Heavy flavour physics I

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MISP

Outline of the lectures

- Introduction to the CKM formalism and objectives
- Historical perspective
- LHCb: a flavour-physics detector at the LHC
- Selected *B*-physics results
- Future prospects

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Introduction

Why flavour physics?

- Some fundamental questions in flavour physics
  - Why three generations?
  - What's the origin of the mass hierarchy?
  - What's the origin of the coupling structure?
  - What's the origin of the baryon asymmetry of the universe?
- You have already heard about the leptonic sector in Carlo Giunti's lectures → focussing now on the quark sector

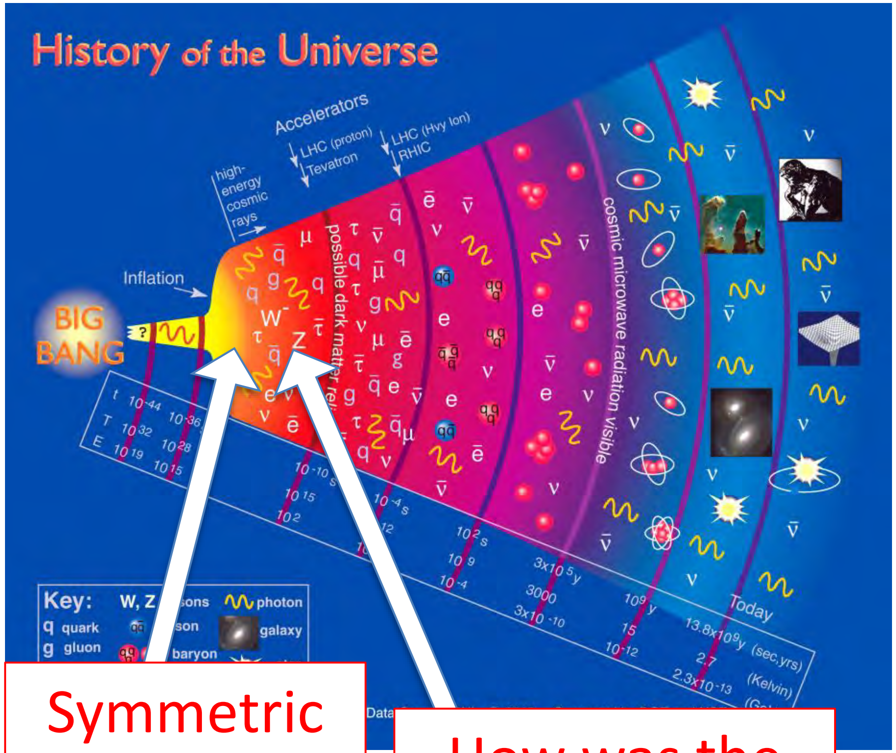
Ipse dixit

> “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.”

- Excerpt of Dirac’s Nobel lecture in 1933
- At the time we were starting to wonder where had antimatter gone...

Matter-dominated universe

- Nowadays we know that there's no evidence of primary antimatter on the scale of the observable universe
- What led to the disappearance of antimatter assuming an initial symmetric state?
- How big the asymmetry should have been?



Symmetric initial state

How was the symmetry broken?

Mainstream explanation

- Antimatter and matter particles annihilated massively in the early universe, but a tiny fraction of matter was left over: every 10 billion particles, a handful was not annihilated away
- The radiation produced by this gigantic initial annihilation is what we see today as the big bang afterglow: the cosmic microwave background

Sakharov conditions

- In 1967 Sakharov enumerated the three conditions which are necessary for the dynamical evolution of an initially symmetric to a matter-dominated universe
  1. Baryon number should not be conserved
     - Otherwise there's no way to produce an excess of baryons
  2. Charge (C) and Charge-Parity (CP) should not be conserved
     - Interactions which produce more baryons should not be counterbalanced by interactions which produce more anti-baryons
  3. Interactions must be out of thermal equilibrium
     - Otherwise the baryonic asymmetry is diluted by inverse processes
- In a few words: the universe is asymmetric because the baryon number is not conserved in C- and CP-violating processes giving rise to more baryons than antibaryons in the expanding universe

Can we explain the asymmetry by known physics?

- Qualitatively: yes
  - The Standard model in principle contains all the necessary ingredients
- It is possible to derive the ratio of the number of baryons to that of photons in the universe

$$\eta = \frac{n_B}{n_\gamma} \sim \frac{(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)\, J}{M^{12}}$$

where $J \approx 3\times10^{-5}$ is the Jarlskog invariant* quantifying the size of CP violation in the Standard Model and M≈100 GeV is the electroweak scale at which the baryon asymmetry freezes out

* defined later

Can we explain the asymmetry by known physics?

- Quantitatively: no
- The previous equation gives $\eta \approx 10^{-19}$, whereas using Planck experimental data on cosmic microwave background one gets

$$\eta = (6.04 \pm 0.08) \times 10^{-10}$$

- This is off by 10 orders of magnitude!
- CP violation in the Standard Model is too small → strong indication that new sources of CP violation should exist in some beyond-the-SM physics

The (CKM) Matrix

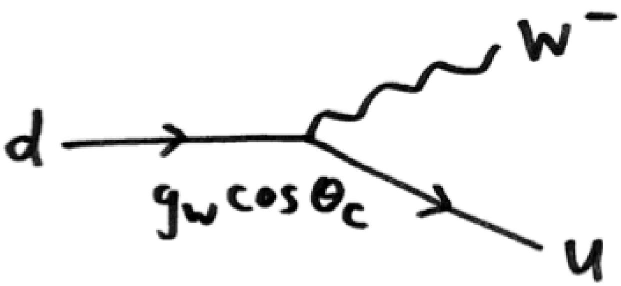
The (CKM) Matrix

PHYSICAL REVIEW LETTERS VOLUME 10, NUMBER 12 15 JUNE 1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

- Strangeness-conserving decays have weak coupling constant proportional to the cosine of the Cabibbo angle θ_c
- Strangeness-violating decays have weak coupling constant proportional to the sine of θ_c



The (CKM) Matrix

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

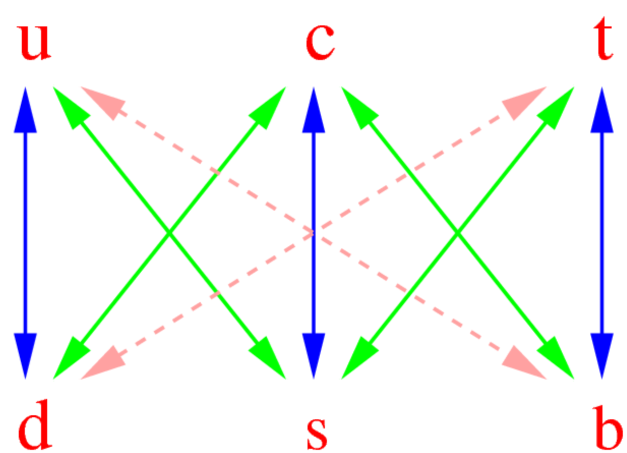
CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

- Generalization to 6 quarks by Kobayashi and Maskawa
- *CP* violation can be introduced in a natural way if there are 6 quarks, with a 3x3 complex matrix accounting for the couplings



The (CKM) Matrix

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Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

2008: Nobel prize in physics

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

Source of CP violation in the SM

- Quark masses arise from the Yukawa couplings to the Higgs field
- The CKM matrix arises from the misalignment of the Yukawa matrices for the up- and down-type quarks

$$V_{CKM} = U_u U_d^+ \qquad \mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}}\overline{U_{Li}}\gamma^\mu \left(V_{\rm CKM}\right)_{ij} D_{Lj} W_\mu^+ + h.c.$$

- 3x3 complex unitary matrix
  - After reabsorbing phase differences between the quark fields, only four real parameters remain
  - Of these four, three can be expressed as Euler mixing angles (θ_{ij}) and the last one makes the CKM matrix complex by giving it a phase (δ)

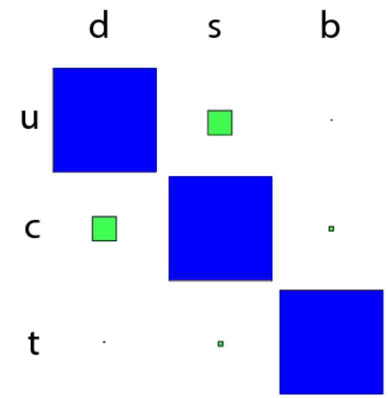
$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\boxed{s_{ij} = \sin\theta_{ij}} \quad \boxed{c_{ij} = \cos\theta_{ij}} \quad \boxed{\delta}$$

- Owing to this complex phase, weak-interaction couplings differ between quarks and antiquarks → CP violation

Features of the CKM matrix

$$V_{\mathrm{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



http://www.utfit.org

$$V_{CKM} = \begin{pmatrix} (0.97431 \pm 0.00012) & (0.22514 \pm 0.00055) & (0.00365 \pm 0.00010)e^{i(-66.8\pm2.0)^\circ} \\ (-0.22500 \pm 0.00054)e^{i(0.0351\pm0.0010)^\circ} & (0.97344 \pm 0.00012)e^{i(-0.001880\pm0.000052)^\circ} & (0.04241 \pm 0.00065) \\ (0.00869 \pm 0.00014)e^{i(-22.23\pm0.63)^\circ} & (-0.04124 \pm 0.00056)e^{i(1.056\pm0.032)^\circ} & (0.999112 \pm 0.000024) \end{pmatrix}$$

- The CKM matrix exhibits a strong hierarchical pattern

$$s_{13} \ll s_{23} \ll s_{12} \ll 1$$

- It is highly predictive as several phenomena depend only on four independent parameters
- It provides the only source of CP violation in the Standard Model (barring the strong CP problem)

Wolfenstein parameterization of the CKM matrix

- The hierarchy of the CKM matrix elements can be conveniently made explicit by adopting a suitable parameterization originally due to Wolfenstein
- This is obtained by defining

$$s_{12} = \lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}} \qquad s_{23} = A\lambda^2 = \lambda \left| \frac{V_{cb}}{V_{us}} \right|$$

$$s_{13} e^{i\delta} = V_{ub}^* = A\lambda^3(\rho + i\eta)$$

- Using these, the CKM matrix can be recasted in terms of the four real parameters A, λ, ρ and η

Wolfenstein parameterization of the CKM matrix

- Up to order λ^4, it turns out that

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- As experimentally one has $\lambda \approx 0.22$, the hierarchy is clearly made visible

Unitarity triangle

- As we said, the CKM matrix is unitary, i.e. $V_{\text{CKM}}^{\dagger} \cdot V_{\text{CKM}} = \hat{1}$
  or in terms of matrix elements

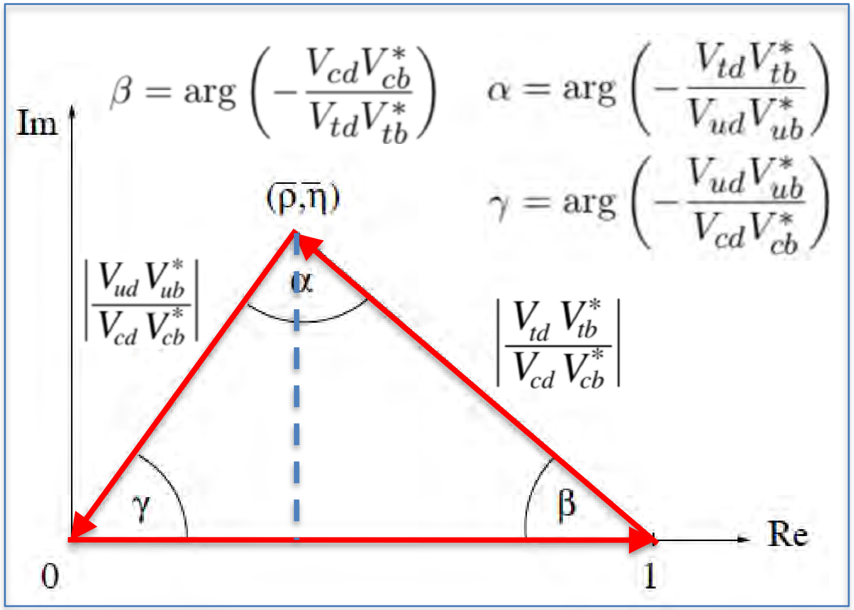
$$\sum_i V_{ij} V_{ik}^* = \delta_{jk} \qquad \sum_j V_{ij} V_{kj}^* = \delta_{ik}$$

- Amongst these, there are six vanishing combinations that can be represented as triangles in a complex plane, all with the same area equal to half of the Jarlskog invariant (J), defined by

$$\mathrm{Im}[V_{ij} V_{kl} V_{il}^* V_{kj}^*] = J \sum_{m,n} \varepsilon_{ikm} \varepsilon_{jln} \qquad J = c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \delta_{CKM} \approx \lambda^6 A^2 \eta$$

- One of these triangles arises from $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$
- By normalizing each side to $V_{cd} V_{cb}^*$ the triangle has apex at coordinates

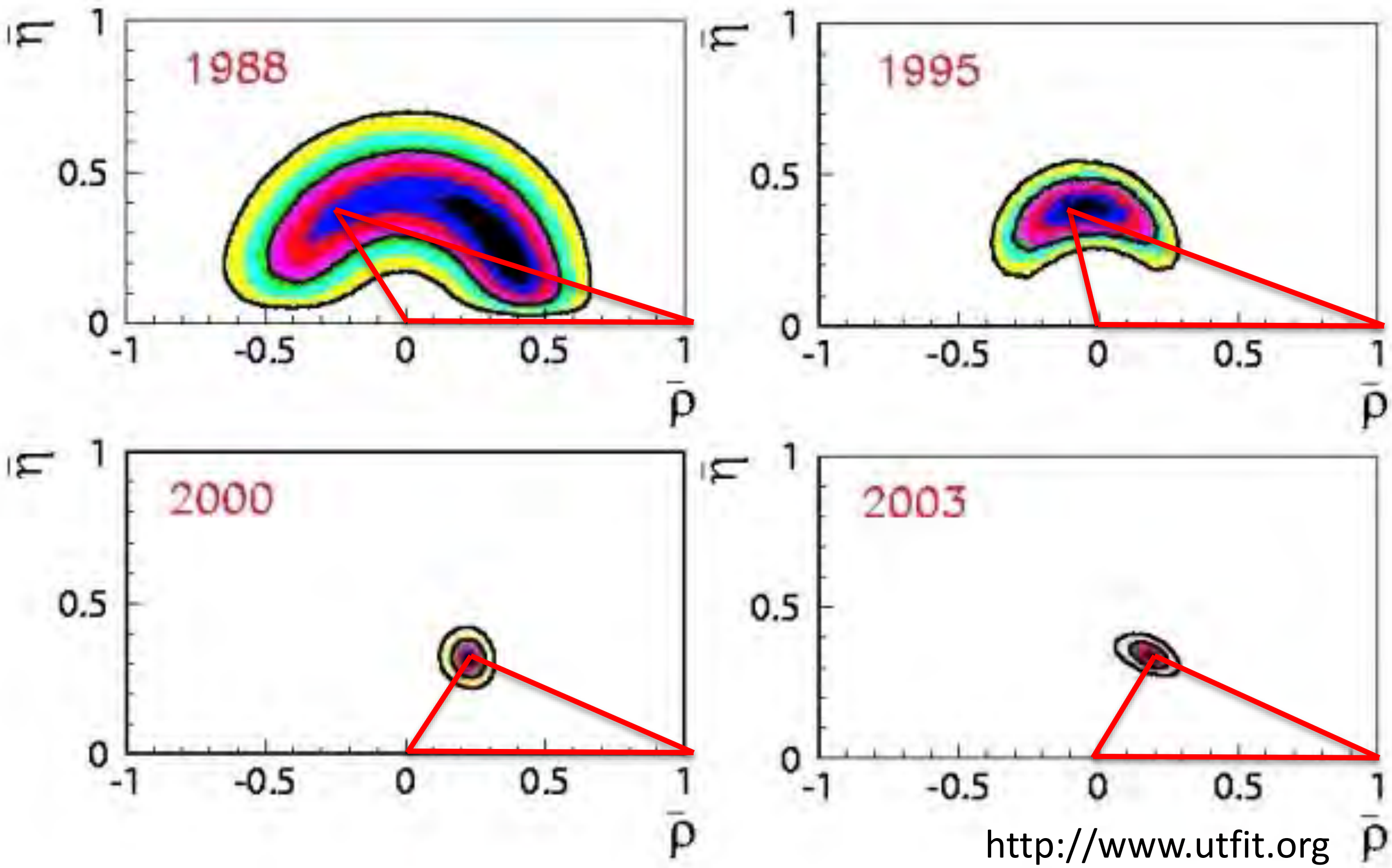
$$\bar{\rho} \equiv \rho \left(1 - \frac{1}{2}\lambda^2\right) \qquad \bar{\eta} \equiv \eta \left(1 - \frac{1}{2}\lambda^2\right)$$



- This is called "unitarity triangle"

Unitarity triangle

- Overconstraining the CKM elements is amongst the major goals of flavour physics → many measurements can be conveniently displayed and their mutual agreement compared in the $(\bar{\rho}, \bar{\eta})$ plane
- Huge experimental improvements over last decades



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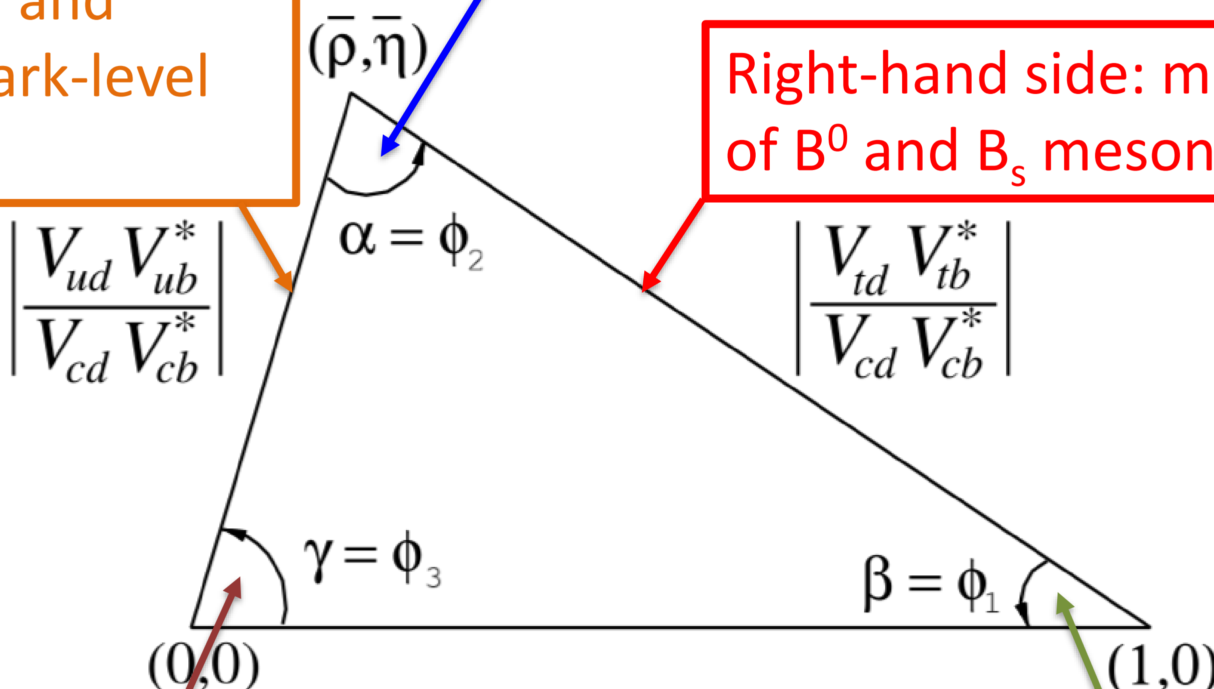
Measuring the unitarity triangle

Left-hand side: rates of decays mediated by $b \rightarrow ul\nu$ and $b \rightarrow cl\nu$ quark-level processes

Angle α: decay rates and CP violation in $B \rightarrow \pi\pi$, $B \rightarrow \rho\pi$, $B \rightarrow \rho\rho$ decays

Right-hand side: mixing rate of B^0 and B_s mesons

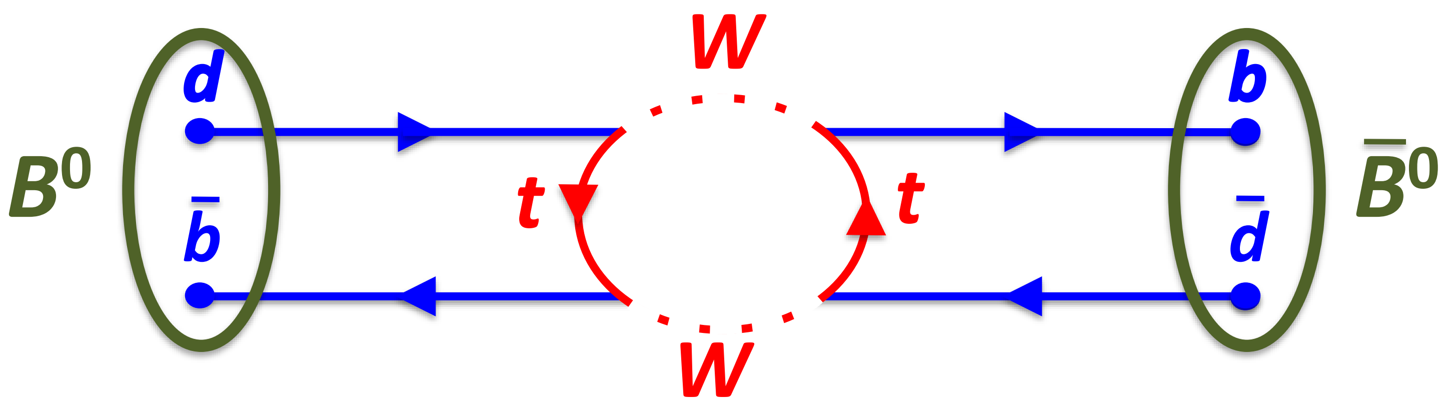


Angle γ: CP violation in $B \rightarrow DK$, $B \rightarrow D\pi$ decays

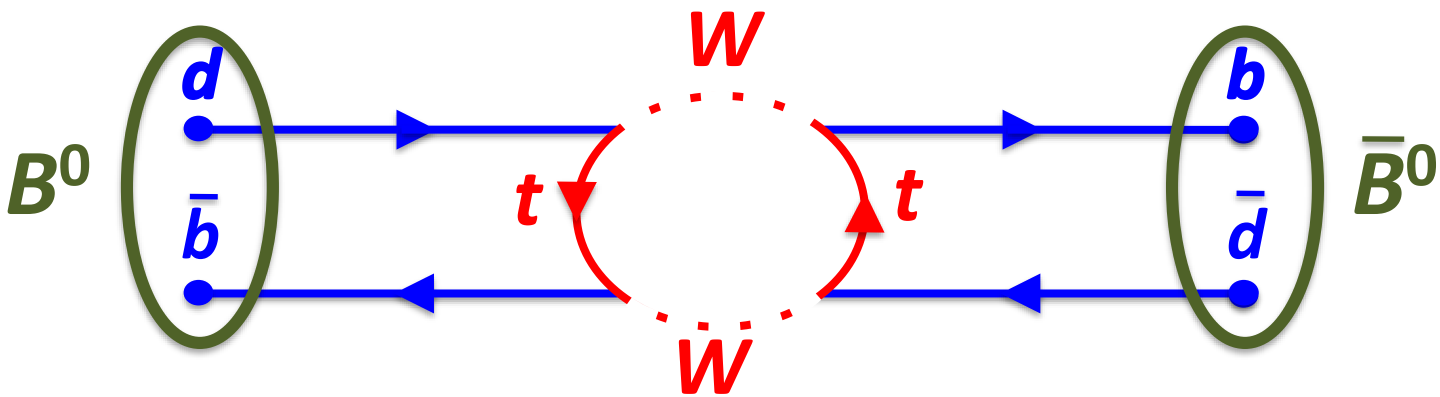
Angle β: CP violation in $B \rightarrow c\bar{c}K_S$, $B \rightarrow c\bar{c}K_L$ decays

A concrete example

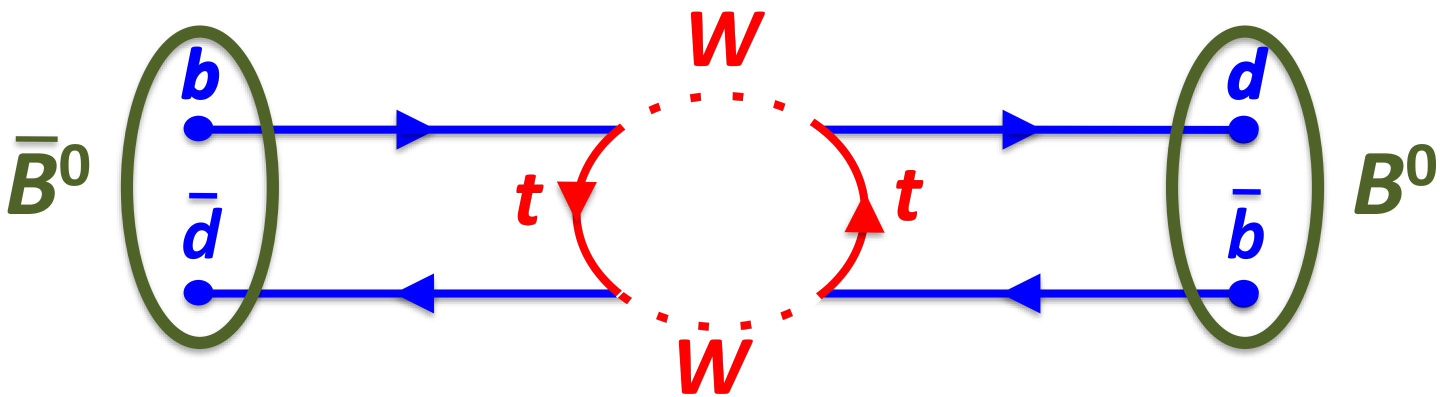
- To give a better idea for now, let's take the specific example of neutral B^0-meson mixing, used to measure the right-hand side of the unitarity triangle



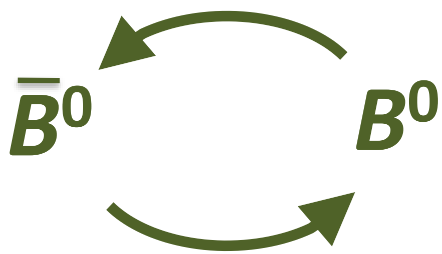
Neutral B^0-meson mixing



Neutral B^0-meson mixing



- These mesons are continuously transformed into each other by weak interactions



- At the same time, they decay weakly to several different possible final states with a lifetime of about 1.5 ps

Neutral B^0-meson mixing

- The oscillation frequency Δm_d in the SM is related to the CKM parameters by

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_d S(x_t) \underbrace{A^2\lambda^6 \overbrace{\left[(1-\bar{\rho})^2+\bar{\eta}^2\right]}^{\text{Right-hand side of the unitarity triangle}}}_{\text{Wolfenstein parameters}} m_{B_d} f_{B_d}^2 \hat{B}_{B_d}$$

Perturbative QCD short-distance correction

Known (Inami-Lim) function of $x_t = m^2_t / m^2_W$

Non-perturbative QCD

- Δm_d is experimentally known very precisely to be

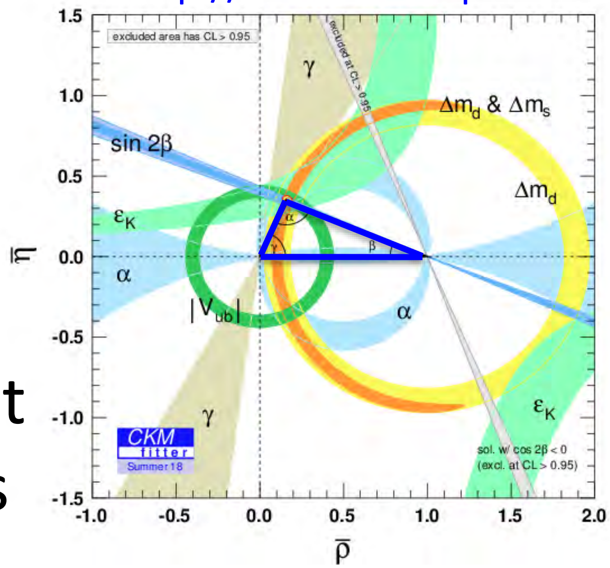
$$\Delta m_d = 0.5065 \pm 0.0019 \text{ ps}^{-1}$$

  hence it imposes a constraint on the right-hand side of the unitarity triangle
- The example also shows the fundamental interplay with QCD, in particular with non-perturbative quantities that must be calculated on the lattice

Consistency of global CKM fits

- Each coloured band defines the allowed region of the apex of the unitarity triangle according to the measurement of a specific process

http://ckmfitter.in2p3.fr



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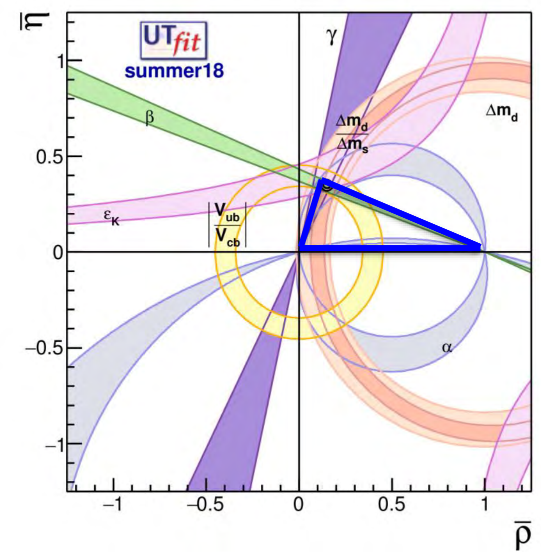
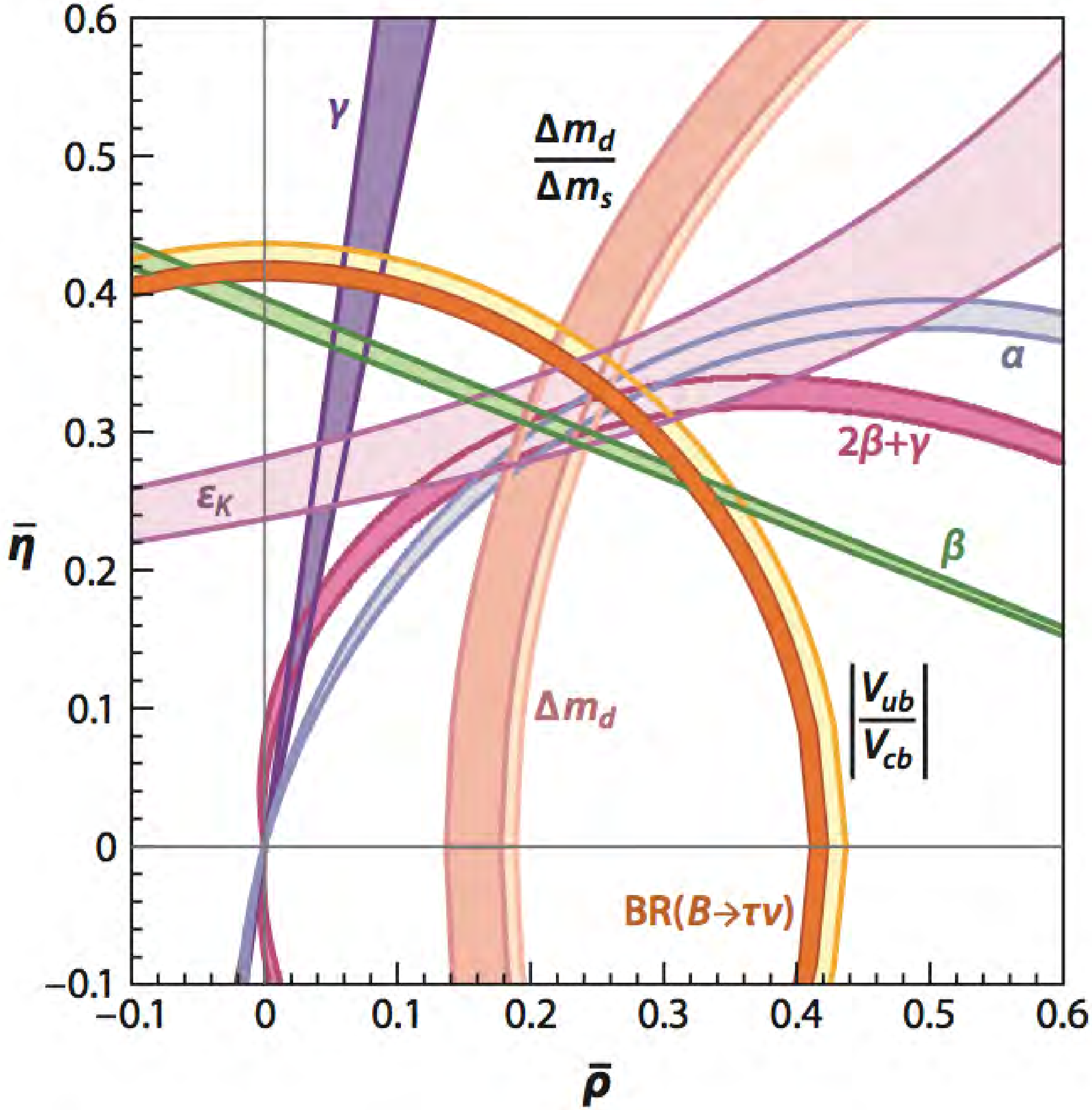


- Tremendous success of the CKM paradigm!
  - All of the available measurements agree in a highly profound way to the current level of precision
  - In presence of BSM physics affecting the measurements, the various contours would not cross each other into a single point
- The quark flavour sector is generally well described by the CKM mechanism → we must look for small discrepancies

Dream scenario, for illustration



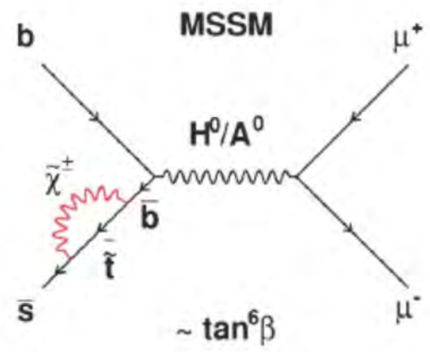
Complementarity between low-energy and high-energy measurements

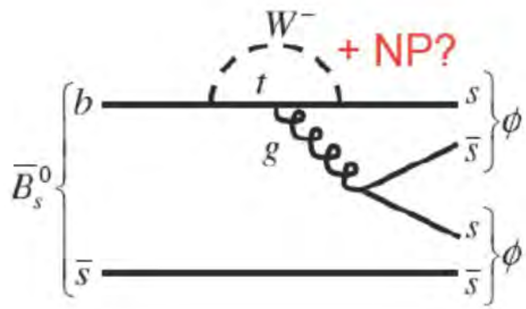
- Experiments like ATLAS and CMS look for the direct production of new heavy particles, e.g. SUSY → Albert De Roeck's lectures
  - Obviously they can be produced and then revealed if the LHC energy is large enough with respect to their masses
- Dedicated flavour-physics experiments, like e.g. BaBar, Belle(-2), LHCb and NA62, operate instead in a low-energy regime, at the beauty-, charm- or even kaon-quark scales
  - Looking for indirect effects of virtual new physics particles on certain process rates of heavy hadrons, whose real incarnations may live at energy scales even larger to those accessible at the LHC
  - As such, flavour-physics is a tool to explore the existence of new physics to energy scales which may be too large to be ever reached by particle accelerators!

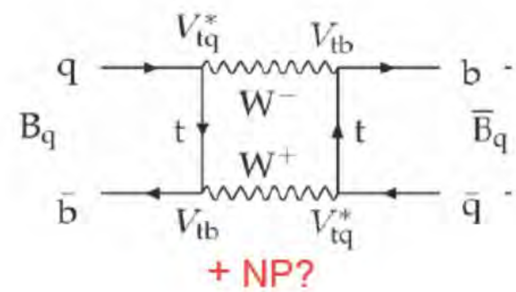
Complementarity between low-energy and high-energy measurements

- In a few words, the aim is to magnify virtual effects to low-energy process amplitudes in order to look for the existence of new particles

Precision measurements of CP violation and rare decays







- General decomposition in terms of couplings and scales

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

- Must know the SM contribution precisely, otherwise the SM coupling can hide NP effects
  - Need to go to high precision measurements of theoretically clean observables
- Unfortunately, we cannot work with free quarks, and we must deal with composite hadrons → as we have already seen, QCD is at work!

Where we are

- The first run of the LHC has led to the discovery of the Higgs boson, but no hint of the existence of other new particles has been found yet
  - Neither SUSY nor any other direct sign of BSM physics has popped out of the data so far
- Besides the Higgs discovery, analyses from the first years of running have also firmly established the great impact of the LHC experiments, in particular of LHCb, in the field of CP violation and rare decays of heavy-flavoured hadrons
  - LHCb has produced a plethora of results on a broad range of flavour observables in the c- and b-quark sectors
  - ATLAS and CMS have given contributions to the b-quark sector, mainly using final states containing muon pairs

Where we go

- It is of fundamental importance for future developments of elementary particle physics to keep improving the theoretical and experimental knowledge of flavour physics
- Such improvements increase the reach of indirect searches for BSM physics, probing higher and higher mass scales in the event that no BSM effects were discovered by direct detection at the next LHC run(s)
- On the other hand, they would enable the BSM Lagrangian to be precisely determined, if any new particle were detected in direct searches

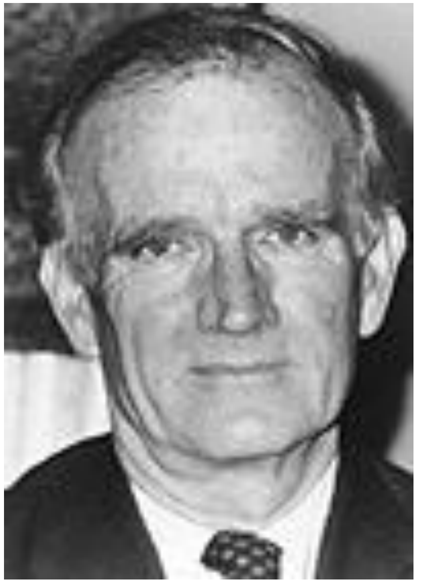
Historical perspective

CKM enters SM

- The idea of Kobayashi and Maskawa, formalised into the CKM quark mixing matrix, was considered an integral part of the SM by the beginning of the 1980’s
- As we have already seen, the phenomenon of CP violation, first revealed in 1964 using decays of neutral kaons, was elegantly accounted for as an irreducible complex phase in the CKM matrix
- The experimental proof of the validity of the CKM mechanism and the precise measurement of the value of the CP-violating phase soon became questions of paramount importance

Cronin and Fitch

James Cronin

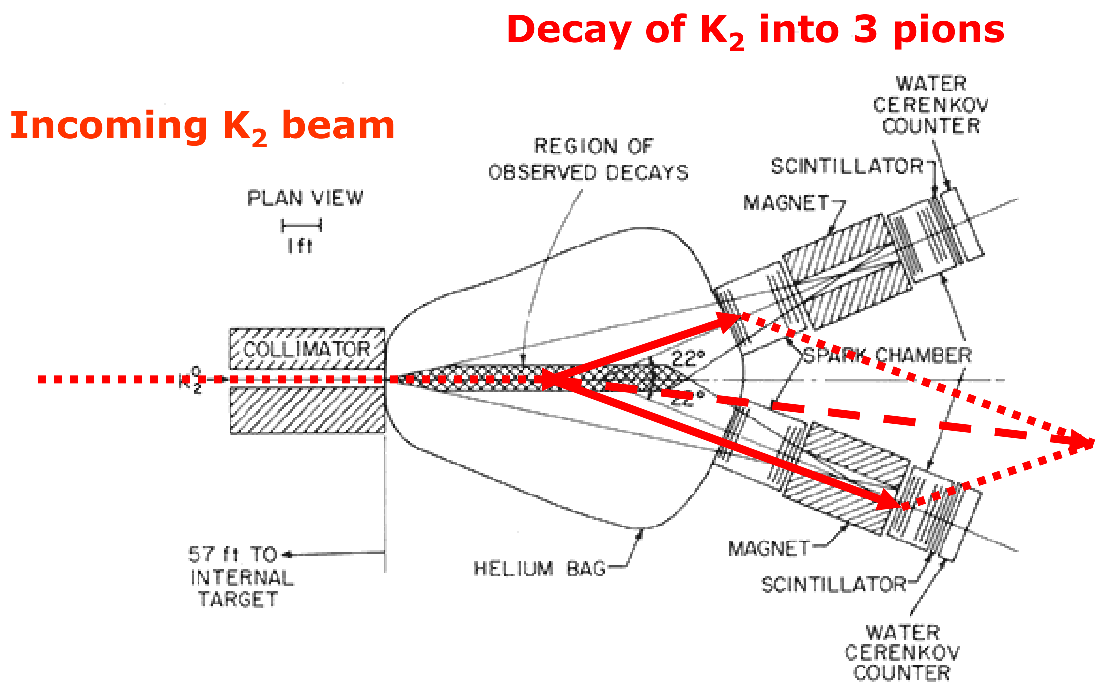


Val Fitch

- In 1980 Cronin and Fitch received the Nobel Prize in Physics for their 1964 experiment
- They detected for the first time CP violation in the decay of neutral K mesons

The Cronin and Fitch experiment

- Conceptually very simple: they looked for (CP-violating) $K_2 \rightarrow \pi\pi$ decays 20 meters away from K^0 production point



- If you detect two of the three pions of a $K_2 \rightarrow \pi\pi\pi$ decay they will generally not point along the beam line

The Cronin and Fitch experiment

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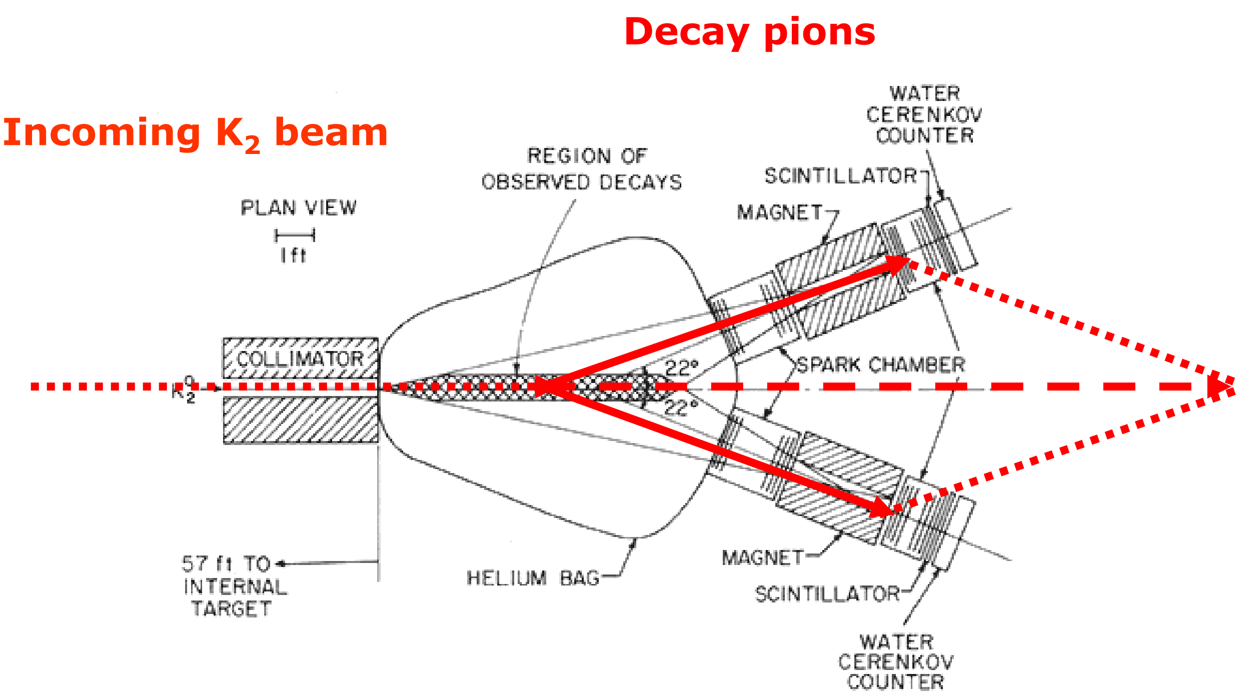

- If K_2 decays into two pions instead of three, the reconstructed direction should be exactly along the beamline

The Cronin and Fitch experiment

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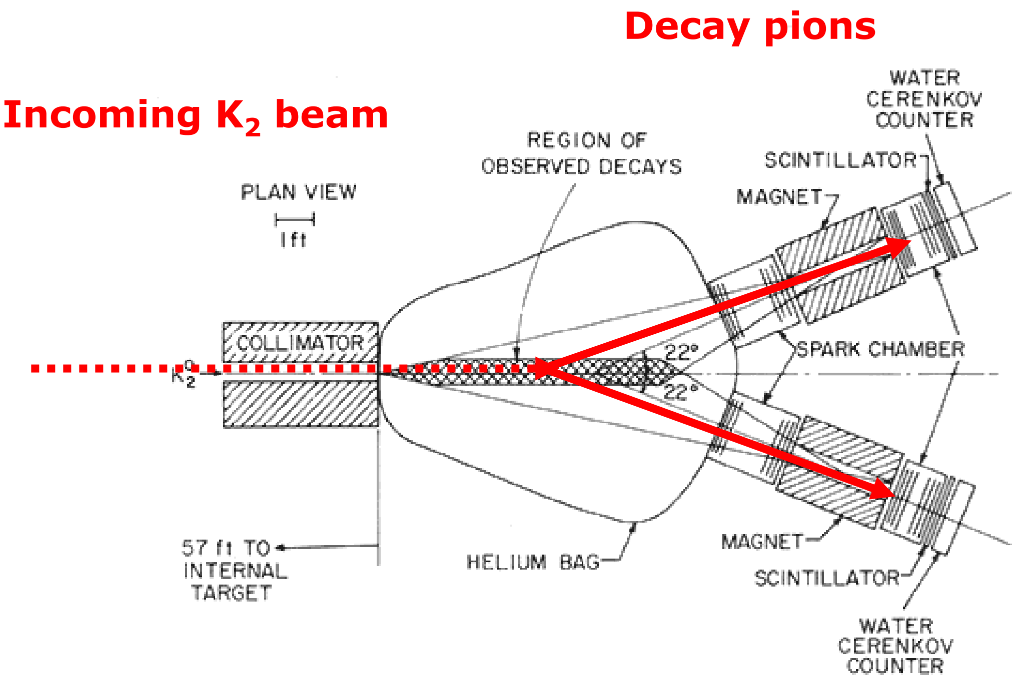
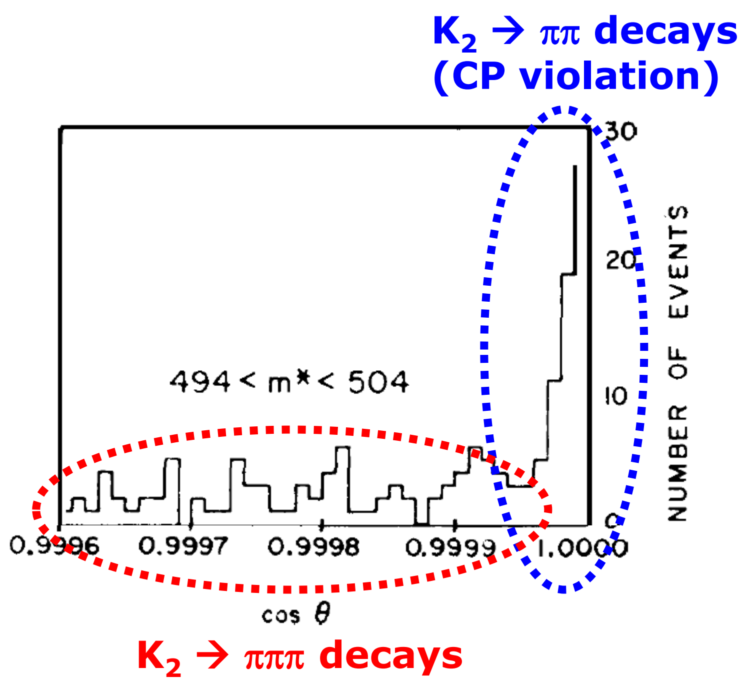


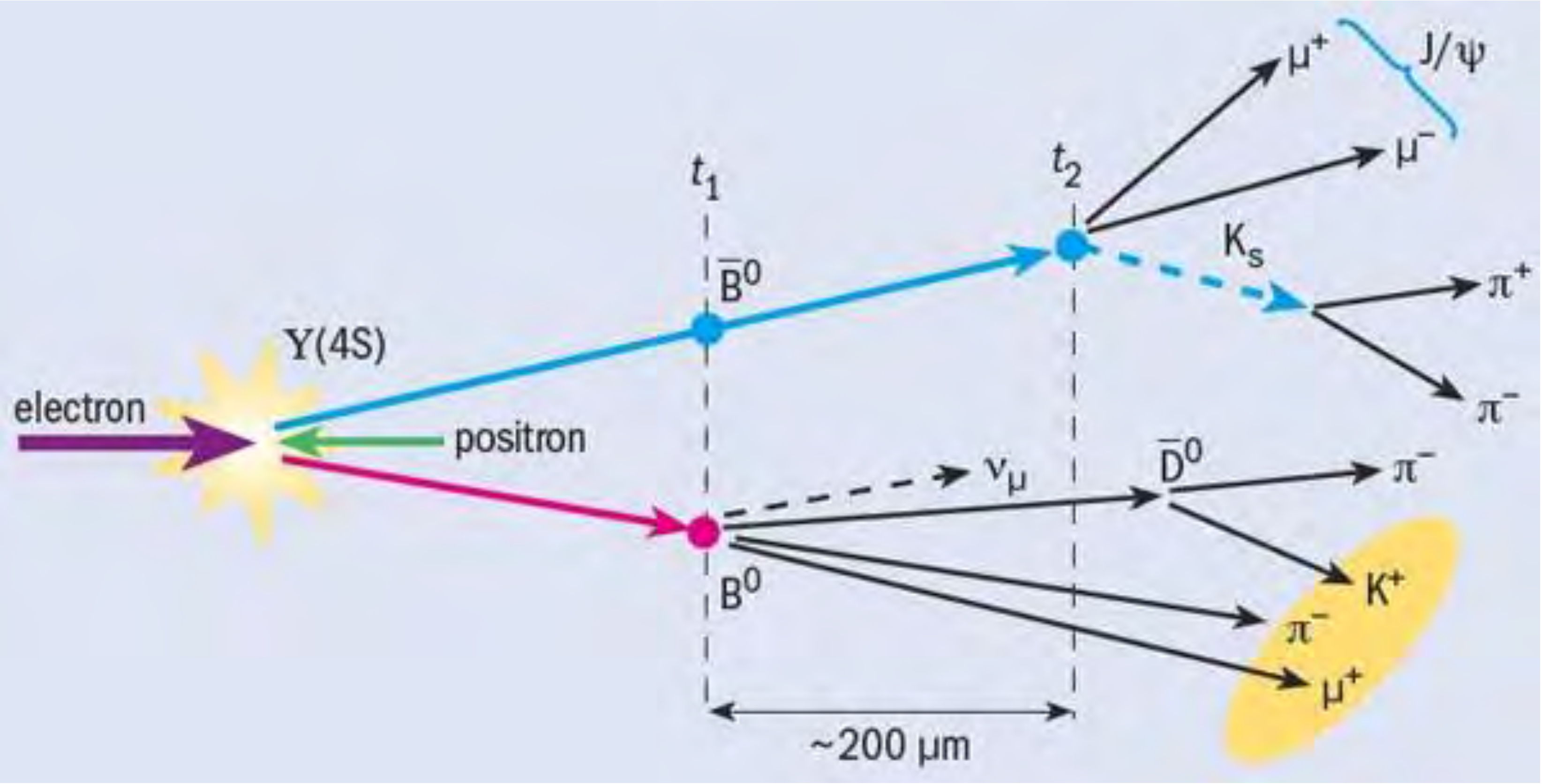


- Result: an excess of events at θ=0 degrees → impossible without violating CP

The rise of B physics

- Due to the nature of the CKM matrix, an accurate test of the CKM flavour picture required an extension of the physics programme to heavy-flavoured hadrons, in particular B-meson decays
- Pioneering steps in the b-quark flavour sector were moved at the beginning of the 1980s by the CLEO experiment at CESR
- At the same time, Ikaros Bigi, Ashton Carter and Tony Sanda explored the possibility that large CP-violating effects could be present in the decay rates of B^0 mesons decaying to the $J/\psi K_S$ CP eigenstate
  - In addition, they pointed out that such a measurement could be interpreted in terms of the CP-violating phase without relevant theoretical uncertainties due to strong interaction effects

The $B^0 \rightarrow J/\psi K_s$ decay

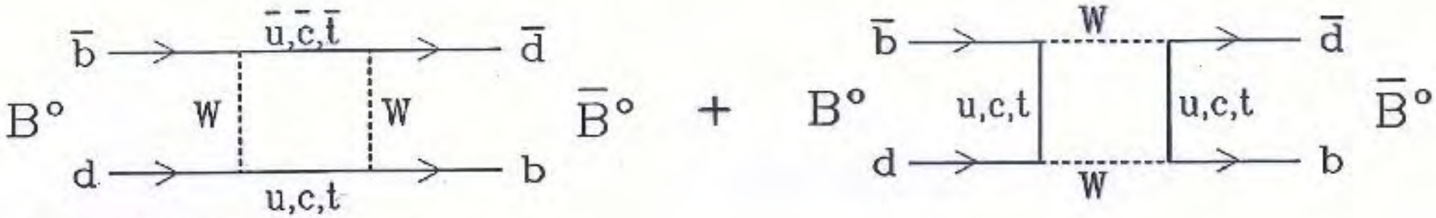


- To measure CP violation with B-meson decays to CP eigenstates, the information from the B (proper) decay time is extremely important
- If B^0 mesons are at rest, such as in the decay of a Y(4S) produced at rest in a symmetric e^+e^- collision, the decay time is not accessible (need to measure the decay length) → this is not the case in the picture above

Experimental issues

- There were two formidable obstacles to overcome
  - an experimental observation required an enormous amount of B^0 mesons, well beyond what was conceivable to produce and collect at the time
  - a precise measurement of the decay time was required, together with the knowledge of the flavour of the B^0 meson at production (flavour tagging)
- In 1987 the ARGUS experiment at DESY measured for the first time the mixing rate of B^0 and $\bar{B}^0$ mesons, whose knowledge was an important ingredient to understand the feasibility of measuring CP violation with $B^0 \rightarrow J/\psi K_S$ decays

B^0 meson mixing at ARGUS



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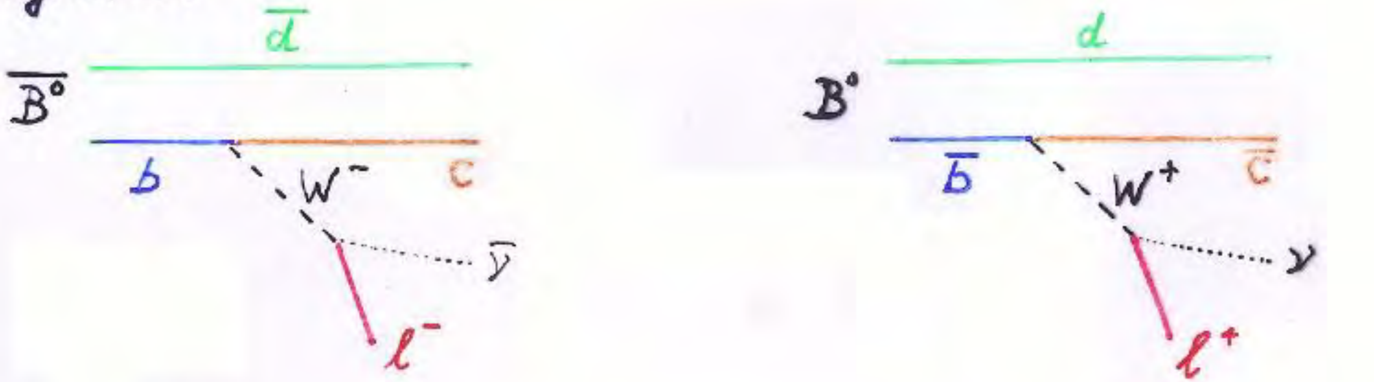

normal

$$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0 \to \ell^+\ell^-$$

unlike sign leptonpairs

mixing

$$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0 \left\langle \begin{array}{l} B^0B^0 \to \ell^+\ell^+X \\ \bar{B}^0\bar{B}^0 \to \ell^-\ell^-X \end{array} \right.$$

like sign leptonpairs

The ARGUS golden event


news

search & discovery

Neutral B mesons show surprisingly large flavor mixing

In its heydey in the 1950s and 60s, the K meson was a spectacular source of profound surprises. Its "strange" longevity gave us the first hint of flavor conservation in the strong interactions, and eventually the concept of quarks as the carriers of these hadronic flavors. Its decay into states of opposite parity freed us from rigid adherence to mirror symmetry. Then the neutral kaon was seen to oscillate wondrously between states of opposite strangeness, and finally, in 1964, one of its decay modes yielded up the last great surprise. It provided us the only example we have to this day of *CP* violation. We had known since 1957 that *P* (parity inversion) was not an inviolate symmetry of nature. Now the last hope for mirror symmetry—invariance under the combined operation of *P* and *C* (charge conjugation)—was also dashed.

The neutral kaon could show us things to be seen nowhere else—flavor mixing and *CP* violation—because it was, in its day, unique among the known elementary particles. The K^0 differs from the $\bar{K}^0$, its antiparticle, only by virtue of its hadronic flavor, a quantum number not respected by the weak interactions; they are states of opposite strangeness. Thus the two neutral kaons are coupled by their ability to decay weakly to the same states, for example $\pi^+\pi^-$. Such couplings give rise to "flavor mixing." The two neutral-kaon states of definite mass are superpositions of the two states of opposite strangeness, with slightly different masses and very different lifetimes. This flavor mixing was the *sine qua non* for the observation of *CP* violation in the decay of the longer-lived neutral kaon.

The neutral kaon is no longer unique. In 1977 Leon Lederman and coworkers at Fermilab found the first indication of the bottom-flavored quark, the "third-generation" analog of the strange quark, and in 1983 the Cleo collaboration at CESR, the Cornell electron–positron storage ring, announced the first direct observation of the B^0 meson, the bottom-flavored analog of the K^0, with a mass of about 5 GeV—more than ten times that of the K (PHYSICS TODAY, April 1983, page 20.)

Second-order weak process couples B^0 to its antiparticle, thus permitting a mixing metamorphosis. A $\bar{B}^0$, consisting of a bottom quark (charge $-\frac{1}{3}$) and an antidown quark, becomes a B^0 by the exchange of two charged weak vector bosons W. In the intermediate state, all 3 generations of charge $+\frac{2}{3}$ quarks (up, charmed, top) can contribute, together with their antiquarks. The top quark, being the heaviest, dominates the amplitude.

Now we have the first clear evidence of flavor mixing between the B^0 and its antiparticle, the $\bar{B}^0$. In February, the ARGUS collaboration reported[1] that their data from the DORIS electron–positron storage ring at DESY in Hamburg indicate a mixing parameter of about 20%, much bigger than the fondest hopes of the theorists.

Briefly stated, if the B^0 meson did not engage in flavor mixing with the $\bar{B}^0$ during its brief picosecond lifetime, its semileptonic decay modes (those that yield leptons and hadrons) would always produce a characteristic *positive* lepton—a positron or a positive muon, never an electron or a μ^-. Correspondingly the $\bar{B}^0$ would signal its semileptonic decay with an e^- or a μ^-, never a positive lepton. What the ARGUS group found, in essence, was that roughly one semileptonic neutral B decay in six produced the wrong lepton charge, thus signaling that the B meson's bottom flavor had changed sign between its birth and death. By convention, in keeping with the analogy to K mesons, the bottom quark b, with bottom flavor (or "bottomness") −1 and electric charge $-\frac{1}{3}$, resides in the $\bar{B}^0$ meson while its antiquark $\bar{b}$, with positive flavor and charge, inhabits the B^0.

Theorists had jumped on the first hint of B mesons in 1977 with great enthusiasm, pointing out that nature might well be offering here a second chance to see flavor mixing and *CP* violation. So long as *CP* violation data were limited to the decay of the neutral kaon, one couldn't really be sure what physics underlay this striking phenomenon. The data were consistent with the "standard model" of elementary particle interactions, with its 3 generations of quarks and leptons, but the data were painfully limited. Theorists longed for a new vantage point from which to observe *CP* violation. Even if the new observations remained consistent with the standard model, they might shed light on the observed value of the *CP*-violating phase angle in the three-generation formalism, which remains an unexplained free parameter in the model. The abundance of such arbitrary parameters in the standard model impels the search for a deeper theory. Furthermore, as Andrei Sakharov pointed out 20 years ago, by seeking to understand *CP* violation we come to grips with the matter–antimatter asymmetry of the cosmos.

But the surprising and welcome ARGUS result comes at a time when the

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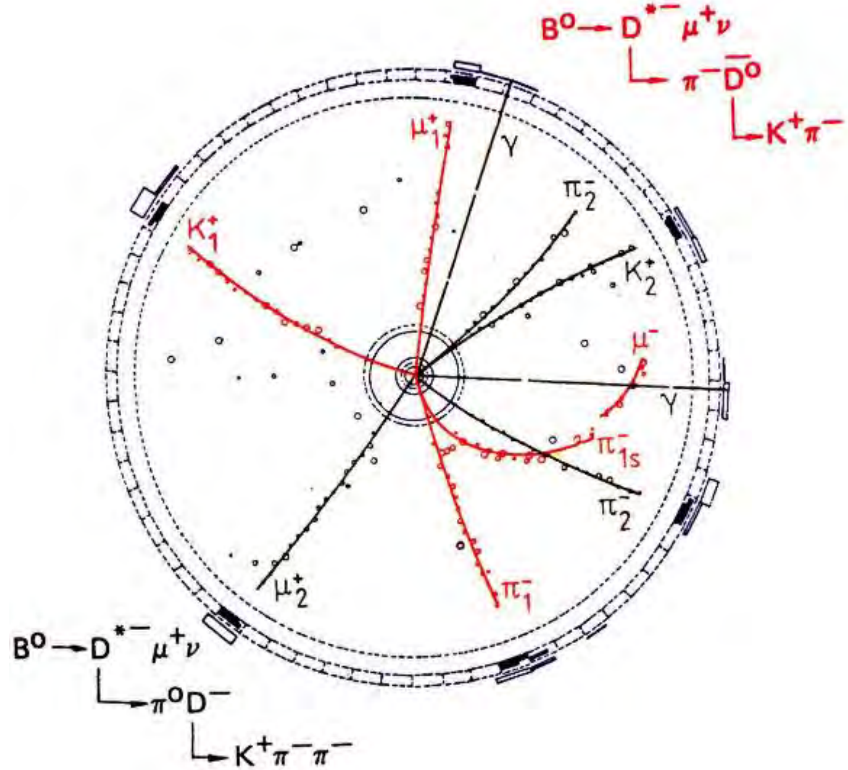


$$r = \frac{N(B^0 B^0) + N(\overline{B}^0 \overline{B}^0)}{N(B^0 \overline{B}^0)}$$

$$r = 0.21 \pm 0.08$$

Pier Oddone's idea

- Another crucial ingredient came along due to tremendous developments in the performance of e^+e^- storage rings
- By the late 1980s, many different possible designs for new machines were being explored
- A novel idea was put forward by Pier Oddone in 1987: a high-luminosity asymmetrical e^+e^- circular collider operating at the centre-of-mass energy of the Υ(4S) meson

e^+e^- asymmetric B-factories

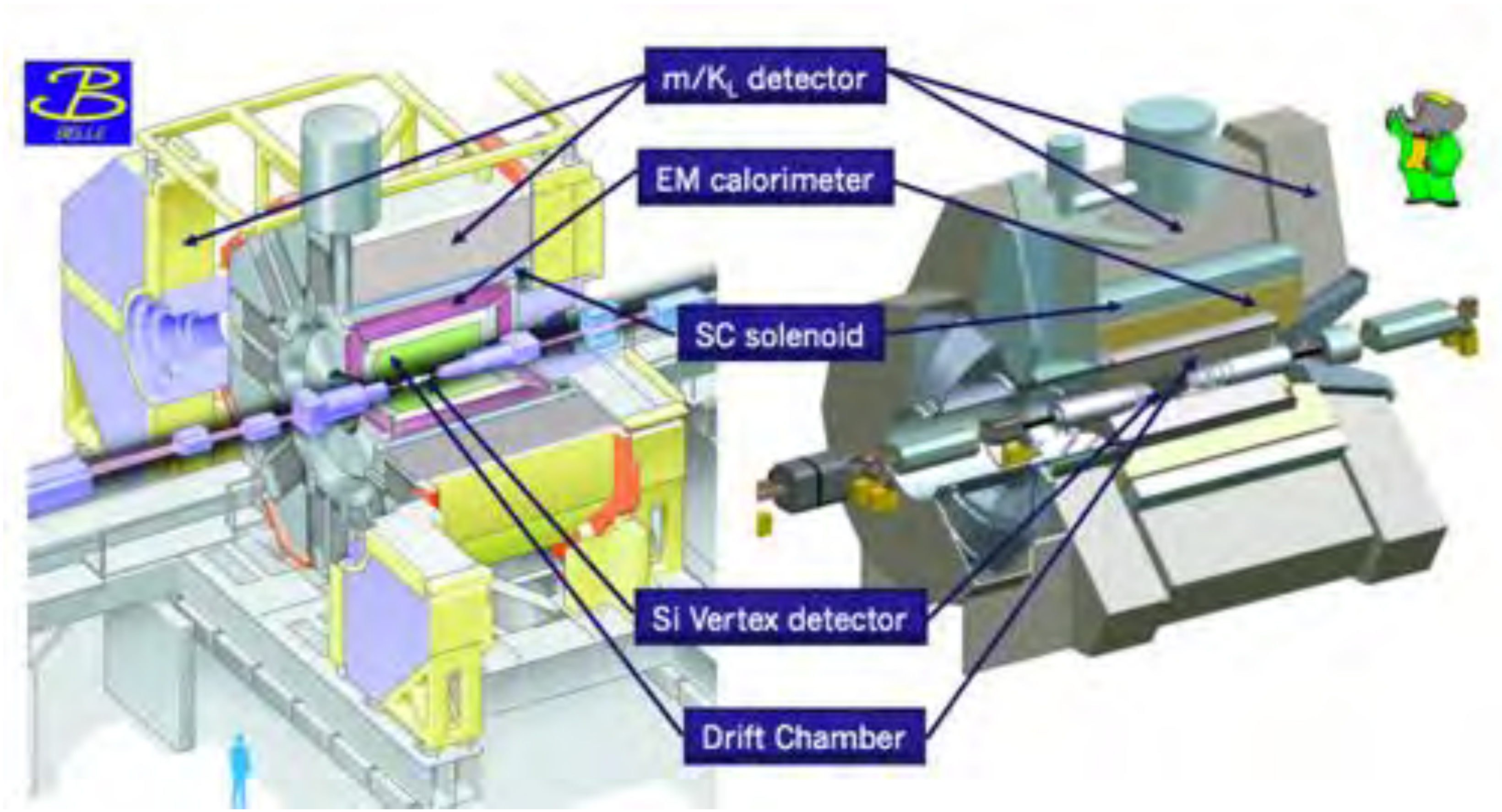
- Owing to the beam-energy asymmetry, B mesons would have been produced with a boost in the laboratory frame towards the direction of the most energetic beam
  – The consequent nonzero decay length, measured by means of state-of-the-art silicon vertex detectors, would have enabled precise measurements of the decay time to be achieved
- Two machines based on Oddone's concept, so-called B-factories, were eventually built
  – KEKB at KEK in Japan
  – PEP-II at SLAC in the United States

KEKB e PEP-II

8 GeV e^- x 3.5 GeV e^+ **9 GeV e^- x 3.1 GeV e^+**

- If CESR was initially able to produce few tens of $b\bar{b}$ pairs per day, KEKB and PEP-II were capable of producing order of one million $b\bar{b}$ pairs per day

BaBar and Belle



- The associated detectors, BaBar at PEP-II and Belle at KEKB, were approved in 1993 and in 1994, starting data taking in 1999

Meanwhile...

- During the course of the 1990s many b -physics measurements were being performed at the Z^0 factories, i.e. LEP experiments at CERN and SLD at SLAC
- Despite the relatively small statistics, if compared to today's standards, b hadrons produced in Z^0 decays were naturally characterized by a large boost, enabling measurements of lifetimes of all b-hadron species and of oscillation frequencies of neutral B mesons to be performed
  - For the first time it was possible to study samples of B_s-meson, b-baryon and even a handful of B_c-meson decays
- Similar pioneering measurements were also made at the Tevatron with Run I data, using hadronic collisions as a source of b quarks
- A very challenging attempt also made at DESY with the HERA-B experiment, using fixed-target collisions of the 920 GeV HERA protons to produce beauty-quark pairs
  - Unsuccessful, but set the basis for the success of a very similar detector concept, LHCb, which has been very successful later

The B-factory revolution

- Soon after PEP-II and KEKB were turned on, the two machines broke any existing record of instantaneous and integrated luminosity of previous particle colliders
- By the end of their research programmes, BaBar and Belle measured CP violation in $B^0 \rightarrow J/\psi K_S$ decays with a relative precision of about 3%
  - The large sample of B-meson decays collected at BaBar and Belle enabled a series of further measurements in the flavour sector to be performed, well beyond the initial expectations

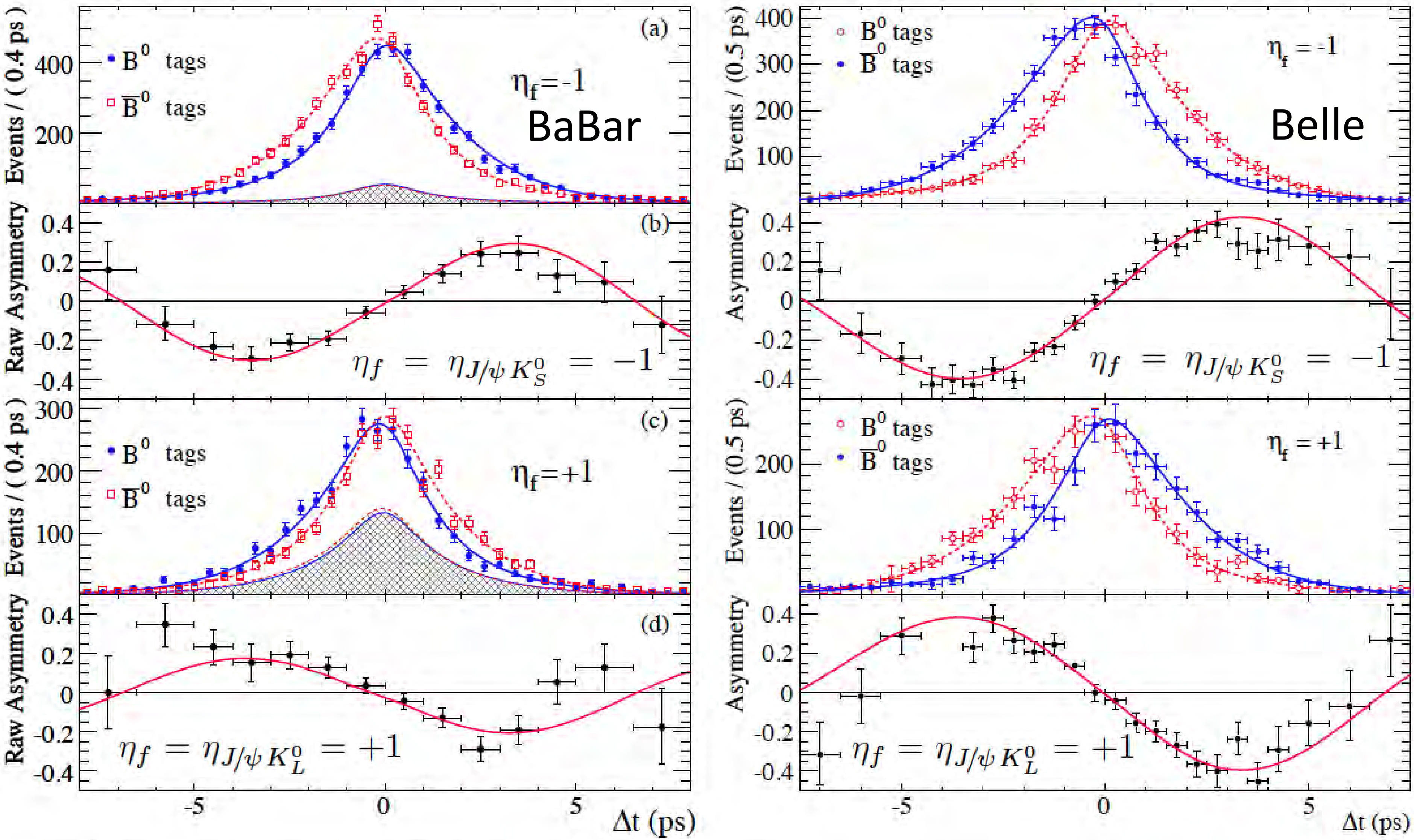
PEP-II and KEKB luminosity

Experiment	Resonance	On-resonance Luminosity (fb^{-1})	Off-resonance Luminosity (fb^{-1})
BABAR	$\Upsilon(4S)$	424.2	43.9
	$\Upsilon(3S)$	28.0	2.6
	$\Upsilon(2S)$	13.6	1.4
	Scan $> \Upsilon(4S)$	n/a	$\sim$4
Belle	$\Upsilon(5S)$	121.1	1.7
	$\Upsilon(4S)$ - SVD1	140.7	15.6
	$\Upsilon(4S)$ - SVD2	562.6	73.8
	$\Upsilon(3S)$	2.9	0.2
	$\Upsilon(2S)$	24.9	1.7
	$\Upsilon(1S)$	5.7	1.8
	Scan $> \Upsilon(4S)$	n/a	25.6

- The two machines produced more than 1 billion Y(4S) decaying to $B\overline{B}$ meson pairs

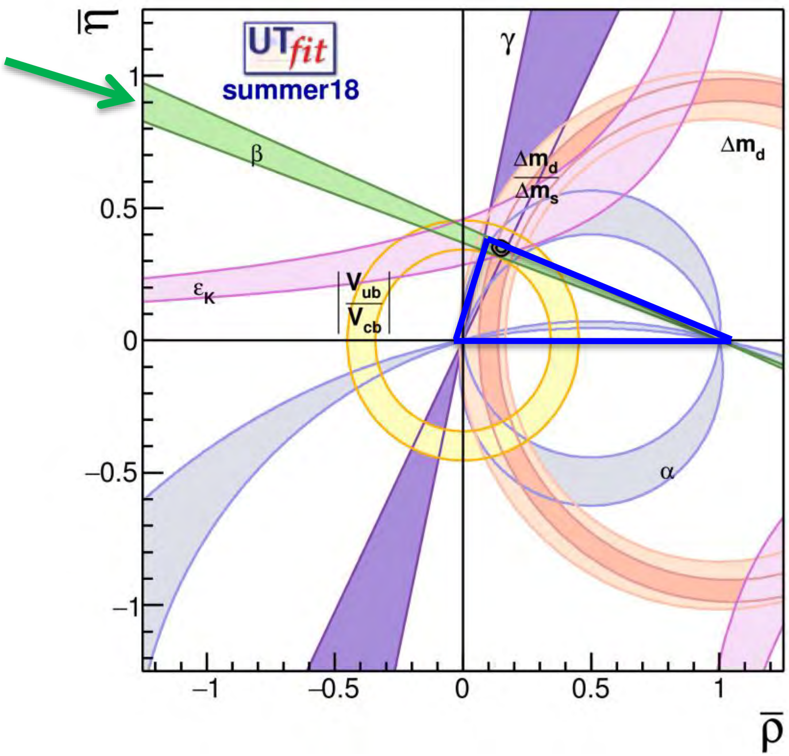
Experiment	Resonance	Υ number
BABAR	$\Upsilon(4S)$	$(471.0 \pm 2.8) \times 10^6$
	$\Upsilon(3S)$	$(121.3 \pm 1.2) \times 10^6$
	$\Upsilon(2S)$	$(98.3 \pm 0.9) \times 10^6$
Belle	$\Upsilon(5S)$	$(7.1 \pm 1.3) \times 10^6$
	$\Upsilon(4S)$ - SVD1	$(152 \pm 1) \times 10^6$
	$\Upsilon(4S)$ - SVD2	$(620 \pm 9) \times 10^6$
	$\Upsilon(3S)$	$(11 \pm 0.3) \times 10^6$
	$\Upsilon(2S)$	$(158 \pm 4) \times 10^6$
	$\Upsilon(1S)$	$(102 \pm 2) \times 10^6$

$B^0 \rightarrow (c\bar{c})K_{S/L}$ at BaBar and Belle



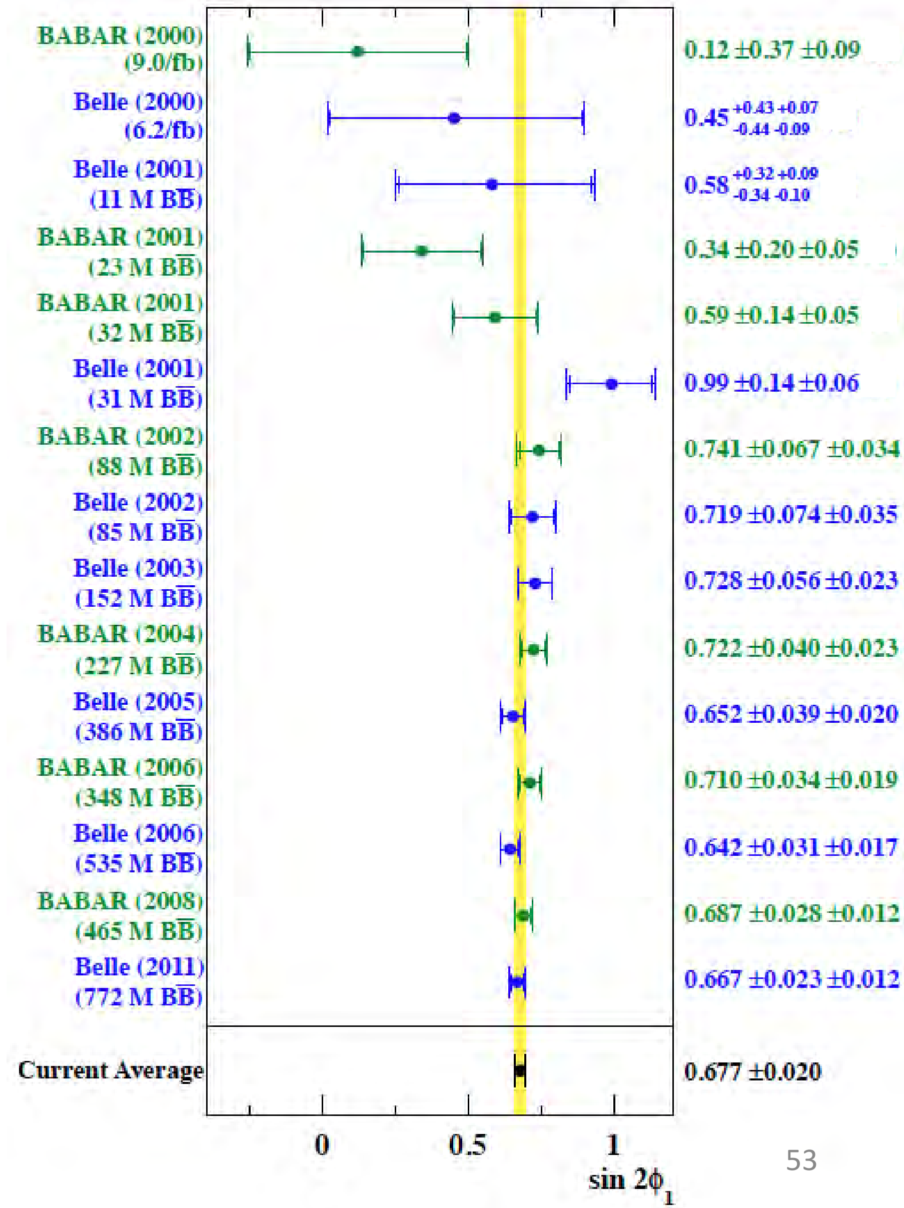
$$\mathcal{A}(\Delta t) = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t) \qquad S = -\eta_f \sin 2\beta \qquad C = 0$$

$B^0 \rightarrow (c\bar{c})K_{S/L}$ at BaBar and Belle



- Legacy B-factory result

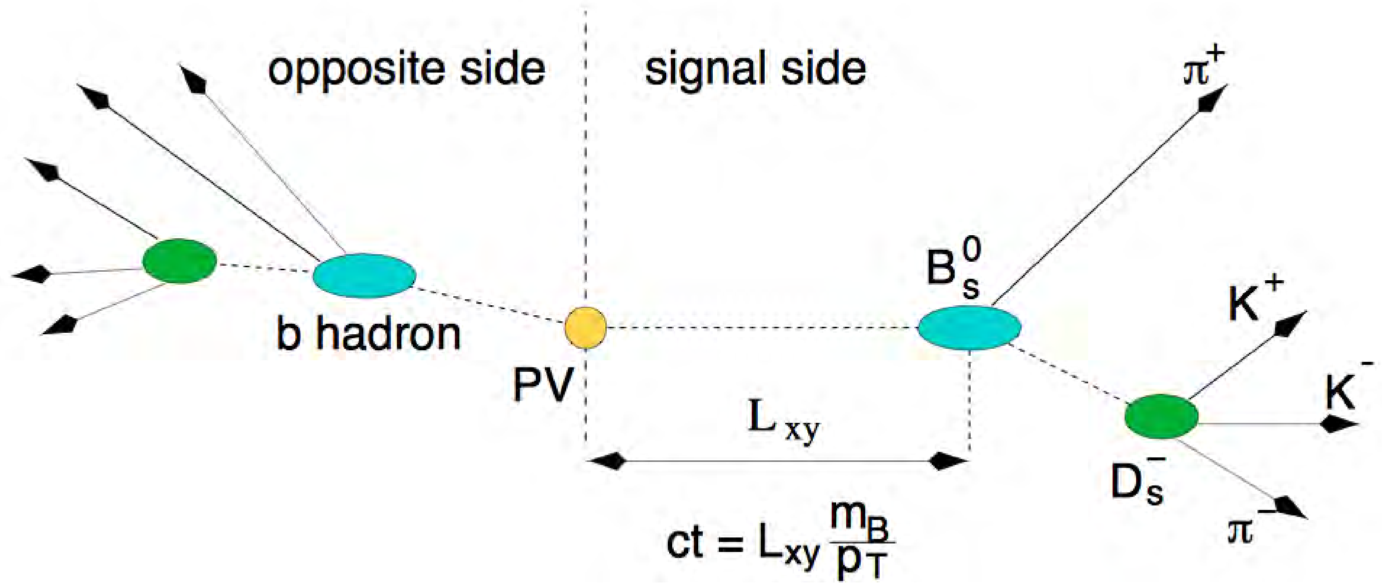
$$\sin 2\beta = 0.677 \pm 0.020$$
$$C = 0.006 \pm 0.017$$



Flavour physics at the Tevatron

- In the same years, a major step forward in these topics was also made at the Tevatron with Run II data
- Although with a somewhat limited scope if compared to B-factories, the CDF and D0 experiments at FNAL collected large amounts of heavy-flavoured-hadron decays, performing some high precision measurements, notably including the first observation of B_s-meson mixing in 2006

B_s-$\overline{B}_s$ mixing at the Tevatron



$$\mathcal{A}(t) \equiv \frac{N(t)_{mixed} - N(t)_{unmixed}}{N(t)_{unmixed} + N(t)_{mixed}} = \mathcal{D}\cos(\Delta m_s t)$$

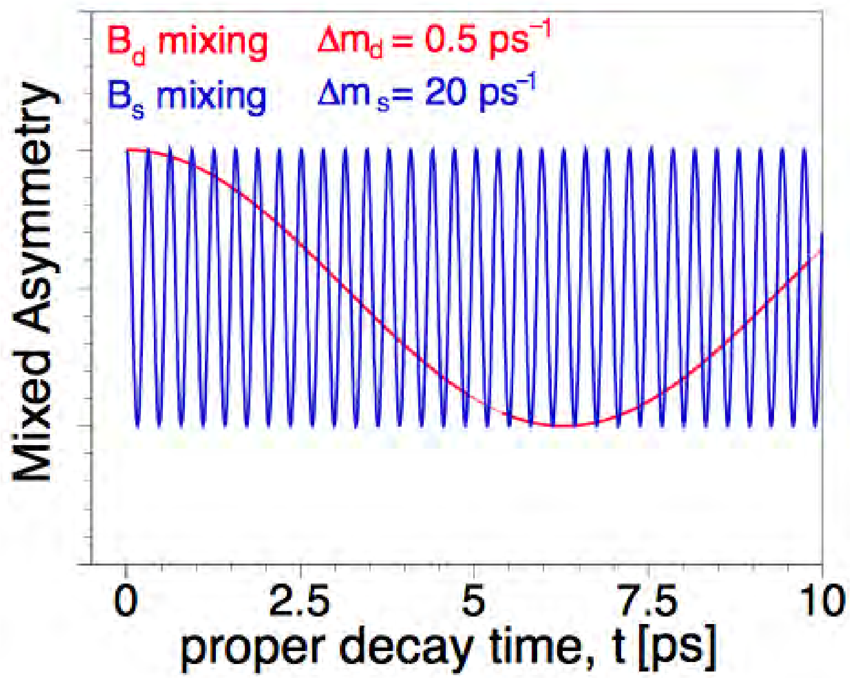
$$\mathcal{D} = 1 - 2P_{mistag}$$

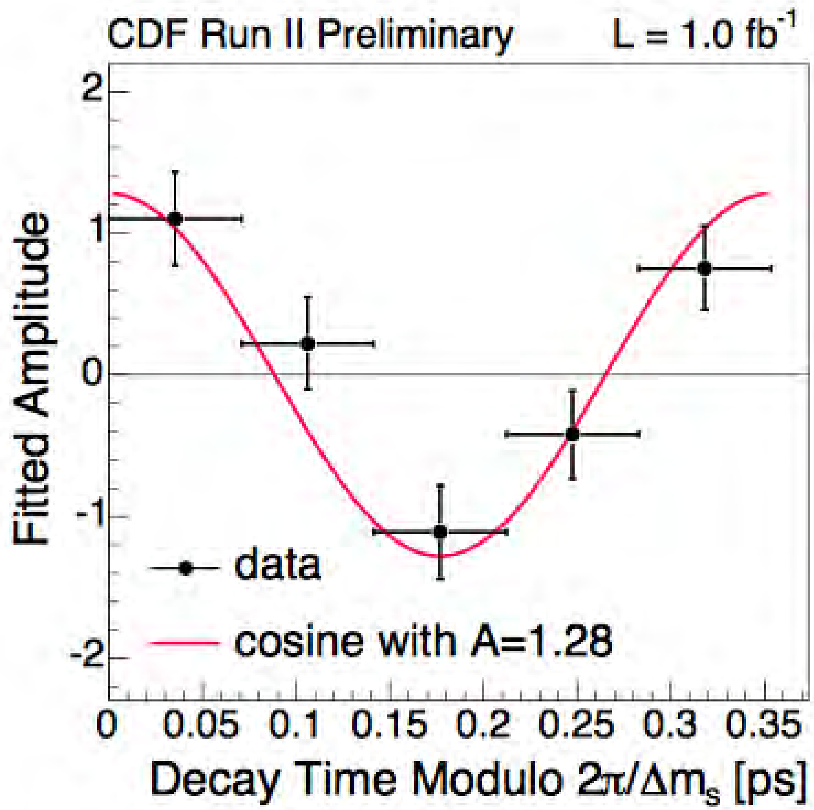
Challenges

- B_s reconstruction/selection
- Proper time measurement
- Flavour tagging (major challenge at hadron colliders)

significance $\propto \sqrt{\frac{S\epsilon D^2}{2}}\sqrt{\frac{S}{S+B}}e^{-\frac{(\Delta m_s \sigma_{ct})^2}{2}}$

B_s-$\overline{B}_s$ mixing is very fast





- Excellent vertex and momentum resolutions
- Large number of signal events
- Relatively good tagging performance

$$\Delta m_s = 17.77 \pm 0.10(\text{stat.}) \pm 0.07(\text{syst.})\ \text{ps}^{-1}$$

Finally, the LHC!