1994-1995 ACADEMIC TRAINING PROGRAMME

LECTURE SERIES

SPEAKER: T. NAKADA / Paul Scherrer Institut (PSI), Willigen, CH
TITLE: B- Physics, now and future
TIME: 24, 25, 26 & 28 April, from 11.00 to 12.15 hrs
PLACE: Auditorium

ABSTRACT

The b-quark surprised us already twice. Unexpectedly large B-meson lifetimes told us that the third generation of the quark pair mixed very little with others. The later discovery of large $B^0$–$B^0$ mixing showed us that the top quark mass was much larger than expected. There could be a third surprise, may be in CP violation. In this lecture series, we quickly review the past and present of B- physics. This is followed by a more detailed discussion on future, in particular CP violation studies with future accelerators.
B-physics
- past, present and future -

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I) Introduction

The third generation of the quark family was "predicted". ———> CP violation

M. Kobayashi and K. Maskawa, Prog. Theor. Phys. 49 (1973) 652

The $b$ quark lifetime was much larger than "expected".

E. Fernandez et al. (MAC) 
N. S. Lockyer et al. (Mark II) 

The $B^0$-$\bar{B}^0$ oscillation frequency was much larger than "expected".

H. Albrecht et al. (ARGUS) 
Outline of lectures

discovery of b quark

first lifetime measurements
  physics implications

discovery of $B^0\bar{B}^0$ oscillations
  physics implications

future goal of b physics, i.e. CP violation
  reminder for CP violation phenomenology
  what has to be measured?
  where can they be measured?
II) Past and Present

1) discovery of b quark

"Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleon Collisions"


\[ p + Cu, Pt \rightarrow \mu^+\mu^- + \text{anything} \]

A statistically significant enhancement is observed at 9.5 GeV \( \mu^+\mu^- \) mass.
The observed width of the enhancement is greater than the apparatus resolution.

Mass = 9.44 \( \pm 0.03 \) and 10.17 \( \pm 0.05 \) GeV

"Observation of Structure in the \( \Upsilon \) Region"


\[ \Upsilon = 9.4, \ Upsilon' = 10.01, \ Upsilon'' = 10.4 \text{ GeV} \]

\[ \text{a bound state of new quark antiquark bound states, } Q = -1/3 \]
They are now called
\( \Upsilon(1S), \Upsilon(2S) \) and \( \Upsilon(3S) \)

They are \( \text{bb} \) bound states below
BB threshold.
2) Impact of the b quark discovery

quark flavour mixing

Cabibbo mixing

Unitary Symmetry and Leptonic Decays
N. Cabibbo, Phys. Lett. 10 (1963) 531

\[ s' = s \sin \theta_{\text{Cabibbo}} + d \cos \theta_{\text{Cabibbo}} \]

\[
\frac{\Gamma (K^- \rightarrow \mu^- \bar{\nu})}{\Gamma (\pi^- \rightarrow \mu^- \bar{\nu})} = 2
\]

\[
\sin \theta_{\text{Cabibbo}} \approx 0.23
\]
Quarks come in always as a pair

GIM mechanism:
- Weak Interaction with Lepton-Hadron Symmetry
- S. L. Glashow, J. Illiopoulos and L. Maiani


suppression of effective flavour
changing neutral current

\[
\frac{\Gamma(K^0 \rightarrow \mu^- \mu^+)}{\Gamma(K^0 \rightarrow \mu^- \pi^+ \nu^-)} = 2.7 \times 10^{-8} \ll g^4
\]

\[
\text{Br}(K \rightarrow \mu^+ \mu^-) = \cos \theta_{\text{cabibbo}} \sin \theta_{\text{cabibbo}} \left( f(m_u) - f(m_c) \right)
\]

\[
\text{0 if } m_u = m_c
\]
Three families of quarks

Three families can generate CP violation in charged current weak interactions

CP-Violation in the Renormalizable Theory of Weak Interaction
M. Kobayashi and K. Maskawa,
Prog. Theor. Phys. 49 (1973) 652

Flavour eigenstates

\[ Q = 2/3 \quad u \quad c \quad t \rightarrow U = \begin{pmatrix} u \\ c \\ t \end{pmatrix} \]

\[ Q = -1/3 \quad d \quad s \quad b \rightarrow D = \begin{pmatrix} d \\ s \\ b \end{pmatrix} \]

mass (electroweak) eigenstates

\[ U \text{ and } D' = VD \]

\[ V = \text{Cabibbo Kobayashi Maskawa mixing matrix} \]

\[ V: \text{unitary} \quad V^\dagger V = E \]

Charged current

\[ \bar{U} W_\mu (1 - \gamma_5) \gamma_\mu D' \]
Effective coupling for
\[ D_i \rightarrow U_j + W^- \]

\[ \propto V_{ij} \]

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

How many parameters?

Unitarity conditions

\[ 2 \left( \frac{n_f}{2} \right)^2 - \left( \frac{n_f}{2} \right)^2 - (n_f - 1) = \]

1 for 4 flavours

4 for 6 flavours

Total free parameters: arbitrary quark phases

Standard parametrization of CKM matrix

\[ V = (\text{d-s rotation}) \times (\text{s-b rotation}) \times (\text{d-b rotation}) \]

\[ \theta_{12} \quad \theta_{23} \quad \theta_{13} \]

\( \approx \) Cabibbo angle

Complex \( e^{i\delta} \)
exact parametrization

\[
\begin{pmatrix}
  c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
  -s_{12}c_{23}c_{12}s_{13}e^{i\delta} & c_{12}c_{23}c_{23}s_{13}e^{i\delta} & c_{23}s_{13} \\
  s_{12}s_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12}s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\]

\[c_{ij} = \cos \theta_{ij}, \quad s_{ij} = \sin \theta_{ij}\]

generally thought to be

\[\theta_{12} \approx \theta_{23}\]

i.e. \[|V_{cb}| \sim |V_{us}|\]
3) b hadron lifetime measurements

Two experiments using PEP at SLAC

E. Fernandez et al. (MAC)

N. S. Lockyer et al. (Mark II)

e^+ e^- \rightarrow b \overline{b} \text{ at } E_{cm} = 29 \text{ GeV}

Impact parameter technique

MAC = [1.8 \pm 0.6 \text{ (stat.)} \pm 0.4 \text{ (syst.)}] \text{ ps}

Mark II = [1.20^{+0.45}_{-0.36} \pm 0.30] \text{ ps}

the measurements are for an "average" of all b-hadrons.

Surprise !!
The lifetime difference between different $b$-hadrons (after correcting the phase space) are due to strong interactions. → QCD

\[ \Gamma_b \propto b \rightarrow c + b \rightarrow u \]

very very roughly

\[ \tau_b - \tau_c \propto \left( \frac{m_K}{m_b} \right)^5 \times \left| \frac{V_{us}}{V_{cb}} \right|^2 \times 10^{-13} \times \left| \frac{V_{us}}{V_{cb}} \right|^2 \]

\[ |V_{cb}| < |V_{us}| \]

general pattern of the CKM matrix looks like

\[
V = \begin{pmatrix}
\approx 1 & \approx 0.23 & \approx 0.23^3 \\
\approx 0.23 & \approx 1 & \approx 0.23^2 \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

Now at LEP and Tevatron, **individual** lifetimes are measured from the **proper decay time** distribution.

**ALEPH, DELPHI, OPAL and CDF**

\[
B^+ : 1.652^{+0.035}_{-0.034} \pm 0.060 \\
B^0 : 1.614^{+0.073}_{-0.069} \pm 0.050 \\
B_s : 1.54^{+0.14}_{-0.13} \pm 0.05 \\
\Lambda_b : 1.16^{+0.10}_{-0.09} \pm 0.05
\]

P. Roudeau

ICHEP 1994
Using unitarity, pattern of the CKM matrix becomes

\[
V = \begin{pmatrix}
\approx 1 & \approx 0.23 & \approx 0.23^3 \\
\approx 0.23 & \approx 1 & \approx 0.23^2 \\
\approx 0.23^3 & \approx 0.23^2 & \approx 1
\end{pmatrix}
\]

very good approximation with the standard parametrization

\[
\begin{pmatrix}
c_{12} & s_{12} & s_{13}e^{-i\delta} \\
-s_{12}c_{12}s_{23}s_{13}e^{i\delta} & c_{12}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23} \\
s_{12}s_{23}-c_{12}s_{13}e^{i\delta} & -s_{23}c_{12}-s_{12}s_{13}e^{i\delta} & 1
\end{pmatrix}
\]

good approximation a la Wolfenstein's parametrization

\[
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\
-\lambda\left[1 + A^2\lambda^4(\rho+i\eta)\right] & \left(1 - \frac{\lambda^2}{2}\right) & A\lambda^2 \\
A\lambda^3\left[1 - (\rho+i\eta)\left(1 - \frac{\lambda^2}{2}\right)\right] & -A\lambda^2\left[1 - \frac{\lambda^2}{2} + \lambda^2(\rho+i\eta)\right] & 1
\end{pmatrix}
\]

\[\lambda = s_{12}, \ A\lambda^2 = s_{23}, \ A\lambda^3(\rho-i\eta) = s_{13}e^{-i\delta}\]
From the $b$ quark decays with tree diagrams

\[ |V_{cb}| \text{ and } |V_{ub}| \]

are measured.

\[ \begin{array}{c}
W \\
\downarrow \\
b \rightarrow c \\
\end{array} \quad \begin{array}{c}
W \\
\downarrow \\
b \rightarrow u \\
\end{array} \]

the problem is

\[ \begin{array}{c}
\text{cloud of strong interactions} \\
B^- \\
\downarrow \\
b \rightarrow c \\
\end{array} \quad \begin{array}{c}
\text{s} \\
\downarrow \\
\bar{u} \\
\end{array} \quad \begin{array}{c}
K^- \\
\downarrow \\
\bar{u} \\
\end{array} \]

extraction of $|V_{cb}|$ and $|V_{ub}|$ requires a good understanding of (non perturbative) QCD...

One of the main goals of the current $B$ physics is centred around the reliable extraction of $|V_{cb}|$ and $|V_{ub}|$. 
Where does this pattern of CKM come from?? hopefully answered by future theories...

Is $3\times3$ CKM matrix really unitary?

$$\sum_{j=1}^{3} V_{ij}V_{jk}^* = \delta_{ik}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad - \text{best direct tested}$$

Another way is
determination of four parameters

$$\theta_{12} \quad \theta_{23} \quad \theta_{13} \quad \delta$$

including all the virtual processes.
ARGUS oscillated event

$B^0 \overline{B}^0 \rightarrow B^0 B^0$
4) Discovery of $B^0$-$\bar{B}^0$ oscillations

The b-quark can probe the t-quark through LOOPS!!

\[ \Delta m = 2 |M_{12}| \]

\[ P_{B \rightarrow \bar{B}}(t) \propto e^{-\Gamma t} \left( 1 - \cos \Delta m t \right) \]

\[ P_{B \rightarrow B}(t) \propto e^{-\Gamma t} \left( 1 + \cos \Delta m t \right) \]

\[ |M_{12}| \propto B_0 f^2 \times |V_{td}|^2 |V_{tb}|^2 \times m_t^2 \]

B-meson decay constant and B parameter (correction to the vacuum insertion)

from the unitarity of CKM \( \sim (0.23)^6 \)

was thought to be \( 20 \sim 30 \text{ GeV} \)

100 \sim 250 \text{ MeV} (theory: sum role, lattice etc.)
B-meson decay constant

\[ \Gamma(B^- \rightarrow l^- \bar{\nu}) = \]

\[ \propto f^2 |V_{ub}|^2 m_B m_l^2 \left( 1 - \frac{m_l^2}{m_B^2} \right) \]

except (even) \( l = \tau \) difficult decay mode to measure

\[ < 2.2 \times 10^{-3} \text{ (90\% CL) } \]

CLEO-II
For the decay time integrated rate, we define

\[ \chi = \text{time integrated probability to oscillate} \]

\[
\chi = \frac{\int_0^\infty P_B \rightarrow \bar{B}(t) \, dt}{\int_0^\infty P_B \rightarrow \bar{B}(t) \, dt + \int_0^\infty P_B \rightarrow B(t) \, dt}
\]

\[
= \frac{1}{2} \frac{x^2}{1 + x^2} + \frac{1}{8} \frac{y^2}{1 + y^2}
\]

\[
\chi = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta \Gamma}{\Gamma}
\]

\(\Delta m, \Delta \Gamma\): mass and decay widths

difference between neutral B-meson weak eigenstates (like \(K_S-K_L\)).

\(\Gamma\): averaged decay width

For \(B^0\), \(\Delta \Gamma = 0\) is assumed

Note that \(\chi_{\text{max}} = 0.5\)
Experiment using $\gamma(4S)$

- total spin = 1 (b-b) bound state above B-B threshold

\[
C = -1 \quad C = -1 \\
P = -1 \quad P = -1
\]

\[
t = 0 \quad \gamma(4S) \to B(\bar{p}) \bar{B}(-\bar{p}) - B(-\bar{p}) \bar{B}(\bar{p})
\]

neutral B's oscillate

at \( t \)

both oscillated \( B(\bar{p}) \bar{B}(-\bar{p}) - B(-\bar{p}) \bar{B}(\bar{p}) \)

or both did not oscillate

\[
\begin{aligned}
\text{only one oscillated} & \quad \bar{B}(\bar{p}) \bar{B}(-\bar{p}) - \bar{B}(-\bar{p}) \bar{B}(\bar{p}) \\
\text{or} & \quad B(\bar{p}) B(-\bar{p}) - B(-\bar{p}) B(\bar{p})
\end{aligned}
\]

\[= 0\]

Until one decays, always

\[
\overline{B}B
\]
For $\Upsilon(4S)$ events:

\[ B \rightarrow B \rightarrow l^+ X \]

\[ \bar{B} \rightarrow \bar{B} \rightarrow B \rightarrow l^+ X \quad \chi \]

they never oscillate

\[ \chi = f_d \chi_d \]

\( f_d \): fraction of \( B^0 \)
\( \chi_d \): \( \chi \) of \( B^0 \)

\[ \frac{N(l^+ l^+) + N(l^- l^-)}{N(l^+ l^-) + N(l^+ l^+) + N(l^- l^-)} = \frac{\chi + \chi}{2(1-\chi) + \chi + \chi} = \chi \]

H. A. Albrecht et al. (ARGUS),

\( \chi_d = 0.17 \pm 0.05 \)

\( m_t > 50 \text{ GeV} \)
A similar measurements at p p colliders UA1, CDF e^+ e^- collider at higher energies PEP, LEP

The $B$ and $\bar{B}$ are not produced as a pair $B^0$ with uncorrelated $B^0, B^-, \Lambda_b$ etc.

-no correlation

$$\frac{N(l^+ l^+) + N(l^- l^-)}{N(l^+ l^-) + N(l^+ l^+) + N(l^- l^-)} = \frac{\chi(1 - \chi) + \chi(1 - \chi)}{(1 - \chi)^2 + \chi^2} = 2\chi(1 - \chi)$$

They measure a mixture of $B^0$ and $B_s$

$$\chi = \phi \chi_d + \phi_s \chi_s$$
Unfortunately, $\chi$ saturate quickly to its maximum value for large $x$.

\[ \chi \]

\[ x \]

not suited for $B_s$ oscillations

limitation of the decay time integrated method

Another limitation is that $\Delta \Gamma$ is assumed.
at LEP, we can directly see the oscillations
- "long" B decay length of few mm
- Si micro vertex detector with a small diameter beam pipe

\[ \Delta m \text{ is directly extracted from the time dependent decay rates} \]
\[ \cos \Delta m t \]

No assumption of \( \Delta \Gamma = 0 \)
No uncertainty due to \( \tau_B \)

\[ \Delta m = (3.26 \pm 0.21) \times 10^{-4} \text{ eV} \]
LEP average
R. Forty,
ICHEP 1994

~100 times \( \Delta m(K) \)

LEP also gives far better limit on

\[ \Delta m_s > 3.84 \times 10^{-3} \text{ eV} \]
important input to CKM

\[
\frac{\Delta m(B_s)}{\Delta m(B_d)} = \frac{B_s f_s^2}{B_d f_d^2} \times \frac{|V_{ts}|^2}{|V_{td}|^2} > 11
\]

ratio of the hadronic effects are thought to be reliably predicted theoretically

\[
\frac{f_s}{f_d} = 1.1 \sim 1.2 \quad \text{lattice J. Shigemitsu ICHEP, 1994}
\]

B-B oscillations (loops) are sensitive to

\[
|V_{td}|, |V_{tb}| \text{ and } \frac{|V_{ts}|}{|V_{td}|}
\]

Unitarity gives

\[
|V_{tb}| = 1
\]

to a very good accuracy.
Other loops measure $|V_{ts}|$ and $|V_{td}|$

**Penguin decays**

**γ penguin**

\[ b \rightarrow W^+ \gamma \]

\[ B \rightarrow K^* + \gamma \]

\[ Br = (4.5 \pm 1.7) \times 10^{-5} \]

R. Ammar et al. (CLEO)


**first direct observation of decays via penguin diagram**

good $\gamma$ calorimeter (Csl)

\[ B \rightarrow s\text{-inclusive} + \gamma \]

\[ Br = (2.32 \pm 0.67) \times 10^{-4} \]

CLEO, 1994

- theoretical interpretation is simpler

**gluon penguin**

\[ b \rightarrow W^+ g \rightarrow s, d \]

\[ \bar{q} \]

\[ q \]

difficult to observe
2. The $K^*\gamma$ mass distributions for $B^0 \rightarrow K^{*0}\gamma$, $B^-\gamma$, $K^{*-} \rightarrow K_{S}^{0}\pi^{-}$; and $B^- \rightarrow K^{*-}\gamma$, $K^{*-} \rightarrow K^-\pi^0$ latens.

FIG. 3. The $\ln \mathcal{L}$ distributions for 10,000 "experiment 8 events each, drawn from $B^0 \rightarrow K^{*0}\gamma$ Monte Carlo (
5) Future surprise, i.e. CP violation

CP violation phenomenology
quick tour!

Exact time evolution is given by solving

\[ i \frac{\partial}{\partial t} \left( \frac{B^0}{\bar{B}^0} \right) = \left( M - i \frac{\Gamma}{2} \right) \left( \frac{B^0}{\bar{B}^0} \right) \]

\[ M_{12} = \sum_f \frac{\langle B^0 \mid H_W \mid f \rangle \langle f \mid H_W \mid \bar{B}^0 \rangle}{m - E_f} \]

\[ \Gamma_{12} = \sum_f A_f^* \bar{A}_f \]

\[ A_f = \langle B^0 \mid H_W \mid f \rangle \]

decay amplitudes

\[ M_{21} = M_{12}^*, \quad \Gamma_{21} = \Gamma_{12}^* \quad M_{11}, M_{22}, \Gamma_{11}, \Gamma_{22} : \text{real} \]

\[ M_{11} = M_{22} = M_0 \quad \Gamma_{11} = \Gamma_{22} = \Gamma_0 \quad \text{CPT} \]

this is assumed

\[ \text{Im} \left( \frac{\Gamma_{12}}{M_{12}} \right) = 0 \quad \text{CP} \]

"small" CP violation is assumed:

\[ \left| \text{Im} \left( \frac{\Gamma_{12}}{M_{12}} \right) \right| << 1 \]
mass eigenstates are given by

\[ B_{1(h)} = \frac{1}{\sqrt{1 + |\alpha|^2}} (|B^0\rangle + (-) \alpha |\bar{B}^0\rangle) \]

\[ m_{1(h)} = M_0 - (+) |M_{12}| \]

\[ \Gamma_{1(h)} = \Gamma_0 + (-) |\Gamma_{12}| \]

for small CP violation

\[ \Delta m = m_h - m_1 = 2|\Delta m|, \quad \Delta \Gamma = \Gamma_1 - \Gamma_h = 2|\Delta \Gamma| \]

\[ \alpha = \sqrt{\frac{M_{12}^* - i \frac{\Gamma_{12}^*}{2}}{M_{12} - i \frac{\Gamma_{12}}{2}}} \approx \left[ 1 - \frac{2}{4 + |\Delta \Gamma/\Delta m|^2} \text{Im} \left( \frac{\Gamma_{12}}{M_{12}} \right) \right] e^{i\phi} \]

\[ \phi = - \text{arg} M_{12} + \pi, \quad \frac{\Delta \Gamma}{\Delta m} \ll 1 \]

\[ \text{shown later} \]

for the kaon system:

\[ B_1 \leftrightarrow K_S, \quad B_h \leftrightarrow K_L \]

\[ \phi = - \frac{4 \Delta m^2}{4 \Delta m^2 + 1} \frac{\Delta m}{\Delta \Gamma} \text{Im} \left( \frac{\Gamma_{12}}{M_{12}} \right) - \text{arg} \Gamma_{12}, \quad \frac{\Delta \Gamma}{\Delta m} \approx 2 \]
In general:

- decay rates allow to measure $| V_{ij} |$
- CP violation allow to measure $\arg V_{ij} V_{kj}^*$

CP violation is generated by interference phenomena

(at least) two processes contribution one final state

$$f = A + B \leftarrow CP \rightarrow \bar{f} = \bar{A} + \bar{B}$$

$$M_{12}$$

all virtual states common to B and B

$$-i \Gamma_{12} / 2$$

all real decay states common to B and $\bar{B}$

$$M_{21} = M_{12}^*$$

$$-i \Gamma_{21} / 2 = -i \Gamma_{12} / 2$$
\[ \Gamma(B \rightarrow B) = \left| M_{12} - \frac{i\Gamma_{12}}{2} \right|^2, \quad \Gamma(B \rightarrow \bar{B}) = \left| M_{12}^* - \frac{i\Gamma_{12}^*}{2} \right|^2 \]

two rates are different, i.e.
CP violation
if
\[ \arg M_{12} \neq \arg \Gamma_{12} \]
and the difference is proportional to
\[ \sin \left[ \arg(M_{12} \Gamma_{12}^*) \right] \]

\[ \Gamma_{12} \rightarrow M_{12} \]

**CP violation in oscillations**

**K system:** \( \Gamma_{12} (V_{ud}, V_{us}), M_{12} (V_{td}, V_{ts}, V_{cd}, V_{cs}) \)

**B system:** \( M_{12} (V_{td}, V_{tb}), \Gamma_{12} (V_{cb}, V_{ub}, V_{cd}, V_{cs}, V_{ud}, V_{us}) \)

\[ \sin \left[ \arg(M_{12} \Gamma_{12}^*) \right] \] depends on the CKM phase
a straightforward to demonstrate CP violation is to compare CP conjugated processes

\[ f_\pm(t) = \frac{1}{2} \left( e^{-i m_1 t - \Gamma_1} \pm e^{-i m_2 t - \Gamma_2} \right) \]

\[ A_{B \rightarrow f}(t) = f_+(t) A_f + \alpha f(t) \bar{A}_f \]

\[ A_{B \rightarrow \bar{f}}(t) = \frac{1}{\alpha} f(t) A_{\bar{f}} + f_-(t) \bar{A}_{\bar{f}} \]
Let us consider $f = f$ first, i.e. $\pi \pi$

$$\Gamma_f(t) = |f|^2 |A_f|^2 + |f|^2 |\alpha|^2 |\bar{A}_f|^2 + 2\text{Re}(f^*f)\text{Re}(\alpha^*A_f\bar{A}_f^*) + 2\text{Im}(f^*f)\text{Im}(\alpha^*A_f\bar{A}_f^*)$$

$$\bar{\Gamma}_f(t) = |f|^2 |\bar{A}_f|^2 + |f|^2 \left|\frac{1}{\alpha}\right|^2 |A_f|^2 + 2\text{Re}(f^*f)\text{Re}\left(\frac{1}{\alpha}A_f\bar{A}_f^*\right) - 2\text{Im}(f^*f)\text{Im}\left(\frac{1}{\alpha}A_f\bar{A}_f^*\right)$$

\[\text{CP violation} \rightarrow \bar{\Gamma}_f(t) \neq \Gamma_f(t)\]

\[|\bar{A}_f| \neq |A_f|\]

CP violation in decay amplitudes

in the kaon system, this is $\text{Re}(\epsilon')$ and very very small

$< 10^{-6}$

in the B-meson system, this may not be negligible for some cases
usually neglected for B !

for the B-meson system,

\[ \Re(\varepsilon) = \frac{\frac{1}{2} \frac{\Gamma_2}{M_2}}{4 + \frac{\Delta \Gamma^2}{\Delta m^2}} \approx 1.7 \times 10^{-3} \]

for the K-meson system, this is

\[ \Im(\varepsilon) \approx 10^{-3} \]

expected to be small

\[ |\alpha| \neq 1 \]

oscillations

CP violation in
**K-meson system**

\[ \begin{align*}
M_{12} & \quad \bar{K}^0 \quad \bar{d} \\
\bar{d} & \quad \bar{u} \quad \bar{u}' \quad W \\
W & \quad \bar{U}' \quad W \\
U & \quad \bar{U} \quad d \\
d & \quad \bar{s} \quad \bar{s}
\end{align*} \]

\[ |M_{12}| = \begin{align*}
t - \bar{t} & \quad |V_{ts} V_{td}^*| \sim \lambda^2 \times m_t^2 \\
t - \bar{c} & \quad |V_{ts} V_{td}^* V_{cs} V_{cd}^*| \sim \lambda^6 \times m_t m_c \\
c - \bar{c} & \quad |V_{cs} V_{cd}^*| \sim \lambda^2 \times m_c^2
\end{align*} \]

\[ \text{charm dominates!!} \]

\[ \arg M_{12} \approx \arg (V_{cs} V_{cd}^*) \]

\[ \begin{align*}
\Gamma_{12} & \quad d \quad \bar{u} \quad \bar{d} \\
\bar{K}^0 & \quad \bar{s} \quad u \quad \bar{d}
\end{align*} \]

\[ |\Gamma_{12}| = |V_{us} V_{ud}^*| \sim \lambda^2 \]

\[ \arg \Gamma_{12} \approx \arg (V_{us} V_{ud}^*)^2 \]

\[ \downarrow \]

approximately \[ \arg M_{12} \approx \arg \Gamma_{12} \]

small CP violation
B-meson system

\[ |M_{12}| = t - \bar{t} \]
\[ |V_{tb} V_{td}^*|^2 \sim \lambda^6 \times m_t^2 \]
\[ t - \bar{c} \]
\[ |V_{tb} V_{td} V_{cb} V_{cd}^*| \sim \lambda^6 \times m_t m_c \]
\[ c - \bar{c} \]
\[ |V_{cb} V_{cd}^*|^2 \sim \lambda^6 \times m_c^2 \]

\[ \text{top dominates!!} \]
\[ \arg M_{12} \approx \arg (V_{tb} V_{td}^*)^2 \]

\[ \Gamma_{12} \]
\[ \Gamma_{12} = |V_{cb} V_{cd}^*|^2 \]
\[ 2 \times |V_{cb} V_{cd} V_{ub} V_{ud}^*| \]
\[ \sim \lambda^6 \]
\[ \sim \lambda^b \]

\[ \frac{\Delta \Gamma}{\Delta m} = \frac{\Gamma_{12}}{|M_{12}|} \approx \frac{m_c^2}{m_t^2} \ll 1 \]

\[ V_{tb} V_{td}^* = - V_{cb} V_{cd}^* - V_{ub} V_{ud}^* \]
\[ (V_{tb} V_{td}^*)^2 = (V_{cb} V_{cd}^*)^2 + (V_{ub} V_{ud}^*)^2 \]
\[ - 2 (V_{cb} V_{cd}^* V_{ub} V_{ud}^*) \]

\[ \downarrow \]
\[ \arg \Gamma_{12} \approx \arg M_{12} \] if 
\[ m_u = m_c = m_t = m_b = m_d \]

small CP violation

GIM
\[
\Gamma_f(t) = |f_\tau|^2 \left| \frac{A_f}{\overline{A}_f} \right|^2 + |f|^2 + 2\text{Re}(f_f^* \text{Re} \left( e^{-i\phi} \frac{A_f}{\overline{A}_f} \right) \\
+ 2\text{Im}(f_f^*) \text{Im} \left( e^{-i\phi} \frac{A_f}{\overline{A}_f} \right)
\]

\[
\Gamma_f(t) = |f_\tau|^2 + |f|^2 \left| \frac{A_f}{\overline{A}_f} \right|^2 + 2\text{Re}(f_f^*) \text{Re} \left( e^{-i\phi} \frac{A_f}{\overline{A}_f} \right) \\
- 2\text{Im}(f_f^*) \text{Im} \left( e^{-i\phi} \frac{A_f}{\overline{A}_f} \right)
\]

CP violation in the interplay between the oscillations and decays.

\[
\text{if } \quad \text{Im} \left( e^{-i\phi} \frac{A_f}{\overline{A}_f} \right) \neq 0
\]

in the K-meson system, this is

\[
\text{Im} \left( e^{-i\phi} \frac{A_f}{\overline{A}_f} \right) = 2 \text{ Im} \left( \eta_{+-} \right) \cong 3.4 \times 10^{-3}
\]

in the B-meson system, this is expected to be

\[
\text{Im} \left( e^{-i\phi} \frac{A_f}{\overline{A}_f} \right) = 0.1 \sim 1 \quad \text{this is what we are after!!}
\]

\[
(B_{\tau\tau}, S_{\tau\tau}, \ldots)
\]
more explicitly,

\[
\Gamma_f(t) = e^{-r t} \times \left[ \left( 1 + \frac{|A_f|^2}{\bar{A}_f} \right) - 2 \left( 1 - \frac{|A_f|^2}{\bar{A}_f} \right) \cos(\Delta m t) + 4 \text{Im} \left( e^{-i\phi} \frac{A_f}{\bar{A}_f} \right) \sin(\Delta m t) \right]
\]

\[
\bar{\Gamma}_f(t) = e^{-r t} \times \left[ \left( 1 + \frac{|A_f|^2}{\bar{A}_f} \right) + 2 \left( 1 - \frac{|A_f|^2}{\bar{A}_f} \right) \cos(\Delta m t) - 4 \text{Im} \left( e^{-i\phi} \frac{A_f}{\bar{A}_f} \right) \sin(\Delta m t) \right]
\]

- \cos \Delta m t \text{ term} \rightarrow \text{CP violation in the decay amplitude}
- \text{sensitive at early decay time} \rightarrow \text{don't throw them away}

- \sin \Delta m t \text{ term} \rightarrow \text{CP violation in the interplay between the oscillations and decay}

- \text{CP violation in oscillations is neglected}
  \sim 10^{-3}

- \Delta \Gamma \text{ is assumed to be 0}
  \left( < 10^{-2} \text{ judging from the BR.} \right)
Standard model predictions

and unitarity triangle

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

\[
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(p - i\eta) \\
-\lambda[1 + A^2\lambda^4(p + i\eta)] & \left(1 - \frac{\lambda^2}{2}\right) & A\lambda^2 \\
A\lambda^3\left[1 - (p + i\eta)\left(1 - \frac{\lambda^2}{2}\right)\right] - A\lambda^2\left[\left(1 - \frac{\lambda^2}{2}\right) + \lambda^2(p + i\eta)\right] & 1
\end{pmatrix}
\]

two unitarity relations

\[ V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* \]

\[ = \frac{V_{td}}{A\lambda^3} - 1 + \frac{\left(1 - \frac{\lambda^2}{2}\right)V_{ub}^*}{A\lambda^3} = 0 \]

\[ V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* \]

\[ = \frac{\left(1 - \frac{\lambda^2}{2}\right)V_{td}}{A\lambda^3} - \frac{V_{ts}}{A\lambda^2} + \frac{V_{ub}^*}{A\lambda^3} = 0 \]
in the complex plane

\[
\frac{V_{ub}^*}{A\lambda^3} \quad \frac{(1 - \lambda^2/2)V_{td}}{A\lambda^3} \quad 1 - \lambda^2\left(\frac{1}{2} - \rho\right) + i\eta\lambda^2
\]

\[
\frac{V_{ts}}{A\lambda^2} \quad \frac{V_{td}}{A\lambda^3}
\]

\[
\text{arg} V_{ub} = -\gamma, \text{arg} V_{td} = -\beta, \text{arg} V_{ts} = \pi + (\gamma - \gamma')
\]

the rest of elements are all real


\[
\begin{align*}
|V_{td}|, |V_{cb}|, |V_{ub}|
\end{align*}
\]

are measured, the two triangles are determined !!

\[
|V_{td}|, |V_{cb}|, |V_{ub}|
\]

from B decays and BB oscillations

$\alpha, \beta, \gamma, \gamma'$
\[ \text{Im} \left( e^{-i\phi} \frac{A_f}{\overline{A}_f} \right) \]

\[ \phi = - \arg M_{12} + \pi, \]

\[ M_{12} \propto \left( V_{tb} V_{td}^* \right)^2, \arg M_{12} = 2\arg V_{td}^* = 2\beta \]

\[ e^{-i\phi} = -e^{2\beta} \]

\[ \text{B} \rightarrow \text{J/}\psi \text{K}_S \]

\[ \begin{array}{c}
\overline{b} \\
\text{B}^0 \quad \text{W} \\
\overline{s} \quad \text{d} \\
\end{array} \quad \frac{c}{\text{c}} \quad \frac{d}{\text{d}} \quad \text{J/}\psi \\
\frac{c}{\text{c}} \quad \text{W} \\
\frac{s}{\text{d}} \quad \overline{u} \\
\frac{d}{\text{d}} \end{array} \quad \text{K}_S \]

\[ A_f \propto V_{cs} V_{cb}^* V_{ud} V_{us}^*, \arg A_f = 0 \]

\[ \overline{A}_f \propto -V_{cs}^* V_{cb} V_{ud}^* V_{us}, \arg \overline{A}_f = \pi \]

\[ \text{CP( J/}\psi \text{ K}_S) = -1 \]

\[ \text{Im} \left( e^{-i\phi} \frac{A_f}{\overline{A}_f} \right) = \text{Im} \left( -e^{i2\beta + \pi} \right) = \sin 2\beta \]

For f = J/\psi Ks if ONLY the b \rightarrow c tree diagram contributes

CP violation in the oscillation is neglected

No uncertainty due to strong interactions
CKM fit: fit of four CKM parameters using

\[
\begin{align*}
|V_{ud}|, |V_{us}|, |V_{ub}|, |V_{cd}|, |V_{cs}|, |V_{cb}|
\end{align*}
\]

\(\Delta m(B_d)\), lower limit on \(\Delta m(B_s)\)

triangles can be still

if we include \(\text{Re}(\varepsilon_K)\)

\[
\begin{align*}
\sin 2\beta & \approx 0.4 \text{ to } 0.8
\end{align*}
\]

If we observe

\[
\text{Im}\left(e^{-i\phi}\frac{A_f}{\bar{A}_f}\right) = 0.6
\]

does this mean that CP violation is generated by CKM?

Not really...
Superweak model

Suppose we have a new heavy neutral particle generating

\[ s \rightarrow H \rightarrow d \]

with COMPLEX coupling

and CKM elements are all real

\[ M_{12} = \text{CKM box (real)} + H \text{ (complex)} \]

\[ \Gamma_{12} = \left[ \text{CKM tree (real)} \right]^2 \]

\[ \arg \Gamma_{12} \neq \arg M_{12} \]

All the decay amplitudes are real

\[ \text{Re} (\varepsilon_K) \neq 0 \quad \text{and} \quad \text{Im} \left( e^{-i\phi \frac{A_{2\pi}}{A_{2\pi}}} \right) \neq 0 \]

\[ = \text{Re} \eta_{+-} = \text{Re} \eta_{00} = 2 \text{Im} \eta_{+-} = 2 \text{Im} \eta_{00} \]

\[ \eta_{+-} = \eta_{00} \quad \text{and} \quad \arg \eta_{+-} = \tan^{-1} \left( \frac{2\Delta m}{\Delta \Gamma} \right) \]

One can explain observed CP violation in K system

Superweak model (K system)

L. Wolfenstein, Phys. Rev. Lett. 13 (1964) 562
if we assume the coupling of H to quarks is proportional to the quark masses, like a Higgs,

\[ \text{arg} M_{12}(B) \gg \text{arg} M_{12}(K) \]

\[ \Gamma_{12} = [\text{CKM tree(real)}]^2 \]

all the decay amplitudes are real

CP violation in oscillation is proportional to

\[ -\frac{1}{2} \text{Im} \left( \frac{\Gamma_{12}}{M_{12}} \right) = \frac{1}{2} \frac{\Delta \Gamma}{\Delta m} \sin (\text{arg} M_{12}) \]

\( \Delta \Gamma \) is unaffected by H and \( \Delta \Gamma/\Delta m \) is still very small.

CP violation in oscillations is still small

\[ \sin (\text{arg} M_{12}) \]

\[ \phi = -\text{arg} M_{12} + \pi \]

\[ A_{J/\psi K_S} = \text{real}, \quad \bar{A}_{J/\psi K_S} = -A_{J/\psi K_S} \]

CP(\( J/\psi K_s \)) = -1

\[ \text{can be } = \sim 0.6 \]
CP violation in other decay mode, e.g. \( \pi\pi \)

\[
\text{Im}\left( e^{-i\phi \frac{A_{\pi^+\pi^-}}{\bar{A}_{\pi^+\pi^-}}} \right) \quad \phi = -\arg M_{12} + \pi
\]

\( A_{\pi^+\pi^-} = \text{real, } \bar{A}_{\pi^+\pi^-} = A_{\pi^+\pi^-} \)

\( \text{CP}(\pi\pi) = +1 \)

\[= -\sin(\arg M_{12}) \]

we have a definite relation:

**Superweak model prediction for CP violating decays into any CP eigenstates**

\[
\text{Im}\left( e^{-i\phi \frac{A_f}{\bar{A}_f}} \right) = \text{CP}(f) \times \sin(\arg M_{12})
\]
standard model prediction for $B \rightarrow \pi \pi$

if $B \rightarrow \pi \pi$ is produced only by $b \rightarrow u$ tree diagram

$$\begin{array}{c}
\text{W} \\
\text{b} \\
\text{d}
\end{array} \quad \begin{array}{c}
\text{d} \\
\text{u} \\
\text{u}
\end{array}$$

$A_f \propto V_{ud}V_{ub}^*$, $\arg A_f = \arg V_{ub}^* = \gamma$

$\bar{A}_f \propto V_{ub}V_{ud}^*$, $\arg \bar{A}_f = \arg V_{ub} = -\gamma$

$\phi = - \arg M_{12} + \pi,$

$M_{12} \propto (V_{tb}V_{td}^*)^2$, $\arg M_{12} = 2\arg V_{td}^* = 2\beta$

$$\text{Im} \left( e^{-i\phi \frac{A_f}{\bar{A}_f}} \right) = \text{Im} \left( e^{i \left( 2\beta + \pi + 2\gamma \right)} \right)$$

$$= - \sin \left( 2\beta + 2\gamma \right) = - \sin (2\alpha)$$

CKM fit $\sin 2\alpha = \sim -0.2$ to $\sim 1$

By studying different final states, one can test whether CP violation is due to CKM.

if $B \rightarrow \pi \pi$ is produced only by $b \rightarrow u$ tree diagram
Penguin "pollution"

\[ b \rightarrow c \] process

\[ B \rightarrow J/\psi K_s \]

\[ \begin{array}{c}
\text{tree: } T \\
V_{ts}V_{tb}^*P + V_{cs}V_{cb}^* + V_{us}V_{ub}^* = 0
\end{array} \]

\[ \text{unitarity} \]

\[ A_{J/\psi K_s} \propto V_{cs}V_{cb}^*T + V_{ts}V_{tb}^*P = V_{cs}V_{cb}^*(T - P) - V_{us}V_{ub}^*P \]

\[ \lambda^2 \]

\[ \lambda^4 \]

\[ V_{us}V_{ub}^* \text{ contribution is } O\left(\frac{P}{T} \times \lambda^2\right) \approx 10^{-3} \]

little pollution

\[ B \rightarrow D^+ D^- \]

\[ \begin{array}{c}
\text{penguin: } P \\
V_{us}V_{ub}^* \text{ contribution is } O\left(\frac{P}{T} \times \lambda^2\right) \approx 10^{-3} \]

can be a serious pollution
For $\sin 2\beta$ measurement

$$B \rightarrow J/\psi \, K_S$$

is by far the best channel.

$b \rightarrow u$ process: $\sin 2\alpha$

\[ A_{\pi\pi} \propto V_{ud} V_{ub}^* T + V_{td} V_{tb}^* P = V_{ud} V_{ub}^* (T - P) - V_{cd} V_{cb}^* P \]

\[ \lambda^3 \quad \lambda^3 \]

$V_{cd} V_{cb}^*$ contribution is $O\left(\frac{P}{T}\right) \approx 10^{-1}$

can be a serious pollution
\[ B_S \rightarrow J/\psi \phi \]
\[ \text{Im} \left( e^{-i\phi \frac{A_f}{\bar{A}_f}} \right) = -\text{Im} \left( -e^{i2(\gamma' - \gamma) + \pi} \right) = \sin 2(\gamma' - \gamma) = 2\eta \lambda^2 \]

**the standard model prediction** for CP violation in \( B_S \rightarrow J/\psi \phi \) is **very small**

**the superweak model** predicts
\[ \text{arg} M_{12} (B_d) \approx \text{arg} M_{12} (B_s) \]

CP violation in \( B_S \rightarrow J/\psi \phi \) is **as large as** in \( B \rightarrow J/\psi K_S \)**
very good decay time resolution is needed!!

\[ B( B_s \rightarrow J/\psi \phi ) \sim 7 \times 10^{-4} \]
\[ \Gamma_f(t) = |f|^2 |A_f|^2 + |f|^2 |\alpha|^2 |\bar{A}_f|^2 + 2\text{Re}(f\cdot f^*) \text{Re}(\alpha^* A_f \bar{A}_f^*) + 2\text{Im}(f\cdot f^*) \text{Im}(\alpha^* A_f \bar{A}_f^*) \]

\[ \bar{\Gamma}_f(t) = |\bar{f}|^2 |\bar{A}_f|^2 + |\bar{f}|^2 |\frac{1}{\alpha}|^2 |A_f|^2 + 2\text{Re}(\bar{f} \cdot f^*) \text{Re}(\frac{1}{\alpha} A_f \bar{A}_f^*) - 2\text{Im}(\bar{f} \cdot f^*) \text{Im}(\frac{1}{\alpha} A_f \bar{A}_f^*) \]

\[ \text{CP violation} \rightarrow \bar{\Gamma}_f(t) \neq \Gamma_f(t) \]
An interesting idea to measure the angle $\gamma$ using charged B-meson decay

(Gronau, Wyler)

$\mathbf{B}^+ \rightarrow \mathbf{D}^0 \mathbf{K}^+$

$\mathbf{B}^+ \rightarrow \overline{\mathbf{D}}^0 \mathbf{K}^+$

$\mathbf{D}^0 \rightarrow \mathbf{K}^- \pi^+, \mathbf{K}^- \pi^+ \pi^- \pi^+$

$\overline{\mathbf{D}}^0 \rightarrow \mathbf{K}^+ \pi^-, \mathbf{K}^+ \pi^- \pi^+ \pi^-$

$\lambda^3$

$D_{1,2} = \frac{D^0 \pm \overline{D}^0}{\sqrt{2}}$

$\sqrt{2} \ A(B^+ \rightarrow D_1, K^+) = A(B^+ \rightarrow D^0, K^+) + A(B^+ \rightarrow \overline{D}^0, K^+)$

$= V_{cs} V_{ub}^* T + V_{us} V_{cb}^* T'$

$= e^{i\gamma} T + T'$

$\sqrt{2} \ A(B^- \rightarrow D_1, K^+) = A(B^- \rightarrow \overline{D}^0, K^-) + A(B^- \rightarrow D^0, K^-)$

$= V_{cs} V_{ub}^* T + V_{us} V_{cb}^* T'$

$= e^{-i\gamma} T + T'$
\[ \sqrt{2} \, A(B^+ \rightarrow D_1, K^+) \]

\[ A(B^+ \rightarrow D^0, K^+) \]

\[ A(B^- \rightarrow D^0, K^-) \]

\[ A(B^- \rightarrow D_1, K^+) \]

\[ \text{arg } T + \gamma - \text{arg } T' \]

\[ \text{arg } T - \gamma - \text{arg } T' \]

\[ \left| A(B^+ \rightarrow D^0, K^+) \right| = \left| A(B^- \rightarrow \overline{D}^0, K^-) \right| \]

\[ \left| A(B^+ \rightarrow \overline{D}^0, K^+) \right| = \left| A(B^- \rightarrow D^0, K^-) \right| \]

superweak model: \( \gamma = 0 \)

CKM fit: \( \gamma = 60^\circ \sim 120^\circ \)
1) Measure six branching fractions

\[ B^+ \rightarrow D^0 K^+, \bar{D}^0 K^+, D_{1,2} K^+ \]
\[ B^- \rightarrow D^0 K^-, \bar{D}^0 K^-, D_{1,2} K^- \]

2) check

\[ Br(B^+ \rightarrow D^0 K^+) = Br(B^- \rightarrow \bar{D}^0 K^-) \]
\[ Br(B^+ \rightarrow \bar{D}^0 K^+) = Br(B^- \rightarrow D^0 K^-) \]

3) Draw triangles and get \( \sin 2g \)

\( (this \ is \ really \ g) \)

there are some sign ambiguities

useful branching fraction for reconstructing

\[ B^{\pm} \rightarrow D_{1,2} K^{\pm} \]

is small, \( \sim 5 \times 10^{-7} \)
5) Future experiments

Currently running

- electron-positron storage rings
  - CESR: γ(4S), LEP: Z^0
  - CLEO-II, ALDO

- hadron machines
  - SPS (fixed target), Tevatron (p ¯p collider)
  - BEATRICE, CDF, D0

improving the current knowledge on

\[ |V_{ub}|, |V_{cb}| : \text{tree} \quad \text{induced B-meson decay rates} \]

\[ |V_{td}|, |V_{ts}| : \text{penguin} \]

- measure many decay modes, more variables, lifetimes
- theoretical understanding of non perturbative QCD

\[ |V_{td}|, |V_{ts}| : \text{box diagram} \quad \text{B-B oscillations} \]

- B_s may be difficult (statistics, decay time resolution)
- theoretical understanding of non perturbative QCD, f_B
could be a big surprise, i.e. CP violation...

at CESR: if CP violation in decay amplitudes

CDF: in J/ψ K_S

if B^{**+} \rightarrow π^+ B^0 can be used for tag

Near future

leptonic road

B-meson factories

PEP-II, TRISTAN-II
electron-positron storage rings at γ(4S)

L\sim few \lesssim 10^{33} \text{ cm}^{-2} \text{s}^{-1}

few \times 10^7 B-B / 10^7 \text{s}

double ring with a modest beam energy asymmetry

high luminosity is obtained from
large number of bunches

PEP-II: head-on collision with magnetic separation

TRISTAN-II: finite beam crossing
beam energy asymmetry
→ essential for CP violation study

As we discussed, on $\Upsilon(4S)$

until one decays, always

$\bar{B}B$

"tag" $l^+ X$

$B \rightarrow B$

$\bar{B} \rightarrow \bar{B} \rightarrow \bar{B}^0(t - t_1) \rightarrow$

$t = 0 \quad t = t_1 \quad t = t_2$

$\bar{B}^0(t - t_1) = \frac{1}{\alpha} f(t - t_1) B^0 + f(t - t_1) \bar{B}^0$

$I(t_2 - t_1) = \left| \frac{1}{\alpha} f(t_2 - t_1) A_f + f(t_2 - t_1) \bar{A}_f \right|^2$

$\propto e^{-\Gamma \Delta t} \left[ 1 - 2 \text{Im} \left( e^{-i\phi \frac{A_f}{\bar{A}_f}} \sin(\Delta m \Delta t) \right) \right] \quad \Delta t = t_2 - t_1$

neglecting CP violation in the decay amplitude
\[
\begin{align*}
A_f \bar{B}^0(t-t_1) + \bar{A}_f B^0(t-t_1) &= \\
A_f \left[ \frac{1}{\alpha} f(t-t_1) B^0 + f(t-t_1) \bar{B}^0 \right] + \bar{A}_f \left[ \bar{f}(t-t_1) B^0 + \alpha f(t-t_1) \bar{B}^0 \right]
\end{align*}
\]

\( l^+ X \) is from \( B^0 \) decays

\[
\Gamma(t_2 - t_1) = \left| \frac{1}{\alpha} f(t_2 - t_1) A_f + f(t_2 - t_1) \bar{A}_f \right|^2
\]

\[
\propto e^{-\Gamma \Delta t} \left[ 1 - 2 \text{Im} \left( e^{-i\phi A_f / \bar{A}_f} \right) \sin(\Delta m \Delta t) \right]
\]
\[ \text{J}/\psi \, K_S \quad l^+ X \quad \text{events} \]
\[ e^{-\Gamma \Delta t} \left[ 1 - 2 \text{Im} \left( e^{-i\phi \frac{A_f}{\bar{A}_f}} \right) \sin(\Delta m \Delta t) \right] \]

\[ \text{J}/\psi \, K_S \quad l^- X \quad \text{events} \]
\[ e^{-\Gamma \Delta t} \left[ 1 + 4 \text{Im} \left( e^{-i\phi \frac{A_f}{\bar{A}_f}} \right) \sin(\Delta m \Delta t) \right] \]

the rates depend only on
\[ \Delta t = t \text{(second decay)} - t \text{(first decay)} \]

symmetric energy beams \( \rightarrow \gamma(4S) \) at rest

- no particle from the primary vertex (\( \gamma(4S) \rightarrow BB \))
- beam spot > B decay length (\( \sim 20 \mu m \))
asymmetric energy beams \( \rightarrow \gamma(4S) \) moving

\[
E_H E_L = \frac{m(\gamma(4S))^2}{4} \approx 28 \text{ GeV}^2
\]

\[
\Delta t \approx \frac{m(\gamma(4S))}{c \left( E_H - E_L \right)} \Delta z
\]

what is the optimal boost?

- boost
  - \( \frac{\sigma_\tau}{\tau} \)
- statistical sensitivity
- acceptance

Optimal boost is around \( E_H = 8 \sim 9 \text{ GeV} \)
\[ N_{\text{event}} \text{ [arbitrary units]} \]

\[ E_{H} \text{ [GeV]} \]

- \( \sigma_{\Delta z} = 60 \mu m \)
- \( x = 0.7 \)
detectors: BaBar(SLAC) and Bell(KEK)

new feature: dedicated particle ID
detector for K / π

CP reach (10^7 s)

| | \( \sigma (\sin 2\beta) \) | 0.098 | J/ψ K_S |
| | \( \sigma (\sin 2\alpha) \) | 0.20 | \( \pi^+ \pi^- \) |
| | | 0.059 | combining other decays |
| | | 0.085 | combining other decays |

- well understood environment
  simulation is reliable

- question is whether the designed luminosity can
  be reached with a small beam pipe of a few cm radius at the intersection

Hadronic road

HERA-B

HERA proton beam (820 GeV)
+ 8 wire targets (internal target)
  using beam halo
bunch crossing rate: 10 MHz
event rate: 40 MHz
\( \sigma (b\bar{b}) / \sigma (\text{inelastic}) : \sim 9 \times 10^{-7} \)
\( \sigma (b\bar{b}) : \sim 12 \text{ nb} \)

main goal: CP violation in J/\( \psi \) \( K_S \) decays
\[ \rightarrow \text{dimuon J/\( \psi \) trigger} \]

CP reach (10\(^7\) s)
\( \sigma (\sin 2\beta) : 0.13 \)

other trigger possibility (high \( P_T \) hadrons)
for \( \pi^+\pi^- \) under study

**Far future**

ultimate CP experiments at LHC
bunch crossing rate: 40 MHz
event rate: \( > 40 \text{ MHz} \)
\( \sigma (b\bar{b}) / \sigma (\text{inelastic}) : \sim 1 \times 10^{-2} \)
\( \sigma (b\bar{b}) : \sim 500 \mu \text{b} \)

\( 5 \times 10^{12} b\bar{b} / 10^7 \text{ s with } L = 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)
trigger should exploit

B-meson decay properties

- high $P_T$ muon: easiest trigger
- electron: many more background
- hadron: difficult in the collider mode at high energy

B and associated D vertices
tracks with large impact parameters

ATLAS, CMS

- single muon trigger (ATLAS)
- single and dimuon trigger (CMS)

ATLAS uses $e^+$ and $e^-$
for the tag and $J/\psi$ reconstruction

CMS, muon only

- do well for $J/\psi K_S$

$\sigma (\sin 2\beta)$: ~0.02 (ATLAS), ~0.05 (CMS)

also good for $B_s \to J/\psi \phi, \mu\mu$
ATLAS and CMS have no hadron identification

large background in
\[ B \rightarrow \pi^+\pi^- \]
Background / Signal \( \sim 1 \)

coming from two-body B and \( B_s \) decays
\( K\pi, KK \) etc. i.e. peaks at the B mass

- subtracting based on "known" branching fractions
- study decay time dependence

background: exponential
(assuming no CP violation in the background)

\( \sigma (\sin 2\alpha): \sim 0.04 \) (ATLAS), \sim 0.07 \) (CMS)

only with \( \mu \) tag

more complicated decay modes,

\( B_s \rightarrow D_s K, B \rightarrow D^0 K^*^0 \)

are difficult due to the lack of hadron identification

LHC-B: a dedicated experiment to measure CP violation in B-meson decays
- hadron identification
- trigger sensitive to different decay modes:
  - high \( P_T \) muon, electron and hadron combined with a topology trigger
  - tag with \( \mu, e, K \) etc.
LHCC and CERN management have stressed that a dedicated B experiment would be considered as one of the base line experiments at LHC together with ATLAS, CMS and ALICE.