Lecture:

Standard Model of Particle Physics

Heidelberg SS 2012

Flavour Physics I + II

And the winner is

General overview

		Matchdays							Total	
Pos	Name	Fr	1	2	3	QF	SF	F	Wins	Pts
1.	DanielW	0	13	13	20	7	0	2	1.20	55
2.	Mattia	4	8	15	14	11	0	2	0.70	54
3.	SteffenSchmidt	0	9	17	13	11	0	0	0.83	50
4.	S.Dittmeier	8	6	12	13	9	0	2	0.70	50
5.	Jo	0	13	17	10	9	0	0	0.33	49
5.	tuti	0	7	17	15	10	0	0	0.33	49
7.	ssb	8	3	13	14	8	0	0	0.50	46
8.	das	0	14	7	13	9	0	2	0.70	45
9.	CarloL	4	5	9	15	9	3	0	0.50	45
10.	Tango12	0	10	14	10	9	2	0		45
11.	B.Knorr	0	11	10	14	7	0	0		42
11.	W.Rodejohann	0	8	12	14	8	0	0		42
13.	faco	0	8	10	10	8	3	0	0.50	39
14.	Higgs125	0	4	7	15	8	2	2	0.20	38
15.	Neues-Omma-Sofa	0	9	8	11	10	0	0		38
16.	Jiri	0	8	12	16	0	0	0		36
17.	F.Foerster	4	9	13	8	0	0	0		34
18.	Nikolai	0	14	11	0	8	0	0	0.50	33
19.	Knarf	0	0	0	0	0	0	0		0

Congratulations!

Examination

- Who needs a grade for this lecture (e.g. Erasmus students)?
- Oral examination (30 minutes) at **July 24th**, morning
- Please contact me or Werner Rodejohann to fix the time

Contents

PART I

- Determination of the CKM Matrix
- CP Violation in Kaon system
- CP violation in the B-system

PART II

- Search for Flavor Violating Neutral Currents (Lepton Flavor Violation)
- Search for Lepton/Baryon Number Violation

PART III (W.R)

- Massive Neutrinos

CKM Matrix

Definition:

$$V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} .$$

Experimental values:

no theory prediction!

$$V_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix} ,$$

(Particle Data Group 2012)

CKM Matrix

Standdard Parameterisation (Euler Angles):

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

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

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

CKM Matrix

Wolfenstein Parameterisation:

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

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

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note that η and ρ are phase convention dependent, $\bar\eta$ and $\bar\rho$ not

CKM Matrix

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note that η and ρ are phase convention dependent, $\bar\eta$ and $\bar\rho$ not

Experimental values:

no theory prediction!

$$\lambda = 0.22535 \pm 0.00065\,, \qquad A = 0.811^{+0.022}_{-0.012}\,,$$

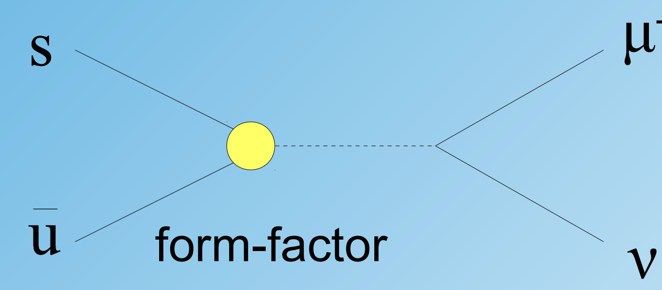
$$\bar\rho = 0.131^{+0.026}_{-0.013}\,, \qquad \bar\eta = 0.345^{+0.013}_{-0.014}\,.$$

Experimental Determination of CKM Matrix Elements

V_{us}: Kaon decay:

$\rightarrow f_K / f_\pi = 1.189 \pm 0.007$

$$\frac{K^- \rightarrow \mu^- \nu}{\pi^- \rightarrow \mu^- \nu} = \frac{s \rightarrow u}{d \rightarrow u}$$

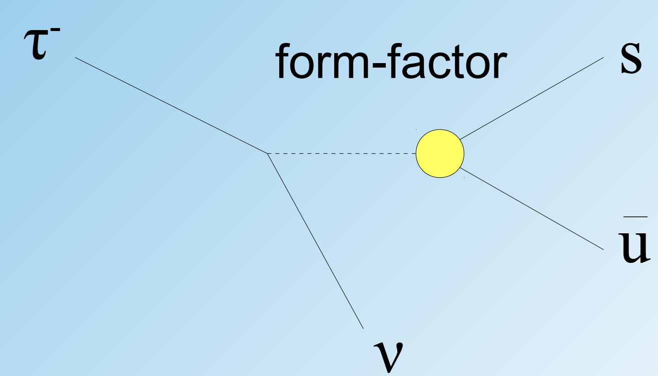


theory uncertainties due to Kaon/Pion formfactors mostly cancel

$|V_{us}| = 0.2252 \pm 0.0009.$

V_{us}: Tau decay:

$$\tau \rightarrow \nu K X$$



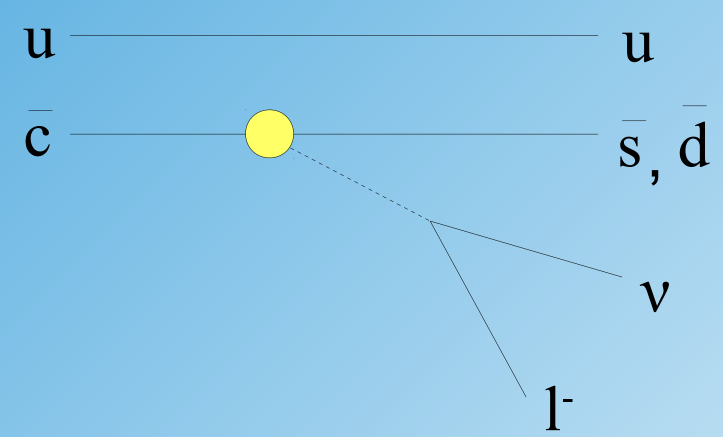
LEP, Barbar, Belle combined:

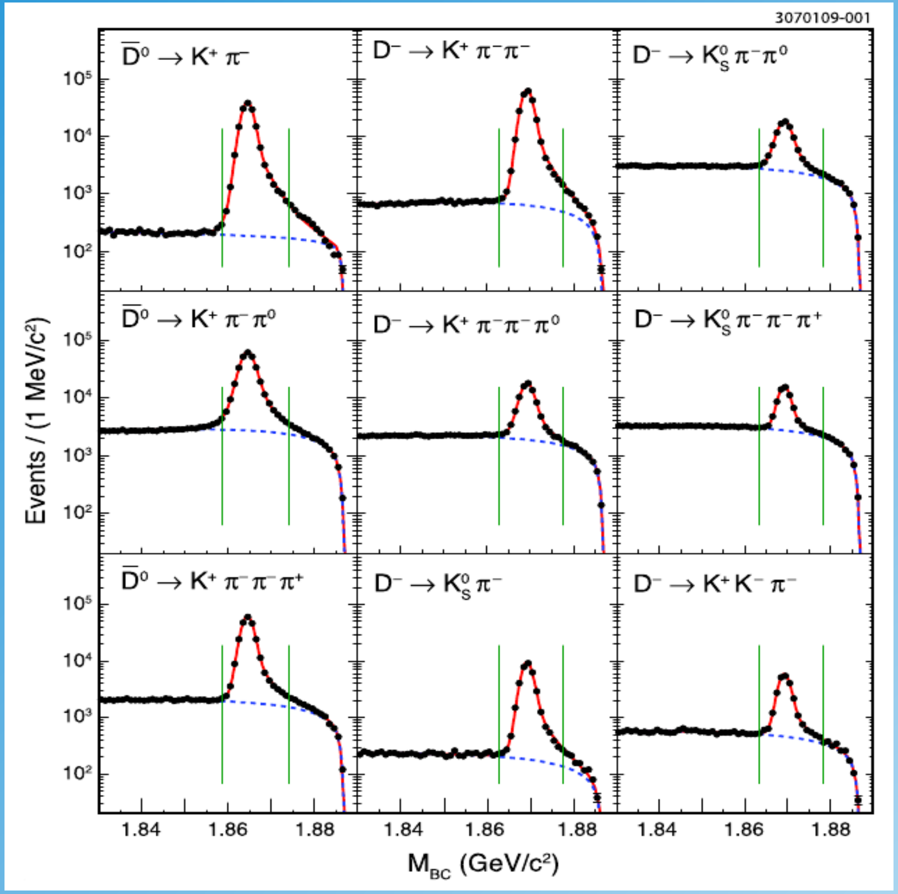
$|V_{us}| = 0.2208 \pm 0.0039$

D^0 - Decays

V_{cd}: D-meson decay:

$$\frac{D^0 \rightarrow K^- l\nu}{D^0 \rightarrow \pi^- l\nu} = \frac{c \rightarrow s}{c \rightarrow d}$$





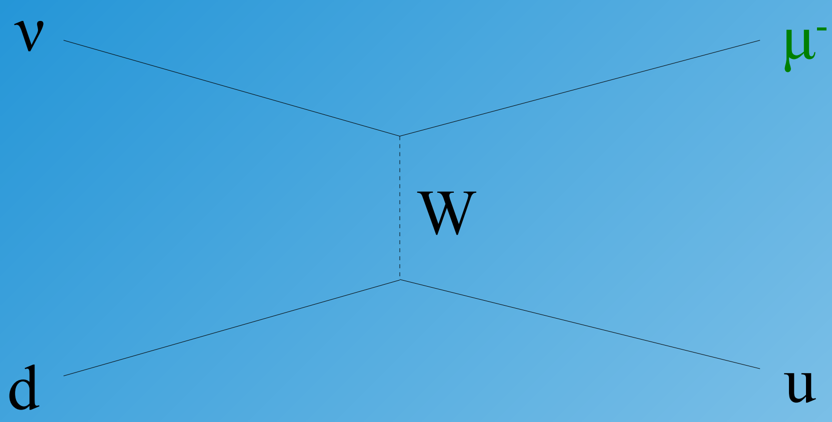
CLEOc + Belle combined:

$|V_{cd}| = 0.229 \pm 0.006 \pm 0.024$

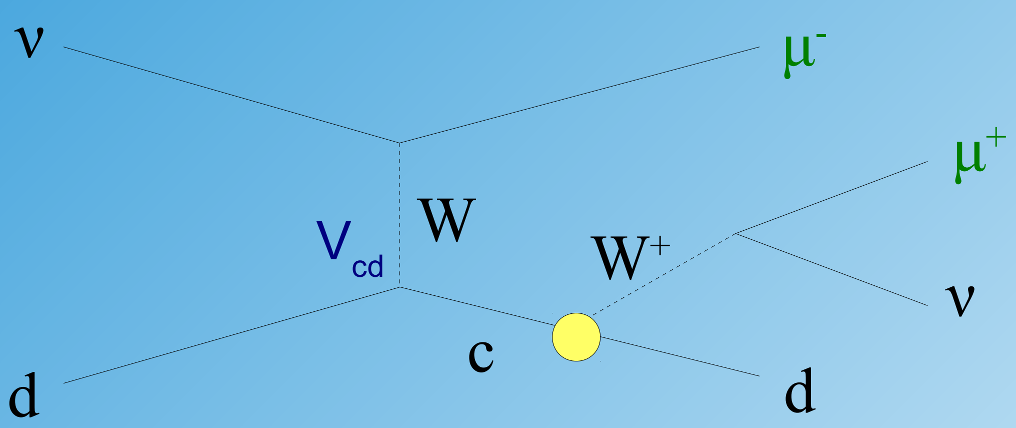
from CLEOc
arXiv 0906.2983

Neutrino Scattering

V_{cd}: from neutrino (antineutrino) scattering



one muons



two muons

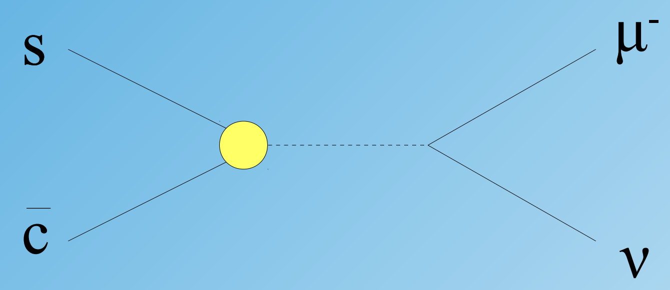
from CDHS, CCFR, CHARM II and CHORUS experiments:

$|V_{cd}| = 0.230 \pm 0.011.$

D_s - Decays

V_{cs}: from D_s decays

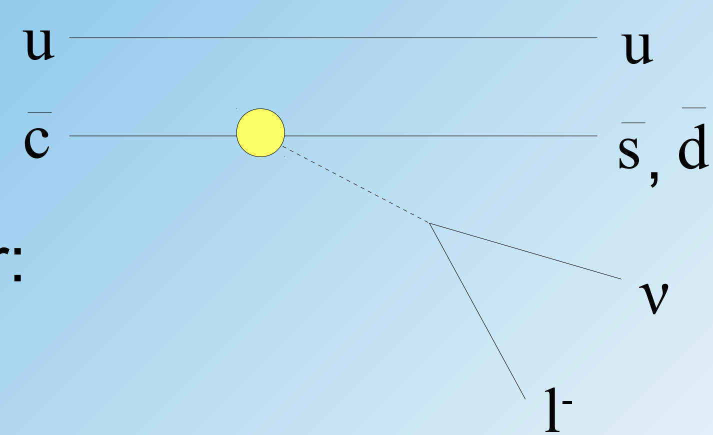
$D_s \rightarrow l\nu$



$$\Gamma = \frac{G_F^2 M_{D_s}^3}{8\pi}\left(\frac{m_\ell}{M_{D_s}}\right)^2\left(1-\frac{m_\ell^2}{M_{D_s}^2}\right)^2 |V_{cs}|^2 f_{D_s}^2$$

V_{cs}: from D_0 decays

$D^0 \rightarrow K^- l\nu$



combined CLEOc, Belle, Babar:

$|V_{cs}| = 1.006 \pm 0.023$

B and Top Decays

Determination of V_{ub} and V_{cb} from B-decays

V_{ub}: $B \to X_u \, l\nu$

$|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}$

V_{cb}: inclusive and exclusive B decays

$|V_{cb}| = (40.9 \pm 1.1) \times 10^{-3}$.

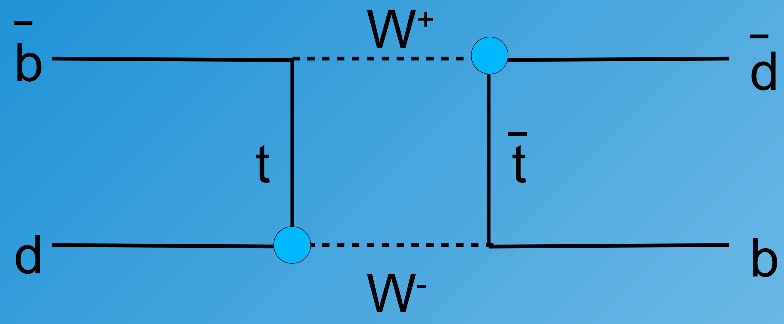
V_{td}:

V_{ts}:

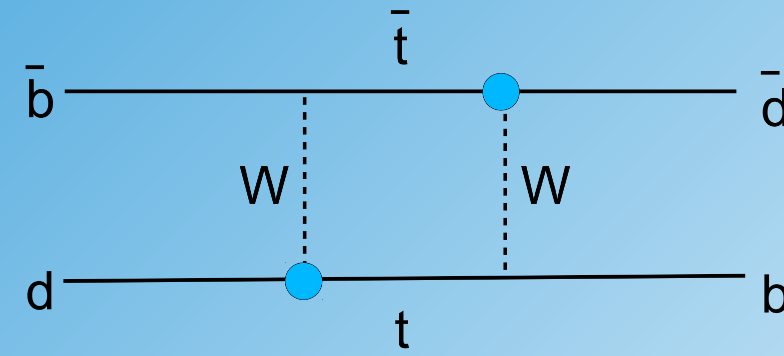
Both difficult to determine from top decays with high precision → instead use trick

B and B_s oscillations

$B^0 - \overline{B^0}$ oscillations

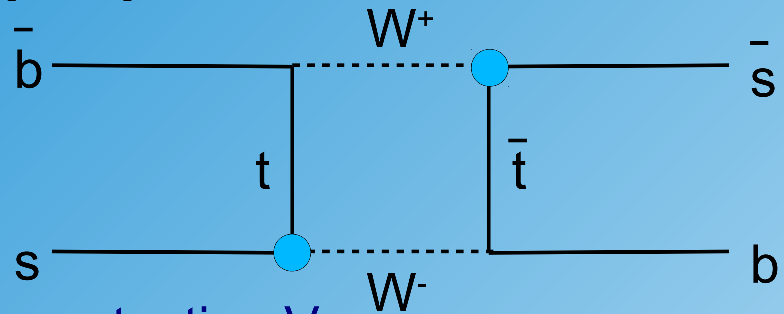


testing V_{td}

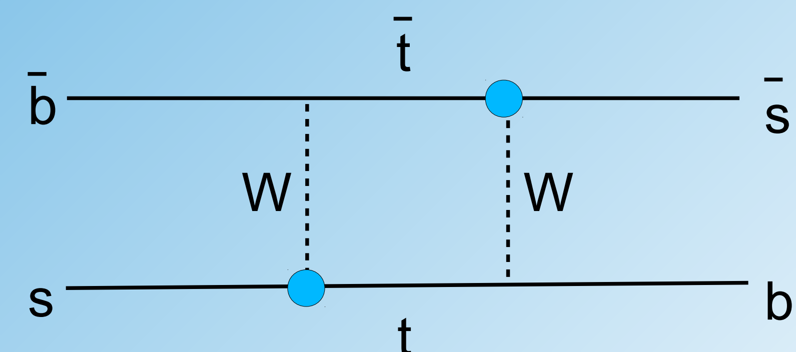


testing V_{td}

$B_s - \overline{B_s}$ oscillations



testing V_{ts}



testing V_{ts}

by measuring time dependence of oscillations:

→ $|V_{td}| = (8.4 \pm 0.6) \times 10^{-3}$, $|V_{ts}| = (42.9 \pm 2.6) \times 10{-}3$

Result

Fitting the four free parameters to the experimental results yields (global fit):

$$V_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix},$$

Representation using the Wolfenstein parameterisation (only 4 parameters!)

$$\lambda = 0.22535 \pm 0.00065\,, \qquad A = 0.811^{+0.022}_{-0.012}\,,$$
$$\bar{\rho} = 0.131^{+0.026}_{-0.013}\,, \qquad \bar{\eta} = 0.345^{+0.013}_{-0.014}\,.$$

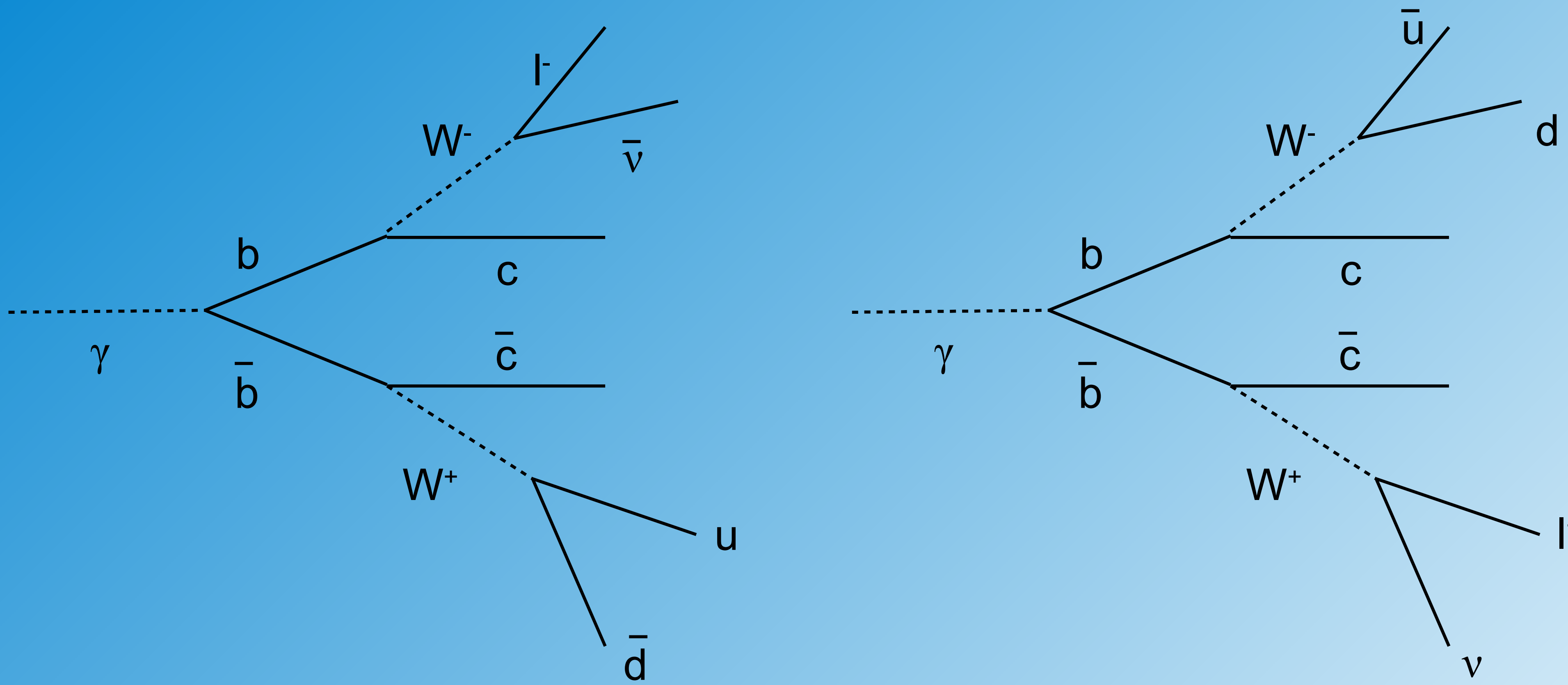
$$|V_{12}| \approx |V_{21}| \approx \lambda$$
$$|V_{23}| \approx |V_{32}| \approx \lambda^2$$
$$|V_{13}| \approx |V_{31}| \approx \lambda^3$$

(mystery!)

As η≠ 0 (ñ≠ 0) the CKM matrix violates CP-invariance!

However, CP-violation is too small to explain observed matter-antimatter asymmetry in universe

CP Violation and the Consequences



If CP-violated, the above final states do not occur with same rate!

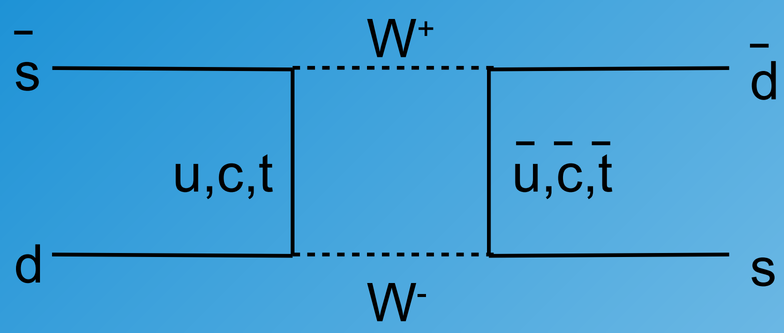
- Direct CP-Violation: different partial decay widths for particles and antiparticles

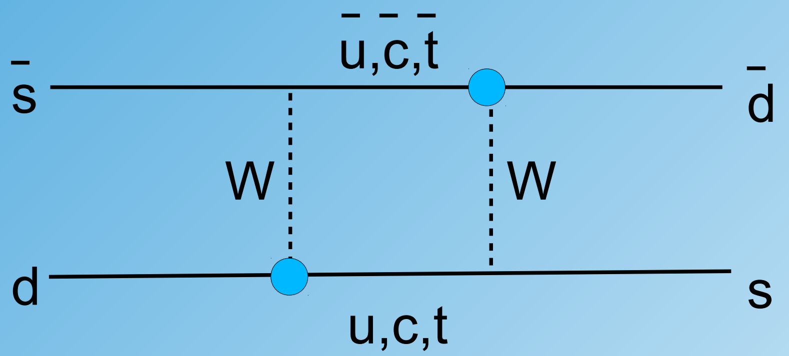
- Might explain observed baryon asymmetry in universe if in addition **baryon-number violating** process exists

CP violation in the Kaon system

first discovered here!

$K^0 - \overline{K}^0$ oscillations





Transition Amplitude:

$$\left(V_{ud}^*\right)^2\left(V_{us}\right)^2 f\left(m_u\right)+\left(V_{cd}^*\right)^2\left(V_{cs}\right)^2 f\left(m_c\right)+\left(V_{td}^*\right)^2\left(V_{ts}\right)^2 f\left(m_t\right)$$

CKM elements of antifermions are complex conjugated

if $\delta_{13}=0$ (V_{td}) then CP is conserved: $\langle K^0|T|\overline{K}^0\rangle = \langle \overline{K}^0|T|K^0\rangle$

if δ_{13}<> 0 (V_{td}) then CP is violated: $\langle K^0|T|\overline{K}^0\rangle \neq \langle \overline{K}^0|T|K^0\rangle$

Kaon Physics

(reminder)

Quarkmodel: $K^0 = d\,\bar{s}$ $\bar{K}^0 = \bar{d}\,s$

Both states can be experimentally distinguished.

Different cross sections with matter (strong interactions):

$$K^0 p \to K^0 p,\ \ K^+ \eta$$
$$\bar{K}^0 p \to \bar{K}^0 p,\ \ \Lambda \pi^+$$

Weak Interactions (oscillations):

Define CP invariant (hypothetical) states:

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right) \qquad CP|K_1\rangle = -|K_1\rangle$$
$$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right) \qquad CP|K_2\rangle = +|K_2\rangle$$

Physical States:

$K_L^0 \to \pi\pi\pi$ CP= -1 $|K_L\rangle \approx |K_1\rangle$ $\tau(K_L^0) = 5\cdot 10^{-8}\,s$

$K_S^0 \to \pi\pi$ CP= +1 $|K_S\rangle \approx |K_2\rangle$ $\tau(K_S^0) = 0.9\cdot 10^{-10}\,s$

$\Delta M = M_L - M_S \approx O(10^{-12}\,MeV)$ very small mass difference!

K^0 Oscillations

Kaons at rest:

$$|K_L(t)\rangle = |K_L(0)\rangle \; e^{-iM_L t} \; e^{-\Gamma_L t/2}$$

$$|K_S(t)\rangle = |K_S(0)\rangle \; e^{-iM_S t} \; e^{-\Gamma_S t/2}$$

oscillation decay

Hamilton operator: $\hat{H} = i\frac{\partial}{\partial} t$ $\rightarrow$ eigenvalues:

$$H = \begin{pmatrix} M_S - \frac{i}{2}\Gamma_S & 0 \\ 0 & M_L - \frac{i}{2}\Gamma_L \end{pmatrix}$$

Oscillations:

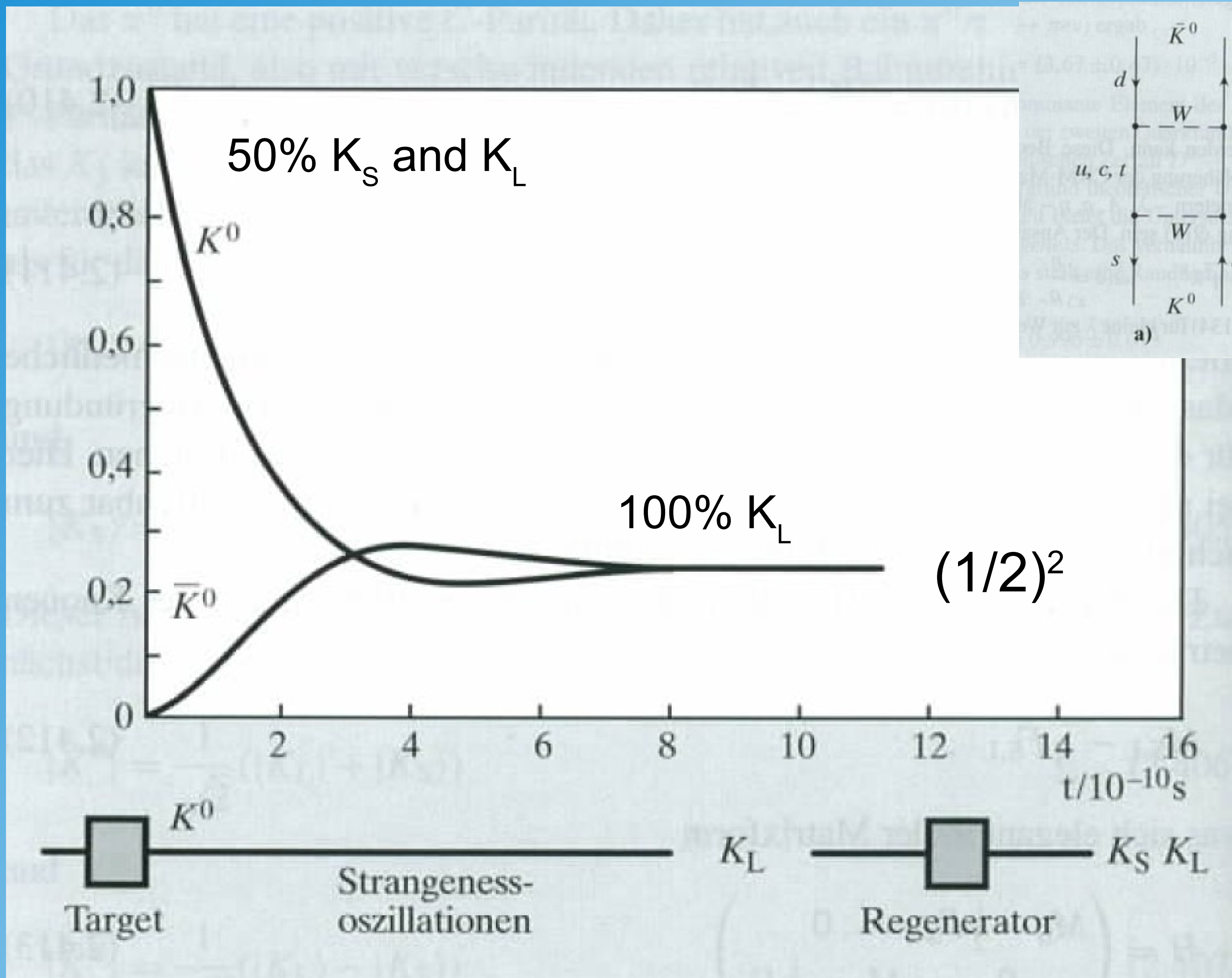
$$A(t) = \langle \bar{K}^0(t) | K^0(0) \rangle = \frac{1}{4} \langle K_L(t) - K_S(t) | K_L(0) + K_S(0) \rangle$$

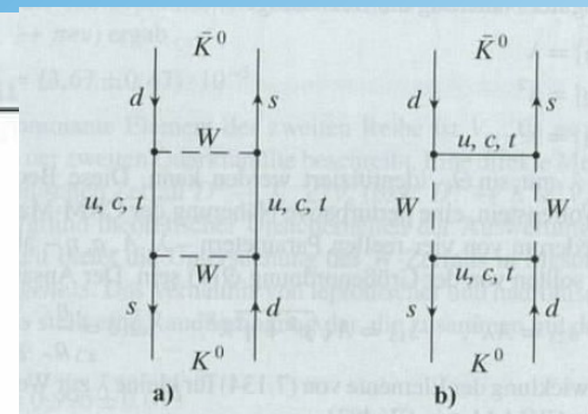
$$P(t) = A^*(t) A(t) = \frac{1}{4}\left(e^{-\Gamma_L t} + e^{-\Gamma_S t} - 2\cos(\Delta M \; t) \; e^{-1/2(\Gamma_L + \Gamma_S) t} \right)$$

with

$$\Delta M = M_L - M_S$$

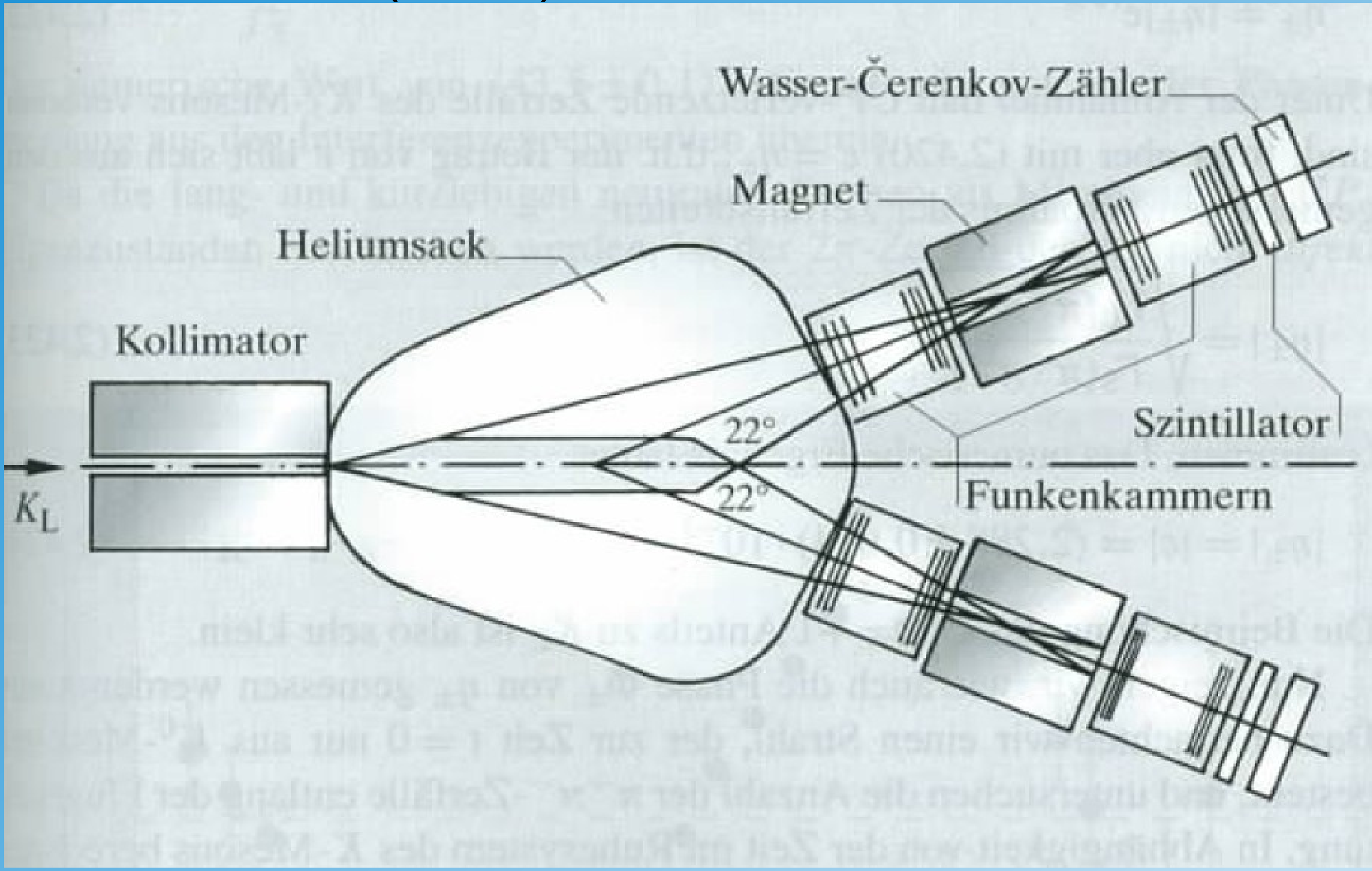
Kaon Oscillations and Regeneration





Discovery of CP Violation

Christensen at al. (1964)



$BR(K_L \to \pi^+\pi^-) = 0.2 \cdot 10^{-3}$ (Nobel Prize Cronin and Fitch 1980)

very small CP-violating effects in Kaon system

Question: CP violation in decay or K_L or in mixing?

How to measure CP violation?

Single CKM matrix element is not enough:

CKM: $V_{td} = A\,\lambda^3 (1-\rho-i\,\eta)$ (Wolfenstein parameterisation)

Example top decay: $t \rightarrow d\,W$ (e.g. LHC, difficult!)

$$B(t \rightarrow d\,W) \propto |V_{td}{}^2| = A^2\,\lambda^6\,[(1-\rho)^2+\eta^2]$$

complex phase not visible!

Complex phase can only be measured in interference processes:

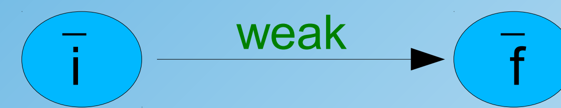
Three possibilities:

- direct CP Violation
- CP violation in mixing
- interference between decays with and without mixing

CP transformation

Consider CP violating (weak) process i → f:

$$CP|a_i\rangle = e^{+i\phi_i}|\bar{a}_i\rangle$$
$$CP|a_f\rangle = e^{+i\phi_f}|\bar{a}_f\rangle$$



$A_f = \langle a_f|O|a_i\rangle$ transition amplitudes: $\bar{A}_{\bar{f}} = \langle \bar{a}_f|O|\bar{a}_i\rangle$

it follows if $[O, CP] = 0$ $\bar{A}_{\bar{f}} = e^{+i(\phi_f - \phi_i)} A_f$

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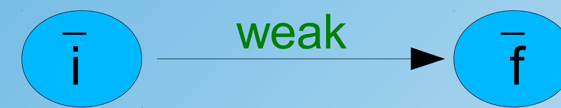

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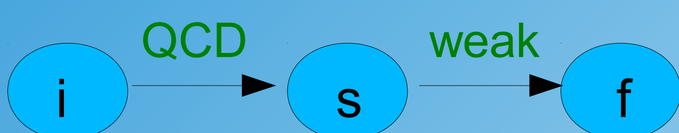
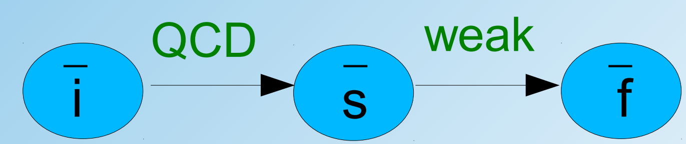
If quarks involved, there is an additional QCD phase shift:





$\bar{A}_{\bar{f}} = |n|\, e^{+i(\theta+\phi_i)}$ $\bar{A}_{\bar{f}} = |n|\, e^{+i(\theta-\phi_i)}$

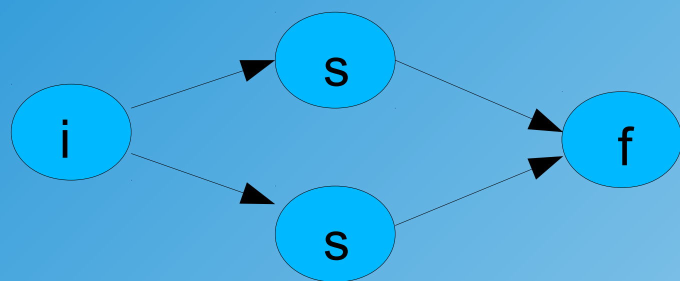
strong interaction (strong phase shift θ) is CP invariant!

I. Direct CP violation

Definition $|\bar{A}_{\bar{f}}/A_f| \neq 1$

not possible with single process as $|\exp(ix)|=1$ (see previous page)

Superposition of two processes:



like a classical double slit experiment

$$|A_f|^2 = n_1^2 + n_2^2 + 2|n_1||n_2| \cos((\theta_1-\theta_2)+(\phi_1-\phi_2))$$
$$|\bar{A}_{\bar{f}}|^2 = n_1^2 + n_2^2 + 2|n_1||n_2| \cos((\theta_1-\theta_2)-(\phi_1-\phi_2))$$

$$A_f = |n_1|\, e^{+i(\theta_1+\phi_1)} + |n_2|\, e^{+i(\theta_2+\phi_2)}$$
$$\bar{A}_{\bar{f}} = |n_1|\, e^{+i(\theta_1-\phi_1)} + |n_2|\, e^{+i(\theta_2-\phi_2)}$$

$|\bar{A}_{\bar{f}}/A_f| \neq 1$ if $\phi_1 \neq \phi_2$ and $\theta_1 \neq \theta_2$

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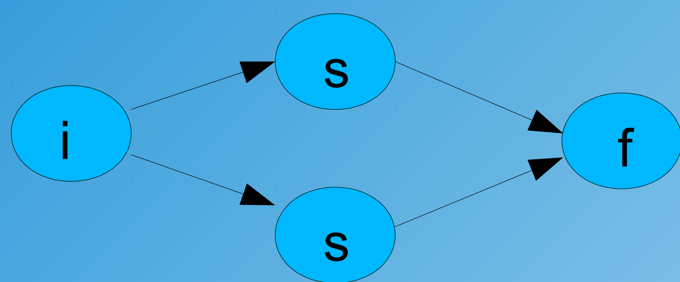

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$$|A_f|^2 = n_1^2 + n_2^2 + 2|n_1||n_2| \cos((\theta_1 - \theta_2) + (\phi_1 - \phi_2))$$
$$|\bar{A}_{\bar{f}}|^2 = n_1^2 + n_2^2 + 2|n_1||n_2| \cos((\theta_1 - \theta_2) - (\phi_1 - \phi_2))$$

$$A_f = |n_1| e^{+i(\theta_1 + \phi_1)} + |n_2| e^{+i(\theta_2 + \phi_2)}$$
$$\bar{A}_{\bar{f}} = |n_1| e^{+i(\theta_1 - \phi_1)} + |n_2| e^{+i(\theta_2 - \phi_2)}$$

$|\bar{A}_{\bar{f}} / A_f| \neq 1$ if $\phi_1 \neq \phi_2$ and $\theta_1 \neq \theta_2$

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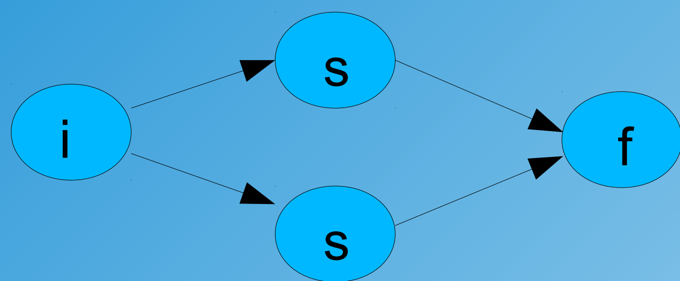


like a classical double slit experiment

$$\left|A_f^2\right| = n_1^2 + n_2^2 + 2|n_1||n_2| \cos\left((\theta_1-\theta_2)+(\phi_1-\phi_2)\right)$$
$$\left|\bar{A}_{\bar{f}}^2\right| = n_1^2 + n_2^2 + 2|n_1||n_2| \cos\left((\theta_1-\theta_2)-(\phi_1-\phi_2)\right)$$

$$A_f = |n_1|\, e^{+i(\theta_1+\phi_1)} + |n_2|\, e^{+i(\theta_2+\phi_2)}$$
$$\bar{A}_{\bar{f}} = |n_1|\, e^{+i(\theta_1-\phi_1)} + |n_2|\, e^{+i(\theta_2-\phi_2)}$$

$\left|\bar{A}_{\bar{f}} / A_f\right| \neq 1$ if $\phi_1 \neq \phi_2$ and $\theta_1 \neq \theta_2$

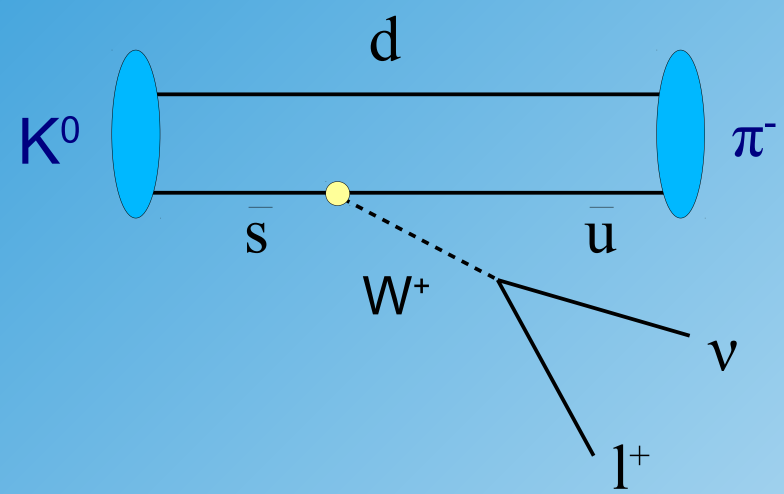
Can be measured in decays of charged and neutral particles!

example: $$\delta_L = \frac{\Gamma(K_L \to l^+ \nu_l \pi^-) - \Gamma(K_L \to l^- \bar{\nu}_l \pi^+)}{\Gamma(K_L \to l^+ \nu_l \pi^-) + \Gamma(K_L \to l^- \bar{\nu}_l \pi^+)}$$

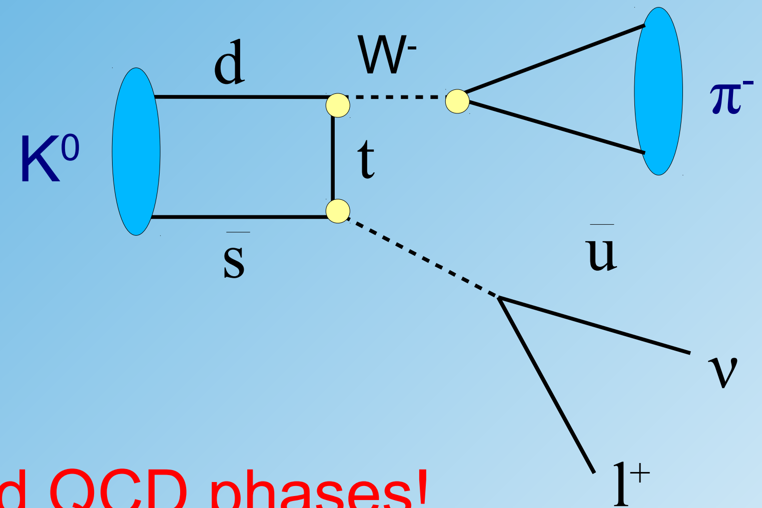
$\delta_L = (3.32 \pm 0.06) \times 10^{-3}$ (experiment)

Note: total decay width is not affect by CP violation (would violate CPT)

Example K_L Decays



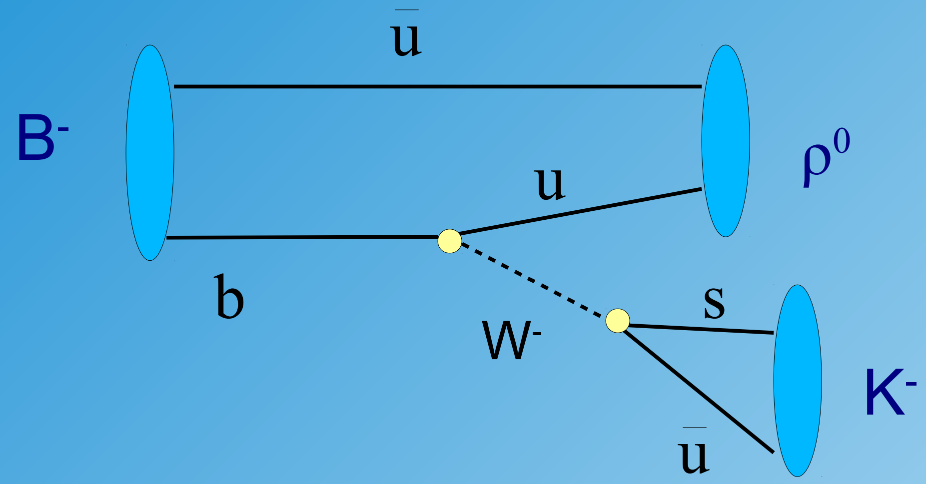
$$|K_L\rangle \approx \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right)$$



different weak and QCD phases!

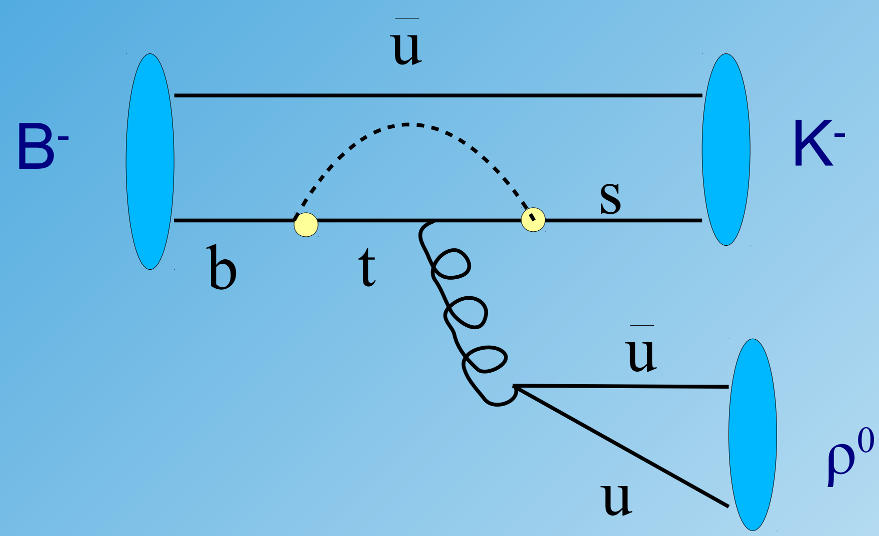
Direct CP Violation in Charged Meson Decay

$B^- \to K^- \rho^0$



V^*_{ub}

V_{us}



V^*_{tb} V_{ts}

W-

different weak and QCD phases!

$$\mathcal{A}_{\rho^0 K^\mp} = +0.37 \pm 0.10.$$

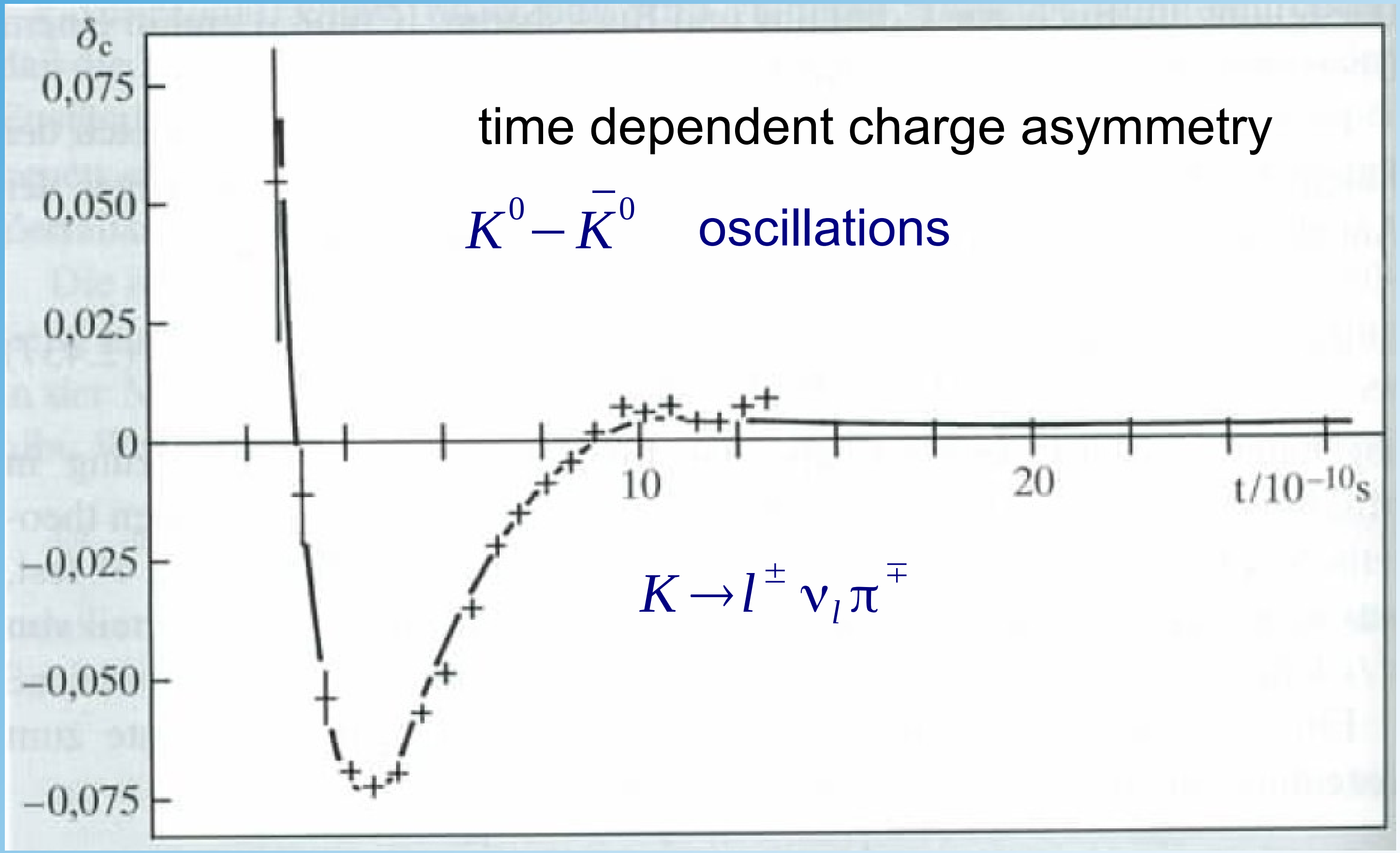
huge!

II. CP violation in mixing

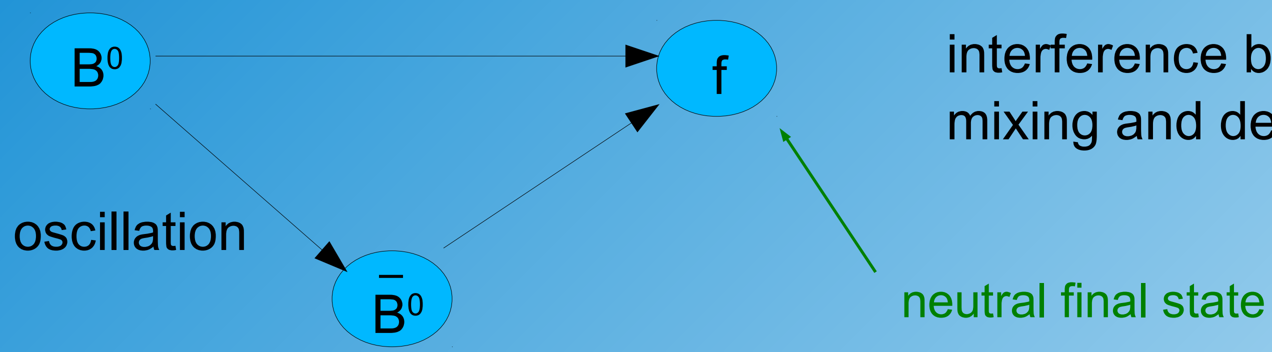
- oscillations of neutral mesons
- measure time dependent decay width

$$A_{osc} = \frac{d\Gamma/dt(\bar{M}^0 \to l^+ X) - d\Gamma/dt(M^0 \to l^- X)}{d\Gamma/dt(\bar{M}^0 \to l^+ X) + d\Gamma/dt(M^0 \to l^- X)}$$

$$\delta_C = A_{osc}$$



III. Interference Decay + Mixing



interference between decay without mixing and decay with mixing

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

- Note, in Kaon system all **three** kinds of CP violating effects were discovered!
- It took about 40 years of measurements and theory to fully understand this subject!

Quantitative Description of K_L state

assume that K_L is not a pure K_1 state:

$$|K_L\rangle = \frac{1}{\sqrt{2+2|\epsilon^2|}}\left(|(1+\epsilon)K^0\rangle + |(1-\epsilon)\bar{K}^0\rangle\right)$$

ε describes CP odd admixture

$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon^2|}}\left(|K_1\rangle + |\epsilon K_2\rangle\right)$$

$$|K_S\rangle = \frac{1}{\sqrt{1+|\epsilon^2|}}\left(|\epsilon K_1\rangle + |K_2\rangle\right)$$

pure CP eigenstates

mixing causes oscillations which are time dependent affects in contrast to direct CP violation

Decompose into mixing and direct CP violation effect

$$\eta_{\pm} = \frac{\langle\pi^+\pi^-|T|K_L\rangle}{\langle\pi^+\pi^-|T|K_S\rangle} = \epsilon + \epsilon' \quad \text{with} \quad \epsilon' = \frac{\langle\pi^+\pi^-|T|\tilde{K}_1\rangle}{\langle\pi^+\pi^-|T|\tilde{K}_2\rangle}$$

mixing (ϵ) direct (ϵ')

K_S and K_L Interference

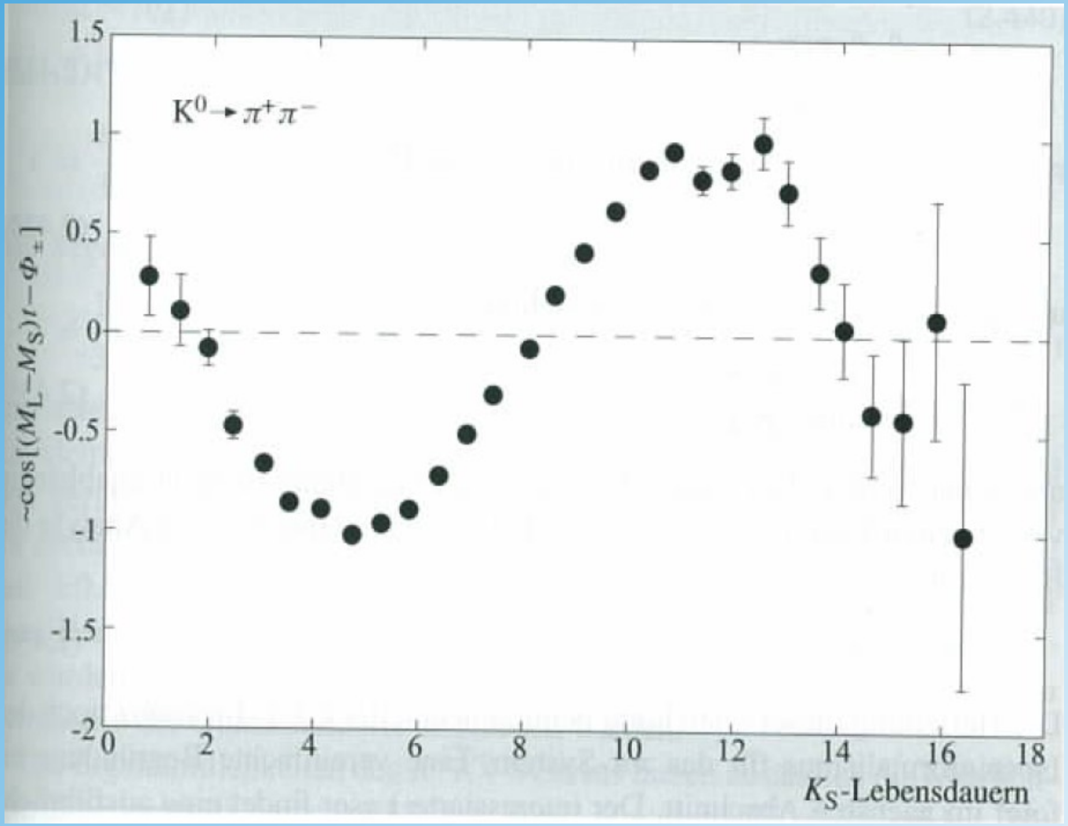
$\delta_C = A_{osc}$

<u>Experimental Result:</u>

$\eta_{\pm} = (2.333 \pm 0.010) \cdot 10^{-3}$

$\eta_{\pm} \approx \epsilon$

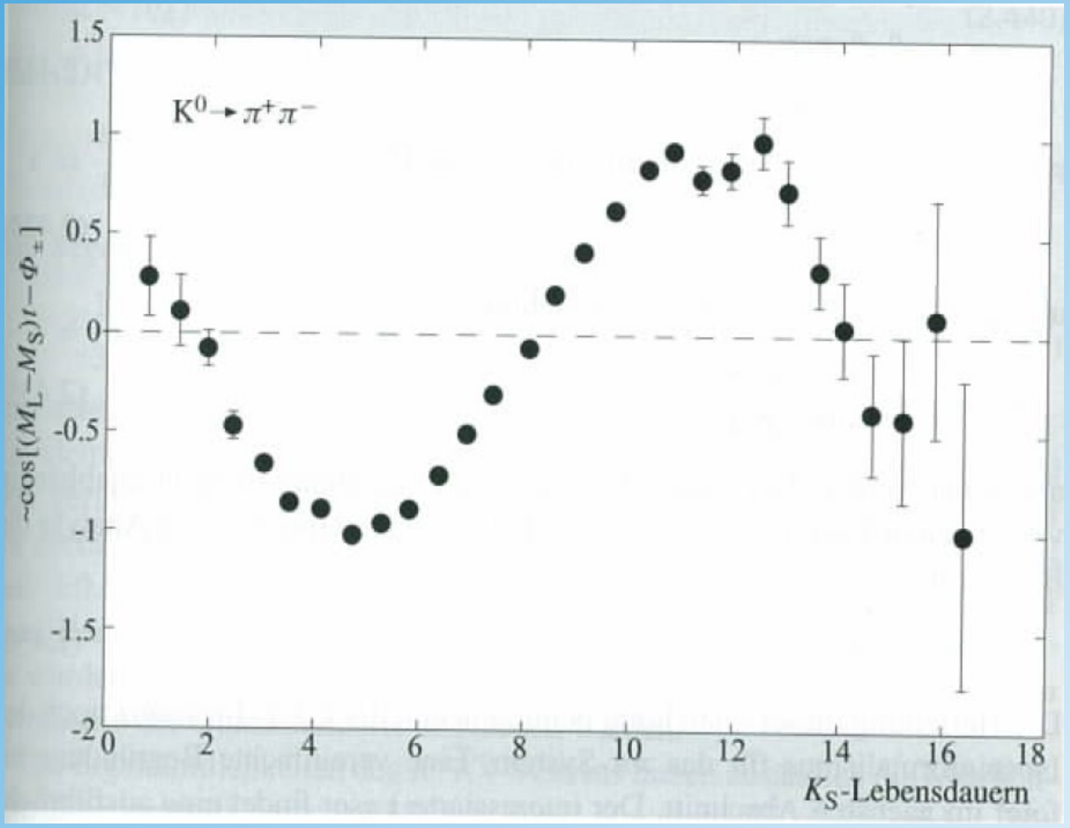
- CP violation mainly due to mixing!



What about ε´ ?

K_S and K_L Interference

$\delta_C = A_{osc}$



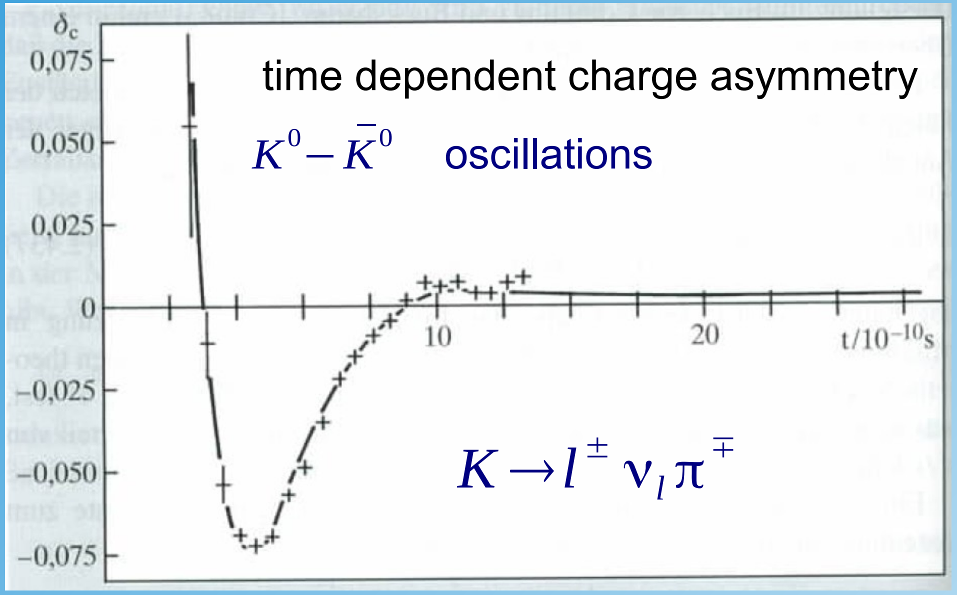
<u>Experimental Result:</u>

$$\eta_{\pm} = (2.333 \pm 0.010) \cdot 10^{-3}$$

$$\eta_{\pm} \approx \epsilon$$

- CP violation mainly due to mixing!
- consistent with type II CP violation result of

$$\delta_C = 2\Re(\epsilon) = (3.33 \pm 0.14) \cdot 10^{-3}$$



What about ε´ ?

Direct CP Violation in K $\rightarrow \pi\pi$ Decays

What about ε´ ?

Idea:

- mixing effects are in the K_0 - anti-K_0 system
- direct CP violation is decay specific
- look into **different** decays!

$$\eta_{00} = \epsilon + \frac{\langle \pi^0 \pi^0 | T | K_L \rangle}{\langle \pi^0 \pi^0 | T | K_S \rangle} = \epsilon - 2\epsilon'$$

note different sign and factor

By measuring Kaon decays into charged and neutral pions with high precision ε´ can be measured:

$$\Re(\epsilon'/\epsilon) = (33 \pm 11) \times 10^{-4} \qquad (1988)$$

$$\Re(\epsilon'/\epsilon) = (16.7 \pm 2.6) \times 10^{-4} \qquad (2000)$$

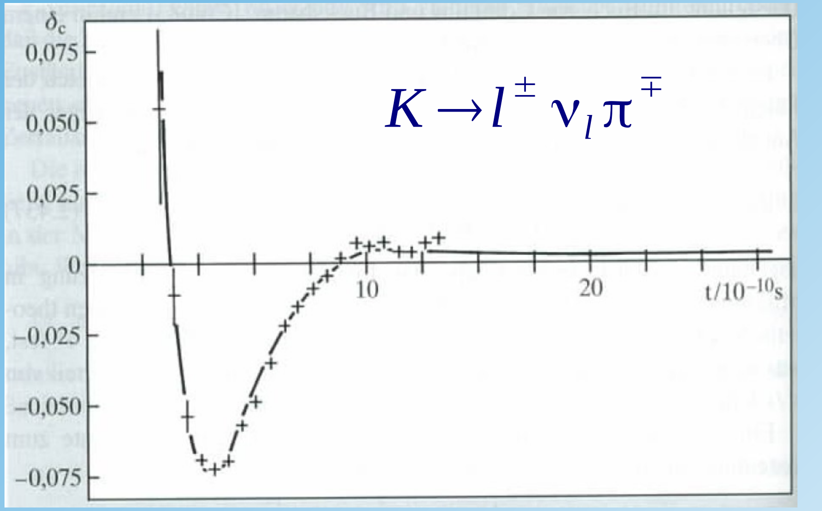
Summary Kaon Physics

- Decay $K \to l^{\pm} \nu_l \pi^{\mp}$
  - **direct** CP violation discovered

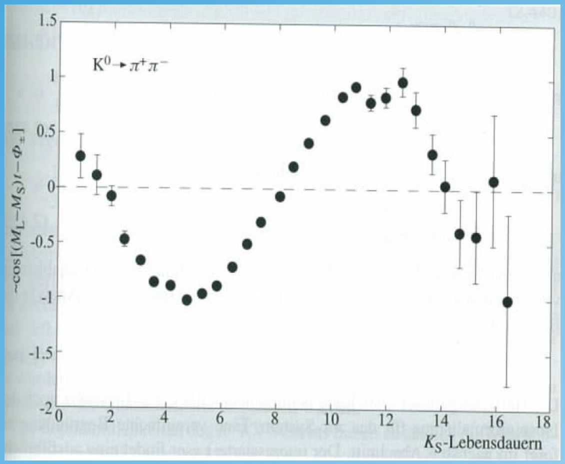
$$\delta_L = \frac{\Gamma\left(K_L \to l^+ \nu_l \pi^-\right) - \Gamma\left(K_L \to l^- \bar{\nu}_l \pi^+\right)}{\Gamma\left(K_L \to l^+ \nu_l \pi^-\right) + \Gamma\left(K_L \to l^- \bar{\nu}_l \pi^+\right)}$$

$\delta_L = (3.32 \pm 0.06) \times 10^{-3}$ (experiment)

  - and CP violation in **mixing**



- Decay $K \to \pi^+ \pi^-, \pi^0 \pi^0$ CP violation in **mixing**



$|\epsilon| = (2.228 \pm 0.011) \cdot 10^{-3}$

and tiny **direct** CP violation

$\Re(\epsilon'/\epsilon) = (16.7 \pm 2.6) \times 10^{-4}$

Unitarity Trigangle

one of six possible unitarity triangles

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

define angles α, β, γ

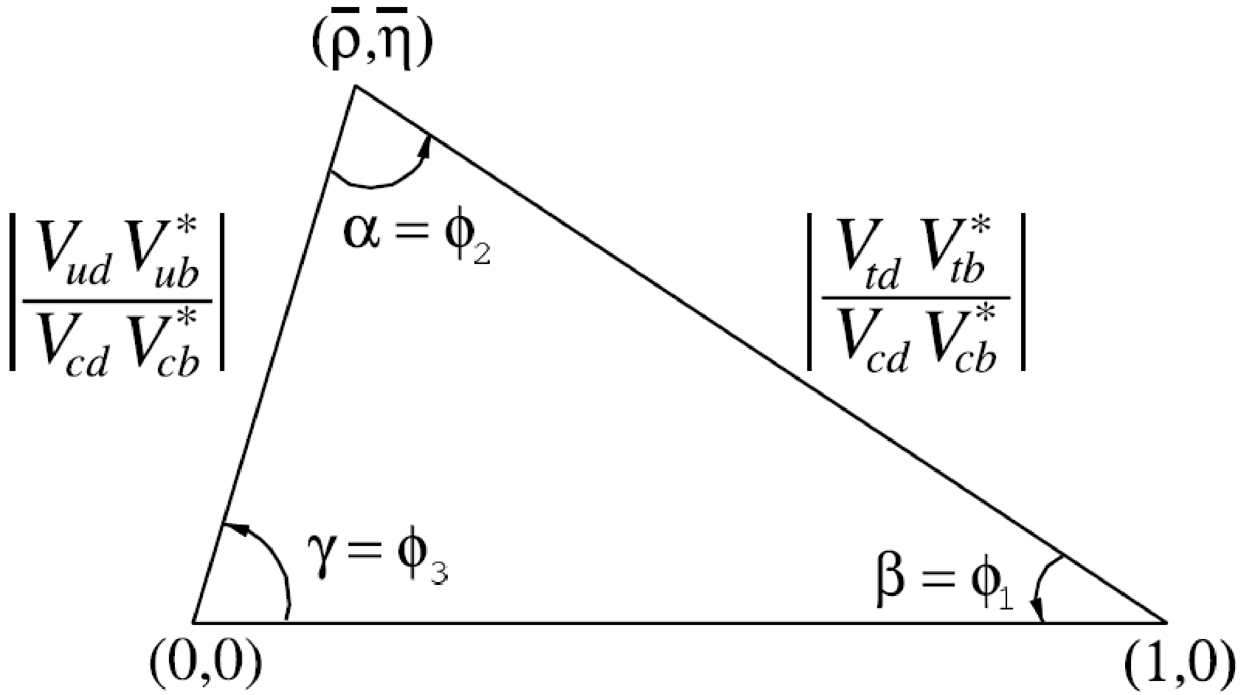


Figure 11.1: Sketch of the unitarity triangle.

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Kaon Constraints

Relation between CP violating ε parameter and CKM matrix elements:

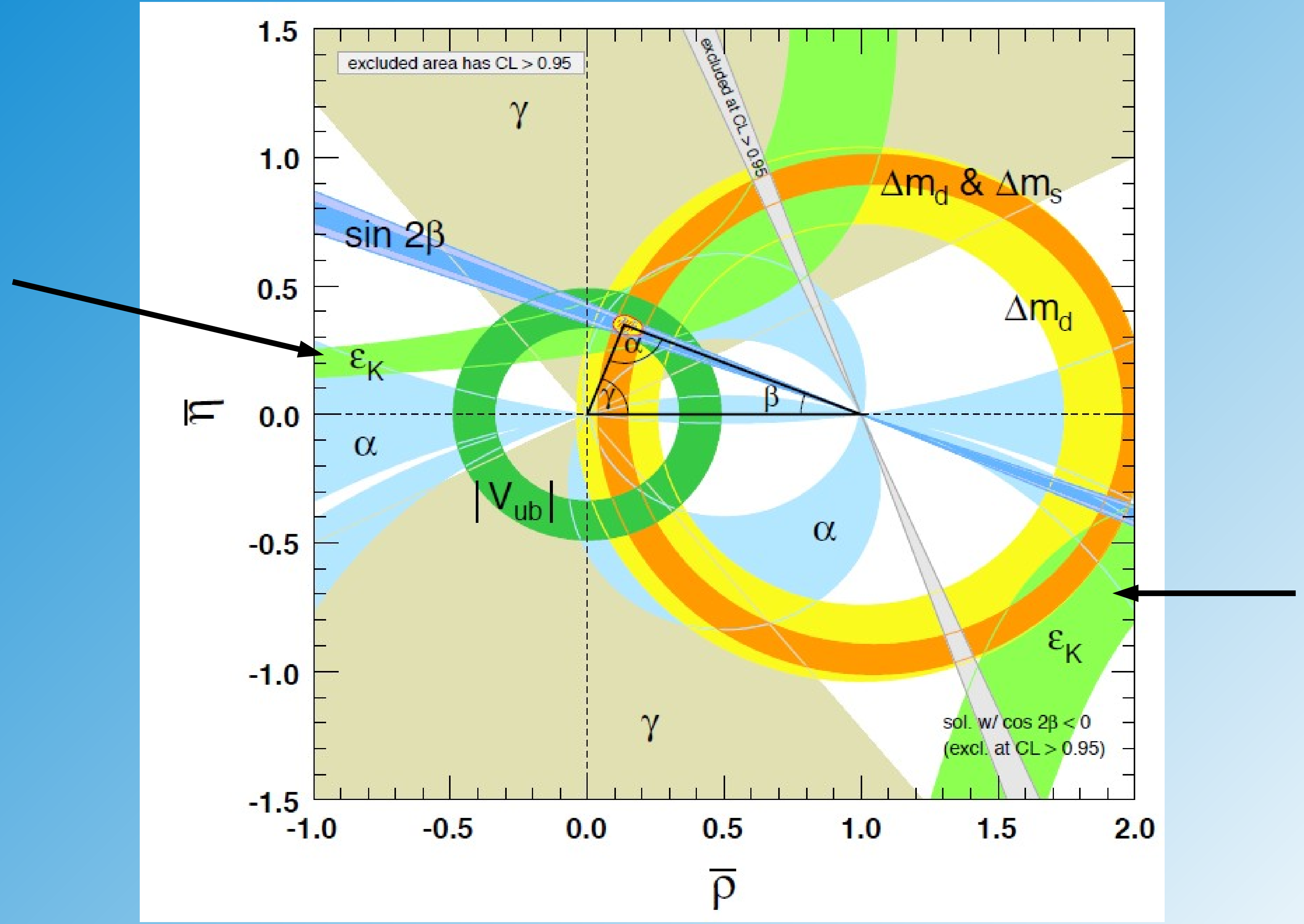
$$|\epsilon| = \frac{G_F^2 f_K^2 m_K m_W^2}{12\sqrt{2}\,\pi^2 \Delta m_K} \widehat{B}_K \Big\{ \eta_1 S(x_c)\,\mathrm{Im}[(V_{cs}V_{cd}^*)^2] + \eta_2 S(x_t)\,\mathrm{Im}[(V_{ts}V_{td}^*)^2] + 2\eta_3 S(x_c, x_t)\,\mathrm{Im}(V_{cs}V_{cd}^* V_{ts}V_{td}^*) \Big\},$$

S is Inami-Lim function

leads to bands (hyperbola) in η-ρ plane:

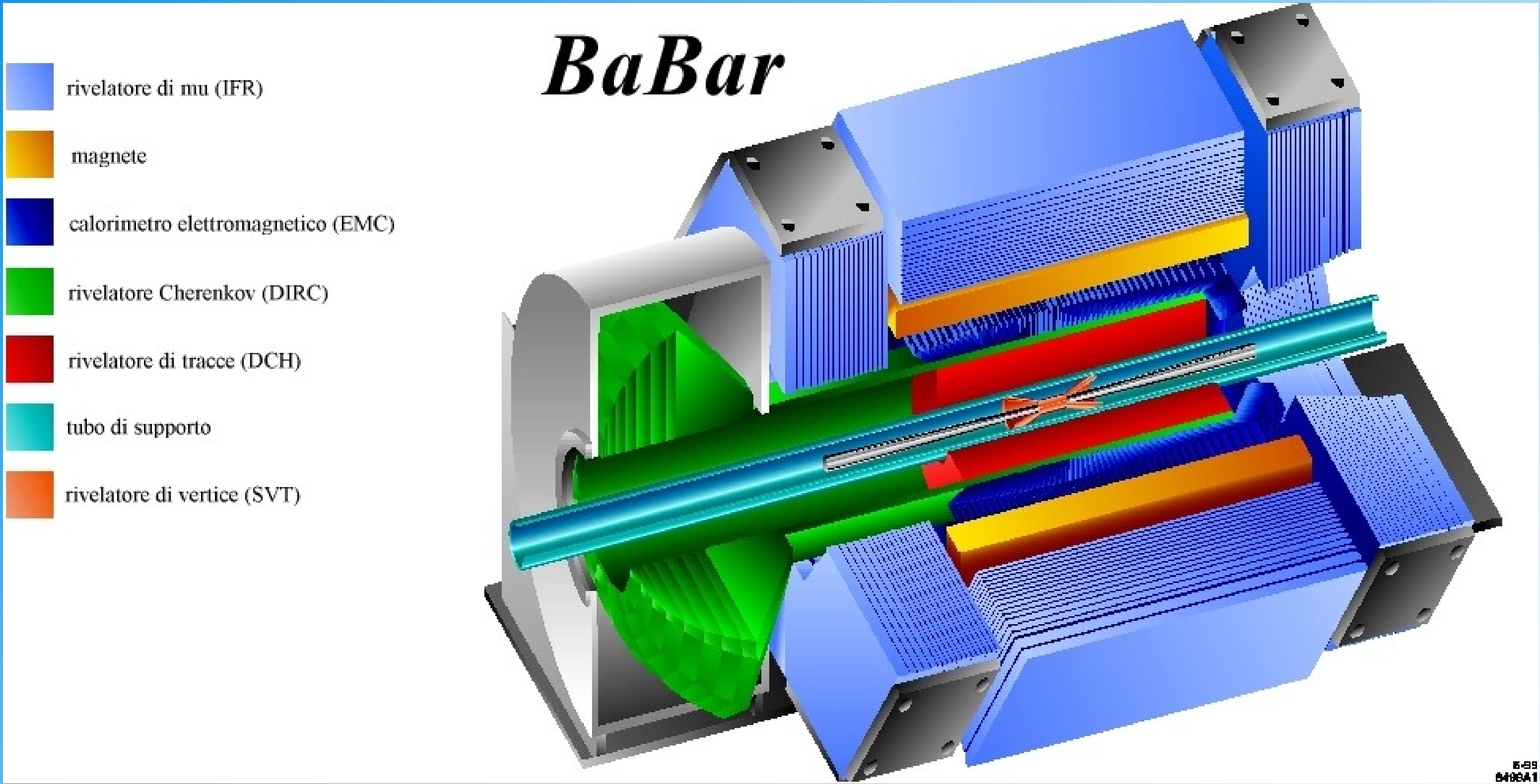
➔ next slide

Summary of experimental Results

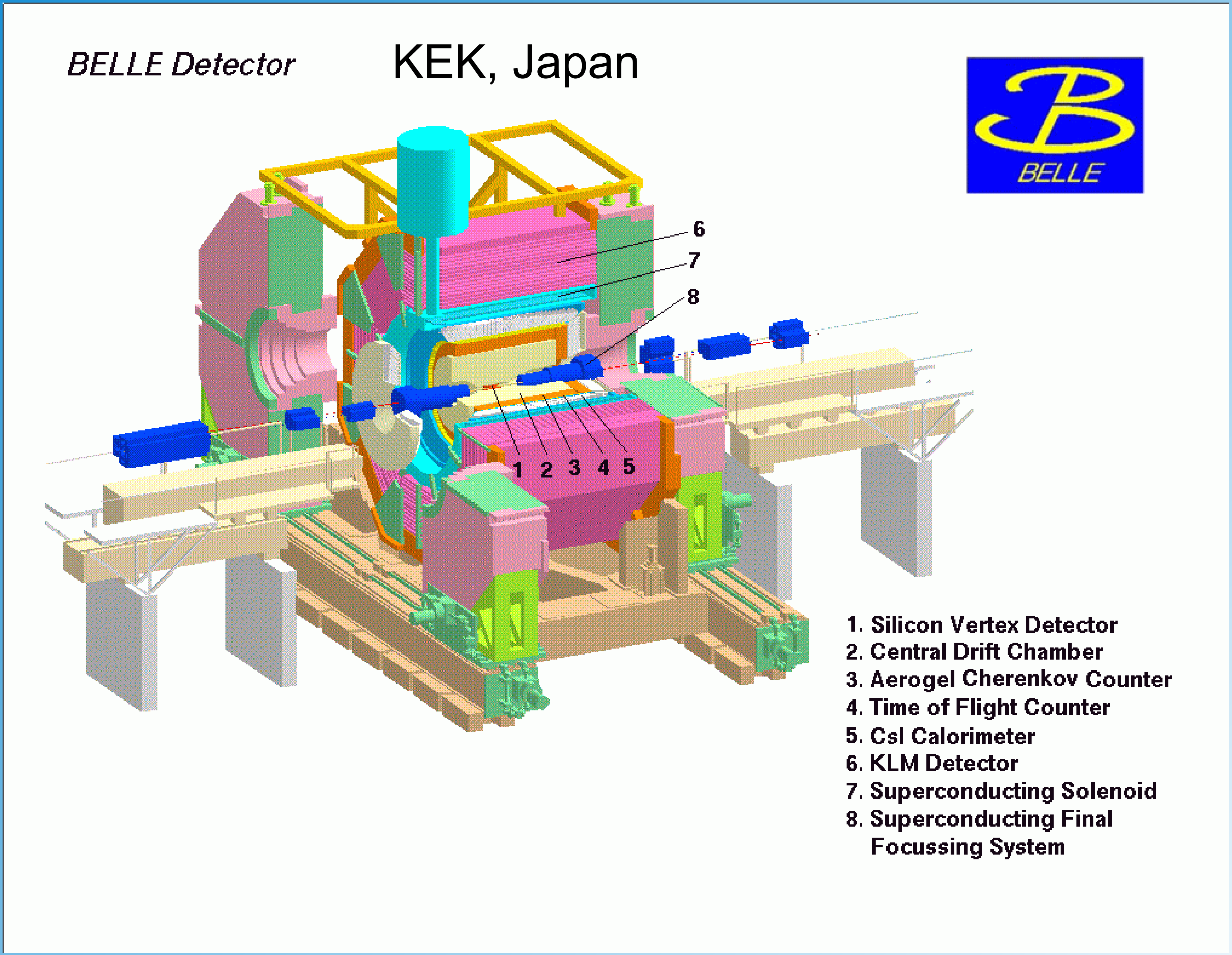


Babar Detector

PEP-C Accelerator, Stanford

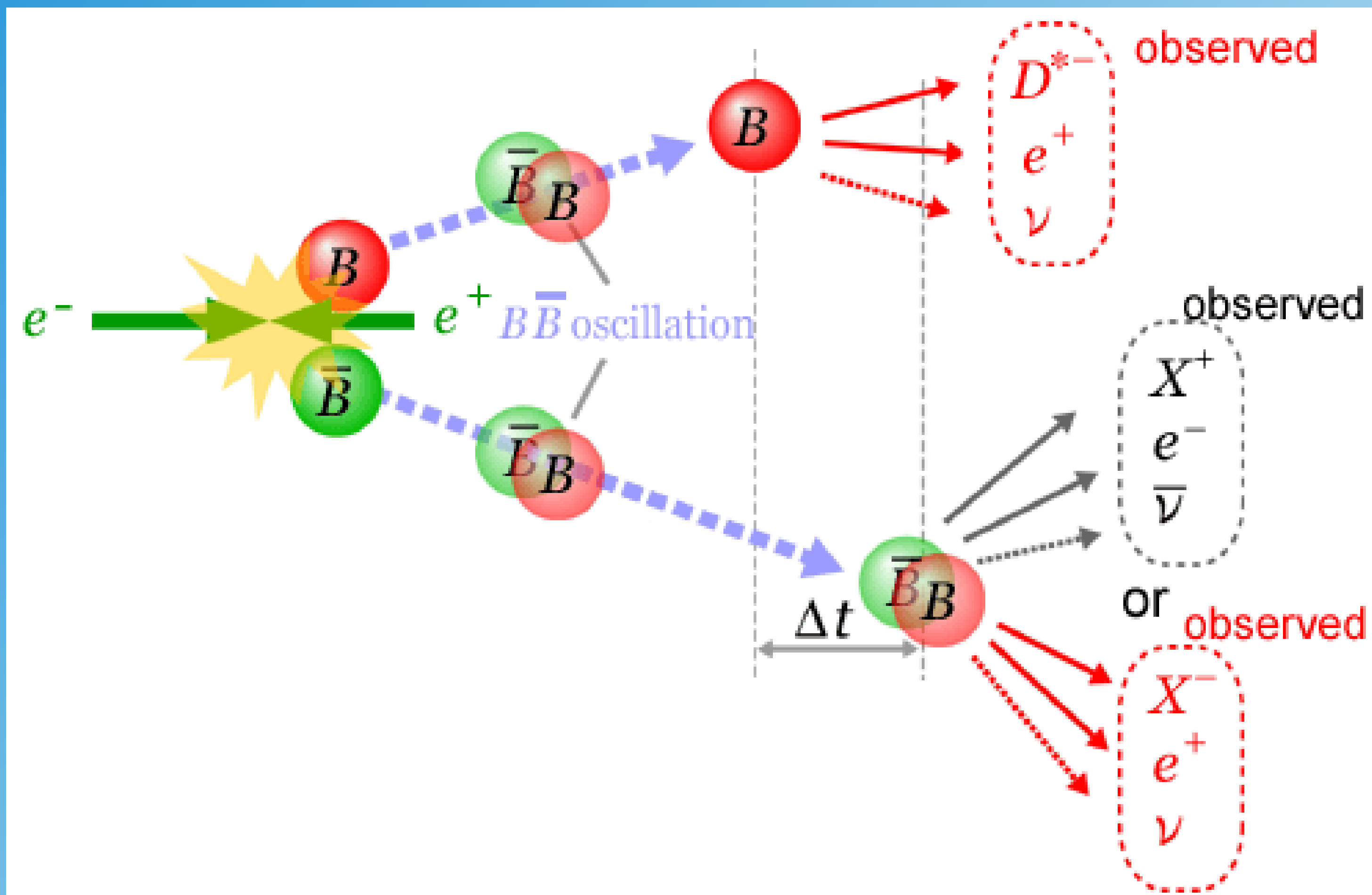


Belle Detector

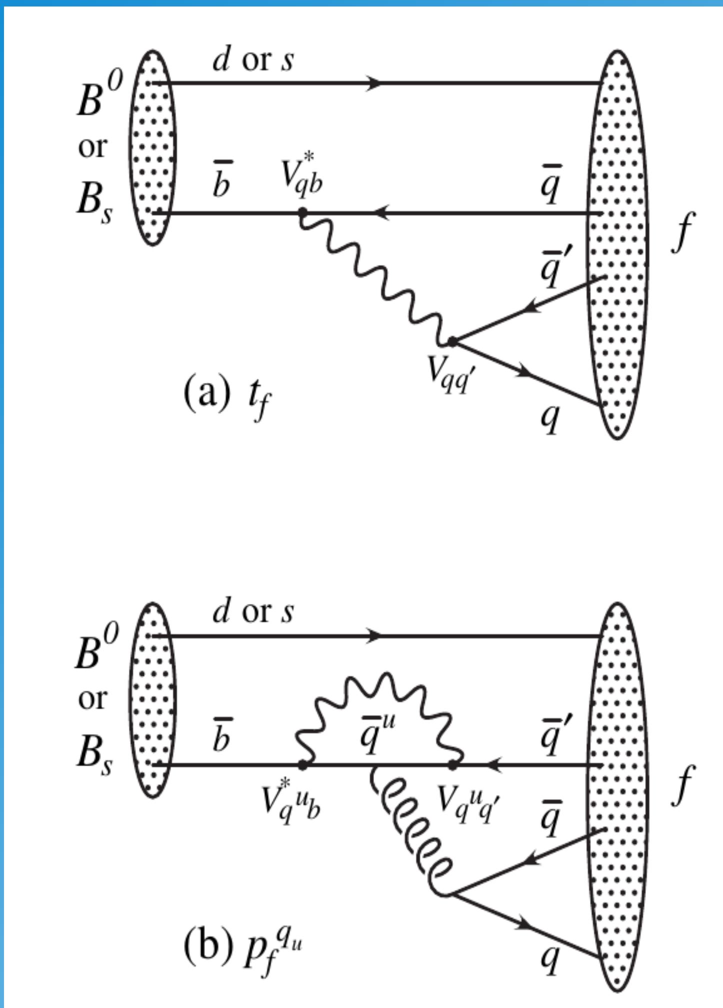


B-Oscillations at B-factories

Exploit different beam energies: $E(e^-) > E(e^+)$



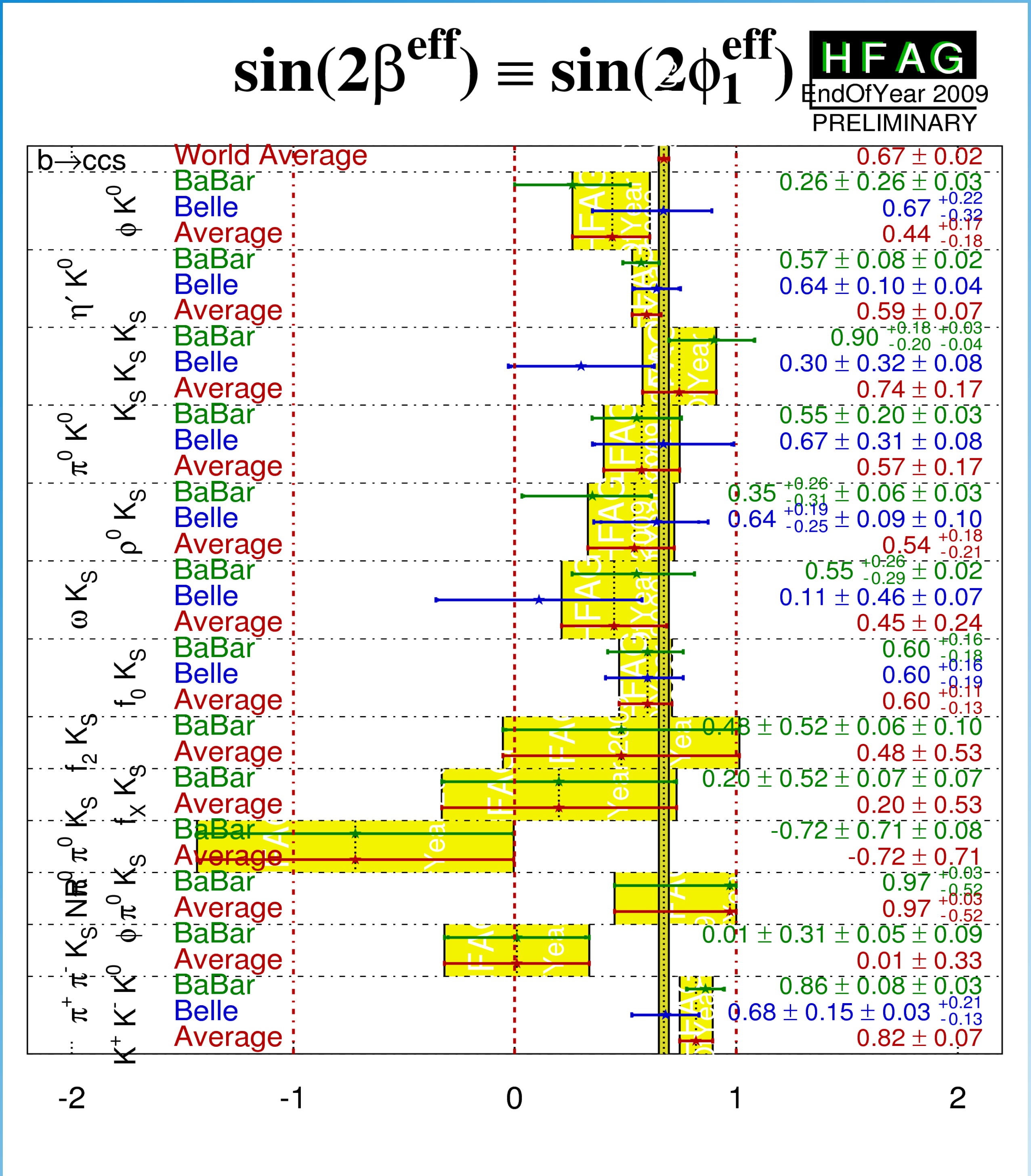
Classification of B-decays



$\bar{b} \to \bar{q}q\bar{q}'$	$B^0 \to f$	$B_s \to f$	CKM dependence of A_f	Suppression
$\bar{b} \to \bar{c}c\bar{s}$	ψK_S	$\psi\phi$	$(V^*_{cb}V_{cs})T + (V^*_{ub}V_{us})P^u$	loop $\times\ \lambda^2$
$\bar{b} \to \bar{s}s\bar{s}$	ϕK_S	$\phi\phi$	$(V^*_{cb}V_{cs})P^c + (V^*_{ub}V_{us})P^u$	λ^2
$\bar{b} \to \bar{u}u\bar{s}$	$\pi^0 K_S$	K^+K^-	$(V^*_{cb}V_{cs})P^c + (V^*_{ub}V_{us})T$	λ^2/loop
$\bar{b} \to \bar{c}c\bar{d}$	D^+D^-	ψK_S	$(V^*_{cb}V_{cd})T + (V^*_{tb}V_{td})P^t$	loop
$\bar{b} \to \bar{s}s\bar{d}$	$\phi\pi$	ϕK_S	$(V^*_{tb}V_{td})P^t + (V^*_{cb}V_{cd})P^c$	$\lesssim 1$
$\bar{b} \to \bar{u}u\bar{d}$	$\pi^+\pi^-$	$\pi^0 K_S$	$(V^*_{ub}V_{ud})T + (V^*_{tb}V_{td})P^t$	loop

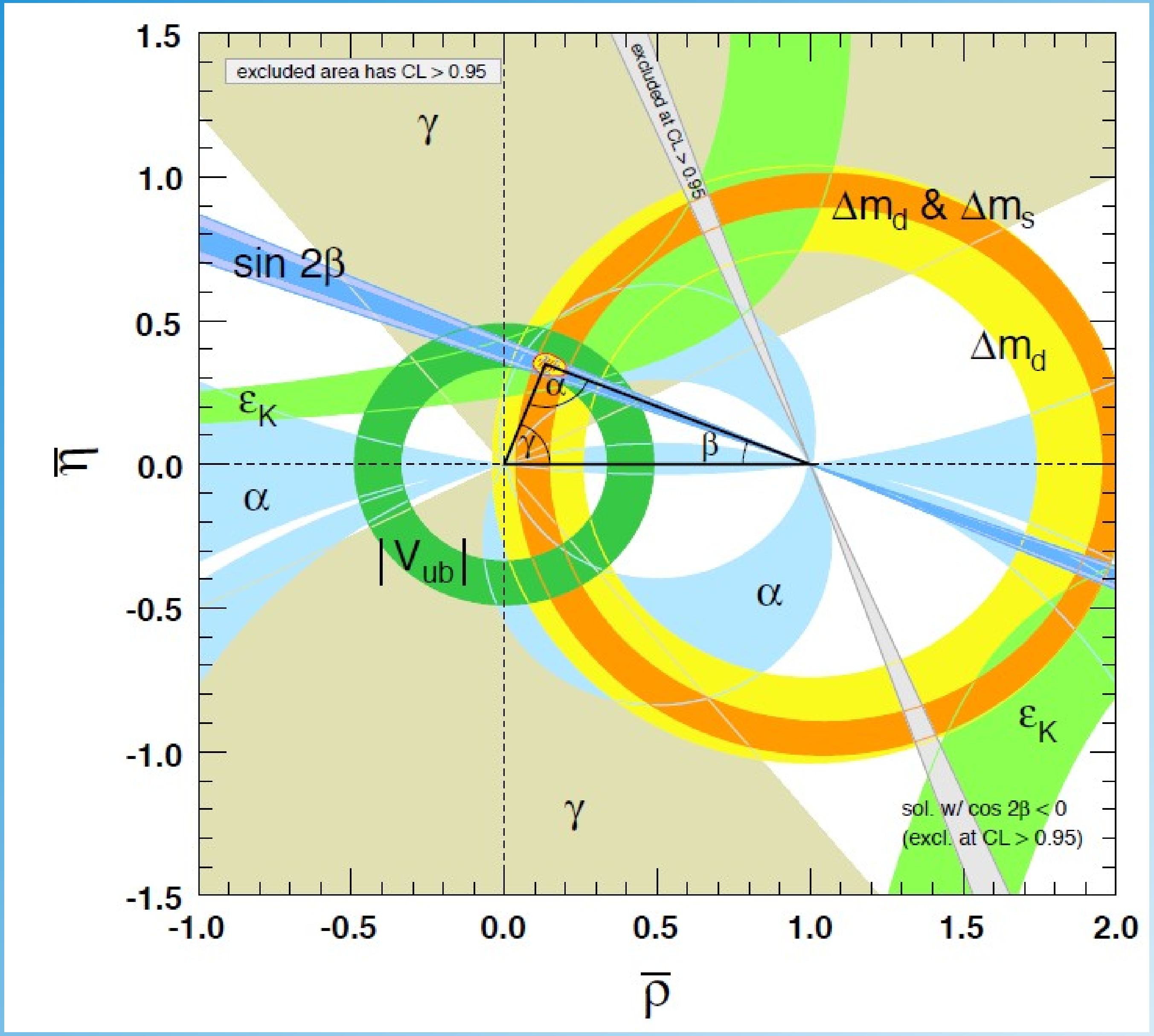
always two identical flavours

interfering diagrams



sin 2β clearly non zero!

Summary of experimental Results



B-Mixing Formalism

Oscillations:

$$\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} \,.$$

$$\begin{pmatrix} |M^0(t)\rangle \\ |\bar{M}^0(t)\rangle \end{pmatrix} = \begin{pmatrix} M_{11} - i\Gamma_1/2 & M_{12} \\ M_{21} & M_{22} - i\Gamma_2/2 \end{pmatrix} \cdot \begin{pmatrix} |M^0(0)\rangle \\ |\bar{M}^0(0)\rangle \end{pmatrix}$$

Linear combination of low and high mass eigenstate

$$|M_L\rangle \propto p\sqrt{1-z}\,|M^0\rangle + q\sqrt{1+z}\,|\overline{M}^0\rangle$$
$$|M_H\rangle \propto p\sqrt{1+z}\,|M^0\rangle - q\sqrt{1-z}\,|\overline{M}^0\rangle$$

slightly different convention c.t. the more historic Kaon conventions

$$\left(\frac{q}{p}\right)^2 = \frac{\mathbf{M}^*_{12} - (i/2)\mathbf{\Gamma}^*_{12}}{\mathbf{M}_{12} - (i/2)\mathbf{\Gamma}_{12}}$$

$$z \equiv \frac{\delta m - (i/2)\delta\Gamma}{\Delta m - (i/2)\Delta\Gamma} \,,$$

$$\delta m \equiv \mathbf{M}_{11} - \mathbf{M}_{22} \quad , \quad \delta\Gamma \equiv \mathbf{\Gamma}_{11} - \mathbf{\Gamma}_{22}$$

$$\Delta m \equiv m_H - m_L = \mathcal{R}e(\omega_H - \omega_L) \quad ,$$
$$\Delta\Gamma \equiv \Gamma_H - \Gamma_L = -2\,\mathcal{I}m(\omega_H - \omega_L) \,.$$

both have been measured for B^0 and B_s

Classification of CP Violation

I. Direct CP-violation

$$|\bar{A}_{\bar{f}} / A_f| \neq 1$$

$$\mathcal{A}_{f\pm} \equiv \frac{\Gamma(M^- \to f^-) - \Gamma(M^+ \to f^+)}{\Gamma(M^- \to f^-) + \Gamma(M^+ \to f^+)} = \frac{|\overline{A}_{f^-}/A_{f^+}|^2 - 1}{|\overline{A}_{f^-}/A_{f^+}|^2 + 1} .$$

II. CP-violation in mixing

$$|q/p| \neq 1$$

$$\mathcal{A}_{\rm SL}(t) \equiv \frac{d\Gamma/dt\left[\overline{M}^0_{\rm phys}(t) \to \ell^+ X\right] - d\Gamma/dt\left[M^0_{\rm phys}(t) \to \ell^- X\right]}{d\Gamma/dt\left[\overline{M}^0_{\rm phys}(t) \to \ell^+ X\right] + d\Gamma/dt\left[M^0_{\rm phys}(t) \to \ell^- X\right]} = \frac{1 - |q/p|^4}{1 + |q/p|^4}.$$

III. CP-violation in decay with and without mixing

$$\Im(\lambda_f) = \left|\frac{q\,\bar{A}_f}{p\,A_f}\right| \neq 0$$

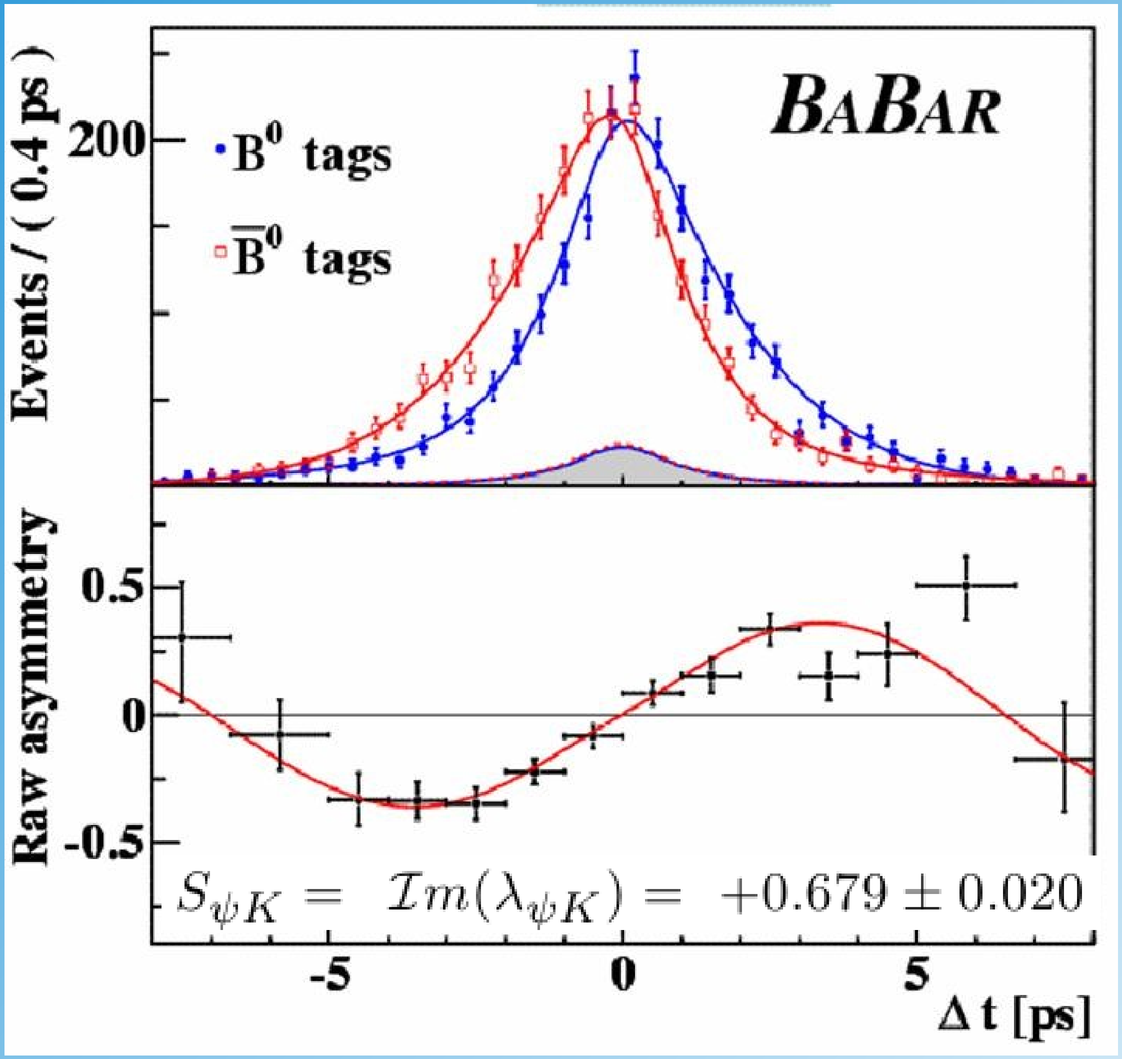
$$\mathcal{A}_{f_{CP}}(t) \equiv \frac{d\Gamma/dt\left[\overline{M}^0_{\rm phys}(t) \to f_{CP}\right] - d\Gamma/dt\left[M^0_{\rm phys}(t) \to f_{CP}\right]}{d\Gamma/dt\left[\overline{M}^0_{\rm phys}(t) \to f_{CP}\right] + d\Gamma/dt\left[M^0_{\rm phys}(t) \to f_{CP}\right]} .$$

asymmetry often called **S**

CP-eigenstate

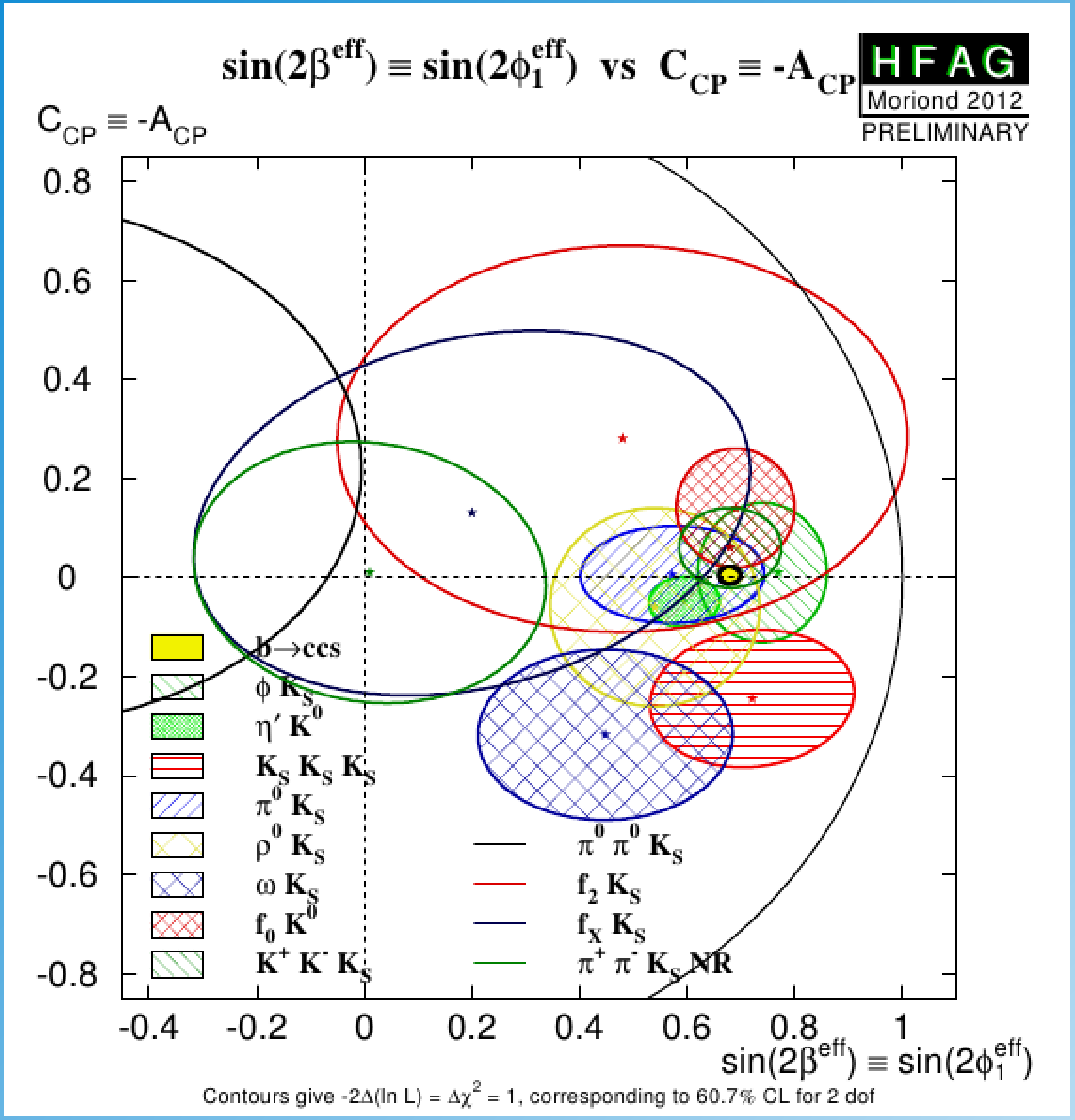
$$S_f = \frac{2\,{\rm Im}\lambda_f}{1 + |\lambda_f|^2}, \qquad C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2},$$

CP Violation in B → J/ψ K



mixing effect in B-sector is much larger than in K-sector!

Correlation “Direct versus Mixing”



large direct CP violation!

small CP violation in mixing

Summary B-Asymmetry Parameters

I. Direct CP-violation is large

$$\mathcal{A}_{K^+\pi^-} = \frac{|\overline{A}_{K^-\pi^+}/A_{K^+\pi^-}|^2 - 1}{|\overline{A}_{K^-\pi^+}/A_{K^+\pi^-}|^2 + 1} = -0.087 \pm 0.008 \quad \text{(I)}$$

II. CP-violation in mixing is very small!

Sensitive to new BSM physics!

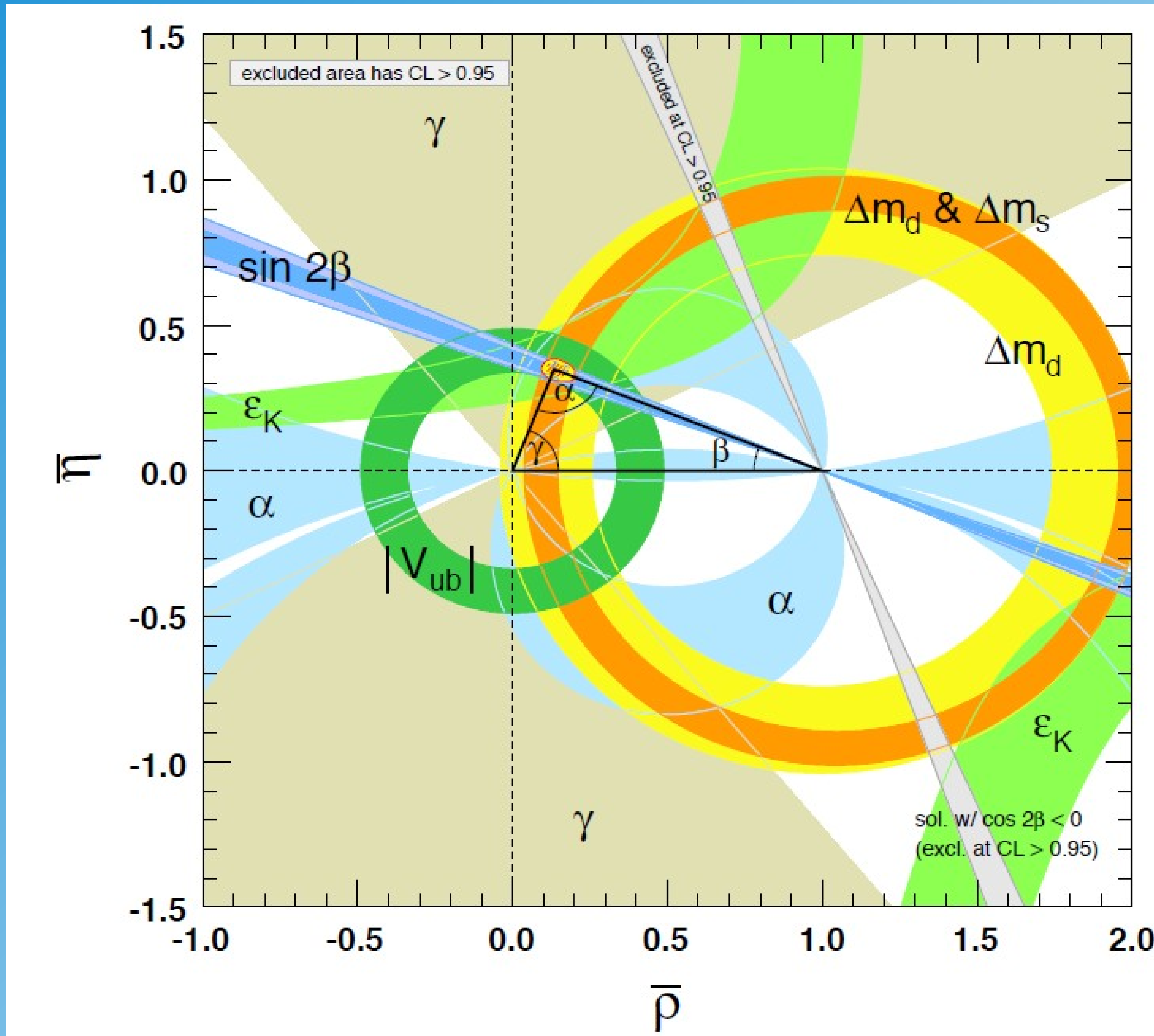
$$\mathcal{A}_{\rm SL}^d = (-3.3 \pm 3.3) \times 10^{-3} \implies |q/p| = 1.0017 \pm 0.0017.$$

$$\mathcal{A}_{\rm SL}^d = \mathcal{O}\left[(m_c^2/m_t^2)\sin\beta\right] \lesssim 0.001.$$

III. CP-violation in decay with and without mixing

$$S_{\psi K} = \mathcal{I}m(\lambda_{\psi K}) = +0.679 \pm 0.020 \;. \qquad \text{(III)}$$

Summary of experimental Results



All measurements very consistent! No sign of non-CKM CP violation

Summary

- The CKM Matrix elements are determined from a global fit to precision measurements
- The CKM matrix is tested to be unitary and has a non-zero CP violating phase
- CP violation can be measured in particle decays if at least two diagrams with different strong and weak phases interfere
- CP violation shows up in decays and mixing (oscillations)
- In Kaon system CP violation in mixing dominates
- In B-system CP violation in direct decays dominates
- CP violation in hadron decays explained by CKM matrix