Lecture:

Standard Model of Particle Physics

Heidelberg SS 2013

Flavour Physics I + II

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

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

Standard Parameterisation (Euler Angles):

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

Unitary matrix has N x N parameters: 3 families → 9 parameters
2 x N -1 trivial phases: → 5 phases
N x (N-1) / 2 rotation angles → 3 angles
N x N - N x (N-1)/ 2 - (2 x N -1) = N x (N-3)/2 +1 → 1 CPV phase

need 3 families for generating CP-violation!

CKM Matrix

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CKM Matrix

Wolfenstein Parameterisation:

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

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

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

note that definition with η and ρ depends on phase convention, $\bar\eta$ and $\bar\rho$ does not

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CKM Matrix

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Experimental values:

no theory prediction!

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

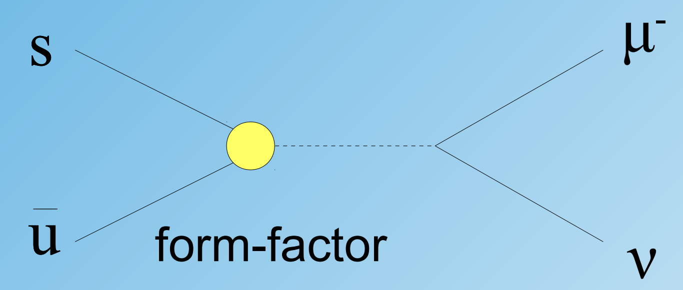
$$\bar\rho = 0.131^{+0.026}_{-0.013}\,, \qquad \bar\eta = 0.345^{+0.013}_{-0.014}\,.$$

Experimental Determination of CKM Matrix Elements

V_{us}: Kaon decay:

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

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

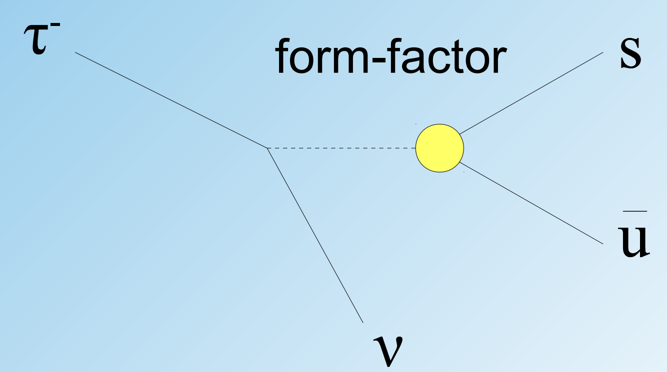


theory uncertainties due to Kaon/Pion formfactors mostly cancel

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

V_{us}: Tau decay:

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



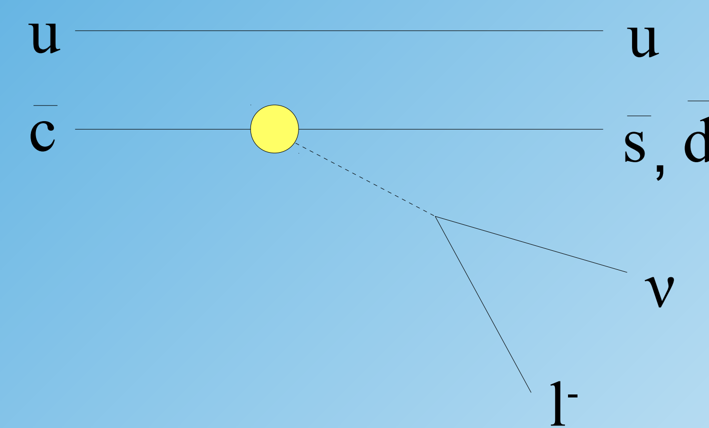
LEP, Barbar, Belle combined:

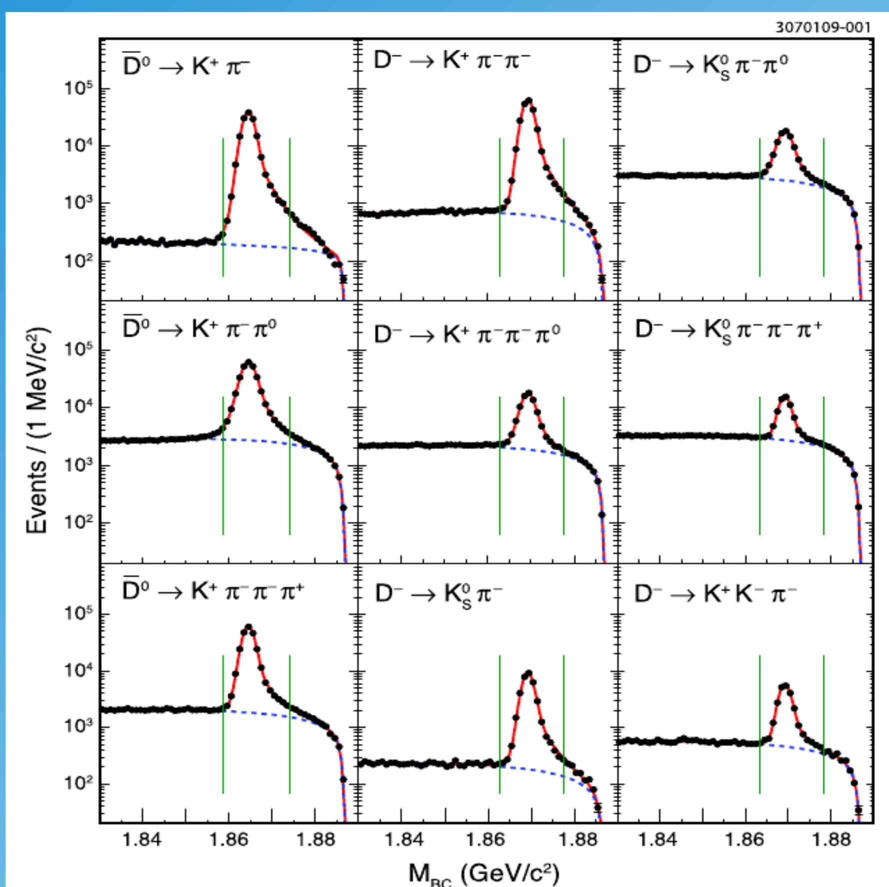
$|V_{us}| = 0.2208 \pm 0.0039$

D^0 - Decays

V_{cd}: D-meson decay:

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





CLEOc + Belle combined:

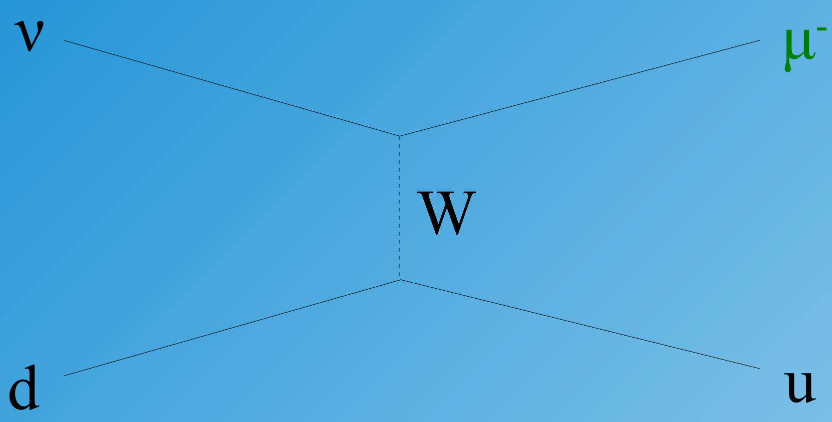
$|V_{cd}| = 0.229 \pm 0.006 \pm 0.024$

Also hadronic decays analysed:

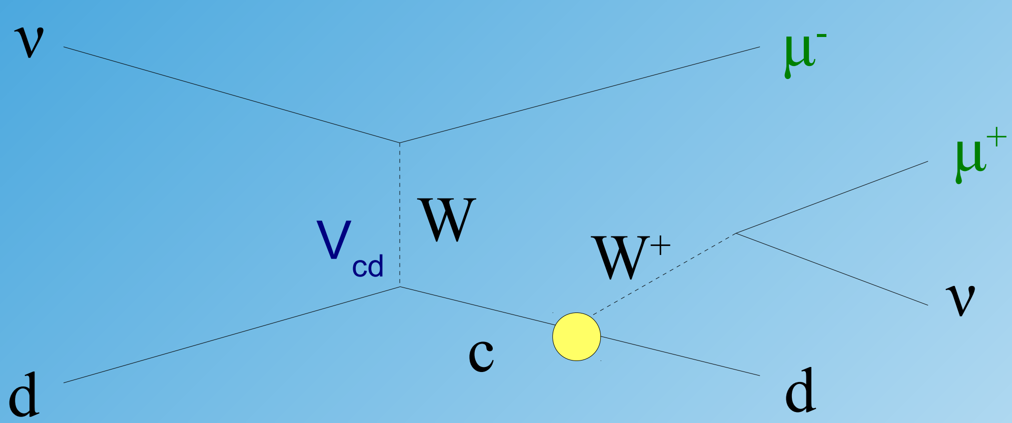
from CLEOc
arXiv 0906.2983

Neutrino Scattering

V_{cd}: from neutrino (antineutrino) scattering



one muons



two muons

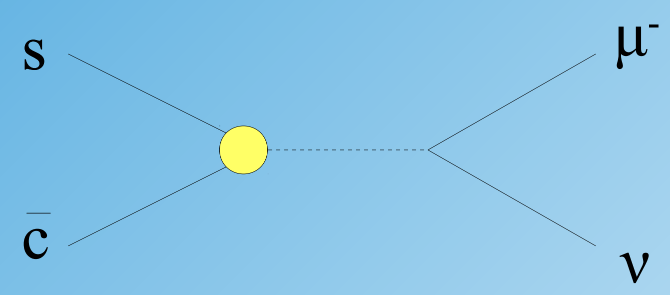
from CDHS, CCFR, CHARM II and CHORUS experiments:

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

D_s - Decays

V_{cs}: from D_s decays

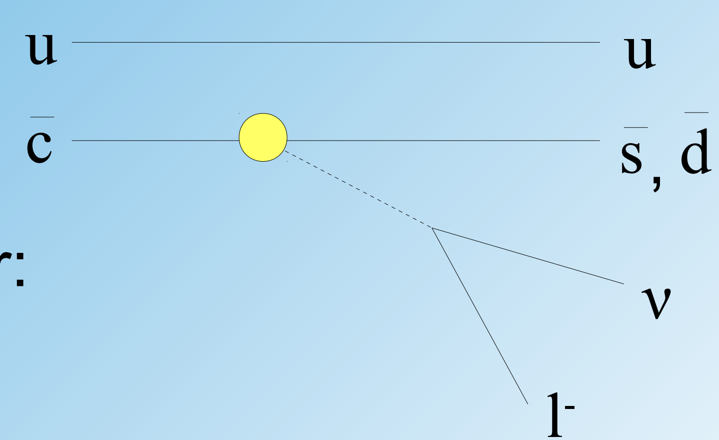
$D_s \to l\nu$



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

V_{cs}: from D_0 decays

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



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

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

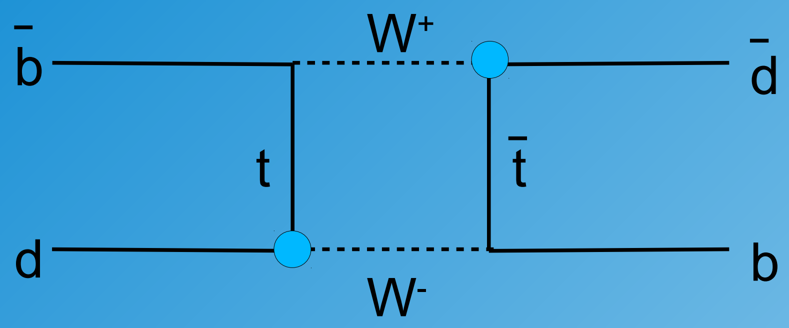
V_{td}:

V_{ts}:

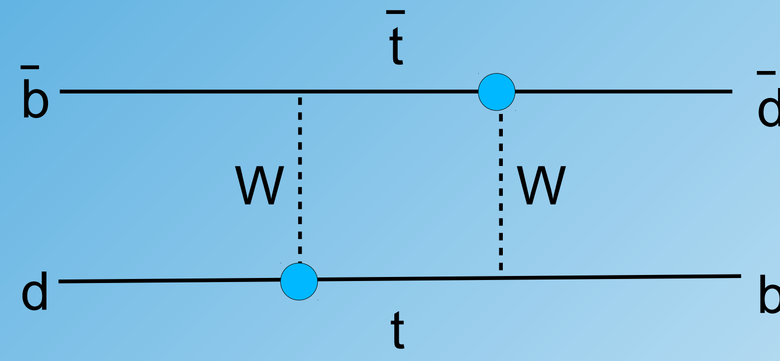
Both difficult to determine from top decays with high precision → instead use trick

B and B_S oscillations

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

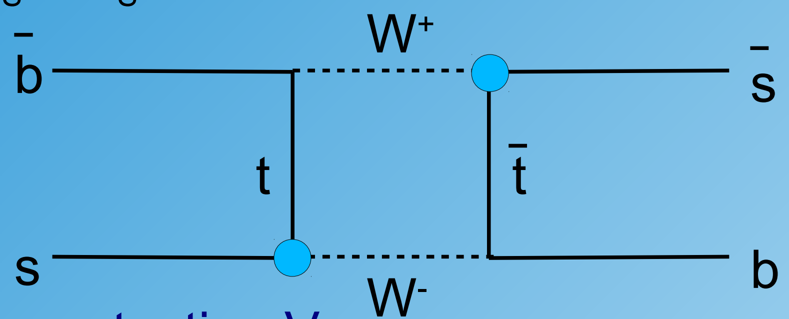


testing V_{td}

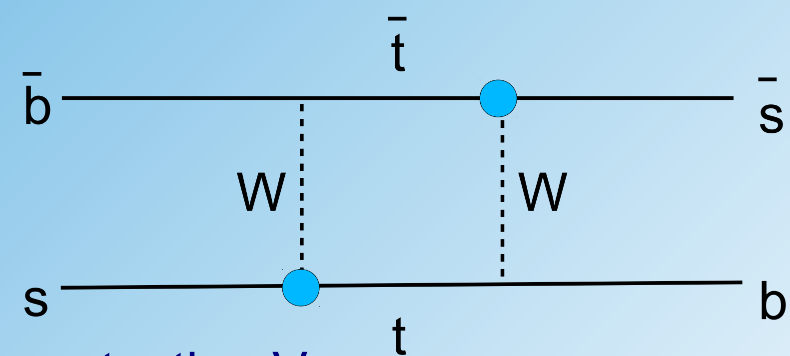


testing V_{td}

$B_S - \overline{B_S}$ 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):

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

Representation using the Wolfenstein parameterisation (only 4 parameters!)

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

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

$$|V_{12}| \approx |V_{21}| \approx \lambda$$

$$|V_{23}| \approx |V_{32}| \approx \lambda^2$$

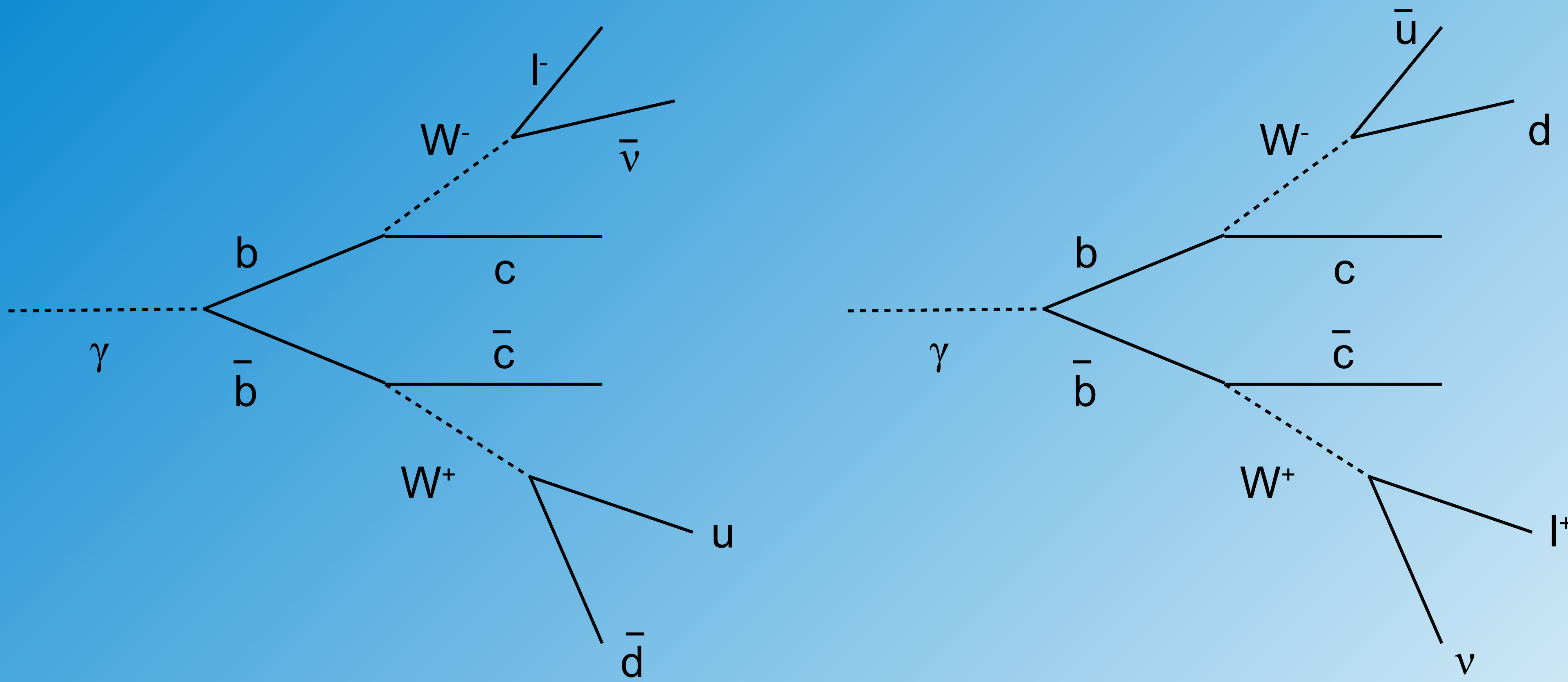
$$|V_{13}| \approx |V_{31}| \approx \lambda^3$$

(mystery!)

As $\eta \neq 0$ ($\bar{\rho} \neq 0$) 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!

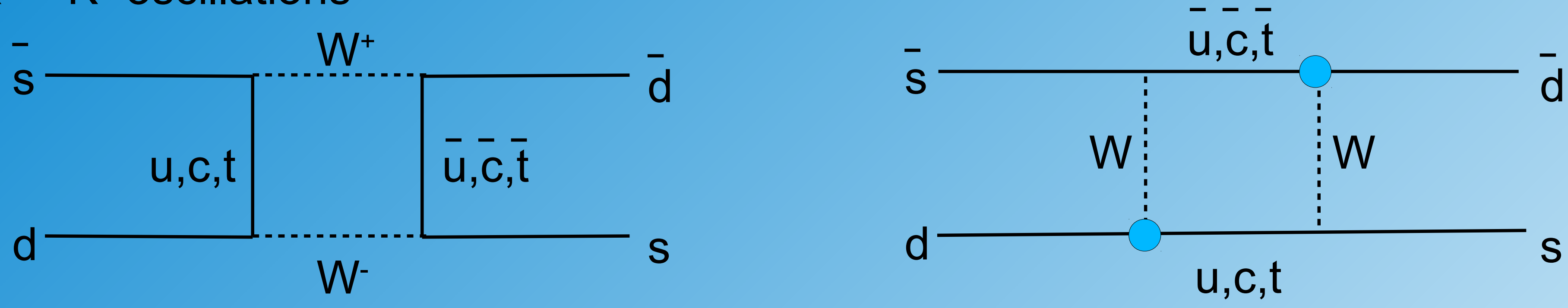
- Direct CP-Violation: different partial decay widths for particles and antiparticles

- CPV can 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 anti-fermions are complex conjugated

if δ_{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)

Quark-Model: $K^0 = d\,\bar{s}$ $\quad \bar{K}^0 = \bar{d}\,s$

Both states can be experimentally distinguished.

Different cross sections with matter (strong interactions):

$$K^0 p \rightarrow K^0 p,\ \ K^+ n$$

$$\bar{K}^0 p \rightarrow \bar{K}^0 p,\ \ \Lambda \pi^+$$ ⟶ large cross section

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:

$K_L^0 \rightarrow \pi\pi\pi$	CP= -1	$\|K_L\rangle \approx \|K_1\rangle$	$\tau(K_L^0)=5\cdot 10^{-8}\,s$
$K_S^0 \rightarrow \pi\pi$	CP= +1	$\|K_S\rangle \approx \|K_2\rangle$	$\tau(K_S^0)=0.9\cdot 10^{-10}\,s$

$$\Delta M = M_L - M_S \approx O\left(10^{-12}\,MeV\right)$$ 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: $\hat{H} = i\frac{\partial}{\partial} t$ → eigenvalues:

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

Oscillations:

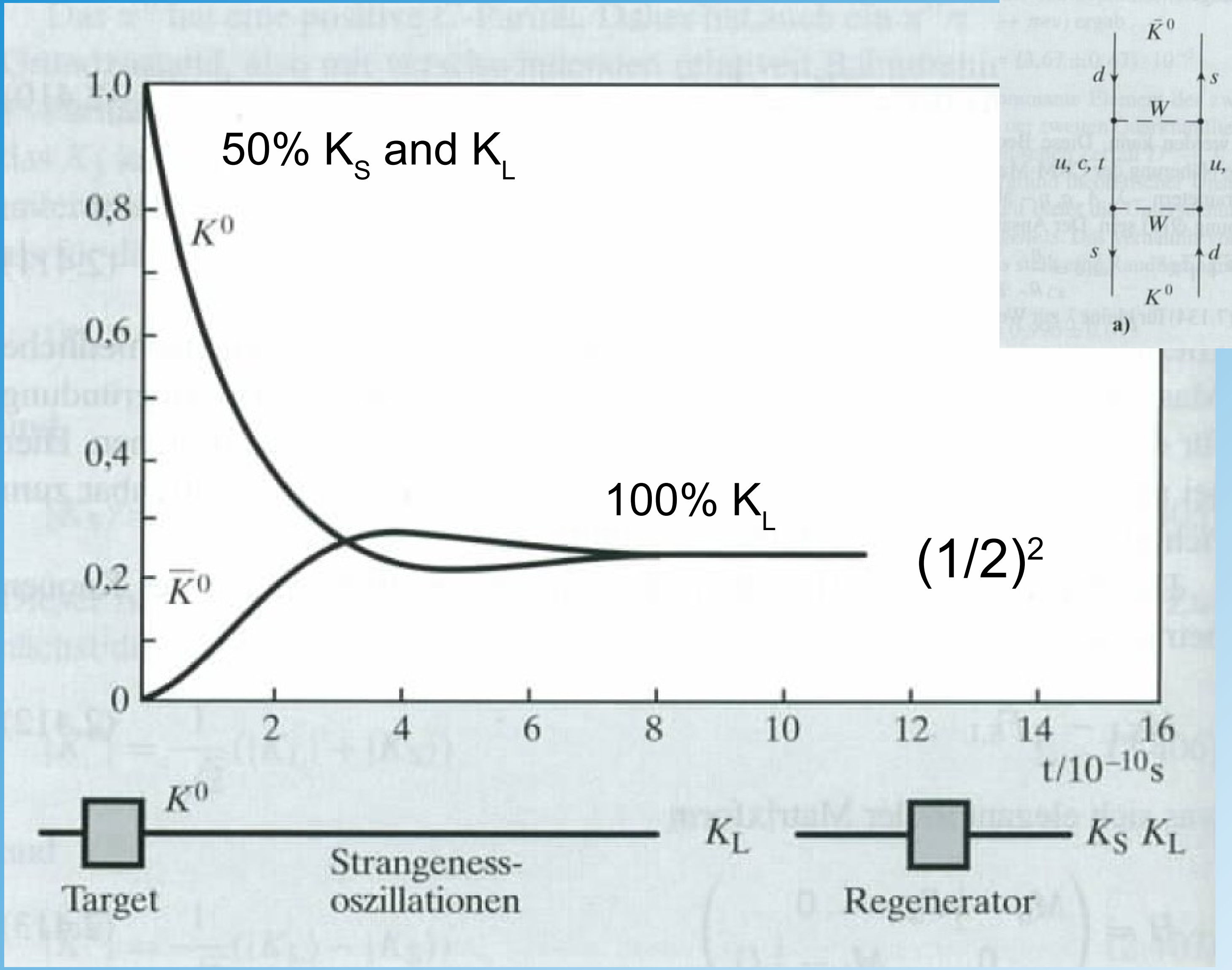
$$A(t) = \langle \bar{K}^0(t) | K^0(0) \rangle = \frac{1}{4} \langle K_L(t) - K_S(t) | K_L(0) + K_S(0) \rangle$$

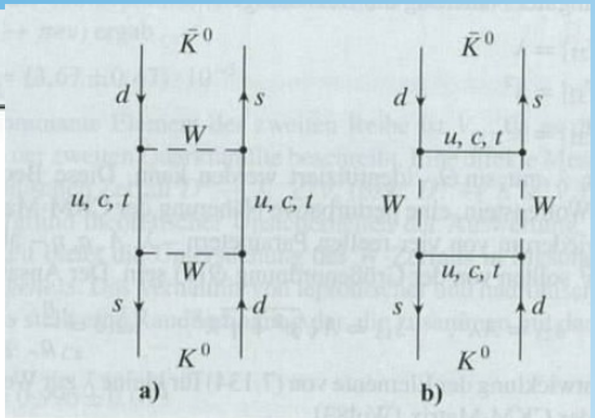
$$P(t) = A^*(t)\,A(t) = \frac{1}{4}\left(e^{-\Gamma_L t} + e^{-\Gamma_S t} - 2\cos(\Delta M\ t)\ e^{-1/2(\Gamma_L + \Gamma_S)t}\right)$$

with

$$\Delta M = M_L - M_S$$

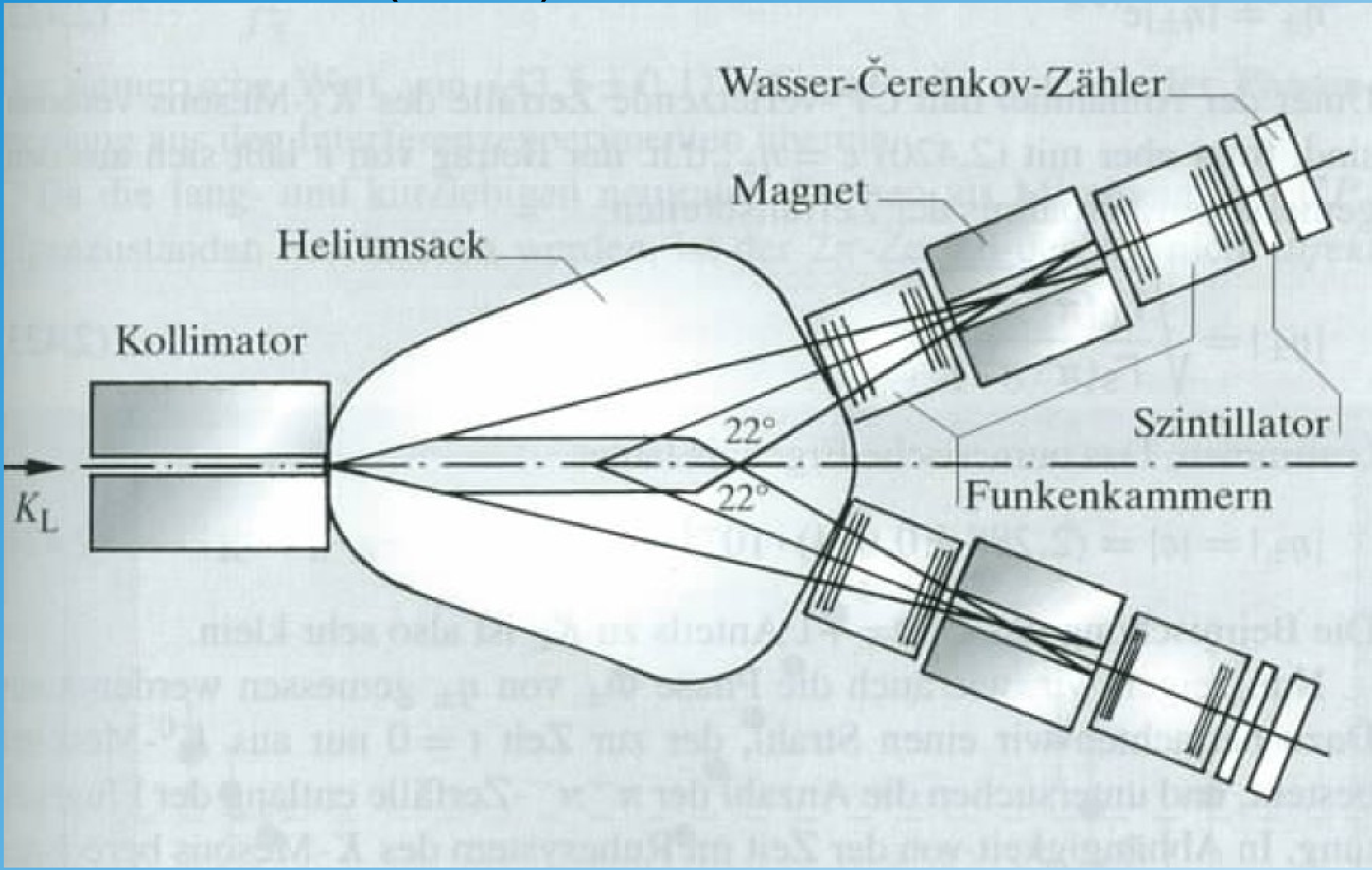
Kaon Oscillations and Regeneration





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 K_L decay or in mixing?

How to measure CP violation?

Need to measure all CKM matrix elements:

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

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

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

but complex phase not visible!

Complex phase can only be measured in interference processes:

Three possibilities:

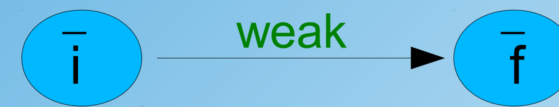
- direct CP Violation
- CP violation in mixing
- interference between decays with and without mixing

CP transformation

Consider CP violating (weak) process i → f:

$$CP\,|a_i\rangle = e^{+i\varphi_i}\,|\bar{a}_i\rangle$$

$$CP\,|a_f\rangle = e^{+i\varphi_f}\,|\bar{a}_f\rangle$$



transition amplitudes:

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

it follows if $[O, CP] = 0$

$$\bar{A}_{\bar{f}} = e^{+i(\varphi_f - \varphi_i)}\,A_f$$

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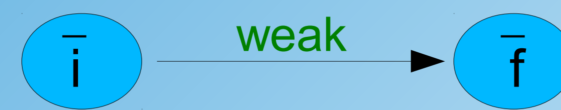

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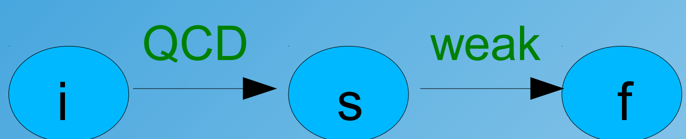
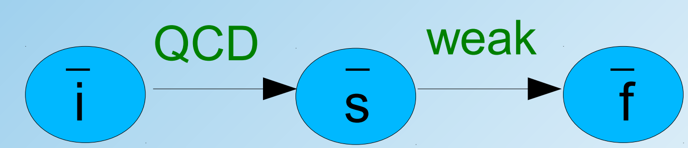
$$\bar{A}_{\bar{f}} = e^{+i(\varphi_f - \varphi_i)}\,A_f$$

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





$$A_f = |n|\,e^{+i(\theta+\varphi_i)}$$

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

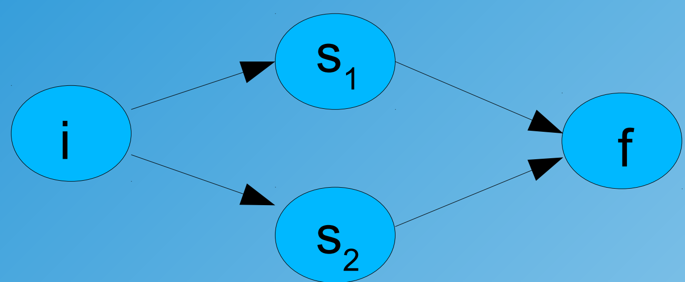
strong interaction (strong phase shift θ) is CP invariant!

I. Direct CP violation

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

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

<u>Superposition of two processes:</u>

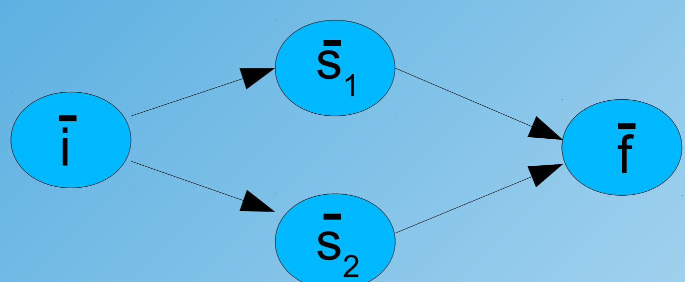


like a classical double slit experiment

$$|A_f^2| = n_1^2 + n_2^2 + 2|n_1||n_2| \cos((\theta_1 - \theta_2) + (\varphi_1 - \varphi_2))$$
$$|\bar{A}_{\bar{f}}^2| = n_1^2 + n_2^2 + 2|n_1||n_2| \cos((\theta_1 - \theta_2) - (\varphi_1 - \varphi_2))$$

$$A_f = |n_1|\, e^{+i(\theta_1 + \varphi_1)} + |n_2|\, e^{+i(\theta_2 + \varphi_2)}$$
$$\bar{A}_{\bar{f}} = |n_1|\, e^{+i(\theta_1 - \varphi_1)} + |n_2|\, e^{+i(\theta_2 - \varphi_2)}$$

$|\bar{A}_{\bar{f}} / A_f| \neq 1$ if $\varphi_1 \neq \varphi_2$ and $\theta_1 \neq \theta_2$



I. Direct CP violation

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

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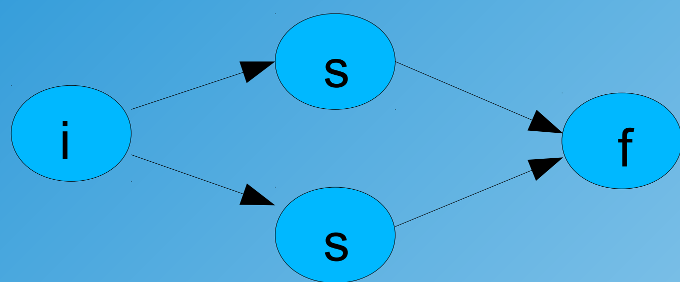
Superposition of two processes:



like a classical double slit experiment

$$|A_f^2| = n_1^2 + n_2^2 + 2|n_1||n_2| \cos((\theta_1 - \theta_2) + (\varphi_1 - \varphi_2))$$

$$|\bar{A}_{\bar{f}}^2| = n_1^2 + n_2^2 + 2|n_1||n_2| \cos((\theta_1 - \theta_2) - (\varphi_1 - \varphi_2))$$

$$A_f = |n_1| \, e^{+i(\theta_1 + \varphi_1)} + |n_2| \, e^{+i(\theta_2 + \varphi_2)}$$

$$\bar{A}_{\bar{f}} = |n_1| \, e^{+i(\theta_1 - \varphi_1)} + |n_2| \, e^{+i(\theta_2 - \varphi_2)}$$

$|\bar{A}_{\bar{f}} / A_f| \neq 1$ if $\varphi_1 \neq \varphi_2$ and $\theta_1 \neq \theta_2$

Can be measured in decays of charged and neutral particles!

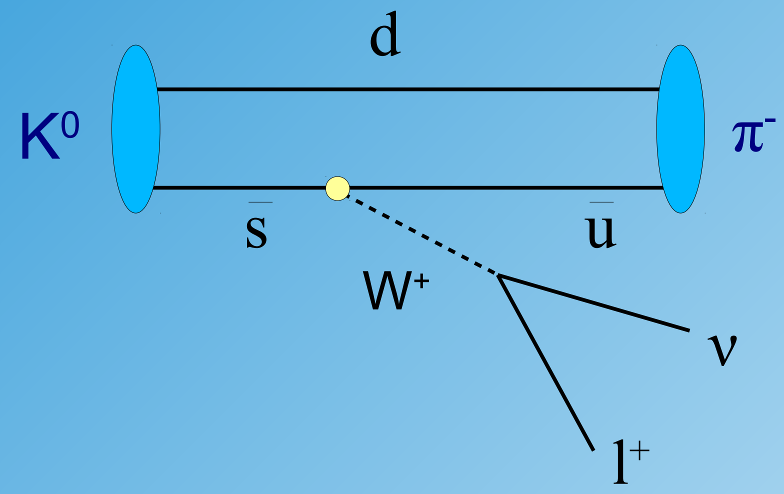
example: $$\delta_L = \frac{\Gamma(K_L \to l^+ \nu_l \pi^-) - \Gamma(K_L \to l^- \bar{\nu}_l \pi^+)}{\Gamma(K_L \to l^+ \nu_l \pi^-) + \Gamma(K_L \to l^- \bar{\nu}_l \pi^+)}$$

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

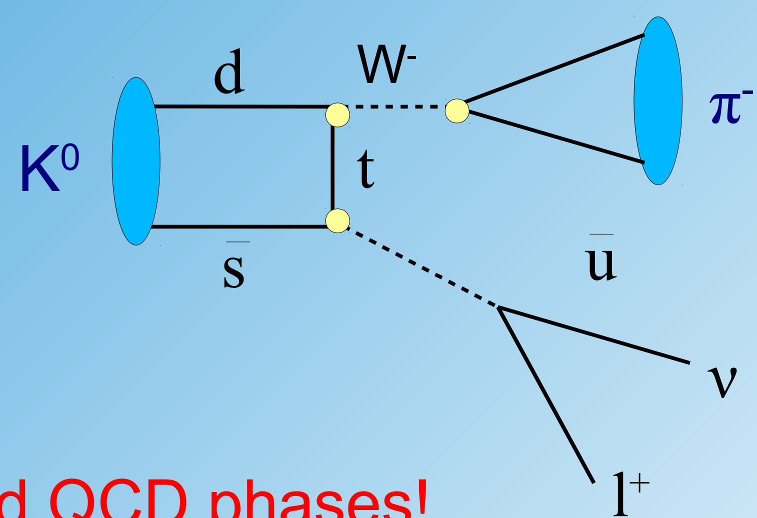
(experiment)

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

Example K_L Decays



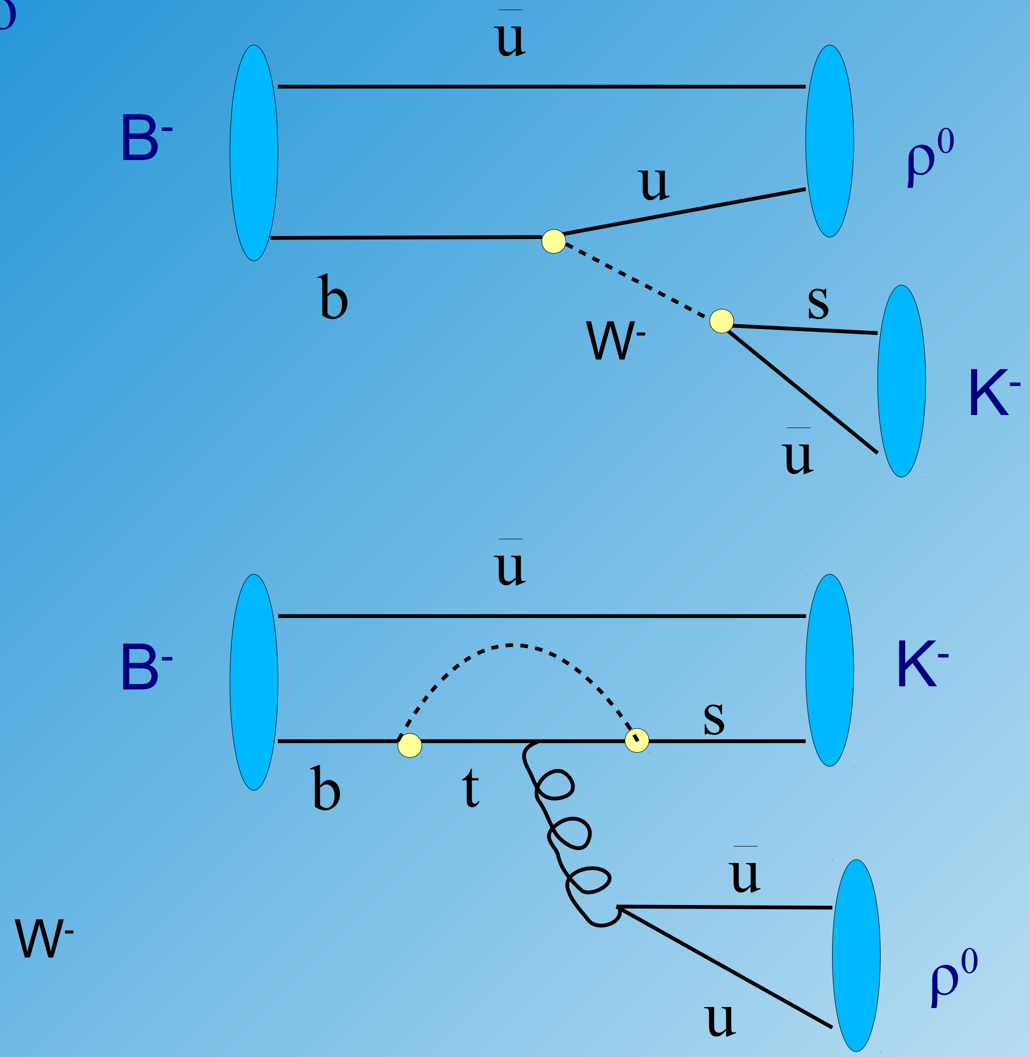
$$|K_L\rangle \approx \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right)$$



different weak and QCD phases!

Direct CP Violation in Charged Meson Decay

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



V^*_{ub}

V_{us}

V^*_{tb} V_{ts}

different weak and QCD phases!

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

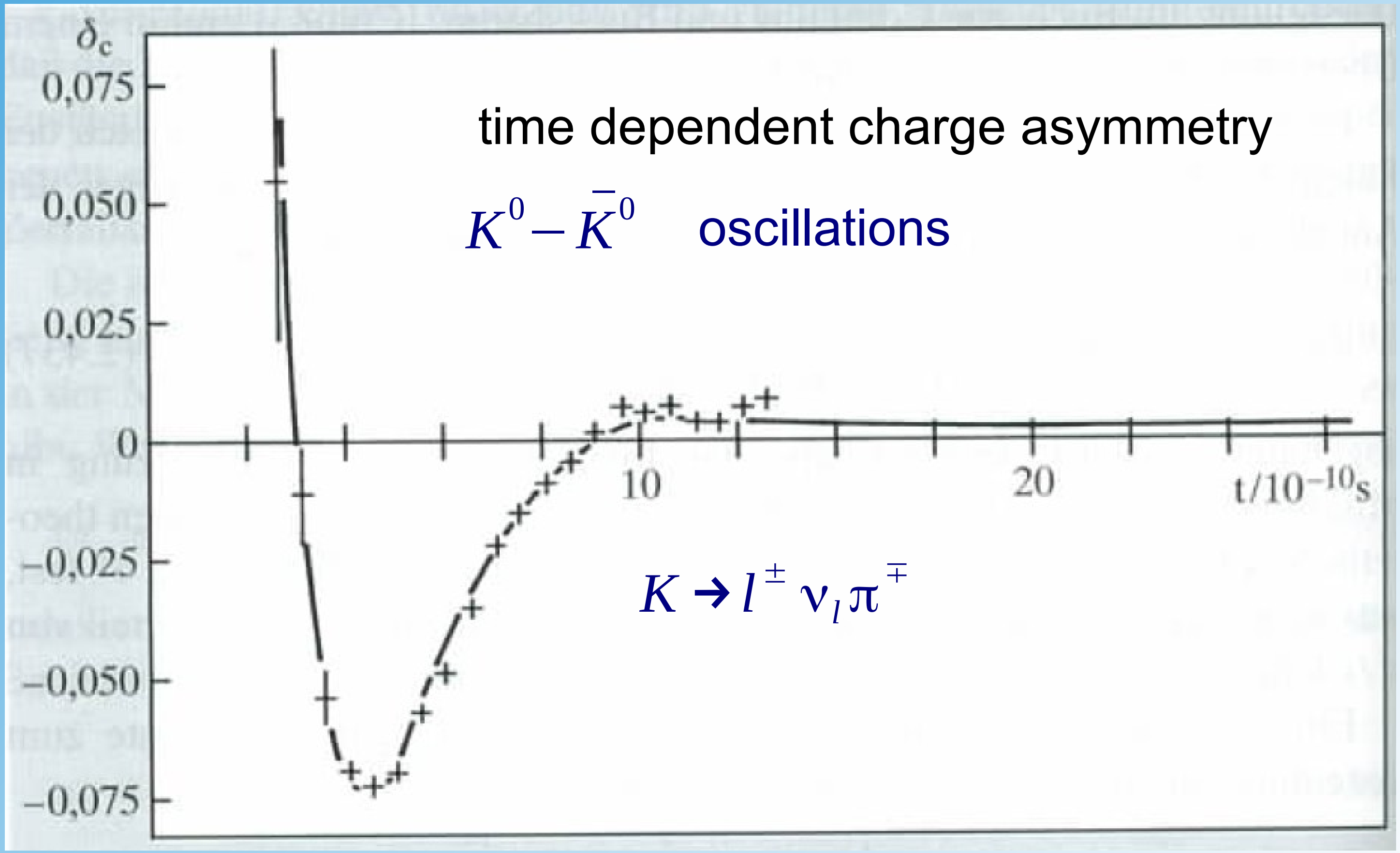
huge asymetry!

II. CP violation in mixing

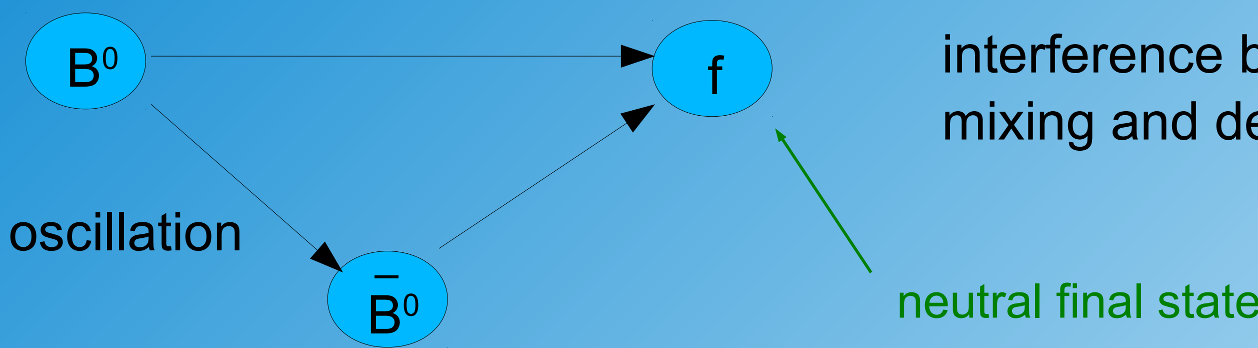
- oscillations of neutral mesons
- measure time dependent decay width

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

$$\delta_C = A_{osc}$$



III. Interference Decay + Mixing



interference between decay without mixing and decay with mixing

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

- 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

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

(mixing: ϵ, direct: ϵ')

with

$$\epsilon' = \frac{\langle\pi^+\pi^-|T|\tilde{K}_1\rangle}{\langle\pi^+\pi^-|T|\tilde{K}_2\rangle}$$

K_S and K_L Interference

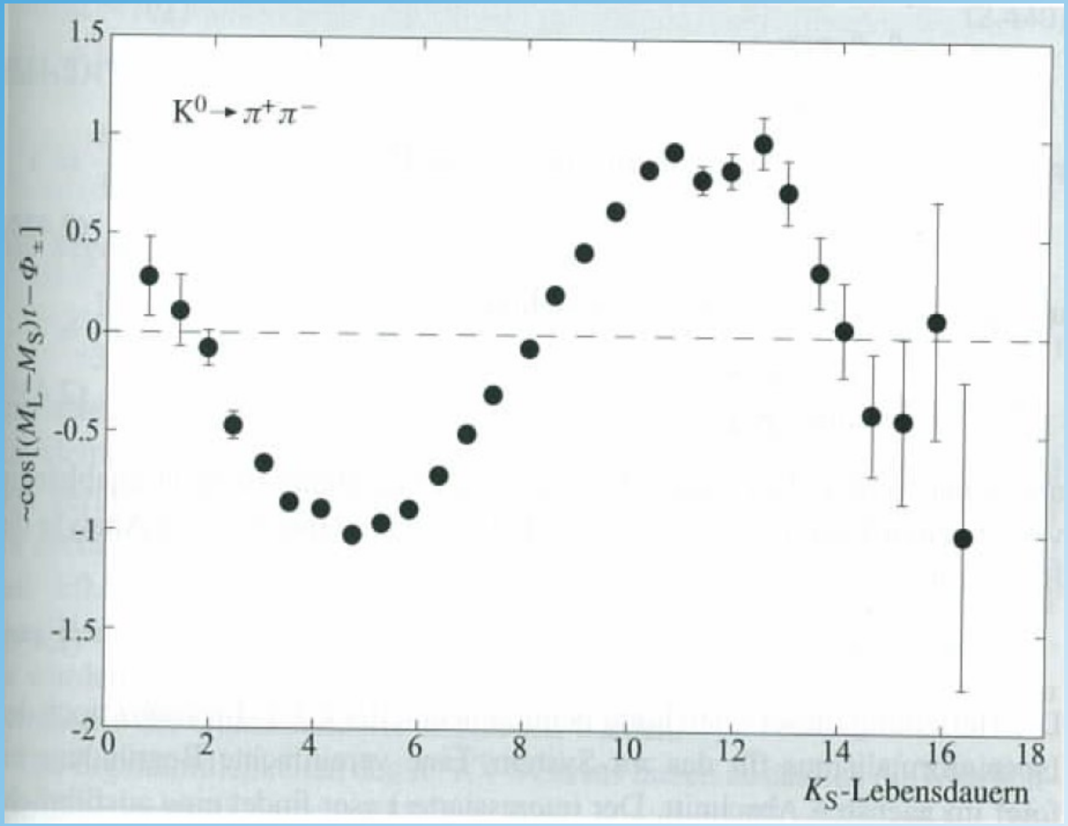
$\delta_C = A_{osc}$

<u>Experimental Result:</u>

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

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

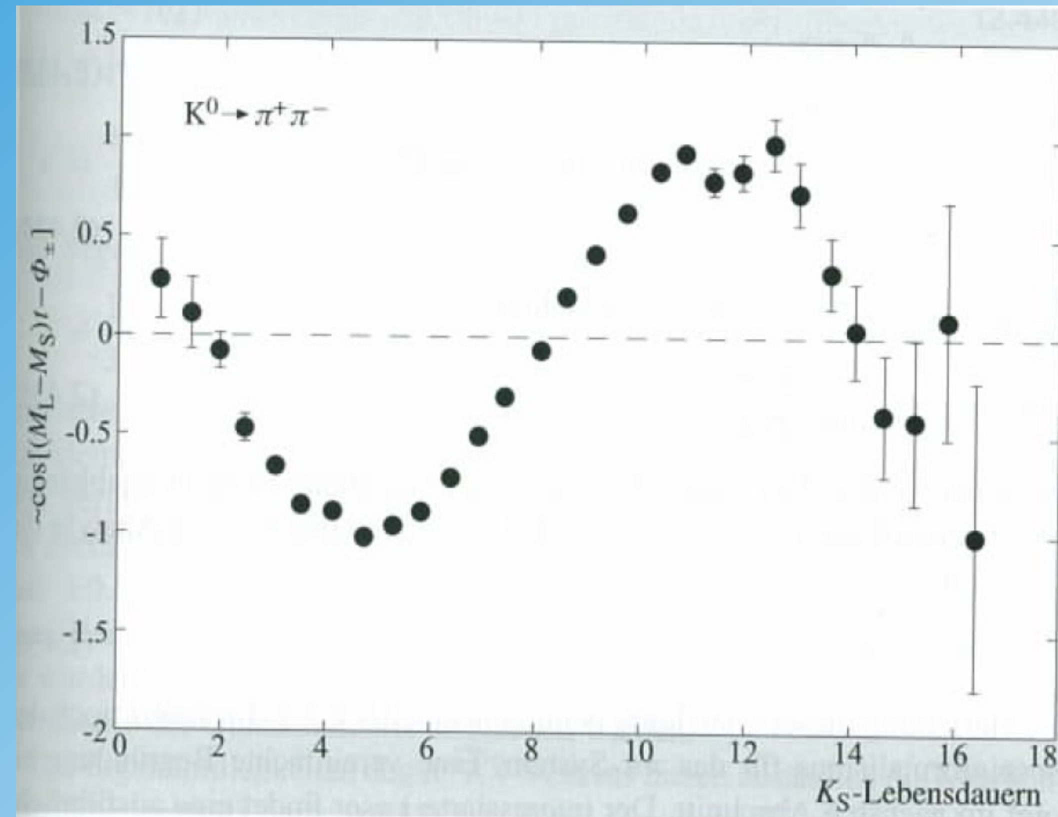
- CP violation mainly due to mixing!



What about ε´ ?

K_S and K_L Interference

$\delta_C = A_{osc}$



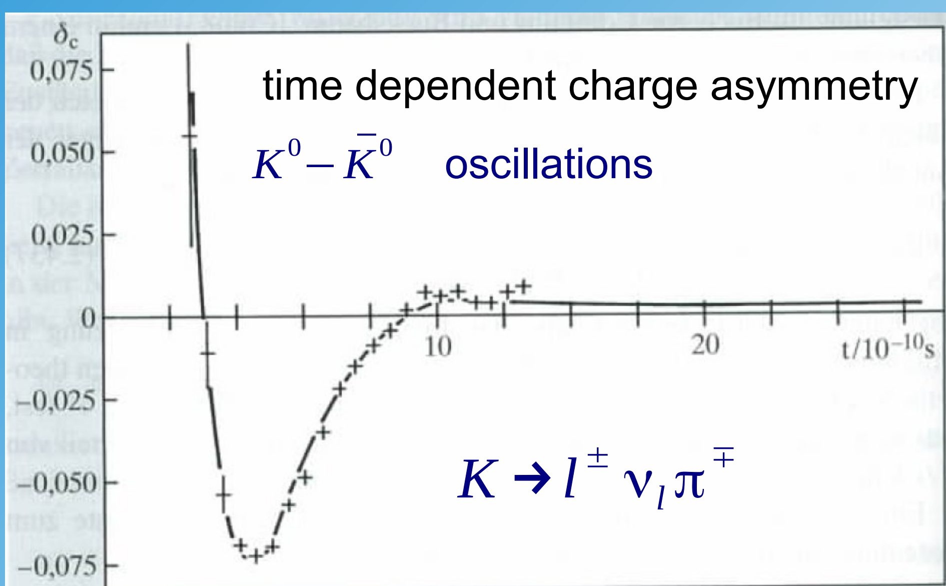
Experimental Result:

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

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

- 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:

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

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

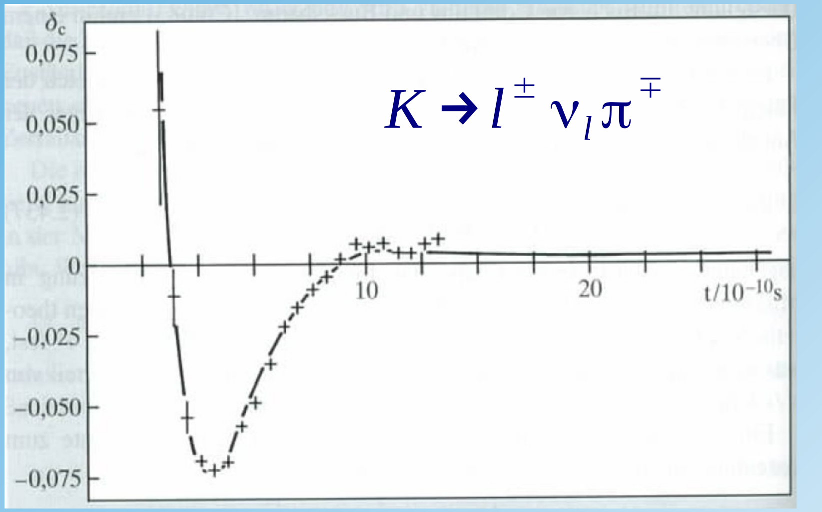
Summary Kaon Physics

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

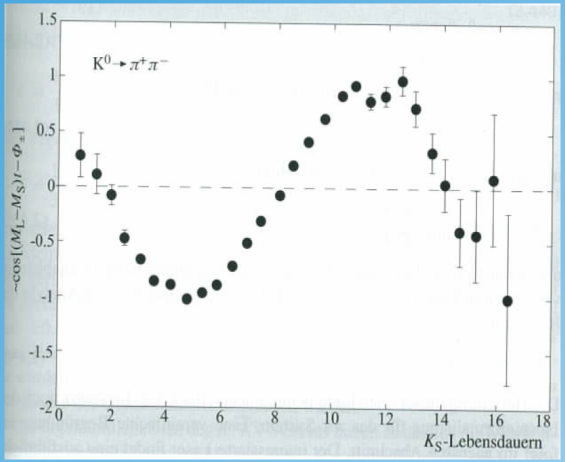
$$\delta_L = \frac{\Gamma(K_L \rightarrow l^+ \nu_l \pi^-) - \Gamma(K_L \rightarrow l^- \bar{\nu}_l \pi^+)}{\Gamma(K_L \rightarrow l^+ \nu_l \pi^-) + \Gamma(K_L \rightarrow l^- \bar{\nu}_l \pi^+)}$$

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

  - and CP violation in **mixing**



- Decay $K \rightarrow \pi^+ \pi^-, \pi^0 \pi^0$ 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 Triangle

one of six possible unitarity triangles

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

define angles α, β, γ

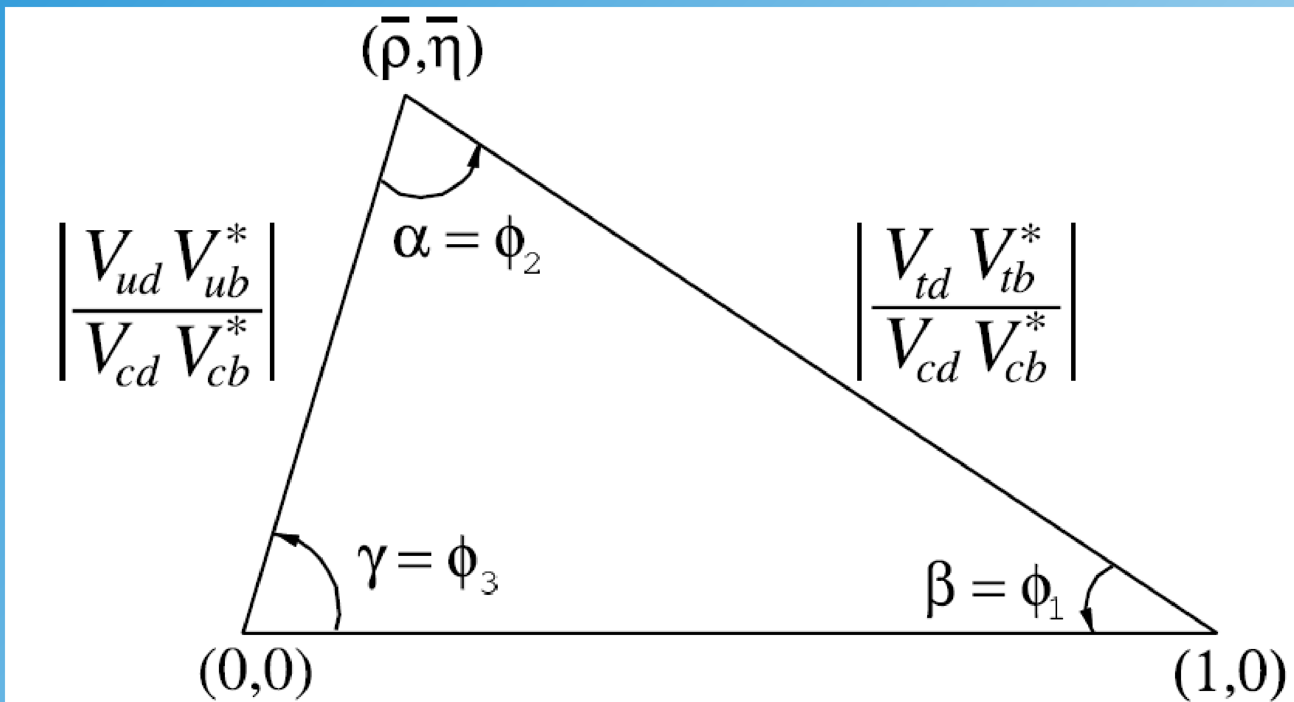


Figure 11.1: Sketch of the unitarity triangle.

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

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

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

Kaon Constraints

Relation between CP violating ε parameter and CKM matrix elements:

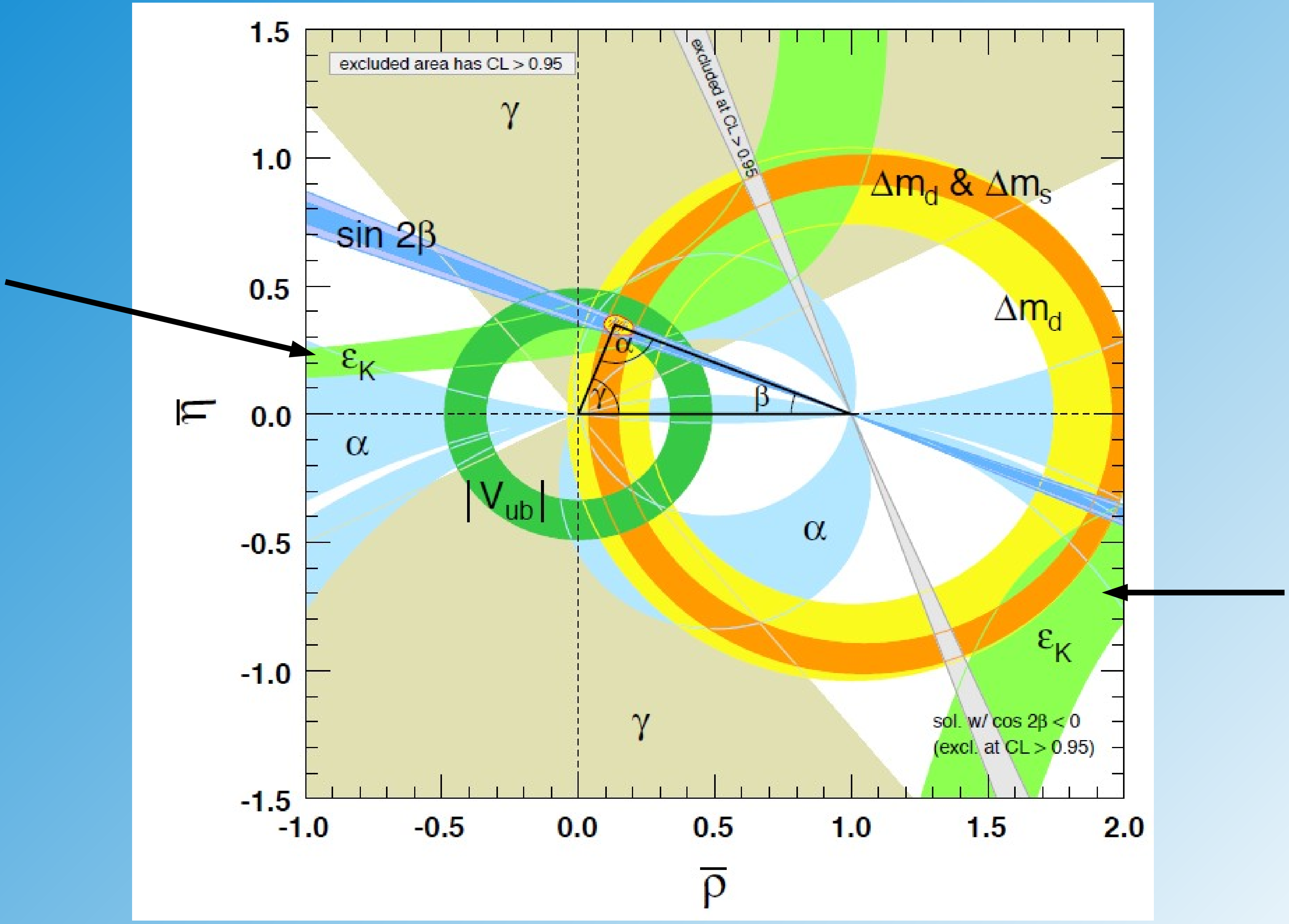
$$|\epsilon| = \frac{G_F^2 f_K^2 m_K m_W^2}{12\sqrt{2}\,\pi^2 \Delta m_K}\,\widehat{B}_K \Big\{ \eta_1 S(x_c)\,\mathrm{Im}[(V_{cs}V_{cd}^*)^2] + \eta_2 S(x_t)\,\mathrm{Im}[(V_{ts}V_{td}^*)^2] + 2\eta_3 S(x_c, x_t)\,\mathrm{Im}(V_{cs}V_{cd}^* V_{ts}V_{td}^*) \Big\},$$

S is Inami-Lim function

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

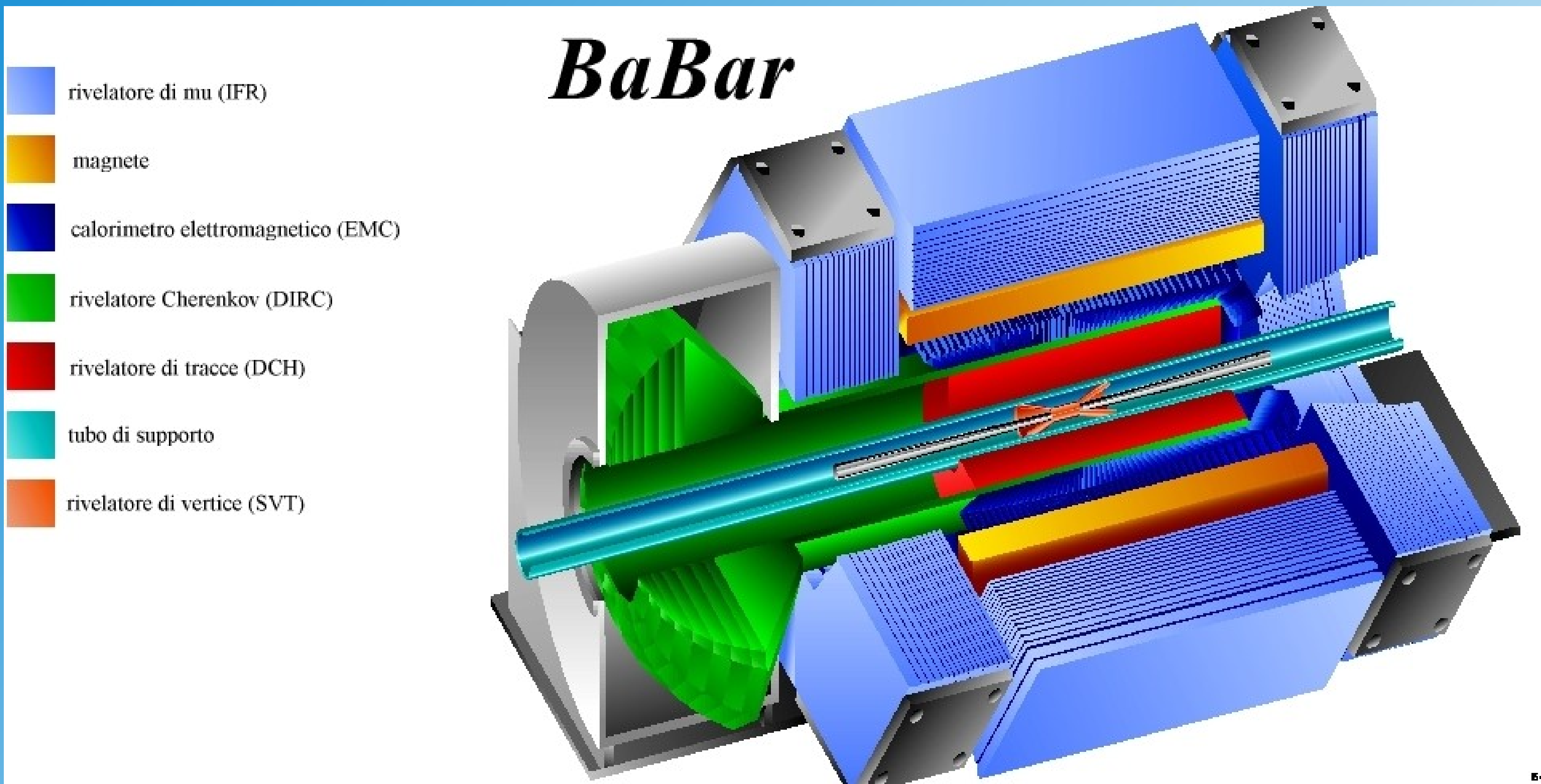
➔ next slide

Summary of experimental Results



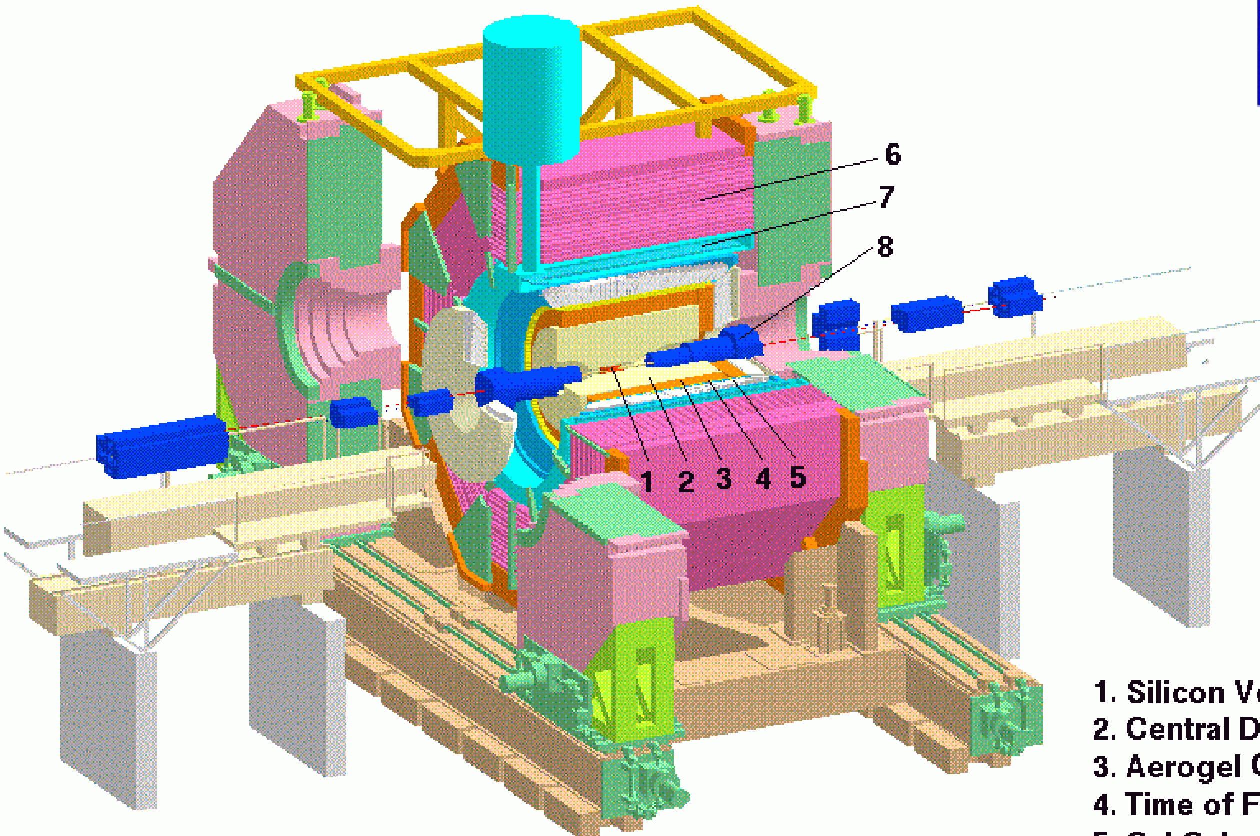
Babar Detector

PEP-C Accelerator, Stanford



Belle Detector

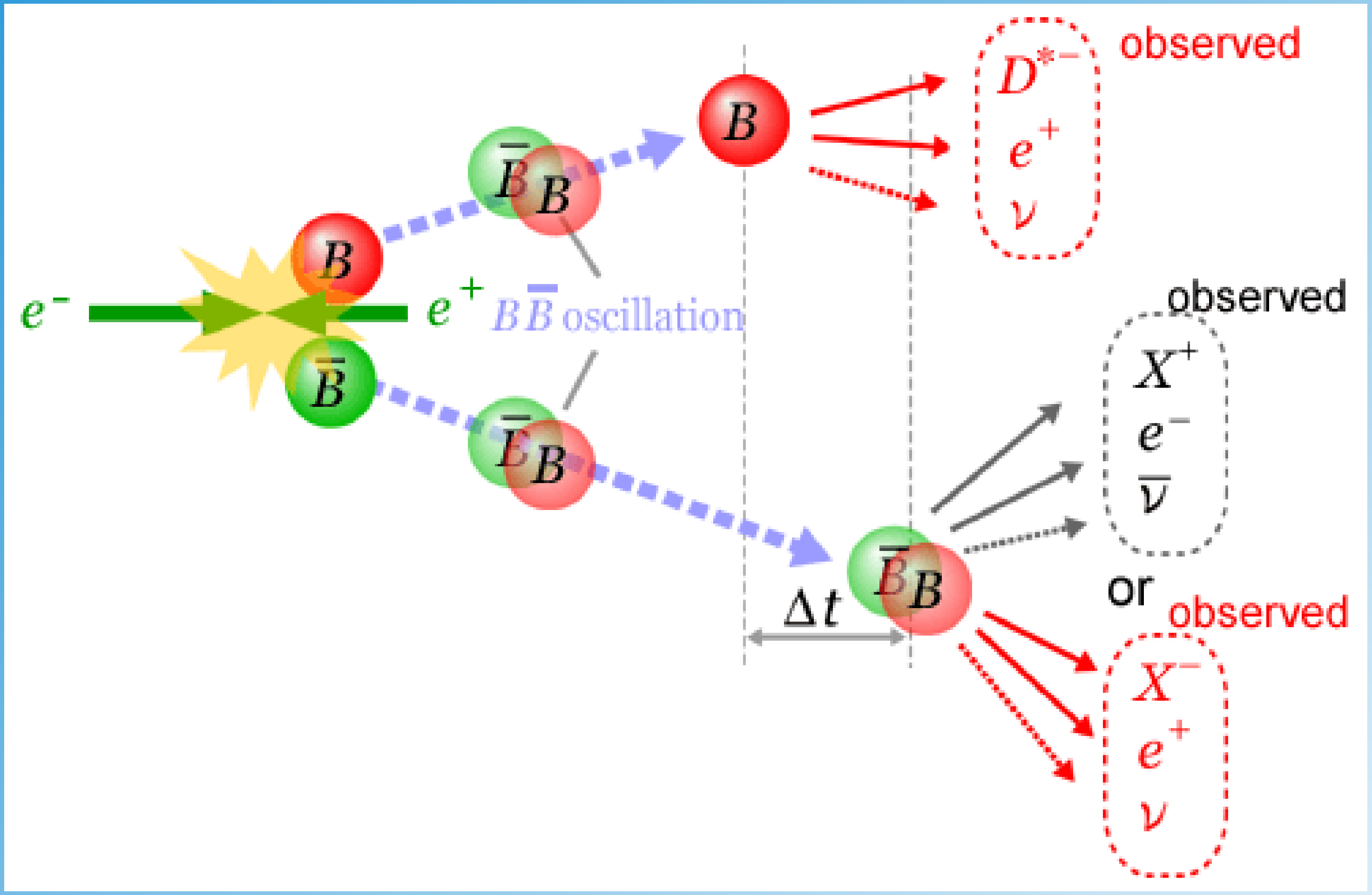
BELLE Detector KEK, Japan



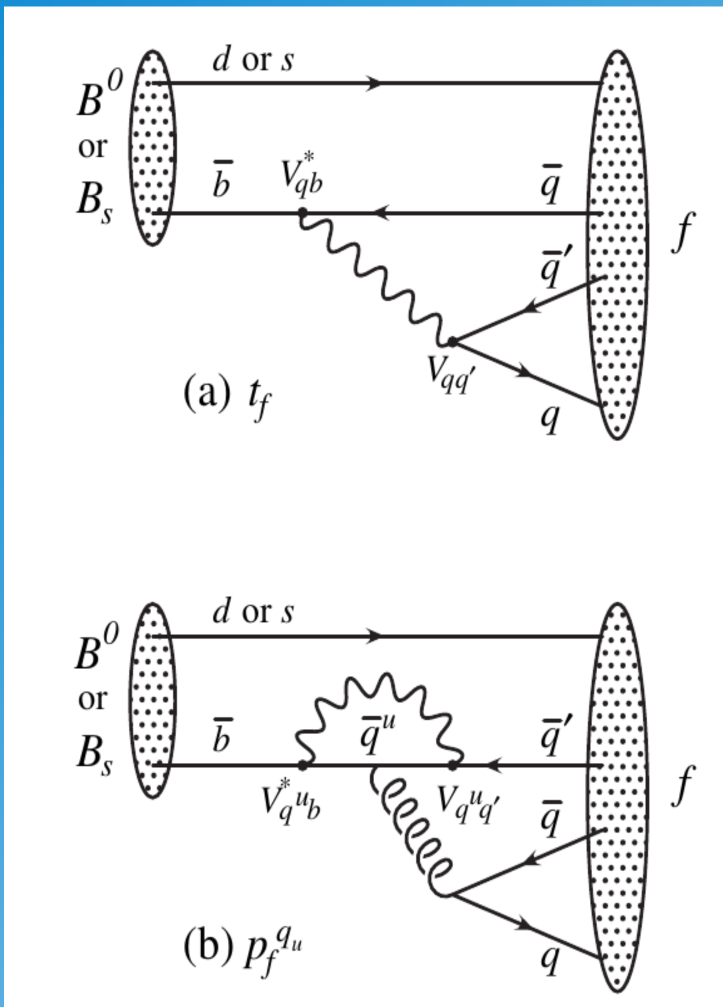
1. Silicon Vertex Detector
2. Central Drift Chamber
3. Aerogel Cherenkov Counter
4. Time of Flight Counter
5. CsI Calorimeter
6. KLM Detector
7. Superconducting Solenoid
8. Superconducting Final Focussing System

B-Oscillations at B-factories

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



Classification of B-decays



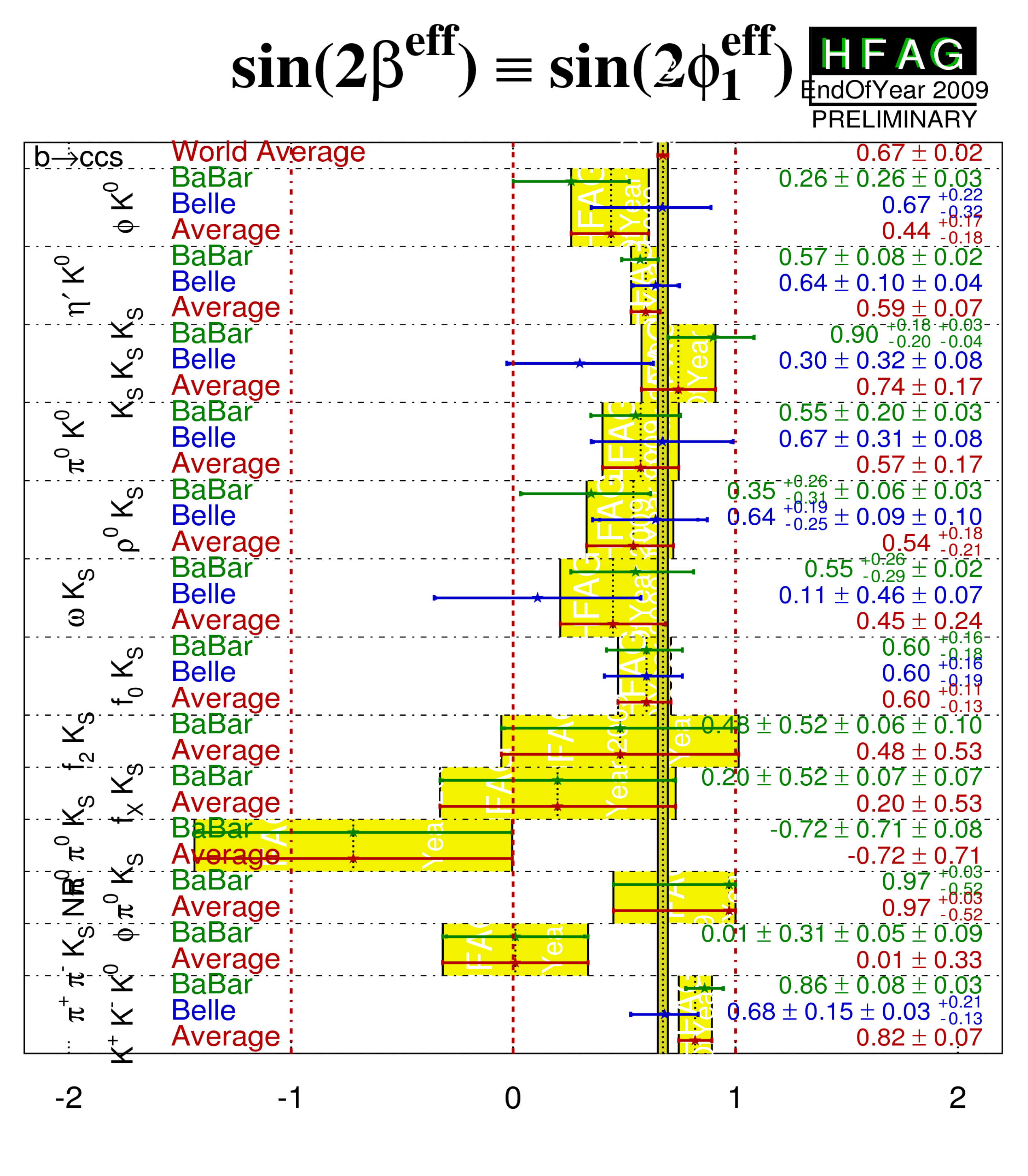
(a) t_f

(b) $p_f^{q_u}$

$\bar b \to \bar q q \bar q'$	$B^0 \to f$	$B_s \to f$	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

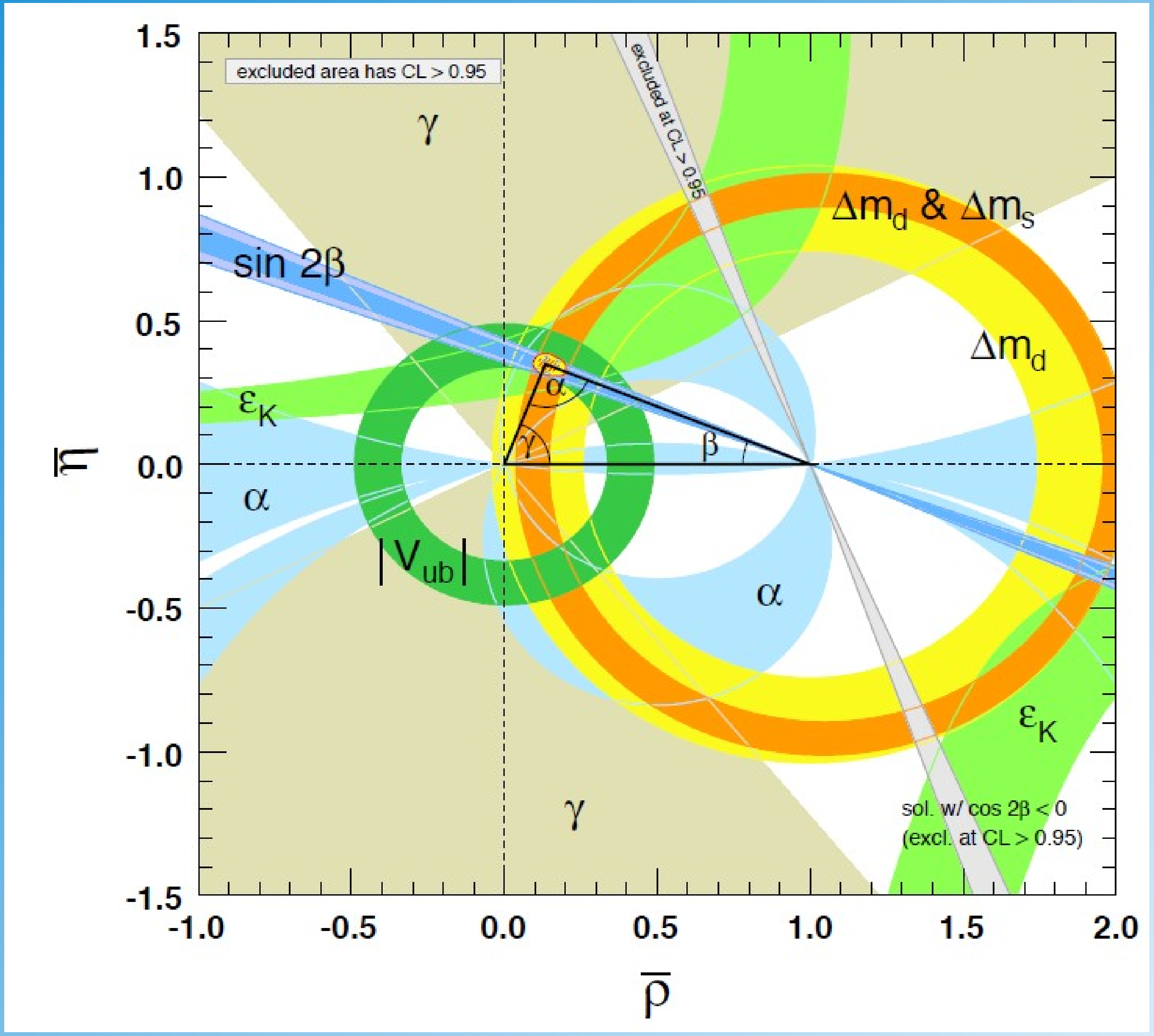
always two identical flavours

interfering diagrams



$\sin 2\beta$ 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

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

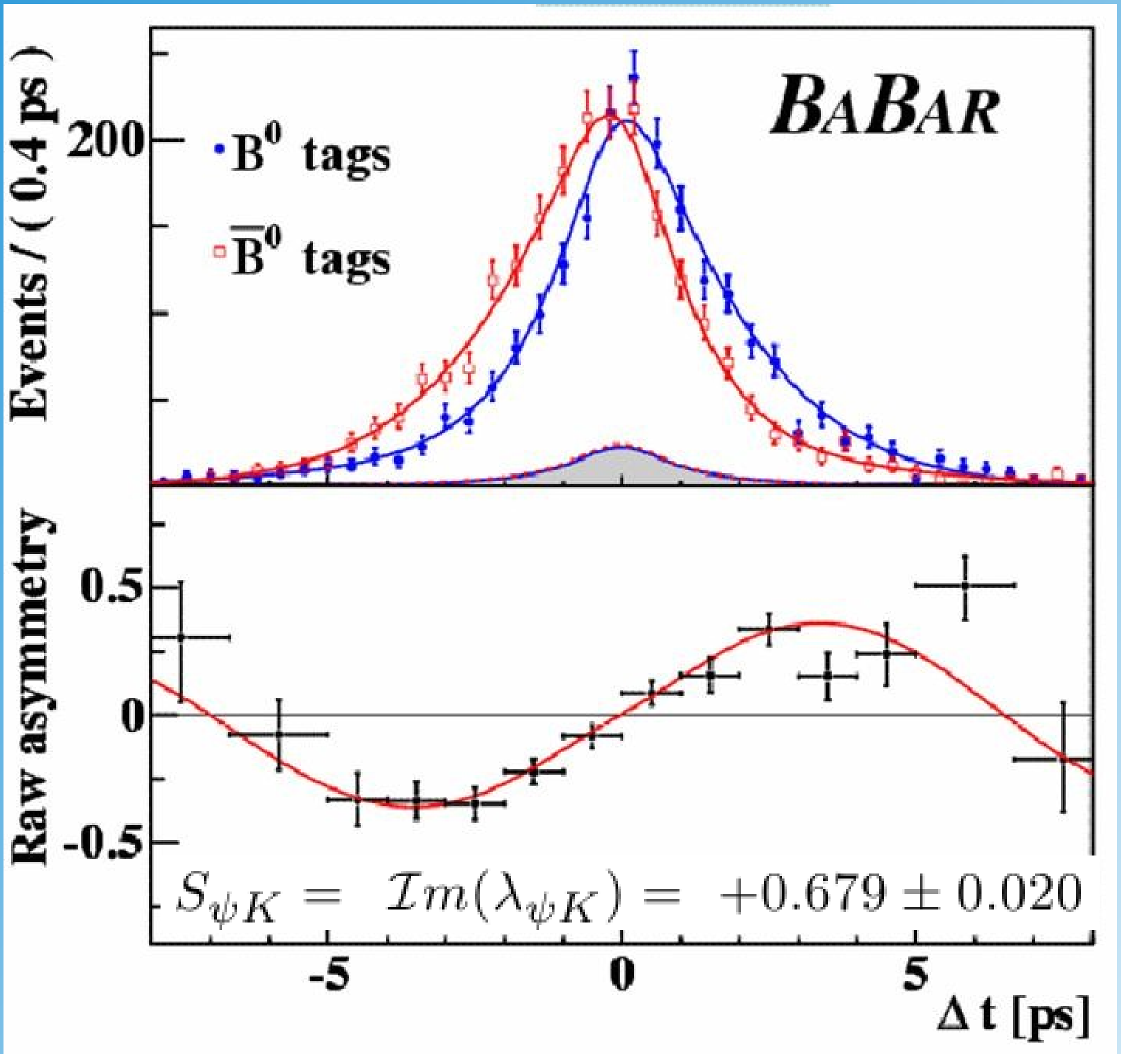
$$\mathcal{A}_{f_{CP}}(t) \equiv \frac{d\Gamma/dt\left[\overline{M}^0_{\rm phys}(t) \to f_{CP}\right] - d\Gamma/dt\left[M^0_{\rm phys}(t) \to f_{CP}\right]}{d\Gamma/dt\left[\overline{M}^0_{\rm phys}(t) \to f_{CP}\right] + d\Gamma/dt\left[M^0_{\rm phys}(t) \to f_{CP}\right]} \,.$$

asymmetry often called **S**

CP-eigenstate

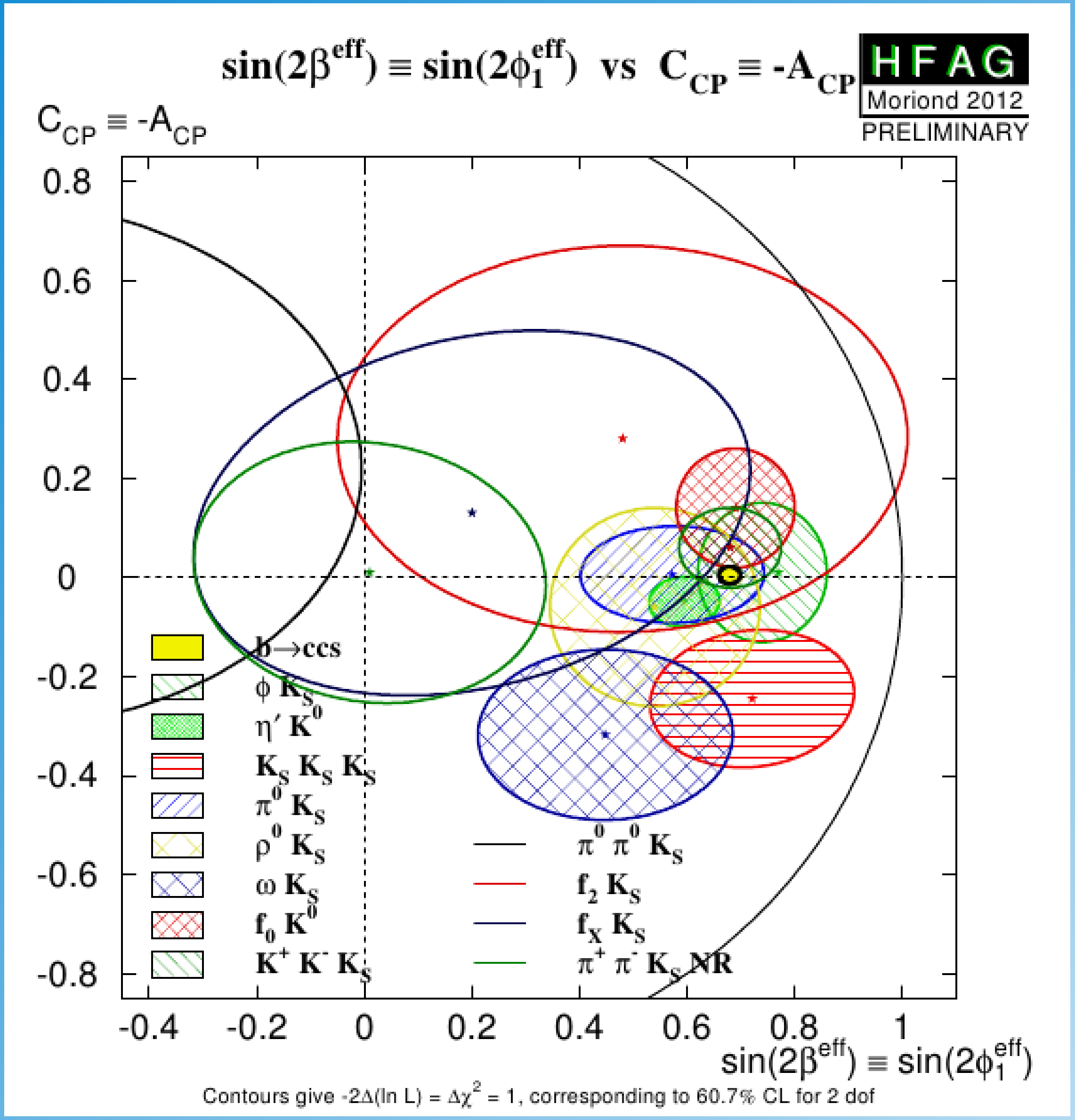
$$S_f = \frac{2\,{\rm Im}\lambda_f}{1 + |\lambda_f|^2}\,, \qquad C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}\,,$$

CP Violation in $B \to J/\psi K$



CP violating effect in B-sector is much larger than in K-sector!

Correlation "Direct versus Mixing"



large CP violation effects
in B-meson decays

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!

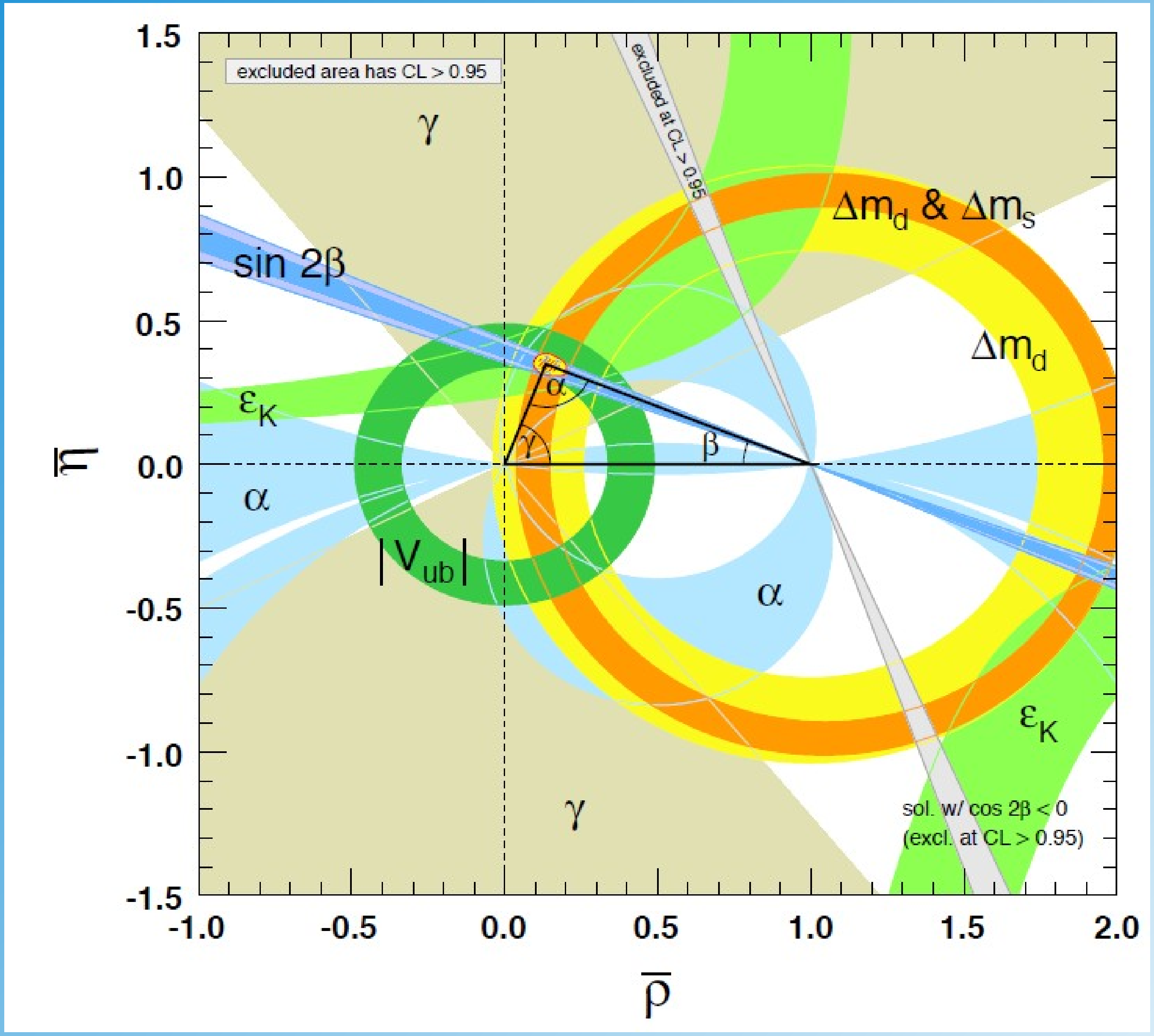
$$\mathcal{A}^d_{\rm SL} = (-3.3 \pm 3.3) \times 10^{-3} \quad \Longrightarrow \quad |q/p| = 1.0017 \pm 0.0017.$$

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

III. CP-violation in decay with and without mixing

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

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