Univerza v Ljubljani

THE UNIVERSITY OF TOKYO

Flavour Physics at B-factories and Hadron Colliders

Part 1: Introduction

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Standard Model: contents

Particles:

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

Interactions:

- Electromagnetic (γ)
- Weak (W^+, W^-, Z^0)
- Strong (g)

Higgs field

Flavour physics

... is about

- quarks
- leptons

and

- their mixing
- CP violation

N.B. Standard Model could also be built with only one generation of leptons and quarks.

Flavour physics and CP violaton

Moments of glory in flavour physics are very much related to CP violation:

Discovery of CP violation (1964)

The smallness of $K_L \to \mu^+\mu^-$ predicts charm quark

GIM mechanism forbids FCNC at tree level

KM theory describing CP violation predicts third quark generation

$\Delta m_K = m(K_L) - m(K_S)$ predicts charm quark mass range

Frequency of B^0B^0 mixing predicts a heavy top quark

Proof of KM theory ($\sin 2\phi_1$)

Tool to find physics beyond SM: search for new sources of flavour/CP-violating terms

Introduction to CP

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

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

nb. baryons (matter) ←

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

→ Nb of photons (microvawe backg)

In the early universe $B + \overline{B} \rightarrow \gamma \leftrightarrow N_\gamma = N_B + N_B$

How did we get from

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

(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

$X \rightarrow f_a \; (N_B^a, r)$ $\quad X \rightarrow f_b \; (N_B^b, 1-r)$

$\overline{X} \rightarrow \overline{f}_a \; (-N_B^a, \overline{r})$ $\quad \overline{X} \rightarrow \overline{f}_b \; (-N_B^b, 1-\overline{r})$

N_B^b: baryon number f_b

$1-r$: decay probability

Change in baryon number in the decay of X:

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

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 $\Delta B=0$ -> need an out-of-equilibrium state

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

Introduction to CP

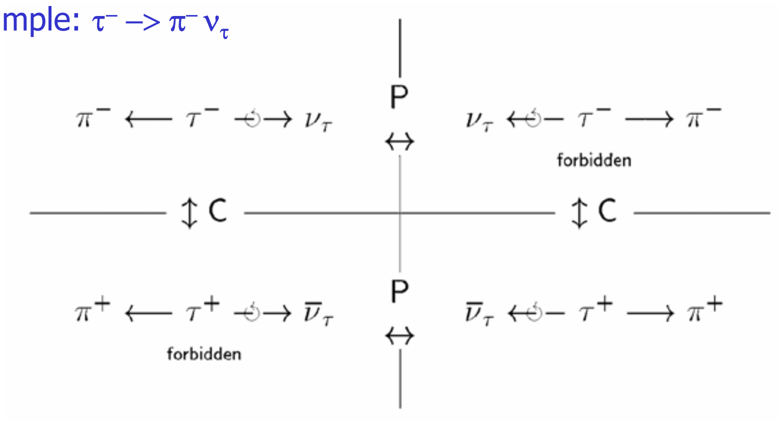
C: charge conjugation $C|B^0\rangle = |\bar{B}^0\rangle$

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

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

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 is it interesting? Need at least one more system to understand the mechanism of CP violation.

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

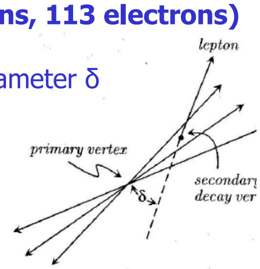
B has a heavy quark, a smaller system, and is easier to interpret the results.

First B meson studies were carried out in 70s 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

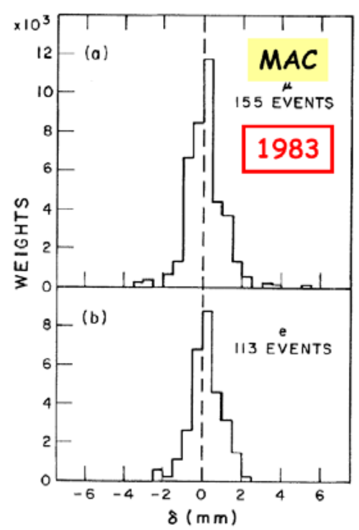


Lifetime implies V_{cb} small

MAC: (1.8±0.6±0.4)ps

Mark II: (1.2±0.4±0.3)ps

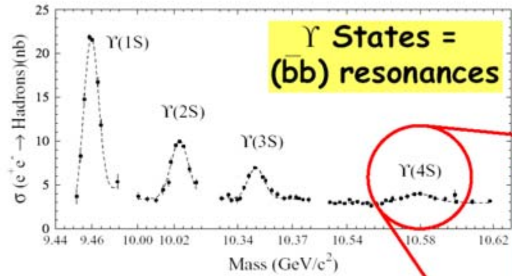
Integrated luminosity at 29 GeV: 109 (92) pb^{-1}~3,500 bb pairs

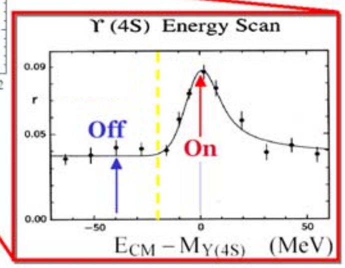


MAC, PRL **51**, 1022 (1983)

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

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





Cross Sections at Υ(4S):

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

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

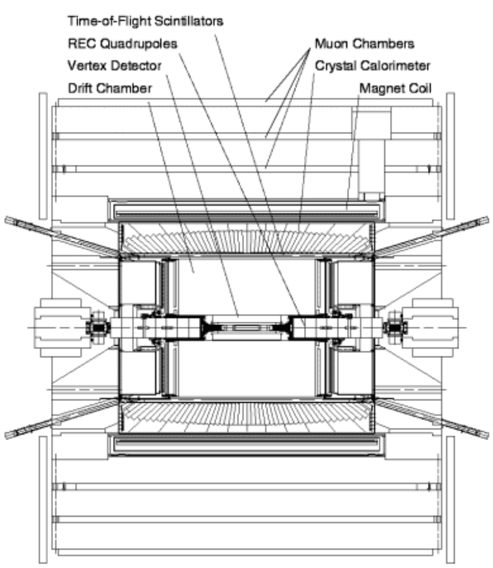
$d\bar{d}$, $s\bar{s} \sim 0.3$ nb

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

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

$L = 1$ state

Systematic studies of B mesons at Υ(4s)



80s-90s: two very successful experiments:

ARGUS at DORIS (DESY)
CLEO at CESR (Cornell)

Magnetic spectrometers at e^+e^- colliders (5.3GeV+5.3GeV beams)

Large solid angle, excellent tracking and good particle identification.

Mixing in the B^0 system

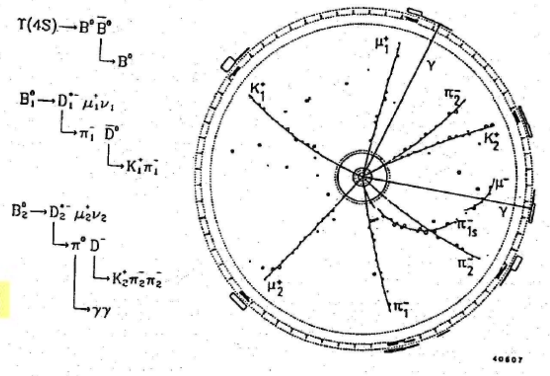
1986: ARGUS discovery of BB mixing: B^0 turns into anti-B^0

Reconstructed event

$\chi_d = 0.17 \pm 0.05$

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

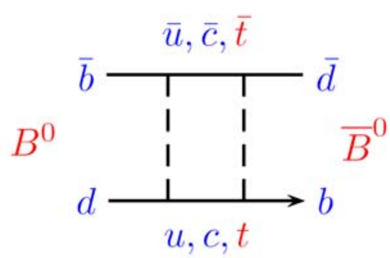
cited >1000 times.



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

Integrated Υ(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!

Systematic studies of B mesons at Y(4s)

ARGUS and CLEO: In addition to mixing many important discoveries or propertis of

B mesons

D mesons

τ^- lepton

and even a measurement of ν_τ mass.

After ARGUS stopped data taking, and CESR considerably improved the operation, CLEO dominated the field in late 90s (and managed to compete successfully even for some time after the B factories were built).

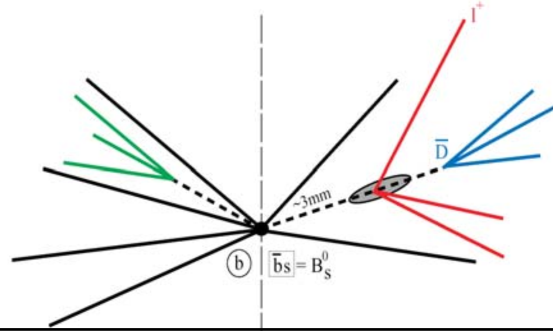
Studies of B mesons at LEP

90s: study B meson properties at the Z^0 mass by exploiting

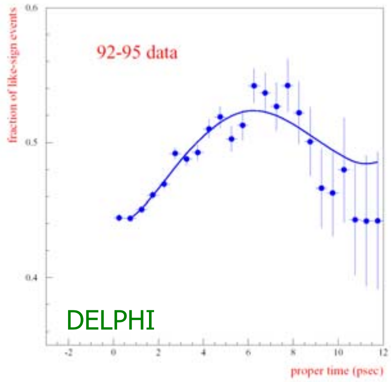
•Large solid angle, excellent tracking, vertexing, particle identification

•Boost of B mesons → time evolution (lifetimes, mixing)

•Separation of one B from the other → inclusive rare b→u



Studies of B mesons at LEP



$B^0 \rightarrow$ anti-B^0 mixing, time evolution

Fraction of events with like sign lepton pairs

Almost measured mixing in the B_s system (bad luck...)

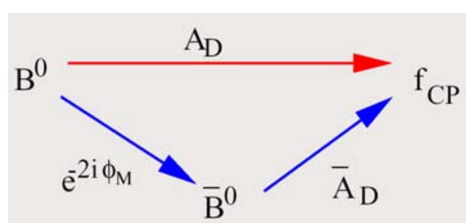
Large number of B mesons (but by far not enough to do the CP violation measurements...)

Mixing → expect sizeable 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

Soon recognized as the best way to study CP violation in the B meson system

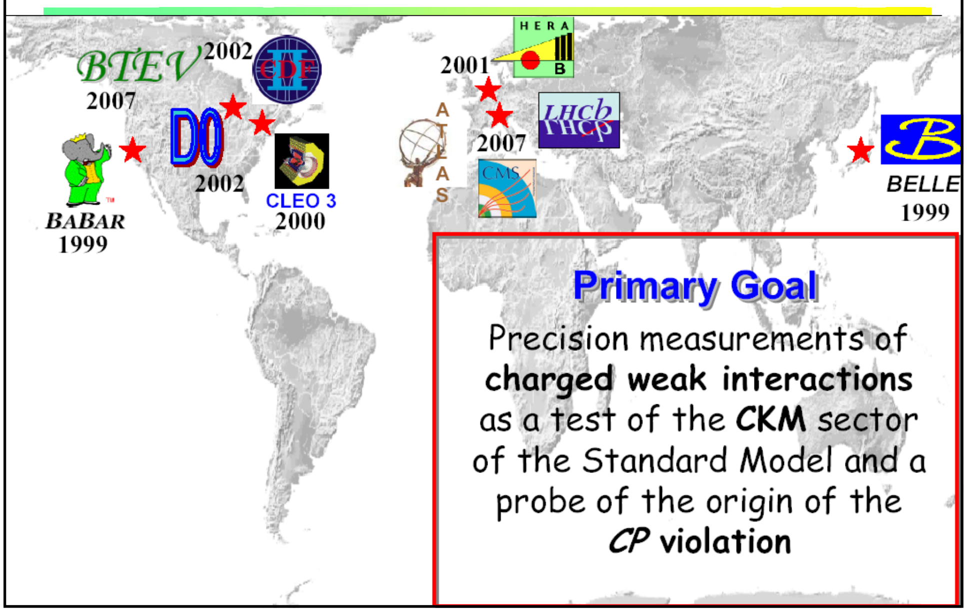
Theoretically clean way to one of the parameters ($\sin 2\phi_1$)

Clear experimental signatures ($J/\psi \rightarrow \mu^+\mu^-$, e^+e^-, $K_S \rightarrow \pi^+\pi^-$)

Relatively large branching fractions for b->ccs (~10^{-3})

→ A lot of physicists were after this holy grail

Genesis of Worldwide Effort

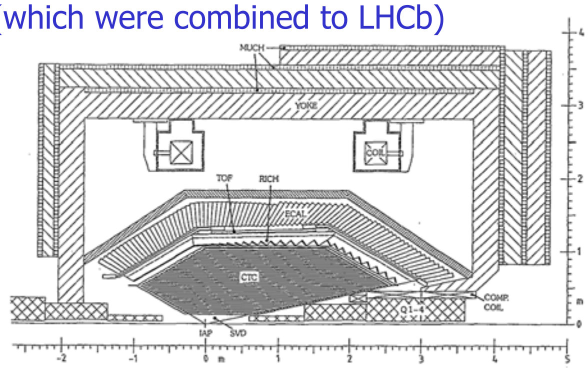


Genesis of Worldwide Effort 2

In late 80s and early 90s there were several proposal which were not approved:

- symmetric e^+e^- in PSI (Villigen, Switzerland)
- Helena, asymmetric e^+e^- collider at DESY
- 3 proposals at LHC (which were combined to LHCb)

Helena:
9.3 GeV + 3 GeV



Contents of this course

Introduction

Standard Model – a quick overview of relevant tools

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 $\sin 2\phi_1$

CP violation in b→s bar s s decays

Measurements of $\sin 2\phi_2$ and ϕ_3

FCNC decays $b \to s\,\gamma$, $b \to s\, l^- l^+$

Measuremnets of V_{ub} in V_{cb}

Mixing measurements

Hadron spectroscopy

Next generation of B-factories

B physics at hadron machines

Rare kaon decays

Summary and outlook

Material for this course

- Slides
- Write-ups of blackboard excercises
- Literature
- Program, timetable

http://www-f9.ijs.si/~krizan/sola/tokyo/tokyo.html

Standard Model – a quick overview of tools

Free fermions satisfy the Dirac equation

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

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

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

Also:

$\bar{u}(p)\ (\gamma_\mu p^\mu - m) = 0$

$\bar{u}(p) = u^+(p)\ \gamma^0$

antiparticle

$(\gamma_\mu p^\mu + m)\ v(p) = 0$

SM – tools overview 2

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

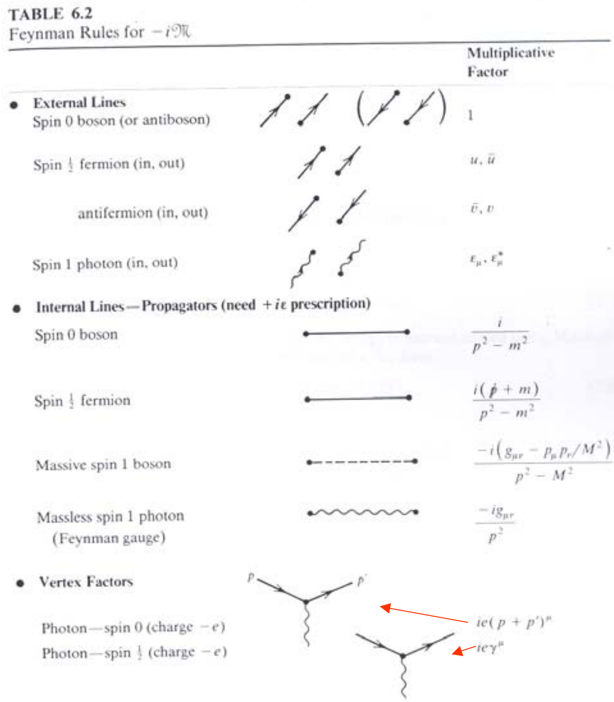


TABLE 6.2
Feynman Rules for $-i\mathfrak{M}$

	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)	$\epsilon_\mu, \epsilon_\mu^*$
• **Internal Lines—Propagators (need $+i\epsilon$ 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 $-e$)	$ie\gamma^\mu$

See e.g. F. Halzen, A.D. Martin, Quarks and Leptons

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

Draw all possible graphs. Evaluate them by taking:

- for a new vertex $ie\gamma^\mu$
- Photon propagator $-\frac{g_{\mu\nu}}{q^2+i\epsilon}$
- External outgoing photon $\epsilon_\mu(p)$
- External incoming photon $\epsilon^*_\mu(p)$
- Fermion propagator $\frac{i(p_\mu\gamma^\mu+m)}{p^2-m^2+i\epsilon}$
- for an external incoming fermion $u^s(p)$
- for an external outgoing fermion $\overline{u}^s(p)$
- for an external incoming antifermion $v^s(p)$
- for an external outgoing antifermion $\overline{v}^s(p)$

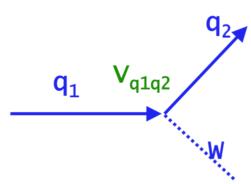
+ impose momentum conservation at each vertex

+ integrate over all undetermined loop momenta.

SM – continued

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

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



Weak interaction: blackboard examples

Muon decay

Pion decay

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

Leptonic B decay

June 5-8, 2006 Course at University of Tokyo Peter Križan, Ljubljana