CP Violation, Baryogenesis

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Before starting

Some bibliography related to the lecture

- A. Höcker and Z. Ligeti, “CP Violation and the CKM Matrix”, hep-ph/0605217
- BaBar physics book: http://www.slac.stanford.edu/pubs/slacreports/slac-r-504.html
- LHCb performance TDR: http://cdsweb.cern.ch/record/630827?ln=en
- W. Bernreuther, “CP Violation and Baryogenesis”, hep-ph/0205279
- A. Riotto, “Theories of Baryogenesis”, hep-ph/9807454

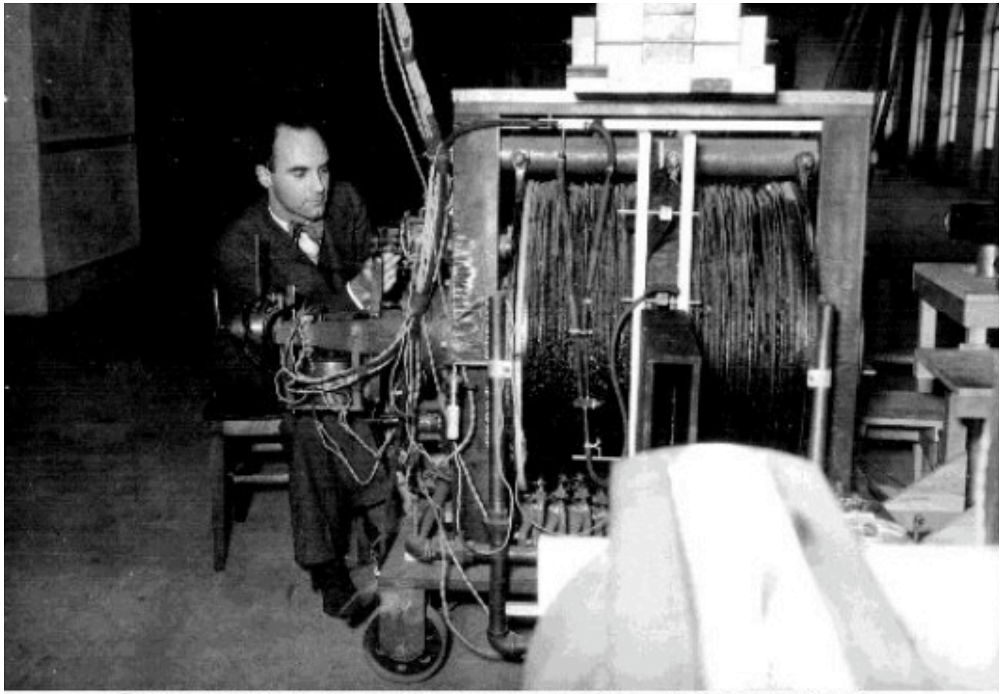
I am very grateful to Stéphane Monteil and Jean Orloff for their precious helps in preparing this lecture

Antimatter exists

In 1929, P.A.M. Dirac solves the free motion of a relativistic spin 1/2 particle (electron or proton).

Dirac spin 1/2 : $(i\gamma^\mu \partial_\mu - m)\psi = 0$

It happened that there should exist a solution of negative energy, which Dirac interpreted as an antiparticle.



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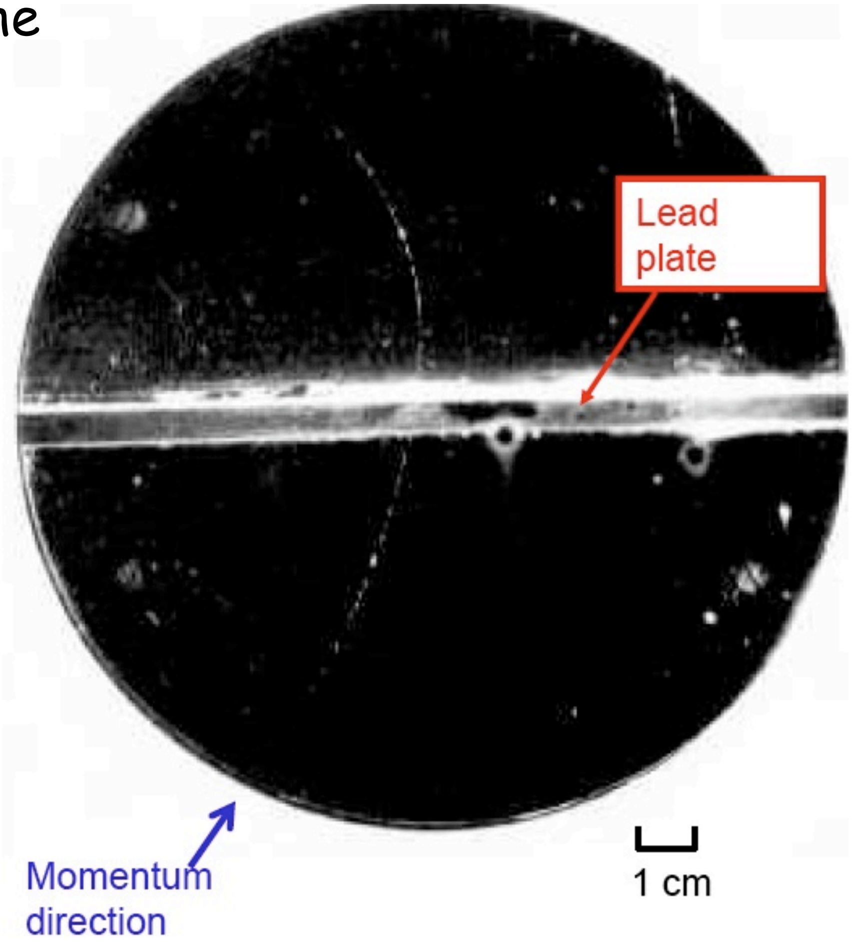
Anderson at work: discovery of the positron in 1932

(Nobel Prize 1936)

Discovery of the positron



- Radius of curvature is smaller above the plate: particle is slow down in the lead
  - ✓Particle is incoming from the bottom
- Magnetic field direction is known
  - ✓Positive charge
- From the density of the drops, one can measure the ionizing power of the particle
  - ✓Minimum ionizing particle
- Similar ionizing power before and after the plate
  - ✓Same particle on the 2 sides
- Curvature measurement after the lead: momentum ~ 23MeV/c
  - ✓Not a non-relativistic proton because it would have lost all its energy after ~ 5 mm (a track of ~ 5 cm is observed)

What is a symmetry?

- In Physics, we say that a system presents a symmetry under a given operation if the result of the transformation leaves invariant the system.
  - ✓ These operations can be continuous or discrete transformations of space-time or transformations acting in internal/local spaces.

- These symmetries are used to describe the properties of elementary constituents of the Nature as well as of their interactions and the underlying dynamics.

- Example: symmetry by translation and momentum conservation
  - ✓ Hypothesis: absolute position of two objects is not an observable
  - ✓ Deduction: interaction energy invariant under space translation
  - ✓ Consequence: the momentum conservation law

Noether's theorem

- Noether's theorem: for any continuous symmetry of a given system corresponds a conservation law for this system.

- In quantum mechanics, Noether's theorem is also at work in:
  - ✓ Invariance/symmetry ⇔ conservation law

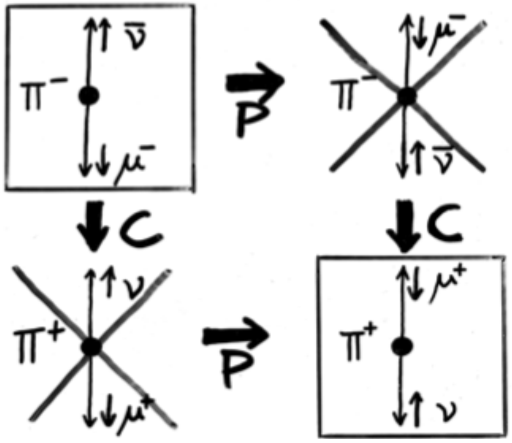
- Symmetry operator T
  - ✓ T unitary: $T^*T = 1$
  - ✓ A given operator T (which can be an observable) is a symmetry operator for H (does not change H) if it commutes with H: $[H, T] = 0$
    - The associated quantum numbers are conserved (selection rules)

Symmetries and conservation laws

Not observable / symmetry	Mathematical transformation	Conservation law
Absolute spatial position	Space translation	Momentum
Absolute time	Time translation	Energy
Absolute spatial direction	Rotation	Angular momentum
The absolute line	Mirror	Parity
Sign of the electric charge	$e \rightarrow -e$	Charge conjugation
Absolute sign of time	$t \rightarrow -t$	Time reversal
Relative phase between different electric charges	Gauge transformation	Electric charge

Symmetries in Physics

- Summary about conservation laws:
  - ➢Preserved by all interactions:
    - ✓Energy
    - ✓Momentum
    - ✓Total angular momentum
    - ✓Electric charge
    - ✓Baryonic and leptonic numbers
  - ➢Preserved by all but weak interaction:
    - ✓Flavour numbers
    - ✓Charge conjugation (C)
    - ✓Parity (P)
    - ✓Time reversal (T)
- C, P, CP and CPT
  - ➢Only υ_L and $\bar{\upsilon}_R$ participate in weak interaction
    - ✓Weak interactions maximally violate C and P
  - ➢$CP(\upsilon_L) = C(P[\upsilon_L]) = C(\upsilon_R) = \bar{\upsilon}_R$
    - ✓CP = symmetry matter/antimatter
    - ✓Weak interactions also violate CP
  - ➢CPT cannot be violated in a relativistically covariant local quantum field theory



Weak interaction and Parity

The Wu experiment

- Before 1956, all interactions were thought to be invariant under parity operation.
- It was (quite comprehensively) tested for strong and electromagnetic interactions.
- Lee and Yang proposed an experiment to test it for weak interaction
- Designed and performed in 1957 by C.S. Wu and collaborators

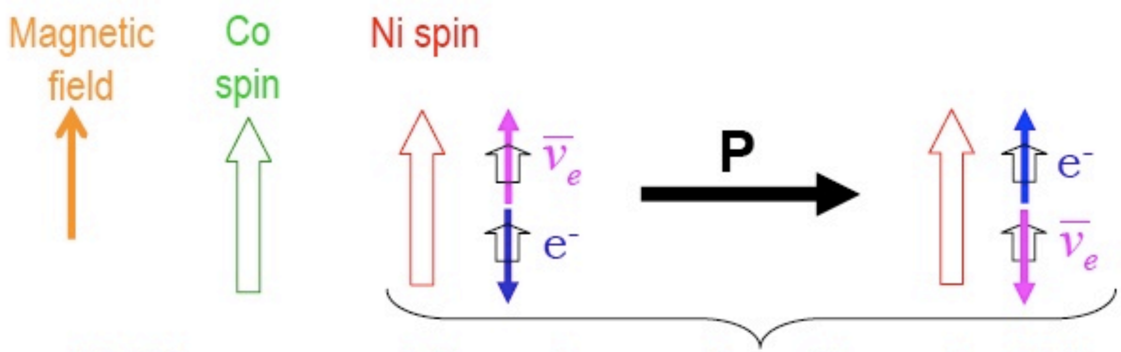
  Phys. Rev. 105, 1413-1414 (1957)

The Wu experiment

- Study the beta decay of ^{60}Co atoms

$$\mathrm{Co}^{60}\ (J=5) \rightarrow \mathrm{Ni}^{60*}\ (J=4)\, e^- \overline{\nu_e}$$

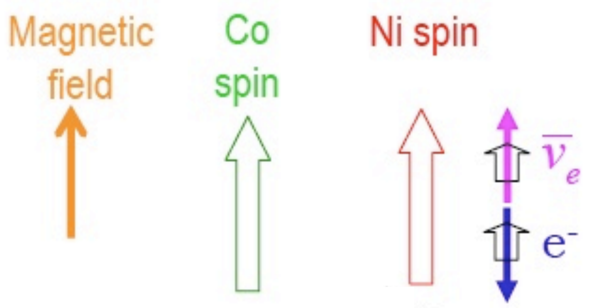
- The spins of the Co^{60} atoms are aligned towards the direction of a magnetic field able to flip polarity.
- The electrons are detected and their direction is measured.

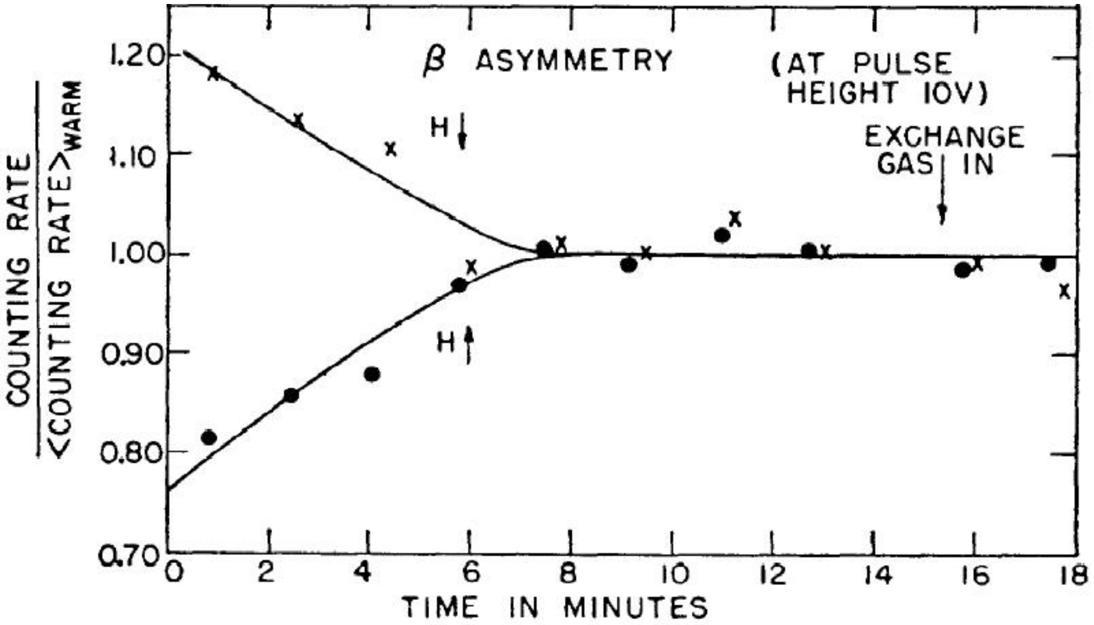


IF P is conserved, these two configurations should have the same probability

Evidence for P violation

- The result of the Wu experiment is that the electrons are preferentially produced in the opposite direction of the spins of the ^{60}Co atoms.





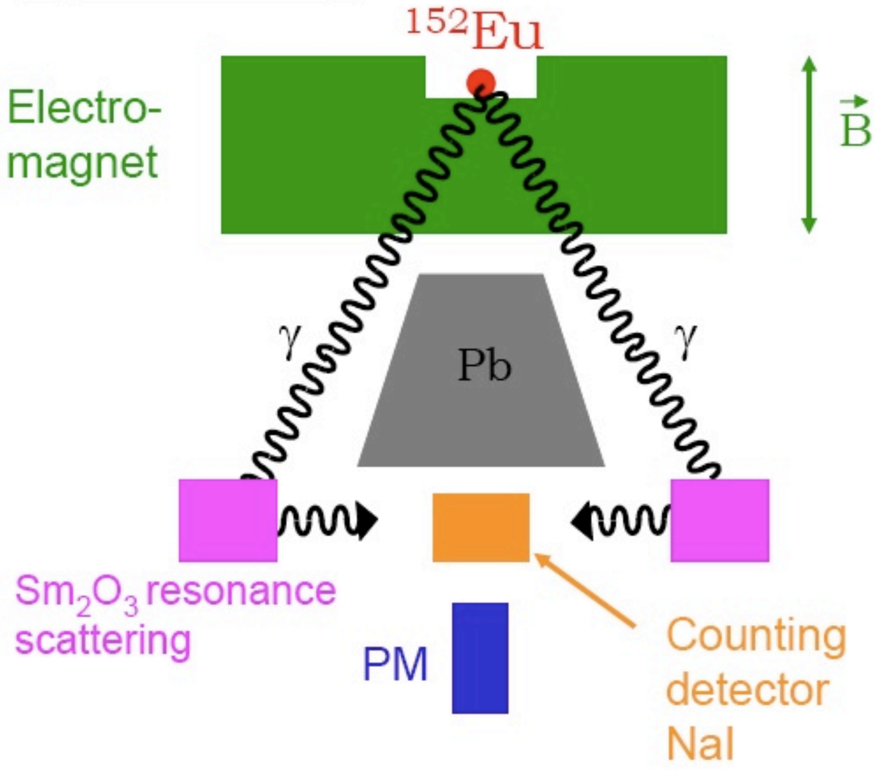
- The magnetic field direction is changed
  - ✓The asymmetry is reversed

Parity is violated: the preferred chiral state is a left electron.

The Goldhaber experiment

Phys. Rev. 109, 1015 (1958)

Experimental set-up:

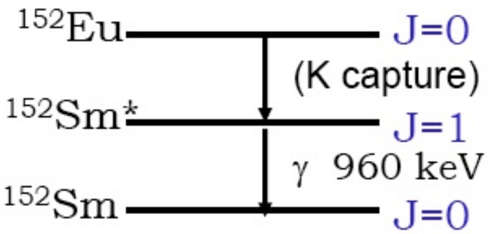


γ emitted in the direction of the momentum of the Sm* are selected

$$^{152}\mathrm{Eu}(J=0) + e^- \rightarrow {}^{152}\mathrm{Sm}^*(J=1) + \nu$$

(K capture)

$$\hookrightarrow {}^{152}\mathrm{Sm}(J=0) + \gamma$$



The spins of all final states particles are constrained. The gammas aligned with the ^{152}Sm are selected and their polarization is measured.

Neutrinos are left-handed

- We write down the spin constraints: the spin of the electron defines the initial and the final states. We shall end up with a one-half spin projection. Two configurations are possible:

- Putting the gamma in the game: $^{152}Sm^*(J=1) \rightarrow {}^{152}Sm(J=0) + \gamma$ and writing the helicities of the particles, two possible configurations emerge:

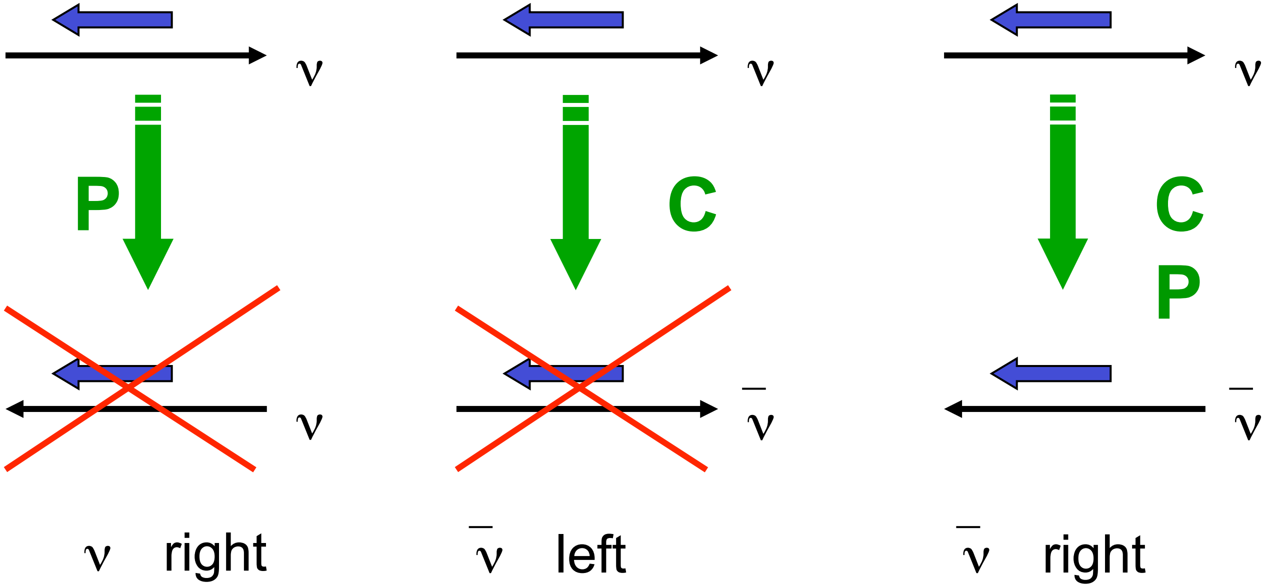
$\lambda\gamma=+1$ $\lambda e=+1/2$ $\lambda\nu=+1/2$

$\lambda\gamma=-1$ $\lambda\varepsilon=-1/2$ $\lambda\nu=-1/2$

- From the gamma polarization measurement, Goldhaber et al. show that only left-handed neutrinos are found (*i.e.* the second configuration)

Interpretation

- One gets from all experimental results the following picture:



- Weak interactions maximally violate C and P
- Any theory of the weak interaction shall include these properties.

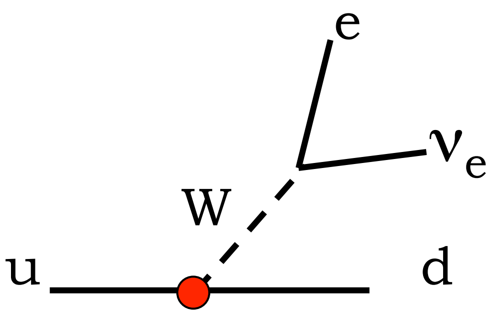
Nobel prize 1957 awarded to Lee and Yang

Cabibbo model (1963)

- Strangeness exists ($K^0 \rightarrow \pi^+\pi^-$)
  - ✓ And is conserved is strong and electromagnetic interactions
- Let's add another additive quantum number S
  - ✓ Strange flavour, not spin !
  - ✓ Lifetimes ~ 20 times bigger for $\Delta S = 1$ transitions than for $\Delta S=0$
- The lifetime of strange particles can be accounted for if we were to consider a mixing between s and d quarks. We say that the mass eigenstates are a linear combination of the weak eigenstates:

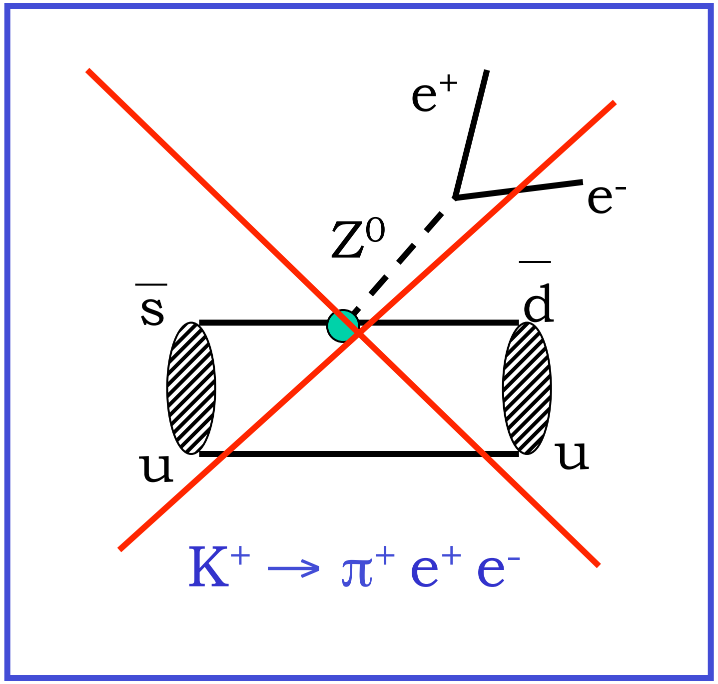
$$\begin{pmatrix} u \\ d_C \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{pmatrix}$$

  - ✓ Experimentally: $\theta_C \simeq 13°$
- The couplings are modified such that:
  - ✓ ud coupling: $G_F \rightarrow G_F \cos\theta_C$
  - ✓ us coupling: $G_F \rightarrow G_F \sin\theta_C$

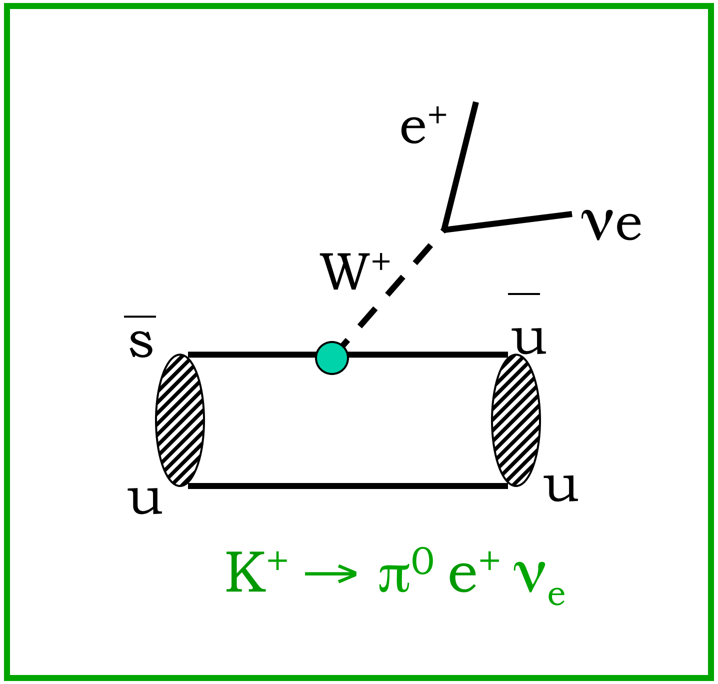


Flavour Changing Neutral Current

- Neutral currents do exist (Gargamelle, 1973) but we never observed:



sd coupling



su coupling

- Let's consider the neutral couplings of a (ud_C) doublet ψ:

$$\bar{\psi}\psi = \bar{u}u + \bar{d}d\cos^2\theta_C + \bar{s}s\sin^2\theta_C + (\bar{d}s + \bar{s}d)\sin\theta_C\cos\theta_C$$

✓The last part allows unobserved FCNC…

The GIM mechanism

- 1970: GIM (Glashow, Iliopoulous, Maiani) introduced a 4th quark c ranked in a second doublet together with the strange quark:

$$\begin{pmatrix} c \\ s_C \end{pmatrix} = \begin{pmatrix} c \\ s\cos\theta_C - d\sin\theta_C \end{pmatrix}$$

- The neutral couplings of a (cs_C) doublet ϕ are:

$$\bar{\phi}\phi = \bar{c}c + \bar{d}d\sin^2\theta_C + \bar{s}s\cos^2\theta_C - (\bar{d}s + \bar{s}d)\sin\theta_C\cos\theta_C$$

- Summing over the 2 doublets, FCNC are suppressed:

$$\bar{\psi}\psi + \bar{\phi}\phi = \bar{u}u + \bar{c}c + \bar{d}d + \bar{s}s$$

- The charged currents have to be written with the proper mixing:

$$\begin{pmatrix} d' \\ s' \end{pmatrix}_{EW} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}_{MASS}$$

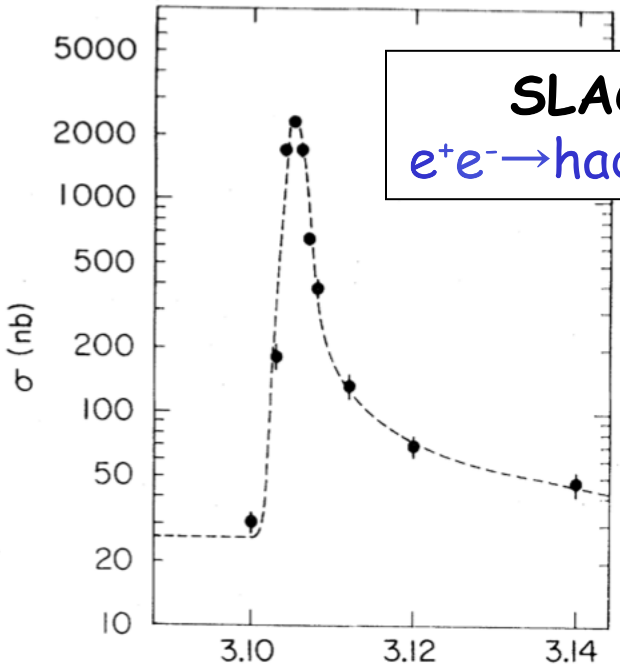
- As a by-product, there shall exist a fourth quark: the charm quark.

Charm discovery

In 1974, at SLAC (e+e-) and at Brookhaven (p on a Be target), a very narrow resonance is seen:

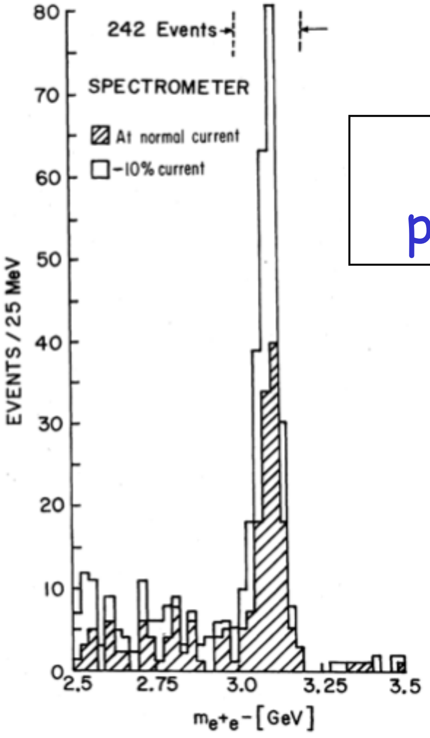
✓Observed in the electronic, muonic and hadronic channels

✓m ~ 3.1 GeV/c^2 → $J/\psi \equiv c\bar{c}$



SLAC

$e^+e^- \rightarrow$ hadrons



BNL

$pBe \rightarrow e^+e^-X$

Nobel prize 1976 awarded to Richter and Ting

K^0 mixing

- Two K^0 decays are possible but they exhibit very different lifetimes:

$$\begin{aligned} K^0 &\rightarrow \pi\pi \ \text{ with } \ \tau_{\pi\pi} \approx 10^{-11}, \\ K^0 &\rightarrow \pi\pi\pi \ \text{ with } \ \tau_{\pi\pi\pi} \approx 10^{-8} \end{aligned}$$

- In quantum mechanics, K^0 and its antiparticle can mix
  - ✓Hence, the decaying particle (weak eigenstate) is a mixture of the mass eigenstates (strong interaction):

$$|K_1\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$$
$$|K_2\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$$

- K_1 and K_2 are CP eigenstates: $CP|K_1\rangle = +|K_1\rangle$; $CP|K_2\rangle = -|K_2\rangle$
- Final states CP eigenvalues are +1 ($\pi\pi$) and -1 ($\pi\pi\pi$).
- If CP is conserved, one then should have: $K_1 \rightarrow \pi\pi$ and $K_2 \rightarrow \pi\pi\pi$
  - ✓Which we'll identify as K^0_S and K^0_L respectively

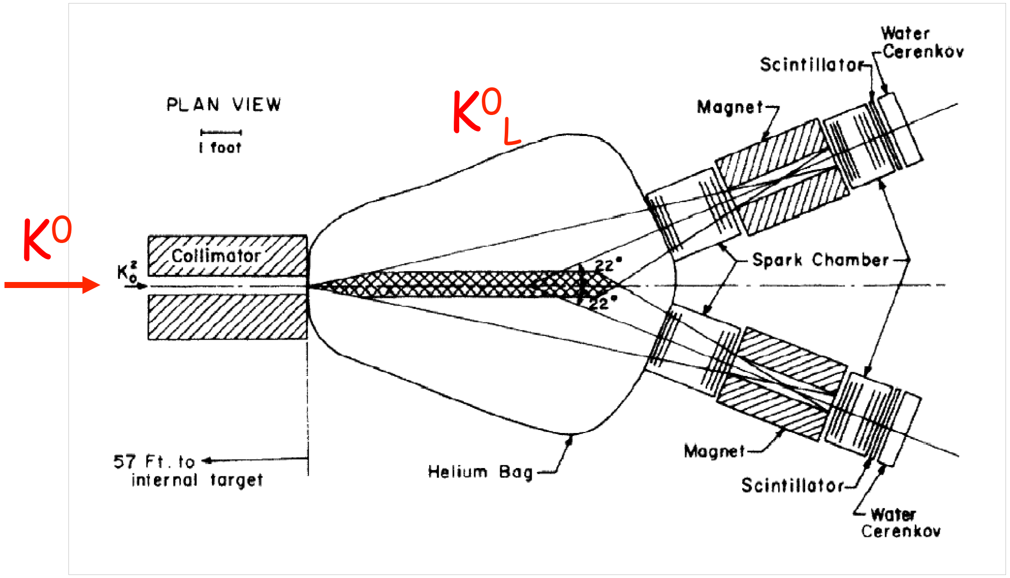
Discovery of CP violation

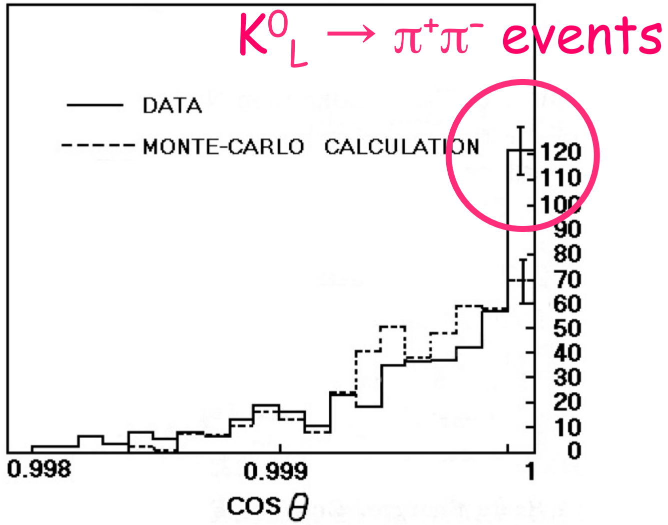
What if we would measure K^0_L decays into two pions?

That would be the indication that CP symmetry is violated in weak interaction.

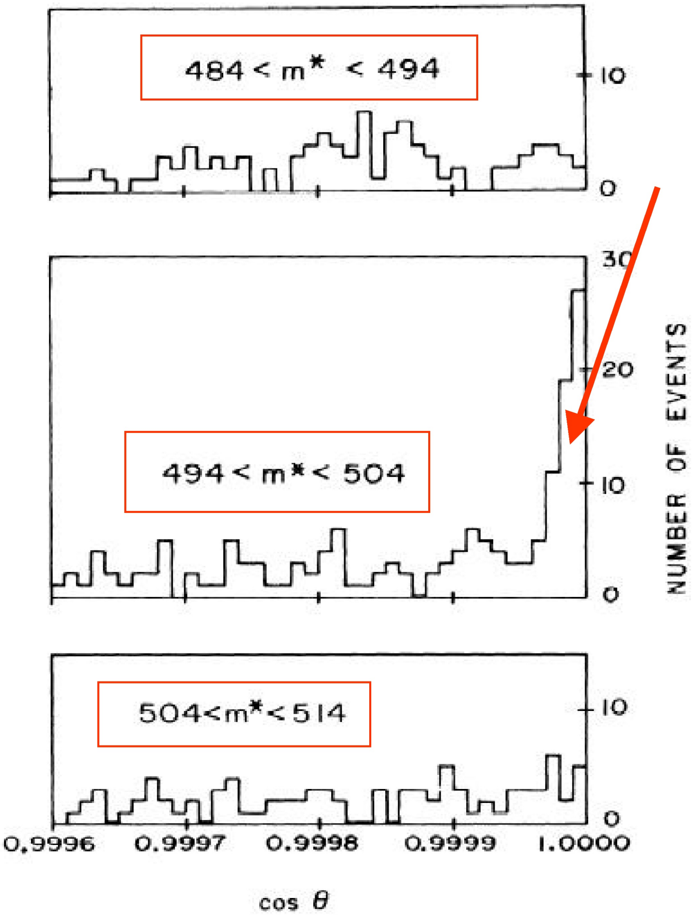
Christenson, Cronin, Fitch and Turlay, Phys. Rev. Lett. 13, 138 (1964)

Far after the target, only K^0_L long survive. They measured:





Discovery of CP violation



- Two body decay: in the K^0 center of mass the 2 pions are back to back
  - ✓ $\cos\theta = 1$
- Today's more precise measurement of the ratio of amplitudes:

$$|\eta_{+-}| = \frac{A(K_L^0 \to \pi\pi)}{A(K_S^0 \to \pi\pi)} = (2.271 \pm 0.017)10^{-3}.$$

- CP is violated. Slightly, but theory has to handle that feature of weak interaction.

Nobel prize 1980 awarded to Cronin and Fitch

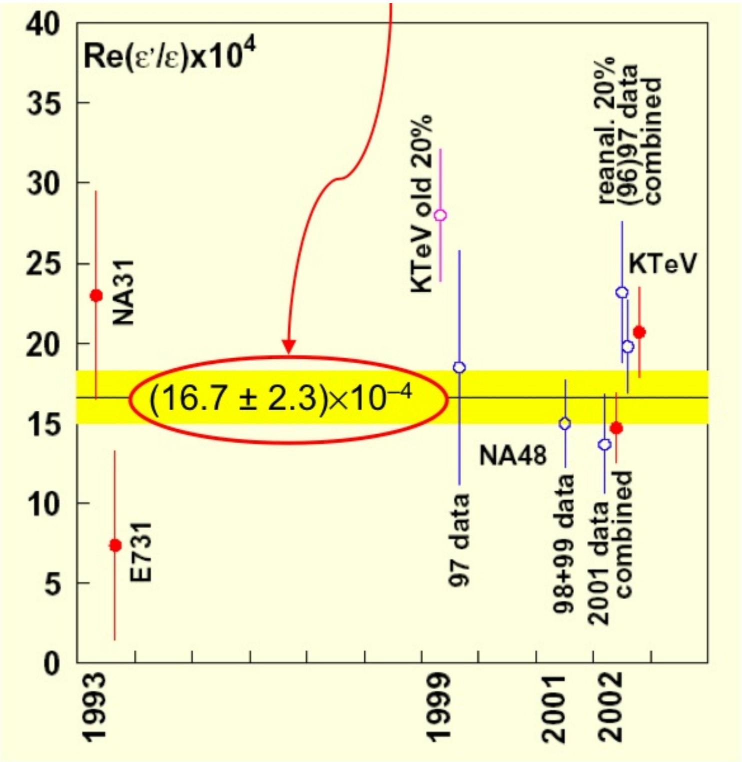
Direct CP violation in K^0 decays

- Not only the CP violation in the kaon mixing has been measured but also the direct CP violation in the kaon decay.

- Ratio of direct CP violation over indirect CP violation (ε′/ε) measured thanks to

$$\frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}$$

$$\approx \; 1 - 6 \times Re(\epsilon'/\epsilon)$$



- This is a very small effect and the first observation was reported in 2001 by NA48 and KTeV experiments, after 30 years of efforts.

The CKM matrix

- In 1972, Kobayashi and Maskawa introduced a 3rd family showing that it enables CP violation in weak interactions.

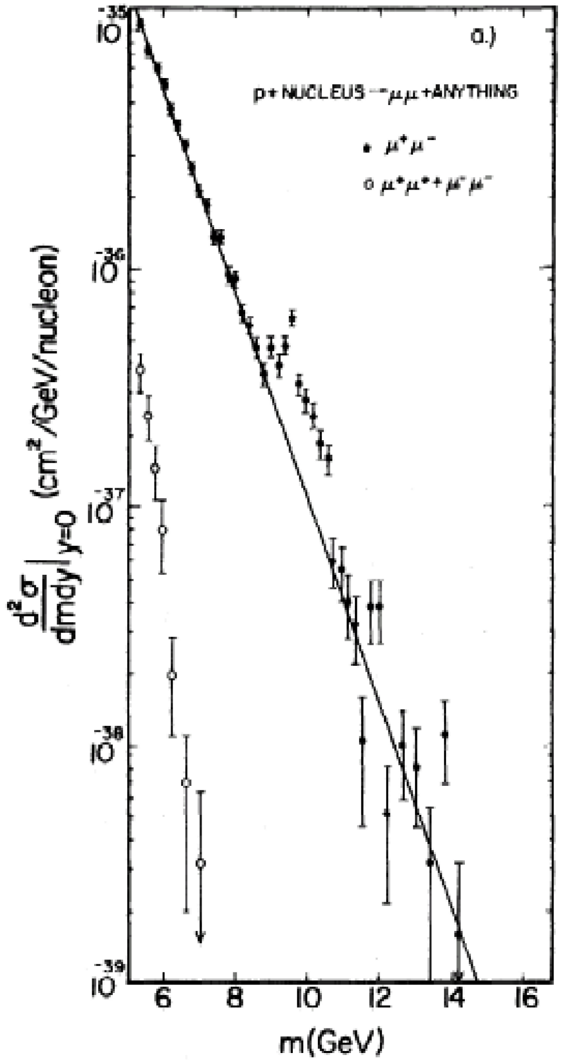
- The description of the weak eigenstates as a mixture of mass eigenstates is then controlled by the so-called CKM matrix (CKM ≡ Cabibbo-Kobayashi-Maskawa):

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{EW} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{MASS}$$

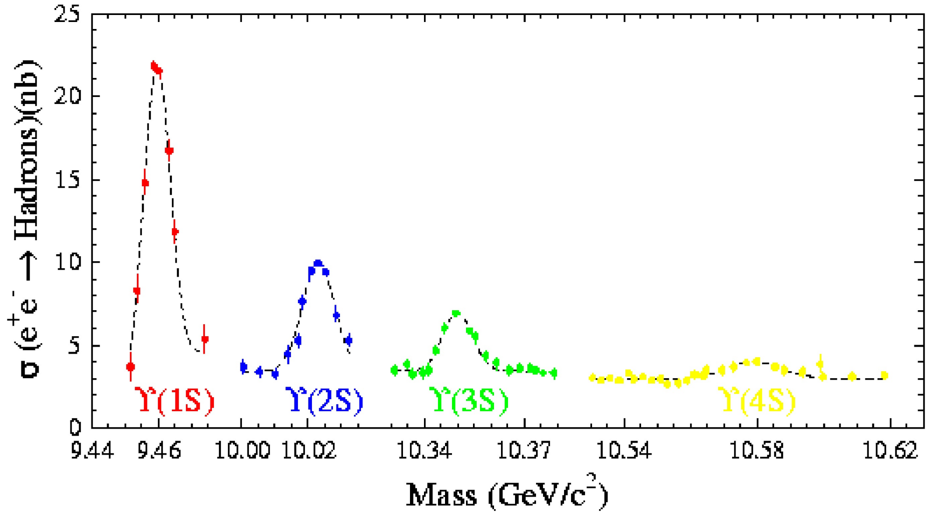
- This matrix is a 3X3, unitary, complex, and hence described by means of four parameters: 3 rotation angles and a phase.
  - ✓The latter, often called the KM phase, makes possible the violation of the CP symmetry in the Standard Model (SM).

- These four parameters are free parameters of the SM.

Beauty discovery



- In 1977 at Fermilab, discovery of the Υ serie ~ 9.5 to 10.5 GeV/c^2
  - ✓ $b\bar{b}$ resonances
  - ⇒ there is a 3rd generation of quarks
- B factories (CLEO, BaBar, BELLE): the Υ(4S) decays into a $B^0\bar{B}^0$ or B^+B^- pair



CKM matrix parameterization

- Consider the Wolfenstein parametrization as in EPJ C41, 1-131, 2005 → unitary-exact and phase convention independent:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad \lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}\ , \quad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}$$

$$\text{and} \quad \overline{\rho} + i\overline{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

- λ is measured from $|V_{ud}|$ and $|V_{us}|$ in superallowed beta decays and semileptonic kaon decays, respectively: $\lambda \simeq 0.227$ ($\sin\theta_C$).

- A is further determined from $|V_{cb}|$, measured from semileptonic charmed B decays: $A \simeq 0.80$.

- The last two parameters are to be determined from angles and sides measurements of the CKM unitarity triangle.

The CKM unitarity triangle

- An elegant way to represent the unitarity relations is to display them in the complex plane.
- $$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{cd}V_{cb}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0.$$

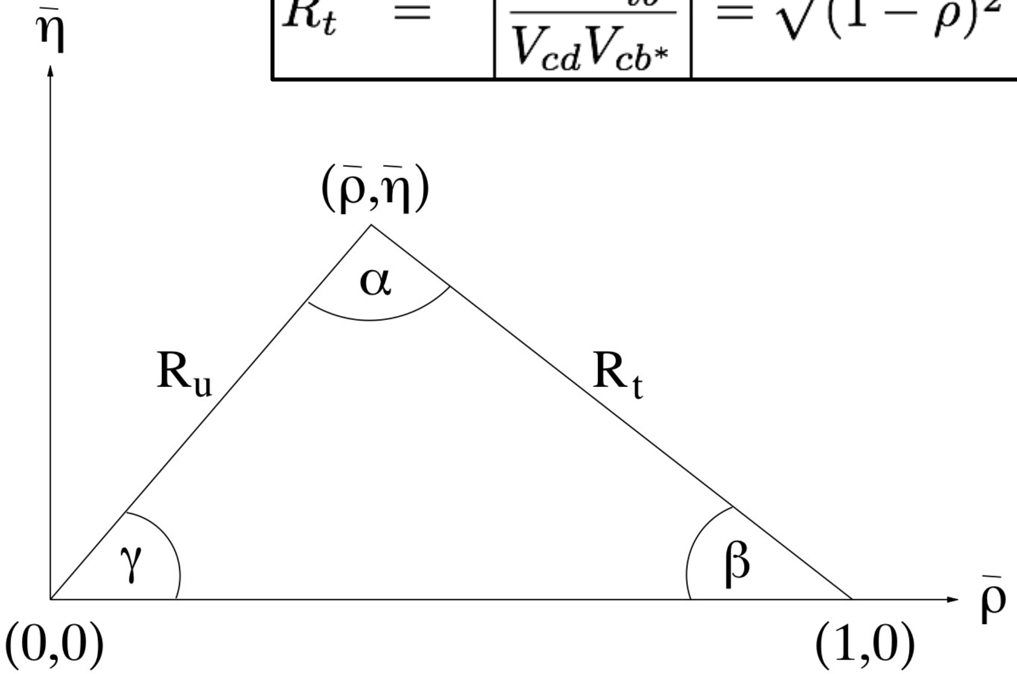
$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb*}}\right| = \sqrt{\bar\rho^2 + \bar\eta^2}\,,$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb*}}\right| = \sqrt{(1-\bar\rho)^2 + \bar\eta^2}\,.$$

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

$$\beta = \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right),$$

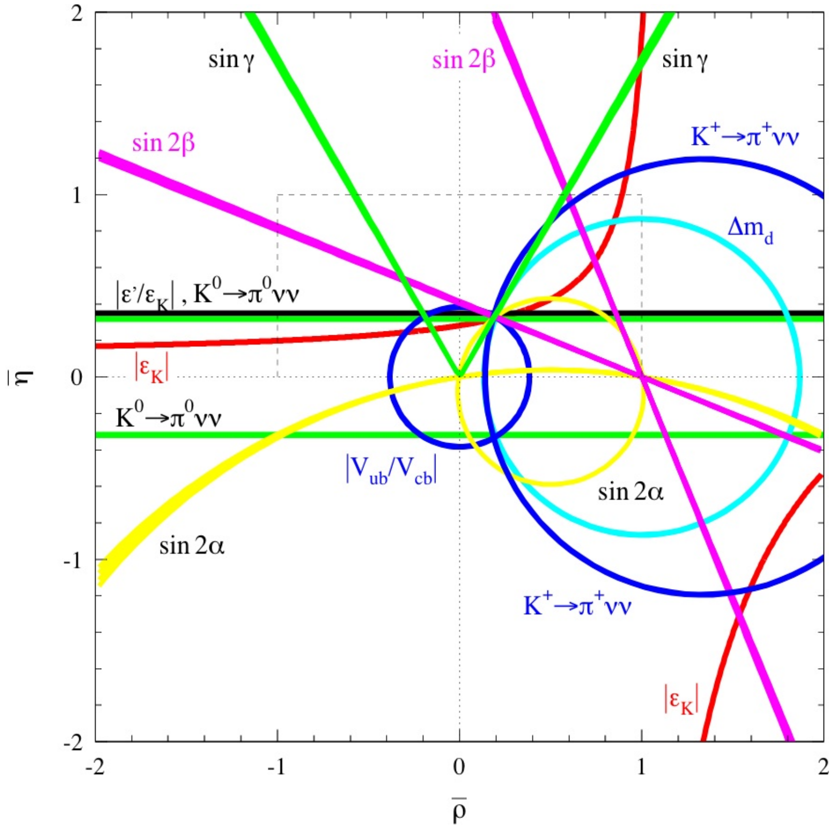
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$



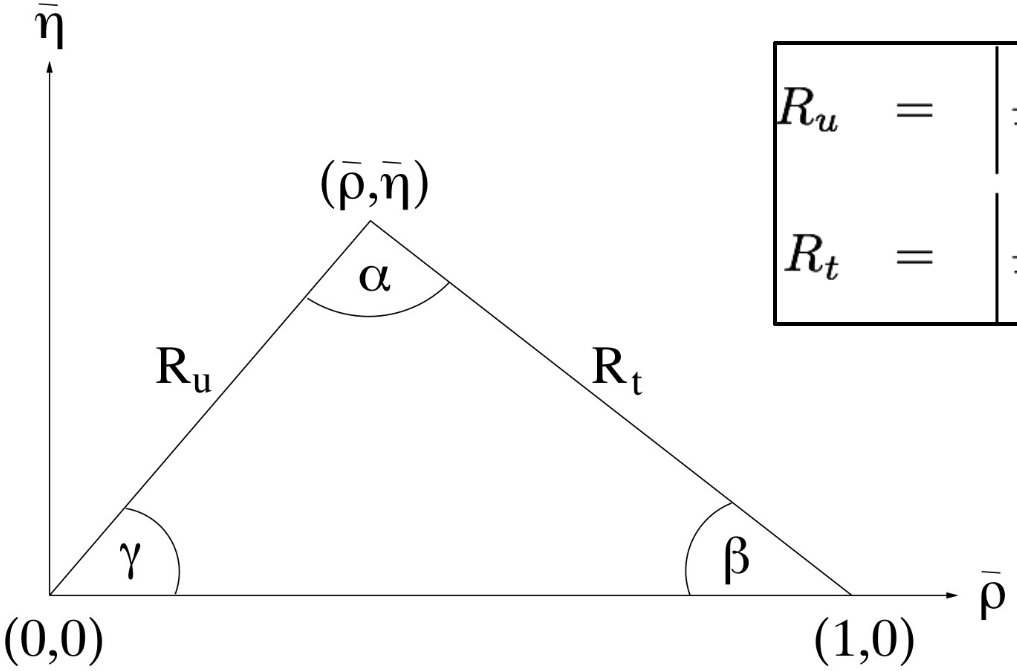
The CKM unitarity triangle

- The area of the triangle is half the Jarlskog invariant and measures the magnitude of the CP violation:

$$J = \mathrm{Im}[V_{ud}V_{cs}V_{us}^{*}V_{cd}^{*}] = A^2\lambda^6\eta\left(1-\lambda^2/2\right) + \mathcal{O}(\lambda^{10}) \sim 10^{-5}$$



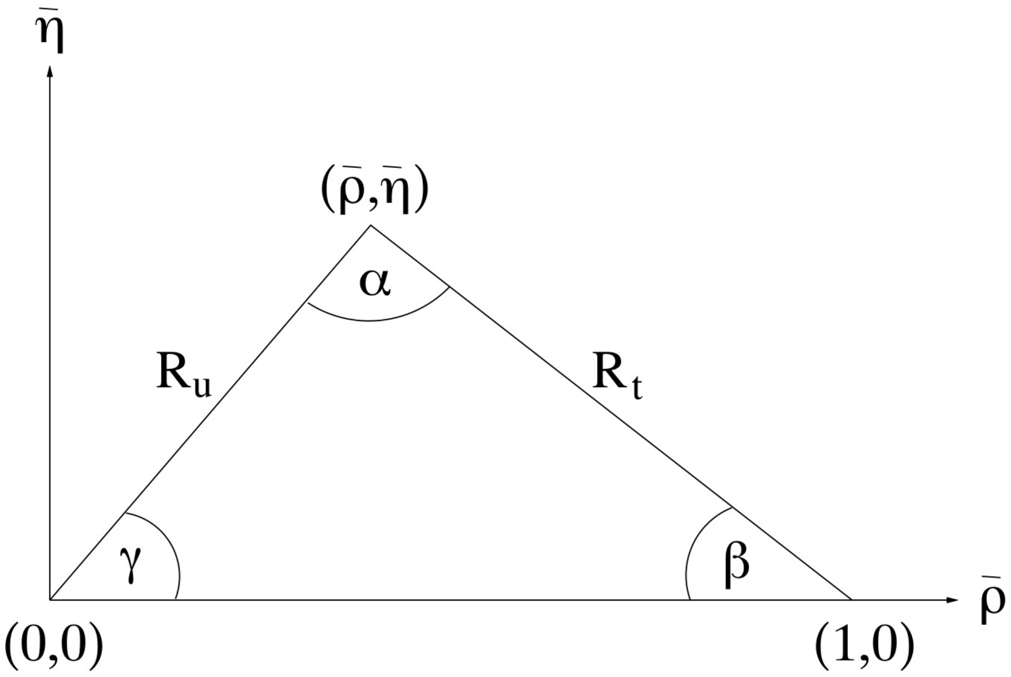
Sides of the unitarity triangle



$$
\begin{aligned}
R_u &= \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb*}}\right| = \sqrt{\bar{\rho}^2+\bar{\eta}^2}\,, \\
R_t &= \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb*}}\right| = \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2}\,.
\end{aligned}
$$

- ➢ R_u is measured by the matrix elements V_{ub} and V_{cb} extracted from the semileptonic decays of b-hadrons.
- ➢ R_t implies the matrix element V_{td} and hence can be measured from the mixing of B^0 mesons.

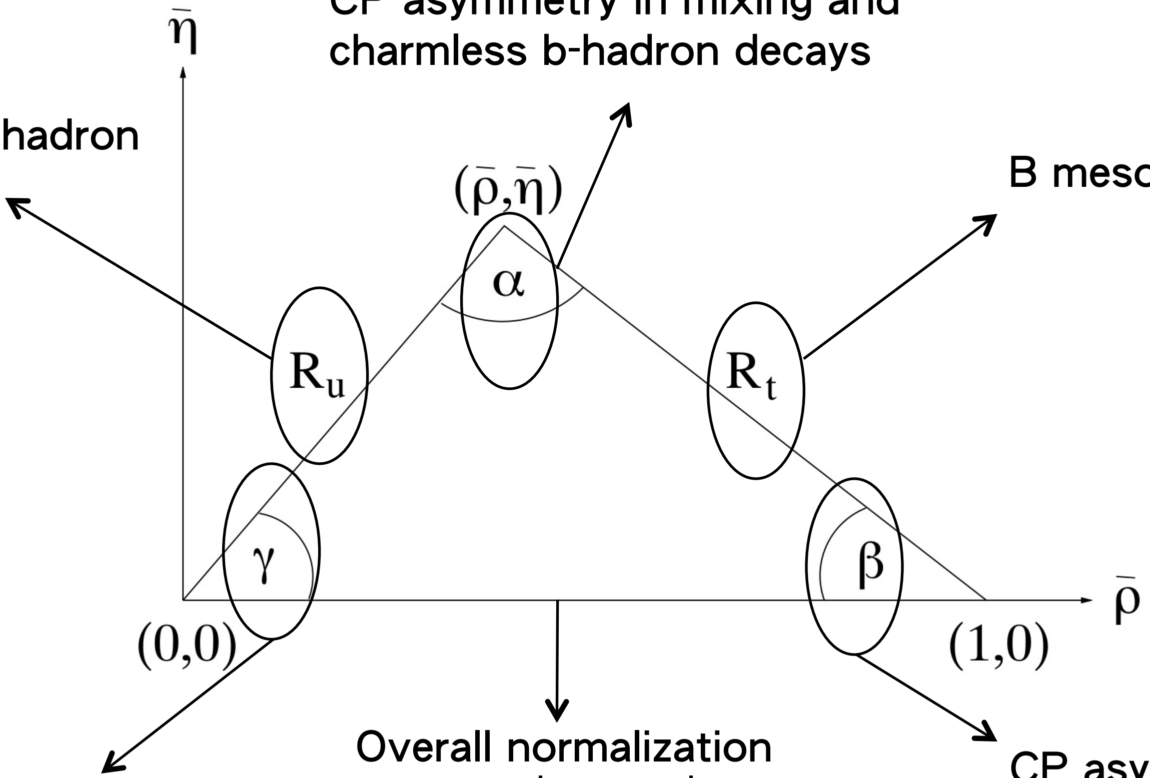
Angles of the unitarity triangle



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$
$$\beta = \pi - \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right),$$
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

- β is directly the weak mixing phase of the B^0 mixing.
- γ is the weak phase at work in the charmless decays of b-hadrons.
- The angle α is nothing else than $(\pi-\beta-\gamma)$ and can be exhibited in processes where both charmless decays and mixing are present.

Constraining the unitarity triangle



CP asymmetry in mixing and charmless b-hadron decays

Semileptonic b-hadron decays

B meson mixing

CP asymmetry in charmless b-hadron decays

Overall normalization given by $|V_{cd}V^*_{cb}|$, hence semileptonic b decays

CP asymmetry in mixing processes

Experiments

- Many experiments are interested in the flavour physics and CP violation.
  - Pioneering role: ARGUS (DESY, Ge), CLEO (Cornell,US) and LEP (CERN, EU) experiments.
  - Major results for kaon sector came from NA48 (CERN, EU) and KTeV (FNAL, US).

- B-physics nowadays
  - Coherent b quarks pair production: the B factories.
    - ✓BaBar (SLAC, US)
    - ✓Belle (KEK, Japan)
  - Incoherent b quarks pair production:
    - ✓Tevatron (FNAL, US) experiments: CDF and D0
    - ✓LHC (CERN, EU) experiments: ATLAS, CMS and LHCb

B factories

Main characteristics of the B factories at the Υ(4s):

- ➢ The series of Υ contains the Υ(4S), above the production threshold of $B\bar{B}$ pairs
  - ✓Almost 100% of the Υ(4S) decays is $B\bar{B}$ production

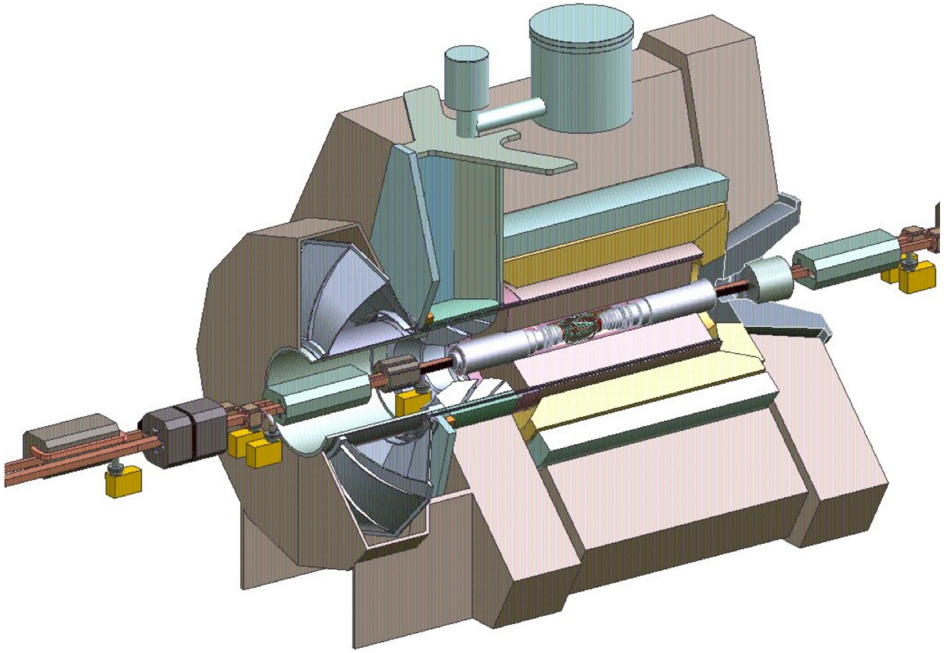
- ➢ Coherent $B\bar{B}$ production: when one decays, you know the flavour of the other at the same time
  - ✓Ideal flavour tagging

- ➢ Beams are asymmetric
  - ✓The Υ(4S) is boosted allowing time separation between the B

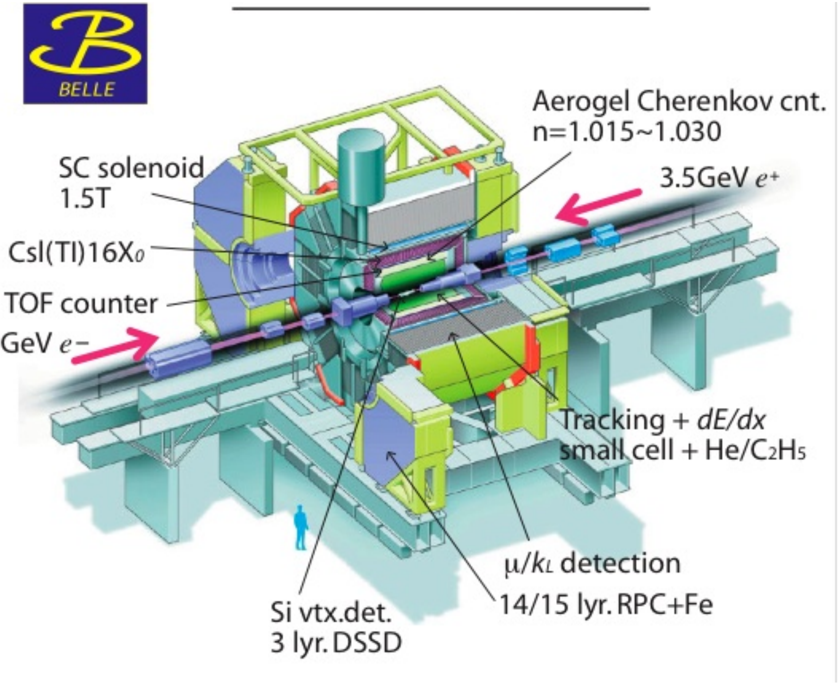
- ➢ No hadronization
  - ✓Very clean experimental environment

BaBar and Belle

BaBar (PEPII, US)
9 vs 3.1 GeV/c: $\beta\gamma=0.56$



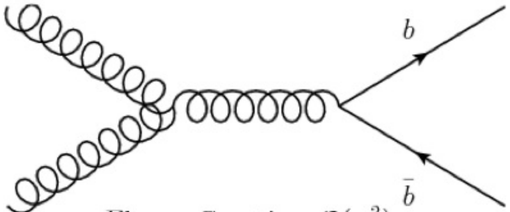
Belle (KEKB, Japan)
8 vs 3.5 GeV/c: $\beta\gamma=0.425$



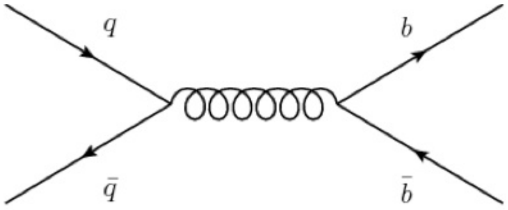
Common detector characteristics: excellent vertexing and particle identification with Cerenkov imaging detectors.

B production at Tevatron and LHC

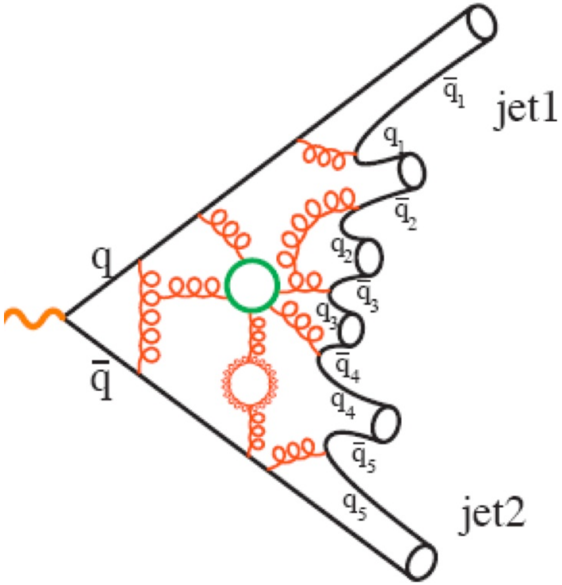
- Incoherent b quarks pair production
  - ✓Flavour tagging much less efficient than at B factories
- There is hadronization
  - ✓Busy hadronic environment
- All the b-hadrons species can be produced
  - ✓Unique laboratory for b baryons and charm B meson
- Huge production cross-sections
  - ✓Hence huge statistics (but a trigger strategy is required)
- Energy: b-hadrons do receive an important boost.
  - ✓Vertexing capability to identify the b-hadron decay vertex.



Flavor Creation $\mathcal{O}(\alpha_s^2)$

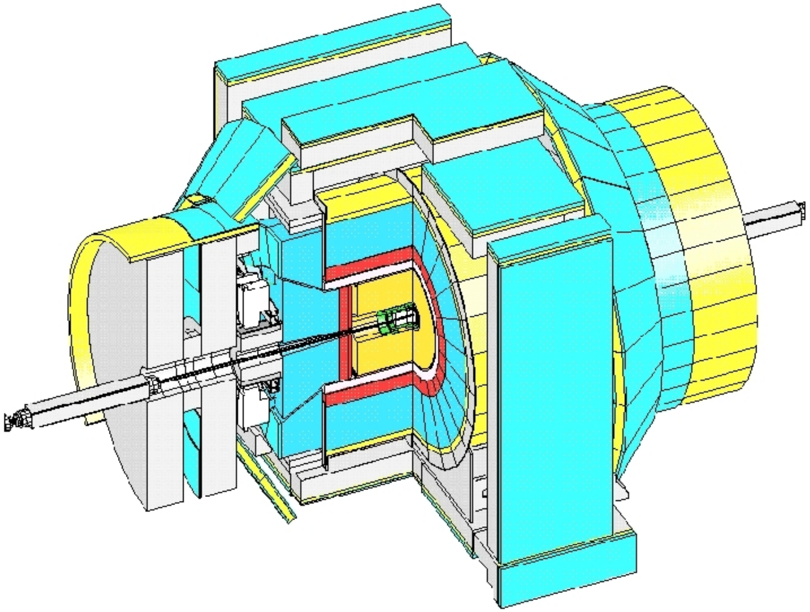


Flavor Creation $\mathcal{O}(\alpha_s^2)$

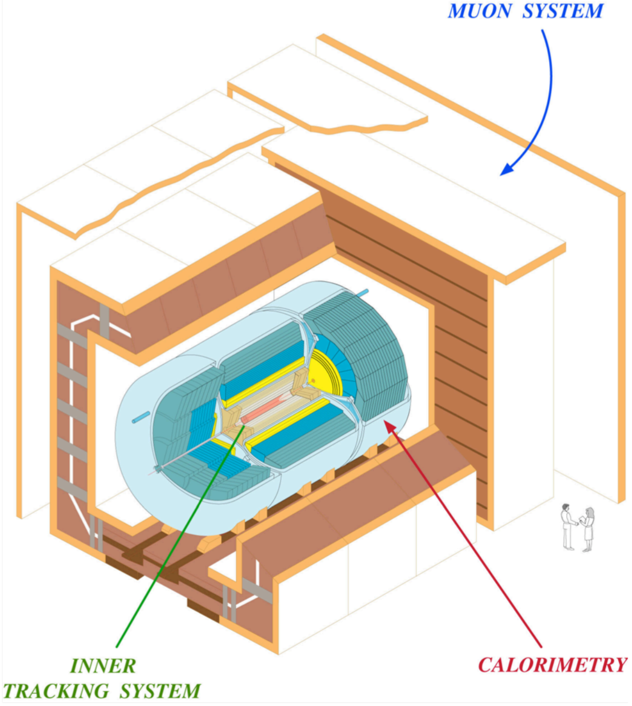


CDF and D0

CDF



D0



CDF and D0 are multipurpose experiments

- ✓D0 has an excellent muon coverage
- ✓CDF has a flexible trigger and excellent tracking for b physics

B^0 mixing

- As we have seen in the kaon system, weakly decaying neutral mesons can mix.
- The B^0 mixing first observation was in 1987 by the Argus collaboration:

B^0-mixing: First Observation at Argus, DESY, 1987

PLB192, 245 (1987)

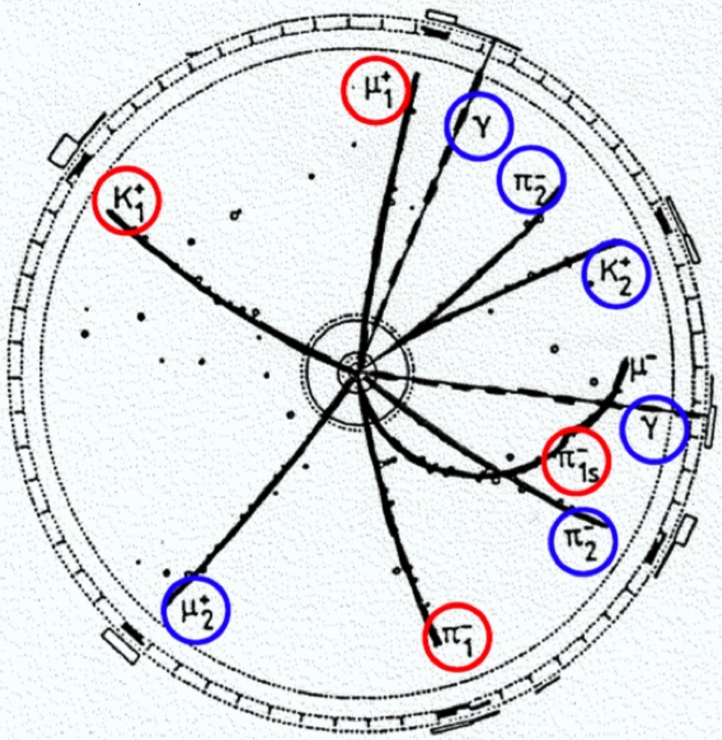


Fig. 11: The fully reconstructed ARGUS event [26]
$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B}^0 \rightarrow B^0B^0$
as the first evidence for the occurance of $B^0\overline{B}^0$ oscillations.
$B^0 \rightarrow D_1^{*-}\mu_1^+\nu,$ ←
$D_1^{*-} \rightarrow \pi_{1s}^-\overline{D}^0,\ \overline{D}^0 \rightarrow K_1^+\pi_1^-.$
$\overline{B}^0 \rightarrow B^0 \rightarrow D_2^{*-}\mu_2^+\nu,$ ←
$D_2^{*-} \rightarrow \pi^0 D_2^-,$
$\pi^0 \rightarrow \gamma\gamma,\ D_2^- \rightarrow K_2^+\pi_2^-\pi_2^-.$

$B^0 \rightarrow D^{*-}\mu^+\nu$

$B^0 \rightarrow D^{*-}\mu^+\nu$

Description of B^0 mixing

- For weakly decaying neutral mesons (K^0, D^0, B^0, B_s), the mass eigenstates (which propagate) are a superposition of the flavour states.

- Example of the B^0 in presence of CP violation:

$$|B_L\rangle = \frac{1}{\sqrt{2}}(p|B^0\rangle + q|\bar{B}^0\rangle)$$
$$|B_H\rangle = \frac{1}{\sqrt{2}}(p|B^0\rangle - q|\bar{B}^0\rangle)$$

- The time evolution of these mass states is derived by solving the Schrödinger equation for the hamiltonian $H=M-i\Gamma/2$:

$$|B_{L,H}\rangle = e^{-i(M_{L,H}-i\frac{\Gamma_{L,H}}{2})t} \cdot |B_{L,H}(t=0)\rangle$$

Time evolution

- One obtains the following time evolution:

$$
\begin{aligned}
|B^0(t)\rangle &= g_+(t)|B^0\rangle + \frac{q}{p} g_-(t)|\bar{B}^0\rangle \\
|\bar{B}^0(t)\rangle &= \frac{p}{q} g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle
\end{aligned}
$$

- With

$$
\begin{aligned}
g_+(t) &= e^{-i(m_B - i\frac{\Gamma_B}{2})t}\left[\cosh\frac{\Delta\Gamma_B t}{4}\cos\frac{\Delta m_B t}{2} - i\,\sinh\frac{\Delta\Gamma_B t}{4}\sin\frac{\Delta m_B t}{2}\right], \\
g_-(t) &= e^{-i(m_B - i\frac{\Gamma_B}{2})t}\left[-\sinh\frac{\Delta\Gamma_B t}{4}\cos\frac{\Delta m_B t}{2} + i\,\cosh\frac{\Delta\Gamma_B t}{4}\sin\frac{\Delta m_B t}{2}\right]
\end{aligned}
$$

- Where we defined the average mass $m_B = (M_H + M_L) / 2$ and width $\Gamma_B = (\Gamma_H + \Gamma_L) / 2$ as well as the mass difference $\Delta m_B = M_H - M_L$ and width difference $\Delta\Gamma_B = \Gamma_H - \Gamma_L$

Time evolution

The master formulae that gives the probability that a B^0 produced as such at t=0 decay in a final state f at t is (neglecting $\Delta\Gamma$ in case of the B^0):

$$\begin{aligned}
P(B^0(0)\rightarrow f) &= \frac{e^{-\Gamma t}}{2}[(1+\cos\Delta m t)\left|\langle f\left|H\right|B^0\rangle\right|^2) \\
&+ (1-\cos\Delta m t)\left|\frac{q}{p}\right|^2\left|\langle f\left|H\right|\bar{B}^0\rangle\right|^2) \\
&- 2\sin\Delta m t\cdot\mathcal{I}m(\left|\frac{q}{p}\right|\left|\langle f\left|H\right|B^0\rangle\right|\cdot\left|\langle f\left|H\right|\bar{B}^0\rangle\right|^*)].
\end{aligned}$$

$$\begin{aligned}
P(\bar{B}^0(0)\rightarrow f) &= \frac{e^{-\Gamma t}}{2}[(1+\cos\Delta m t)\left|\langle f\left|H\right|\bar{B}^0\rangle\right|^2) \\
&+ (1-\cos\Delta m t)\left|\frac{p}{q}\right|^2\left|\langle f\left|H\right|B^0\rangle\right|^2) \\
&- 2\sin\Delta m t\cdot\mathcal{I}m(\left|\frac{p}{q}\right|\left|\langle f\left|H\right|B^0\rangle\right|\cdot\left|\langle f\left|H\right|\bar{B}^0\rangle\right|^*)].
\end{aligned}$$

Δm governs the speed of the oscillations.

Time dependent asymmetry

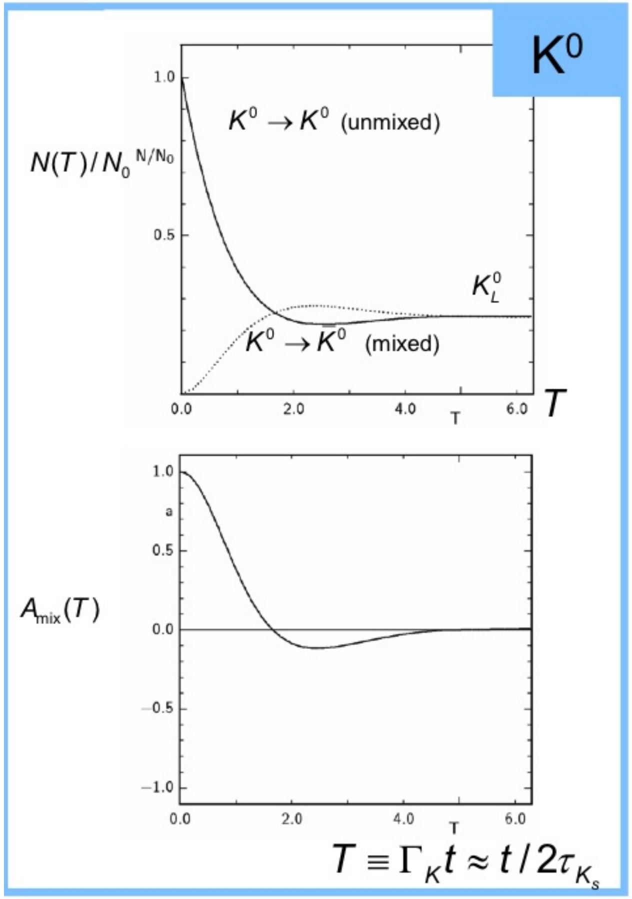
- If we only consider the B^0 mixing in absence of CP violation:

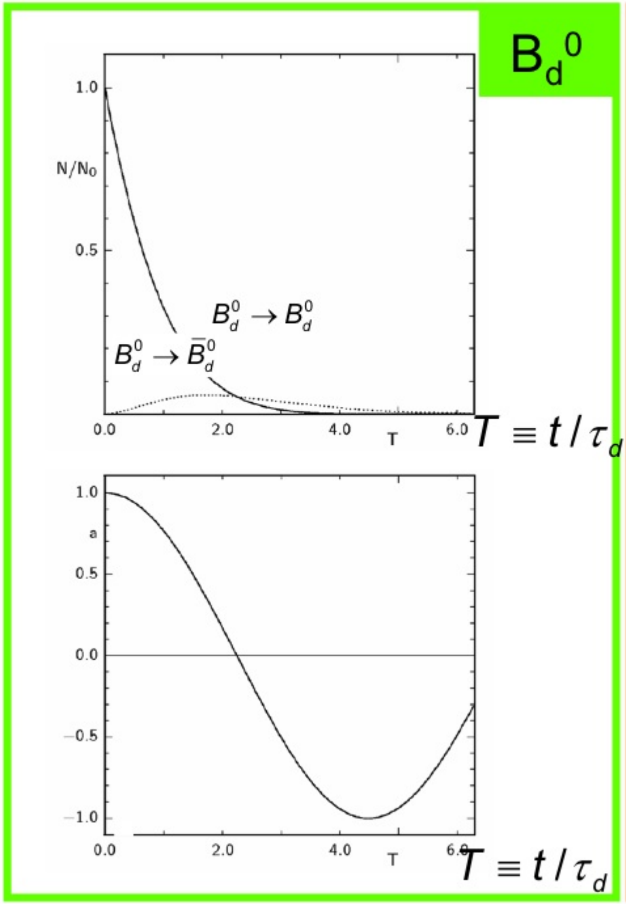
$$\begin{aligned}\left|\langle B^0\,|H|\,B^0(t)\rangle\right|^2 &= \frac{e^{-\Gamma t}}{2}(1+\cos\Delta m t)\\ \left|\langle B^0\,|H|\,\bar{B}^0(t)\rangle\right|^2 &= \frac{e^{-\Gamma t}}{2}(1-\cos\Delta m t)\end{aligned}$$

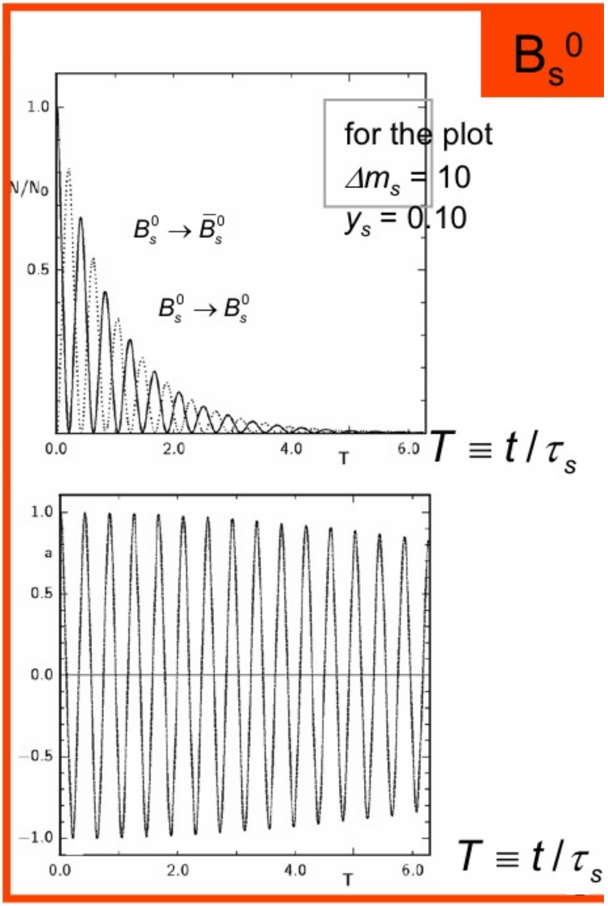
- We want to compare the number of mixed and unmixed events along the evolution. Define the time dependent asymmetry:

$$A_{\mathrm{mix}} = \frac{N(B^0\to B^0) - N(B^0\to\bar{B}^0)}{N(B^0\to B^0) + N(B^0\to\bar{B}^0)} = \cos(\Delta m_d t)$$

Time evolution plots







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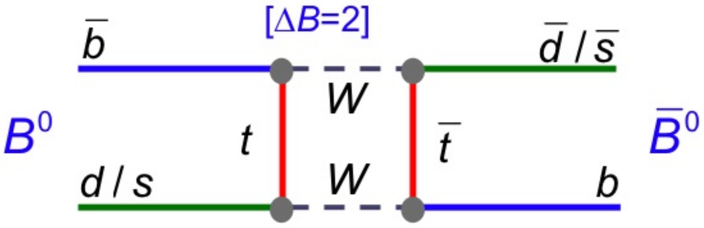
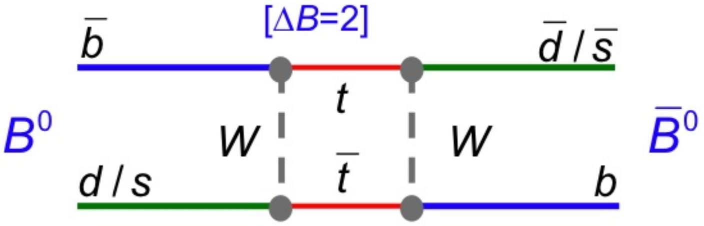
B^0 mixing in the Standard Model

In the SM, the short distance contribution is given by the following diagrams dominated in the loop by the top quark contribution:





and Δm_d is given by:

Non perturbative QCD correction (main uncertainty)

The weak part we are searching for

$$\Delta m_d = \frac{G_F^2}{6\pi^2}\boxed{\eta_B} m_{B_d}\boxed{f_{B_d}^2 B_d} m_W^2 \boxed{S(x_t)}\boxed{|V_{td}V_{tb}^*|^2}$$

Perturbative QCD correction to Inami-Lim function

Inami-Lim function describing the content of the box

Experimental ingredients

The measurements requires several ingredients:

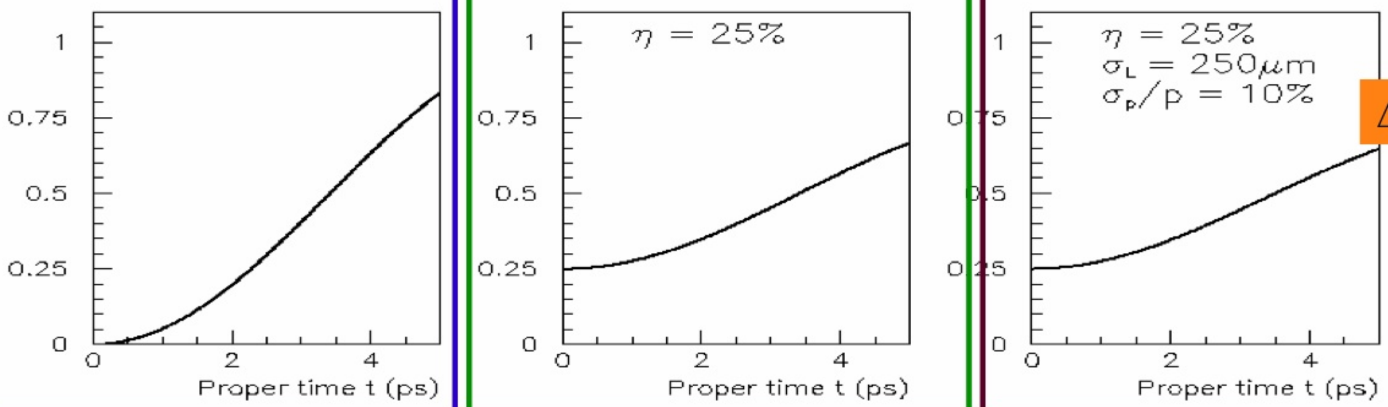
- ➢ Reconstruct the flavour at the decay time
  - ✓ Either use a fully flavour specific hadronic mode or tag the charge with direct semileptonic decays
- ➢ Reconstruct the decay time
  - ✓ Requires excellent vertexing capabilities (in particular to reconstruct the fast Bs oscillations)
- ➢ Reconstruct the flavour at production time: this is the key ingredient
  - ✓ Made easiest at B factories where the B mesons are coherently evolving: the flavour of one B at its decay time gives the flavour of the companion at the same time

Effects on the measurement

Physics →

+tagging →

+ time resolution

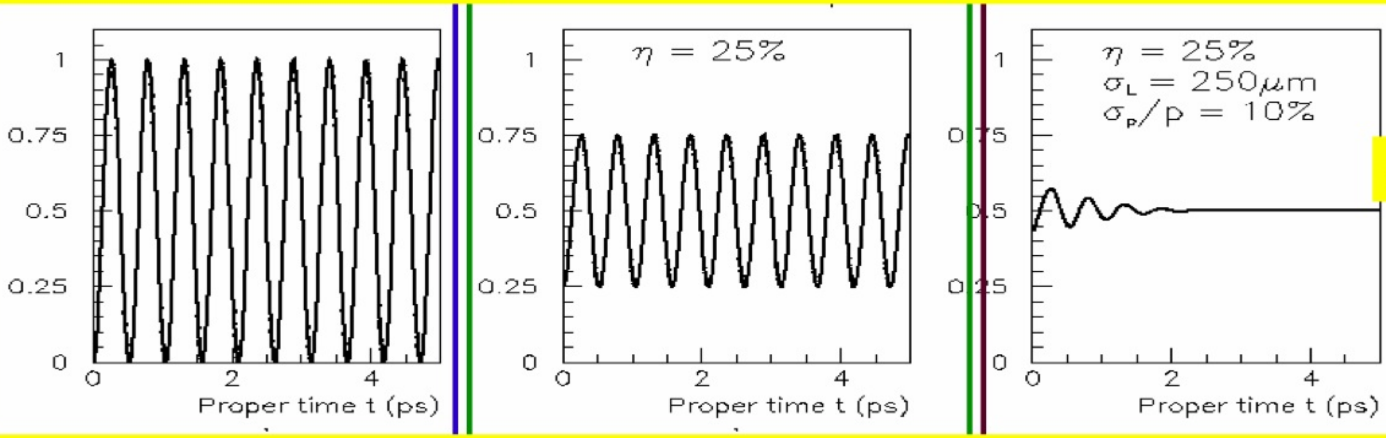


$\Delta m_d = 0.46\ ps^{-1}$

$$A_{\text{mix}} = \frac{(1-\cos\Delta m t)}{2}$$

$$\frac{(1-(1-2\eta)\cos\Delta m t)}{2}$$

$$\frac{(1-(1-2\eta)\cos\Delta m t)}{2} \otimes R(t)$$



$\Delta m_s = 12\ ps^{-1}$

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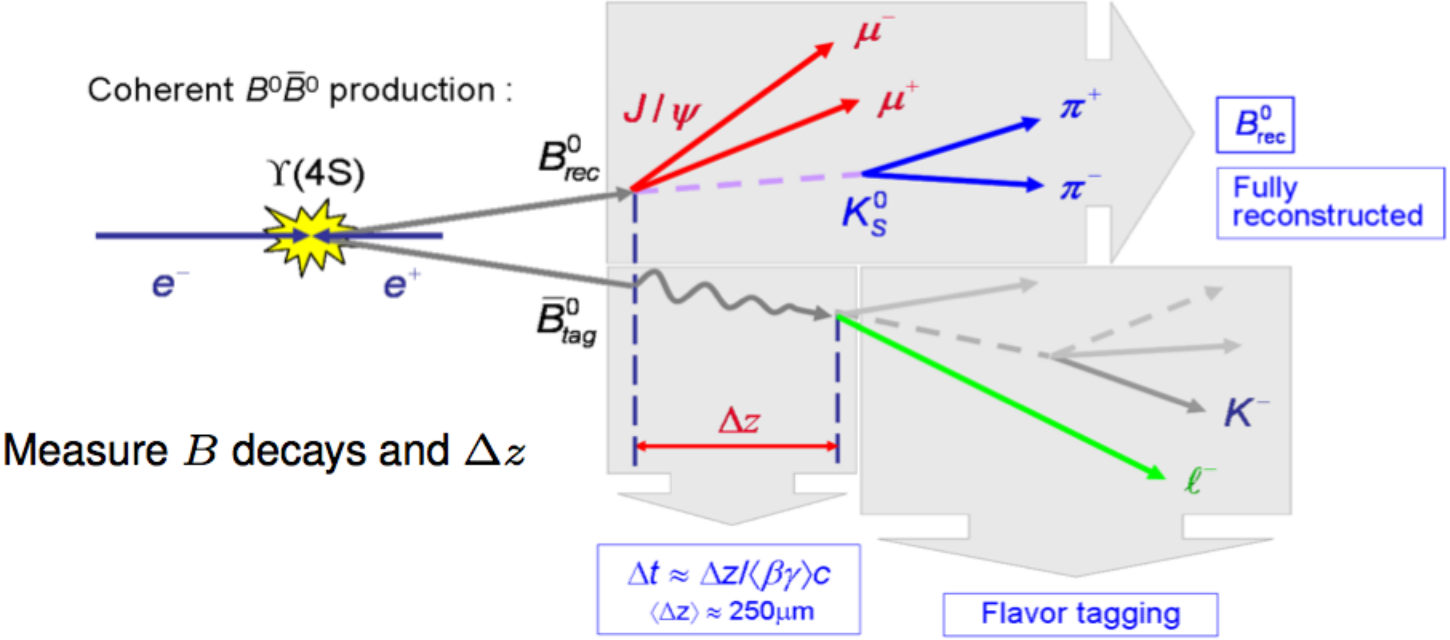
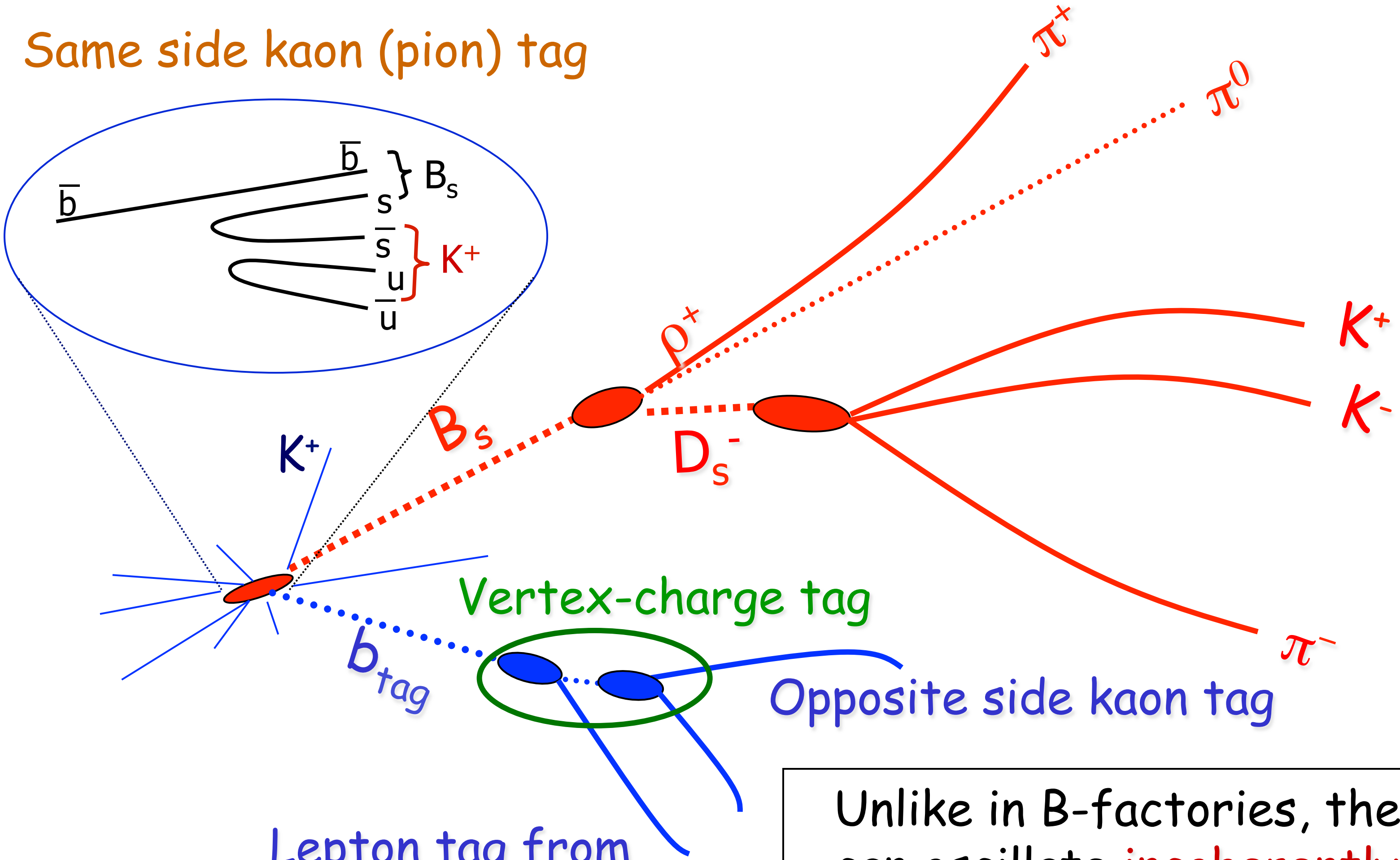
Flavour tagging at B factories

- $B^0\overline{B}^0$ pair evolve coherently and undergo oscillations
  - ✓ Two identical bosons cannot be in an antisymmetric state: if one B decays as B^0 ($\overline{B}^0$), then at the same time the other B must be a $\overline{B}^0$ (B^0)



- EPR effect used for precision physics: first decay ($t = t_1$) ends quantum correlation and tags the flavour of the over B at $t = t_1$

Flavour tagging at hadron colliders



Same side kaon (pion) tag

Vertex-charge tag

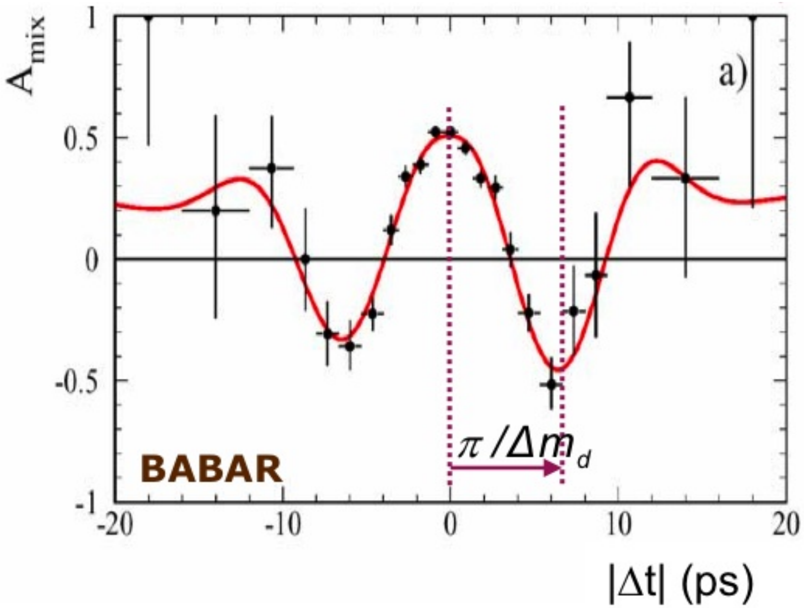
Opposite side kaon tag

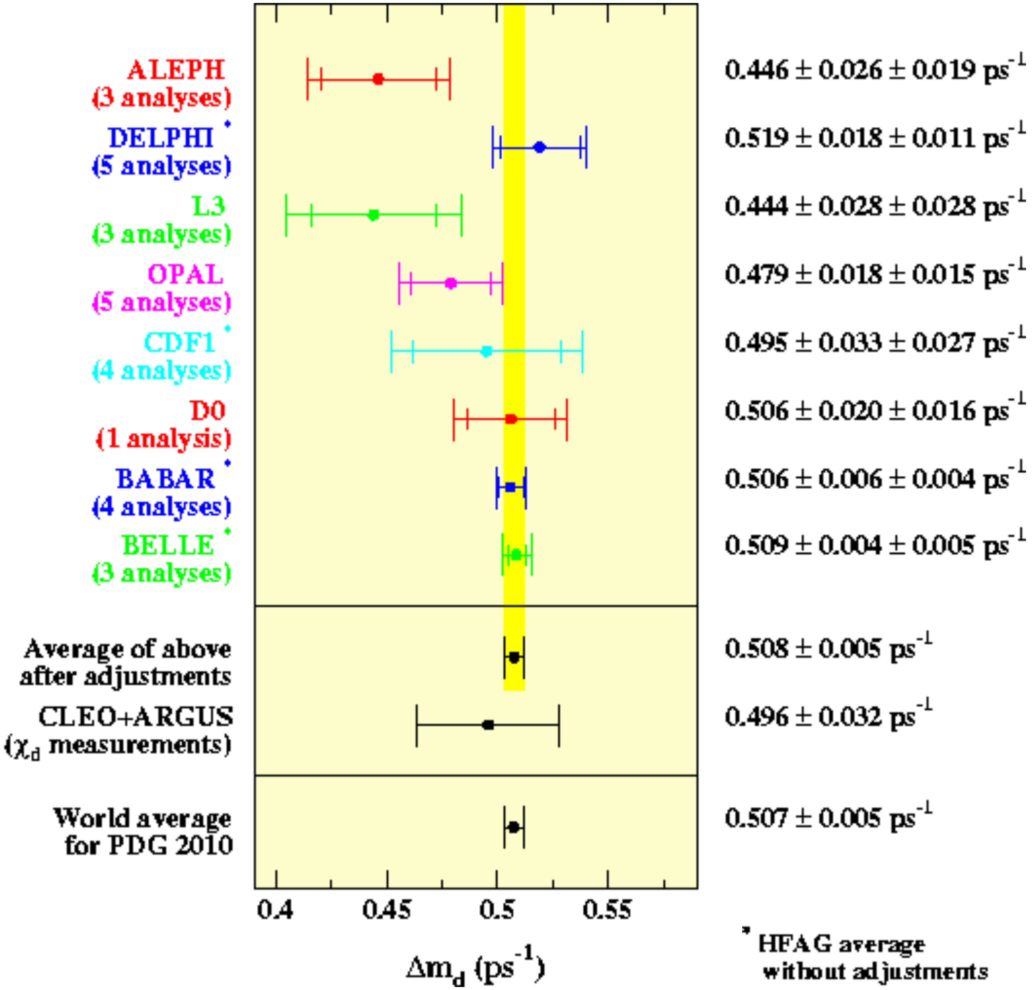
Lepton tag from
b→l and/or b→c→l

Unlike in B-factories, the tagging B can oscillate incoherently :
- 40% $B^\pm$, 10% baryons: no oscillation
- 40% B_d: 17% oscillated
- 10% B_s: 50% oscillated

Δm_d measurements

- An example from BaBar





- A fantastic measurement!
  … among thirty!
- The B factories obviously dominate the world average

R_t from Δm_d

Non perturbative QCD correction (main uncertainty)

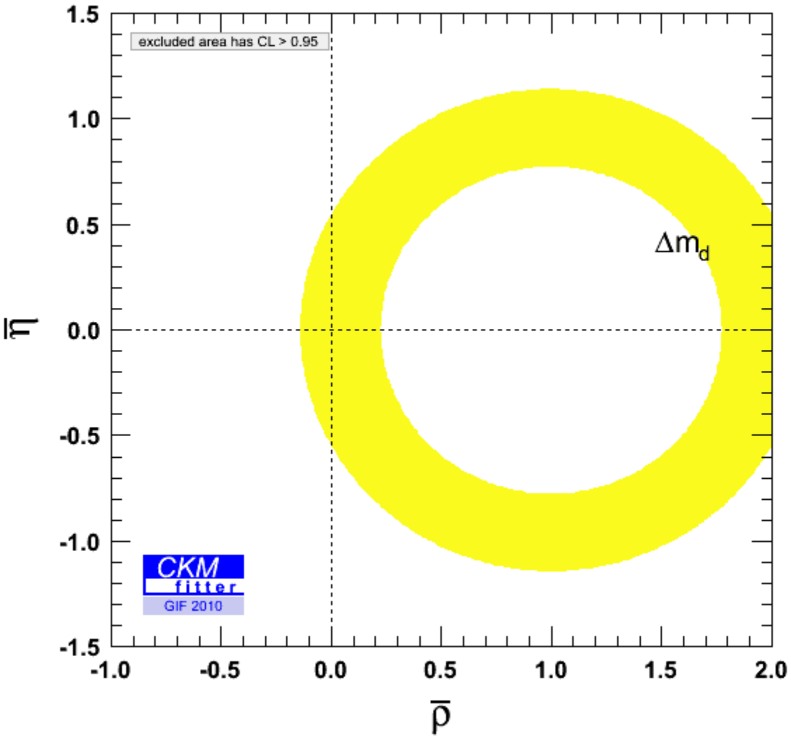
The weak part we are searching for

$$\Delta m_d = \frac{G_F^2}{6\pi^2}\eta_B m_{B_d} \boxed{f_{B_d}^2 B_d} m_W^2 S(x_t) \boxed{\left|V_{td}V_{tb}^*\right|^2}$$

$$\boxed{R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb^*}}\right| = \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2}\,.}$$

- The constraint on the Wolfenstein parameters is entirely dominated by the calculation on the Lattice of the product Decay Constant $*$ Bag Factor.

- Possible to improve the precision with the B_s mixing measurement.



How Δm_s helps

- Though Δm_s only depends marginally on the Wolfenstein parameters, it helps a lot in reducing the Lattice QCD uncertainty. Actually, the ratio:

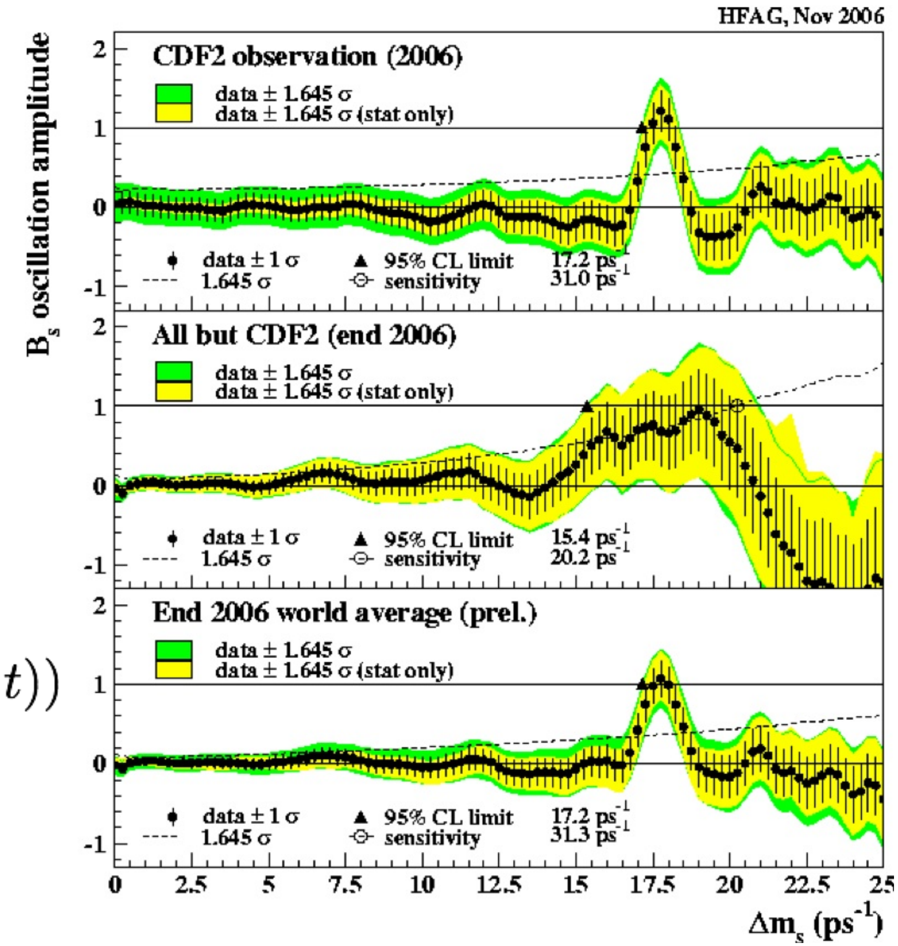
$$\xi = \frac{f_{B_s}\sqrt{B_s}}{f_{B_d}\sqrt{B_d}}$$

is much better determined (better than 5 %) than each of its argument.

- Δm_s is improving the knowledge we have on the B_d product Decay Constant $*$ Bag Factor.

Δm_s measurement

- In 2006, CDF managed to resolve the fast oscillations of the B_s and measured the oscillation frequency Δm_s with a remarkable accuracy.
  - ✓End of a long search starting at LEP in the early nineties



- Amplitude method for combining limits:

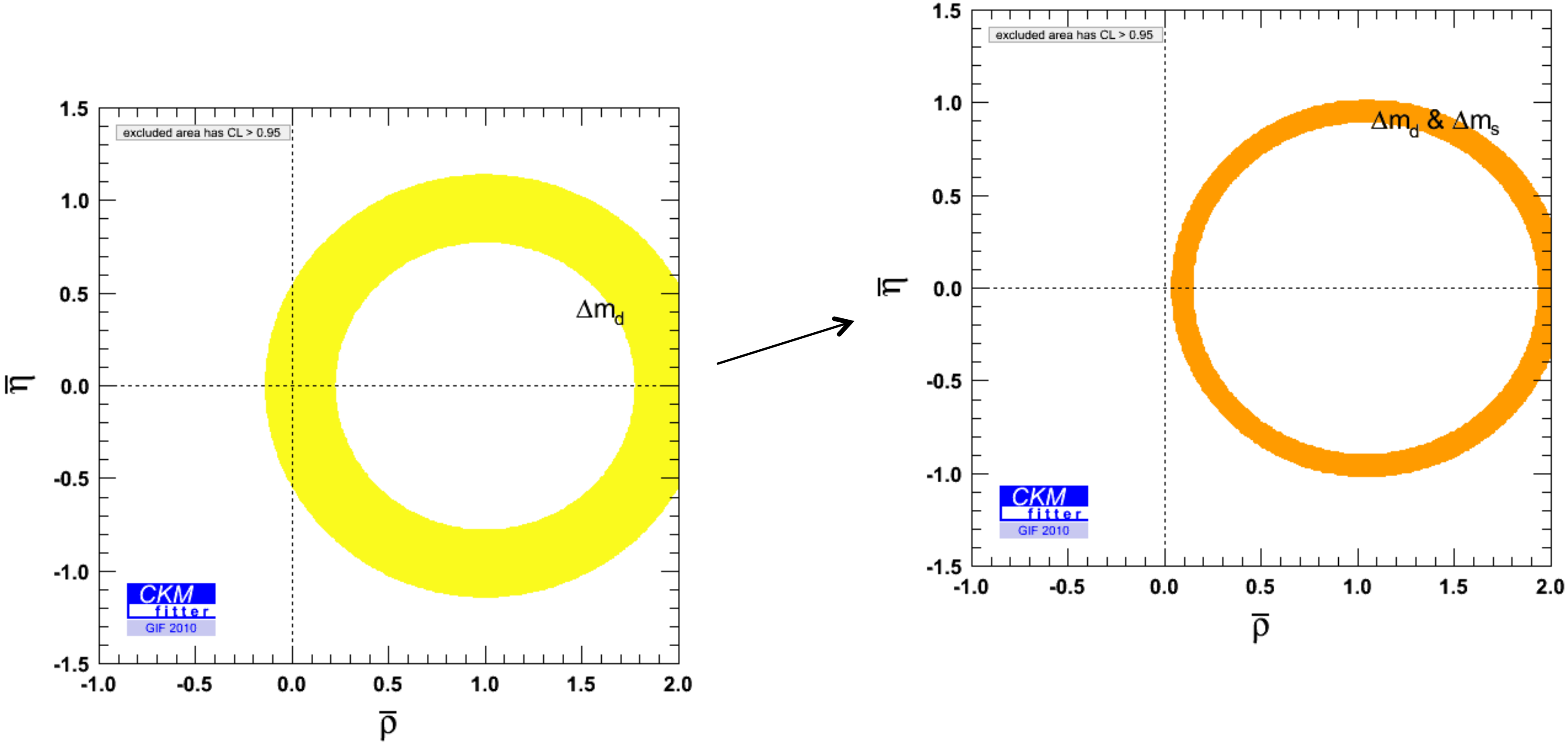
$$P(B_s^0 \rightarrow \bar{B}_s^0) = \frac{e^{-t/\tau}}{2} \cdot (1 + \mathcal{A}\cos(\Delta m_s t))$$

A is measured at each Δm_s hypothesis:

- ✓A=0: no oscillation is seen
- ✓A=1: oscillation are observed

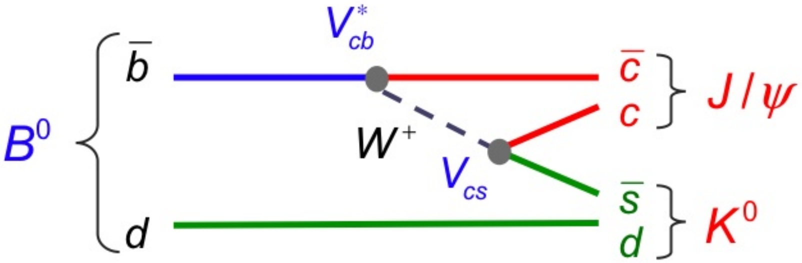
R_t from Δm_d and Δm_s

The simultaneous fit of the two oscillation frequencies leads to a dramatic improvement in the constraint on R_t:

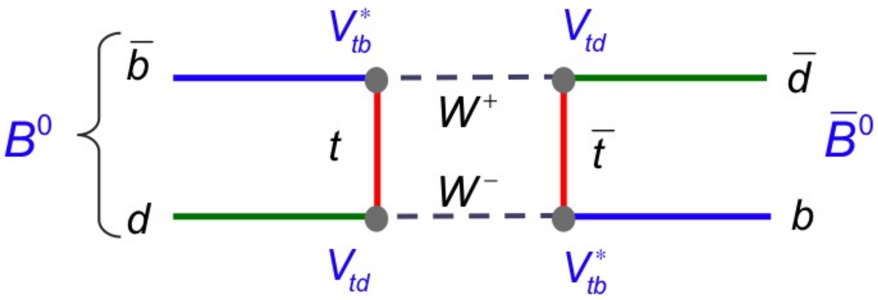


The measurement of $\sin(2\beta)$

- $\bar{b}\to c\bar{c}\bar{s}$ decay: $V_{cs}V^*_{cb}$



- B^0 mixing: $(V_{td}V^*_{tb})^2$



- K^0 mixing: $(V_{cd}V^*_{cs})^2$

$$\boxed{\beta = \pi - \arg\left(\frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}}\right)}$$

Required an interference between processes exhibiting V_{td} and V_{cb} matrix elements

Easy to show that:

$$\arg\left[\frac{A(B^0\to J/\psi K^0)}{A(B^0\to \bar{B}^0\to J/\psi \bar{K}^0\to J/\psi K^0)}\right] = 2\beta$$

The measurement of $\sin(2\beta)$

- The time dependent CP asymmetry:

$$A_{\mathrm{CP}}(f,t) = \frac{N(\bar{B}^0(t) \to f) - N(B^0(t) \to f)}{N(\bar{B}^0(t) \to f) + N(B^0(t) \to f)}$$

can be expressed as a function of the S and C observables:

$$A_{\mathrm{CP}}(f,t) = S \sin(\Delta m_d t) - C \cos(\Delta m_d t)$$

- S can be related to CP violating phase β:

$$S = \frac{2\mathcal{I}m\lambda}{1+|\lambda|^2} \quad \text{with} \quad \lambda = \frac{q}{p}\frac{A(\bar{B}^0 \to f)}{A(B^0 \to f)} = e^{-i2\beta}\frac{\bar{A}_f}{A_f}$$

- In the Standard Model, both CP violation in the mixing and direct CP violation in the $b \to c\bar{c}s$ decay are negligible. One then get $\lambda = n_f\, e^{-i2\beta}$:

$$S = -\, n_f \sin 2\beta$$

with n_f the CP eigenvalue of the final state f (-1 for $J/\psi K_S$)

Dilutions

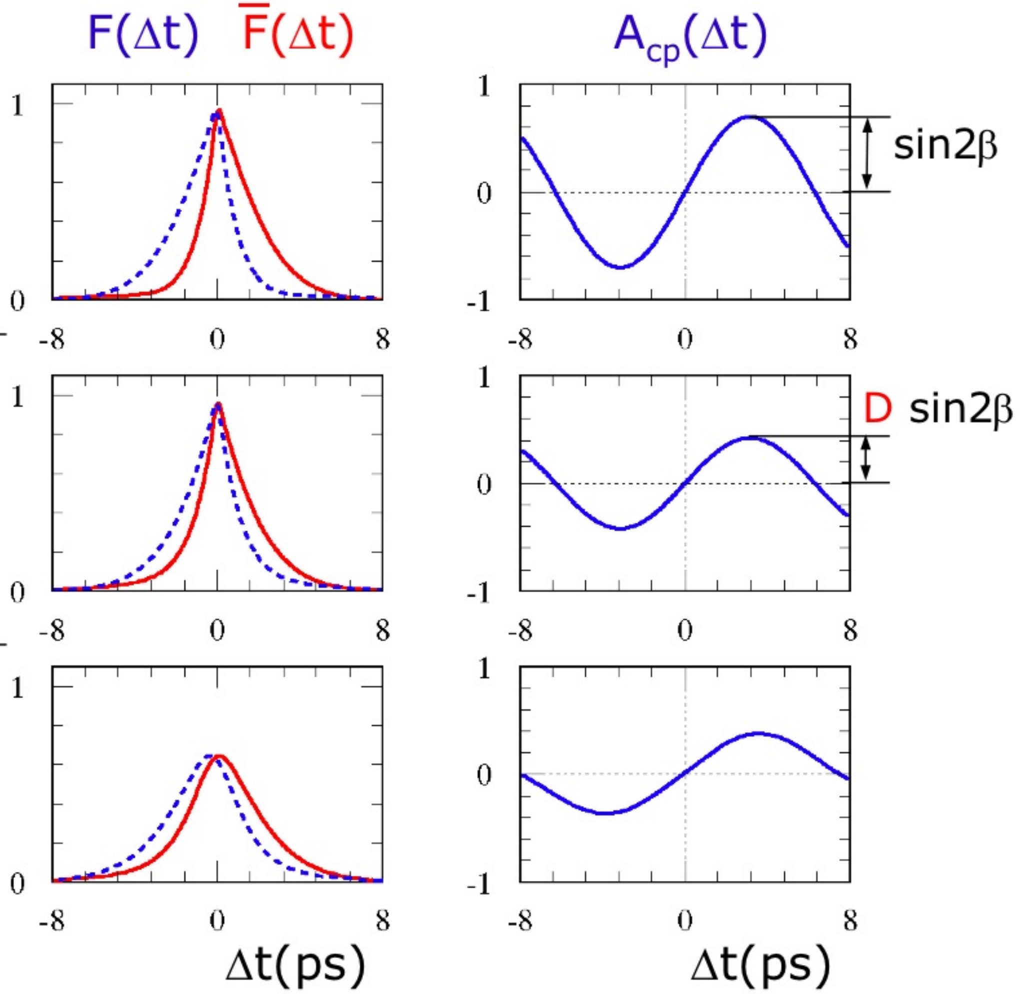
Everything perfect →

Add tag mistakes →

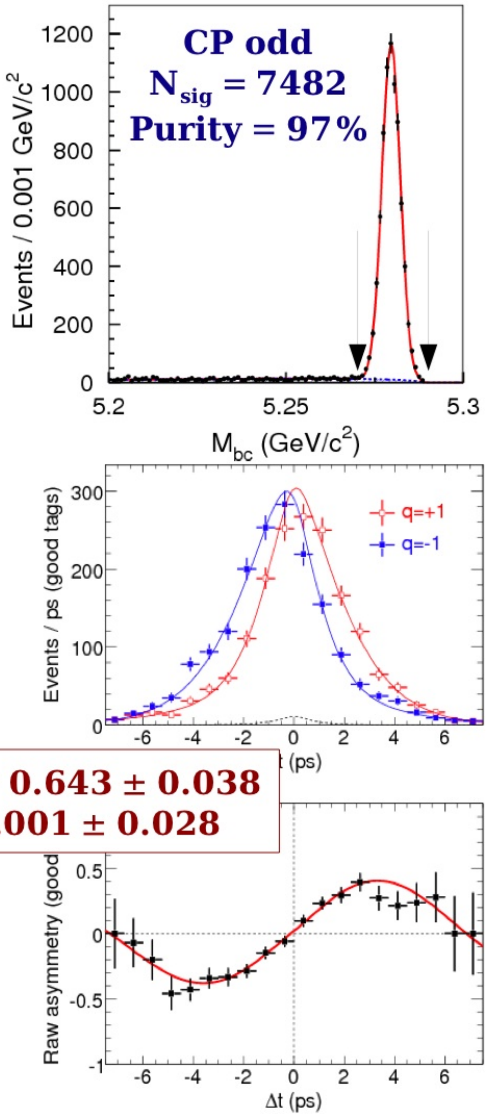
Dilution: D=1-2w

Add imperfect

Δt resolution →

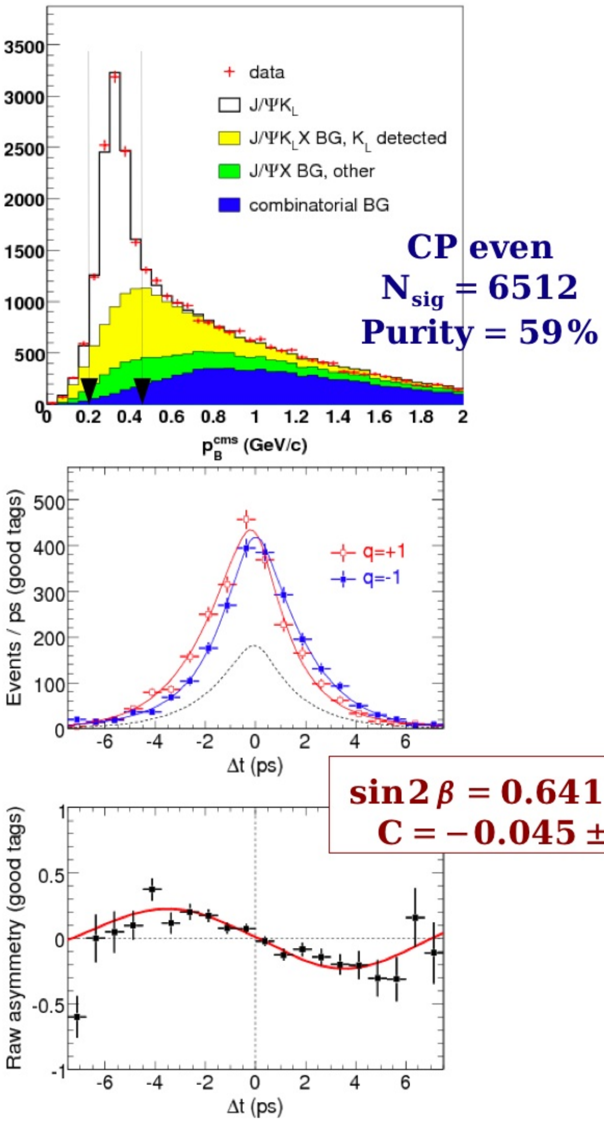


A selection of Belle results



CP odd
$N_{sig} = 7482$
Purity = 97%

$\sin 2\beta = 0.643 \pm 0.038$
$C = 0.001 \pm 0.028$

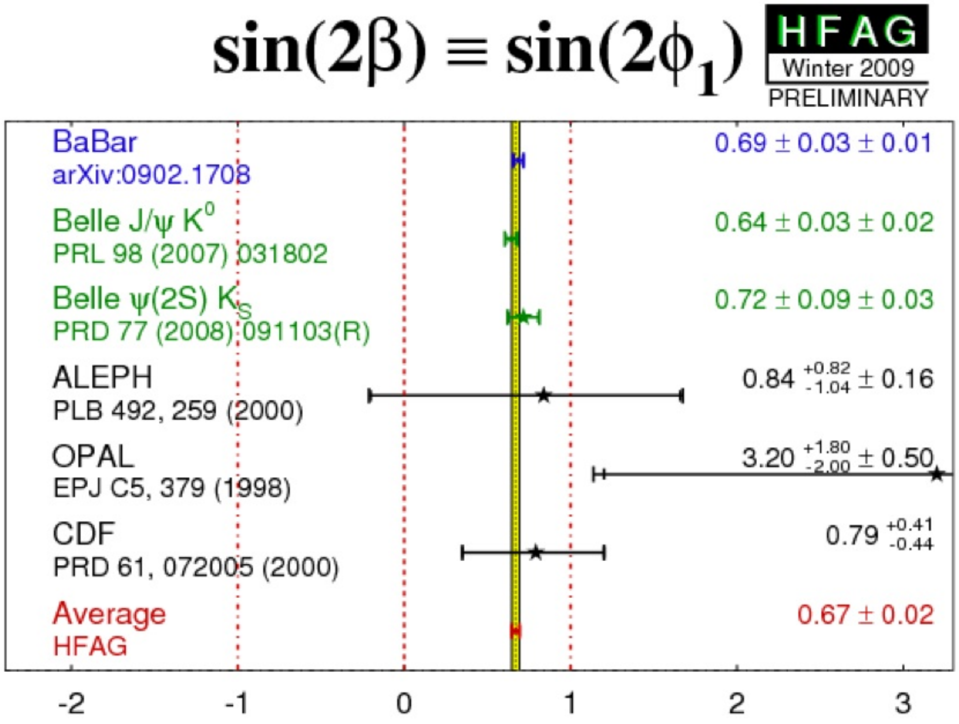


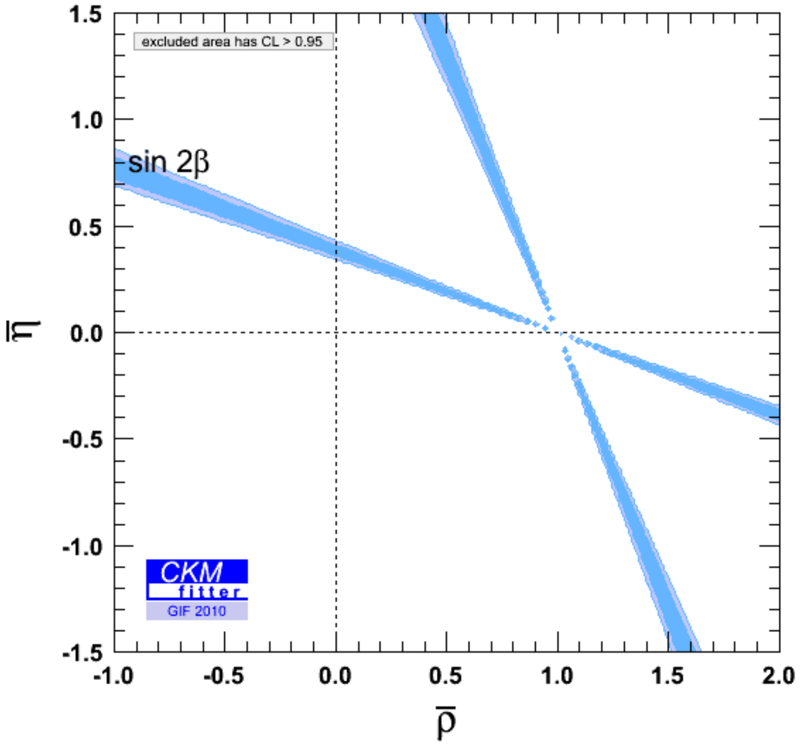
CP even
$N_{sig} = 6512$
Purity = 59%

$\sin 2\beta = 0.641 \pm 0.057$
$C = -0.045 \pm 0.033$

sin(2β) measurements

This measurement was the highlight of the physics case of the B factories and the accuracy of their measurements is a tremendous success.





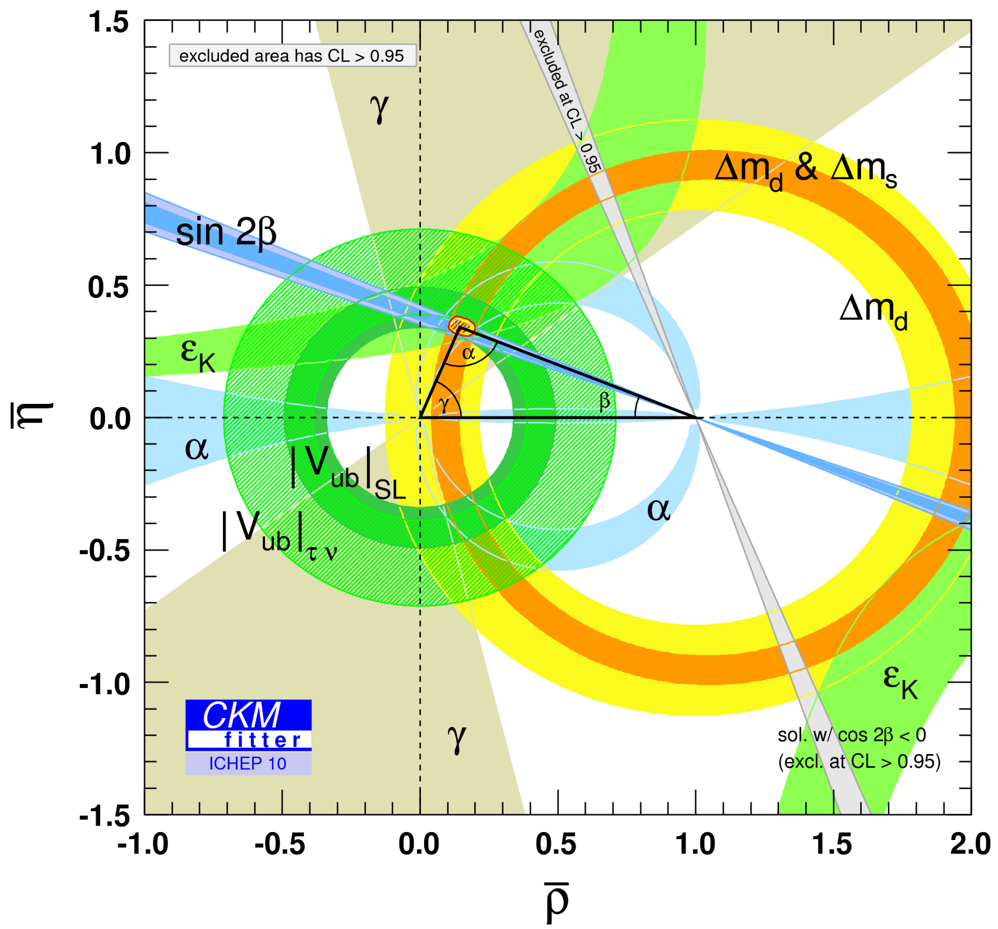
Putting everything together

- The KM phase is established as the dominant source of CP violation in flavor changing transitions of quarks

Kobayashi and Maskawa shared 2008 Nobel Prize with Nambu

- Still room for sizeable contribution from New Physics

- Actuality: D0 reported a 3.9 σ anomaly for like-sign dimuon charge asymmetry in semi-leptonic decays of b hadrons

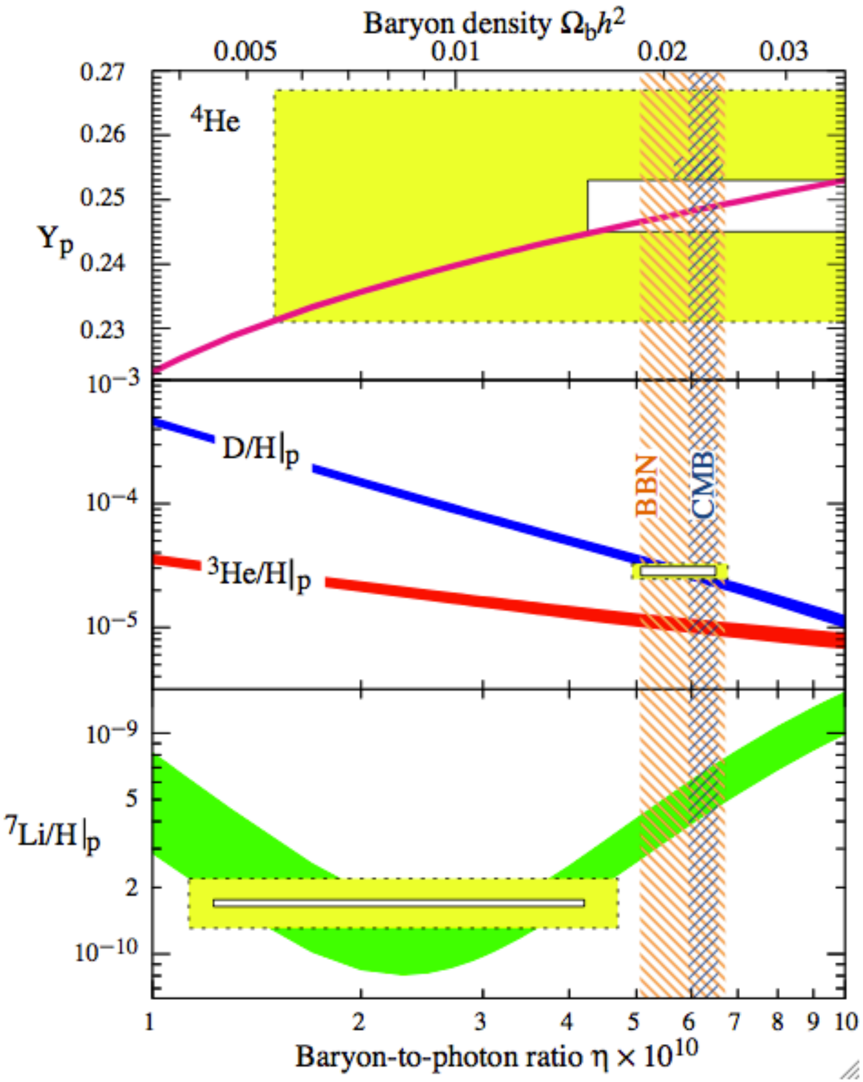


Baryon Asymmetry in the Universe

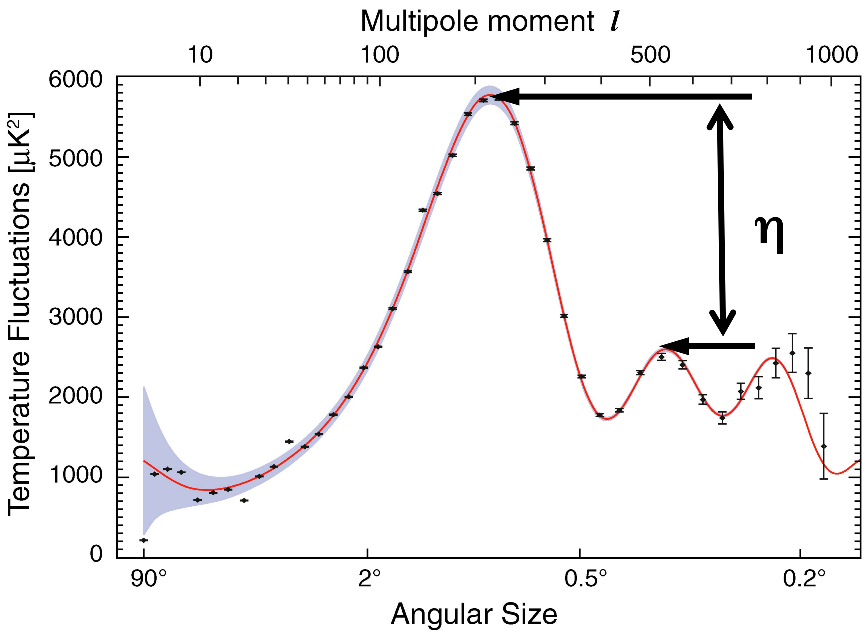
So far, no primordial antimatter has been observed in the cosmos

- In the vicinity of the earth no antinuclei were found
- Cosmic rays contain a few antiprotons: $n_{p\text{-bar}} / n_p \sim 10^{-4}$
  - ✓Consistent with secondary production by protons hitting interstellar matter, for instance: p+p → 3p+p-bar
- If large, separated domains of matter and antimatter in the universe exist, for instance galaxies and anti-galaxies, then one would expect annihilation at the boundaries, leading to a diffuse, enhanced γ ray background.
  - ✓No anomaly was observed in such spectra: on scales of the order 100 Mpc to 1 Gpc the universe consists only of matter
- Does not exclude a universe with net baryon number equal to zero
  - ✓But no mechanism is known that separates matter from antimatter on such large scales
- Thus (for the visible universe): $n_b - n_{\bar{b}} \simeq n_b \quad \Rightarrow \quad \eta \simeq \dfrac{n_b}{n_\gamma}$

η from nucleosynthesis and CMB



WMAP 2008



BAU and SCM

The Baryon Asymmetry in the Universe (BAU) is questioning the Standard Model of Cosmology (SCM).

- Nucleon and antinucleon densities in thermal equilibrium at temperatures below the nucleon mass m_N:

$$\frac{n_b}{n_\gamma} = \frac{n_{\bar{b}}}{n_\gamma} \simeq \left(\frac{m_N}{T}\right)^{3/2} \exp\left(-m_N/T\right)$$

- Freeze-out
  - ✓NN-bar annihilation rate smaller than expansion rate
  - ✓$\sigma_{ann} \sim 1/m_\pi^2 \Rightarrow T \simeq 20$ MeV
  - ✓But at T= 20 MeV: $n_b/n_\gamma = n_{b\text{-}bar}/n_\gamma \simeq 10^{-18}$
- Thermal equilibrium in fact gives $n_b/n_\gamma = n_{b\text{-}bar}/n_\gamma \simeq 10^{-10}$ at $T \simeq 40$ MeV
  - ✓Universe possessed already at early times (T > 40 MeV) an asymmetry between the number of baryons and antibaryons

The Sakharov conditions

I/ Departure from Thermal Equilibrium (DTE)

i.e. an "arrow of time"

Else: n_b and $n_{b\text{-bar}}$ are constant ⇒ so is $n_B = n_b - n_{b\text{-bar}}$

II/ C and CP violation

$$n_B = \frac{1}{3}\left(\underbrace{n_{q_L} - n_{\overline{q_L}}}_{\text{doublets } SU(2)} + \underbrace{n_{q_R} - n_{\overline{q_R}}}_{\text{singlets } SU(2)}\right) \Rightarrow \begin{cases} \mathrm{C}: & q_L \leftrightarrow \overline{q_L}; \quad B \leftrightarrow -B \\ \mathrm{CP}: & q_L \leftrightarrow \overline{q_R}; \quad B \leftrightarrow -B \end{cases}$$

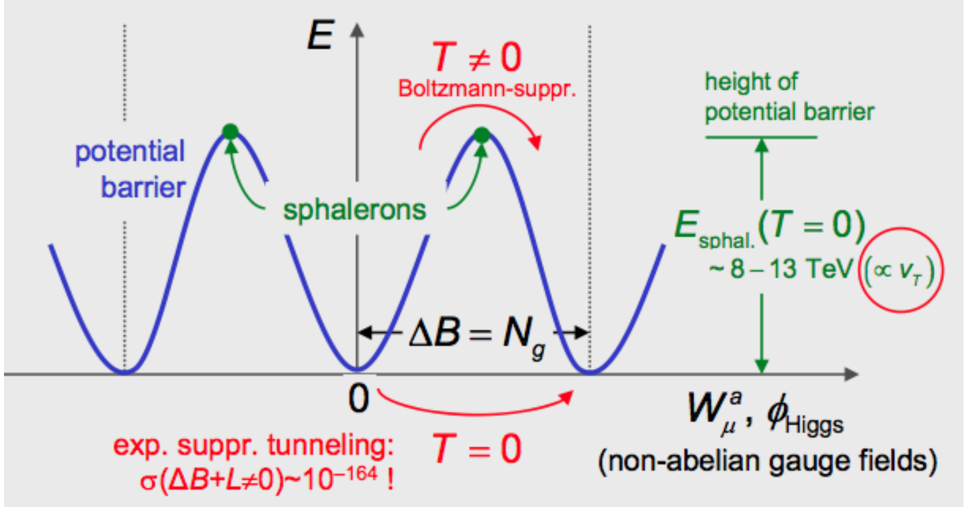
III/ B violation

A process violating B is mandatory to go from $n_B = 0$ to $n_B \neq 0$

B violation in the Standard Model

- At the electroweak (EW) scale (100 GeV ~10^{15} K), where EW forces are still unified, 1st order EW phase transition can occur.
- Non-abelian theories (such as $SU(2)_L$ or QCD) have a non-trivial vacuum structure with an infinite number of ground states.

- Periodic vacuum structure of EW theory: for 3 generations, the distance between two ground states is ΔB = ΔL = 3
  - ✓No proton decay
  - ✓Always: Δ(B–L)=0 ! (B–L is conserved in the SM)



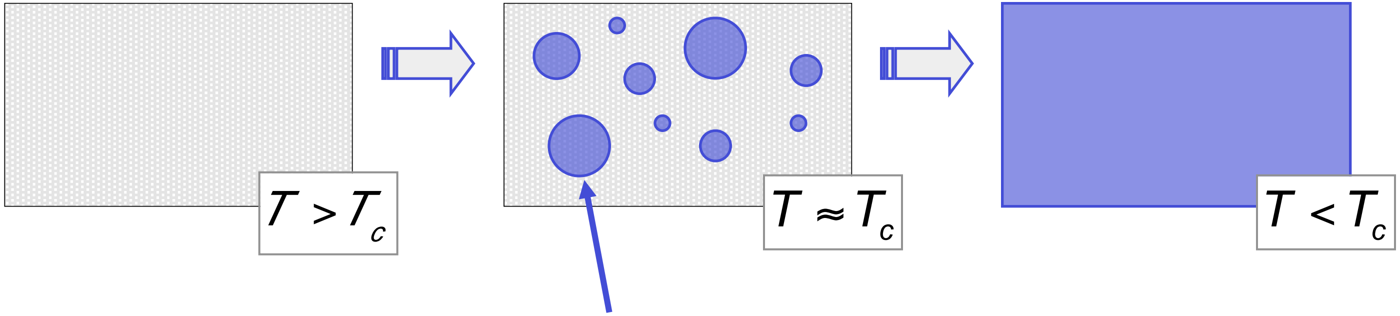
- Sphaleron transition rate proportional to T^4 for $T > T_{EW}$
  - ✓Baryogenesis scenarios above T_{EW} must be based on particle physics models that violate also B-L.

Electroweak baryogenesis

- No departure from local thermal equilibrium for $T<10^{12}$GeV as the reaction rates of most of the SM particles are much larger than the expansion rate of the universe
- SM CP violation (KM mechanism) needs non-zero quark masses to occur, but fermions acquire masses only at T_{EW}

⇒ Only non-local EW baryogenesis is possible

- A 1st order phase transition at $T_C \sim T_{EW}$ is then required
  - ✓ Condensation of Higgs field at T ~ Tc



old phase

new phase

$T > T_c$

$T \approx T_c$

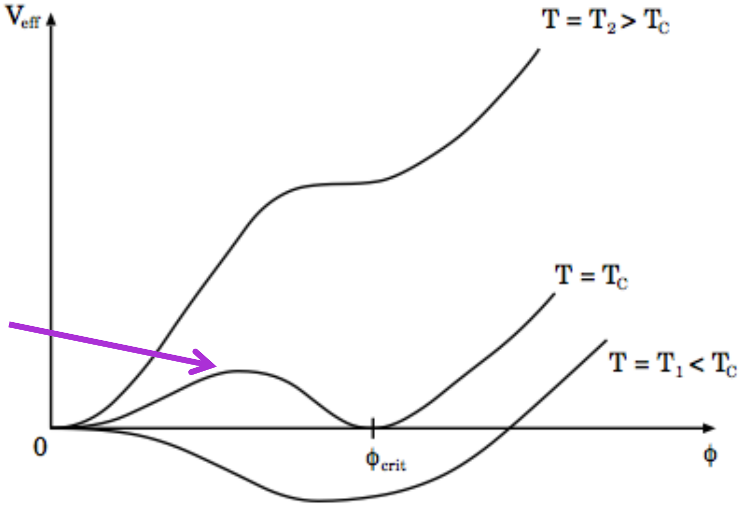
$T < T_c$

expanding bubble (Higgs condensates)

EW phase transition

Higgs potential versus Higgs vacuum expectation value

1st order phase transition

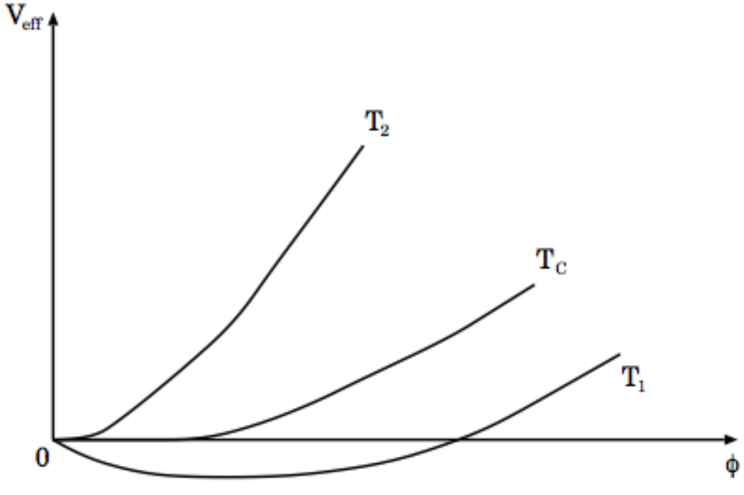


Potential barrier

“spontaneous” phase transition

time scale ~ particle reaction ⇒ DTE

2nd order phase transition



“continous” phase transition

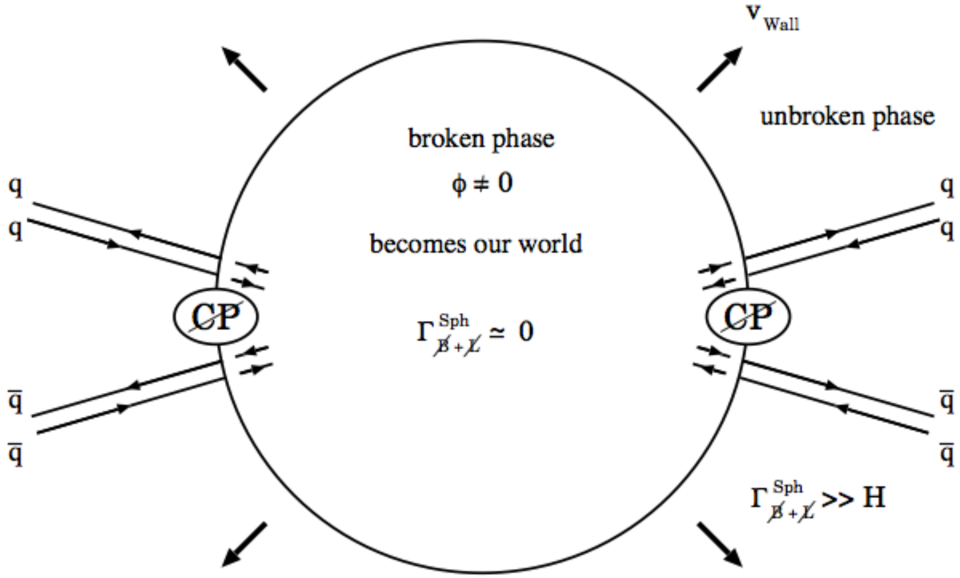
time scale >> particle reaction ⇒ no DTE

- η must be conserved after the transition: it has to be created outside the bubbles
- Sphaleron-induced (B+L)-violating reactions must be strongly suppressed inside the bubbles

Sketch of non local EW baryogenesis

Wall regime: CP violation at the bubble wall

- CP violating interactions with a bubble wall
- Asymmetry in a quantum number (not B) carried by (anti)particle currents into the unbroken phase
- There this asymmetry is converted by the (B+L)-violating sphaleron processes into an asymmetry in baryon number.



Problem: 1st order phase transition only for $m_{Higgs} < 73$ GeV/c^2

- LEP2 limit: $m_{Higgs} > 114$ GeV/c^2
- Require SM extensions ! (SUSY could do it)

A role for the KM phase ?

- Could the KM phase generate baryogenesis?
- KM CP-violating asymmetries, d_{CP}, proportional to the Jarlskog invariant J :

$$d_{CP} = J \cdot \tilde{F}_U \cdot \tilde{F}_D$$

with:

$$J = \mathrm{Im}\left(V_{ud} V_{cs} V_{us}^{*} V_{cd}^{*}\right) = \left(3.1 \pm 0.2\right) \times 10^{-5}$$

$$\tilde{F}_U = \left(m_t^2 - m_c^2\right) \cdot \left(m_t^2 - m_u^2\right) \cdot \left(m_c^2 - m_u^2\right)$$

$$\tilde{F}_D = \left(m_b^2 - m_s^2\right) \cdot \left(m_b^2 - m_d^2\right) \cdot \left(m_s^2 - m_d^2\right)$$

- Since (some) non-zero quark masses are required, CP symmetry can only be broken where the Higgs field has already condensed to $v_T \neq 0$ (i.e., electroweak symmetry is broken)
- To make d_{CP} dimensionless, we divide by dimensioned parameter D at the EW scale (T_{EW} ~ 100 GeV), with $[D] = \mathrm{GeV}^{12}$

$$\frac{d_{CP}}{T_{EW}^{12}} \approx 10^{-19} \ll \eta$$

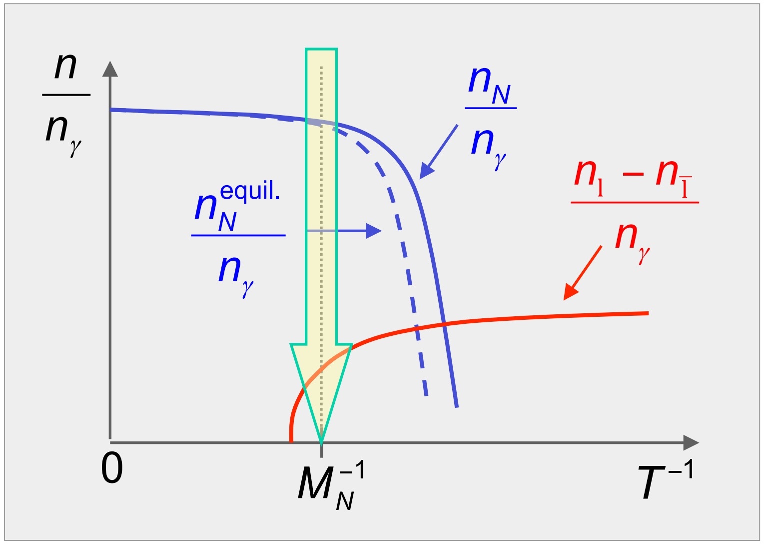
KM CP violation seems to be irrelevant for baryogenesis !

Baryogenesis through Leptogenesis

- Assume existence of 3 heavy right-handed ($M_N \sim 10^{10}$-10^{12} GeV) Majorana neutrinos: N_i=1,2,3
- The $SU(2)_L \times U(1)_Y$ Lagrangian then allows lepton-number-violating decays:

$$N_i \to \ell\phi \quad \text{and} \quad N_i \to \overline{\ell}\phi^*$$

- CP violation would create rate difference: on only tiny ~10^{-6} CP-violating asymmetry required



Departure from thermal equilibrium at T < M_N as $\Gamma_{\Delta L=2}(T) < H(T)$

- ΔL feeds baryogenesis via rapid (B–L)-conserving sphaleron reactions !

Conclusion on Baryogenesis

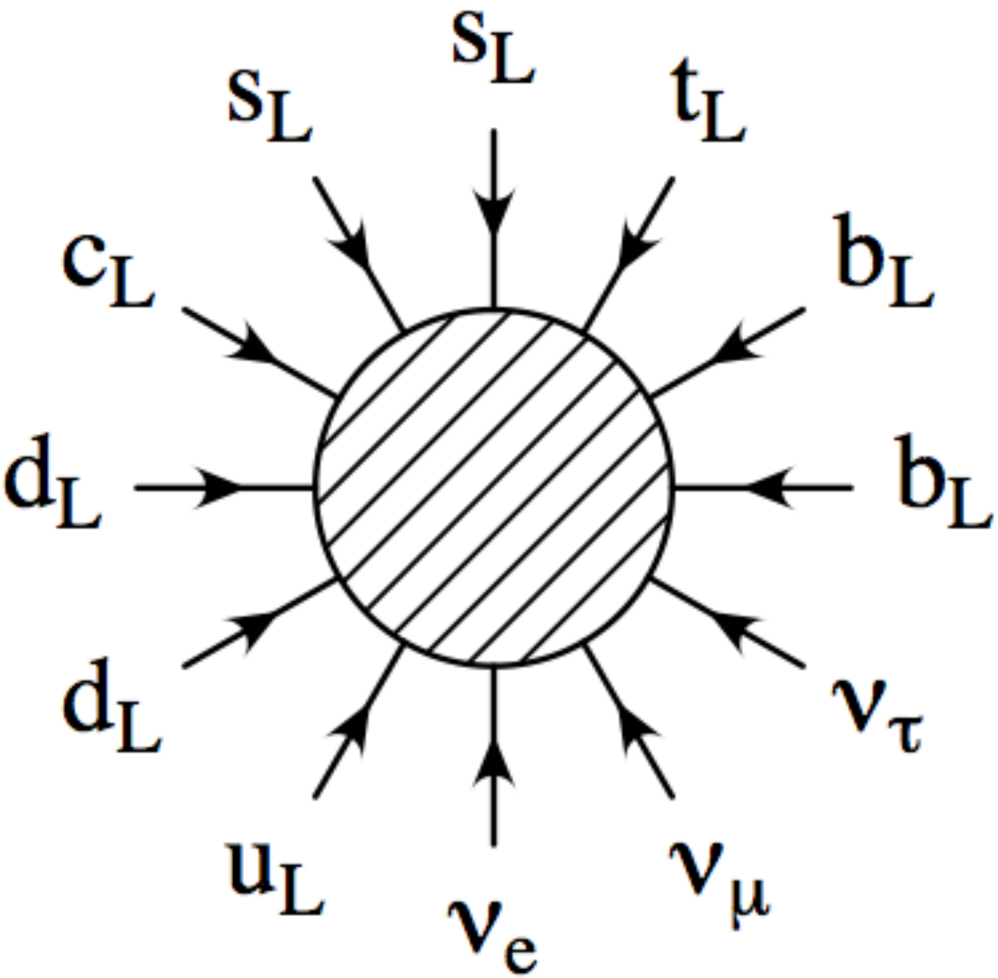
- Baryogenesis (most probably) requires extension of the Standard Model

- Due to heavy Higgs, Baryogenesis via electroweak phase transition fails in the Standard Model ⇒ SUSY ?

- Baryogenesis through leptogenesis seems to be promising
  - ✓ To get the correct baryon asymmetry, the light neutrino masses must lie in ranges consistent with data !

- Other models exist such as GUT-type baryogenesis
  - ✓ GUT theories cannot be verified in laboratory, proton decay would however give empirical support
  - ✓ Only GUT theories able to generate B-L violation are pertinent for Baryogenesis: true for SO(10) but not for SU(5)

Backup



An example of a (B+L)-violating standard model amplitude.