The Physics of CP Violation

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THE UNIVERSITY OF WARWICK

Physics Colloquium
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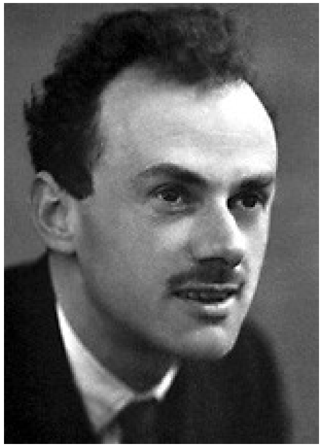
Content of the talk

- Why are we interested in CP violation?
- What is CP violation?
- What do we know about it?
  - Early history
  - Recent measurements
- How will we find out more about it?

Dirac's prescience

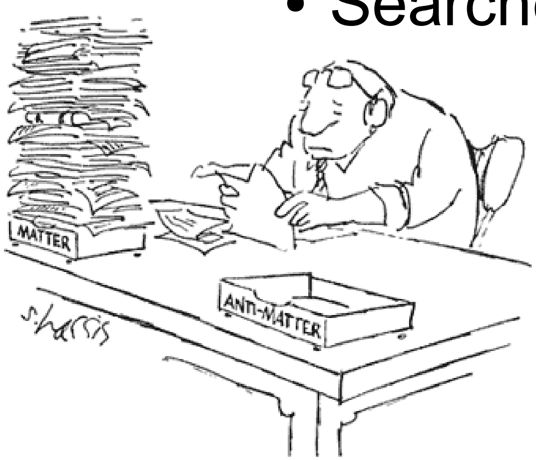


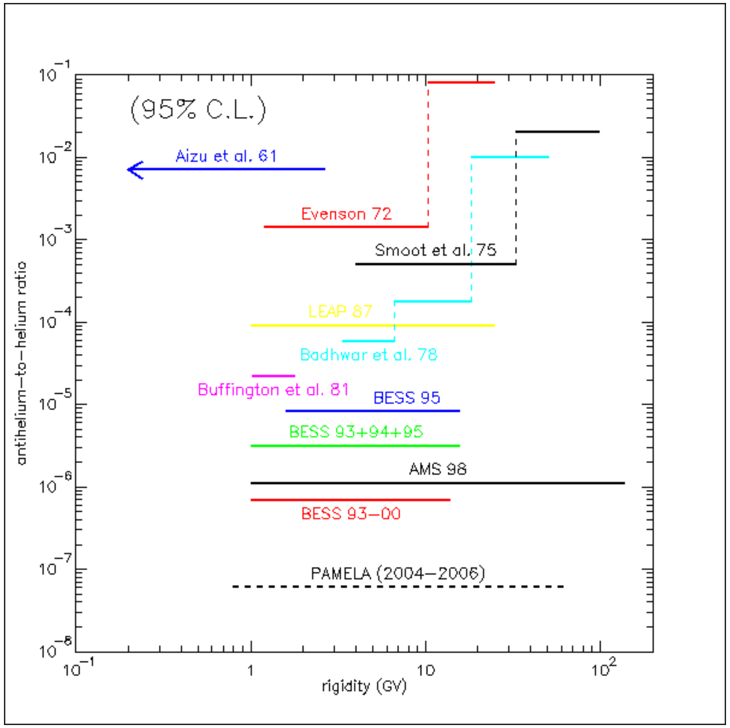
Concluding words of 1933 Nobel lecture

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

Are there antimatter dominated regions of the Universe?

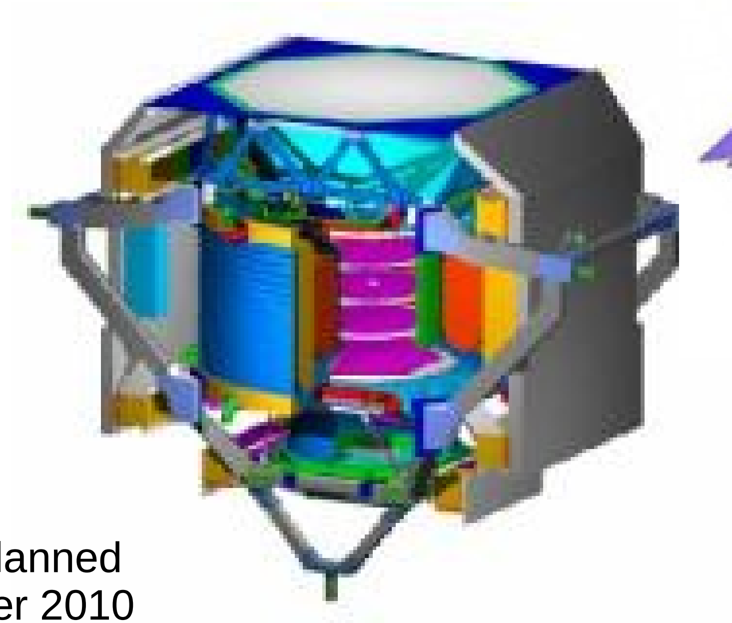
- Possible signals:
  - Photons produced by matter-antimatter annihilation at domain boundaries – not seen
    - Nearby anti-galaxies ruled out
  - Cosmic rays from anti-stars
    - Best prospect: Anti-^{4}He nuclei
    - Searches ongoing ...





Searches for antimatter

Alpha **M**agnetic **S**pectrometer Experiment on board the International Space Station



launch planned September 2010

Payload for **A**nti**M**atter **E**xploration and **L**ight-nuclei **A**strophysics Experiment on board the Resurs-DK1 satellite

launched 15th June 2006

Matter-antimatter asymmetry

- Consider instead violation of the

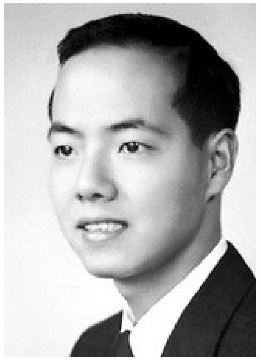
  "complete symmetry between positive and negative electric charge"

- In particle physics, the charge conjugation (C) operator inverts all internal quantum numbers
- It is usually discussed together with other discrete symmetries
  - parity (P) : inversion of all spatial coordinates
  - time-reversal (T) : as the name suggests ...

(will not discuss role of T today)

Discovery of parity violation

- In 1956, T.D.Lee and C.N.Yang (Nobel prize 1957) pointed out that parity conservation had not been tested in the weak interaction



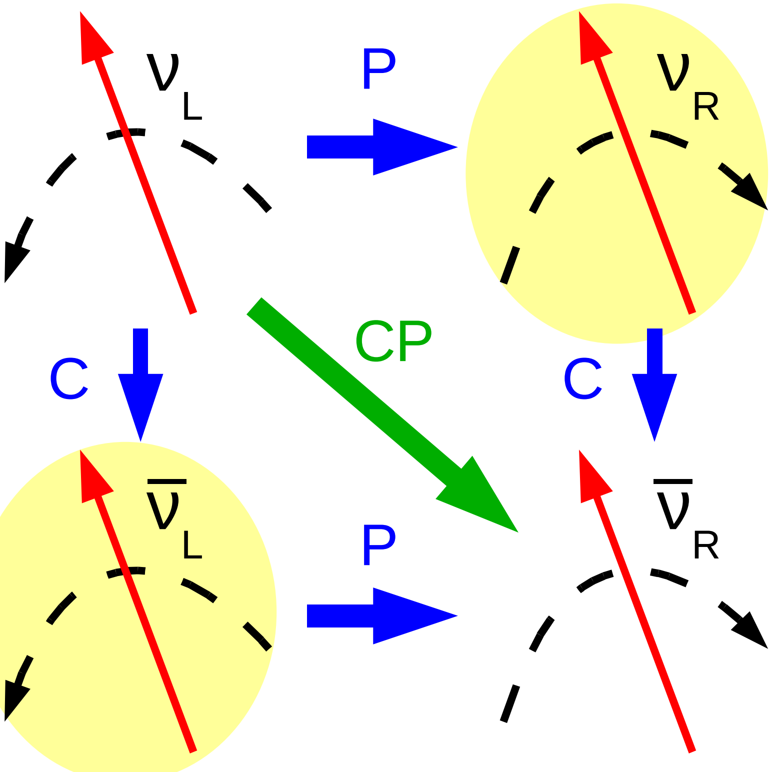
- C.S.Wu *et al.* were the first to make such a test, using β decays of ^{60}Co
  - Other immediate confirmations:

    ($\pi \to \mu \to e$) decay (L.M.Lederman *et al.*),

    ($K \to \mu \to e$) decay, Λ^0 decay, ...

P & C violation but CP conservation

- L.Landau proposed CP as the true matter-antimatter symmetry
  - observed P violation is also C violation



Only left-handed neutrinos and right-handed antineutrinos take part in weak interactions

ν_R and $\bar{\nu}_L$ are unphysical

C violation vs CP violation

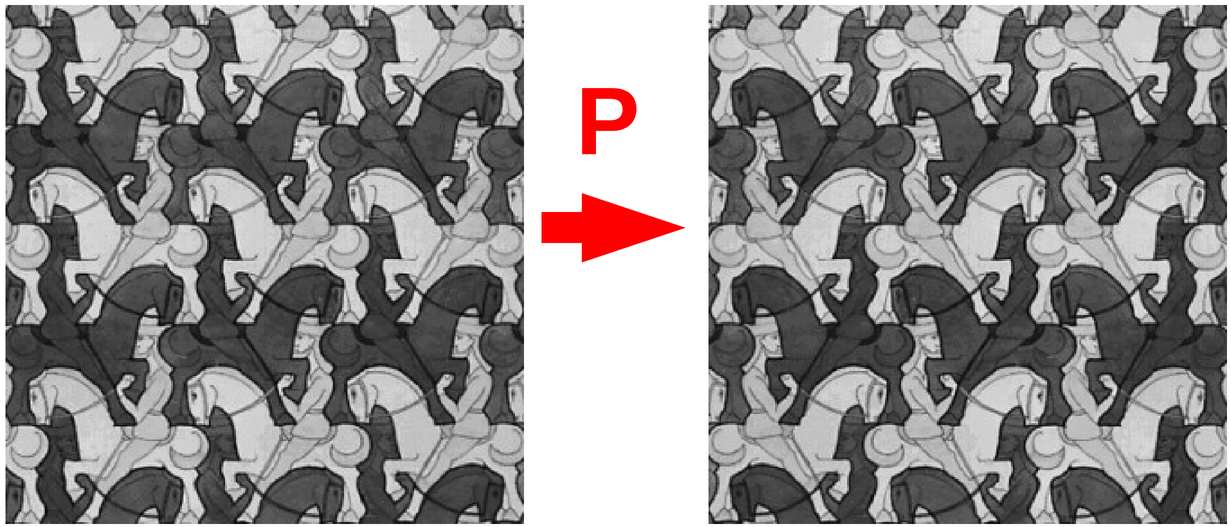
- C violation allows one to say

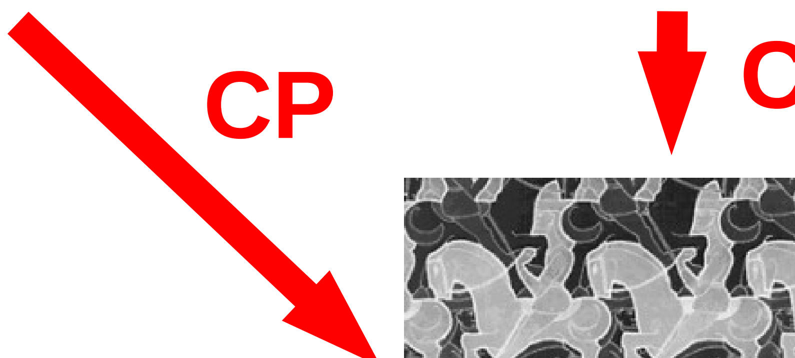
"Nuclei are orbited by electrons, which are emitted together with right-handed antineutrinos in beta decay"

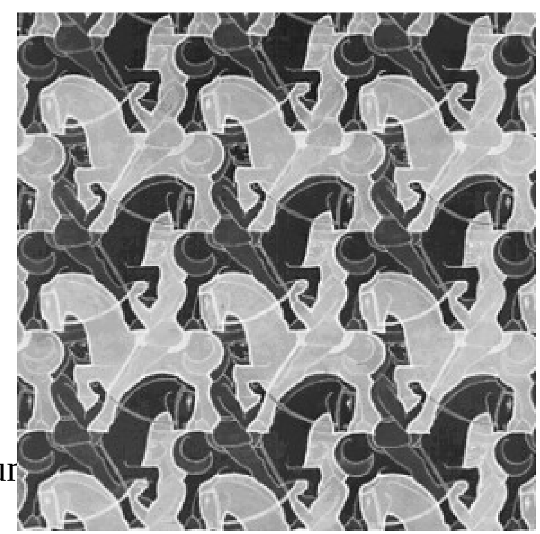
- This does not provide an absolute distinction between matter and antimatter
- CP violation allows one to say

"Nuclei are orbited by electrons, which are emitted less often in semileptonic decays of the long-lived neutral kaon"

Escher: CP conserving

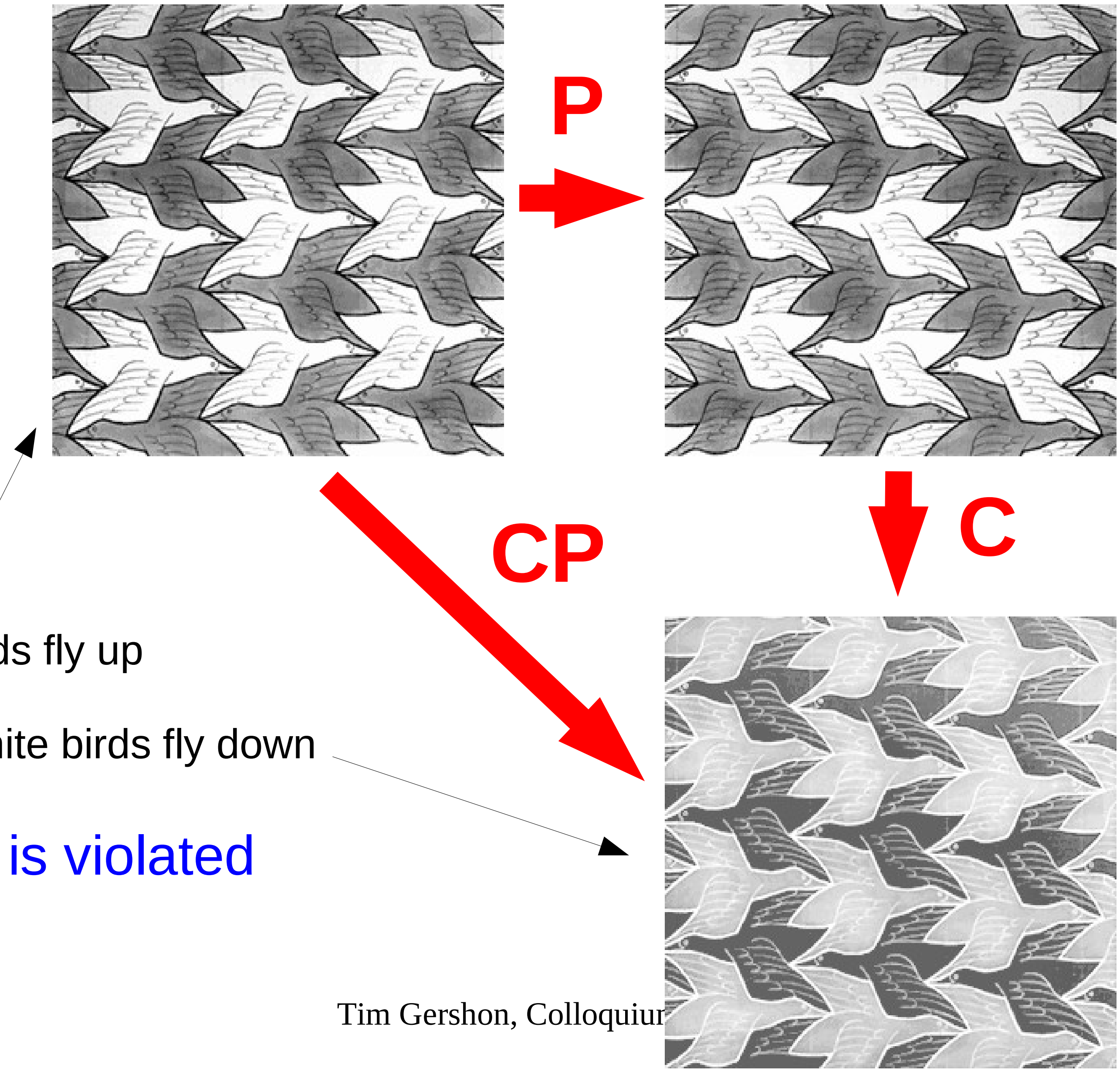






CP is conserved

Escher: CP violating



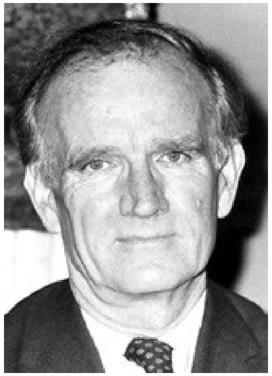
White birds fly up

White birds fly down

CP is violated

Discovery of CP violation

- 1964: J.W.Cronin,V.L.Fitch *et al.* discover $K_L^0 \rightarrow \pi^+\pi^-$
  - K_L^0 was previously thought to be CP-odd state (K_2^0)



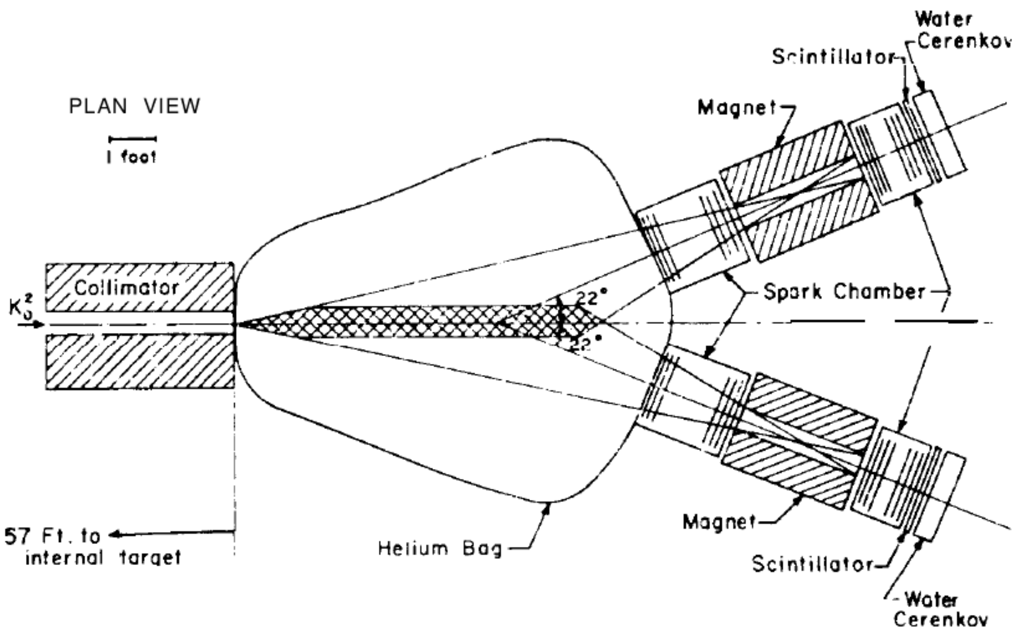


Fig. I. Plan view of the apparatus as located at the A. G. S.

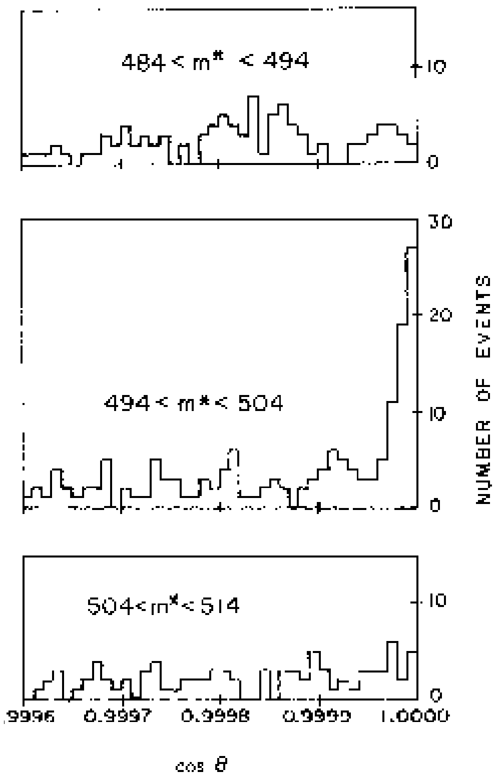


FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

The Sakharov conditions

- Proposed by A.Sakharov, 1967
- Necessary for evolution of matter dominated universe, from symmetric initial state
  - baryon number violation
  - C & CP violation
  - thermal inequilibrium

Dynamic generation of BAU

- Suppose equal amounts of matter (X) and antimatter ($\bar{X}$)
- X decays to
  - A (baryon number N_A) with probability p
  - B (baryon number N_B) with probability (1-p)
- $\bar{X}$ decays to
  - $\bar{A}$ (baryon number $-N_A$) with probability $\bar{p}$
  - $\bar{B}$ (baryon number $-N_B$) with probability $(1-\bar{p})$
- Generated baryon asymmetry:
  - $\Delta N_{TOT} = N_A p + N_B(1-p) - N_A\bar{p} - N_B(1-\bar{p}) = (p - \bar{p})(N_A - N_B)$
  - Require $p \neq \bar{p}$ & $N_A \neq N_B$

The need for more quarks

- In 1973, Kobayashi & Maskawa showed that CP violation could not be accommodated in a theory with only four quark fields
  - At that time only up, down & strange were known
  - Quarks largely considered as a mathematical model, not as real physical entities
  - Existence of charm hypothesised (GIM mechanism) ... but discovery not until the next year
- Among possible extensions, KM considered
  - Introduction of a third family (bottom and top) of quarks
  - Quark mixing following the scheme introduced by Cabibbo

CKM Matrix

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

- 3x3 matrix of complex numbers ⇒ 18 parameters
- Unitary ⇒ 9 parameters
- Quark fields absorb unobservable phases ⇒ 4 parameters
  - 3 mixing angles and 1 phase (V_{CKM} complex)

CKM Matrix : parametrizations

- 3 mixing angles and 1 phase

standard (PDG) parametrization

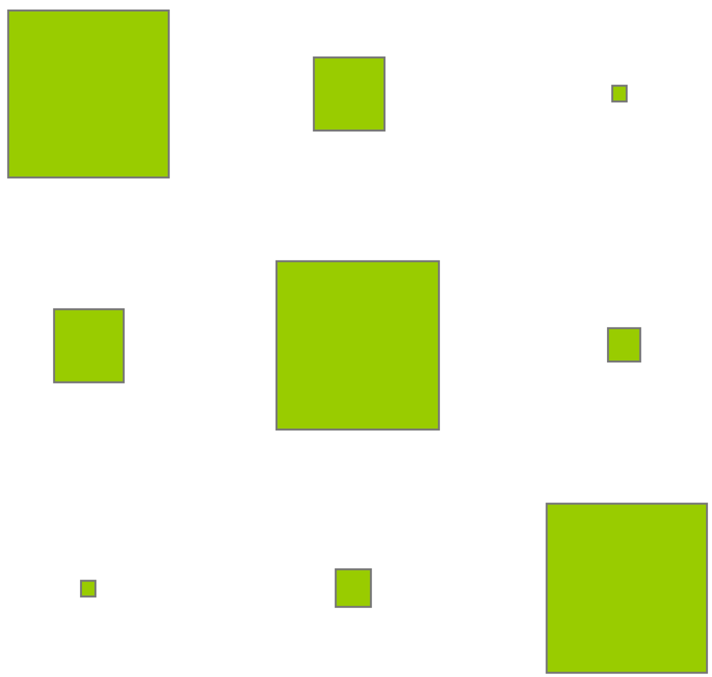
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- $s_{12} \equiv \sin(\theta_{12})$ *etc.*; CP violation possible through $\delta \neq 0$
- Empirically, find $s_{12} \sim 0.2$, $s_{23} \sim 0.04$, $s_{13} \sim 0.004$
- Exploit hierarchy – Wolfenstein parametrization
  – expansion parameter $\lambda \sim \sin\theta_c \sim 0.22$

$$V = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$

Hierarchy in quark mixing

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$

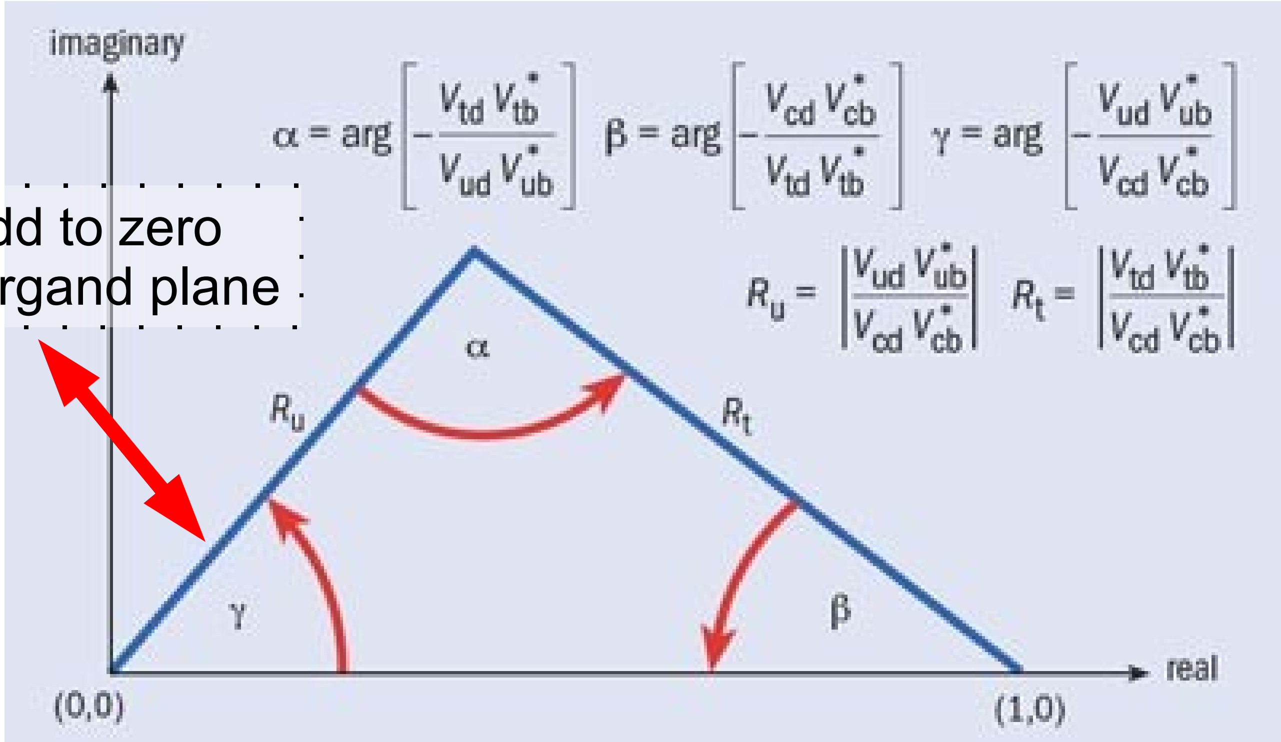


The Unitarity Triangle

Squares of CKM matrix elements describe probabilities
⇒ matrix must be *unitary*

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

Three complex numbers add to zero
⇒ triangle in Argand plane

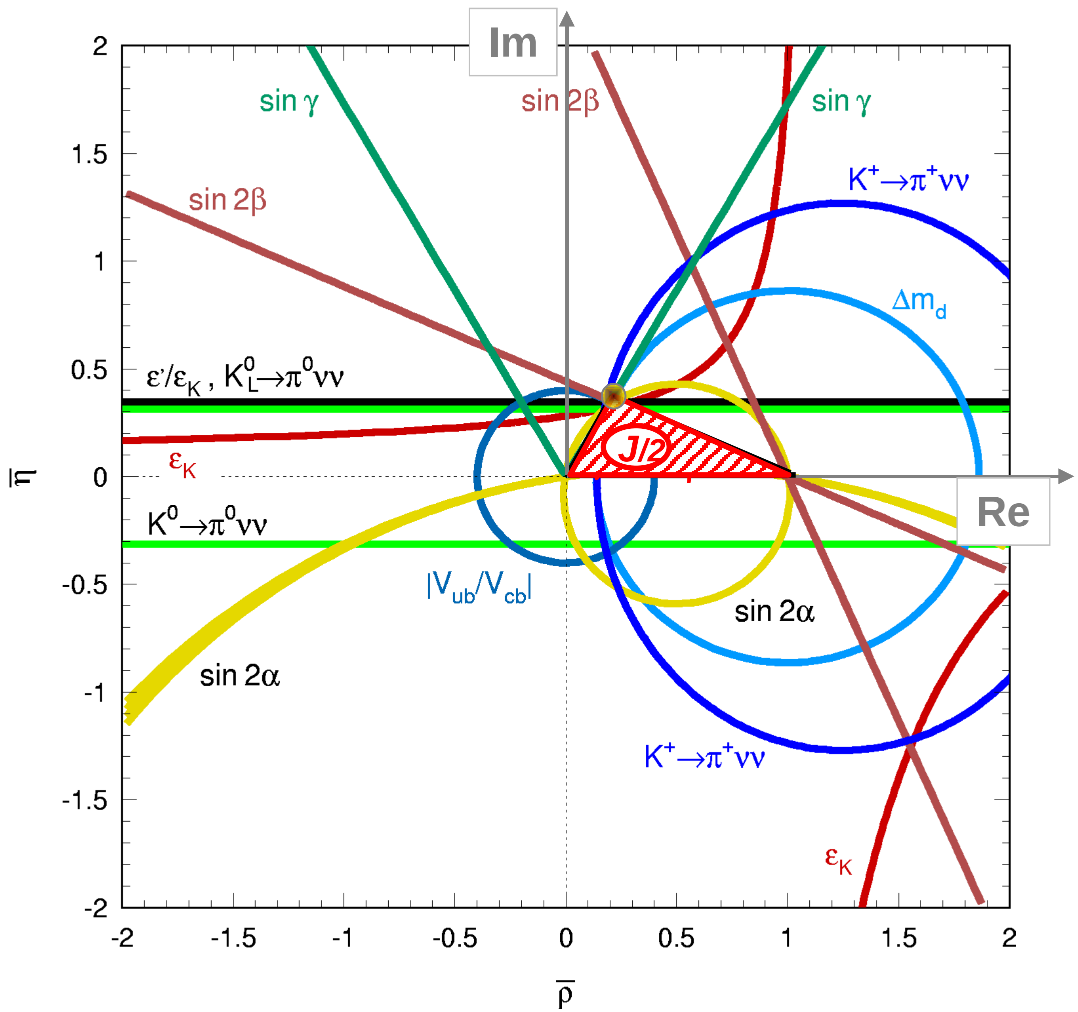


Predictive nature of KM mechanism

In the Standard Model the KM phase is the sole origin of CP violation

Hence:
all measurements must agree on the position of the apex of the Unitarity Triangle

(Illustration shown assumes no experimental or theoretical uncertainties)



Advantages of the B system (1)

- B meson is not too heavy
  - can be produced in e^+e^- machines

Discovery of the Υ(1S) state
- quark content $b\bar{b}$
- mass ~ 9.5 GeV

L.M.Lederman et al., 1977

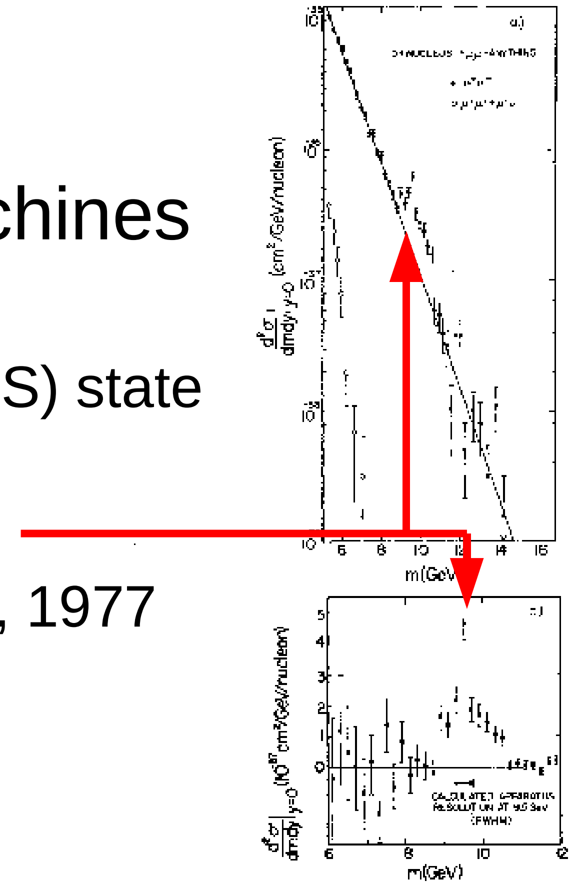


FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign-dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 8–10-GeV region in more detail.

Advantages of the B system (2)

- Surprisingly long lifetime
  - τ(B) ~ 1.5 ps
  - (related to CKM hierarchy)

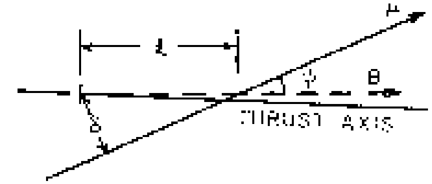


FIG. 1. Direction vectors and production and decay points relevant to heavy-hadron leptonic decay.

1023

MAC experiment (1983)

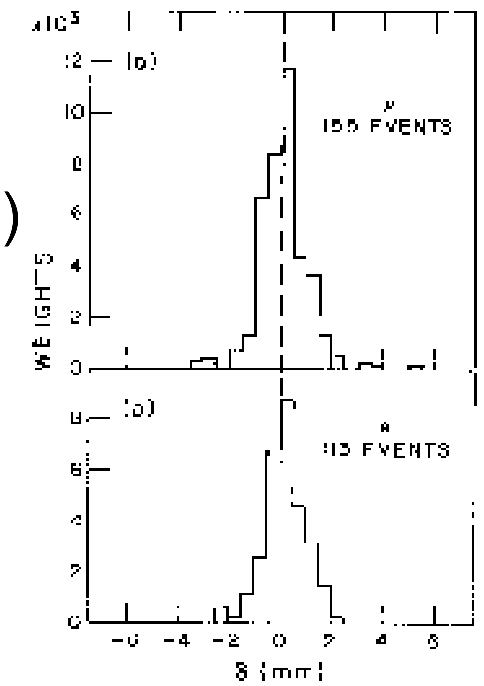
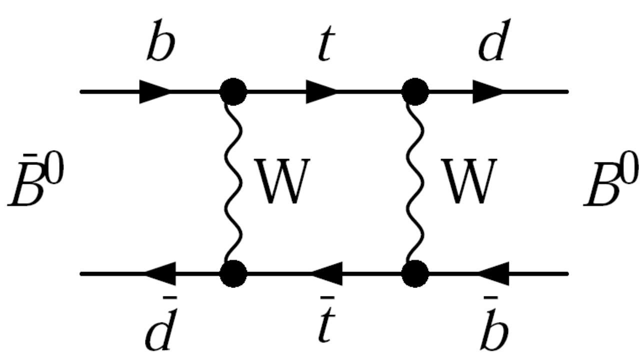


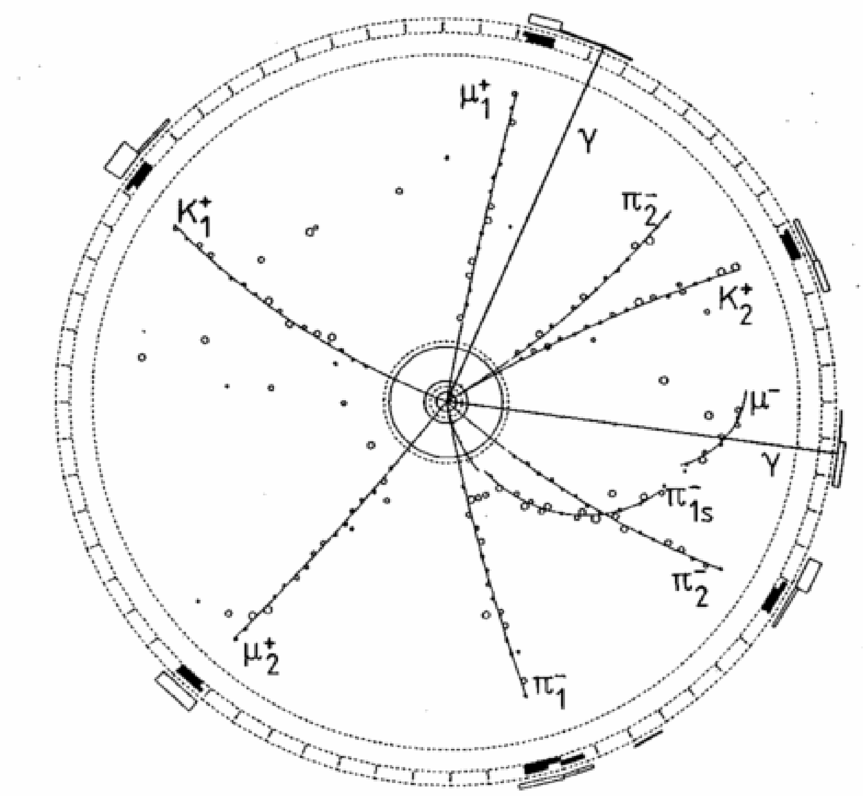
FIG. 3. Distribution of δ for (a) muons and (b) electrons.

Advantages of the B system (3)

- Top quark is very heavy
  - high probability for B mixing

P(mix)/(P(mix)+P(unmix)) = $\chi_d \sim 0.2$





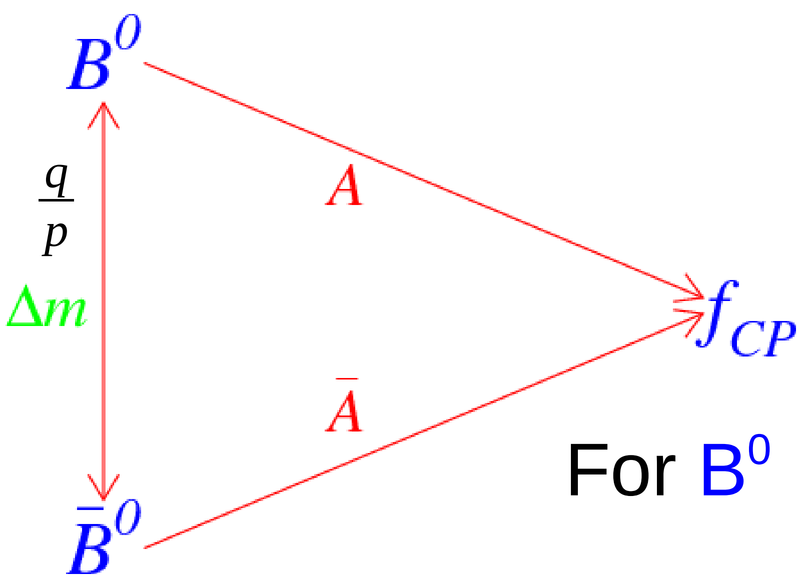
ARGUS experiment (1987)

Time-Dependent CP Violation in the B^0–$\bar{B}^0$ System

- For a B meson known to be 1) B^0 or 2) $\bar{B}^0$ at time t=0, then at later time t:

$$\Gamma\left(B^0_{phys} \rightarrow f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1 - \left(S \sin(\Delta m t) - C \cos(\Delta m t)\right)\right)$$

$$\Gamma\left(\bar{B}^0_{phys} \rightarrow f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1 + \left(S \sin(\Delta m t) - C \cos(\Delta m t)\right)\right)$$



$$S = \frac{2\,\Im(\lambda_{CP})}{1 + |\lambda_{CP}^2|} \qquad C = \frac{1 - |\lambda_{CP}^2|}{1 + |\lambda_{CP}^2|}$$

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$$

For $B^0 \rightarrow J/\psi\, K_S$, $S = \sin(2\beta)$, $C=0$

Bigi & Sanda (1984)

Asymmetric B factory principle

To measure t require B meson to be moving

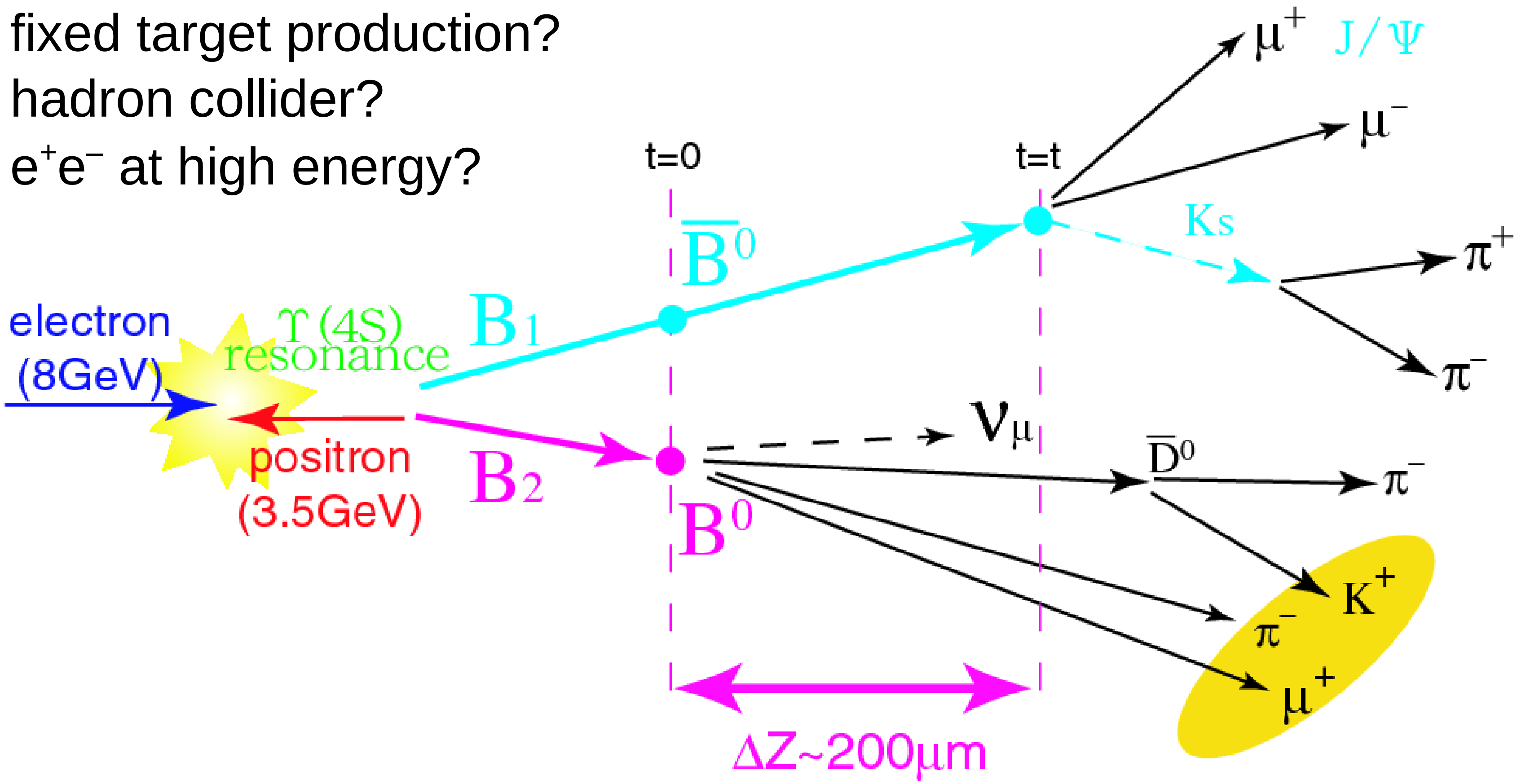
→ e^+e^- at threshold with asymmetric collisions (Oddone)

Other possibilities considered

→ fixed target production?

→ hadron collider?

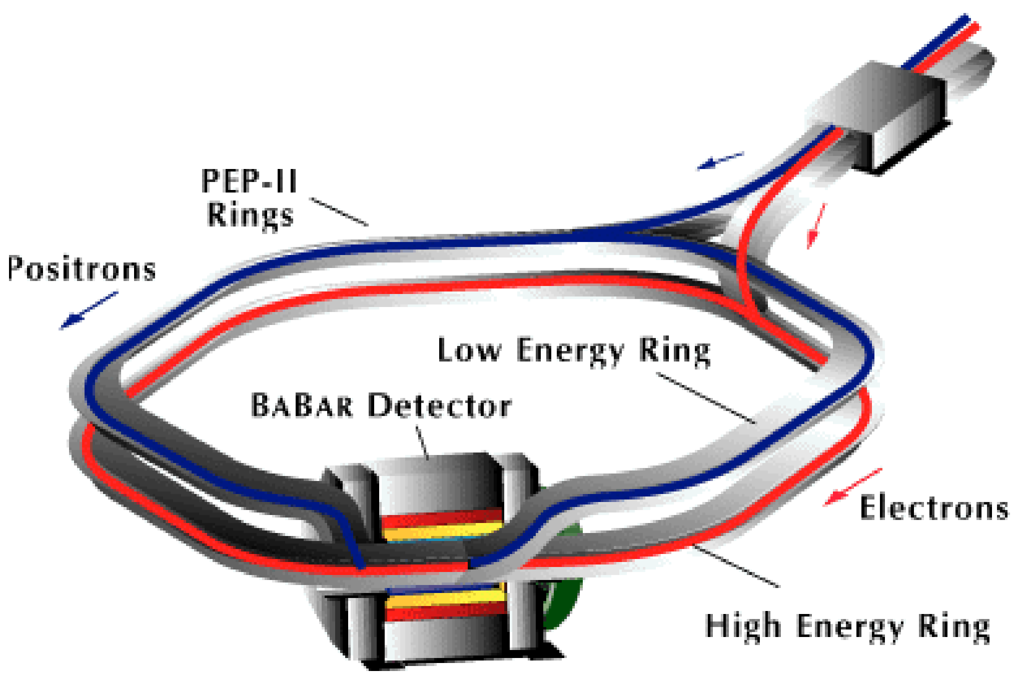
→ e^+e^- at high energy?

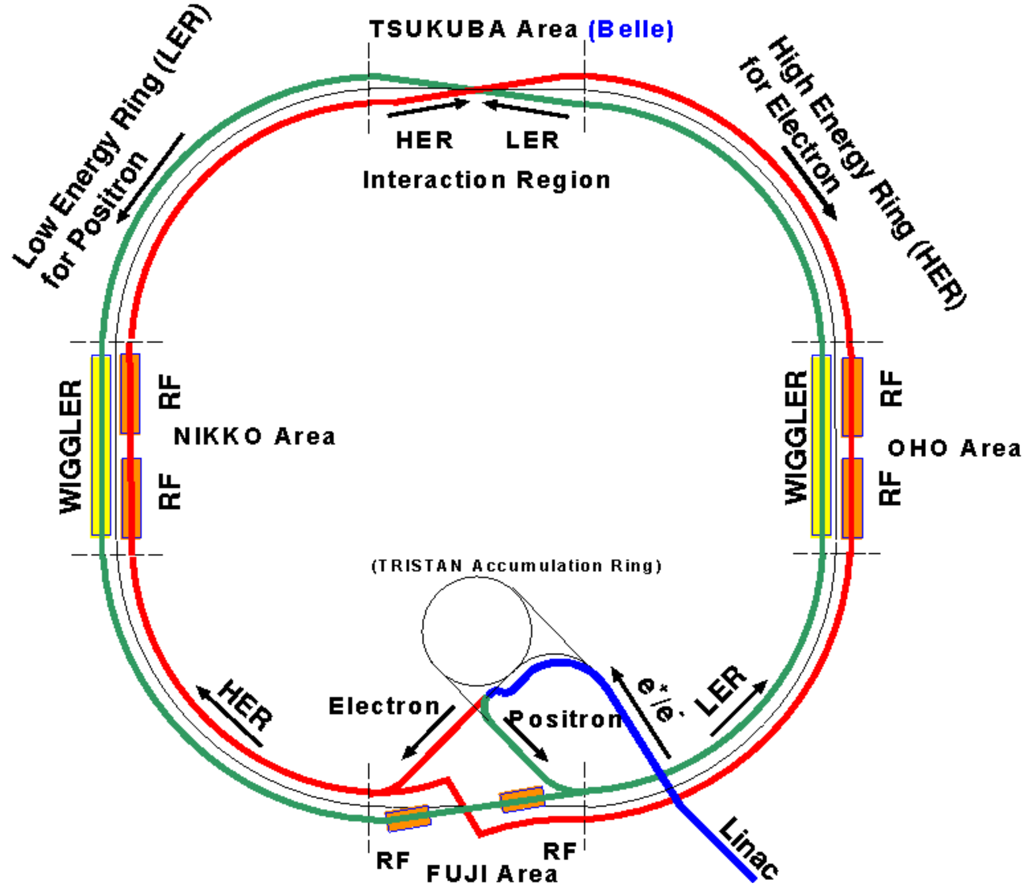


Asymmetric B Factories

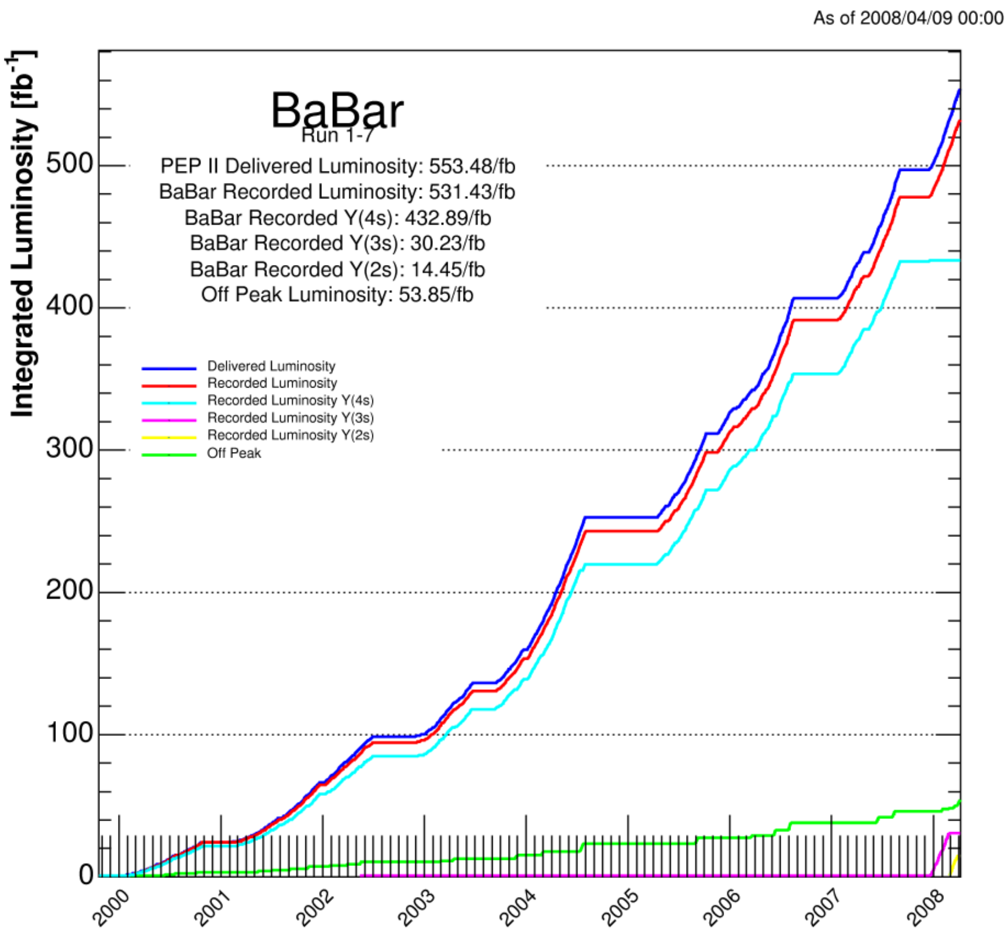
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

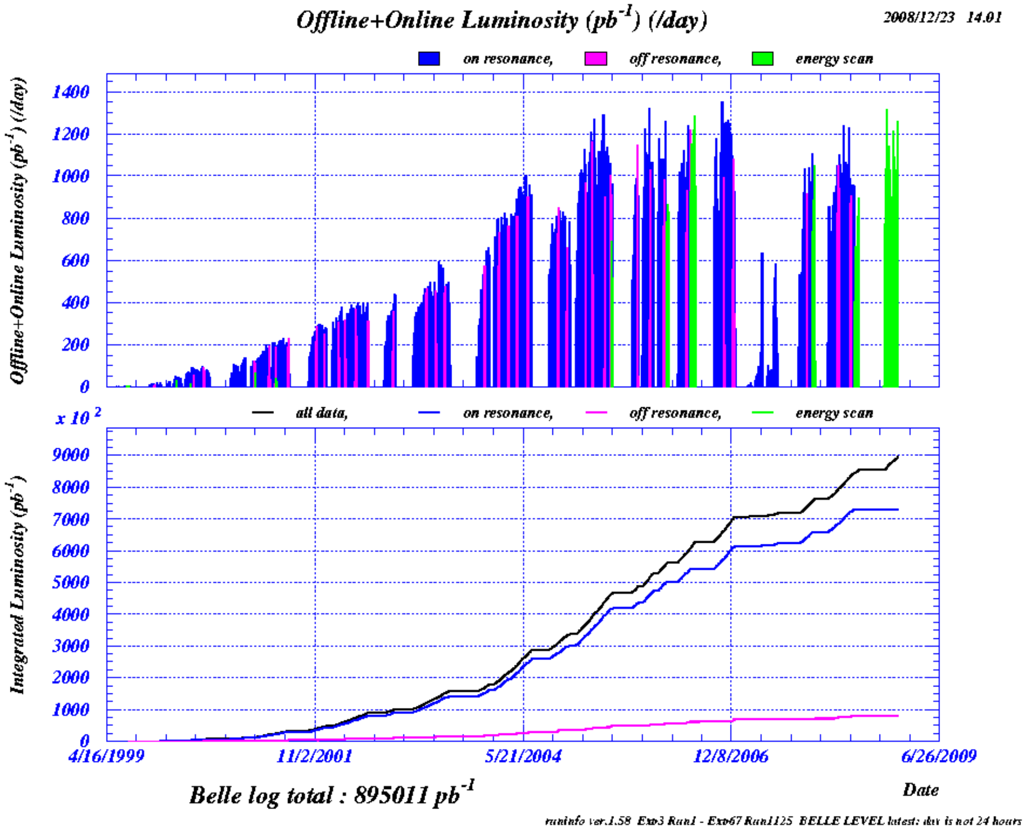
KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+





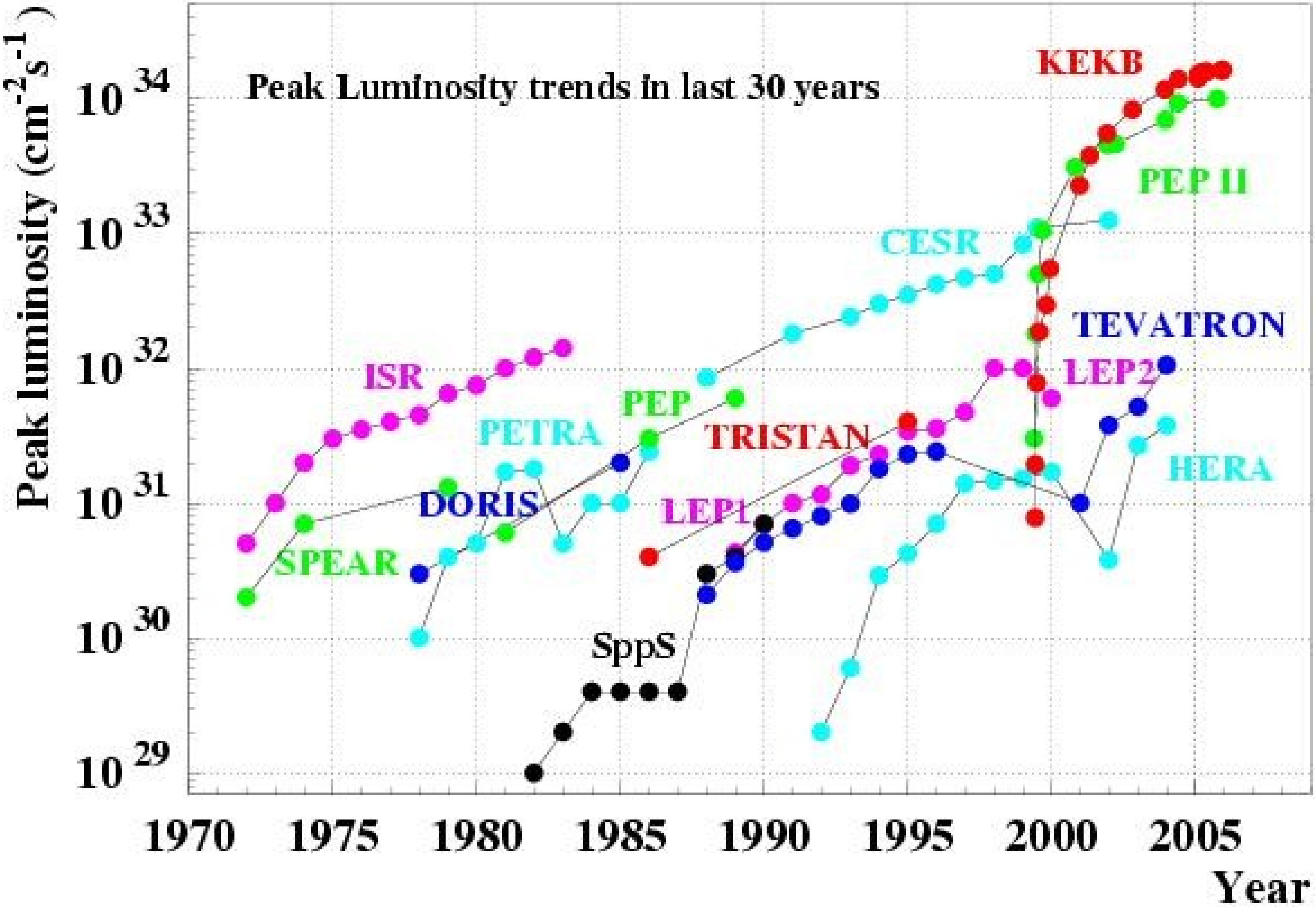
B factories – world record luminosities



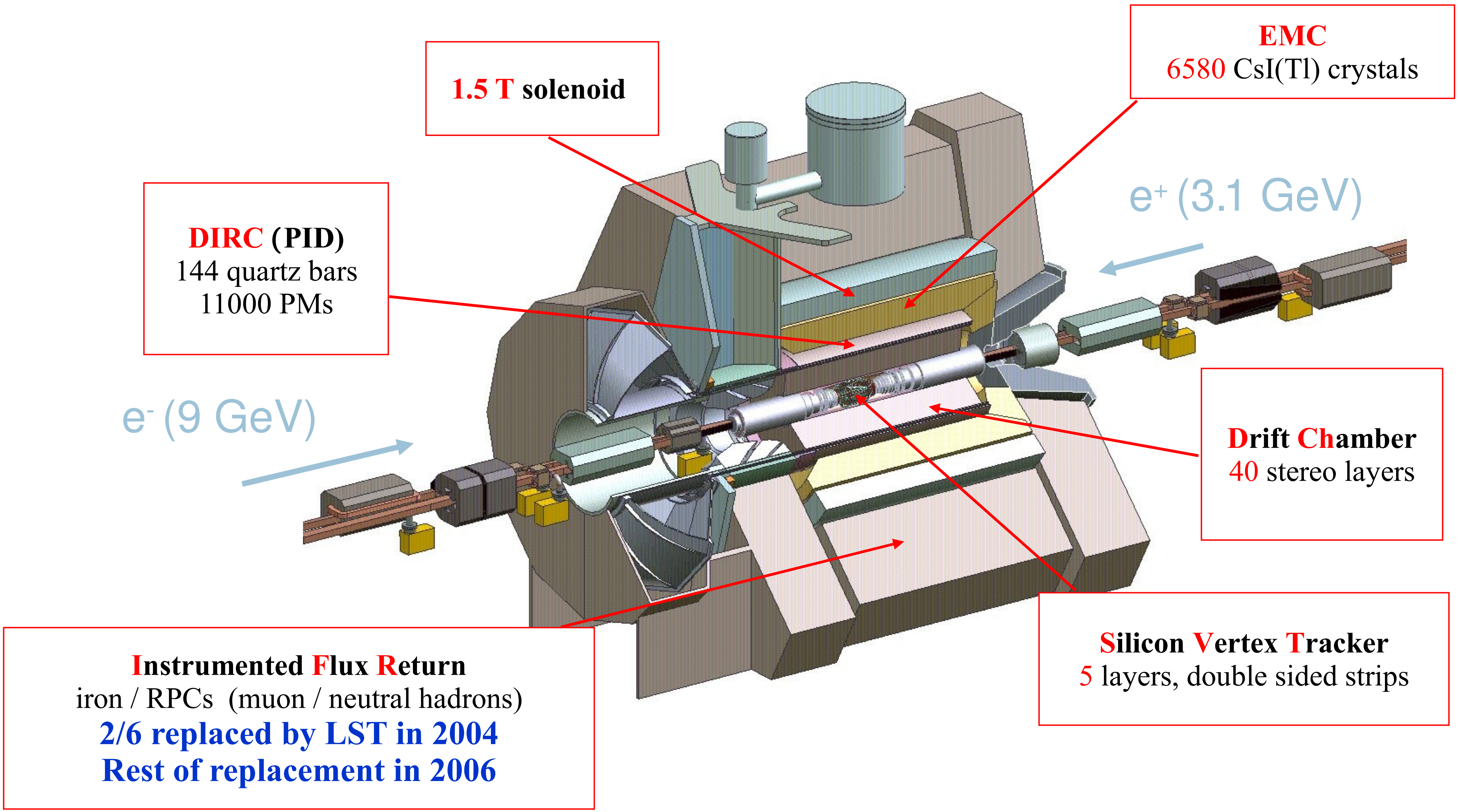


~ 433/fb on Y(4S) **~ 725/fb on Y(4S)**

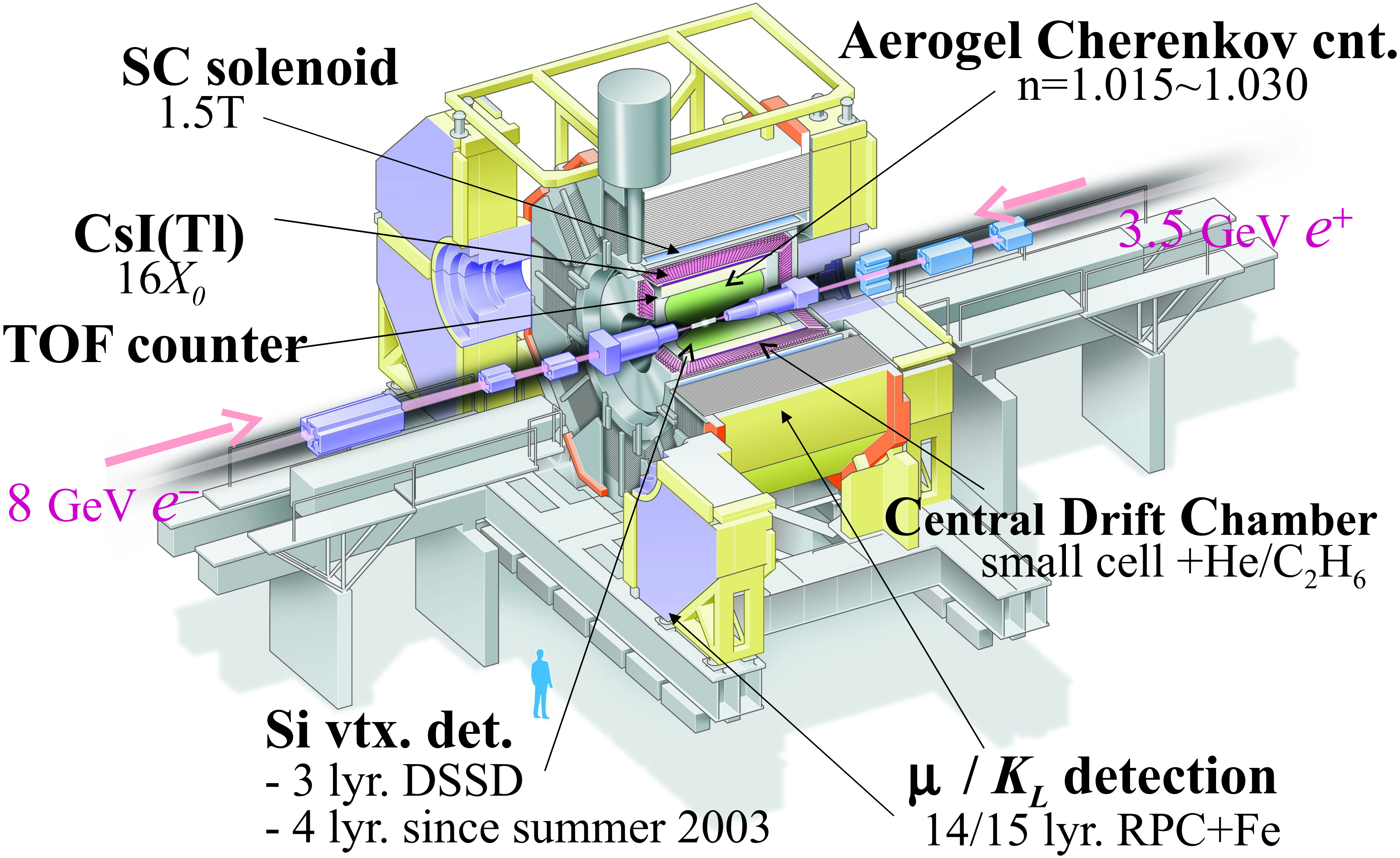
World record luminosities (2)



BaBar Detector



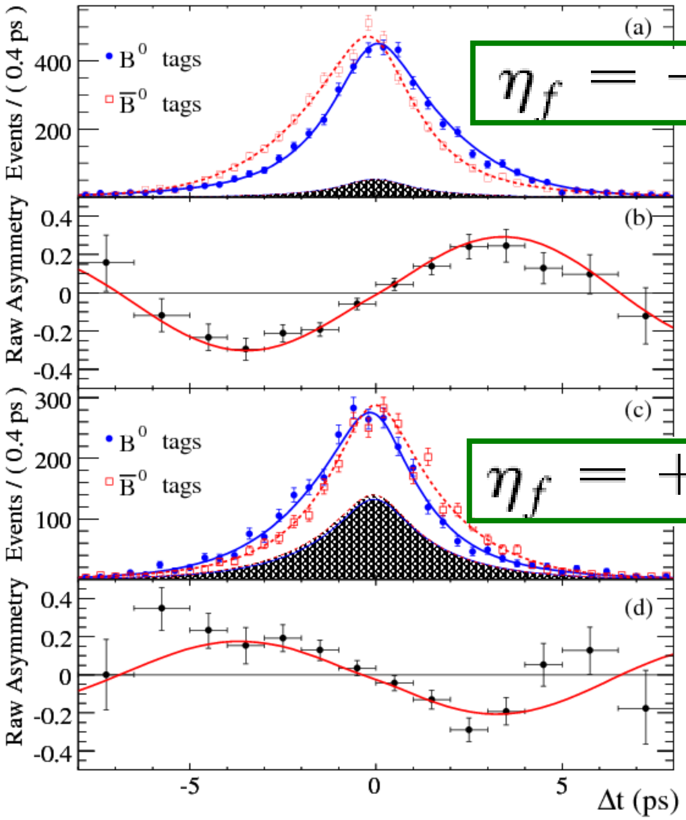
Belle Detector

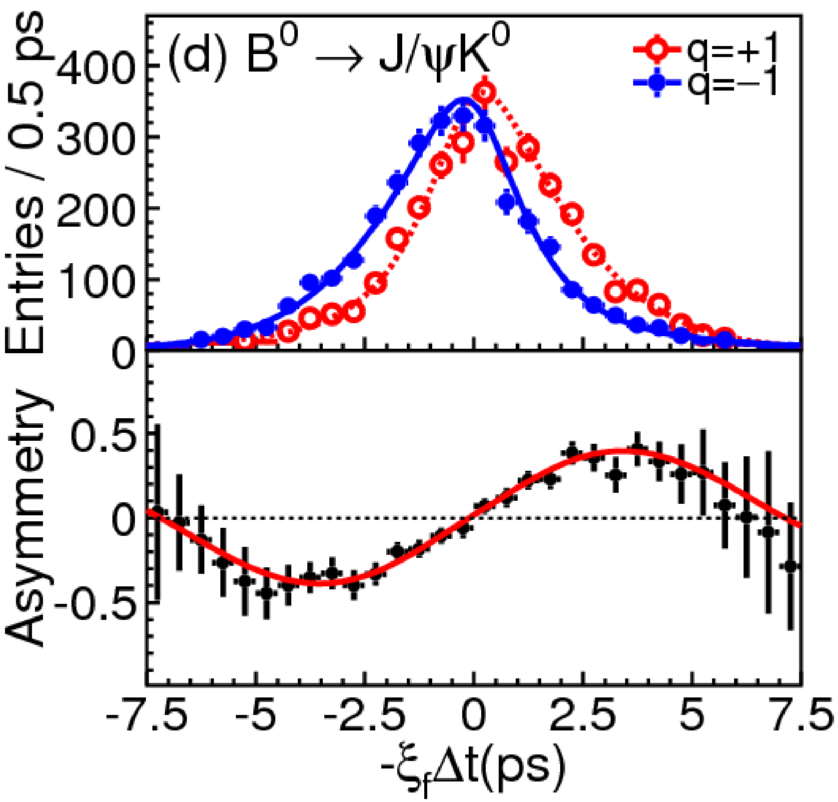


Results for the golden mode

$$B^0 \to J/\psi K^0$$

BABAR **BELLE**

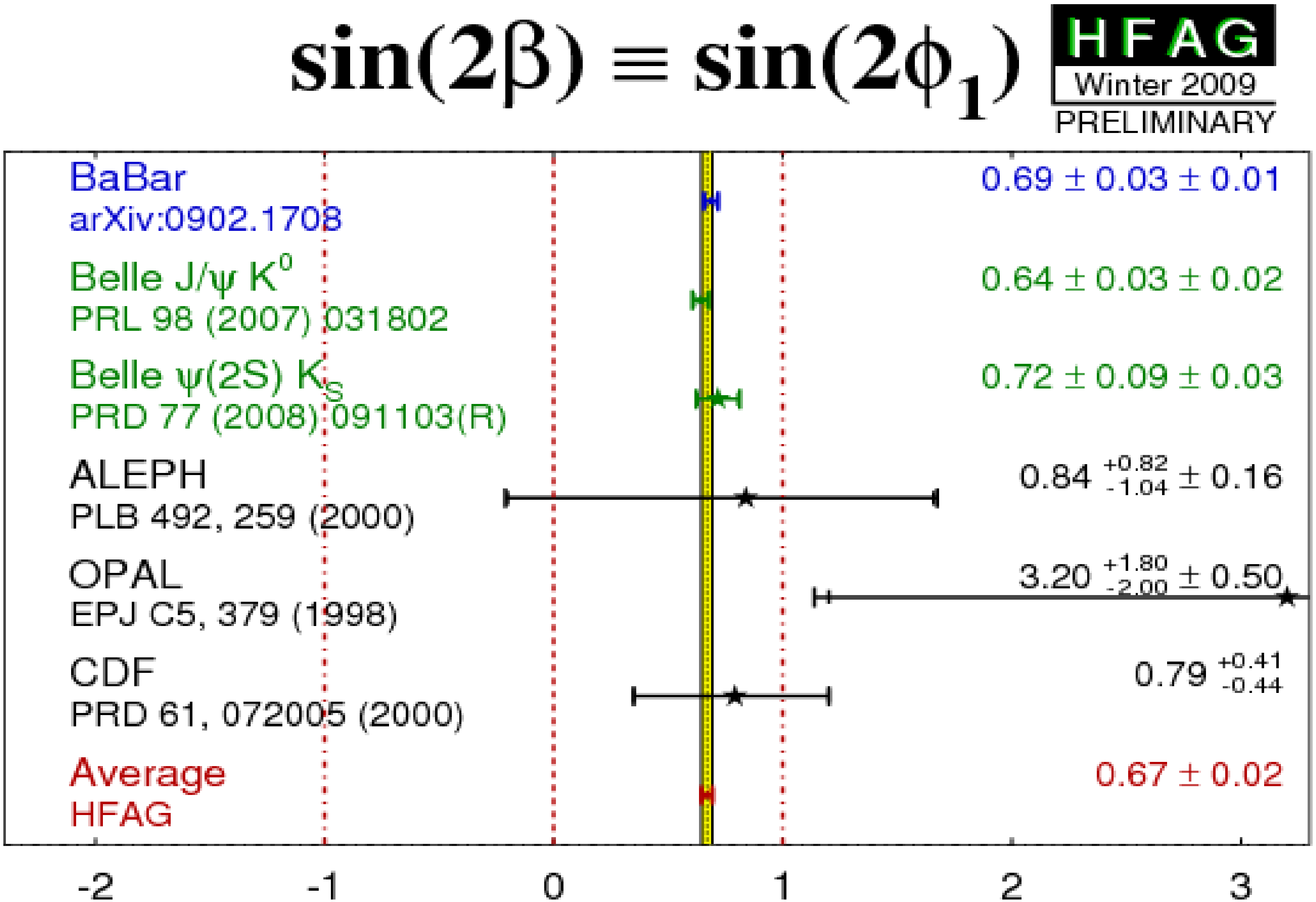




arXiv:0902.1708 (to appear in PRD)

PRL 98 (2007) 031802

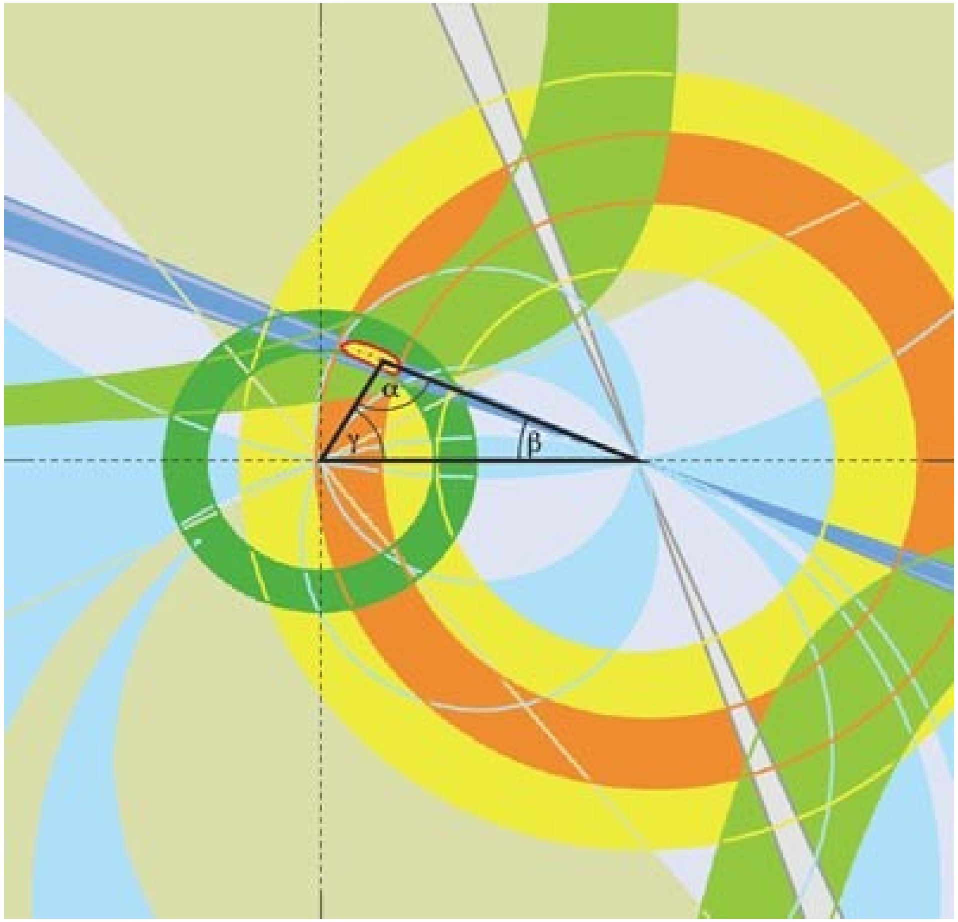
Compilation of results



The Nobel Prize in Physics 2008
Kobayashi & Maskawa

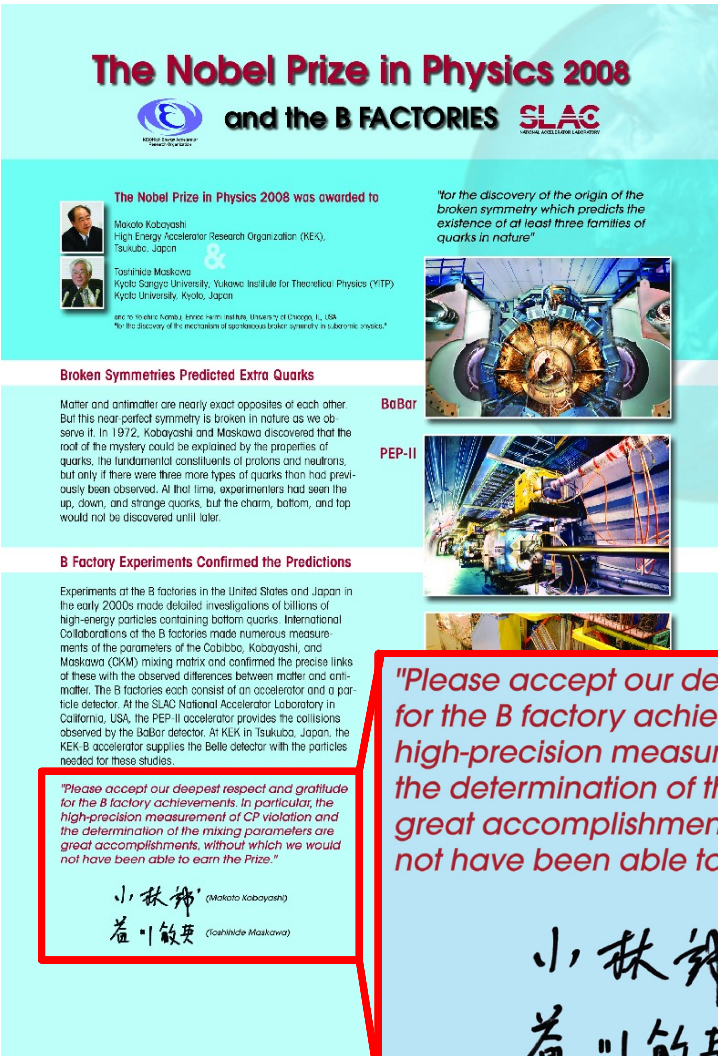
"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

"It is only in recent years that scientists have come to fully confirm the explanations that Kobayashi and Maskawa made in 1972. ... As late as 2001, the two particle detectors BaBar at Stanford, USA and Belle at Tsukuba, Japan, both detected broken symmetries ..."



(the other half of the prize went to Nambu for spontaneous symmetry breaking)

Celebrations at the B factories



The Nobel Prize in Physics 2008
and the B FACTORIES

The Nobel Prize in Physics 2008 was awarded to

Makoto Kobayashi
High Energy Accelerator Research Organization (KEK),
Tsukuba, Japan

&

Toshihide Maskawa
Kyoto Sangyo University; Yukawa Institute for Theoretical Physics (YITP)
Kyoto University, Kyoto, Japan

and to Yoichiro Nambu, Enrico Fermi Institute, University of Chicago, IL, USA
"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics."

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

BaBar

PEP-II

Broken Symmetries Predicted Extra Quarks

Matter and antimatter are nearly exact opposites of each other. But this near-perfect symmetry is broken in nature as we observe it. In 1972, Kobayashi and Maskawa discovered that the root of the mystery could be explained by the properties of quarks, the fundamental constituents of protons and neutrons, but only if there were three more types of quarks than had previously been observed. At that time, experimenters had seen the up, down, and strange quarks, but the charm, bottom, and top would not be discovered until later.

B Factory Experiments Confirmed the Predictions

Experiments at the B factories in the United States and Japan in the early 2000s made detailed investigations of billions of high-energy particles containing bottom quarks. International Collaborations at the B factories made numerous measurements of the parameters of the Cabibbo, Kobayashi, and Maskawa (CKM) mixing matrix and confirmed the precise links of these with the observed differences between matter and antimatter. The B factories each consist of an accelerator and a particle detector. At the SLAC National Accelerator Laboratory in California, USA, the PEP-II accelerator provides the collisions observed by the BaBar detector. At KEK in Tsukuba, Japan, the KEK-B accelerator supplies the Belle detector with the particles needed for these studies.

"Please accept our deepest respect and gratitude for the B factory achievements. In particular, the high-precision measurement of CP violation and the determination of the mixing parameters are great accomplishments, without which we would not have been able to earn the Prize."

小林誠 (Makoto Kobayashi)
益川敏英 (Toshihide Maskawa)

"Please accept our deepest respect and gratitude for the B factory achievements. In particular, the high-precision measurement of CP violation and the determination of the mixing parameters are great accomplishments, without which we would not have been able to earn the Prize."

小林誠 (Makoto Kobayashi)

益川敏英 (Toshihide Maskawa)

CP violation and the BAU

- We can estimate the magnitude of the baryon asymmetry of the Universe caused by KM CP violation

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

$$J = \cos(\theta_{12})\cos(\theta_{23})\cos^2(\theta_{13})\sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin(\delta)$$
$$P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)$$
$$P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

- The Jarlskog parameter J is a parametrization invariant measure of CP violation in the quark sector: J ~ $O(10^{-5})$
- The mass scale M can be taken to be the electroweak scale O(100 GeV)
- This gives an asymmetry $O(10^{-17})$
  - much much below the observed value of $O(10^{-10})$

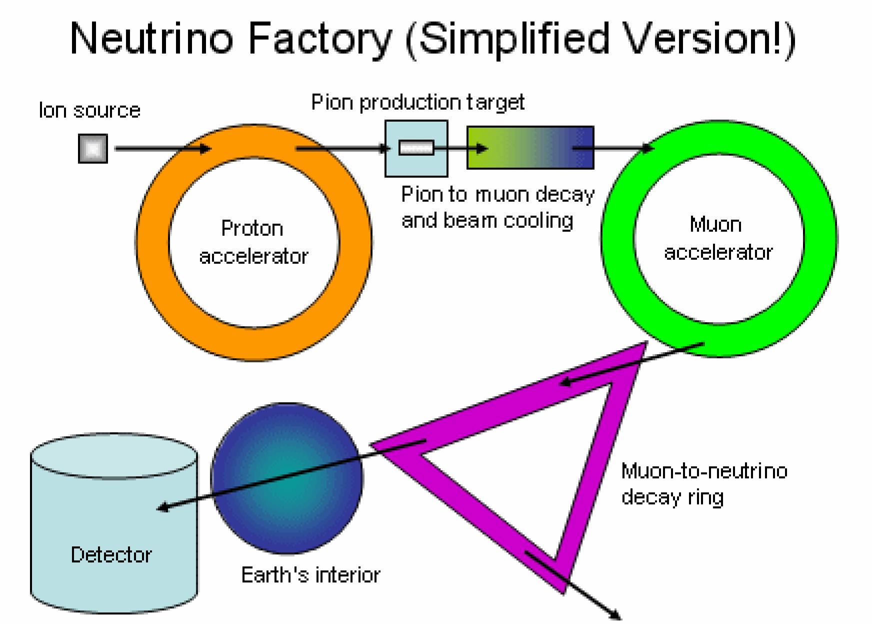
What caused the asymmetry?

- To create a larger asymmetry, require
  - new sources of CP violation
  - that occur at higher energy scales
- Where might we find it?
  - lepton sector: CP violation in neutrino oscillations
  - quark sector: discrepancies with KM predictions
  - gauge sector, extra dimensions, other new physics: precision measurements of flavour observables are generically sensitive to additions to the Standard Model

Neutrino factory

- Neutrinos have mass (as observed by Kamiokande, KAMLAND, SNO, SuperK, MINOS, etc.)
- Leptons have a mixing matrix analogous to the quarks
  - the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- It may provide an additional source of CP violation
- To measure it, need
  - mixing angle θ_{13} not too small

    (T2K, Daya Bay, Double Chooz)
  - intense source of ν and $\bar{\nu}$



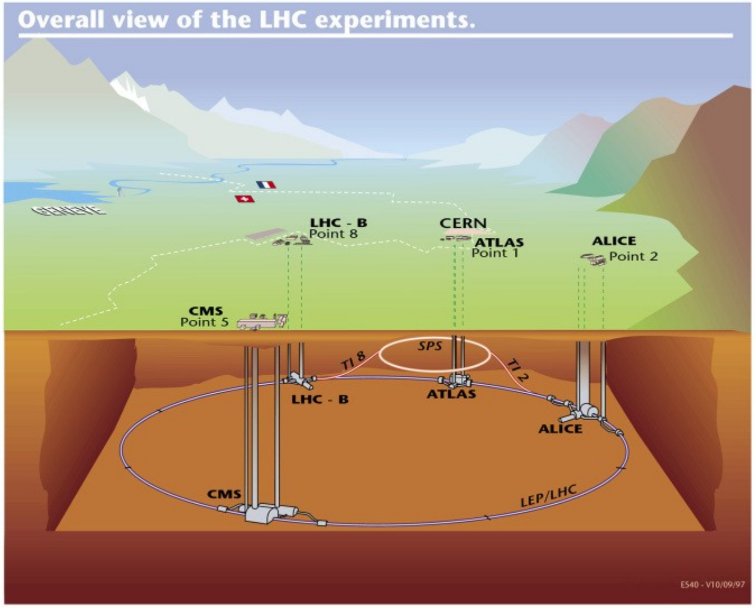
Majorana neutrinos

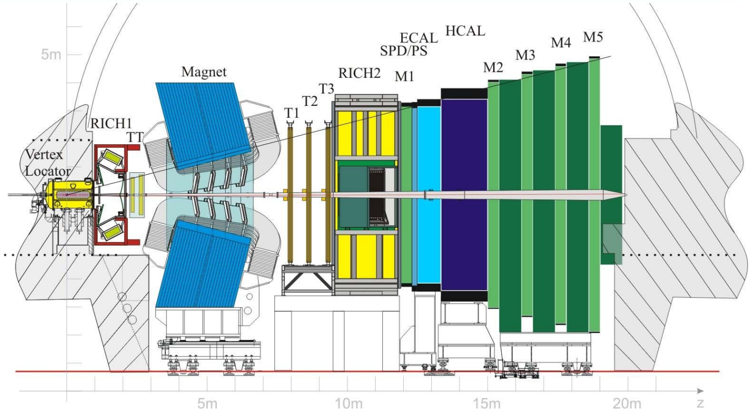
- Neutrinos carry no quantum numbers except a hypothesis lepton number
- What if there is no lepton number?
  - then the neutrino is its own antiparticle

    formalism (for fermions): Weyl, Majorana
  - distinctive experimental signature: neutrinoless double-beta decay (CUORE, EXO, MAJORANA, GERDA, COBRA, SuperNEMO)
  - sensitive to high-energy scale via seesaw mechanism
  - makes leptogenesis theoretically attractive

The LHCb experiment

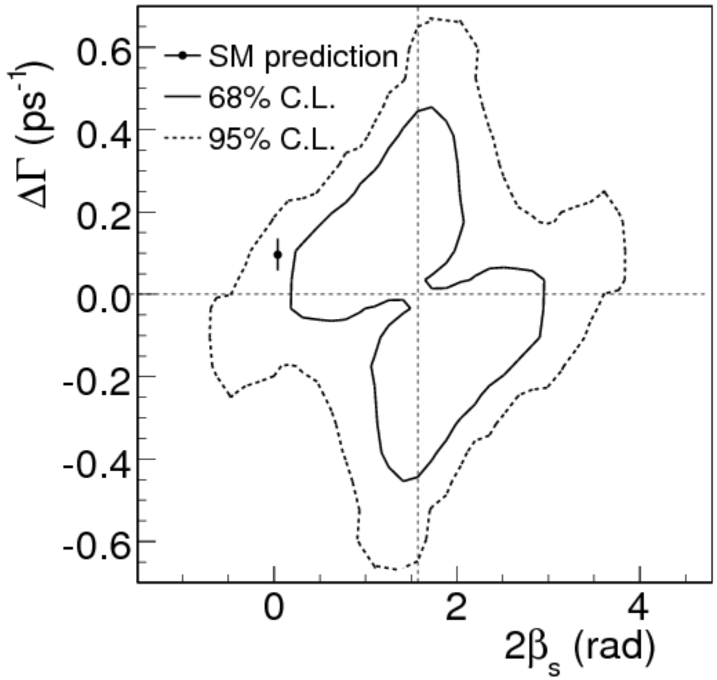
- By now $s \to d$ and $b \to d$ transitions quite well studied
- Far less experimental knowledge of the $b \to s$ transition
- LHCb experiment: utilize LHC massive production rate of b quarks and study
  - B_s oscillations
  - $B_s \to \mu^+\mu^-$
  - $B \to K^*\mu^+\mu^-$
  - and many other things ...



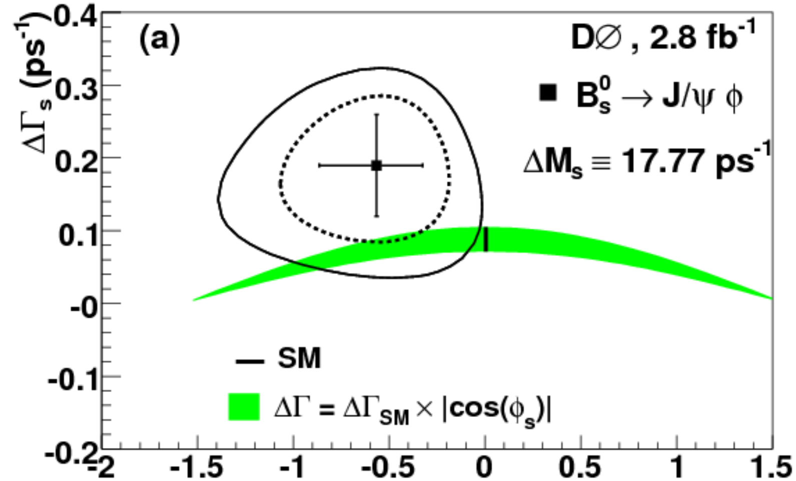


A Taste of Things to Come?

CDF

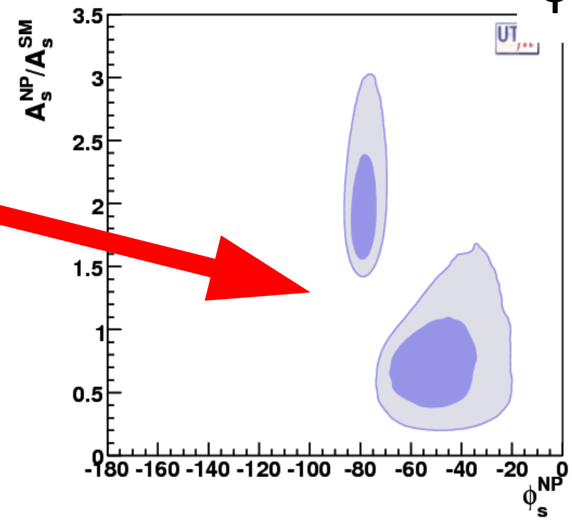


D0



$\varphi_s = -2\beta_s$

Putting it together
(UTfit arXiv:0803.0659 [hep-ph])



$$C_{B_s} e^{2i\phi_{B_s}} = \frac{A_s^{\rm SM} e^{-2i\beta_s} + A_s^{\rm NP} e^{2i(\phi_s^{\rm NP}-\beta_s)}}{A_s^{\rm SM} e^{-2i\beta_s}} = \frac{\langle B_s|H_{\rm eff}^{\rm full}|\bar{B}_s\rangle}{\langle B_s|H_{\rm eff}^{\rm SM}|\bar{B}_s\rangle},$$

Future flavour physics

The field of flavour physics and CP violation is booming, with many new planned experiments

- Lepton flavour violation
  - MEG, COMET, PRISM/PRIME, SuperBelle, SuperB
- Rare kaon decays
  - $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at CERN, $K^0 \rightarrow \pi^0 \nu\bar{\nu}$ at JPARC
- Charm physics
  - BESIII, SuperBelle, SuperB, LHCb & LHCb upgrade
- B physics
  - SuperBelle, SuperB, LHCb & LHCb upgrade

and ... LHC results might dramatically change the field

Summary

- The field of CP violation has developed rapidly since its unexpected discovery in 1964
- The Kobayashi-Maskawa theory explains all results to date
- There must be more CP violation out there

and we must keep looking for it!

The need for more precision

- “Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed”

  – A.Soni

- “A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky.”

  – L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

Further reading

- If you liked this, you'll love ...