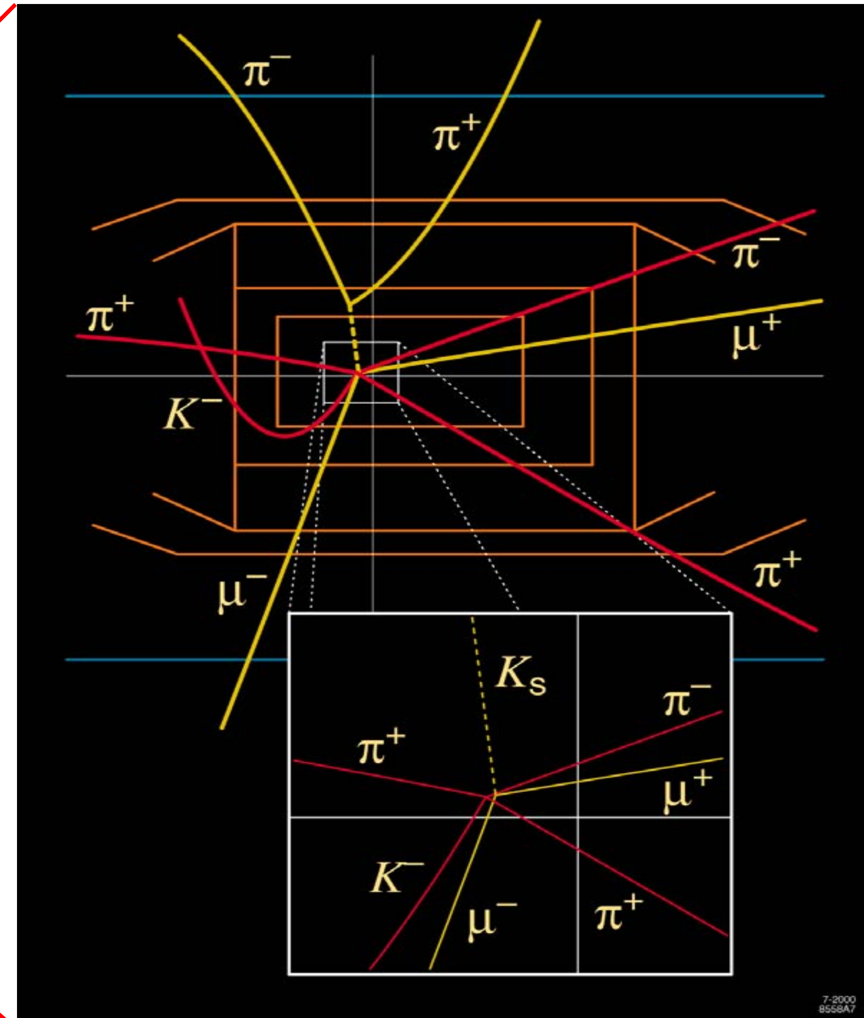
CP eigenstate

After a time Δt, the second B (call it B_{CP}) decays into a CP eigenstate that is fully reconstructed

A Real Event: $B^0 \to J/\psi K_S^0(\pi^+\pi^-)$

Beam's eye view

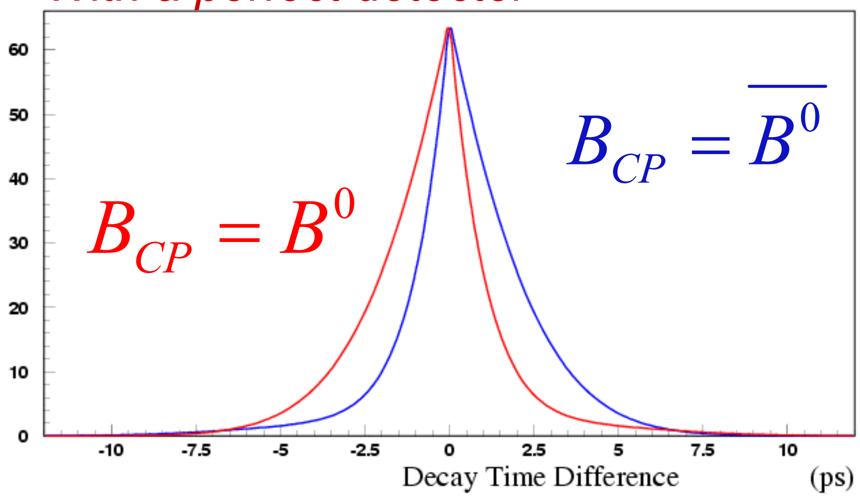




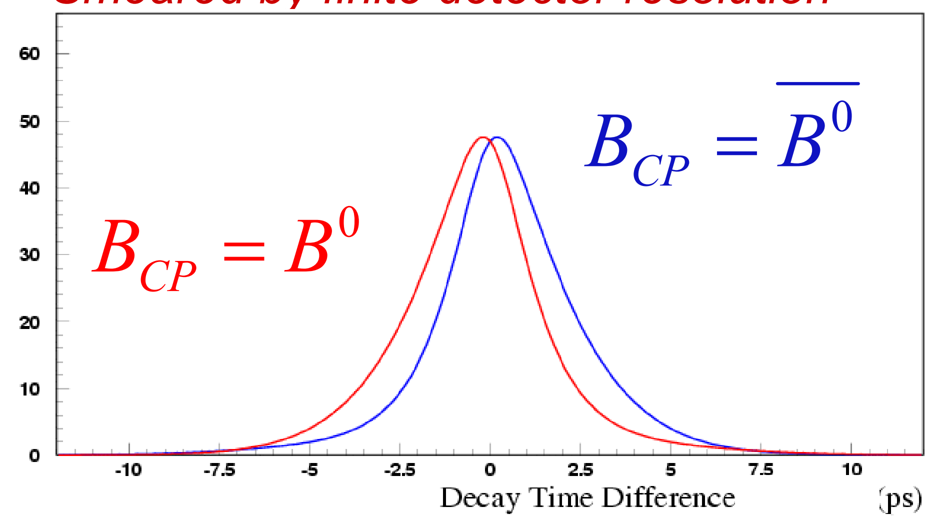
Zoom in…

What Do We Expect?

With a perfect detector

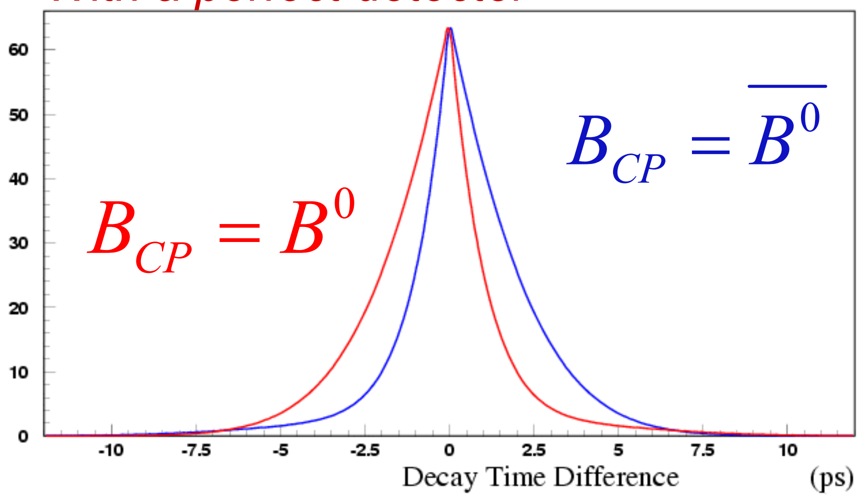


Smeared by finite detector resolution

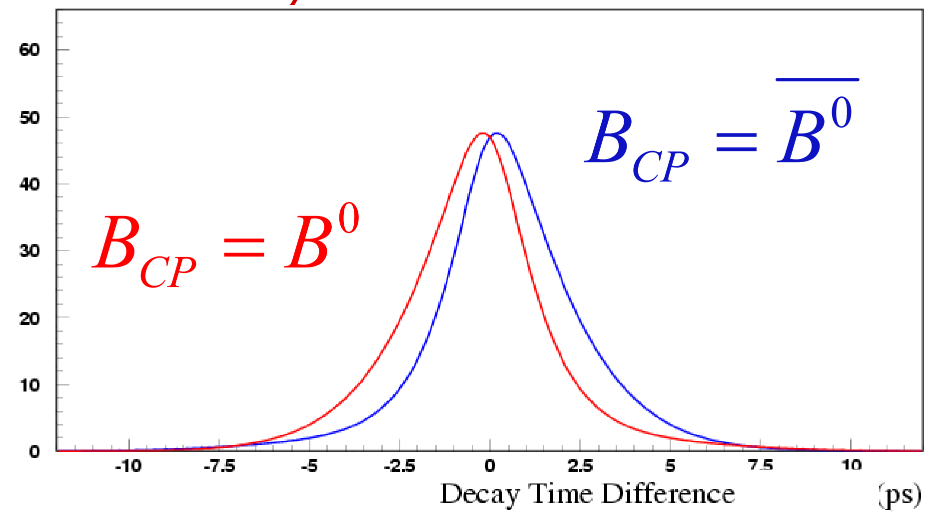


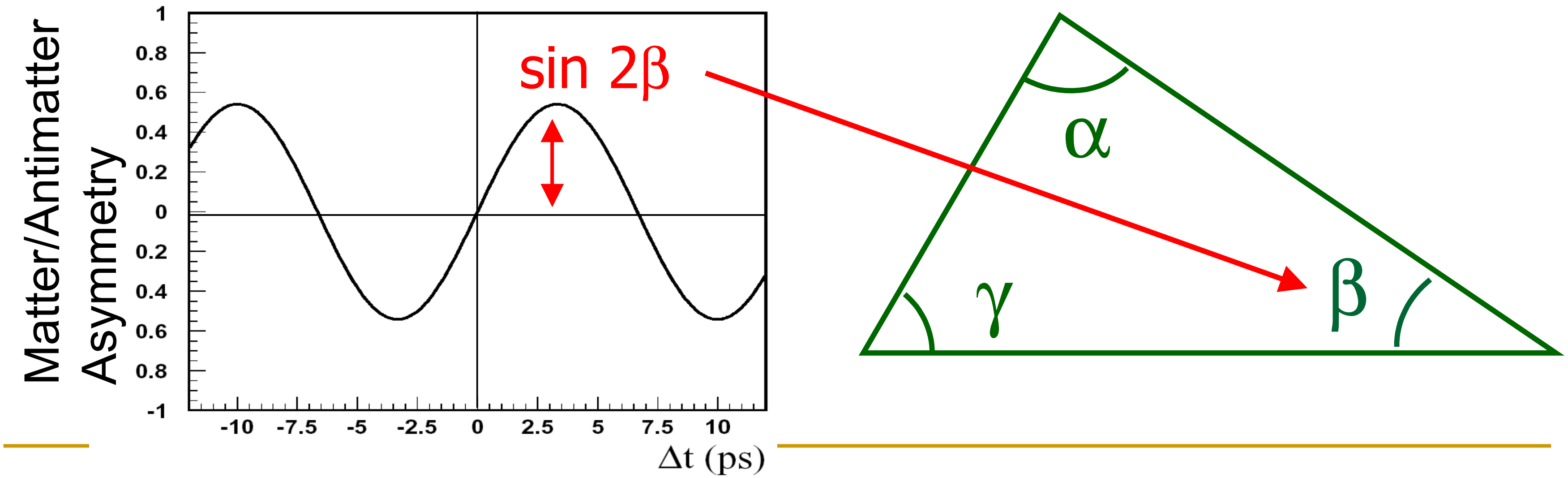
What Do We Expect?

With a perfect detector

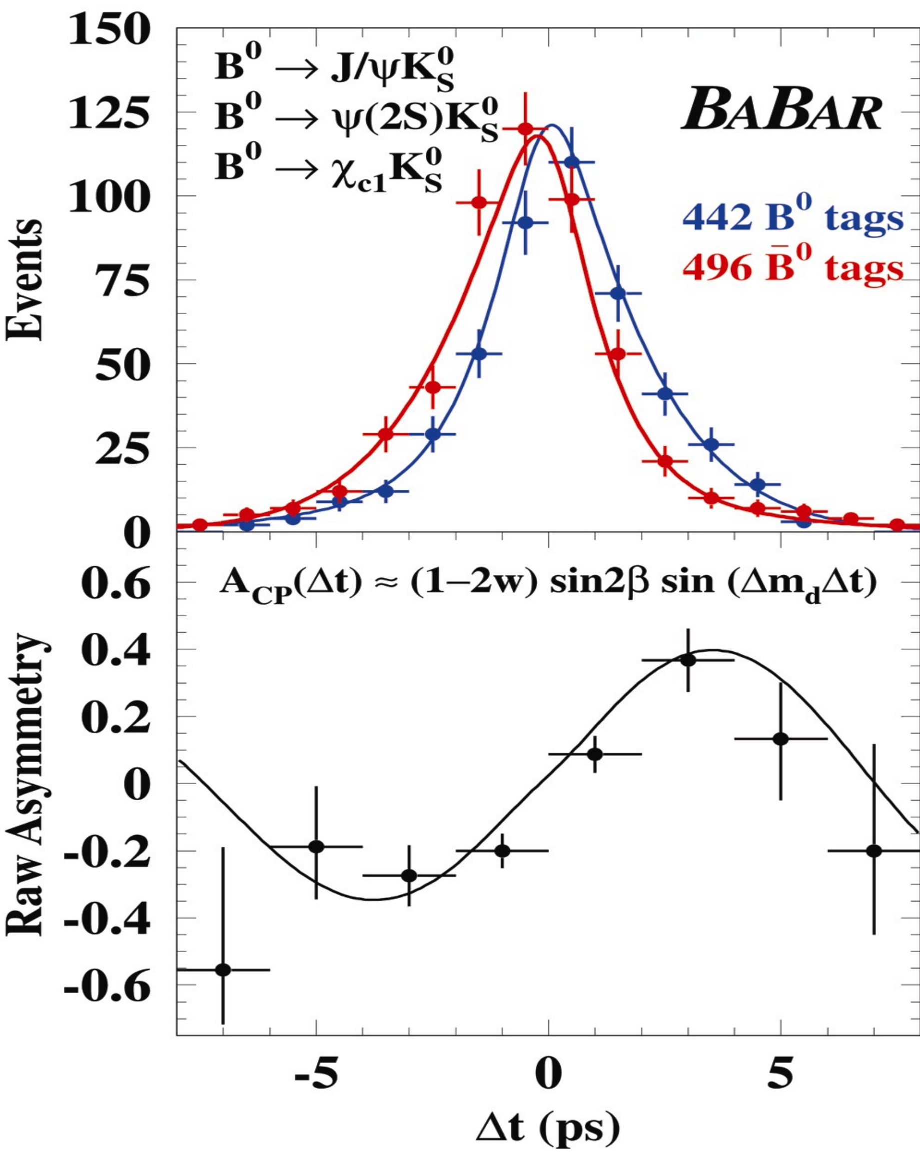


Smeared by finite detector resolution





Observation of CP Violation in B Decays



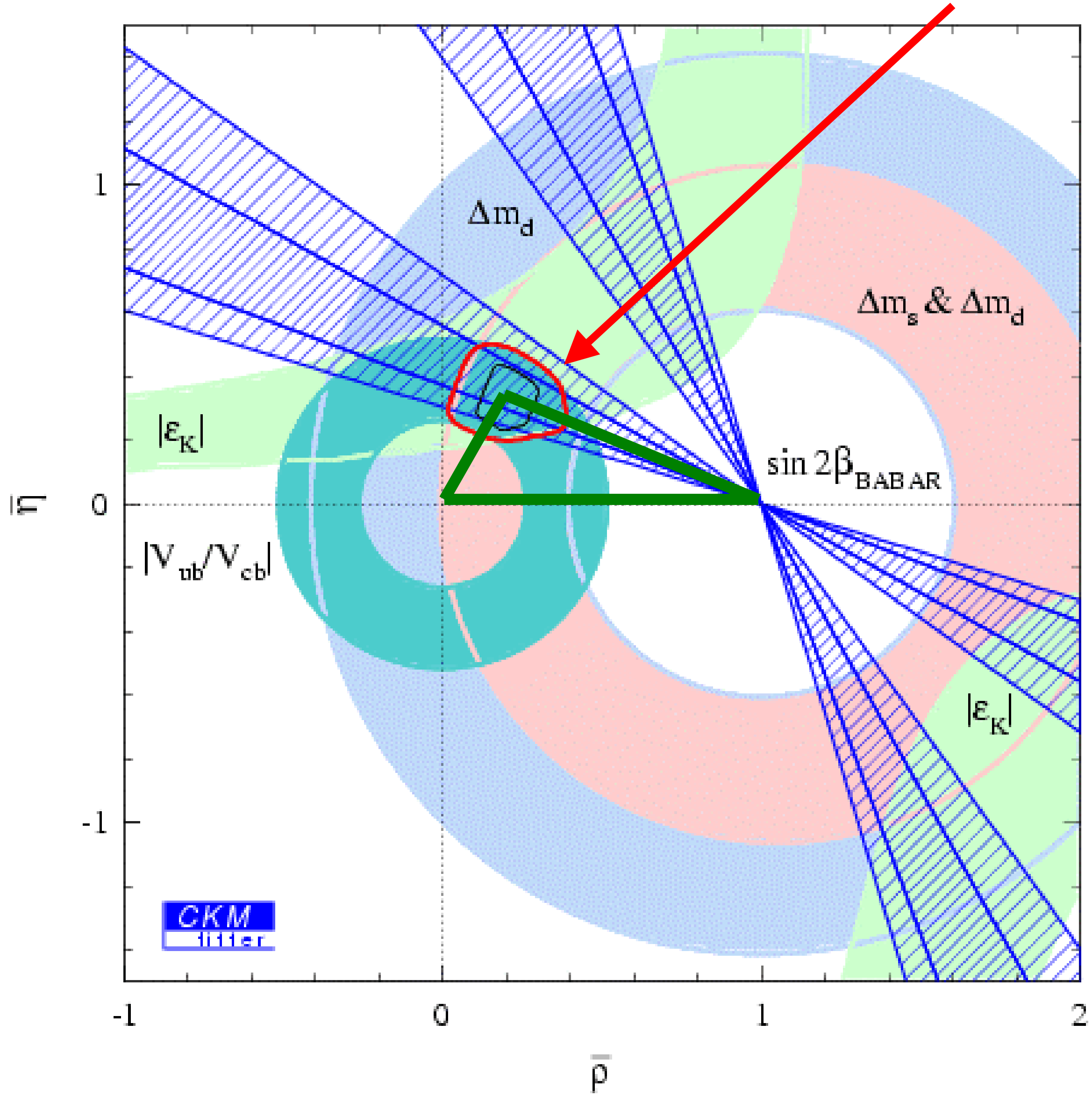
- Matter/antimatter asymmetry visible to the naked eye!
- First observation July 2001
- Latest measurement (yesterday!):

$\sin 2\beta = 0.741 \pm 0.067$ (stat) ± 0.033 (syst)

(hep-ex/0207042)

So β = 24 degrees ≠ 0 or 180!

What is the Predicted Value?



A triumph for the Standard Model!

So What Does it All Mean?

- The observation of CP violation in B decays, and the extraordinary agreement with the Standard Model prediction, leave little doubt that the CKM paradigm is the common source of CP violation in B and K mesons
- But this still leaves us billions of times short of describing the cosmological CP violation that led to our matter-dominated Universe!
  - Is it “New Physics”, or something less exotic?
- We are now in a new phase of the experiments, looking at different, and rarer decay modes
- The B Factories continue taking data at ever-higher rates in order to squeeze the Triangle until it cracks!

A Final Thought…

"This is not the end.
It is not even the
beginning of the end.
It is, perhaps, the end
of the beginning…"

-- Winston Churchill