
Good
Morning !

CP Violation and Minimal Flavour Violation

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Zakopane Lectures 2003

Lecture I

(Basics)

1. Grand View
2. TH Framework
3a. Particle-Antiparticle Mixing

Lecture II

3b. Various Types of ~~CP~~
4. Standard Analysis of Δ
5. A Note on ε'/ε

Lecture III

6. α, β, γ from B′s
7. $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$
8. Beyond the Standard Model
9. Special Topic*
10. Outlook

* Seminar

Literature

Buchalla, AJB, Lautenbacher

Rev. Mod. Phys. 68 (1996) 1125

AJB, Fleischer

in Heavy Flavours II (World Scientific) (1998) (hep-ph / 9704376)

AJB

Les Houches Lectures (1997) (hep-ph / 9806471)
Erice Lectures (2000) (hep-ph / 0101336)

Y. Nir

SLAC Summer Institute on Particle Physics (hep-ph / 9911321)
Scottish Universities Summer School (hep-ph / 0109090)

The BABAR Physics Book

B-Physics at the LHC (hep-ph / 0003238)

Books: Branco, Lavoura, Silva;
Bigi, Sanda

B Physics at the Tevatron (Run II and Beyond) (hep-ph/0201071)

Fleischer:

Physics Reports (hep-ph/0207108)

1.

Grand View

The Standard Model

Quarks

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L \qquad \begin{matrix} u_R & c_R & t_R \\ d_R & s_R & b_R \end{matrix} \qquad \begin{matrix} +2/3 \\ -1/3 \end{matrix}$$

+ Leptons

Fundamental Forces

Gauge Theory : $SU(3) \otimes SU(2)_L \otimes U(1)_Y$

$SU(3)$: QCD — Strong Interactions (Gluons)

$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{QED}$: Electroweak Interactions ($W^{\pm}$, Z^0, γ)

Mesons

$K^0 = (d\bar{s}) \quad K^+ = (u\bar{s}) \quad K^- = (\bar{u}s)$

$\pi^+ = (u\bar{d}) \quad \pi^0 = (\bar{u}u - \bar{d}d)/\sqrt{2} \quad \pi^- = (\bar{u}d)$

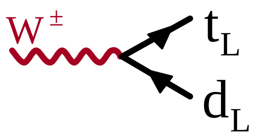
$B_d^0 = (d\bar{b}) \quad \bar{B}_d^0 = (\bar{d}b) \quad B^+ = (u\bar{b})$

$B_s^0 = (s\bar{b}) \quad \bar{B}_s^0 = (\bar{s}b) \quad B^- = (\bar{u}b)$

$q\bar{q}$ Bound States

Four Basic Properties in the SM

1. **Charged Current Interactions only between left-handed Quarks**



$$\frac{g_2}{2\sqrt{2}}\gamma_\mu(1-\gamma_5)\cdot V_{td}$$

2. **Quark Mixing**

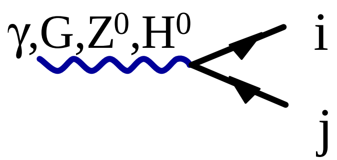
{ Weak Eigenstates } ≠ {Mass Eigenstates }

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{ub} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

(Weak Eigenstates) (Unitarity CKM-Matrix) (Mass Eigenstates)

3. **GIM Mechanism**

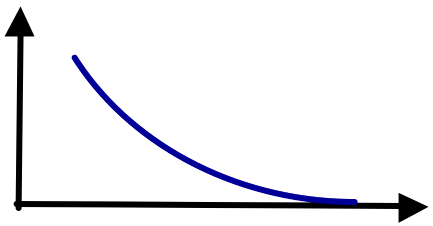
Natural suppression of FCNC

{ 

= 0 } ⇒ {Loop Induced Decays, sensitive to short distance flavour dynamics}

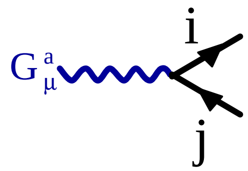
4. Asymptotic Freedom

α_{QCD}



Q

LD ⇐ RG ⇒ SD



$g_{QCD}\, T^a_{ij}\, \gamma_\mu$

$$\alpha_{QCD} = \frac{g^2_{QCD}}{4\pi}$$

$$\alpha_{QCD}(Q) = \frac{4\pi}{\beta_0 \ln\left(Q^2/\Lambda^2_{\overline{MS}}\right)}\left[1 - \frac{\beta_1}{\beta_0^2}\frac{\ln\ \ln\left(Q^2/\Lambda^2_{\overline{MS}}\right)}{\ln\left(Q^2/\Lambda^2_{\overline{MS}}\right)} + \ldots\right]$$

$\Lambda^{(5)}_{\overline{MS}} = 225 \pm 40$ MeV $\qquad \alpha^{(5)}_{\overline{MS}}(M_Z) = 0.118 \pm 0.003$

SD = Short Distances (Perturbation Theory)

⇑

RG = Renormalization Group Effects

⇓

LD = Long Distances (Non-Perturbative Physics)

CP

Kobayashi-Maskawa Picture of CP Violation

CP Violation arises from a single phase δ
in $W^{\pm}$ interactions of Quarks

ud $c_{12}c_{13}$	us $s_{12}c_{13}$	ub $s_{13}e^{-i\delta}$
cd $-s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta}$	cs $c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta}$	cb $s_{23}c_{13}$
td $s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta}$	ts $-s_{23}c_{12}-s_{12}s_{23}s_{13}e^{i\delta}$	tb $c_{23}c_{13}$

Four Parameters: $(\theta_{12} \approx \theta_{cabibbo})$

$s_{12} = |V_{us}|$, $s_{13} = |V_{ub}|$, $s_{23} = |V_{cb}|$, δ

$c_{ij} \equiv \cos\theta_{ij}$; $s_{ij} \equiv \sin\theta_{ij}$; $c_{13} \cong c_{23} \cong 1$

Wolfenstein Parametrization

Parameters: λ, A, ρ, η

	d	s	b
u	$1-\frac{\lambda^2}{2}$	λ	V_{ub}
c	$-\lambda$	$1-\frac{\lambda^2}{2}$	V_{cb}
t	V_{td}	V_{ts}	1

$\lambda=0.22$

$V_{us}=\lambda+0(\lambda^7)$

$V_{cb}=A\lambda^2+0(\lambda^8)$

$V_{ts}=-A\lambda^2+0(\lambda^4)$

$(A=0.83\pm0.02)$

$$V_{ub} \equiv A\lambda^3(\rho - i\eta) \qquad V_{td} = A\lambda^3(1-\bar{\rho}-i\bar{\eta})$$

$$\bar{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right) \qquad \bar{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

(AJB, Lautenbacher, Ostermaier, 94)

$$R_b \equiv \sqrt{\bar{\rho}^2+\bar{\eta}^2} = \left(1-\frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

Circle around $(\bar{\rho},\bar{\eta}) = (0,0)$

$$R_t \equiv \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$

Circle around $(\bar{\rho},\bar{\eta}) = (1,0)$

Particular Definition of λ, A, ρ, η

$$s_{12} \equiv \lambda$$

$$s_{23} \equiv A\,\lambda^2$$

$$s_{13}e^{i\delta} \equiv A\,\lambda^3(\rho - i\eta)$$

BLO: Phys.Rev. (94); (Schmidtler, Schubert)

At $0(\lambda^5)$ equivalent to (Branco, Lavoura, 88)

Basic Virtues of this Definition:

$$V_{us} = \lambda + 0\left(\lambda^7\right)$$

$$V_{ub} = A\lambda^3\left(\rho - i\eta\right)$$

$$V_{cb} = A\lambda^2 + 0\left(\lambda^8\right)$$

$$V_{td} = A\lambda^3\left(1 - \bar{\rho} - i\bar{\eta}\right)$$

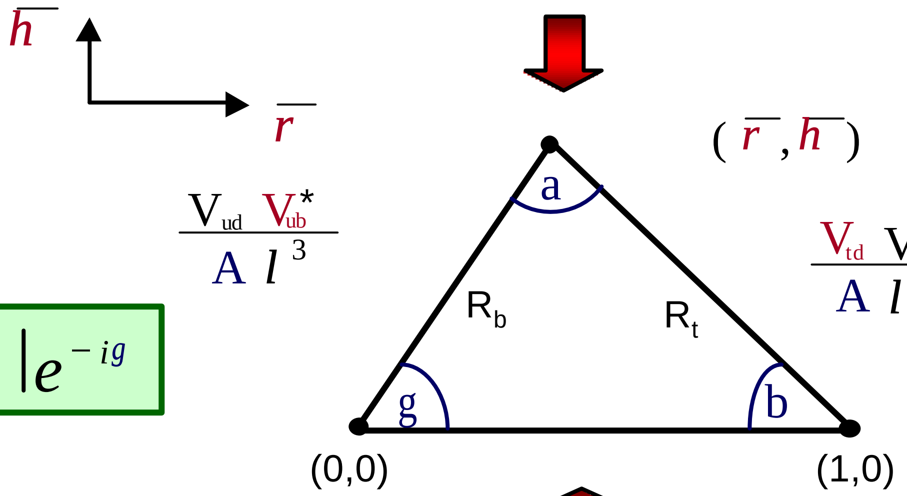
The apex of UT given by $\left(\bar{\rho}, \bar{\eta}\right)$ (BLO)

Unitarity Triangle

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

$\bar\eta \neq 0$ Signals CP Violation

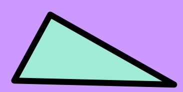
$$\frac{V_{ud} V_{ub}^*}{A \lambda^3} \qquad \frac{V_{td} V_{tb}^*}{A \lambda^3}$$



$$V_{ub} = |V_{ub}| e^{-i\gamma}$$

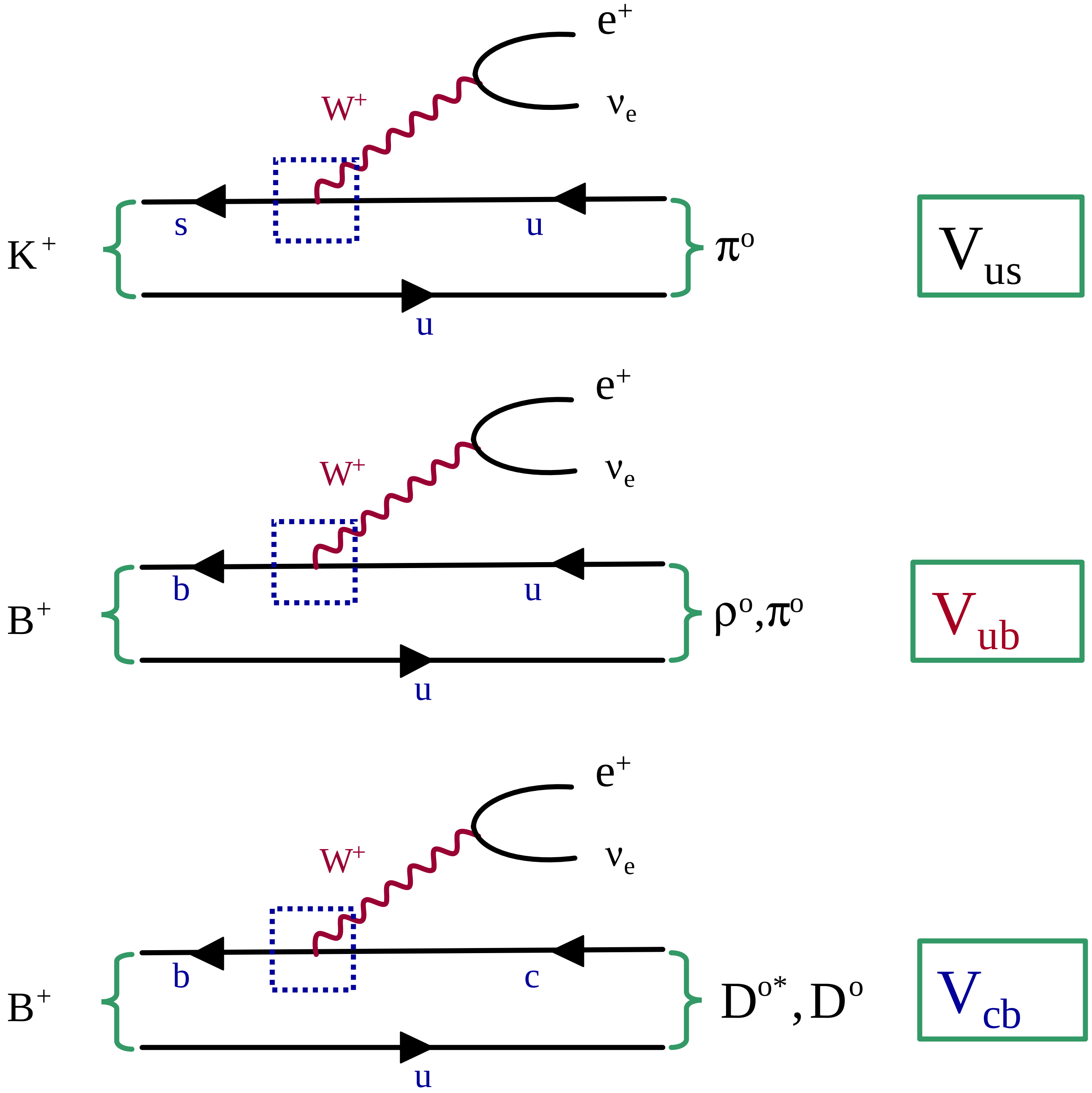
$$V_{td} = |V_{td}| e^{-i\beta}$$

An Important Target of Particle Physics

$$J_{CP} = \lambda^2 |V_{cb}|^2 \bar\eta = 2 \cdot$$ 

Area of unrescaled UT

Tree Level Decays

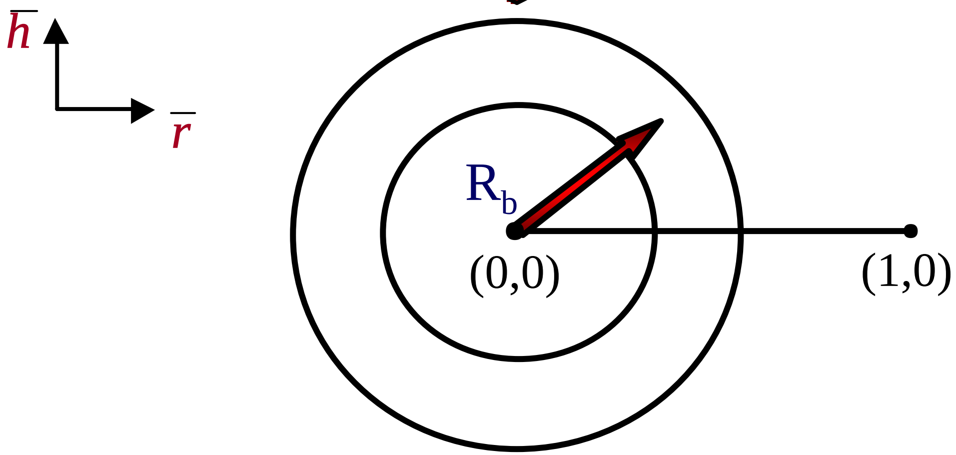


Information from Tree Level Decays

$$|V_{us}| = 0.2240 \pm 0.0036 = \lambda$$

$$|V_{cb}| = (41.5 \pm 0.8)\cdot 10^{-3} \qquad (A = 0.83 \pm 0.02)$$

$$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.086 \pm 0.008 \qquad (R_b = 0.37 \pm 0.04)$$



Apex of Unitarity Triangle somewhere on this Band

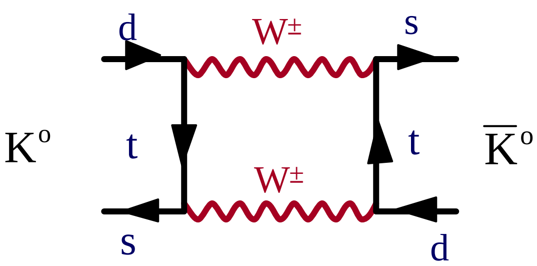
To find it **GO TO**

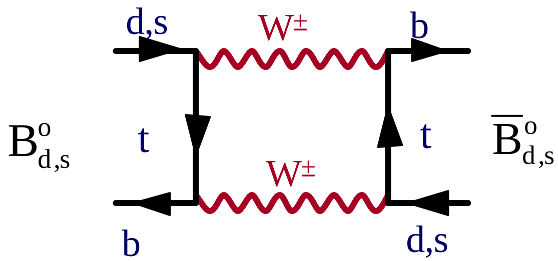
Loop Induced Decays

CP-Violation in K-Decays

CP-Violation in B-Decays

View at Short Distance Scales

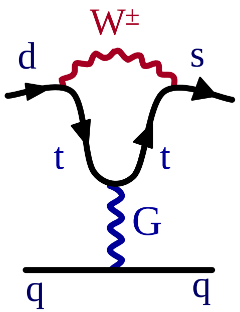


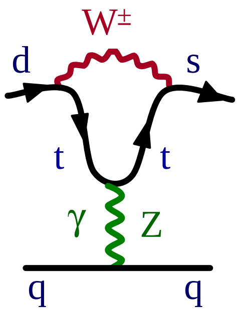


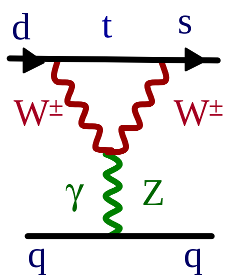
~~CP~~ ε_K-Parameter
$\Delta M\ (K_L - K_S)$

$B^o_d - \overline{B}^o_d$ Mixing

ε'

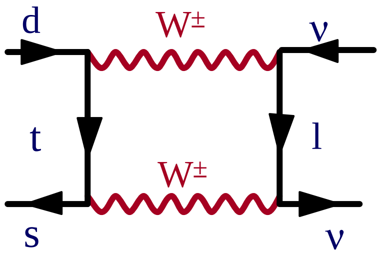


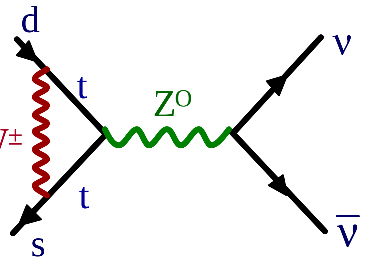


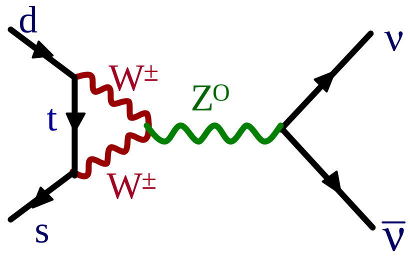


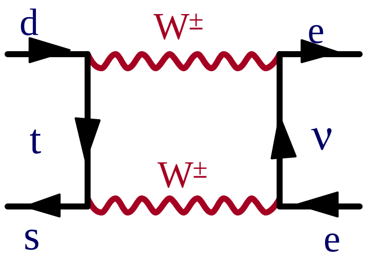
View at Short Distance Scales

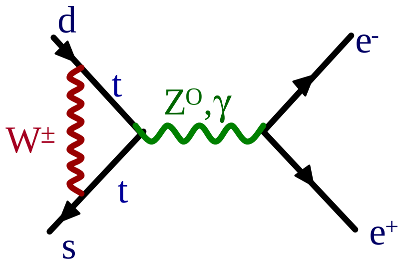
$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$ $K_L \to \mu\bar{\mu}$, $B \to \mu\bar{\mu}$, $B \to X_S \nu\bar{\nu}$

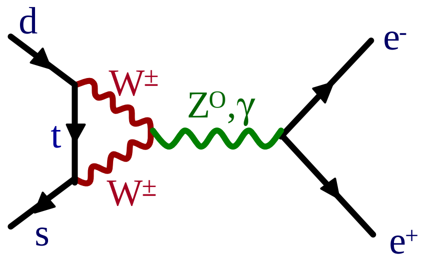




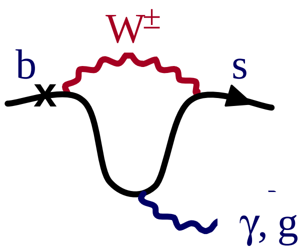








$K_L \to \pi^0 e^+ e^-$ $B \to X_S e^+ e^-$, $X_S \mu\bar{\mu}$

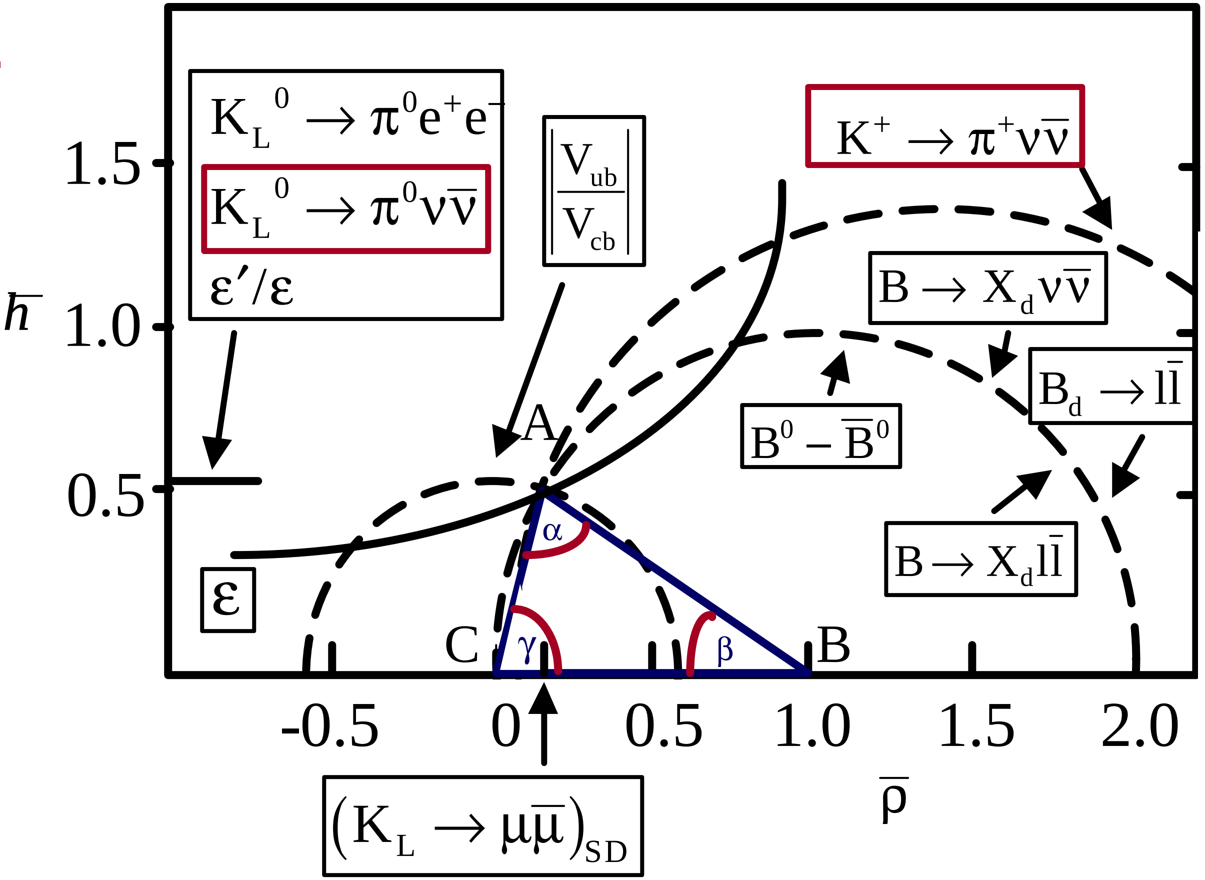


$B \to X_S \gamma$ $B \to K^* \gamma$

$B \to X_d \gamma$ $b \to s$ gluon

Hunting Δ with Rare and ~~CP~~ Decays

2011:



★ **Quark Mixing and CP Violation closely related in the St. Model**

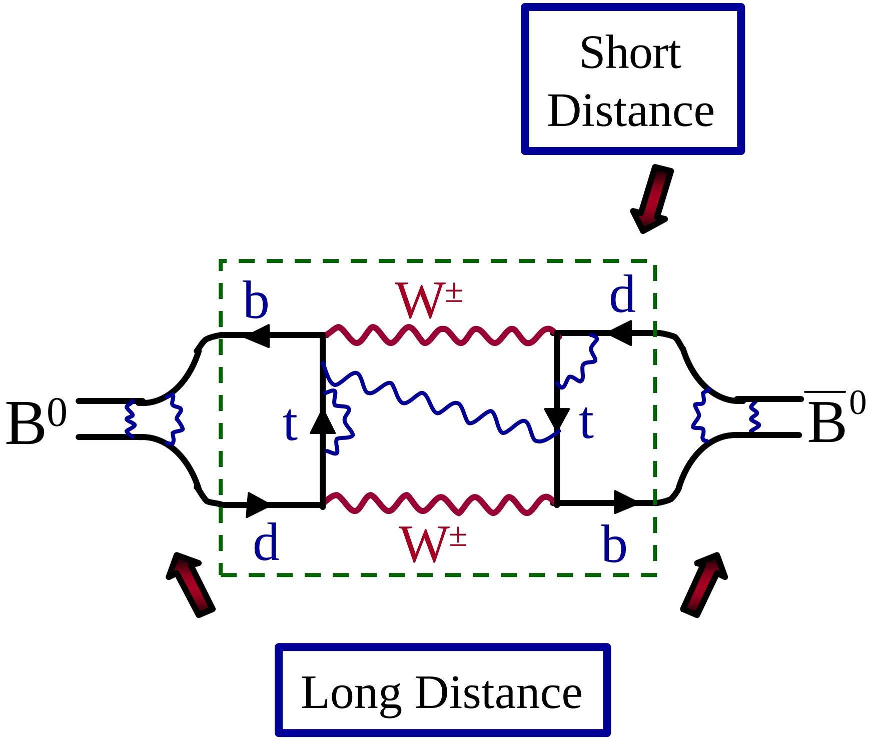
★ {CP Asymmetries in B – Decays} ➡ {α, β, γ}

2.

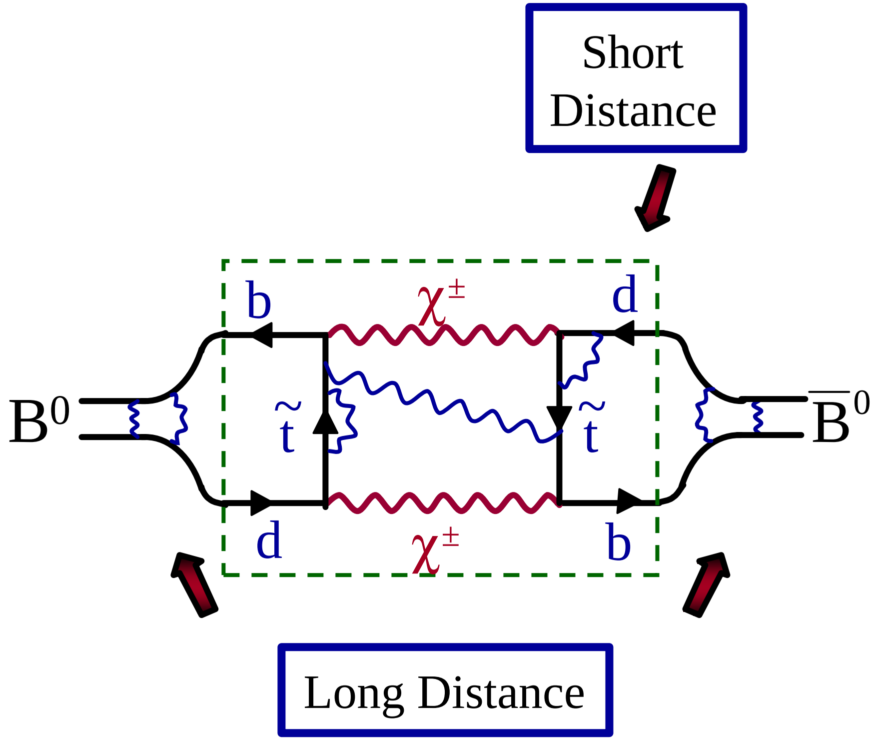
Theoretical Framework

The Problem of Strong Interactions

$B_d^0 - \overline{B}_d^0$ Mixing (SM)



$B_d^0 - \overline{B}_d^0$ Mixing (MSSM)



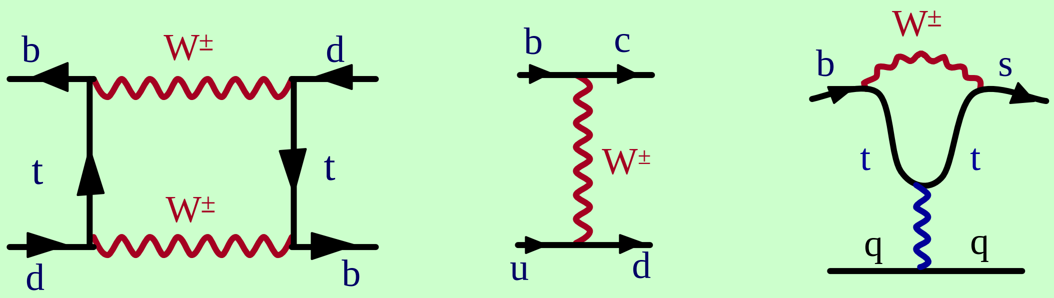
SD : Perturbative
(Asymptotic Freedom)

LD : Non-Perturbative
(Confinement)

Effective Field Theory

Full Theory

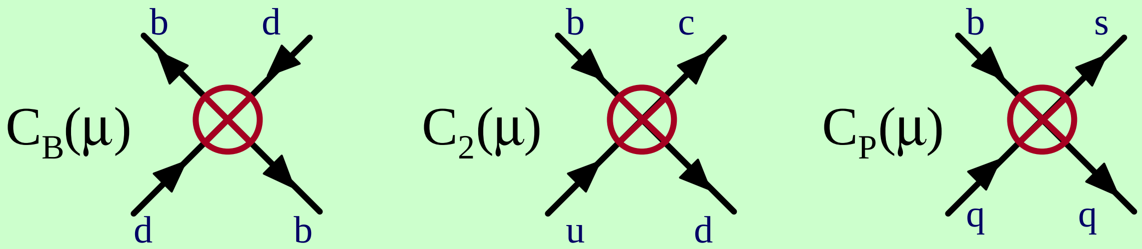
($W^{\pm}$, Z^0, G, γ, t, H^0, b, u, d, s, c, l)



$\mu \geq M_W$

Effective Theory

(G, γ, b, u, d, s, c, l)



$\mu \cong 0(m_b)$

"Generalized Fermi Theory" with calculable "couplings" $C_B(\mu)$, $C_2(\mu)$,...

Operator Product Expansion

$\left\{\begin{array}{l}\text{Wilson}\\ \text{Coefficients}\end{array}\right\}$ $\left\{\begin{array}{l}\text{Local}\\ \text{Operators}\end{array}\right\}$

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{CKM} \sum_i C_i(\mu)\, Q_i$$

Q_i ⟺

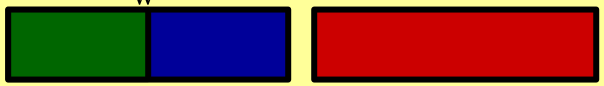
Four Quark Interaction Vertex $(\bar{s}d)_{V-A}(\bar{s}d)_{V-A}$

$C_i(\mu)$ ⟺ **Coupling Constants** $C(\mu) = \left[\frac{\alpha_s(M_W)}{\alpha_s(\mu)}\right]^{\frac{6}{23}}$

$\{K, B, D, \ldots\}$

$$A(M \to F) = \frac{G_F}{\sqrt{2}} V_{CKM} \sum_i C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

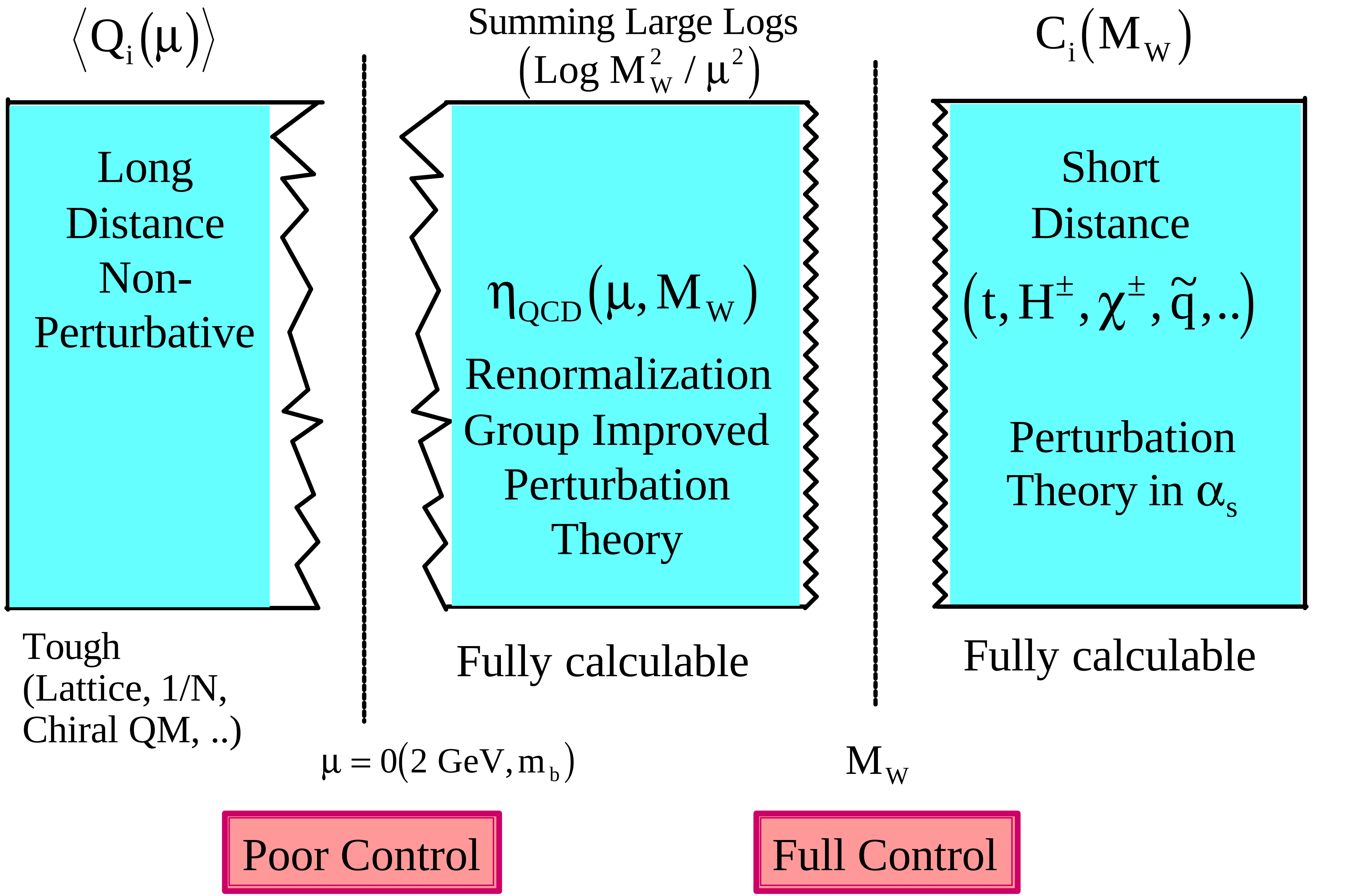
$\left\{\begin{array}{l}\pi\pi,\ \pi\nu\bar{\nu}\\ \mu\bar{\mu},\ K^*\gamma, \ldots\end{array}\right\}$



$\left\{\begin{array}{l}\text{Top}\\ \text{SUSY}\\ H^{\pm}\ldots\end{array}\right\}$ $\left\{\begin{array}{l}\text{Renormalization}\\ \text{Group}\\ \sum \alpha_s \log \frac{M_w}{\mu}\ {}^n\end{array}\right\}$ $\left\{\begin{array}{l}\text{Lattice, 1/N}\\ \text{HQET, QCDS}\\ \text{ChPTh}\end{array}\right\}$

$$\langle \bar{K}^0 | (\bar{s}d)_{V-A}(\bar{s}d)_{V-A} | K^0 \rangle = \frac{8}{3} \hat{B}_K F_K^2 m_K^2 [\alpha_s(\mu)]^{2/9}$$

Problem of Matching (Non-Leptonic Decays)



Prime Motivations for NLO Efforts

★ $\Lambda_{\overline{MS}}$ in Weak Decays

★ Reduction of μ dependences *)

(RG evolution; $\overline{m}_t(\mu_t)$, $\overline{m}_c(\mu_c)$)

★ Proper Matching to Lattice Calculations

*) Physics cannot depend on particular choice of $\mu_b,\ \mu_t,\ \mu_c$

for

$$\frac{1}{2} m_b \le \mu_b \le 2 m_b$$

$$\frac{1}{2} m_t \le \mu_t \le 2 m_t$$

$$1\ \text{GeV} \le \mu_c \le 3\ \text{GeV}$$

$C(\mu_b), \overline{m}_b(\mu_b)$

Renormalization Group Transformation

(Operator Mixing)

$$\begin{bmatrix} C_1(\mu) \\ C_2(\mu) \\ \vdots \\ C_n(\mu) \end{bmatrix} = \hat{U}(\mu, M_W) \begin{bmatrix} C_1(M_W) \\ C_2(M_W) \\ \vdots \\ C_n(M_W) \end{bmatrix}$$

Case of a single Operator

$$\mathbf{C(\mu) = U(\mu, M_W)\, C(M_W)}$$

$$U(\mu, M_W) = \left(1 + J\frac{\alpha_s(\mu)}{4\pi}\right)\left[\frac{\alpha_s(M_W)}{\alpha_s(\mu)}\right]^{\frac{\gamma^{(0)}}{2\beta_0}}\left(1 - J\frac{\alpha_s(M_W)}{4\pi}\right)$$

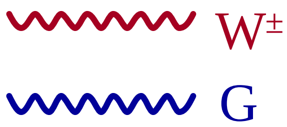
$$J = \frac{\gamma^{(0)}}{2\beta_0^2}\beta_1 - \frac{\gamma^{(1)}}{2\beta_0}$$

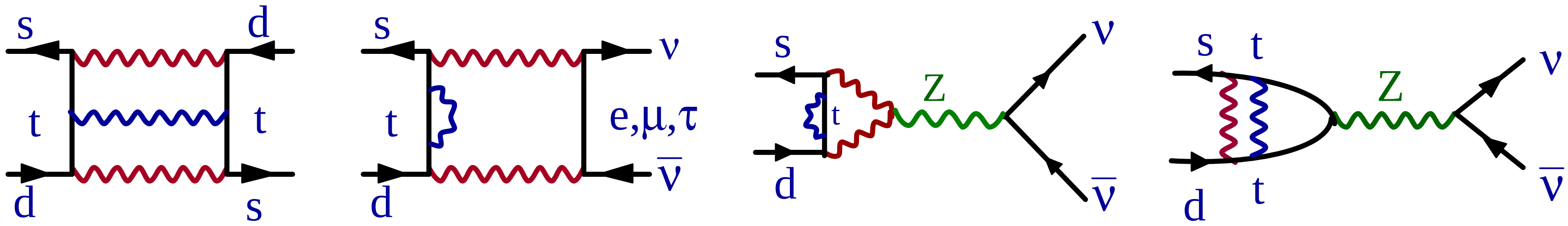
$$\gamma(\alpha_s) = \gamma^{(0)}\frac{\alpha_s}{4\pi} + \gamma^{(1)}\left(\frac{\alpha_s}{4\pi}\right)^2$$

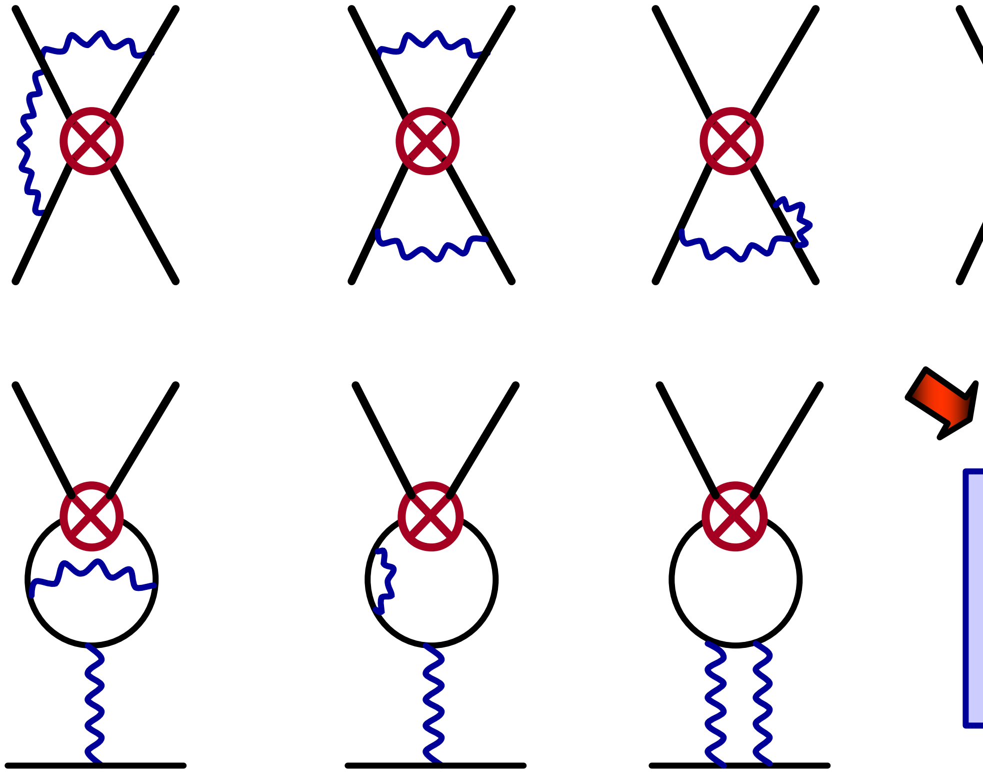
Anomalous Dimension

$$\beta(g_s) = -\beta_0\frac{g_s^{\,3}}{16\pi^2} - \beta_1\frac{g_s^{\,5}}{\left(16\pi^2\right)^2}$$

Typical Two-Loop Diagrams







Two-Loop
Anomalous
Dimensions

Status of NLO

Review: Buchalla, AJB, Lautenbacher (Rev. Mod. Phys. 96)

Decay	Authors
$\Delta F=1$ Hamiltonians (Current – Current)	Altarelli, Curci, Martinelli, Petrarca; AJB + Weisz
NLO Corrections to B_{SL}	ACMP, Buchalla; Bagan, Ball, Braun, Gosdzinsky; Lenz, Nierste, Ostermaier
ΔM (K_L-K_S)	Herrlich, Nierste (η_1)
$B^0_{d,s} - \bar{B}^0_{d,s}$ Mixing	AJB, Jamin, Weisz (η_2^B), see also Urban, Krauss, Jentschura, Soff
ε_K	AJB, Jamin, Weisz (η_2^K) Herrlich, Nierste (η_3^K)
$\Delta S=1$, $\Delta B=1$ Hamiltonians with QCD and EW Penguins ε'/ε	AJB, Jamin, Lautenbacher, Weisz Ciuchini, Franco, Martinelli, Reina
$K_L \to \pi^0 e^+ e^-$	AJB, Lautenbacher, Misiak, Münz
$B \to X_{s,d}\,\gamma$ $B \to X_{s,d}\,g$	Chetyrkin, Misiak, Münz; Greub, Hurth, Wyler; AJB, Czarnecki, Misiak, Urban; Ali, Greub; Pott; Adel, Yao; Ciuchini, Degrassi, Gambino, Giudice
$B \to X_{s,d}\, l^+ l^-$	Misiak; AJB, Münz
$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$, $B \to \mu\bar{\mu}$ $K_L \to \mu\bar{\mu}$, $B \to X_s \nu\bar{\nu}$, $K^+ \to \pi^+ \mu\bar{\mu}$	Buchalla, AJB (94) Misiak, Urban (98)
Inclusive $\Delta S=1$	Jamin, Pich

Most Recent

$(\Delta\Gamma)_{B_s^0-\bar{B}_s^0}$ $(\Delta\Gamma)_{B_d^0-\bar{B}_d^0}$	Beneke, Buchalla, Greub, Lenz, Nierste
Two Loop $\hat{\gamma}$ for "New" $\Delta F=2$ Operators	Ciuchini, Franco, Lubicz, Martinelli, Scimeni, Silvestrini; AJB, Misiak, Urban
Charmonium Decays	Beneke, Maltoni, Rothstein
SUSY $B\to X_s\gamma$	Ciuchini, Degrassi, Gambino; Bobeth, Misiak, Urban; Giudice
SUSY $B_d^0-\bar{B}_d^0$, ε_K	Ciuchini, Lubicz, Conti, Vladikas; Donini, Franco, Martinelli, Scimeni; Gimenz, Giusti, Masiero, Silvestrini; Talevi
2 HDM $B\to X_s\gamma$	Ciuchini, Degrassi, Gambino, Giudice; Ciafaloni, Romanino; Strumia; Borzumati, Strumia
$B\to D\pi$, $B\to\pi\pi$	Beneke, Buchalla, Neubert, Sachrajda
SUSY $B\to X_s l^+l^-$	Bobeth, Misiak, Urban, Ewerth
SUSY $K\to\pi\nu\bar{\nu}$, $K_L\to\mu\bar{\mu}$ $B\to X_s\nu\bar{\nu}$, $B\to\mu\bar{\mu}$	Bobeth, AJB, Krüger, Urban

Master Formula for Weak Decays

Non-Perturbative Factors in the SM

QCD RG Factors

Short Distance Loop Functions (Penguins, Boxes)

New Flavour-Changing Parameters

Represent different Dirac and Colour Stuctures

$$A(\text{Decay}) = B_i \, \eta^i_{QCD} \, V^i_{CKM} \left[F^i_{SM} + F^i_{New} \right] + B_i^{New} \left[\eta^i_{QCD} \right]^{New} V^i_{New} \left[G^i_{New} \right]$$

Non-Perturbative Factors beyond SM

Short Distance Loop Functions Penguins, Boxes)

$F^i_{SM}, \; F^i_{New}, \; G^i_{New}$: **Fully calculable in Perturbation Theory**

$\eta^i_{QCD}, \; \left[\eta^i_{QCD} \right]^{New}$: **Fully calculable in RG improved Perturbation Theory**

$B_i, \; B_i^{New}$: **Require Non-Perturbative Methods or can be extracted from leading decays**

$\left(\text{represent } \langle Q_i \rangle\right)$

Possible Dirac Structures in $K^0 - \bar{K}^0$ and $B^0_{d,s} - \bar{B}^0_{d,s}$

SM:

$$\gamma_\mu (1-\gamma_5) \otimes \gamma^\mu (1-\gamma_5)$$

Beyond SM:

$$\gamma_\mu (1-\gamma_5) \otimes \gamma^\mu (1+\gamma_5)$$

$$(1-\gamma_5) \otimes (1+\gamma_5)$$

$$(1-\gamma_5) \otimes (1-\gamma_5)$$

$$\sigma_{\mu\nu} (1-\gamma_5) \otimes \sigma^{\mu\nu} (1-\gamma_5)$$

MSSM with large $\tan\beta$

General Supersymmetric Models

Models with complicated Higgs System

NLO $\left[\eta^i_{QCD}\right]^{New}$: Ciuchini, Franco, Lubicz, Martinelli, Scimemi, Silvestrini

AJB, Misiak, Urban, Jäger

General Structure in Models with Minimal Flavour Violation

Ciuchini, Degrassi, Gambino, Giudice;
AJB, Gambino, Gorbahn, Jäger, Silvestrini;

- **No new Operators** (Dirac and Colour Structures) beyond those present in the SM
- Flavour Changing Transitions governed by CKM. **No new complex phases** beyond those present in the SM

$$A(\text{Decay}) = B_i\, \eta^i_{QCD}\, V^i_{CKM} \Big[\underbrace{F^i_{SM} + F^i_{New}}_{\text{real}} \Big]$$

Examples: SM

MSSM at not too large $\tan\beta = \frac{v_2}{v_1}$

Main Targets of $\not{CP}$

Useful for CKM and $\triangle$

(Rather clean)

Standard Analysis of $\triangle$

$$\varepsilon_K,\ |V_{ub}/V_{cb}|,\ \Delta M_d(B_d^0-\overline{B}_d^0),\ \Delta M_s(B_s^0-\overline{B}_s^0)$$

(Mixture of K- and B-Physics)

CP-Violation in Rare K-Decays

$K_L \to \pi^0\nu\bar{\nu}$ $(K^+ \to \pi^+\nu\bar{\nu})$

$(K_L \to \pi^0 e^+ e^-)$

($\sin 2\beta$)
(η)
($|V_{td}|$)

CP-Violation in B-Decays
(Asymmetries and other Strategies)

(α,β,γ)

Important Tests of $\not{CP}$, $\not{T}$:
ε'/ε, Electric Dipole Moments
$\not{CP}$ in Hyperon Decays
$\not{CP}$ in D-Decays

Large
Hadronic
Uncertainties

3.

Particle Mixing and Various Types of CP Violation

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

$K^0 = d\bar{s}$

$\overline{K}^0 = \bar{d}s$

$\left\{ CP\left|K^0\right\rangle = -\left|\overline{K}^0\right\rangle \right\}$

Due to $K^0 - \overline{K}^0$ Mixing

(discovered: 1960)

K^0 and $\overline{K}^0$ <u>are not Mass Eigenstates</u>

<u>Mass Eigenstates</u>: (when CP conserved)

$$K_1 = \frac{K^0 - \overline{K}^0}{\sqrt{2}}$$ CP = +1 (K_S) S = Short

$$K_2 = \frac{K^0 + \overline{K}^0}{\sqrt{2}}$$ CP = -1 (K_L) L = Long

$$M(K_L) - M(K_S) = 3.5 \cdot 10^{-15}\,\mathrm{GeV}$$

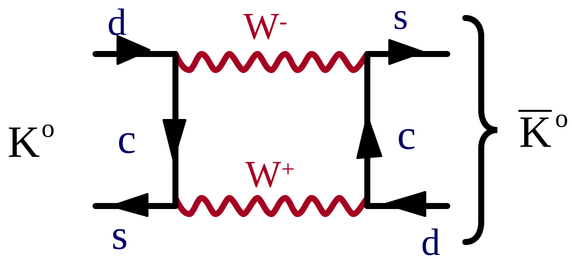
$$\frac{\tau(K_L)}{\tau(K_S)} \approx 600$$

$$\overset{(+)}{K}_1 \to \pi^+\pi^-, \pi^0\pi^0 \qquad (CP = +1)$$

$$\overset{(-)}{K}_2 \to \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0 \qquad (CP = -1)$$

$$\not\to \pi^+\pi^-, \pi^0\pi^0 \qquad \text{(forbidden if CP conserved)}$$

Gaillard - Lee (1974)



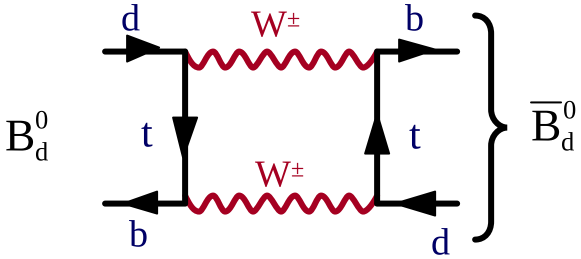
(c = charm)

$$\Delta M \cong 5.\left[\frac{m_c^2}{M_w^2}\right]10^{-12}\,\text{GeV}$$

($M_w \cong 80$ GeV)

$(\Delta M)_{Exp} \approx 3.5 \cdot 10^{-15}\,\text{GeV}$ → $m_c \approx 2$ GeV Prediction

$B_d^0 - \overline{B}_d^0$ Mixing



$$B_H = pB^0 + q\overline{B}^0$$
$$B_L = pB^0 - q\overline{B}^0$$

$B_d^0 = (\overline{b}d) \qquad \overline{B}_d^0 = (b\overline{d})$

<u>Mass Eigenstates:</u>

$(\Delta M)_B \equiv M_{B_H} - M_{B_L}$

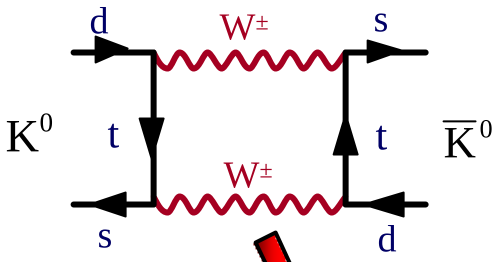
$$(\Delta M)_B = \begin{cases} (4.2 \pm 0.8) \cdot 10^{-13}\,\text{GeV} & \text{(DESY, 87)} \\ (3.1 \pm 0.1) \cdot 10^{-13}\,\text{GeV} & \text{(CERN, 97 Cornell)} \end{cases}$$

$\{(\Delta M)_B \approx 100 (\Delta M)_K\}$ → {Top Quark has to be heavy}

Indirect and Direct $\not{CP}$ in $K_L \to \pi\pi$

$$K_{1,2} = \frac{K^0 \mp \overline{K}^0}{\sqrt{2}}$$

$$CP\left|K^0\right\rangle = -\left|\overline{K}^0\right\rangle$$



$(K^0 - \overline{K}^0\ \text{Mixing})$

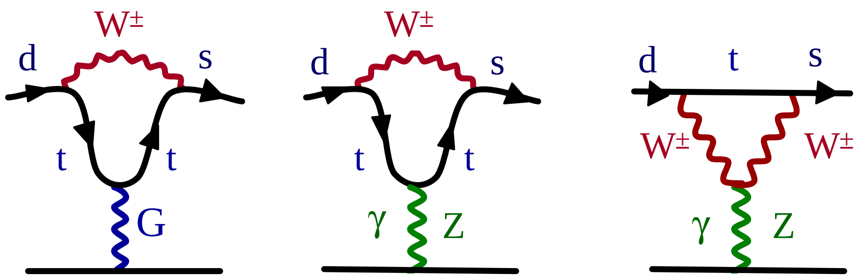
Mass Eigenstates are not CP Eigenstates

indirect CP violation (ε)

CP (+)

$$K_L = \overset{(-)}{K_2} + \varepsilon \overset{(+)}{K_1} \xrightarrow{\varepsilon} \overbrace{\pi^+\pi^-,\ \pi^0\pi^0}^{CP\,(+)}$$

direct CP-Violation (ε´)



$$\eta_{+-} \equiv \frac{A\left(K_L \to \pi^+\pi^-\right)}{A\left(K_S \to \pi^+\pi^-\right)} = \varepsilon + \varepsilon'$$

$$\eta_{00} \equiv \frac{A\left(K_L \to \pi^0\pi^0\right)}{A\left(K_S \to \pi^0\pi^0\right)} = \varepsilon - 2\varepsilon'$$

ε′=0 in Superweak Models
Wolfenstein (64)

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \frac{1}{6}\left(1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right)$$

February 2003

$$\Delta M_K = (0.5301 \pm 0.0016) \cdot 10^{-2} / \mathrm{ps}$$

$$\Delta M_d = (0.503 \pm 0.006) / \mathrm{ps}$$

$$\Delta M_s > 14.4 / \mathrm{ps} \quad (95\% \text{ C.L.})$$

$$1/\mathrm{ps} = 6.582 \cdot 10^{-13}\,\mathrm{GeV}$$

$$\varepsilon = (2.280 \pm 0.013) \cdot 10^{-3} e^{i\pi/4}$$

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (16.6 \pm 1.6) \cdot 10^{-4}$$

Express Review of $K^0 - \overline{K}^0$ Mixing

Flavour Eigenstates

$$K^0 = (\overline{s}d)$$

$$\overline{K}^0 = (s\overline{d})$$

$$CP|K^0\rangle = -|\overline{K}^0\rangle$$

$$CP|\overline{K}^0\rangle = -|K^0\rangle$$

In the absence of $K^0 - \overline{K}^0$ Mixing:

$$|K^0(t)\rangle = |K^0(0)\rangle \exp[-i\,Ht]$$

$$|\overline{K}^0(t)\rangle = |\overline{K}^0(0)\rangle \exp[-i\,Ht]$$

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

(M: Mass; Γ: Width)

Time Evolution in the Presence of Mixing

$$i\frac{d\psi(t)}{dt} = \hat{H}\,\psi(t) \qquad \psi(t) = \begin{pmatrix} |K^0(t)\rangle \\ |\overline{K}^0(t)\rangle \end{pmatrix}$$

Hermitian Matrices with positive (real) eigenvalues ($\hat{M}$, $\hat{\Gamma}$)

$$\hat{H} = \hat{M} - i\frac{\hat{\Gamma}}{2} = \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{21} - i\frac{\Gamma_{21}}{2} & M_{22} - i\frac{\Gamma_{22}}{2} \end{pmatrix}$$

M_{ij}-transition with virtual intermediate states

Γ_{ij}- transition with physical intermediate states

Diagonalization

Eigenstates

$$K_S = \frac{K_1 + \bar{\varepsilon} K_2}{\sqrt{1+|\bar{\varepsilon}|^2}} \qquad K_L = \frac{K_2 + \bar{\varepsilon} K_1}{\sqrt{1+|\bar{\varepsilon}|^2}}$$

$$K_1 = \frac{K^0 - \bar{K}^0}{\sqrt{2}} \qquad CP|K_1\rangle = |K_1\rangle \qquad CP = +$$

$$K_2 = \frac{K^0 + \bar{K}^0}{\sqrt{2}} \qquad CP|K_2\rangle = -|K_2\rangle \qquad CP = -$$

★ Mass Eigenstates are not CP-Eigenstates

$$\bar{\varepsilon} = \frac{i}{1+i}\frac{\operatorname{Im} M_{12}}{\Delta M} + \frac{\xi}{1+i} \qquad \xi = \frac{\operatorname{Im} A_0}{\operatorname{Re} A_0}$$

Eigenvalues

$$\Delta M = M_L - M_S = 2 \operatorname{Re} M_{12}$$

$$\Delta\Gamma = \Gamma_L - \Gamma_S = 2 \operatorname{Re} \Gamma_{12}$$

$$\Delta\Gamma \approx -2\Delta M$$

ε and ε' in $K_L \to \pi\pi$

- **Isospin Decomposition :** $K \to (\pi\pi)_I$

$$A\left(K^+ \to \pi^+\pi^0\right) = \sqrt{\frac{3}{2}} A_2 e^{i\delta_2}$$

$$A\left(K^0 \to \pi^+\pi^-\right) = \sqrt{\frac{2}{3}} A_0 e^{i\delta_0} + \sqrt{\frac{1}{3}} A_2 e^{i\delta_2}$$

$$A\left(K^0 \to \pi^0\pi^0\right) = \sqrt{\frac{2}{3}} A_0 e^{i\delta_0} - 2\sqrt{\frac{1}{3}} A_2 e^{i\delta_2}$$

A_I = Isospin Amplitudes (contain weak phases)
δ_I = Strong Phases

$$\mathrm{Re}\, A_0 = 3.33 \cdot 10^{-7}\, \mathrm{GeV}$$

$$\frac{\mathrm{Re}\, A_0}{\mathrm{Re}\, A_2} \approx 22 \qquad \left(\Delta I = 1/2 \text{ Rule}\right)$$

$$\delta_0 \approx 37^0 \pm 3^0 \qquad \delta_2 \approx -7^0 \pm 1^0 \qquad \delta_0 - \delta_2 \approx \pi/4$$

Basic Definitions of ε and ε′

Denote:

$$A_{I,L} \equiv A\left(K_L \to (\pi\pi)_I\right)$$

$$A_{I,S} \equiv A\left(K_S \to (\pi\pi)_I\right)$$

$$\varepsilon \equiv \frac{A_{0,L}}{A_{0,S}}$$ (I=0 only)

$$\varepsilon' \equiv \frac{1}{\sqrt{2}}\left(\frac{A_{2,L}}{A_{0,S}} - \frac{A_{2,S}}{A_{0,S}}\frac{A_{0,L}}{A_{0,S}}\right)$$ (I=0,2)

$$\varepsilon = \bar{\varepsilon} + i\xi \qquad \xi = \frac{\operatorname{Im} A_0}{\operatorname{Re} A_0}$$

$$\varepsilon' = \frac{1}{\sqrt{2}} \operatorname{Im}\left(\frac{A_2}{A_0}\right) \exp\left(i\Phi_{\varepsilon'}\right)$$

$$\Phi_{\varepsilon'} = \frac{\pi}{2} + \delta_2 - \delta_0 \approx \frac{\pi}{4}$$

◆ Basic Formulae for ε and ε′

$$\varepsilon = \frac{\exp\left[i\frac{\pi}{4}\right]}{\sqrt{2}\Delta M_K}\left[\mathrm{Im}\, M_{12} + 2\xi\, \mathrm{Re}\, M_{12}\right]$$

Phase convention independent

Phase convention dependent

$$\mathrm{Re}\,\varepsilon = \mathrm{Re}(\bar{\varepsilon}) \qquad \xi = \frac{\mathrm{Im}\, A_0}{\mathrm{Re}\, A_0}$$

$$\varepsilon' = \frac{\exp\left[i\frac{\pi}{4}\right]}{\sqrt{2}}\left[\frac{\mathrm{Im}\, A_2}{\mathrm{Re}\, A_0} - \omega\frac{\mathrm{Im}\, A_0}{\mathrm{Re}\, A_0}\right]$$

Phase convention independent

Phase convention dependent

$$\omega = \frac{\mathrm{Re}\, A_2}{\mathrm{Re}\, A_0} \cong \frac{1}{22}$$

The second term ~ 2%
(can be neglected)

$\mathrm{Im}\, A_0$ - dominated by QCD-Penguins

$\mathrm{Im}\, A_2$ - dominated by Electroweak Penguins

CP Violation in Mixing

$$\overline{K}^0 \to K^0 \to \pi^- l^+ \nu$$

(Phase Difference)

$$K^0 \to \overline{K}^0 \to \pi^+ l^- \overline{\nu}$$

"wrong charge" leptons

$$a_{SL} = \frac{\Gamma(K_L \to \pi^- l^+ \nu) - \Gamma(K_L \to \pi^+ l^- \overline{\nu})}{\Gamma(K_L \to \pi^- l^+ \nu) + \Gamma(K_L \to \pi^+ l^- \overline{\nu})}$$

$$a_{SL} = \frac{1-r^2}{1+r^2} = 2\,\mathrm{Re}\,\overline{\varepsilon} = \mathrm{Im}\frac{\Gamma_{12}}{M_{12}}$$

$$r \approx 1 - \mathrm{Im}\frac{\Gamma_{12}}{M_{12}}$$

(for $K^0 - \overline{K}^0$ system)

Note a_{SL} measures the difference between the phases of Γ_{12} and M_{12}

$\left\{ a_{SL} \neq 0 \text{ Signal of } ~~CP~~ \right\} \equiv \left\{ K_L, \text{ which should be a CP eigenstate for conserved CP, decays into CP conjugate final states with different rates} \right\}$

Express Review of B^0-$\bar{B}^0$ Mixing

- **Flavour Eigenstates**

$$B_d^0 = (\bar{b}d)$$

$$\bar{B}_d^0 = (b\bar{d})$$

$$B_s^0 = (\bar{b}s)$$

$$\bar{B}_s^0 = (b\bar{s})$$

- **Mass Eigenstates**

$$B_{H,L} = p\,B^0 \pm q\,\bar{B}^0$$

$$p = \frac{(1+\bar{\varepsilon}_B)}{\sqrt{2(1+|\bar{\varepsilon}_B|^2)}} \qquad q = \frac{(1-\bar{\varepsilon}_B)}{\sqrt{2(1+|\bar{\varepsilon}_B|^2)}}$$

$$\frac{q}{p} = \frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta M - i\frac{\Delta\Gamma}{2}}$$

$$\Delta M = M(B_H) - M(B_L)$$

$$\Delta\Gamma = \Gamma(B_H) - \Gamma(B_L)$$

All exact formulae from $K^0 - \bar{K}^0$ system apply but now:

$$|M_{12}| >> |\Gamma_{12}|$$

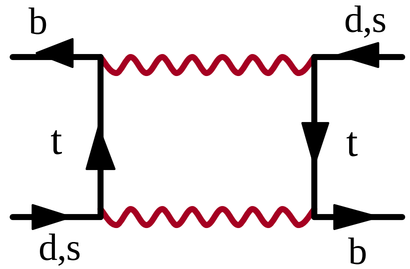
Master Formulae $(B^0\text{-}\bar{B}^0)$

$$\Delta M = 2\left|M_{12}\right|$$

$$\Delta\Gamma = 2\frac{\mathrm{Re}\left(M_{12}\Gamma_{12}^*\right)}{\left|M_{12}\right|}$$

$$\frac{q}{p} \cong \frac{M_{12}^*}{\left|M_{12}\right|}\left[1-\frac{1}{2}\mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)\right]$$

$$M_{12}^* = \left\langle \overline{B}^0 \middle| H_{eff} \middle| B^0 \right\rangle \approx$$



$$\left(M_{12}^*\right)_d \sim \left(V_{td}V_{tb}^*\right)^2 \qquad \left(M_{12}^*\right)_s \sim \left(V_{ts}V_{tb}^*\right)^2$$

$$V_{td} = \left|V_{td}\right|e^{-i\beta} \qquad V_{ts} = \left|V_{ts}\right|e^{-i\beta_s} \qquad \left(\beta_s \cong 0\right)$$

$$\frac{q}{p} \cong e^{i2\varphi_M} \qquad \varphi_M = \begin{cases} -\beta & B_d^0 - \overline{B}_d^0 \\ -\beta_s & B_s^0 - \overline{B}_s^0 \end{cases}$$

(Pure Phase)

The Route to ΔM_d

- Box Diagrams with internal top

$$H_{eff}^{(\Delta B=2)} = \frac{G_F^2}{16\pi^2} M_W^2 \left(V_{tb}^* V_{td}\right)^2 \eta_B S(x_t) \cdot \alpha_s(\mu_b)^{-6/23} \left[1 + \frac{\alpha_s(\mu_b)}{4\pi} J\right] Q(\Delta B = 2)$$

$$Q(\Delta B = 2) = \left(\bar{b}d\right)_{V-A} \left(\bar{b}d\right)_{V-A}$$

$$S(x_t) = 0.78\, x_t^{0.76} \qquad \eta_B = 0.55 \pm 0.01 \qquad \text{(AJB, Jamin, Weisz)}$$

- Define the RG-invariant B_d

$$\hat{B}_d \equiv B_d(\mu_b)\left[\alpha_s(\mu_b)\right]^{-6/23} \left[1 + \frac{\alpha_s(\mu_b)}{4\pi} J\right]$$

$$\left\langle \bar{B}_d^0 \middle| Q(\Delta B = 2) \middle| B_d^0 \right\rangle \equiv \frac{8}{3} B_d(\mu_b) F_{B_d}^2 m_B^2$$

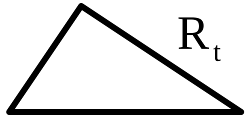
$$x_t = \frac{m_t^2}{M_w^2}$$

- Use:

$$\Delta M_d = \frac{1}{m_B} \left| \left\langle \bar{B}_d^0 \middle| H_{eff}^{(\Delta B=2)} \middle| B_d^0 \right\rangle \right|$$

$$\Delta M_d = \frac{G_F^2}{6\pi^2} m_b M_W^2 \underbrace{\left(\hat{B}_d F_{B_d}^2\right)}_{\text{Independent of } \mu_b} \underbrace{\eta_B S(x_t)}_{\text{Independent of } \mu_b \text{ and } \mu_t \text{ in } \overline{m}_t(\mu_t)} \left|V_{td}\right|^2$$

$(\Delta M)_{d,s}$, $|V_{td}|/|V_{ts}|$ and R_t



$$(\Delta M)_d = \frac{0.50}{ps}\left[\frac{\sqrt{\hat{B}_d}F_{Bd}}{230MeV}\right]^2\left[\frac{|V_{td}|}{7.8\cdot10^{-3}}\right]^2\left[\frac{\eta_B}{0.55}\right]\left[\frac{S(x_t)}{2.34}\right]$$

$$(\Delta M)_s = \frac{18.4}{ps}\left[\frac{\sqrt{\hat{B}_s}F_{Bs}}{270MeV}\right]^2\left[\frac{|V_{ts}|}{0.040}\right]^2\left[\frac{\eta_B}{0.55}\right]\left[\frac{S(x_t)}{2.34}\right]$$

$$S(x_t) = 2.39 \pm 0.12$$

$$\eta_B = 0.55 \pm 0.01$$

AJB, Jamin, Weisz

$$|V_{td}| = \lambda|V_{cb}|R_t$$

$$|V_{ts}| = |V_{cb}|\left(1-\frac{\lambda^2}{2}+\bar{\rho}\lambda^2\right)$$

$$\xi = \frac{\sqrt{\hat{B}_s}F_{B_s}}{\sqrt{\hat{B}_d}F_{B_d}} = 1.22 \pm 0.07$$

$$\frac{|V_{td}|}{|V_{ts}|} = 1.01\,\xi\sqrt{\frac{\Delta M_d}{\Delta M_s}}$$

$$R_t = 0.90\sqrt{\frac{\Delta M_d}{0.50/ps}}\sqrt{\frac{18.4/ps}{\Delta M_s}}\left[\frac{\xi}{1.22}\right]$$

Modern Classification of CP Violation

We have:

Particle-Antiparticle Mixing

and

Decay

1. CP Violation in Mixing
2. CP Violation in Decay
3. CP Violation in the Interference of Mixing and Decay

Classification of ~~CP~~ in B- and K-Decays

(Nir 99),...

1. CP Violation in Mixing

$$B_{H,L} = p\left|B^0\right\rangle \pm q\left|\overline{B}^0\right\rangle$$

Mass Eigenstates

(Not CP Eigenstates)

$$\not{CP}: \quad |q/p| \neq 1$$

$$a_{SL} = \frac{\Gamma\left(\overline{B}^0(t) \to l^+ \nu X\right) - \Gamma\left(B^0(t) \to l^- \nu X\right)}{\Gamma\left(\overline{B}^0(t) \to l^+ \nu X\right) + \Gamma\left(B^0(t) \to l^- \nu X\right)}$$

$$a_{SL} = \frac{1 - |q/p|^4}{1 + |q/p|^4} = \mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}}$$

$$\hat{H} = \hat{M} - i\frac{\hat{\Gamma}}{2}$$

Observed in K-system: $\mathrm{Re}\,\varepsilon_K \neq 0$

$$\overline{B}^0 \to B^0 \to l^+ \nu X$$

(Phase Difference)

$$B^0 \to \overline{B}^0 \to l^- \nu X$$

"wrong charge" leptons

Hadronic Uncertainties in Γ_{12}, M_{12}

2. CP Violation in Decay

$$A_f = \langle f | H^{weak} | B \rangle \qquad \bar{A}_{\bar{f}} = \langle \bar{f} | H^{weak} | \bar{B} \rangle$$

$$\not{CP}: \quad \left| \bar{A}_{\bar{f}} / A_f \right| \neq 1 \qquad f \xrightarrow{CP} \bar{f}$$

$$a_{f^\pm}^{Decay} = \frac{\Gamma(B^+ \to f^+) - \Gamma(B^- \to f^-)}{\Gamma(B^+ \to f^+) + \Gamma(B^- \to f^-)} = \frac{1 - \left| \bar{A}_{f^-} / A_{f^+} \right|^2}{1 + \left| \bar{A}_{f^-} / A_{f^+} \right|^2}$$

Requires at least two different contibutions
with different weak (φ_i) and strong (δ_i) phases

$$A_f = \sum_i A_i e^{i(\delta_i + \varphi_i)} \qquad \bar{A}_{\bar{f}} = \sum_i A_i e^{i(\delta_i - \varphi_i)} \qquad (A_2 \ll A_1) \qquad r \equiv \frac{A_2}{A_1} \ll 1$$

$$i = 1,\ 2$$

$$a_{f^\pm}^{Decay} \approx -2r \sin(\delta_2 - \delta_1) \sin(\varphi_2 - \varphi_1)$$

Observed in K-system: $\mathrm{Re}\,\varepsilon'_K \neq 0$

Hadronic Uncertainties in A_i , δ_i

B^0-Decays into CP-Eigenstate

$B^0 \to \overline{B}^0$, $B^0 \to B^0$ $\to f$

ΔM = Difference between Mass Eigenstates in $(B^0, \overline{B}^0)$ System

$f \equiv f_{CP}$ = CP eigenstate

η_f = CP-parity = ±1

Time-dependent asymmetry:

$$a_{CP}(t,f) = \frac{\Gamma\left(B^0(t) \to f\right) - \Gamma\left(\overline{B}^0(t) \to f\right)}{\Gamma\left(B^0(t) \to f\right) + \Gamma\left(\overline{B}^0(t) \to f\right)}$$

$$a_{CP}(t,f) = a_{CP}^{Decay} \cos(\Delta M t) + a_{CP}^{"mix-ind"} \sin(\Delta M t)$$

$$a_{CP}^{Decay} = \frac{1-|\xi_f|^2}{1+|\xi_f|^2} \equiv C_f \qquad a_{CP}^{"mix-ind"} = \frac{2\,\mathrm{Im}\,\xi_f}{1+|\xi_f|^2} \equiv -S_f$$

$$\xi_f = \underbrace{\exp[i2\varphi_M]}_{\text{Mixing}} \frac{\overline{A}_f(\overline{B}^0 \to f)}{A_f(B^0 \to f)}$$

← Decay Amplitudes

For a **single** decay contribution or sum of contributions with **the same weak phase**

$$\xi_f = -\eta_f \exp[i2\varphi_M] \cdot \exp[-i2\varphi_D]$$

$|\xi_f|^2 = 1$ $\qquad \varphi_D$: weak phase in the B^0 decay

⇒ ξ_f = given only in terms of CKM phase

$$a_{CP}^{decay} = 0$$

Dominance of a single CKM Amplitude

A_{Tree}, A_P - hadronic matrix elements
δ_T, δ_P - final state interaction phases
φ_T, φ_P - weak CKM phases

$$\frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)} = -\eta_f \left[\frac{A_{Tree} e^{i(\delta_T - \varphi_T)} + A_P e^{i(\delta_P - \varphi_P)}}{A_{Tree} e^{i(\delta_T + \varphi_T)} + A_P e^{i(\delta_P + \varphi_P)}} \right]$$

Tree Dominance

$$\frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)} = -\eta_f e^{-i2\varphi_T}$$

(Pure Phase)
Very Clean !

Penguin Dominance

$$\frac{\overline{A}_f\left(\overline{B}^0 \to f\right)}{A_f\left(B^0 \to f\right)} = -\eta_f e^{-i2\varphi_P}$$

(Pure Phase)
Very Clean !

Also pure phase if $\varphi_T = \varphi_P$!! $\left(\text{Example: } B_d^0 \to J/\psi\, K_S\right)$

3. CP Violation in the Interference of Mixing and Decay

Misnomer: (“Mixing induced CP-Violation“)

$$a_{CP}(t,f) = \mathrm{Im}\,\xi_f \sin(\Delta M t)$$

$$\mathrm{Im}\,\xi_f = \eta_f \sin(2\varphi_D - 2\varphi_M) \equiv -S_f$$

Very clean TH

Measures the difference between the phases of B^0-$\overline{B}^0$ mixing ($2\varphi_M$) and of decay amplitude ($2\varphi_D$)

Examples:

$B_d^0 \to \psi K_S$: $\varphi_D = 0 \quad \varphi_M = -\beta \quad \eta_f = -1$

$$\mathrm{Im}\,\xi_{\psi K_S} = -\sin 2\beta$$

$B_d^0 \to \pi^+\pi^-$: $\varphi_D = \gamma \quad \varphi_M = -\beta \quad \eta_f = +1$

$$\mathrm{Im}\,\xi_{\pi\pi} = \sin(2(\gamma+\beta)) = -\sin 2\alpha$$

$K_L \to \pi^0 \nu\bar{\nu}$: Measures the difference between the phases in K^0-$\overline{K}^0$ mixing and $\bar{s} \to \bar{d}\nu\bar{\nu}$ amplitude

B^0-Decays into CP Eigenstates

$$\left(\text{Two Contributions} \quad r = \frac{A_2}{A_1} \ll 1 \right)$$

$$a_{CP}(t,f) = C_f \cos(\Delta M t) - S_f \sin(\Delta M t)$$

$$C_f = -2r \sin(\varphi_1 - \varphi_2) \sin(\delta_1 - \delta_2)$$

$$S_f = -\eta_f \left[\sin 2(\varphi_1 - \varphi_M) + 2r \cos 2(\varphi_1 - \varphi_M) \sin(\varphi_1 - \varphi_2) \cos(\delta_1 - \delta_2) \right]$$

φ_i = weak phases $\qquad$ δ_i = strong phases

$$\{r = 0\} \Rightarrow \quad C_f = 0 \qquad S_f = -\eta_f \sin 2(\varphi_1 - \varphi_M)$$

Comparison of Two-Languages

CP violation in mixing	$\equiv$	Manifestation of indirect $\not{CP}$
CP violation in decay	$\equiv$	Manifestation of direct $\not{CP}$
CP violation in interference of mixing and decay	$\equiv$	With a single decay it is impossible to state whether $\not{CP}$ in mixing or decay. But $\mathrm{Im}\,\xi_{f_1} \neq \mathrm{Im}\,\xi_{f_2}$ signals CP violation in decay (Direct $\not{CP}$)

ε, ε' and B-Physics Language

- ★ $\mathrm{Re}\,\varepsilon \neq 0$: $\not{CP}$ in Mixing
- ★ $\mathrm{Im}\,\varepsilon \neq 0$: $\not{CP}$ in the Interference of Mixing and Decay

$$\varepsilon' = \frac{1}{\sqrt{2}}\,\mathrm{Im}\left(\frac{A_2}{A_0}\right) e^{i\Phi_{\varepsilon'}} = \frac{i}{\sqrt{2}}\left|\frac{A_2}{A_0}\right| \sin(\varphi_2 - \varphi_0)\, e^{i(\delta_2 - \delta_0)} \qquad \Phi_{\varepsilon'} = \frac{\pi}{2} + \delta_2 - \delta_0$$

Weak Phases

$$\mathrm{Re}\;\varepsilon' = -\frac{1}{\sqrt{2}}\left|\frac{A_2}{A_0}\right| \sin(\varphi_2 - \varphi_0)\sin(\delta_2 - \delta_0)$$

$$\mathrm{Im}\;\varepsilon' = \frac{1}{\sqrt{2}}\left|\frac{A_2}{A_0}\right| \sin(\varphi_2 - \varphi_0)\cos(\delta_2 - \delta_0)$$

- ★ $\mathrm{Re}\,\varepsilon' \neq 0$: $\not{CP}$ in Decay ($\varphi_2 \neq \varphi_0$, $\delta_2 \neq \delta_0$)
- ★ $\mathrm{Im}\,\varepsilon' \neq 0$: Requires $\varphi_2 \neq \varphi_0$

Classification of CP Violation

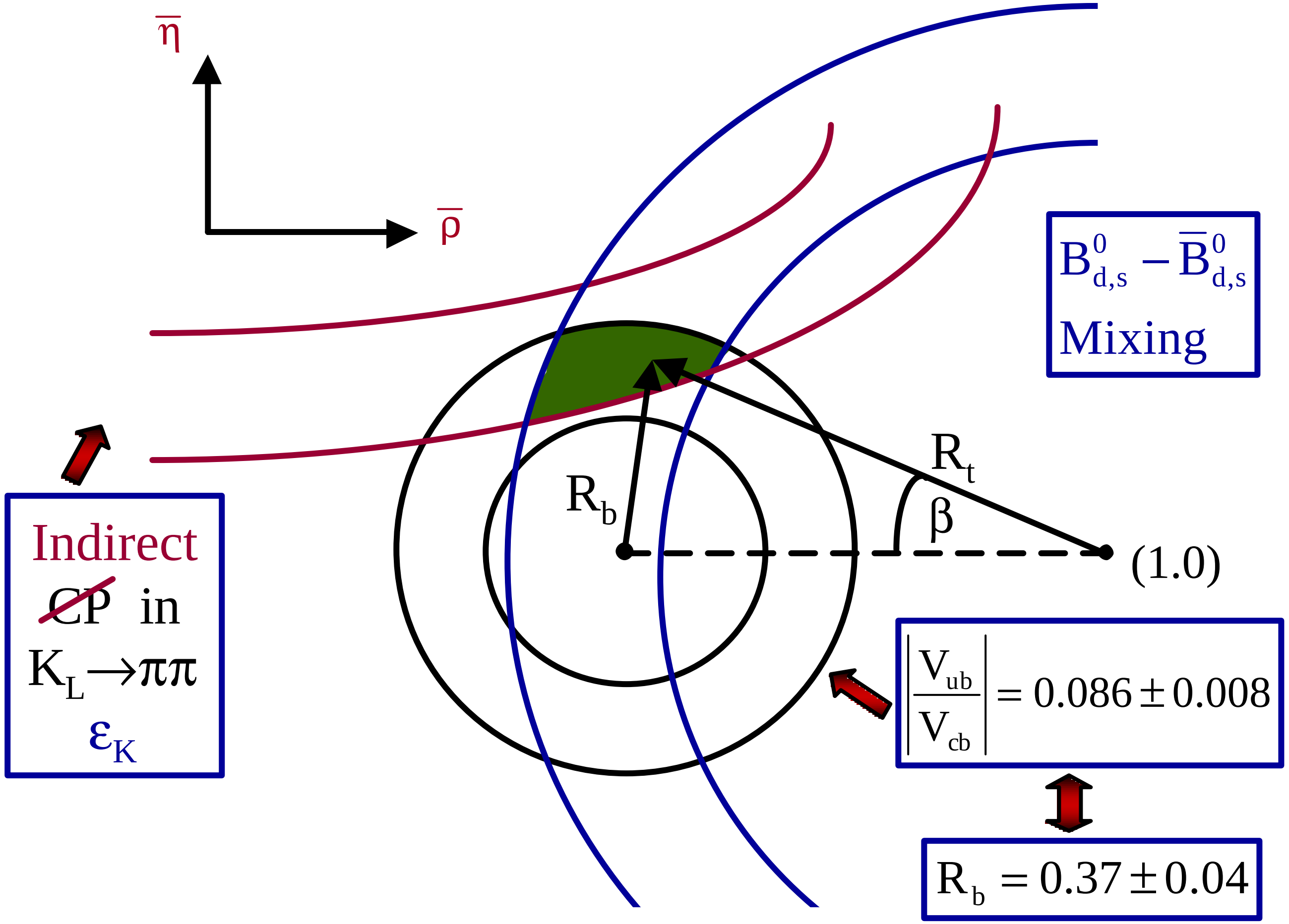
$\not{CP}$ in	Examples	Old Terminology
Mixing	$Re(\varepsilon_K)$, $a_{SL}(K)$, $a_{SL}(B)$	Indirect $\not{CP}$
Decay	ε'/ε, $a_{CP}(B^{\pm})$	Direct $\not{CP}$
Interference of Mixing and Decay	$K_L \rightarrow \pi^0 \nu\bar{\nu}$, $a_{CP}(\psi K_S)$ $Im(\varepsilon_K)$	*)

*) In order to find out the presence of $\not{CP}$ in Decay (direct $\not{CP}$) at least two processes, asymmetries have to be measured

4.

Standard Analysis of Unitarity Triangle

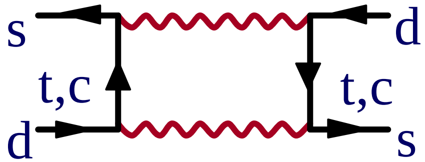
Standard Analysis of UT



Relevant Parameters

$\hat{B}_K,\ F_{B_d}\sqrt{\hat{B}_{B_d}},\ \ \xi = F_{B_s}\sqrt{\hat{B}_{B_s}}\,/\,F_{B_d}\sqrt{\hat{B}_{B_d}}$ ⟺ $\varepsilon_K \qquad \Delta M_d \qquad \Delta M_s / \Delta M_d$

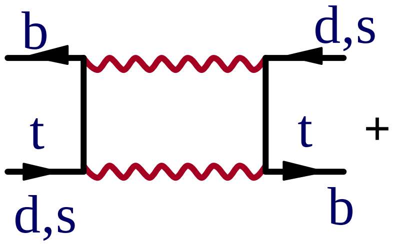
Indirect CP in $K_L \to \pi\pi$

$\left\{ \text{Im} \right.$ 

$\left. + \textbf{QCD} \right\}$ ⇒ ε_K ⇐ $\{\text{Experiment}\}$

exp: $\varepsilon_K = (2.280 \pm 0.013) \cdot 10^{-3} e^{i\frac{\pi}{4}}$

$B^0_{d,s} - \overline{B}^0_{d,s}$ Mixing

$\{$ 

$+ \textbf{QCD} \}$ ⇒ $(\Delta M)_{d,s}$ ⇐ {CLEO, ARGUS, 4∗LEP,SLD, BaBar, Belle}

$$(\Delta M)_{d,s} \equiv M(B^0_H)_{d,s} - M(B^0_L)_{d,s}$$

Mass Eigenstates

exp: ★

$(\Delta M)_d = (0.503 \pm 0.006)/\text{ps}$

$(\Delta M)_s > 14.4/\text{ps}$ (95% C.L.) (LEP/SLD)

Basic Formulae

1. ε_K - Hyperbola

$$\bar\eta\left[\left(1-\bar\rho\right)A^2F_{tt}\eta_{QCD}^{tt}+P_c\left(\varepsilon\right)\right]A^2\hat{B}_K=0.213$$

$\eta_{QCD}^{tt}=0.57\pm0.01$; $P_C\left(\varepsilon\right)=0.28\pm0.05$; $F_{tt}=2.39\pm0.12$
$\left(F_{tt}\equiv S\left(x_t\right)\right)$

2. $B_d^0-\bar{B}_d^0$ Mixing Constraint

$$R_t=0.86\left[\frac{0.041}{\left|V_{cb}\right|}\right]\sqrt{\frac{2.34}{F_{tt}}}\sqrt{\frac{\Delta M_d}{0.50/ps}}\left[\frac{230MeV}{\sqrt{\hat{B}_d}F_{B_d}}\right]\sqrt{\frac{0.55}{\eta_B^{QCD}}}$$

$\left|V_{cb}\right|=0.041\pm0.001$; $\Delta M_d=\left(0.503\pm0.006\right)/ps$; $\eta_B^{QCD}=0.55\pm0.01$

3. $B_s^0-\bar{B}_s^0$ Mixing Constraint ($\Delta M_d/\Delta M_s$)

$$R_t=0.90\sqrt{\frac{\Delta M_d}{0.50/ps}}\sqrt{\frac{18.4/ps}{\Delta M_s}}\left[\frac{\xi}{1.22}\right]$$

$$\xi=\frac{\sqrt{\hat{B}_s}F_{B_s}}{\sqrt{\hat{B}_d}F_{B_d}}$$

$\Delta M_s > 14.4$ / ps (95% C.L.) LEP (SLD)

4. $\sin 2\beta$ from $A_{CP}(\psi K_S)$

$$A_{CP}(\psi K_S) \equiv -a_{\psi K_S} \sin(\Delta M_d t)$$

$$a_{\psi K_S} = \sin 2\beta \qquad \text{(SM)}$$

$$\sin 2\beta_{\psi K_S} = \begin{cases} 0.79 \pm {}^{0.41}_{0.44} & \text{(CDF)} \\ 0.741 \pm \underset{\text{(stat)}}{0.067} \pm \underset{\text{(syst)}}{0.033} & \text{(BaBar)} \\ 0.719 \pm 0.074 \pm 0.035 & \text{(Belle)} \end{cases}$$

$$\left(\text{ALEPH} : 0.84 \;{}^{+0.82}_{-1.04} \pm 0.16\right)$$

(Nir) $\sin 2\beta = 0.734 \pm 0.054$ $\left(a_{\psi K_S}\right)$

$$\beta = \begin{cases} (23.6 \pm 2.2)^{\circ} \\ (66.4 \pm 2.2)^{\circ} & \text{(excluded in the SM)} \end{cases} \qquad (\sin\beta = 0.400 \pm 0.035)$$

Different Treatments of Errors

Particle Data Group

Gilman, Kleinknecht, Renk

"Gaussian" Approach

Ali + London; Mele, ...

Bayesian Approach

Ciuchini, D´Agostini, Franco, Lubicz, Martinelli, Parodi, Roudeau, Stocchi

Frequentist Approach

Höcker, Lacker, Laplace, Diberder

95% CL Scan Method

Plaszczynski, Shune; BaBar

Naive Scanning

Rosner; Stone; AJB

↳ Bayesian

Crucial Parameters in SM and Beyond

CERN
CKM Workshop

$\lvert V_{us}\rvert = \lambda$	0.2240 ± 0.0036	
$\lvert V_{ub}\rvert$	$(3.57 \pm 0.31)\cdot 10^{-3}$	
$\lvert V_{cb}\rvert$	$(41.5 \pm 0.8)\cdot 10^{-3}$	★
$\left\lvert \frac{V_{ub}}{V_{cb}} \right\rvert$	0.086 ± 0.008	★
$m_t(m_t)$	(167 ± 5) GeV	
$\hat{B}_K$	0.86 ± 0.15	(ε_K)
$\sqrt{\hat{B}_d} F_{Bd}$	$(235 {}^{+33}_{-41})$ MeV	(ΔM_d)
$\xi = \frac{\sqrt{\hat{B}_s} F_{Bs}}{\sqrt{\hat{B}_d} F_{Bd}}$	1.24 ± 0.08 (1.22 ± 0.07)*	$\left(\frac{\Delta M_s}{\Delta M_d}\right)$

Lellouch,
Bećirević
(Amsterdam)

Valid for all extensions of SM !!

*Bećirević et al.

Universal Unitarity Triangle

AJB, Gambino, Gorbahn, Jäger, Silvestrini (00)

In the full class of MFV-models it is possible to construct quantities that depend on CKM parameters but in which the dependence on new physics parameters cancels out

↓

CKM Matrix determined without "New Physics Pollution"

↓

Universal Unitarity Triangle

Examples

$$R_t = 0.90\sqrt{\frac{\Delta M_d}{0.50/\mathrm{ps}}}\sqrt{\frac{18.4/\mathrm{ps}}{\Delta M_s}}\left[\frac{\xi}{1.22}\right]$$

$$a_{\psi K_s} = \sin 2\beta$$

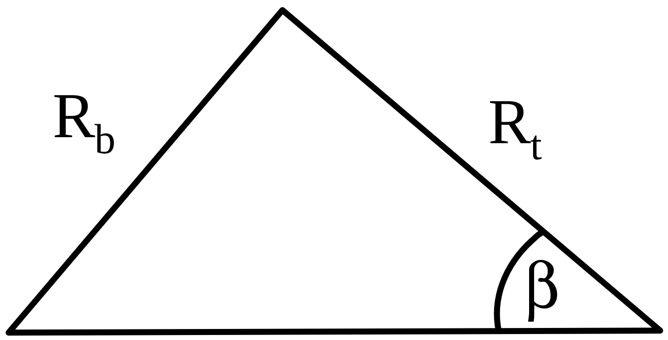
Universal Unitarity Triangle 2002

AJB, Parodi, Stocchi

Use only quantities that are independent of parameters specific to a given Minimal Flavour Violation model

$$\left|\frac{V_{ub}}{V_{cb}}\right| \Rightarrow R_b = \frac{\left(1-\lambda^2/2\right)}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

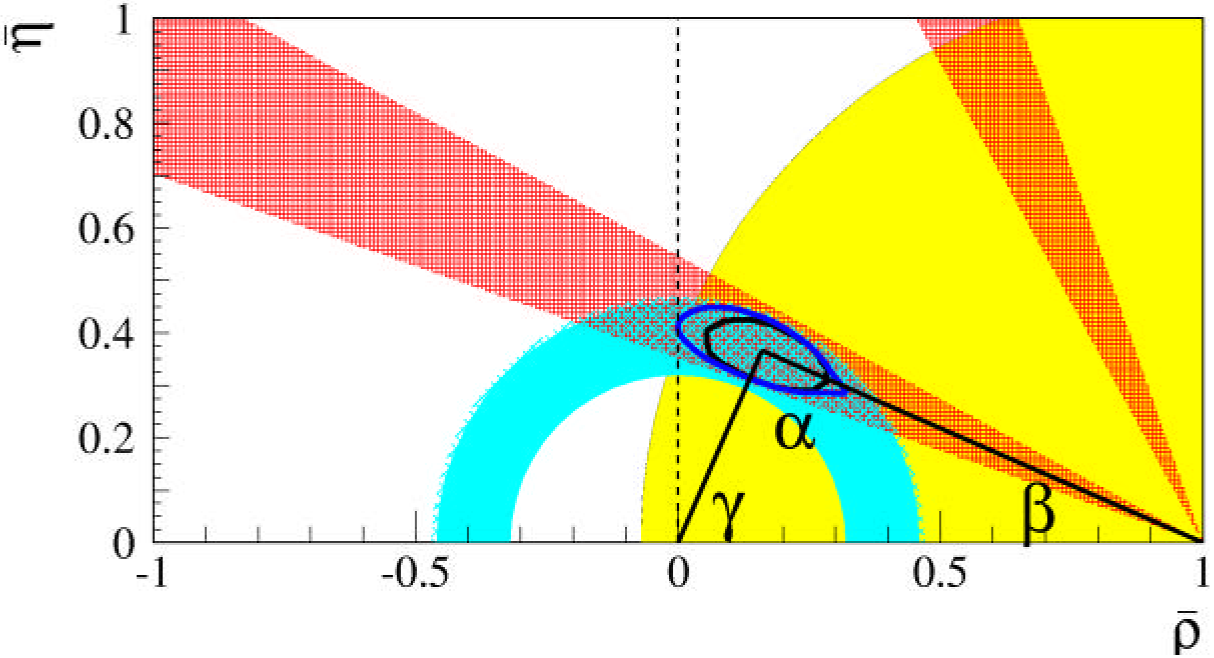
$$\frac{\Delta M_d}{\Delta M_s} \Rightarrow R_t = \frac{\xi_{th}}{\lambda}\sqrt{\frac{\Delta M_d}{\Delta M_s}} \qquad a_{\psi K_s} \Rightarrow \sin 2\beta$$



$$\xi_{th} = \frac{\sqrt{\hat{B}_s}\,F_{B_s}}{\sqrt{\hat{B}_d}\,F_{B_d}}$$

Unitarity Triangle 2002 (SM and MFV Models)

(AJB, Parodi, Stocchi)
(95% C.L. ranges)
(AJB, hep-ph/0210291)



$$\sin 2\beta = \begin{cases} 0.734 \pm 0.054 & \left(a_{\psi K_s}\right) \\ 0.715^{+0.055}_{-0.045} & (\text{UT without } a_{\psi K_s}) \end{cases}$$

Perfect Agreement

$$\left(\sin 2\beta\right)_{\substack{\text{World}\\ \text{Average}}} = 0.725 \pm 0.033$$

$$\beta = \left(23.2 \pm 1.4\right)^{\circ}$$

Bayesian Output (November 2002)

AJB, Parodi, Stocchi   hep-ph/0207101

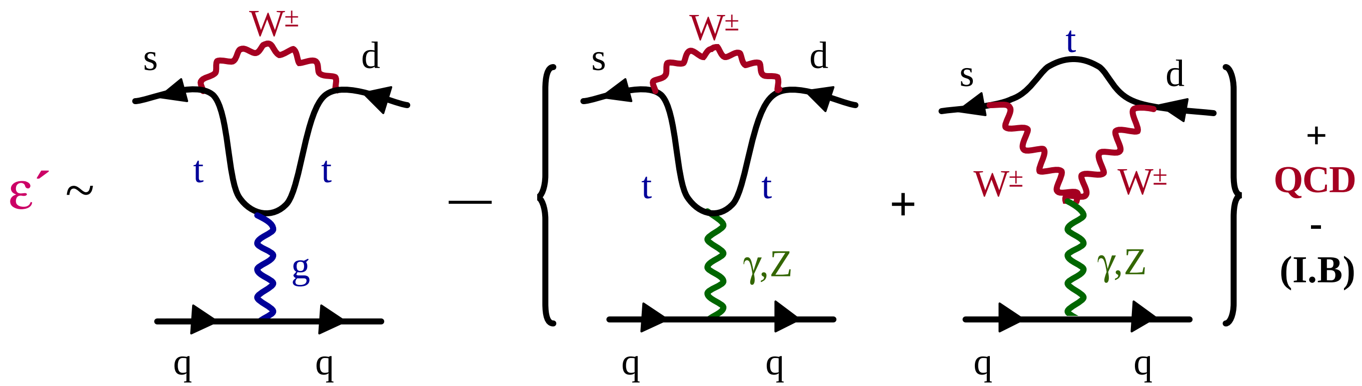
	SM	UUT	
$\bar{\eta}$	0.357 ± 0.027	0.369 ± 0.032	
$\bar{\rho}$	0.173 ± 0.046	0.151 ± 0.057	
$\sin 2\beta$	0.725 ± 0.033	0.725 ± 0.034	
$\sin 2\alpha$	-0.09 ± 0.25	0.05 ± 0.31	★
γ	$(63.5\pm7.0)^0$	$(67.5\pm9.0)^0$	★
R_b	0.400 ± 0.022	0.404 ± 0.023	
R_t	0.900 ± 0.050	0.927 ± 0.061	★
$\|V_{td}\|/10^{-3}$	8.15 ± 0.41	8.36 ± 0.55	
$\|\mathrm{Im}\lambda_t\|/10^{-4}$	1.31 ± 0.09	1.35 ± 0.12	$\left(\lambda_t = V_{ts}^{*}V_{td}\right)$
$\|V_{td}\|/\|V_{ts}\|$	0.205 ± 0.011	0.209 ± 0.014	
$\Delta M_s\,(ps^{-1})$	$18.0\ ^{+1.7}_{-1.5}$	$17.3\ ^{+2.2}_{-1.3}$	

Good Morning !

5.

ε'/ε

ε'/ε in the Standard Model



QCD - Penguins   Electroweak - Penguins

$$\frac{\varepsilon'}{\varepsilon} = 10^{-4}\left[\frac{\mathrm{Im}\,\lambda_t}{1.20\cdot 10^{-4}}\right] F\left(m_t, \Lambda^{(4)}_{\overline{MS}}, m_s, B_6, B_8, \Omega_{IB}\right)$$

$$F \approx 16\cdot\left[\frac{110\ \mathrm{Mev}}{m_s(2\ \mathrm{GeV})}\right]^2 \left[B_6(1-\Omega_{IB}) - \tilde{Z}(m_t)B_8\right]\left(\frac{\Lambda^{(4)}_{\overline{MS}}}{340\ \mathrm{MeV}}\right)$$

P_{QCD} (→ B_6) P_{EW} (→ B_8)

$$\tilde{Z}(m_t) \cong 0.4\left[\frac{m_t}{165\ \mathrm{GeV}}\right]^{2.5} \quad ; \qquad \Omega_{IB} = \text{Isospin Breaking}$$

$$\mathrm{Im}\,\lambda_t = \mathrm{Im}\left(V^*_{ts}V_{td}\right) = |V_{ub}||V_{cb}|\sin\delta$$

Basic Parameters : $\mathrm{Im}\,\lambda_t,\ \Lambda^{(4)}_{\overline{MS}},\ B_6,\ B_8,\ m_s,\ \Omega_{IB}$

First Round of Measurements

$$\frac{\varepsilon'}{\varepsilon} = \begin{cases} (23 \pm 6.5) \cdot 10^{-4} & \text{(NA31)} \\ (7.4 \pm 5.9) \cdot 10^{-4} & \text{(E731)} \end{cases}$$

Second Round of Measurements

$$\frac{\varepsilon'}{\varepsilon} = \begin{cases} (14.7 \pm 2.2) \cdot 10^{-4} & \text{(NA48)} \\ (20.7 \pm 2.8) \cdot 10^{-4} & \text{(KTeV)} \end{cases}$$

Grand Average :

$$\frac{\varepsilon'}{\varepsilon} = (16.6 \pm 1.6) \cdot 10^{-4}$$

Waiting for KLOE

Direct CP Violation
firmly established

ε'/ε 2003

$$(\varepsilon'/\varepsilon)_{exp} = (16.6 \pm 1.6) \cdot 10^{-4}$$

(NA48, KTeV)

$$(\varepsilon'/\varepsilon)_{SM} \simeq \frac{1}{(0.5-3)} \; (\varepsilon'/\varepsilon)_{exp}$$

Lattice: $(\varepsilon'/\varepsilon)_{SM} < 0$?

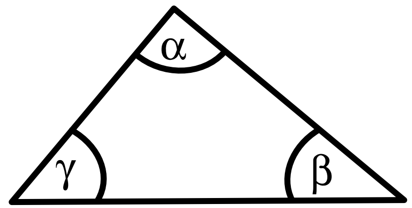
A lot of room for New Physics
(SUSY, etc.)

Targets for ε'/ε

1. ε'/ε from KLOE
2. B_6, B_8, m_s, $\mathrm{Im}\lambda_t$
3. $\Omega_{\eta+\eta'}$, $\Lambda^{(4)}_{\overline{MS}}$

6.

α, β, γ from B-Decays



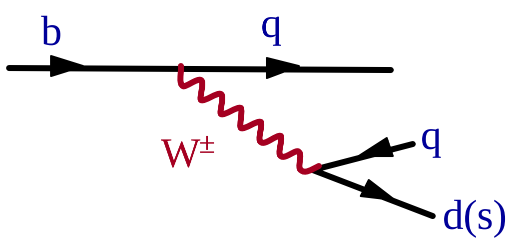
$$V_{td} = |V_{td}| e^{-i\beta}$$

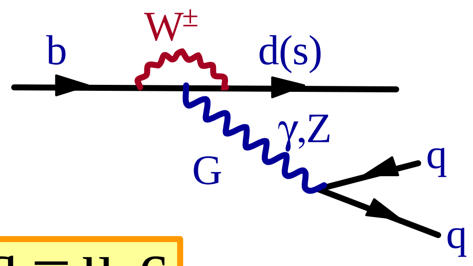
$$V_{ts} = |V_{ts}| e^{-i\beta_s}$$

$$V_{ub} = |V_{ub}| e^{-i\gamma}$$

Basic Contributions

Class I Decays with Trees and Penguins

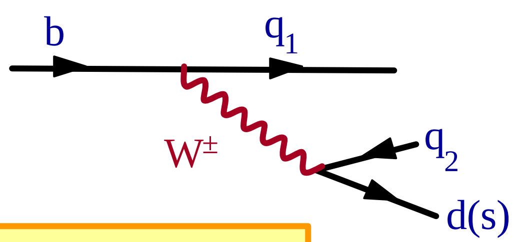




$q = u, c$

$b \to c\bar{c}s$
$b \to c\bar{c}d$
$b \to u\bar{u}s$
$b \to u\bar{u}d$

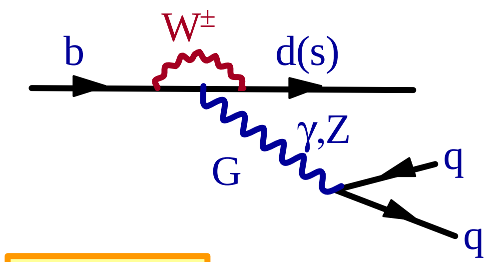
Class II Trees only



$q_1 \neq q_2 \in \{u, c\}$

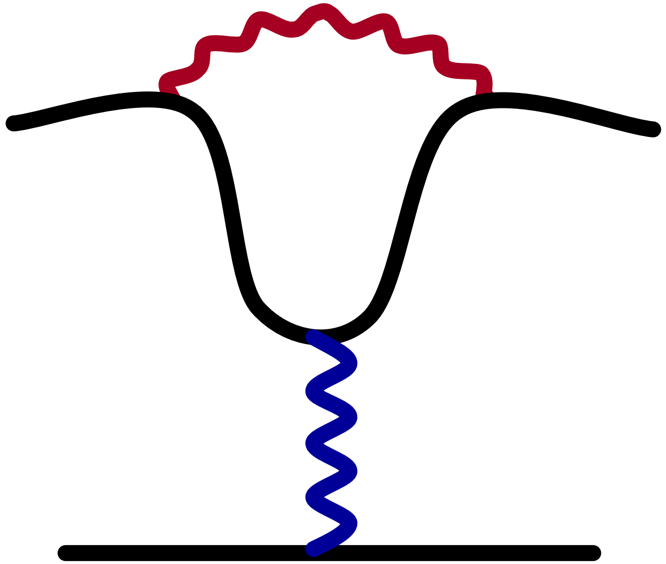
$b \to c\bar{u}s$
$b \to c\bar{u}d$
$b \to u\bar{c}s$
$b \to u\bar{c}d$

Class III Penguins only

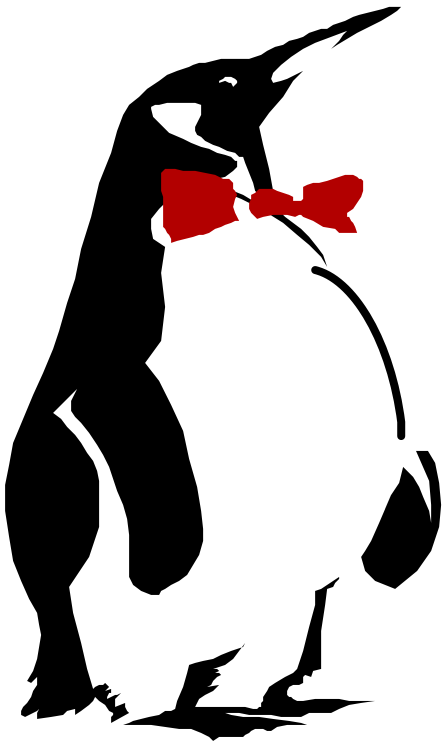


$q = d, s$

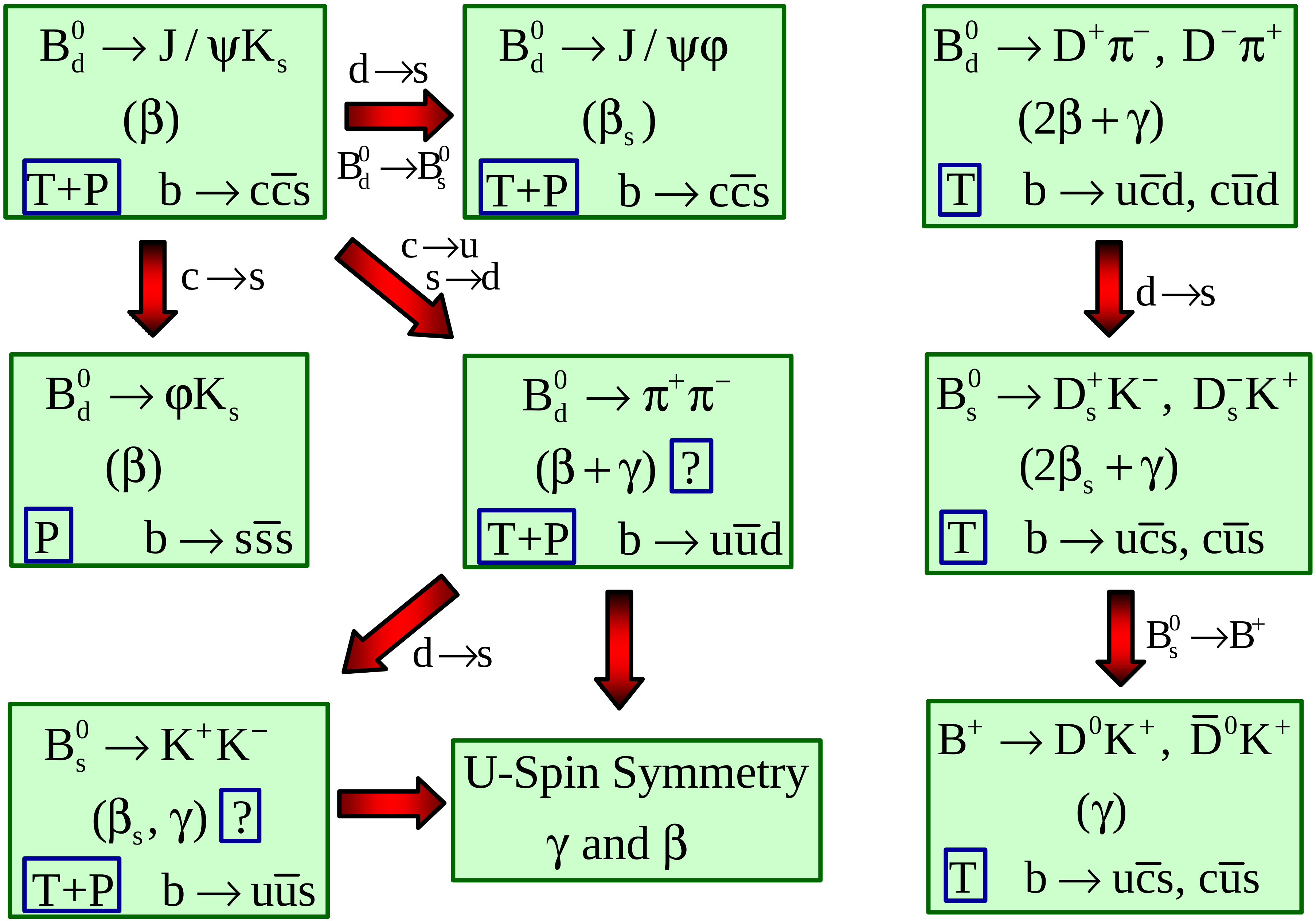
$b \to s\bar{s}s$
$b \to s\bar{s}d$
$b \to d\bar{d}s$
$b \to d\bar{d}d$



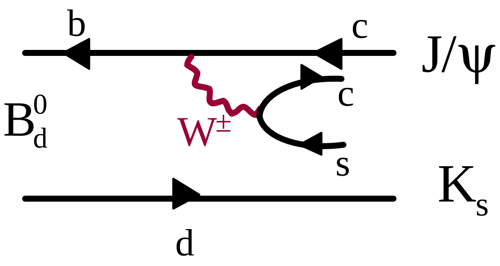
Penguin Diagram

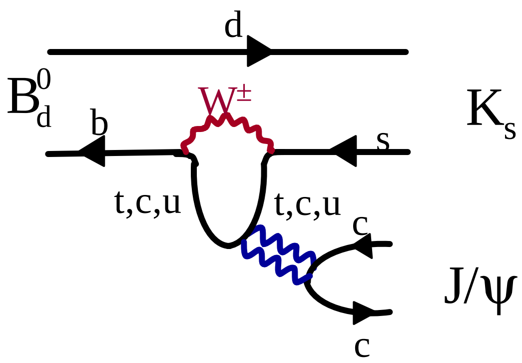


α, β, γ from B-Decays



$B_d^0 \to J/\psi K_S$ and β





$$V_{td} = |V_{td}| e^{-i\beta}$$

$$V_{cs} V_{cb}^* \cong A\lambda^2$$

$$V_{us} V_{ub}^* \cong A\lambda^4 R_b e^{i\gamma}$$

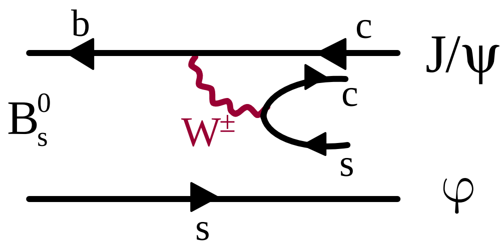
$$V_{ts} V_{tb}^* = -V_{cs} V_{cb}^* - V_{us} V_{ub}^*$$

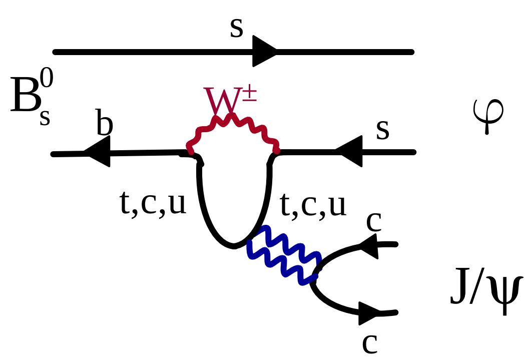
$$A\left(B_d^0 \to J/\psi K_S\right) = V_{cs} V_{cb}^* \left(A_T + P_c\right) + V_{us} V_{ub}^* P_u + V_{ts} V_{tb}^* P_t$$
$$= V_{cs} V_{cb}^* \left(A_T + P_c - P_t\right) + V_{us} V_{ub}^* \left(P_u - P_t\right)$$

(Dominance of a single phase)

$$\left\{ \begin{array}{l} \left| \dfrac{V_{us} V_{ub}^*}{V_{cs} V_{cb}^*} \right| \le 0.02 \\ \dfrac{P_u - P_t}{A_t + P_c - P_t} \ll 1 \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} \varphi_D = 0 \\ \varphi_M = -\beta \\ \left| \xi_{\psi K_S} \right| = 1 \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} a_{CP}^{mix}\left(\psi K_S\right) = \eta_{\psi K_S} \sin 2\left(\varphi_D - \varphi_M\right) = -\sin 2\beta \\ a_{CP}^{dir}\left(\psi K_S\right) = 0 \qquad a_{CP}\left(\psi K^+\right) \simeq 0 \\ C_{\psi K_S} = 0 \qquad S_{\psi K_S} = \sin 2\beta \end{array} \right\}$$

$B_s^0 \to J/\psi\varphi$ and β_s





$$V_{ts} = |V_{ts}| e^{-i\beta_S}$$

Differs from

$B_d^0 \to J/\psi K_S$ only by

"spectator" quark $d \to s$

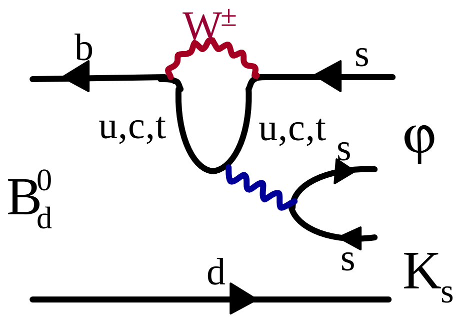
$(\varphi_D = 0)$

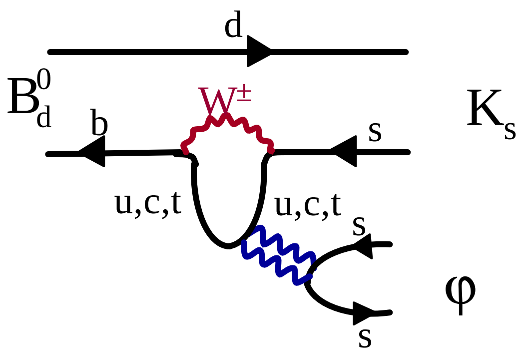
Complication: $(J/\psi\varphi)$ admixture of CP = + and CP = –

(Can be resolved: see Page 40: "B-Decays at the LHC ")

$$\begin{Bmatrix} \varphi_D = 0 \\ \varphi_M = -\beta_S \simeq -\lambda^2\eta \\ |\xi_{\psi\varphi}| = 1 \end{Bmatrix} \Rightarrow \begin{Bmatrix} a_{CP}^{mix} = \sin 2(\varphi_D - \varphi_M) \simeq \underbrace{2\lambda^2\eta}_{2\beta_S} \simeq 0.03 \\ a_{CP}^{dir} \simeq 0 \\ \text{A lot of room for New Physics!} \end{Bmatrix}$$

$B_d^0 \to \varphi K_S$ and β (Pure Peguin Decay)





$$V_{cs}V_{cb}^* \simeq A\lambda^2$$
$$V_{us}V_{ub}^* \simeq A\lambda^4 R_b e^{i\gamma}$$
$$V_{ts}V_{tb}^* = -V_{cs}V_{cb}^* - V_{us}V_{ub}^*$$

$$A\left(B_d^0 \to \varphi K_S\right) = V_{cs}V_{cb}^* P_c + V_{us}V_{ub}^* P_u + V_{ts}V_{tb}^* P_t$$
$$= V_{cs}V_{cb}^*\left(P_c - P_t\right) + V_{us}V_{ub}^*\left(P_u - P_t\right)$$

(Dominance of a single phase)

$$\left\{ \left|\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*}\right| \le 0.02, \quad \frac{P_u - P_t}{P_c - P_t} \approx 0(1) \right\} \Rightarrow \left(\text{neglecting } V_{us}V_{ub}^*\right)$$

$$\left\{ \begin{array}{l} a_{CP}^{mix}\left(\varphi K_S\right) = -\sin 2\beta = a_{CP}^{mix}\left(\psi K_S\right) \\ C_{\varphi K_S} \approx 0 \qquad S_{\psi K_S} = S_{\varphi K_S} = \sin 2\beta \\ \left|S_{\psi K_S} - S_{\varphi K_S}\right| \le 0.04 \ (\text{SM}) \end{array} \right\}$$

Grossman, Isidori, Worah, London, Soni

First Results for $B_d^0 \to \varphi K_S$

$$(\sin 2\beta)_{\varphi K_S} = \begin{cases} -0.19^{+0.52}_{-0.50}\ (\text{stat}) \pm 0.09\ (\text{syst}) & (\text{BaBar}) \\ -0.73 \pm 0.64 \pm 0.18 & (\text{Belle}) \end{cases}$$

(World) $S_{\varphi K_S} = -0.39 \pm 0.41$

(Belle) $C_{\varphi K_S} = 0.56 \pm 0.43$

(Belle)

$S_{\eta' K_S} = 0.76 \pm 0.36$

$C_{\eta' K_S} = -0.26 \pm 0.22$

(BaBar)

$S_{\eta' K_S} = 0.02 \pm 0.035$

$\left| S_{\varphi K_S} - S_{\psi K_S} \right| \simeq 1.12 \pm 0.41$

(Violation of SM by 2.7σ)

(fully consistent with SM)

but $S_{\varphi K_S} \neq S_{\eta' K_S}$ possible
as non-leading terms
could be different

Grossman, Isidori Worah

Ciuchini Silvestrini

New Physics:

Enhanced QCD Penguins
Z^0 Penguins, ..

Hiller, Raidal, Ciuchini + Silvestrini
Fleischer, Mannel

Decays to CP non-eigenstates and γ

$\overset{(-)}{B}{}^0_d \to D^{\pm}\pi^{\mp}$

(Dunietz+Sachs)

$d \to s$

$\overset{(-)}{B}{}^0_s \to D^{\pm}_s K^{\mp}$

Aleksan, Dunietz, Kayser

- $B^0_d \left(B^0_s\right)$ and $\overline{B}{}^0_d \left(\overline{B}{}^0_s\right)$ can decay to the same final state
- Requires full time-dependent analysis: 4 time dependent rates

  $B^0_{d,s}(t) \to f, \quad \overline{B}{}^0_{d,s}(t) \to f,$

  $B^0_{d,s}(t) \to \overline{f}, \quad \overline{B}{}^0_{d,s}(t) \to \overline{f},$
- Tree diagrams only

$$\xi_f = e^{i2\varphi_M} \frac{A\left(\overline{B}{}^0 \to f\right)}{A\left(B^0 \to f\right)}$$

$\overline{B}{}^0 \to f$, $B^0 \to f$, $\overline{B}{}^0 \updownarrow B^0$

$$\xi_{\overline{f}} = e^{i2\varphi_M} \frac{A\left(\overline{B}{}^0 \to \overline{f}\right)}{A\left(B^0 \to \overline{f}\right)}$$

$\overline{B}{}^0 \to \overline{f}$, $B^0 \to \overline{f}$, $\overline{B}{}^0 \updownarrow B^0$

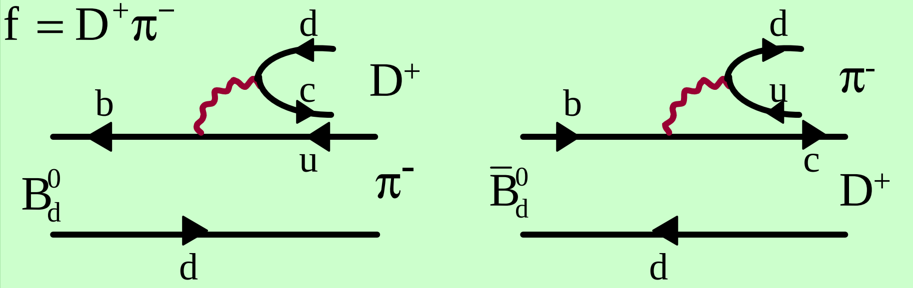
$$\varphi_M = \begin{cases} -\beta & B^0_d \\ -\beta_s & B^0_s \end{cases}$$

$$\xi_f \cdot \xi_{\overline{f}} = F\left(\gamma, \beta_{(s)}\right)$$

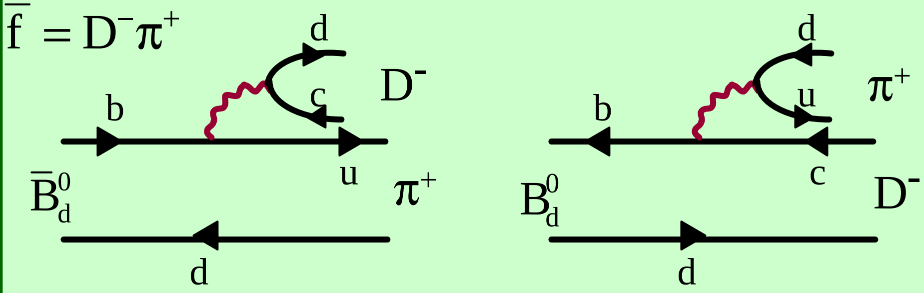
(Dunietz, Sachs)

$B_d^0 \to D^{\pm}\pi^{\mp},\ \bar{B}_d^0 \to D^{\pm}\pi^{\mp}$ and γ

$f = D^+\pi^-$



$\bar{f} = D^-\pi^+$



$\left(M_f A\lambda^4 R_b e^{i\gamma}\right)$ $\left(\bar{M}_f A\lambda^2\right)$ $\left(\bar{M}_{\bar{f}} A\lambda^4 R_b e^{-i\gamma}\right)$ $\left(M_{\bar{f}} A\lambda^2\right)$

$$\xi_f^{(d)} = e^{-i2\beta}\frac{A\left(\bar{B}_d^0 \to f\right)}{A\left(B_d^0 \to f\right)} = e^{-i(2\beta+\gamma)}\frac{1}{\lambda^2 R_b}\frac{\bar{M}_f}{M_f}$$

$$\xi_{\bar{f}}^{(d)} = e^{-i2\beta}\frac{A\left(\bar{B}_d^0 \to \bar{f}\right)}{A\left(B_d^0 \to \bar{f}\right)} = e^{-i(2\beta+\gamma)}\lambda^2 R_b\frac{\bar{M}_{\bar{f}}}{M_{\bar{f}}}$$

$$\bar{M}_f = M_{\bar{f}} \qquad M_f = \bar{M}_{\bar{f}}$$

Hadronic Matrix Elements

$$\xi_f^{(d)} \cdot \xi_{\bar{f}}^{(d)} = e^{-i2(2\beta+\gamma)}$$

$2\beta+\gamma$ without hadronic uncertainties

(β known)

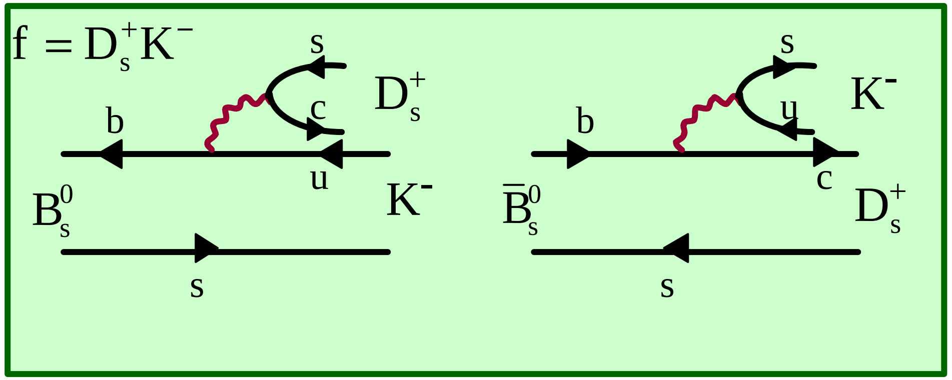
γ

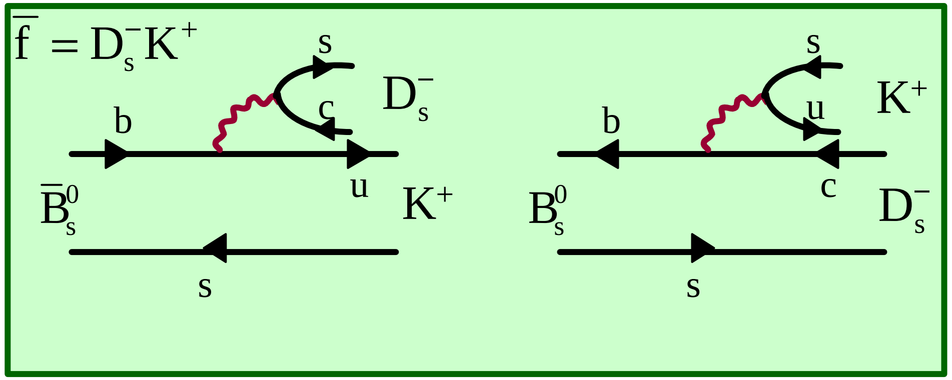
Small Interference: difficult exp. task

Aleksan
Dunietz
Kayser

$B_s^0 \to D_s^\pm K^\mp,\ \bar{B}_s^0 \to D_s^\pm K^\mp$ and γ

Directly obtained from $B_d^0,\ \bar{B}_d^0 \to D^\pm \pi^\mp$ through $d \to s$





$\left(M_f A\lambda^3 R_b e^{i\gamma}\right)$ $\left(\bar{M}_f A\lambda^3\right)$ $\left(\bar{M}_{\bar{f}} A\lambda^3 R_b e^{-i\gamma}\right)$ $\left(M_{\bar{f}} A\lambda^3\right)$

In analogy to $B_d^0,\ \bar{B}_d^0 \to D^\pm \pi^\mp$

$$\xi_f^{(s)} \cdot \xi_{\bar{f}}^{(s)} = e^{-i2(2\beta_s + \gamma)}$$

β_s – phase in $B_s^0 - \bar{B}_s^0$

→ $2\beta_s + \gamma$ without hadronic uncertainties

→ γ

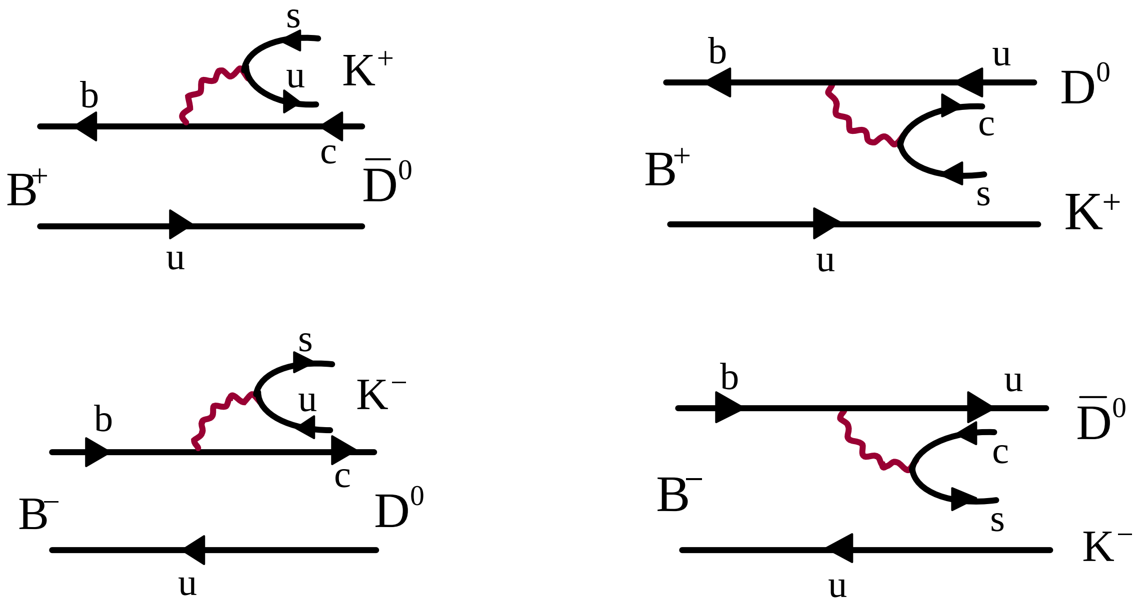
β_s from $B_s^0 \to \varphi\psi$

Much bigger interference than in $B_d^0,\ \bar{B}_d^0 \to D^\pm \pi^\mp$

$B^\pm \to D^0 K^\pm,\ \bar{D}^0 K^\pm$ and γ

(Gronau + Wyler)

Directly obtained from $B_s^0,\ \bar{B}_s^0 \to D_s^\pm K^\pm$ through $B_s \to B^\pm$



$K^+\bar{D}^0 \neq K^+D^0$

Need

$B^+ \to D_+^0 K^+$

$$D_+^0 = \frac{1}{\sqrt{2}}\left(D^0 + \bar{D}^0\right)$$

To each process only single diagram contributes

$A\left(B^+ \to \bar{D}^0 K^+\right) = A\left(B^- \to D^0 K^-\right)$

$A\left(B^+ \to D^0 K^+\right) = A\left(B^- \to \bar{D}^0 K^-\right) e^{2i\gamma}$

$0\left(A\lambda^3\right)$

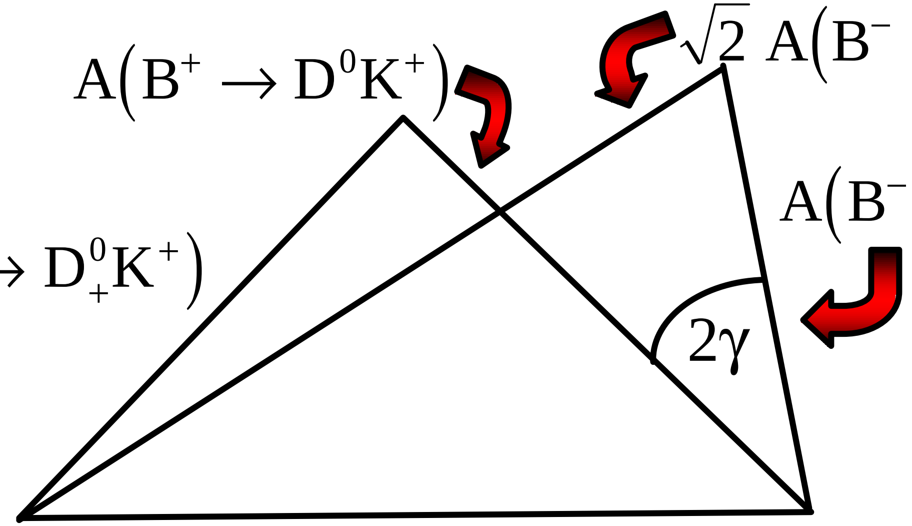
$0\left(A\lambda^3 R_b\right)$ Colour suppressed

Gronau-Wyler Method for γ

$$\sqrt{2}\,A\left(B^+ \to D^0_+ K^+\right) = A\left(B^+ \to D^0 K^+\right) + A\left(B^+ \to \overline{D}^0 K^+\right)$$

$$\sqrt{2}\,A\left(B^- \to D^0_+ K^-\right) = A\left(B^- \to \overline{D}^0 K^-\right) + A\left(B^- \to D^0 K^-\right)$$

$$D^0_+ = \frac{1}{2}\left(\left|D^0\right\rangle + \left|\overline{D}^0\right\rangle\right) \qquad CP = +$$



Advantages

- Pure Trees
- No tagging
- No time dependent measurements
- Only rates

Disadvantages

- $Br\left(B^+ \to D^0 K^+\right) \sim 0\left(10^{-6}\right)$
- $Br\left(B^+ \to \overline{D}^0 K^+\right) \sim 0\left(10^{-4}\right)$
- Detection of D^0_+

Other clean Strategies for γ and β

Gronau + London; Fleischer

Analogous arguments as in:

$B_d^0 \to D^{\pm}\pi^{\mp},\ \bar{B}_d^0 \to D^{\pm}\pi^{\mp}$ $(2\beta+\gamma)$

$B_s^0 \to D_s^{\pm}K^{\mp},\ \bar{B}_s^0 \to D_s^{\pm}K^{\mp}$ $(2\beta_s+\gamma)$

$B^{\pm} \to D^0K^{\pm},\ \bar{D}^0K^{\pm}$ (γ)

$B_d^0 \to K_sD^0,\ K_s\bar{D}^0$ $(2\beta+\gamma),\ \gamma$

$B_d^0 \to \pi^0D^0,\ \pi^0\bar{D}^0$ $(2\beta+\gamma),\ \gamma$

$B_s^0 \to \varphi D^0,\ \varphi\bar{D}^0$ $(2\beta_s+\gamma),\ \gamma$

$B_s^0 \to K_sD^0,\ K_s\bar{D}^0$ $(2\beta_s+\gamma),\ \gamma$

$B^{\pm} \to D^0\pi^{\pm},\ \bar{D}^0\pi^{\pm}$ (γ)

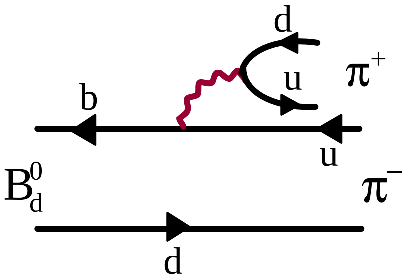
$B_c^{\pm} \to D^0D_s^{\pm},\ \bar{D}^0D_s^{\pm}$ (γ)

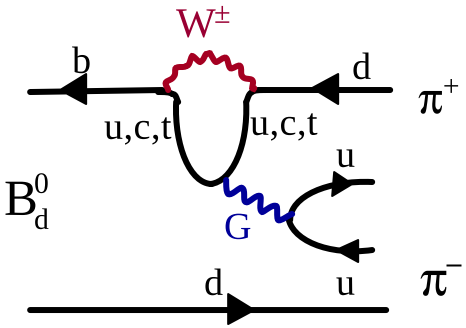
$B_c^{\pm} \to D^0D^{\pm},\ \bar{D}^0D^{\pm}$ (γ)

$(2\beta+\gamma)$, $(2\beta_s+\gamma)$: Time dependence tagging

γ : Rates only

$B_d^0 \to \pi^+\pi^-$ and α





$$V_{ub}^* V_{ud} = A\lambda^3 R_b e^{i\gamma}$$
$$V_{cb}^* V_{cd} = A\lambda^3$$
$$V_{tb}^* V_{td} = -V_{ub}^* V_{ud} - V_{cb}^* V_{cd}$$

$$A\left(B_d^0 \to \pi^+\pi^-\right) = V_{ub}^* V_{ud}\left(A_T + P_u\right) + V_{cb}^* V_{cd} P_c + V_{tb}^* V_{td} P_t$$
$$= V_{ub}^* V_{ud}\left(A_T + P_u - P_t\right) + V_{cb}^* V_{cd}\left(P_c - P_t\right)$$

$$\left|\frac{V_{cb}^* V_{cd}}{V_{ub}^* V_{ud}}\right| = \frac{1}{R_b} \approx 0(2)$$
$$\frac{P_c - P_t}{A_T + P_u - P_t} = \frac{P_{\pi\pi}}{T_{\pi\pi}} \quad ?$$

Dominance of a single amplitude uncertain

Assuming

$$\frac{P_{\pi\pi}}{T_{\pi\pi}} \ll 1$$

$$\varphi_D = \gamma \qquad \varphi_M = -\beta \qquad \left|\xi_{\pi\pi}\right| = 1$$

$$a_{CP}^{mix} = \eta_{\pi\pi} \sin 2\left(\varphi_D - \varphi_M\right) = \sin 2\left(\gamma + \beta\right) = -\sin 2\alpha$$

$$a_{CP}^{dir} = 0 \qquad C_{\pi\pi} = 0 \qquad S_{\pi\pi} = \sin 2\alpha$$

First Results for $B_d^0 \to \pi^+\pi^-$

$$C_{\pi\pi} = \begin{cases} -0.77 \pm 0.27(\text{stat}) \pm 0.08(\text{syst}) & \text{Belle} \\ -0.30 \pm 0.25 \pm 0.04 & \text{BaBar} \end{cases}$$

CP (crossed out)

Consistent with 0

$$S_{\pi\pi} = \begin{cases} -1.23 \pm 0.41 \pm 0.08 & \text{Belle} \\ -0.02 \pm 0.34 \pm 0.05 & \text{BaBar} \end{cases}$$

CP (crossed out)

Consistent with 0

Isospin analysis (Gronau + London)
Model independent determination of α

Model independent upper bound (Grossman, Quinn; Charles)

$$\sin^2(\alpha_{eff} - \alpha) \le \frac{Br\left(B^0 \to \pi^0\pi^0\right)}{Br\left(B^+ \to \pi^+\pi^0\right)}$$

$$\sin 2\alpha_{eff} \equiv \frac{\text{Im}\,\xi_{\pi\pi}}{\left|\xi_{\pi\pi}\right|}$$

Model dependent determination of α using $\left(P_{\pi\pi}/T_{\pi\pi}\right)_{TH}$

Beneke, Buchalla, Neubert, Sachrajda: small $C_{\pi\pi}$

Keum,Li,Sanda: large $C_{\pi\pi}$

U-Spin Strategies

(d↔s)

Fleischer:

$$\left\{\begin{array}{l} B_d^0 \to \pi^+\pi^- \\ B_s^0 \to K^+K^- \end{array}\right\} \Rightarrow \beta, \gamma$$

$$\left\{\begin{array}{l} B_d^0 \to J/\psi K_s \\ B_s^0 \to J/\psi K_s \end{array}\right\} \Rightarrow \gamma$$

$$\left\{\begin{array}{l} B_d^0 \to D^+D^- \\ B_s^0 \to D_s^+D_s^- \end{array}\right\} \Rightarrow \gamma$$

Uncertainty from U-Spin breaking

Gronau + Rosner; Chiang Wolfenstein:

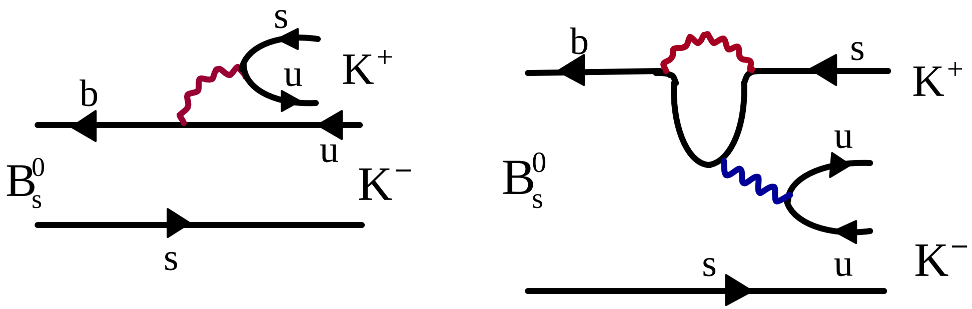
$$\left\{\begin{array}{l} B_d^0 \to \pi^-K^+ \\ B_s^0 \to \pi^+K^- \end{array}\right\} \Rightarrow \gamma$$

Uncertainty from U-Spin breaking, rescattering, colour suppressed EW-Penguins

$B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ $(\beta$ and $\gamma)$

(Fleischer)

$\{$Replace in $B_d^0 \to \pi^+\pi^-$: $d \to s\}$



$$V_{ub}^* V_{us} = A\lambda^4 e^{i\gamma} R_b$$
$$V_{cb}^* V_{cs} = A\lambda^2$$
$$V_{tb}^* V_{ts} = -V_{ub}^* V_{us} - V_{cb}^* V_{cs}$$

$$A\left(B_s^0 \to K^+K^-\right) = V_{ub}^* V_{us}\left(A_T' + P_u' - P_t'\right) + V_{cb}^* V_{cs}\left(P_c' - P_t'\right)$$

U-Spin Symmetry:

$$\frac{P_{\pi\pi}}{T_{\pi\pi}} = \frac{P_c - P_t}{A_T + P_u - P_t} = \frac{P_c' - P_t'}{A_T' + P_u' - P_t'} = \frac{P_{KK}}{T_{KK}} \equiv d e^{i\delta}$$

strong phase

$a_{CP}^{mix}\left(B_d^0 \to \pi^+\pi^-\right)$ $\quad$ $a_{CP}^{mix}\left(B_s^0 \to K^+K^-\right)$

$a_{CP}^{dir}\left(B_d^0 \to \pi^+\pi^-\right)$ $\quad$ $a_{CP}^{dir}\left(B_s^0 \to K^+K^-\right)$

$\Rightarrow$ d, δ, β, γ subject to U-Spin breaking corrections

$(\beta_s$ from $B_s \to J/\psi\varphi)$

β present in $B_d^0 - \bar{B}_d^0$ mixing

γ from $B \to \pi K$

CLEO, BaBar
Belle

Penguin dominated decays

$$Br\left(B^{\pm} \to \pi^{\mp} K^{0}\right) = (18.1 \pm 1.7) \cdot 10^{6}$$

$$Br\left(B^{\pm} \to \pi^{0} K^{\pm}\right) = (12.7 \pm 1.2) \cdot 10^{-6}$$

$$Br\left(\overset{(-)}{B}_{d} \to \pi^{\mp} K^{\pm}\right) = (18.5 \pm 1.0) \cdot 10^{-6}$$

$$Br\left(\overset{(-)}{B}_{d} \to \pi^{0} K^{0}\right) = (10.2 \pm 1.5) \cdot 16^{-6}$$

<u>Uncertainties</u> from: Non-Factorization

$SU(3)_F$ breaking
Final State Interactions
Electroweak Penguins

General Parametrizations

AJB, Fleischer; Neubert
Gronau, Pirjol

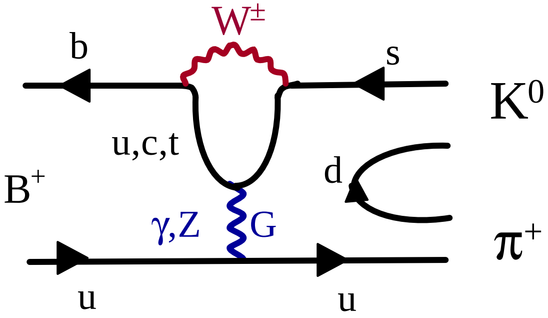
Parametrization through
Wick contractions

Ciuchini et al.;
AJB, Silvestrini

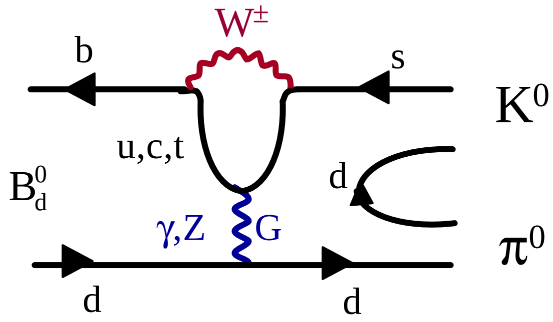
Strategies

$B^{\pm} \to \pi^{\pm} K^{0},\ \overset{(-)}{B}{}^{0}_{d} \to \pi^{\mp} K^{\pm}$	Fleischer - Mannel Bound	"mixed"
$B^{\pm} \to \pi^{\pm} K^{0},\ B^{\pm} \to \pi^{0} K^{\pm}$	Neubert-Rosner Bound	"charged"
$\overset{(-)}{B}{}^{0}_{d} \to \pi^{0} K^{0},\ \overset{(-)}{B}{}^{0}_{d} \to \pi^{\mp} K^{\pm}$	AJB - Fleischer	"neutral"

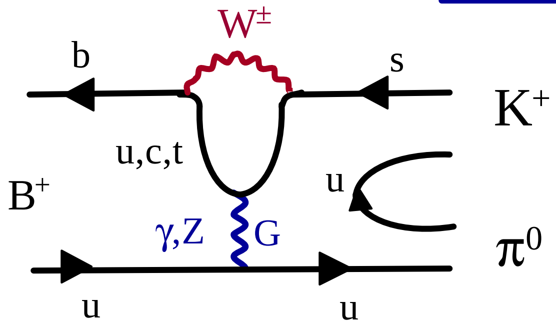
$B^+ \to \pi^+ K^0$

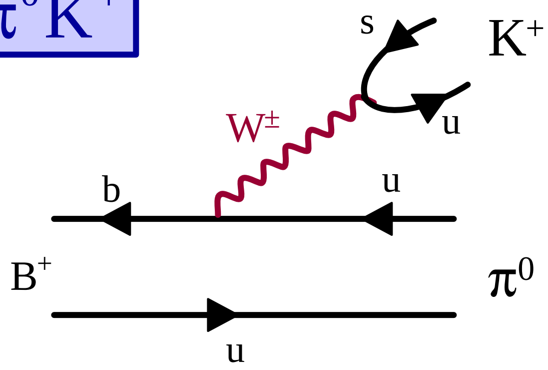


$B_d^0 \to \pi^0 K^0$



$B^+ \to \pi^0 K^+$

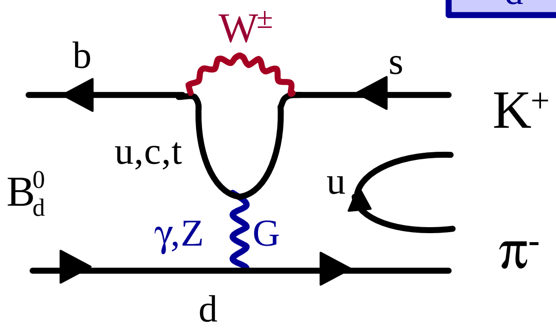


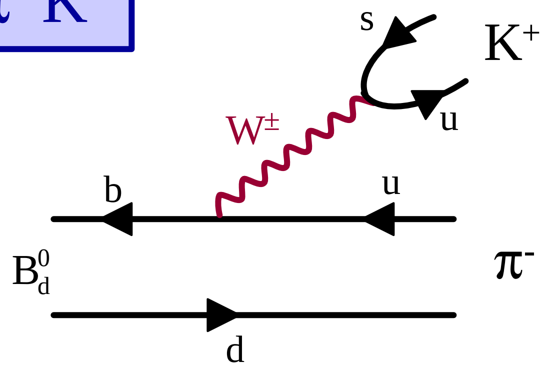


Penguins: λ^2 (c,t)
(P) $\lambda^4 e^{i\gamma}$ (u)

Trees: $\lambda^4 e^{i\gamma}$
(T)

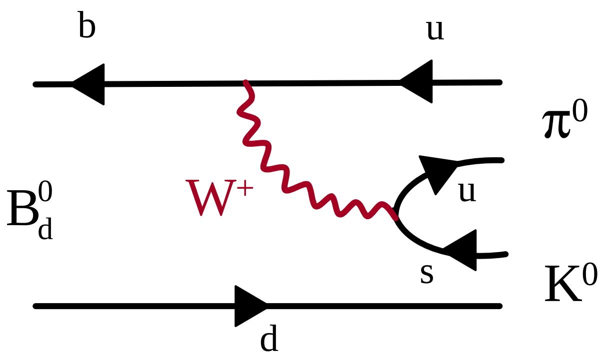
$B_d^0 \to \pi^- K^+$





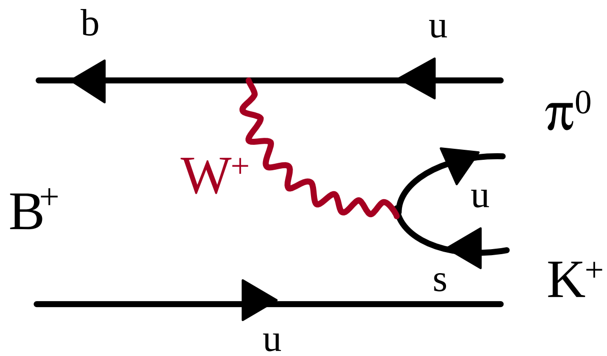
Colour suppressed Tree Topologies (C)

$B_d^0 \rightarrow \pi^0 K^0$



$\lambda^4 e^{i\gamma}$

$B^+ \rightarrow \pi^0 K^+$



$\lambda^4 e^{i\gamma}$

General Parametrization of $B \to \pi K$

(AJB + Fleischer, hep-ph / 9810260; CERN-TH / 98-319)

SU(2) Relations

$$A(B^+ \to \pi^+ K^0) + A(B_d^0 \to \pi^- K^+) = -\left[T + P_{EW}^C\right]$$

$$A(B^+ \to \pi^+ K^0) + \sqrt{2}\, A(B^+ \to \pi^0 K^+) = -\left[(T + C) + P_{EW}\right] \equiv 3\, A_{3/2}$$

$$\sqrt{2}\, A(B_d^0 \to \pi^0 K^0) + A(B_d^0 \to \pi^- K^+) = -\left[(T + C) + P_{EW}\right] \equiv 3\, A_{3/2}$$

$$P_{ch} \equiv A(B^+ \to \pi^+ K^0) = -\lambda^2 A \left[1 + \underbrace{\rho_{ch} e^{i\theta_{ch}} e^{i\gamma}}_{\text{u-Penguin rescattering}}\right] \underbrace{\left|P_{tc}^{ch}\right| e^{i\delta_{tc}^{ch}}}_{\text{t,c-Penguins}}$$

$$P_n \equiv \sqrt{2}\, A(B_d^0 \to \pi^0 K^0) = -\lambda^2 A \left[1 + \overbrace{\rho_n e^{i\theta_n} e^{i\gamma}}\right] \overbrace{\left|P_{tc}^{n}\right| e^{i\delta_{tc}^{n}}}$$

$$T + C = |T + C|\, e^{i\delta_{T+C}} e^{i\gamma} \qquad P_{EW} = -|P_{EW}|\, e^{i\delta_{EW}} \quad \text{etc.}$$

General Parametrization of $B \to \pi K$

cont.

Parameters

Mixed Strategy: $r = \frac{|T|}{\sqrt{|P_{ch}|^2}}$ $q = \frac{P_{EW}^c}{T}$ $\delta = \delta_T - \delta_{tc}$

Charged Strategy: $r_{ch} = \frac{|T+C|}{\sqrt{|P_{ch}|^2}}$ $q_{ch} = \frac{P_{EW}}{T+C}$ $\delta_{ch} = \delta_{T+C} - \delta_{tc}^{ch}$

Neutral Strategy: $r_n = \frac{|T+C|}{\sqrt{|P_n|^2}}$ $q_n = q_{ch} = \frac{P_{EW}}{T+C}$ $\delta_n = \delta_{T+C} - \delta_{tc}^{n}$

Determining the Parameters through $SU(3)_F$ Symmetry

★ r_{ch}, r_n, $q_{ch} = q_n$ can be fixed by $SU(3)_F$ Symmetry

r, q cannot be fixed by $SU(3)_F$ → Larger TH uncertainties in the "mixed" strategy

$$q_{ch} = q_n = 0.66\left[\frac{0.39}{R_b}\right]$$

(Neubert, Rosner)

$$r_{ch} = \sqrt{2}\left|\frac{V_{us}}{V_{ud}}\right|\frac{F_K}{F_\pi}\sqrt{\frac{Br(B^\pm \to \pi^\pm\pi^0)}{Br(B^\pm \to \pi^\pm K^0)}}$$

(Gronau, London, Rosner)

$|T+C|$ from $B^\pm \to \pi^\pm\pi^o$

$$r_n = \left|\frac{V_{us}}{V_{ud}}\right|\frac{F_K}{F_\pi}\sqrt{\frac{Br(B^\pm \to \pi^\pm\pi^0)}{Br(B^0 \to \pi^0 K^0)}}$$

(AJB, Fleischer)

$$Br(B^\pm \to \pi^\pm\pi^o) = (5.8 \pm 1.0)\cdot 10^{-6}$$

(CLEO, Babar, Belle)

$r_{ch} \cong 0.22 \pm 0.02$ $\quad$ $r_n \cong 0.21 \pm 0.02$

Non-Factorizable $SU(3)_F$ –Breaking and Strong Phases

Very interesting and important developements

Recent dynamical approaches to non-leptonic Decays (beyond Factorization)

QCD Factorization Approach

(Beneke, Buchalla, Neubert, Sachrajda)

Perturbation QCD Approach

(Chang, Li; Cheng, Li, Yang; Keum, Li, Sanda)

Soft-Collinear Effective Theory

(Bauer, Fleming, Pirjol, Stewart; Chay, Kim; Beneke et al.)

Phenomenological power of these approaches still to be seen and tested

The measurements of CP asymmetries and branching ratios will give insight in these issues:

$$A_{CP}\left(\pi^+ K^0\right) = 0.05 \pm 0.08$$

$$A_{CP}\left(\pi^0 K^+\right) = -0.10 \pm 0.08$$

$$A_{CP}\left(\pi^0 K^0\right) = 0.03 \pm 0.37$$

$$A_{CP}\left(\pi^- K^+\right) = -0.08 \pm 0.04$$

Clash between $B \to \pi K$ and Unitarity Triangle fits?

Studies by many authors
1999, 2000:
He, Hou, Yang, Smith, Würthwein,
AJB, Fleischer; Fleischer, Matias,
Neubert, Rosner, BBNS, ...
Bargiotti et al.

$\gamma \geq 90°$ favoured by $B \to \pi K$

$\gamma = (64 \pm 7)°$ UT fits

Large non-factorizable SU(3)breaking effects?

New Physics in EW penguins?

Critical Analysis:

{Ciuchini, Franco
Martinelli, Pierini
Silvestrini} :

- Inclusion of large "charming" penguins could shift γ below 90°
- No useful constraint on γ from $B \to \pi K$ to be expected

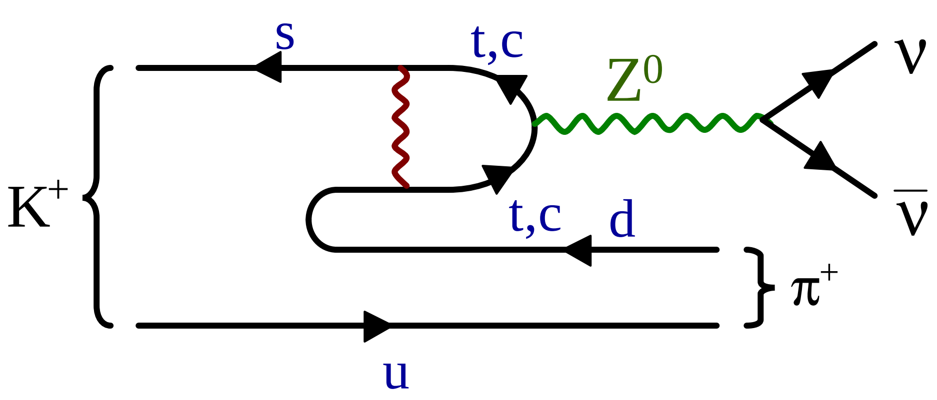
?

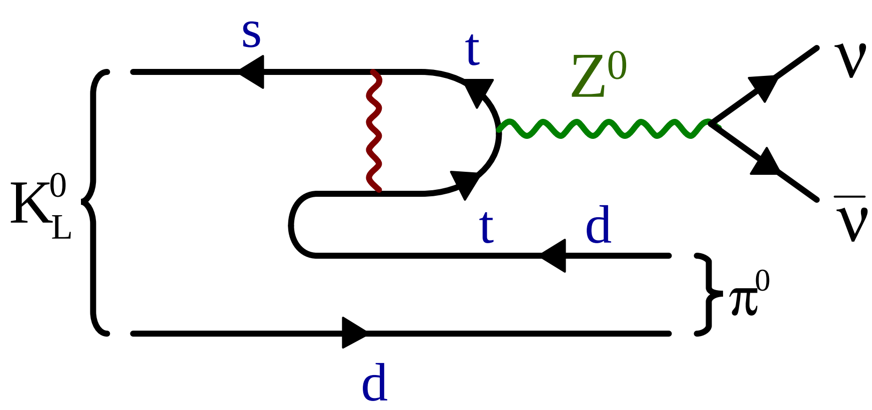
7.

$$K_L \rightarrow \pi^0 \nu \bar{\nu}$$

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

Decays $K \to \pi\nu\bar{\nu}$





Isospin Symmetry

$$\langle \pi^+ | (\bar{s}d)_{V-A} | K^+ \rangle = \sqrt{2} \langle \pi^0 | (\bar{s}u)_{V-A} | K^+ \rangle$$

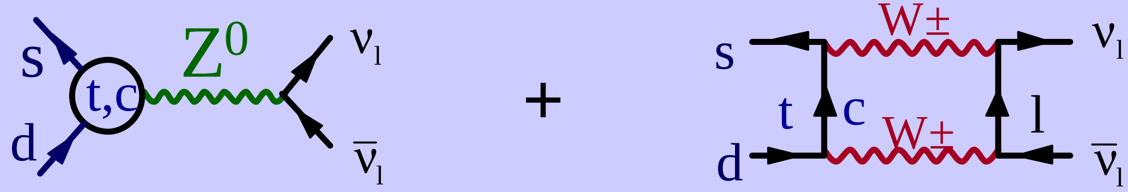
$$\langle \pi^0 | (\bar{s}d)_{V-A} | K^0 \rangle = \langle \pi^0 | (\bar{s}u)_{V-A} | K^+ \rangle$$

Leading Decay: $K^+ \to \pi^0 e^+ \nu$

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$

(CP Conserving) (Direct ~~CP~~)

$\sum_{\nu_l}$



LO: Dib, Dunietz, Gilman (91)
NLO: Buchalla, AJB (94); Misiak, Urban (98)
Isospin Breaking Effects: Marciano, Parsa (95)

$$\left\{\begin{array}{c}\text{Basic}\\ \text{Virtue}\end{array}\right\} : \left(\begin{array}{c}\text{Theoretically Very Clean}\\ \left(\Delta Br\left(K^+ \to \pi^+\nu\bar{\nu}\right)\right)_{TH} : \pm 7\% \quad \left(m_c\left(\mu_c\right)\right)\\ \left(\Delta Br\left(K_L \to \pi^0\nu\bar{\nu}\right)\right)_{TH} : \pm 2\% \quad \left(m_t\left(\mu_t\right)\right)\end{array}\right)$$

$$Br\left(K^+ \to \pi^+\nu\bar{\nu}\right) = \begin{cases}(7.6 \pm 1.2)\cdot 10^{-11} & \text{(SM)}\\ \left(15.7^{+17.5}_{-8.2}\right)\cdot 10^{-11} & \text{(E787 Brookhaven)} \star\end{cases}$$

$$Br\left(K_L \to \pi^0\nu\bar{\nu}\right) = \begin{cases}(2.7 \pm 0.5)\cdot 10^{-11} & \text{(SM)}\\ < 5.9 \cdot 10^{-7} & \text{(KTeV)}\end{cases}$$

Future: KEK E391, KAMI, KOPIO; AGS E949; CKM (Fermilab)

Model Independent Bound: (Grossman, Nir)

$$Br\left(K_L \to \pi^0\nu\bar{\nu}\right) < 4.4\ Br\left(K^+ \to \pi^+\nu\bar{\nu}\right) < 2\cdot 10^{-9} \quad (90\%\ \text{C.L.})$$

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 4.31 \cdot 10^{-11} \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(m_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c + \frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(m_t) \right)^2 \right]$$

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = 1.88 \cdot 10^{-10} \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(m_t) \right)^2 \right]$$

$$P_c = 0.40 \pm 0.06$$

(Buchalla + AJB)

$$\mathrm{Re}\,\lambda_c = -\lambda \left(1 - \frac{\lambda^2}{2} \right)$$

$$\mathrm{Re}\,\lambda_t = -\lambda \left(1 - \frac{\lambda^2}{2} \right) A^2 \lambda^5 \left(1 - \bar{\rho} \right)$$

$$\mathrm{Im}\,\lambda_t = \eta A^2 \lambda^5$$

$$X(m_t) = 1.51 \pm 0.05$$

$$\lambda = 0.221 \pm 0.002$$

$$A\lambda^2 = V_{cb} = (40.6 \pm 0.8) \cdot 10^{-3}$$

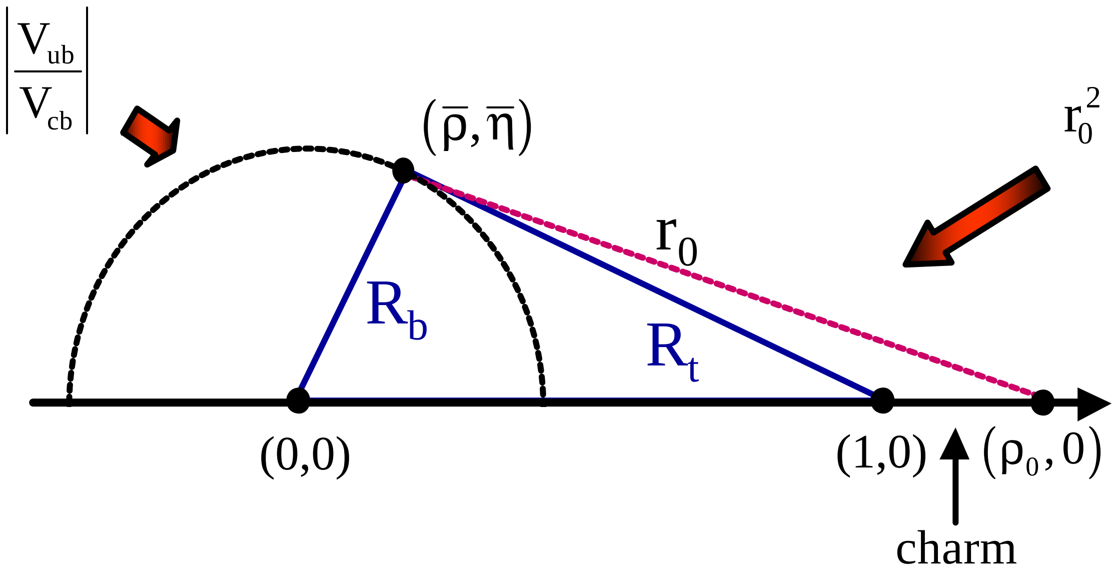
$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$, $Br\left(K_L \to \pi^0 \nu\bar{\nu}\right)$ ⇒ $\mathrm{Im}\,\lambda_t$, $\mathrm{Re}\,\lambda_t$ ⇒ $\bar{\rho}$, $\bar{\eta}$, Unitarity Triangle, $\sin 2\beta$, $|V_{td}|$

$$\lambda_t = V_{ts}^* V_{td}$$

$K^+ \to \pi^+ \nu\bar{\nu}$ in the $(\bar{\rho}, \bar{\eta})$ Plane

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 4.31 \cdot 10^{-11} A^4 X^2 (m_t) \frac{1}{\sigma}\left[(\sigma\bar{\eta})^2 + (\rho_0 - \bar{\rho})^2\right]$$

$$\sigma = \frac{1}{\left(1-\lambda^2/2\right)^2} \qquad \rho_0 = 1 + \frac{P_c}{A^2 X(m_t)} \approx 1.4$$



$$r_0^2 = \frac{1}{A^4 X^2 (m_t)}\left[\frac{\sigma Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)}{4.31 \cdot 10^{-11}}\right]$$

$$R_t = 1 + R_b^2 - 2\bar{\rho}$$

$$V_{td} = A\lambda^3\left(1 - \bar{\rho} - i\bar{\eta}\right)$$

$$|V_{td}| = \lambda |V_{cb}| R_t$$

Anatomy of $|V_{td}|$ from $K^+ \to \pi^+ \nu\bar{\nu}$

$$\frac{\Delta|V_{td}|}{|V_{td}|} = \underbrace{0.044}_{\text{scale}} + \frac{\Delta|V_{cb}|}{|V_{cb}|} + 0.73\frac{\Delta\bar{m}_c}{\bar{m}_c} + 0.66\frac{\Delta Br(K^+)}{Br(K^+)}$$

Uncertainties from $R_b,\ m_t,\ \Lambda_{\overline{MS}}$ very small

$\Delta|V_{cb}| = \pm 0.001 \qquad \Delta\bar{m}_c = \pm 50\text{MeV} \qquad \Delta Br(K^+) = \pm 10\%$

$$\frac{\Delta|V_{td}|}{|V_{td}|} = 0.044 + 0.025 + 0.028 + 0.066$$

⇒ $|V_{td}|$ with 8.7% accuracy

Can be improved through:

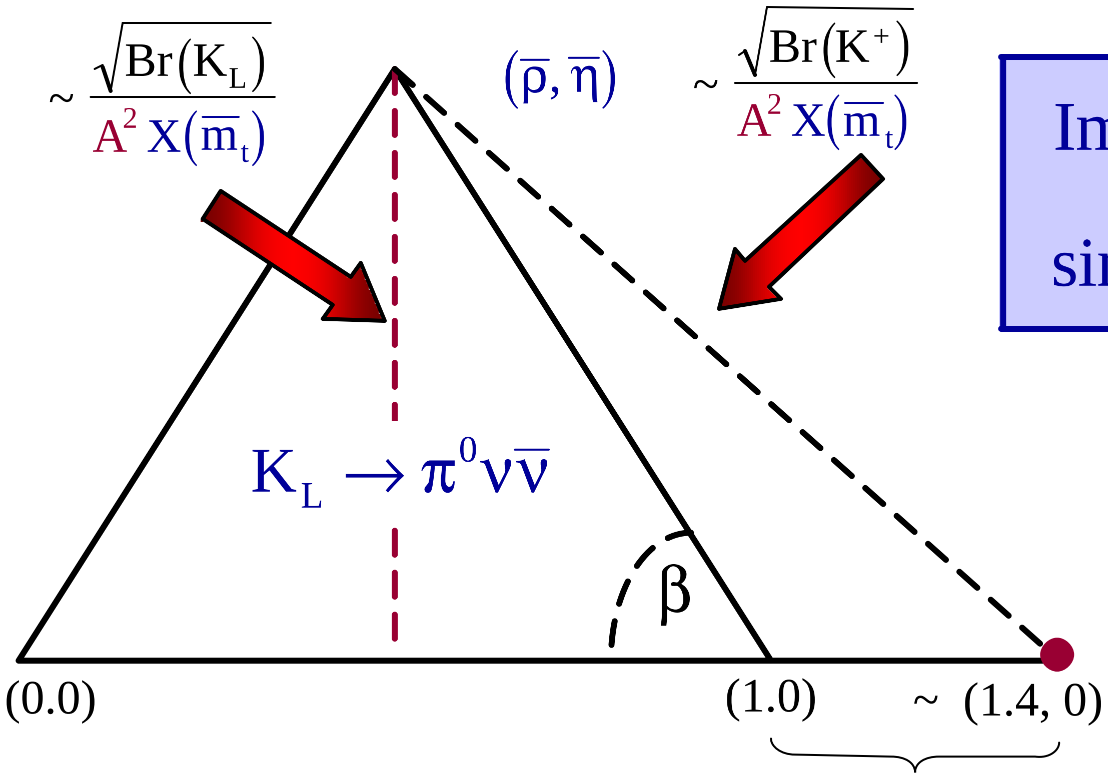
- NNLO analysis
- Reduction of $\Delta|V_{cb}|$
- Reduction of $\Delta\bar{m}_c$
- Reduction of $\Delta Br(K^+)$

⇒ $4-5\%$ Determination possible

Present knowledge of $|V_{td}|$: $6-12\%$ dependently on error analysis

UT from $K \rightarrow \pi\nu\bar{\nu}$

Buchalla
AJB



$$\mathrm{Im}\,\lambda_t = F_1(\bar{m}_t, Br(K_L))$$

$$\sin 2\beta = F_2(P_c, Br(K_L), Br(K^+))$$

$$\lambda_t = V_{ts}^* V_{td}$$

$\sin 2\beta$ $(K \rightarrow \pi\nu\bar{\nu})$ ⟷ $\sin 2\beta$ $(B \rightarrow J/\psi, K_s)$ $\rightarrow \varphi\, K_s$

[$X(\bar{m}_t) \sim \bar{m}_t^{1.15}$]

(0.40 ± 0.06) ⟹ $\sim \frac{P_c}{A^2 X(\bar{m}_t)}$

K-Physics ⟷ B - Physics

Test of SM and Beyond

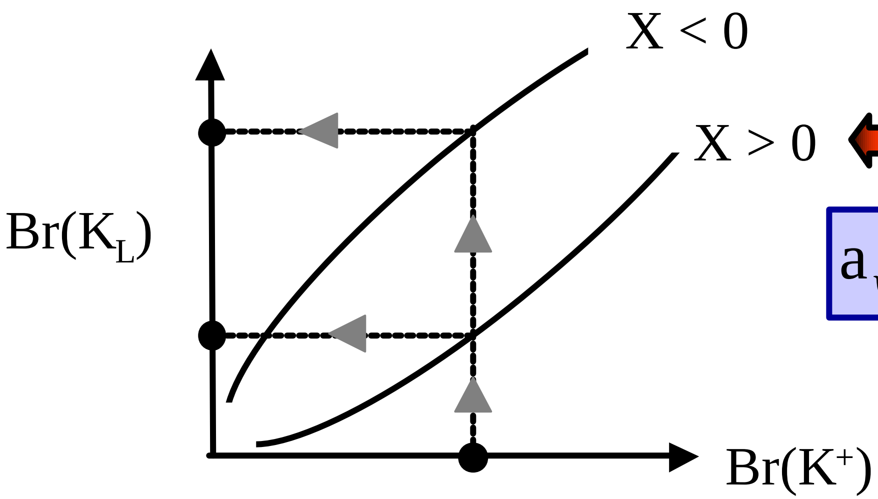
Intriguing Property of Models with Minimal Flavour Violation

AJB, Fleischer (01)

$$Br(K_L) = F\left(Br(K^+),\ a_{\psi K_S},\ sgn(X)\right)$$

TH very clean

Independently of any parameters, for given $Br(K^+)$ and $a_{\psi K_S}$ only two values of $Br(K_L)$ possible.



(SM, MSSM)

$a_{\psi K_S}$ = fixed

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) \leq 3.9 \cdot 10^{-10}$$

(90% C.L.)

$a_{\psi K_S} \leq 0.8$

$$Br(K_L \to \pi^0 \nu\bar{\nu}) \leq \begin{cases} 3.1 \cdot 10^{-10} & X > 0 \\ 4.9 \cdot 10^{-10} & X < 0 \end{cases}$$

KTeV: $\leq 5.9 \cdot 10^{-7}$

8.

Brief Look Beyond Standard Model

What is affected by New Physics?

Assume: 3 Generations Unitarity

1

V_{ud}	V_{us}	
V_{cd}	V_{cs}	V_{cb}
		V_{tb}

All determined in tree level processes → Essentially independent of New Physics

2

$$\frac{V_{ts}}{V_{cb}} = -1 + \frac{1}{2}\lambda^2\left[1 - 2(\rho + i\eta)\right]$$

$(R_b < 0.5)$ → At most 5% effect; Typically: 1% effect } Possible impact of New Physics

$$V_{ts} \cong -V_{cb}$$

Independently of New Physics

3

$$V_{ub} = |V_{ub}|e^{-i\gamma}$$

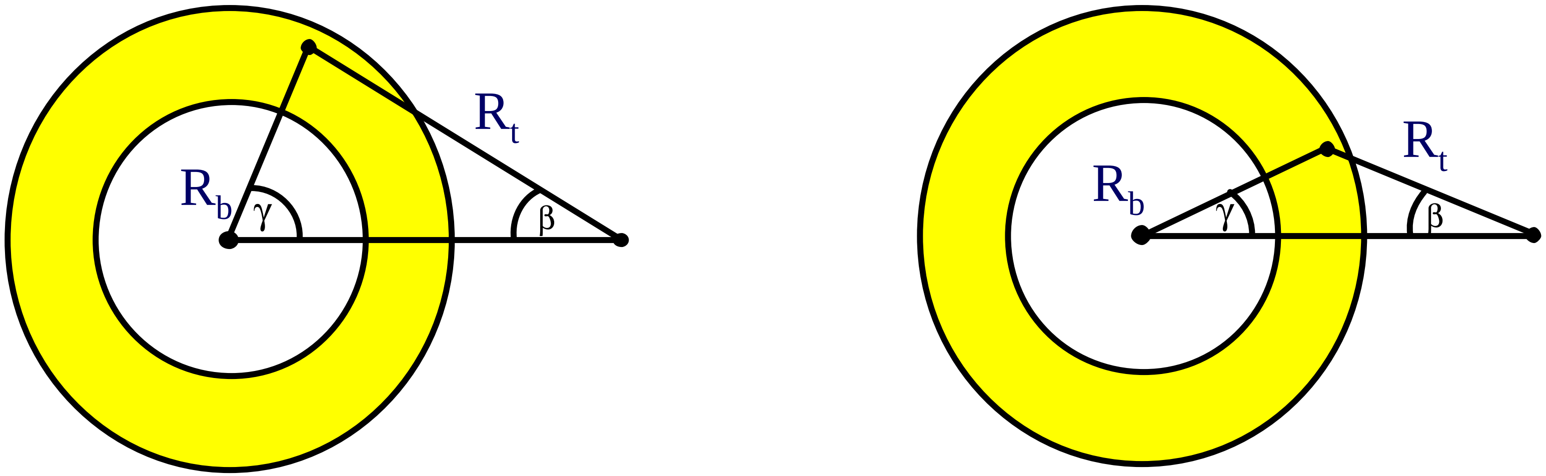
Essentially independent of New Physics

$$V_{td} = |V_{td}|e^{-i\beta}$$

Can be affected by New Physics

Unitarity Connection: $|V_{ub}|e^{-i\gamma} \Leftrightarrow |V_{td}|e^{-i\beta}$

$$R_b e^{i\gamma} + R_t e^{-i\beta} = 1$$



R_b = Independent of New Physics

R_t, β, γ = Can be affected by New Physics

Impact of New Physics

General Comments

- Essentially no impact on tree-decays

- Possible substantial impact on loop induced decays (on short distance physics)

⇓

- No impact on determination of
  $\lambda \equiv |V_{us}|$, $|V_{cb}|$, $|V_{ub}/V_{cb}|$

- No impact on calculations of non-perturbative parameters (B_i) (except for new B_i's from new operators or new strong forces)

- Possible substantial impact on
  $\bar{\rho}$, $\bar{\eta}$, $\triangle$, ~~CP~~, rare decays

Special Features of $\not{CP}$ in SM

1. CP is **<u>explicitly</u>** broken (Yukawa couplings)

2. **Single** complex phase (δ_{KM})

3. $\not{CP}$ only in charged current weak interactions ($W^{\pm}$) of quarks (flavour changing)

4. CP strongly suppressed in **neutral current** transitions (Z^0,γ,G,H^0) and very strongly suppressed in **flavour diagonal** transitions (electric dipole moments)

5. CP is not an approximate symmetry ($\sin\delta_{KM}$=0(1)).
$\not{CP}$ small only because of small quark mixing angles

Possible Features of $\not{C}P$ beyond SM

1. CP is **<u>explicitly</u>** and/or **<u>spontaneously</u>** ($ve^{i\alpha}$) broken

2. **Several** complex phases

3. $\not{C}P$ occurs at tree-level in both charged current and **neutral current** (Z^0) interactions of quarks, in lepton interactions, in new sectors beyond SM (extended Higgs, SUSY, ...), in **strong interactions**, in **scalar** interactions, in **flavour diagonal** interactions

4. Large $\not{C}P$ effects in **neutral current** and **flavour diagonal** transitions possible

5. CP is an approximate symmetry (all complex phases small)

Results in MSSM

AJB, Gambino, Gorbahn, Jäger, Silvestrini (hep-ph/0007313)

Define:

$$T(Q) \equiv \frac{[Q]_{MSSM}}{[Q]_{SM}}$$

$$0.53 \le T(\varepsilon'/\varepsilon) \le 1.07$$

$$0.65 \le T(K^+ \to \pi^+ \nu\bar{\nu}) \le 1.02$$

$$0.41 \le T(K_L \to \pi^0 \nu\bar{\nu}) \le 1.03$$

$$0.48 \le T(K_L \to \pi^0 e^+ e^-) \le 1.10$$

$$0.73 \le T(B \to X_S \nu\bar{\nu}) \le 1.34$$

$$0.68 \le T(B_S \to \mu\bar{\mu}) \le 1.53$$

Constraints on supersymmetric parameters from:

i) $B^0_{d,s} - \bar{B}^0_{d,s}$ mixings, ε, $B \to X_S \gamma$

ii) EW – precision studies

iii) Lower bound on M_{H^0}

Rare K Decays in General SUSY Models

AJB, Colangelo, Isidori, Romanino, Silvestrini (hep 9908371)

Main new effects:

γ-magnetic Penguins
Enhanced Z^0-Penguins

Constraints from ΔM_K, ε_K
ε'/ε, $K_L \to \mu\bar{\mu}$ and Renormalization Group

Most probable bounds:	$(SM)_{max}$
$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) \lesssim 1.2 \cdot 10^{-10}$	$0.4 \cdot 10^{-10}$
$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \lesssim 1.7 \cdot 10^{-10}$	$1.1 \cdot 10^{-10}$
$Br\left(K_L \to \pi^0 e^+ e^-\right) \leq 2.0 \cdot 10^{-11}$	$0.7 \cdot 10^{-11}$

Larger values possible, but rather unlikely

Earlier Analyses: Nir, Worah; AJB, Romanino, Silvestrini

9.

Special Topic

10.

Short Outlook

Shopping List 1999-2008

- ★ ε'/ε at $\Delta(\varepsilon'/\varepsilon) = 10^{-4}$
- ★ $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$
- ★ $\sin 2\beta$ from $B \to \psi K_S$, φK_S
- ★ $(\Delta M)_s$ from $B_s^o - \bar{B}_s^o$ Mixing
- ★ $B \to X_{s,d}\mu\bar{\mu}$, $B_{s,d} \to \mu\bar{\mu}$, $B \to X_{s,d}\nu\bar{\nu}$
- ★ $K_{L,S} \to \pi^o e^+ e^-$, $K_L \to \mu e$
- ★ α and γ from B-decays
- ★ Electric Dipole Moment of the Neutron
- ★ Improved Measurements of V_{ub}, V_{cb}, $B \to X_{d,s}\gamma$
- ★ Improved Calculations of Hadronic (Non-Pertubative) Parameters

Shopping List for 2003 - 2004

sin 2β from
$B \to \varphi K_S$
(New Physics?)

Clarification of
CP-Violation in
$B_d^0 \to \pi^+\pi^-$

First Measurements
of ΔM_S and
$B_{s,d} \to \mu\bar{\mu}$ (?)
(Tevatron)

(Improved Calculations
of ξ, $F_{B_d}\sqrt{\hat{B}_d}$, $F_{B_s}\sqrt{\hat{B}_s}$)

Improved
Measurement
of $K^+ \to \pi^+\nu\bar{\nu}$
(Brookhaven)

First Measurements
of γ in
B Decays

Improved Determinations
of $|V_{cb}|$ and $R_b \sim \frac{|V_{ub}|}{|V_{cb}|}$

Parameters in Electroweak Gauge Sector

$\alpha_{QED},\ G_F,\ \sin^2\theta_W$

⇓

$\alpha_{QED},\ G_F,\ M_Z$

⇓

$\alpha_{QED},\ M_W,\ M_Z$

Flavour Sector

Until 2001

$|V_{us}|,\ |V_{cb}|,\ \bar{\rho},\ \bar{\eta}$

For the next years

$|V_{us}|,\ |V_{cb}|,\ R_t,\ \sin 2\beta$

appears like a better choice.

Or, even better:

$|V_{us}|,\ |V_{cb}|,\ R_t,\ \beta$

AJB
Parodi
Stocchi

Fundamental Flavour Parameters

AJB, Parodi, Stocchi, hep-ph/0207101 (updated)

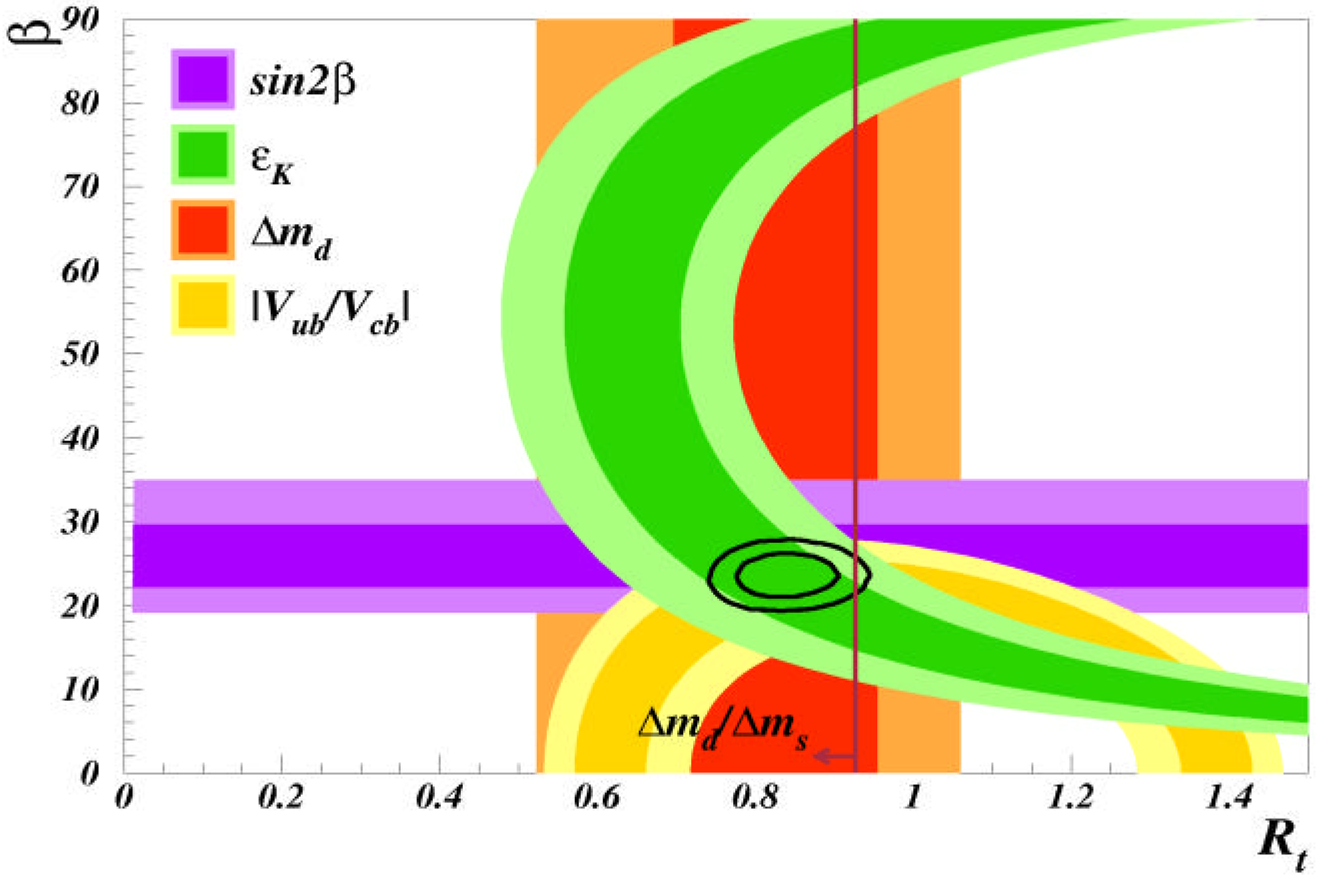
$$|V_{us}| = 0.2240 \pm 0.0036 \qquad |V_{cb}| = (41.3 \pm 0.7) \cdot 10^{-3}$$

$$R_t = 0.91 \pm 0.05 \qquad \beta = \begin{cases} (23.6 \pm 2.2)^\circ \ (a_{\psi K_s}) \\ (23.2 \pm 1.4)^\circ \ (\text{total}) \end{cases}$$

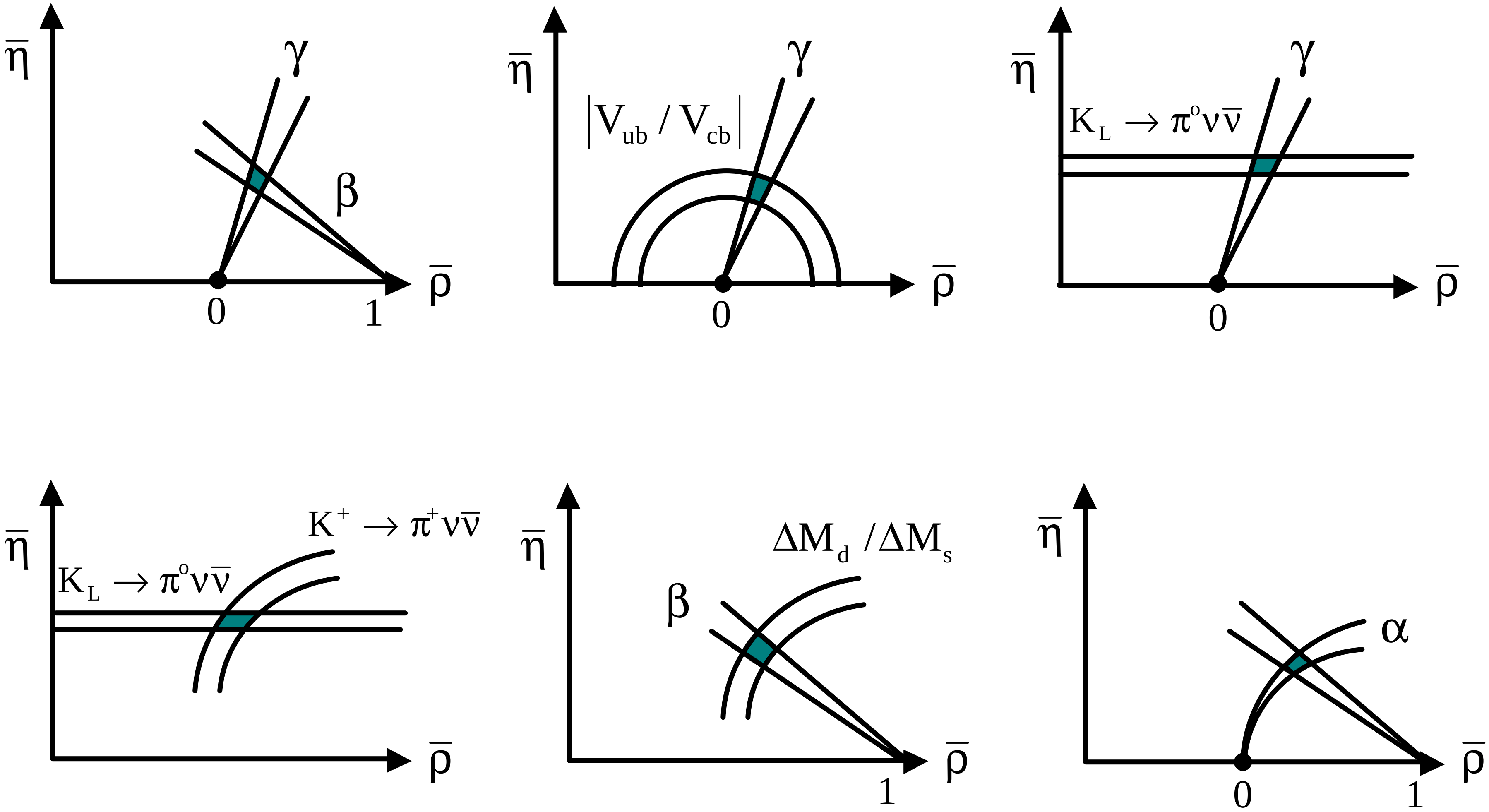
$$\sin 2\beta = \begin{cases} 0.734 \pm 0.054 & (a_{\psi K_s}) \\ 0.725 \pm 0.033 & (\text{total}) \end{cases}$$

(R_t, β) Plot 2002

(AJB, Parodi, Stocchi)



Searching for New Physics



1989-1999

Electroweak Precision Studies

α_{QED} , G_F , M_Z , m_t , M_W, m_H

($\sin^2\theta_W$)

Spontaneous Symmetry Breakdown

2000-2011

CKM Precision Studies

λ , A , $\bar{\rho}$, $\bar{\eta}$, m_t

with the hope to discover **New Physics**
and learn about **Flavour Dynamics**

The Future until 2011 should be very exciting