CP violation -
Violació de la simetria CP

Course at UB, May 2005

Part 1: Introduction

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Introduction to CP

Initial condition of the universe $N_B - N_{\bar{B}} = 0$

Today our vicinity (at least up to ~ 10 Mpc) is made of matter and not of anti-matter

nb. baryons (matter) ←

$$\frac{N_B - N_{\bar{B}}}{N_\gamma} = 10^{-10} - 10^{-9}$$

→ Nb of photons (microwawe backg)

In the early universe $B + \bar{B} \to \gamma \leftrightarrow N_\gamma = N_B + N_B$

How did we get from

$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 0 \quad \text{to} \quad \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 10^{-10} - 10^{-9} \text{ ?}$$

(one out of 10^{10} baryons did not anihillate)

Introduction to CP

Three conditions (A.Saharov, 1967):

- baryon number violation
- violation of CP and C symmetries
- non-equillibrium state

$X \to f_a$ (N_B^a, r) $X \to f_b$ (N_B^b, $1-r$)   → baryon number f_b; → decay probability

$\bar{X} \to \bar{f}_a$ ($-N_B^a$, $\bar{r}$) $\bar{X} \to \bar{f}_b$ ($-N_B^b$, $1-\bar{r}$)

Change in baryon number in the decay of X:

$$\Delta B = rN_B^a + (1-r)N_B^b + \bar{r}(-N_B^a) + (1-\bar{r})(-N_B^b) =$$
$$= (r-\bar{r})(N_B^a - N_B^b)$$

Introduction to CP

$$N_B - N_{\bar{B}} = \Delta B n_X =$$
$$= (r-\bar{r})(N_B^a - N_B^b) n_X$$

X decays to states with $N_B^a \neq N_B^b$
-> baryon number violation

$r \neq \bar{r}$ ->
violation of CP in C

In the thermal equilibrium reverse
processes would cause ΔB=0 ->
need an out-of-equilibrium state

For example: X lives long enough ->
Universe cools down -> no X production
possible

Introduction to CP

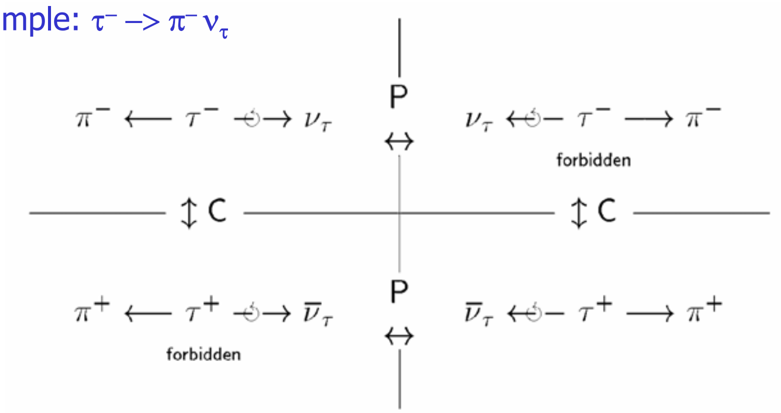
C: charge conjugation $C|B^0\rangle = |\overline{B}^0\rangle$

P: space inversion $P|B^0\rangle = -|B^0\rangle$

CP: combined operation $CP|B^0\rangle = -|\overline{B}^0\rangle$

Introduction to CP

Example: $\tau^- \to \pi^- \nu_\tau$



C or P transformed processes: forbidden.

CP transformed process: allowed

CP Violation

Fundamental quantity: distinguishes matter from anti-matter.

A bit of history:

- First seen in K decays in 1964
- Discovery of B anti-B mixing at ARGUS in 1987 indicated that the effect could be large in B decays
- Many experiments were proposed to measure it, some general purpose experiments tried to do it
- Measured in the B system in 2001 by the two dedicated spectrometers Belle and BaBar at asymmetric e^+e^- colliders - B factories

What happens in the B meson system?

Why bother? Need at least one more system to learn more about CP violation.

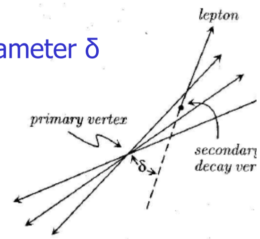
Kaon system: hard to understand what is going on on the quark level (light quark bound system, large dimensions), B has a heavy quark.

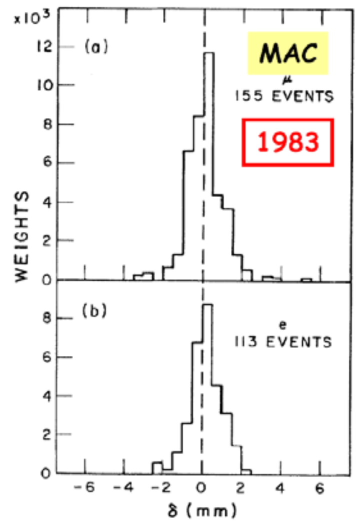
First B meson studies at e^+e^- colliders with cms energies ~20GeV, considerably above threshold (~2x5.3GeV)

B mesons: long lifetime

Isolate samples of high-pT leptons (155 muons, 113 electrons) wrt thrust axis

Measure impact parameter δ wrt interaction point





Lifetime implies V_{cb} small

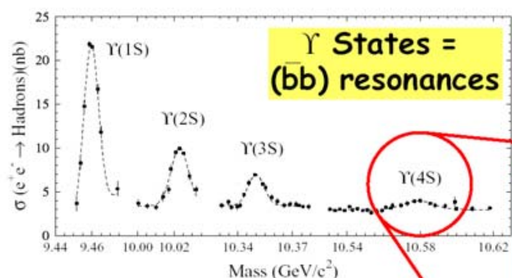
MAC: (1.8±0.6±0.4)ps

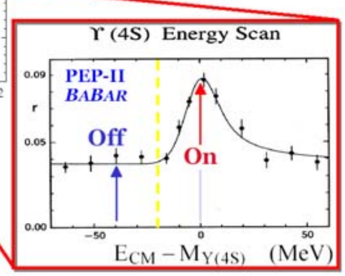
Mark II: (1.2±0.4±0.3)ps

Integrated luminosity at 29 GeV: 109 (92) pb^{-1}~3,500 bb pairs

MAC, PRL **51**, 1022 (1983)
MARK II, PRL **51**, 1316 (1983)

Systematic studies of B mesons: at Y(4s)





Cross Sections at $\Upsilon(4S)$:

$b\bar{b} \sim 1.1$ nb

$c\bar{c} \sim 1.3$ nb

$d\bar{d}, s\bar{s} \sim 0.3$ nb

$u\bar{u} \sim 1.4$ nb

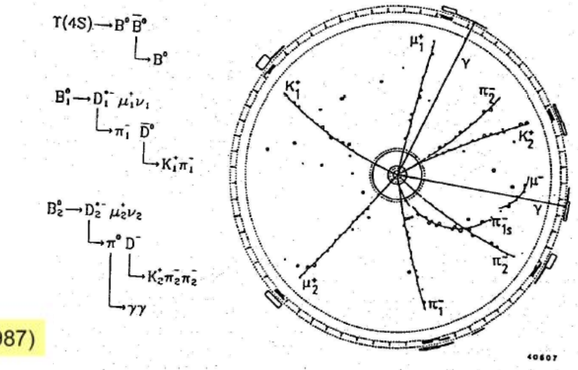
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

$L = 1$ state

Mixing in the B^0 system

1986: Argus discovery of BB mixing: B^0 turns into anti-B^0

Reconstructed event



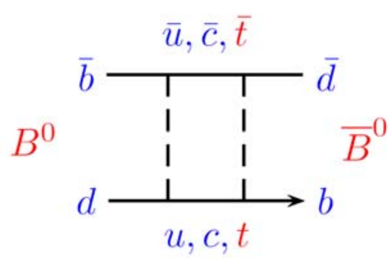
$\chi_d = 0.17 \pm 0.05$

ARGUS, PL B **192**, 245 (1987)

Time-integrated mixing rate: 25 (270) like (opposite) sign dilepton events

Integrated Y(4S) luminosity 1983-87: 103 pb^{-1} ~110,000 B pairs

Mixing in the B^0 system



$\Delta m \propto$

$$|V_{tb}^* V_{td}|^2 m_t^2 \propto \lambda^6 m_t^2$$

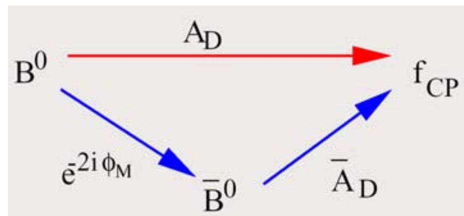
$$|V_{cb}^* V_{cd}|^2 m_c^2 \propto \lambda^6 m_c^2$$

Large mixing rate -> high top mass (in the Standard Model)

The top quark has only been discovered several years later!

Expect CP Violation in the B System

- CPV through interference of decay amplitudes
- CPV through interference of mixing diagram
- CPV through interference between mixing and decay amplitudes

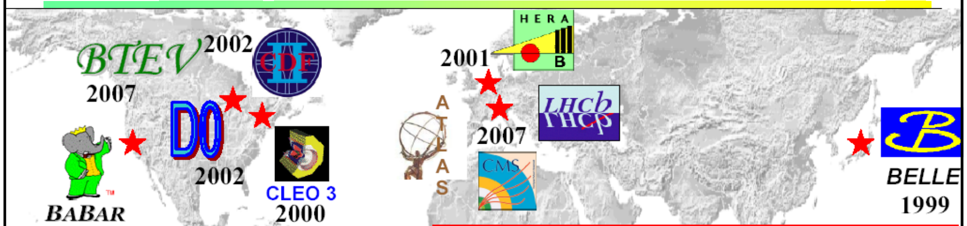


Directly related to CKM parameters in case of a single amplitude

Golden Channel: B -> J/ψ K_S

Theoretically clean way to one of the parameters (sin2β)
Clear experimental signatures (J/ψ -> $\mu^+\mu^-$, e^+e^-, K_S->$\pi^+\pi^-$)
Relatively large branching fractions for b->ccs (~10^{-3})

Genesis of Worldwide Effort



Primary Goal

Precision measurements of **charged weak interactions** as a test of the **CKM** sector of the Standard Model and a probe of the origin of the ***CP* violation**

Contents of this course

- CP violation – introduction
- Standard Model – a quick overview
- CP violation – theory
- CP violation in the B system
- CKM quark mixing matrix
- CP violation in the K system
- Experimental considerations
- Belle and Babar spectrometers
- Measurements of sin2β
- CP violation in b->s bar s s decays
- Measurements of sin2α and γ
- Radiative B decays
- FCNC decays b->s γ, b->s $l^- l^+$
- Measuremnets of V_{ub} in V_{cb}
- Mixing measurements
- Hadron spectroscopy
- B physics at hadron machines
- Next generation of B-factories

Standard Model – a quick overview

Particles:

- leptons (e,ν_e), (μ,ν_μ), (τ,ν_τ)
- quarks (u,d), (c,s), (t,b)

Interactions:

- electromagnetic
- weak
- strong

Standard Model – a quick overview 2

Free fermions satisfy the Dirac equation

$(i\gamma^\mu d/dx_\mu - m)\,\psi(x) = 0$

Solution: $\psi(x) = u(p)\,e^{-ipx}$, $px = Et - \mathbf{px}$

$(\gamma_\mu p^\mu - m)\,u(p) = 0$

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Feynman rules for $-i\mathfrak{M}$: electromagnetic interaction

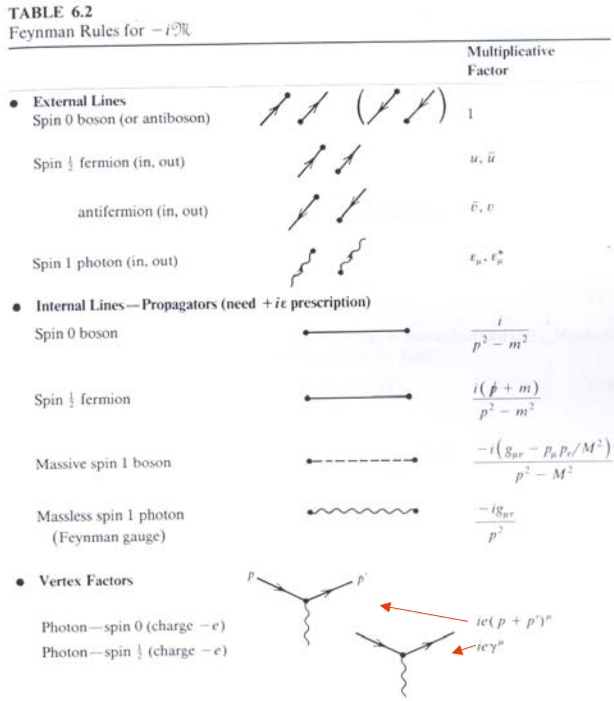

TABLE 6.2
Feynman Rules for $-i\mathfrak{M}$

	Multiplicative Factor
• **External Lines**	
Spin 0 boson (or antiboson)	1
Spin $\frac{1}{2}$ fermion (in, out)	$u, \bar{u}$
antifermion (in, out)	$\bar{v}, v$
Spin 1 photon (in, out)	$\varepsilon_\mu, \varepsilon^*_\mu$
• **Internal Lines—Propagators (need $+i\varepsilon$ prescription)**	
Spin 0 boson	$\frac{i}{p^2 - m^2}$
Spin $\frac{1}{2}$ fermion	$\frac{i(\not{p} + m)}{p^2 - m^2}$
Massive spin 1 boson	$\frac{-i(g_{\mu\nu} - p_\mu p_\nu/M^2)}{p^2 - M^2}$
Massless spin 1 photon (Feynman gauge)	$\frac{-ig_{\mu\nu}}{p^2}$
• **Vertex Factors**	
Photon—spin 0 (charge $-e$)	$ie(p + p')^\mu$
Photon—spin $\frac{1}{2}$ (charge $-e$)	$ie\gamma^\mu$

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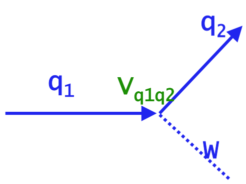
Feynman rules for $-i\mathfrak{M}$ for weak interaction via charged currents: similar as for e.m. except:

- Vertex has an additional $(1-\gamma^5)/2$ factor (weak interactions only 'see' left handed components
- Vertex factor V_{12} for quarks: in charged current interactions a q_1=+2/3 turns into a q_2=-1/3 quark (or vice versa), this factor accounts for the differences in the probability between u->d, u->s, u->b, c->d, ... transitions



Weak interaction: examples

Muon decay

Pion decay

Extraction of V_{us}/V_{ud} from kaon and muon leptonic decays

Leptonic B decay