CP violation and related issues

Part 16: CKM matrix, summary and outlook

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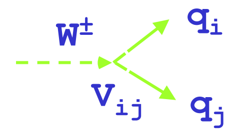
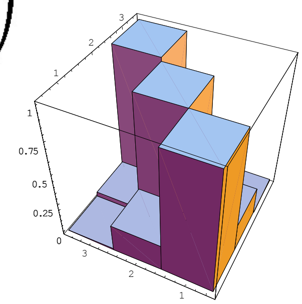
CP violation: consequence of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix



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

Transitions between members of the same family more probable than others



-> CKM: almost a diagonal matrix, but not completely

CKM matrix

If $V_{ij}=V_{ij}^*$ ▶ $\mathcal{L}=\mathcal{L}_{CP}$ ▶ CP is conserved, otherwise not

3x3 unitary matrix: 3 real parameters and 1 phase
-> the matrix is in general complex

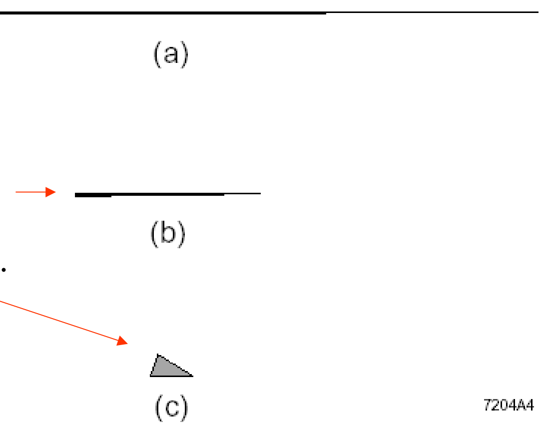
$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{13} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$s_{12}=\sin\theta_{12}$, $c_{12}=\cos\theta_{12}$ etc.

CKM matrix can accomodate the CP violation, and does it well!

Unitary triangles

$$V_{ud}V_{us}^{*}+V_{cd}V_{cs}^{*}+V_{td}V_{ts}^{*}=0,$$
$$V_{us}V_{ub}^{*}+V_{cs}V_{cb}^{*}+V_{ts}V_{tb}^{*}=0,$$
$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0.$$



All triangles have the same area J/2 (about 4x10^{-5})

$$J=c_{12}c_{23}c_{13}^{2}s_{12}s_{23}s_{13}\sin\delta$$

Unitarity triangle

THE unitarity triangle:

$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$$

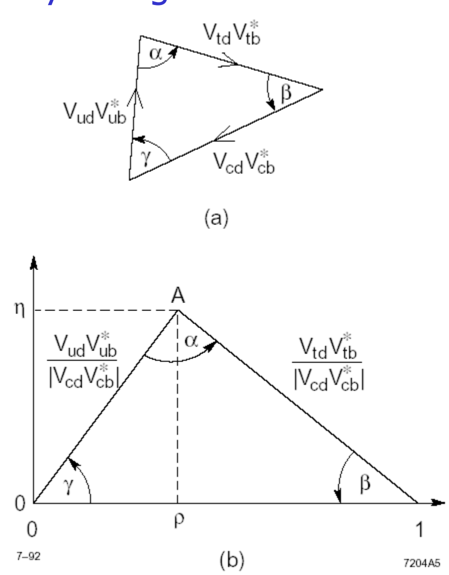
Measure angles and sides:

$\phi_1=\beta$

$\phi_2=\alpha$

$\phi_3=\gamma$

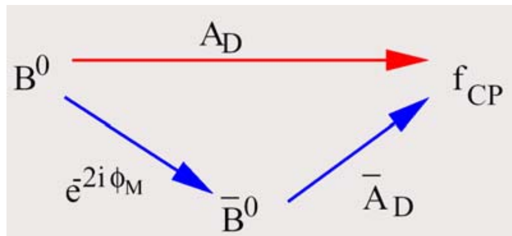
$\mathbf{V_{ub}}$



CP violation measurements: the main tool to study the unitarity triangle

CP violation in the interference between mixing and decay to a state accessible in both B^0 and anti-B^0 decays

For example: a CP eigenstate f_{CP} like $\pi^+ \pi^-$

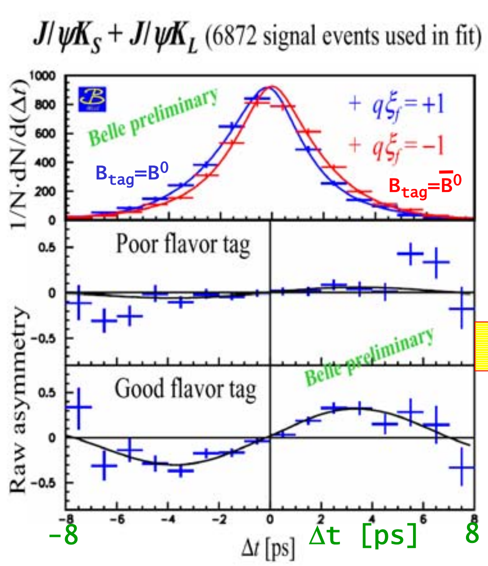


$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP},t) - P(B^0 \to f_{CP},t)}{P(\overline{B}^0 \to f_{CP},t) + P(B^0 \to f_{CP},t)} = \qquad \lambda = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

$$= \frac{(1-|\lambda_{f_{CP}}|^2)\cos(\Delta m t) - 2\,\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)}{1+|\lambda_{f_{CP}}|^2}$$

If $|\lambda| = 1$ -> $a_{f_{CP}} = -\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta m t)$

Angle β (ϕ_1) as $\sin 2\phi_1$ from CP asymmetry measurement



Asymmetry between B and anti-B decaying to the same final CP eigenstate $J/\psi K_S$

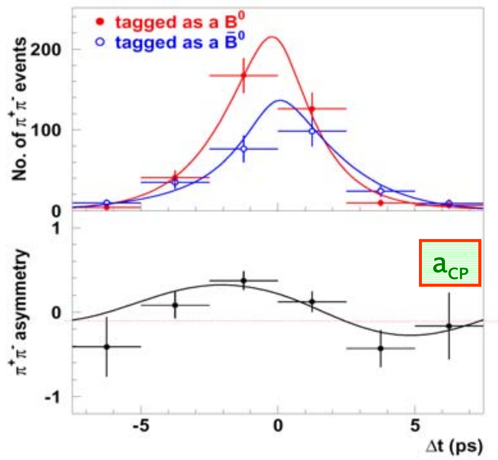
$\sin 2\phi_1 = 0.666 \pm 0.046$

Belle

$\sin 2\phi_1 = 0.722 \pm 0.040 \pm 0.023$

BaBar

Angle α (ϕ_2) from CP asymmetry measurement



Asymmetry between B and anti-B decaying to the same final CP eigenstate $\pi^+\pi^-$, complicated analysis because of penguin diagrams

$\mathcal{S}_{\pi\pi}$ = -0.67±0.16±0.06

$\mathcal{A}_{\pi\pi}$ = 0.56±0.12±0.06

-> direct CP violation!
Evident on this plot:
Number of anti-B events
< Number of B events

Angle α (ϕ_2) from CP asymmetry measurements

Use measured BRs and asymmetries in all three $B \rightarrow \pi\pi$ decays $\rightarrow$ extract ϕ_2

Similar analysis as for $B \rightarrow \pi\pi$ also for $B \rightarrow \rho\rho$
(ϕ_2^{eff} closer to ϕ_2)

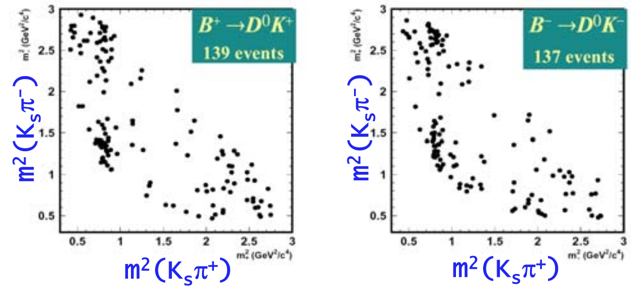
... and for $B \rightarrow \rho\pi$

	BaBar/Belle	BaBar
S_{+-}	$Br(B^0 \rightarrow \pi^0\pi^0)$	Similar from $B \rightarrow \rho\rho$
A_{+-}	$Br(B^0 \rightarrow \pi^+\pi^-)$	BaBar/Belle
$\mathcal{A}_{CP}$	$Br(B^+ \rightarrow \pi^+\pi^0)$	Similar from $B \rightarrow \rho\pi$

$\phi_2 = 106^o \pm {}^{8^o}_{11^o}$

Angle γ (ϕ_3) from a Dalitz plot analysis of the interference of two decay channels

$B^+ \to D^0K^+$ $\qquad$ $B^- \to D^0K^-$



⇨ Visible asymmetry

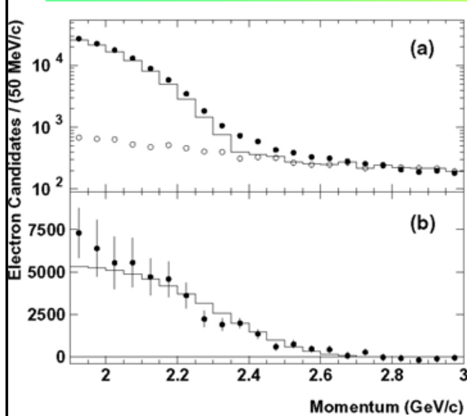
Fit with ϕ_3, δ, r_B free

$\phi_3 = (68 \pm ^{14}_{15} \pm 13 \pm 11)^o$

$22^o < \phi_3 < 113^o$ @ 95% C.L.

$r_B = 0.21 \pm 0.08 \pm 0.03 \pm 0.04$

$|V_{ub}|$ from inclusive measurements



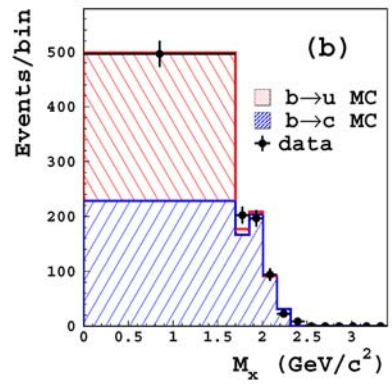
Electron spectrum, extended momentum range

$|V_{ub}| = (4.50 \pm 0.42 \pm 0.32 \pm 0.21) \times 10^{-3}$

Inclusive $|V_{ub}|$ measurements 2

New method: fully reconstruct one of the B mesons, check the properties of the other (semileptonic decay, low mass of the hadronic system)

- Very good signal to noise
- Low yield (full reconstruction efficiency is 0.3-0.4%)



M_x<1.7 GeV/c² / q^2>8 GeV²/c²

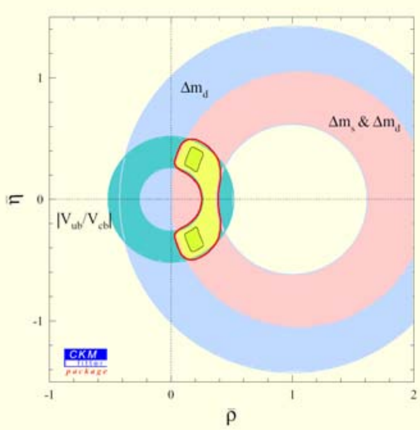
Total error on $|V_{ub}|$ 12%

253 fb^{-1}

$$|V_{ub}| = (4.34 \pm 0.22 \pm 0.19 \pm 0.13 \pm 0.12 \pm 0.33 \,{}^{+0.20}_{-0.22}) \times 10^{-3}$$

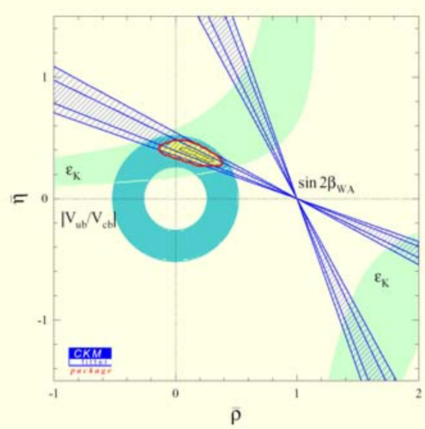
stat syst b→u b→c SF theo model dep.

Unitarity triangle with different sets of data



Tree level + CPC observables

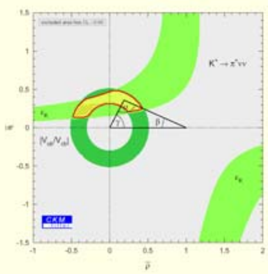
$\Delta m_B, \quad \Delta m_{B_s}$

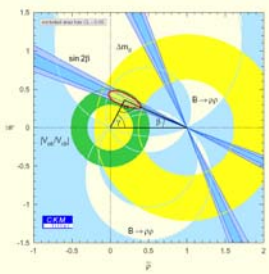


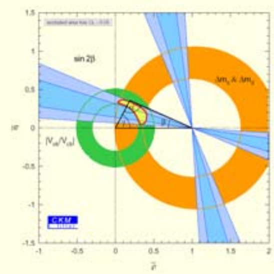
Tree level + CPV observables

$\varepsilon, \quad S_{\psi K_S}$

Unitarity triangle with different sets of data 2004







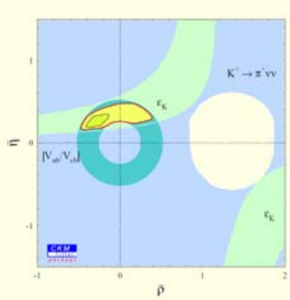
$s \to d$ | $b \to d$ | $b \to s$

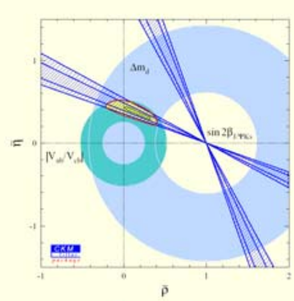
$\varepsilon,\ \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ | $\Delta m_{B_d},\ S_{\psi K},\ S_{\rho\rho}$ | $\Delta m_{B_s},\ S_{\phi K, \eta' K, KKK}$

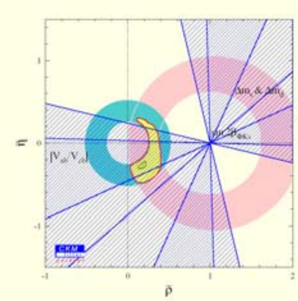
-> CKM matrix can accomodate the CP violation, and does it very well!

… apart from some interesting hints...

Unitarity triangle with different sets of data status 2002







$s \to d$ | $b \to d$ | $b \to s$

$\varepsilon,\ \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ | $\Delta m_{B_d},\ S_{\psi K_S}$ | $\Delta m_{B_s},\ S_{\phi K_S}$

Measurements help...

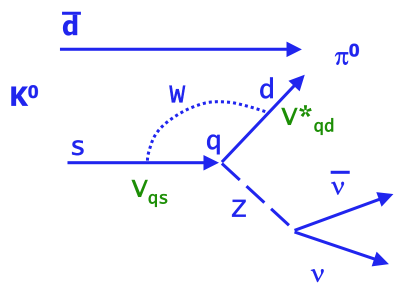
$K^0_L \to \pi^0\nu\nu$ decay

CP violating process (Littenberg PRD 39 (1989) 3322).

In SM dominated by EW penguin and box diagrams.

Calculable with little theoretical uncertainties (for details see A. Buras, hep-ph/0101336)

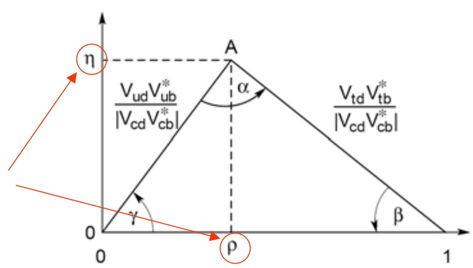
$$Br(K_L \to \pi^0 \nu\bar{\nu}) = CA^4\eta^2$$



$K^0_L \to \pi^0\nu\nu$ decay

$$Br(K_L \to \pi^0 \nu\bar{\nu}) = CA^4\eta^2$$

-> measurement of this BR and of the related $K^+ \to \pi^+\nu\nu$ decay could provide excellent constraints on the parameters η and ρ, can also be used to extract $\sin 2\beta$.



Experimentally very challenging: very rare decay (SM expectation 2.5 10^{-11}) of the type "nothing" to "nothing".

Measured $BR(K^+ \to \pi^+\nu\nu) = (1.6^{+1.8}_{-0.8})\ 10^{-10}$ with 3 events…

Experiments: KOPIO ($K^0 \to \pi^0\nu\nu$), BNL787/949, CKM ($K^+ \to \pi^+\nu\nu$)

Back to the motivation: 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 (microwave backg)

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

How did we get from

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

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

Three conditions

Three conditions (A.Saharov, 1967):

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

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

(baryon number f_b; decay probability)

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

Change in baryon number in the decay of X:

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

Three conditions

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

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

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

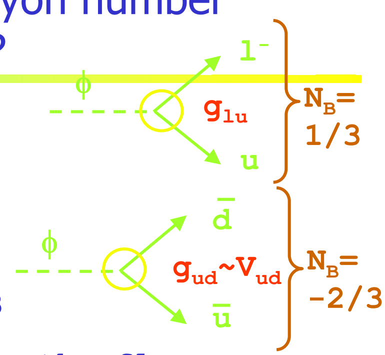
In the thermal equilibrium reverse processes would cause ΔB=0 ->
need an out-of-equilibrium state

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

How to get CP + baryon number violation?

Let ϕ be the particle, whose decay violates the baryon number conservation

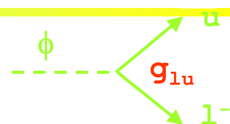
e.g. in GUT SU(5) the Higgs boson with charge -1/3



- In SM the CKM matrix rotates the flavour eigenstates into the mass eingenstates.
H^0 (neutral Higgs boson of SM) couples only to mass eingenstates, coupling constants do not involve V_{ij};
- ϕ couples only to u and d quarks, coupling constants are proportional to V_{ij} -> complex

How to get CP + baryon number violation?

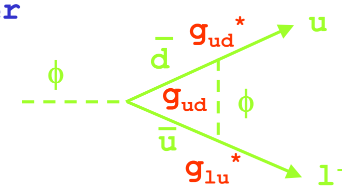
Tree order: no $r \neq \bar{r}$



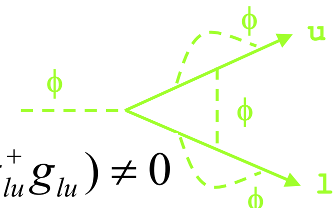
Interference with the next order

$$\Delta B \propto \operatorname{Im} Tr(g_{ud}^{+} g_{ud} g_{lu}^{+} g_{lu}) = 0$$

=trace over all fermions



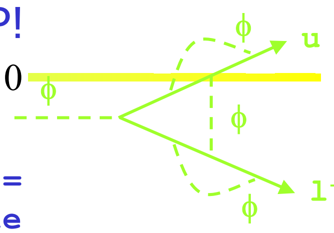
Only in three-loop processes



$$\Delta B \propto \operatorname{Im} Tr(g_{ud}^{+} g_{lu} g_{lu}^{+} g_{ud} g_{ud}^{+} g_{ud} g_{lu}^{+} g_{lu}) \neq 0$$

Not enough CP!

$$\Delta B \propto \operatorname{Im} Tr(g_{ud}^{+} g_{lu} g_{lu}^{+} g_{ud} g_{ud}^{+} g_{ud} g_{lu}^{+} g_{lu}) \neq 0$$



The contribution from the CKM matrix to the above expression = J = 2x area of the uni. triangle

$\operatorname{Im}(V_{11} V_{22} V_{12}^* V_{21}^*) = J$ → $J_{max} = 1/6\sqrt{3}$

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

$$J = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13} \sin\delta \le 4 \cdot 10^{-5}$$

$(N_B - N_B)/N_\gamma = \Delta B n_X/N_\gamma \sim \Delta B \sim 10^{-16}$

$\ll (N_B - N_B)/N_\gamma = 10^{-10} - 10^{-9}$

Not enough CP!

Looking for more CP violating effects that would not fit into the Standard Model:

- Precise determination of unitarity triangle parameters in various processes
- Look for effects in new systems (e.g. B_s)

-> need the next generation of B factories:

- LHCb at the pp collider
- Super B-factory, asymmetric e^+e^- collider at Y(4s). with present luminosity x20++
- Look for CP in the neutrino sector