Meson Mixing and CP Violation

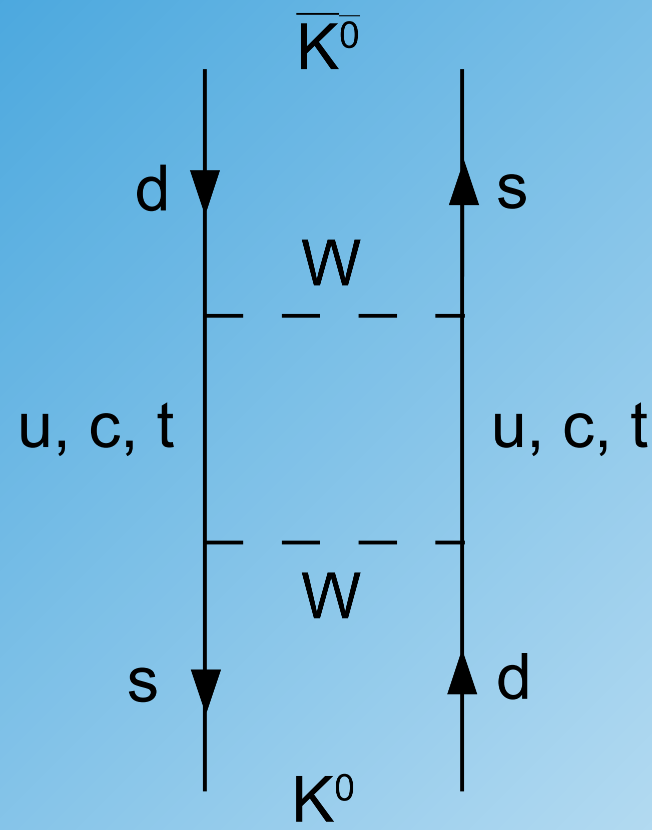
- Kaon Oscillations
- CP-violation
- Direct CP-Violation
- CP-Violation in Mixing
- CP violation in interference
- Unitarity triangle

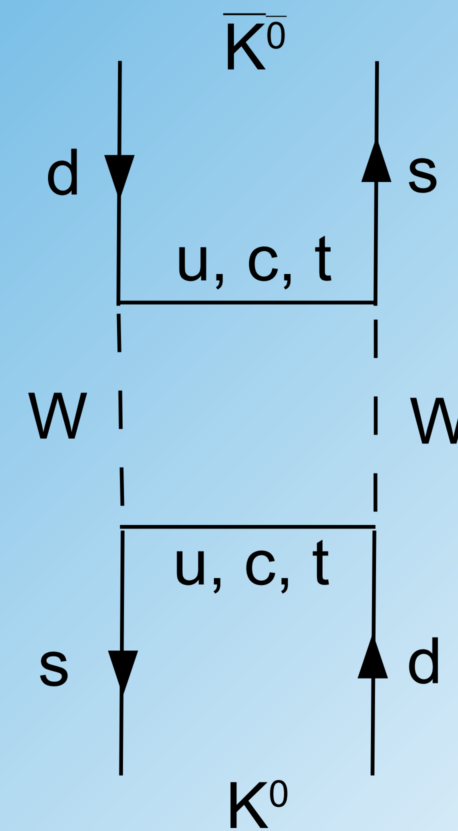
19.1 K^0-$\overline{K}^0$ Mixing

amplitude proportional to:

$$V_{ud}^* \, V_{ud}^* \, V_{us} \, V_{us} \; f(m_u) + V_{cd}^* \, V_{cd}^* \, V_{cs} \, V_{cs} \; f(m_c) + V_{td}^* \, V_{td}^* \, V_{ts} \, V_{ts} \; f(m_t)$$

note: couplings from d-type to u-type are complex conjugated





$< K^0 | \, T \, | \overline{K}^0 > \; = \; < \overline{K}^0 | \, T \, | K^0 >$ if $\delta_{13}=0$ (element V_{td})

if $\delta_{13} <> 0$ then CP violation (nota bene CPT theorem)

Wolfenstein Parameterisation

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)\,.$$

$$s_{12} = \lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}, \qquad s_{23} = A\lambda^2 = \lambda \left| \frac{V_{cb}}{V_{us}} \right|$$

$$s_{13}e^{i\delta} = V_{ub}^* = A\lambda^3(\rho + i\eta) = \frac{A\lambda^3(\bar\rho + i\bar\eta)\sqrt{1-A^2\lambda^4}}{\sqrt{1-\lambda^2}[1 - A^2\lambda^4(\bar\rho + i\bar\eta)]}$$

What is the size of η ?

K_S and K_L mesons

- K^0 and $\overline{K^0}$ are not physical particles (mass eigenstates)
- define CP eigenstates:

$|K_1\rangle = 1/\sqrt{2}\ (\ |K^0\rangle + |\overline{K^0}\rangle\ )$ CP=-1

$|K_2\rangle = 1/\sqrt{2}\ (\ |K^0\rangle - |\overline{K^0}\rangle\ )$ CP=+1

→ K_1 should dominantly decay into 3 pions

→ K_2 should dominantly decay into 2 pions

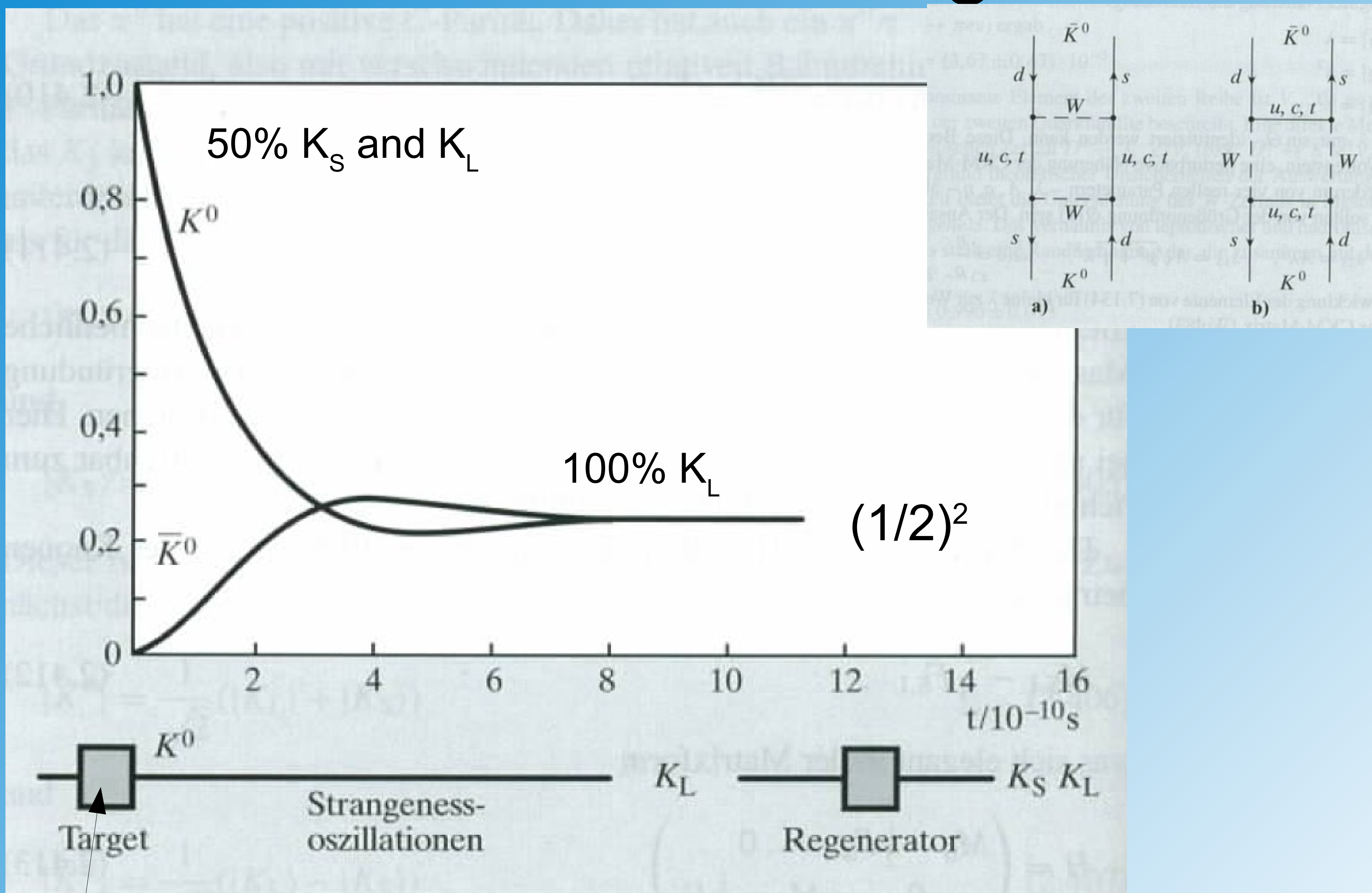
- measured:

	2π	3π	
K_L	$2 \cdot 10^{-3}$	32%	$\sim K_1$
K_S	99.9%	$3.5 \cdot 10^{-7}$	$\sim K_2$

CP-violating decays!

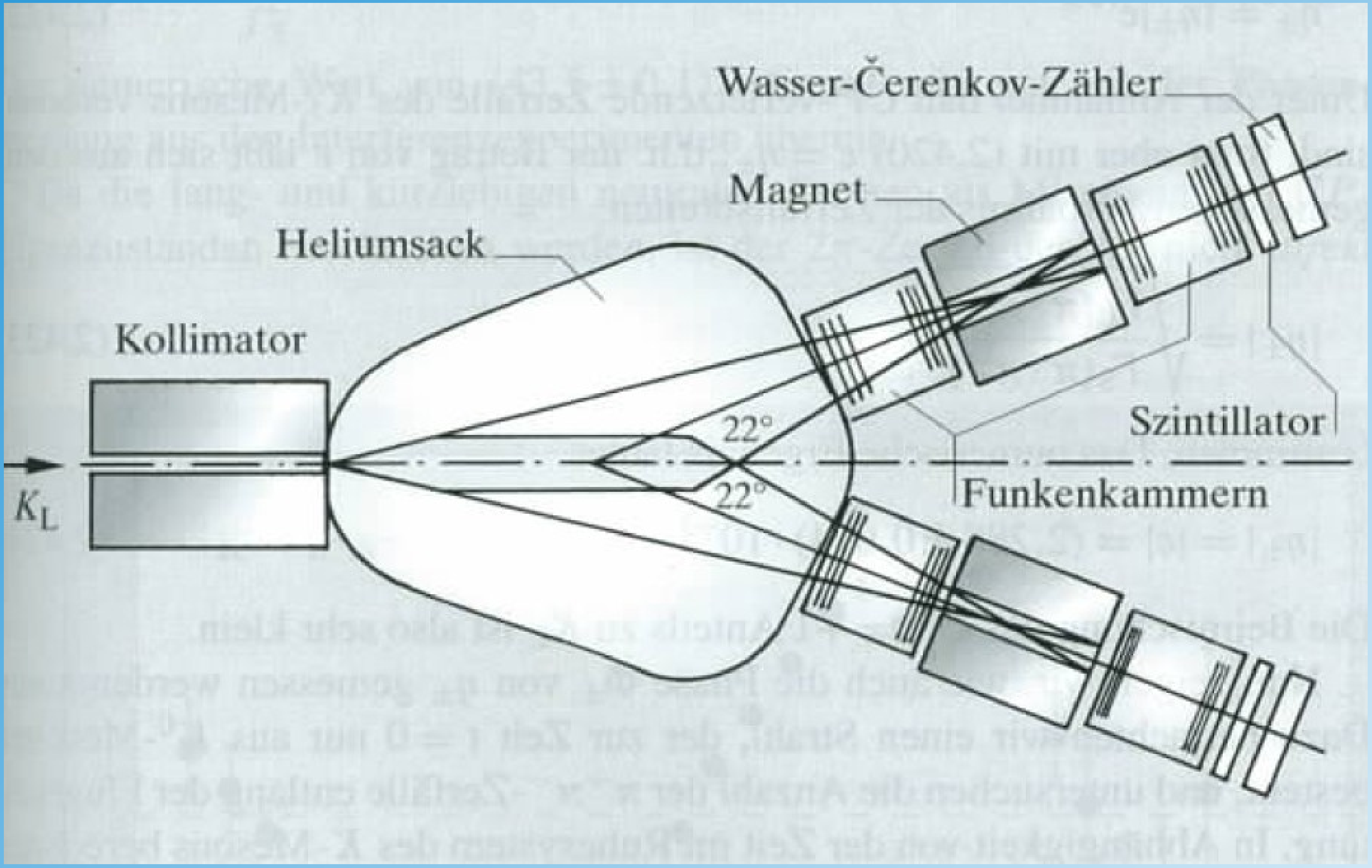
CP violation discovery channel: $K_L \rightarrow 2\pi$

Kaon Oscillations and Regeneration



QCD production of strange (anti-strange) quarks

Discovery of CP Violation



$$BR\left(K_L \rightarrow \pi^+\pi^-\right) = 2\cdot 10^{-3}$$

19.2 CP Volation

<u>General:</u>

CP invariance is violated if the CP transformed reaction is not **identically** observed in nature

<u>Example:</u>

amplitude A_f : $i \rightarrow f$

amplitude $\bar{A}_{\bar{f}}$: $\bar{i} \rightarrow \bar{f}$

different?

<u>Relevance:</u>

Observed matter – antimatter asymmetry in universe

<u>Sakharov conditions:</u>

- baryon number violation
- C and CP violation
- reactions out of equilibrium

e.g.: $\mathbf{p} \leftrightarrow e^{+} \nu_e$

$\bar{p} \leftrightarrow \mathbf{e^{-}} \bar{\boldsymbol{\nu}}_{\mathbf{e}}$

19.3 Direct CP-Violation

amplitude A_f : $i \rightarrow f$

amplitude $\bar{A}_{\bar{f}}$: $\bar{i} \rightarrow \bar{f}$

different?

$| A_f / \bar{A}_{\bar{f}} | <> 1$ $\rightarrow$ direct CP violation

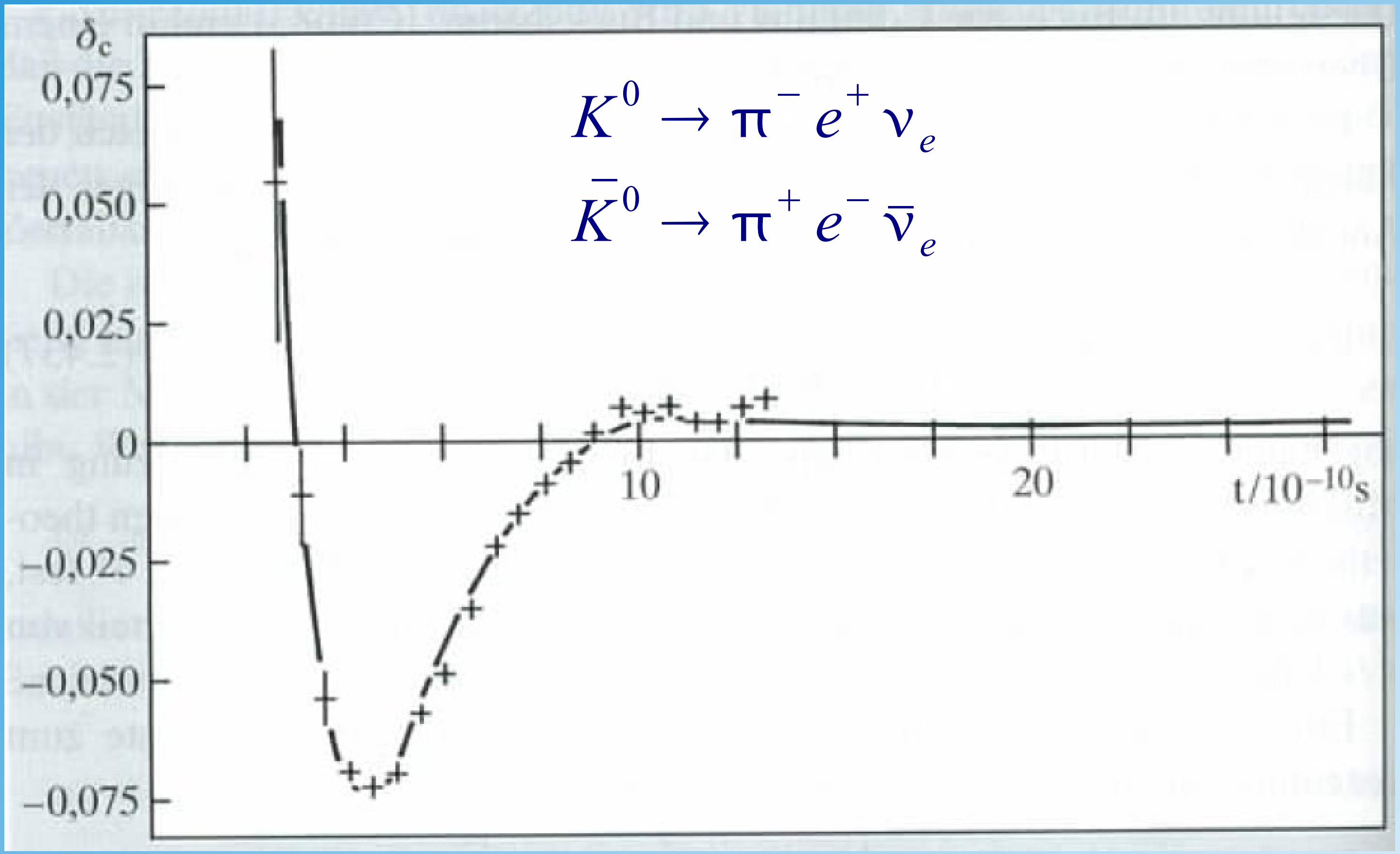
$$\delta_L = \frac{\Gamma\left(K_L \rightarrow l^+ \nu_l \pi^-\right) - \Gamma\left(K_L \rightarrow l^- \bar{\nu}_l \pi^+\right)}{\Gamma\left(K_L \rightarrow l^+ \nu_l \pi^-\right) + \Gamma\left(K_L \rightarrow l^- \bar{\nu}_l \pi^+\right)}$$

experiment: $\delta_L = \left(3.32 \pm 0.06\right) \cdot 10^{-3}$

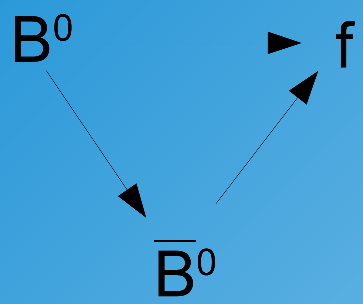
CP violation effects are small in the Kaon system!

19.4 CP Violating in Mixing

Time dependent charge asymmetry in kaon decays



19.5 CP Violation in Interference between Decays with and w/o Mixing



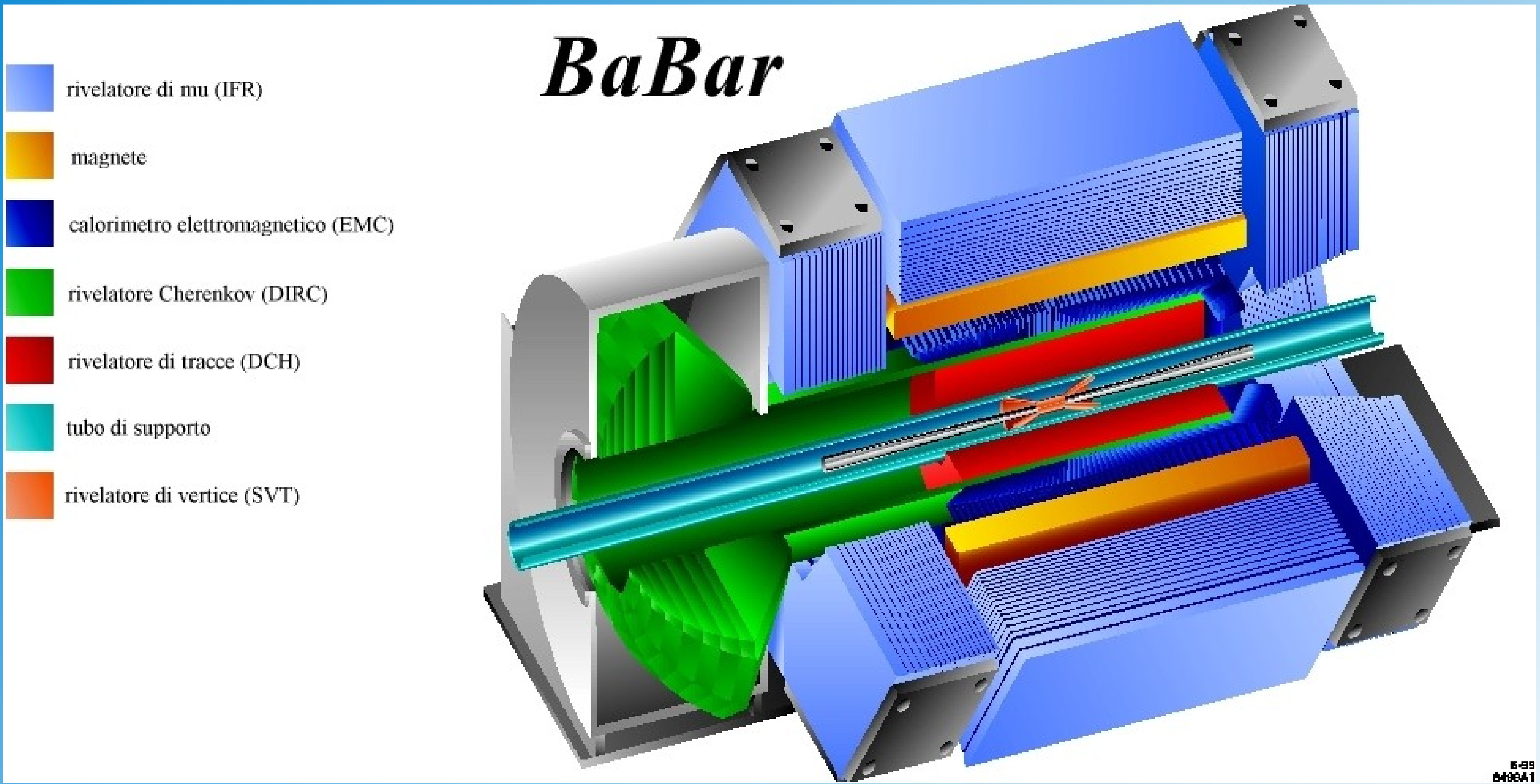
only possible for neutral mesons!

asymmetry:

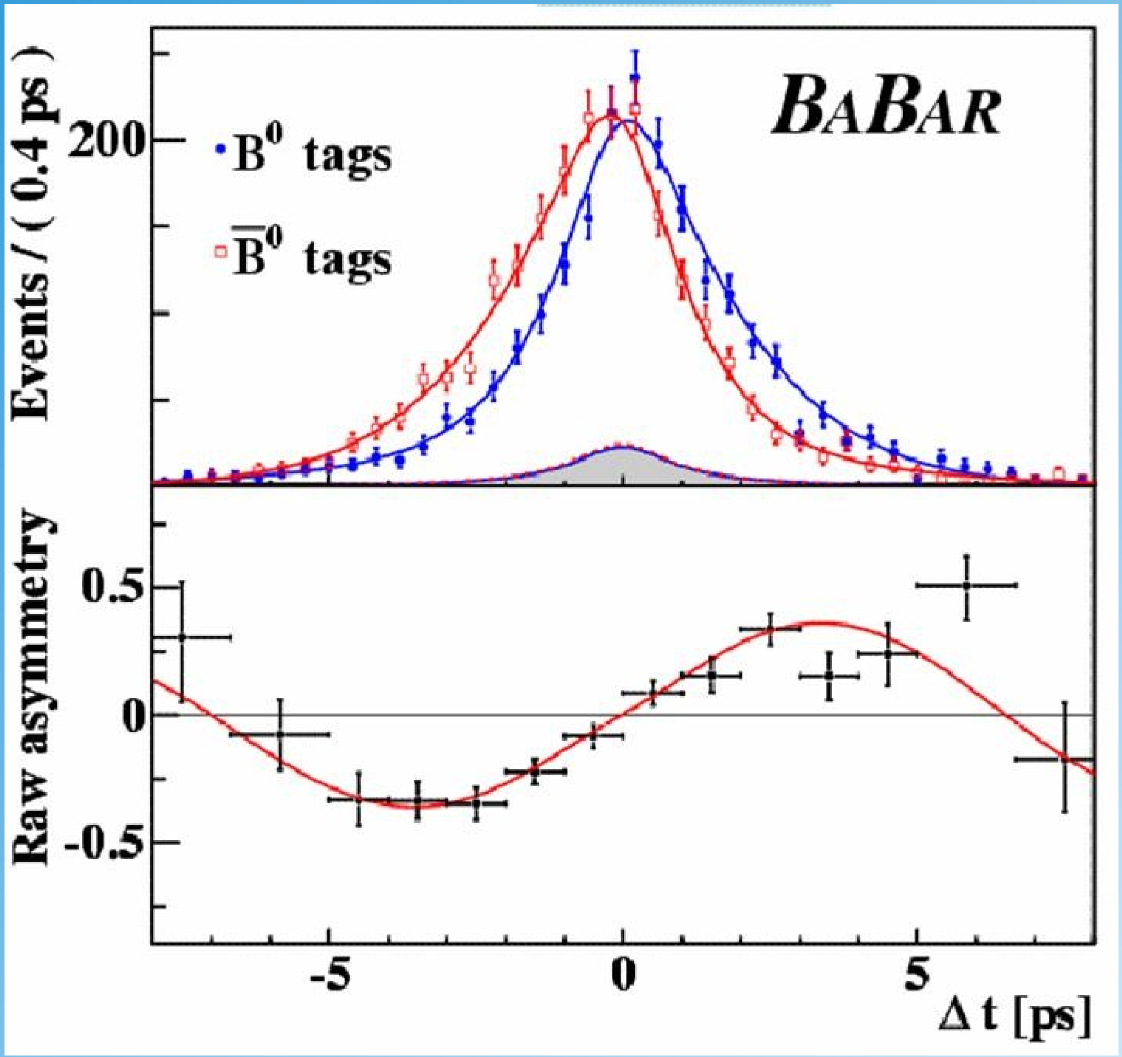
$$A_L = \frac{\Gamma\left(B^0(t) \to f\right) - \Gamma\left(\bar{B}^0 \to f\right)}{\Gamma\left(B^0(t) \to f\right) + \Gamma\left(\bar{B}^0 \to f\right)}$$

example: $B^0 \to$ J/Psi K (Babar, Belle, LHCb)

Babar Detector



CP Violation in B → J/Ψ K



CP-violation effects are large in B system

19.6 Unitarity Trigangle

$$s_{12} = \lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}, \qquad s_{23} = A\lambda^2 = \lambda \left| \frac{V_{cb}}{V_{us}} \right|$$

$$s_{13}e^{i\delta} = V_{ub}^* = A\lambda^3(\rho + i\eta) = \frac{A\lambda^3(\bar\rho + i\bar\eta)\sqrt{1 - A^2\lambda^4}}{\sqrt{1-\lambda^2}[1 - A^2\lambda^4(\bar\rho + i\bar\eta)]}$$

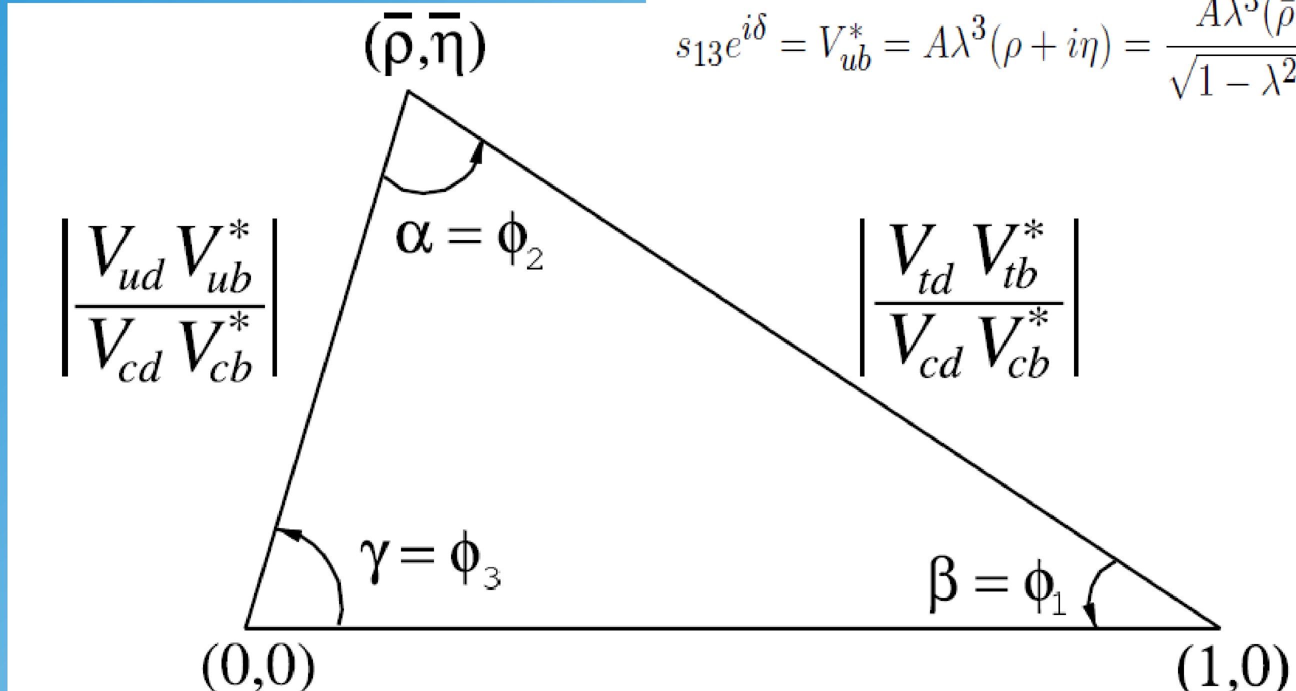
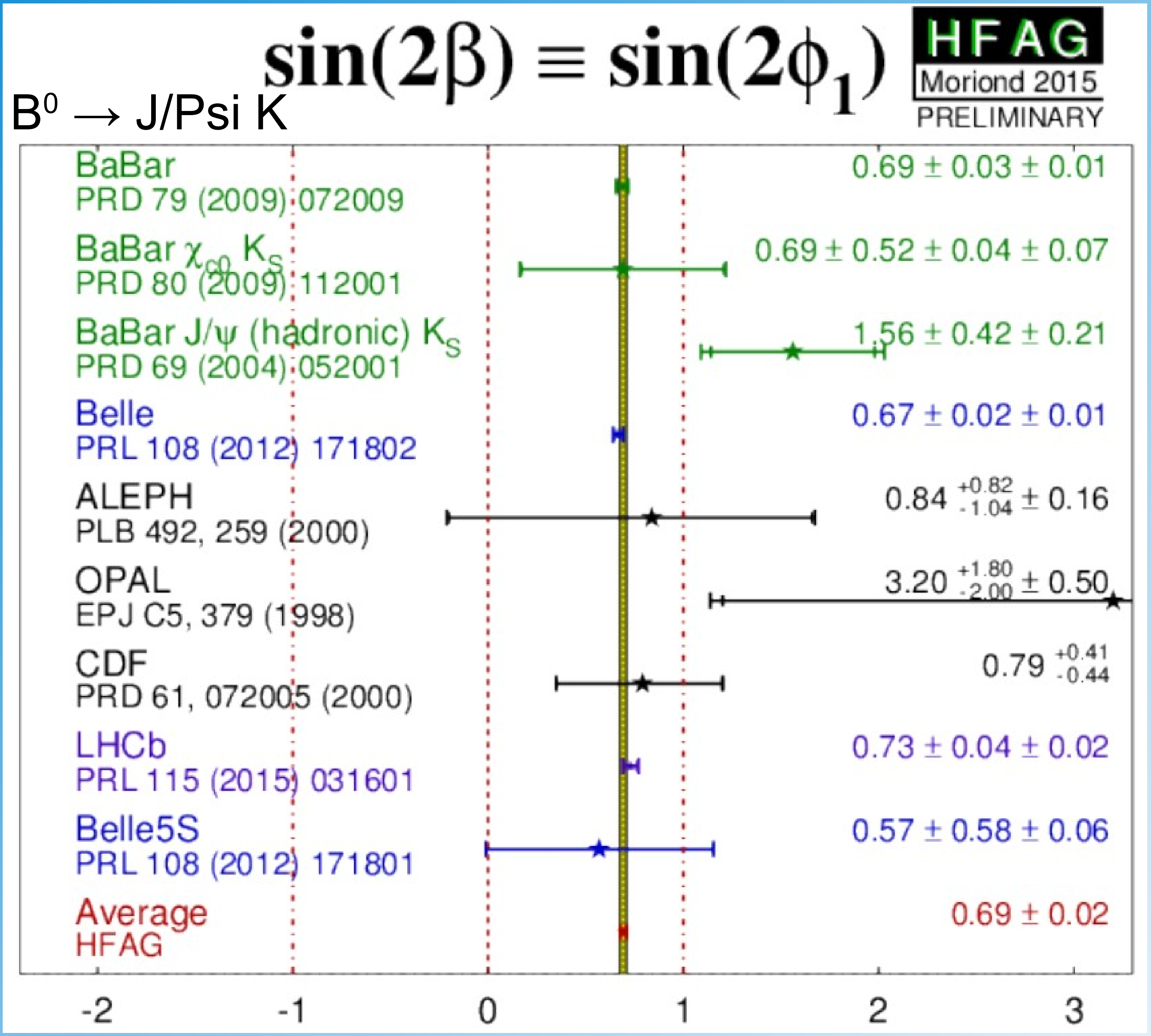


Figure 11.1: Sketch of the unitarity triangle.

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

$B^0 \rightarrow J/Psi\ K$



Summary of Experimental Results