CP Violation and Rare K- and B-Decays at the End of the Second Millennium

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(September 1999)

1. Grand View

2. Present Status of $\triangle$

3. Present Status of ε'/ε

4. Rare B-Decays

5. Rare K-Decays

6. $\cancel{CP}$ in B-Decays

7. Summary

1.

Grand View

Cabibbo-Kobayashi-Maskawa Matrix

Parameters: $\boxed{\lambda, A, \rho, \eta}$ (Wolfenstein)

$\lambda = 0.22$

	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

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

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

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

$(A = 0.82 \pm 0.04)$

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

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

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

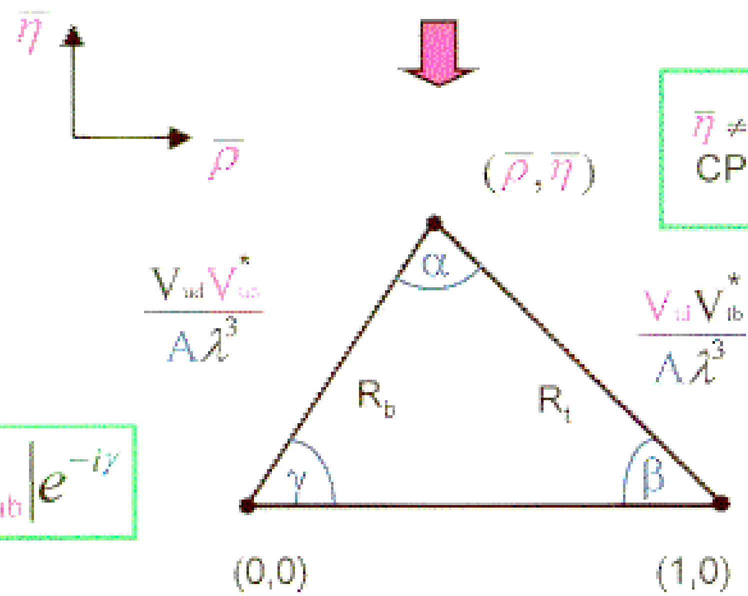
$$R_t \equiv \sqrt{(1-\bar{\rho})^2+\bar{\eta}^2} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$

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

Unitarity Triangle

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

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



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

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

An Important Target of Particle Physics

$$J_{CP} = \lambda\left(1 - \frac{\lambda^{2}}{2}\right) \mathrm{Im}\, \lambda_t \doteq 2 \cdot$$

Area of unrescaled UT

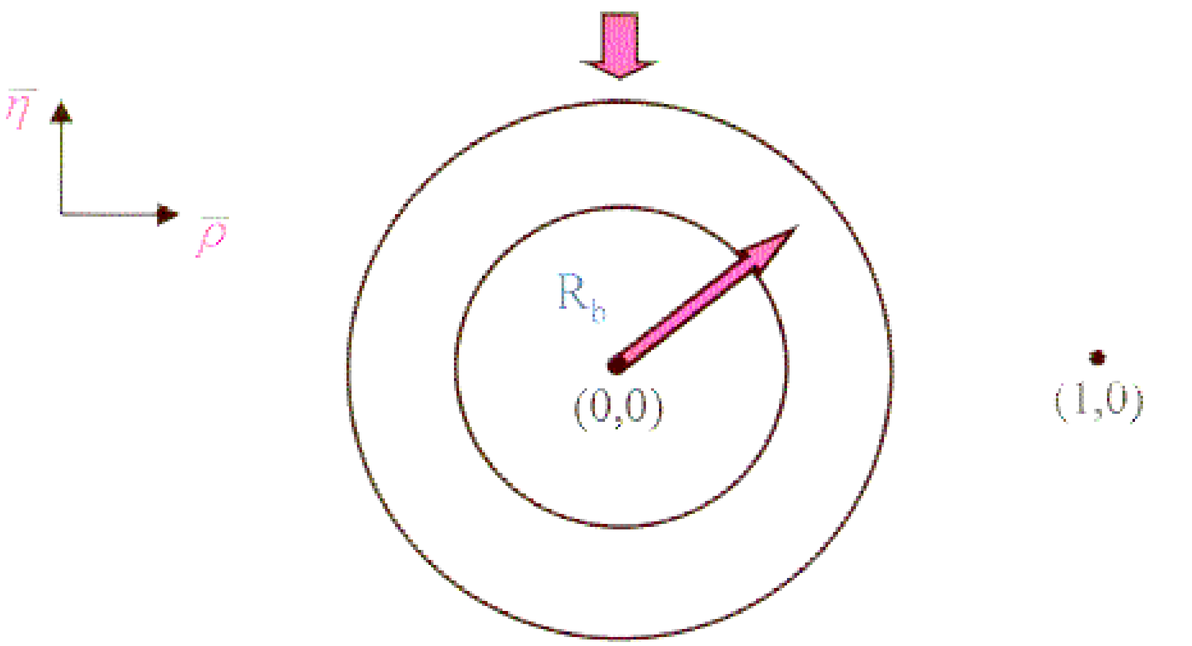
$$\lambda_t = V_{ts}^{*} V_{td}$$

Information from Tree Level Decays

$$|V_{us}| = 0.2205 \pm 0.0018 = \lambda$$

$$|V_{cb}| = 0.040 \pm 0.002 \qquad (A = 0.82 \pm 0.04)$$

$$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.091 \pm 0.016 \qquad (R_b = 0.40 \pm 0.07)$$



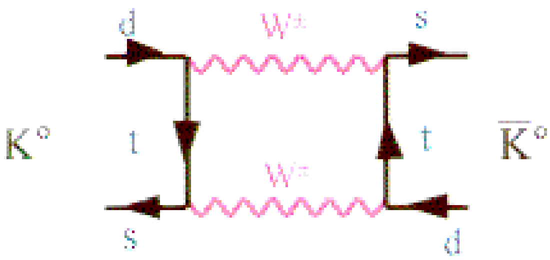
Apex of Unitarity Triangle somewhere on this Band

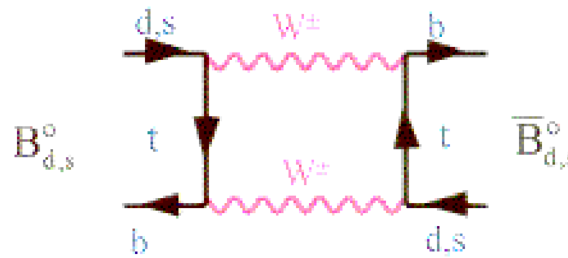
To find it **GO TO**

Loop Induced Decays

CP-Violation in B-Decays

FCNC $\overset{GIM}{\equiv}$ Loop Induced Decays

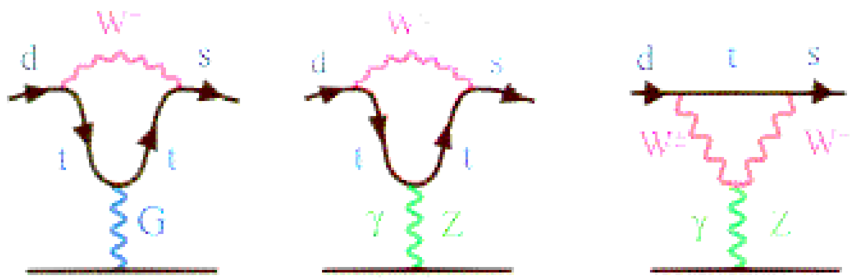


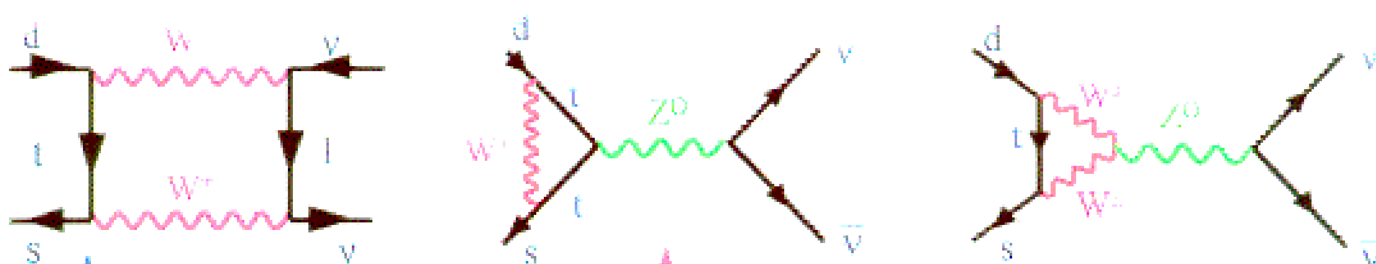


$\cancel{CP}$ ε_K-Parameter
ΔM (K_L-K_S)

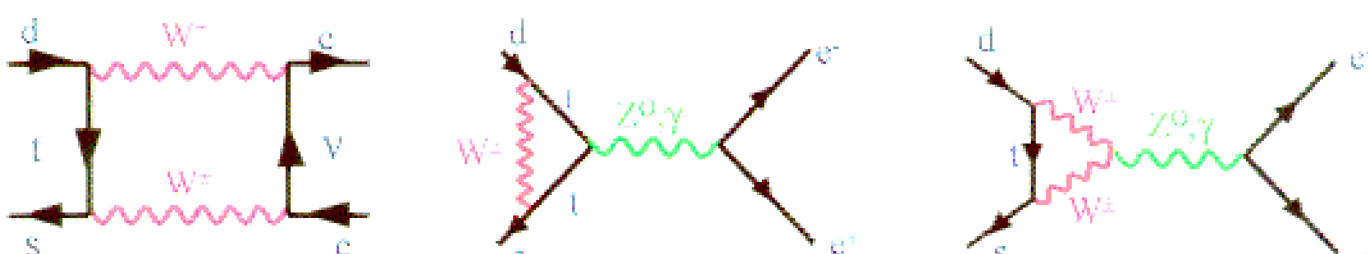
$B^o_d - \overline{B}^o_d$ Mixing

ε'

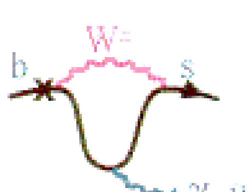




$K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$ $K_L \to \mu\bar{\mu}$, $B \to \mu\bar{\mu}$, $B \to X_s \nu\bar{\nu}$



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

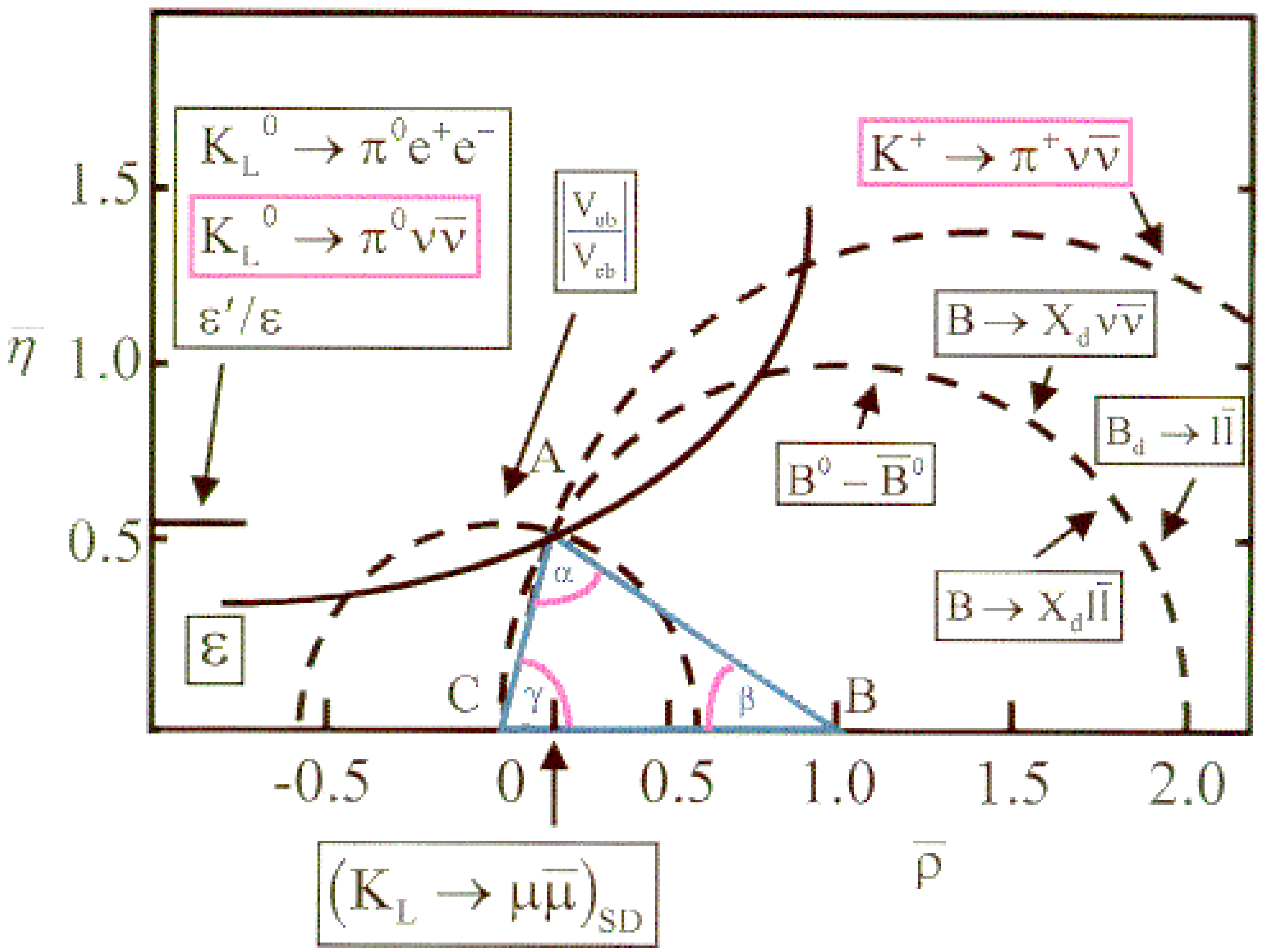


$B \to X_s \gamma$ $B \to K^* \gamma$

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

Hunting Δ with Rare and $\cancel{CP}$ Decays

2011:



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

★ $\begin{Bmatrix} \text{CP Asymmetries} \\ \text{in} \\ \text{B-Decays} \end{Bmatrix} \Rightarrow \begin{Bmatrix} \sin 2\alpha \\ \sin 2\beta \\ \sin\gamma \end{Bmatrix}$

$$\boxed{1989\text{-}1998}$$

Electroweak Precision Studies

$$\boxed{\alpha_{QED}\,,\ G_F\,,\ M_Z\,,\ m_t\,,\ m_H}$$

$(M_W, \sin^2\theta_W)$

Spontaneous Symmetry Breakdown

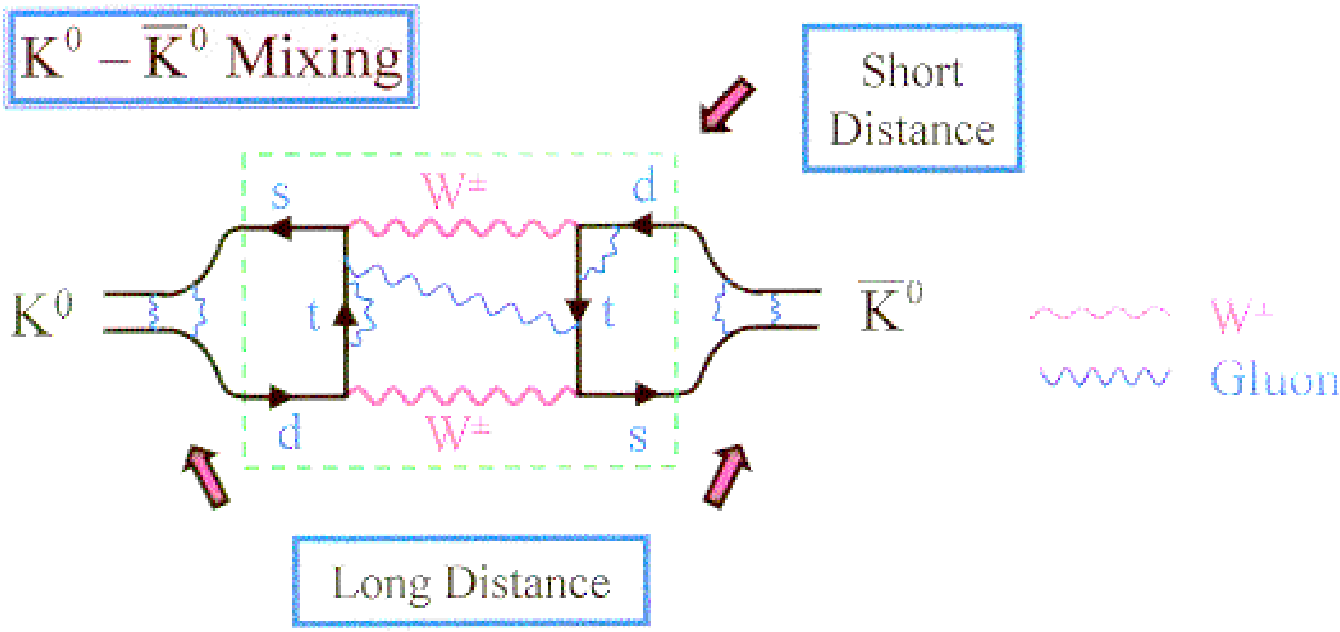
$$\boxed{2000\text{-}2011}$$

CKM Precision Studies

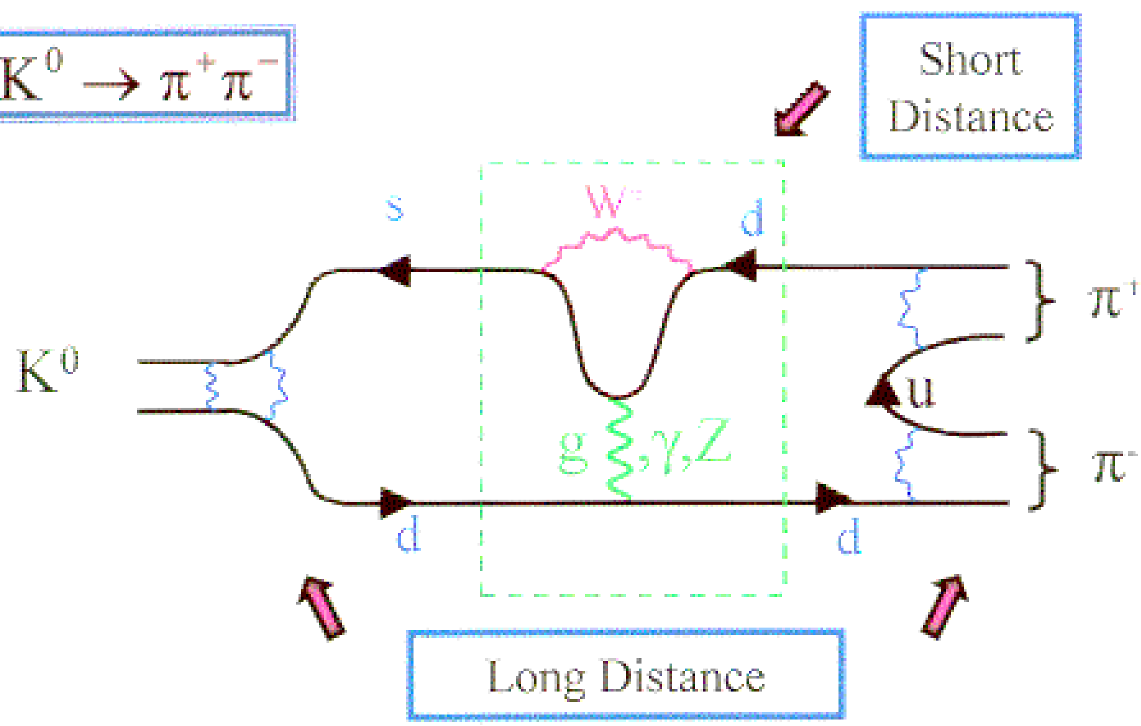
$$\boxed{\lambda\,,\ A\,,\ \rho\,,\ \eta\,,\ m_t}$$

The Problem of Strong Interactions

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



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



SD : Perturbative (Asymptotic Freedom)

LD : Non-Perturbative (Confinement)

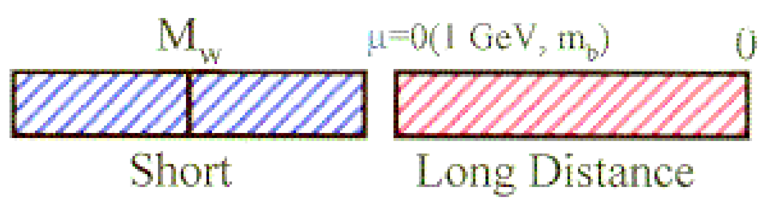
Operator Product Expansion

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

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

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

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



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

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

$$Q_6 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_{V+A} \quad \Rightarrow \quad B_6$$

$$Q_8 = \frac{3}{2} (\bar{s}_\alpha d_\beta)_{V-A} \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\alpha)_{V+A} \quad \Rightarrow \quad B_8$$

$$\langle (\pi\pi)_{I=0} | Q_6 | K^0 \rangle = -4\sqrt{\frac{3}{2}} \left[\frac{m_K^2}{m_s(\mu)}\right]^2 (F_K - F_\pi)\ B_6(\mu)$$

Very weak μ-dependence

Main Theoretical Uncertainties

1. Values of $\langle F|Q_i(\mu)|M\rangle$

2. Matching between

$$C_i(\mu) \text{ and } \langle F|Q_i(\mu)|M\rangle$$

Full control
over μ
and Renormalization
Scheme dependence

Poor control
over μ
and Renormalization
Scheme dependence

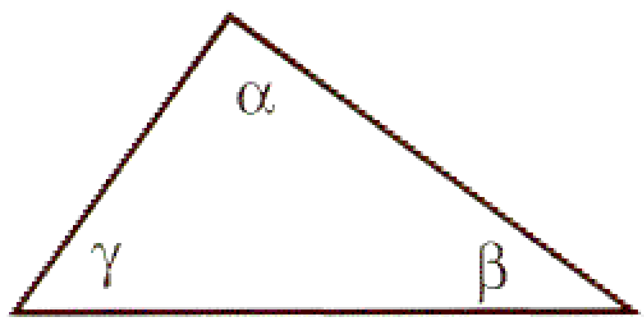
Left over unphysical
μ and RS dependence

Status of NLO

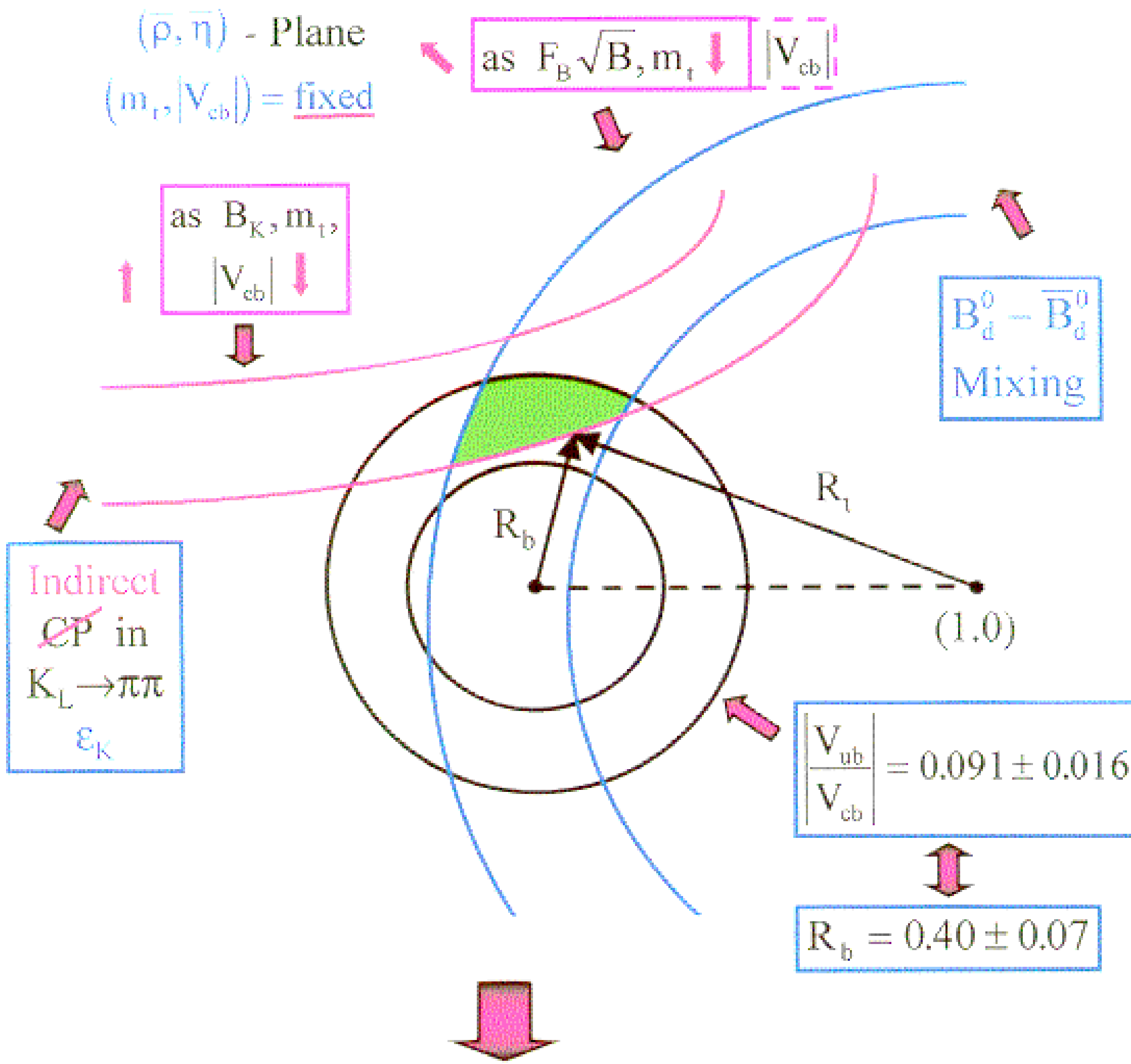
Review: Buchalla, AJB, Lautenbacher (Rev. Mod. Phys. 96)

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)
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; Ali, Greub; Pott; Adel, Yao; AJB, Kwiatkowski, Pott; 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

Present Status of

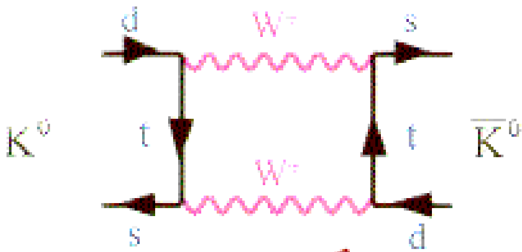


Standard Analysis



$|V_{td}|$, Unitarity Triangle,
Predictions for Rare and
CP Violating Decays

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



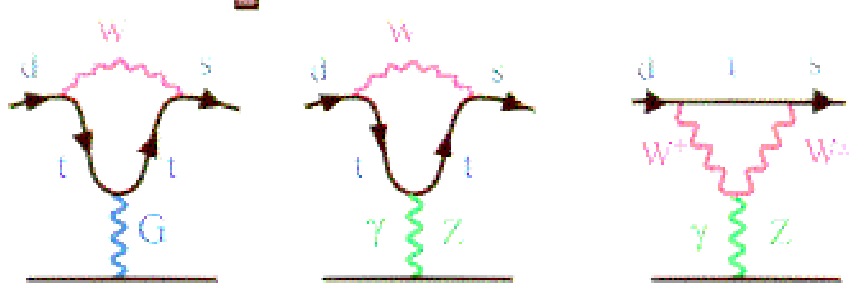
$(K^0 - \overline{K}^0$ Mixing$)$

Mass Eigenstates are not CP Eigenstates

indirect CP violation (ε)

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

direct CP-Violation (ε′)



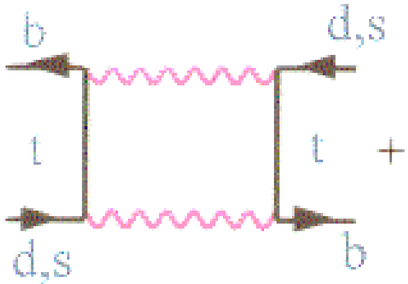
$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon'$$

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

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

ε′=0 in Superweak Models
Wolfenstein (64)

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



+ QCD $\Rightarrow (\Delta M)_{d,s} \Leftarrow$ CLEO, ARGUS, 4*LEP

$$|V_{td}| = 8.8 \cdot 10^{-3} \underbrace{\left[\frac{200\,\text{MeV}}{F_{Bd}\sqrt{B_d}}\right]\sqrt{\frac{0.55}{\eta_B}}}_{\text{Theory}} \underbrace{\left[\frac{170\,\text{GeV}}{\overline{m}_t(m_t)}\right]^{0.76}\left[\frac{(\Delta M)_d}{0.50/\text{ps}}\right]^{1/2}}_{\text{Experiment}}$$

$$R_t = \left[\frac{|V_{td}|}{8.8 \cdot 10^{-3}}\right]\left[\frac{0.040}{|V_{cb}|}\right]$$

$$R_t^{\max} = \xi \sqrt{\frac{10.2/\text{ps}}{(\Delta M)_s}} \qquad \xi = \frac{F_{Bs}\sqrt{B_s}}{F_{Bd}\sqrt{B_d}}$$

Exp:

$\overline{m}(m_t) = 166 \pm 5$ GeV	(CDF, D∅)
$(\Delta M)_d = (0.471 \pm 0.016)/\text{ps}$	(LEP, CLEO)
★ $(\Delta M)_s > 12.4/\text{ps}$	(LEP)

TH:

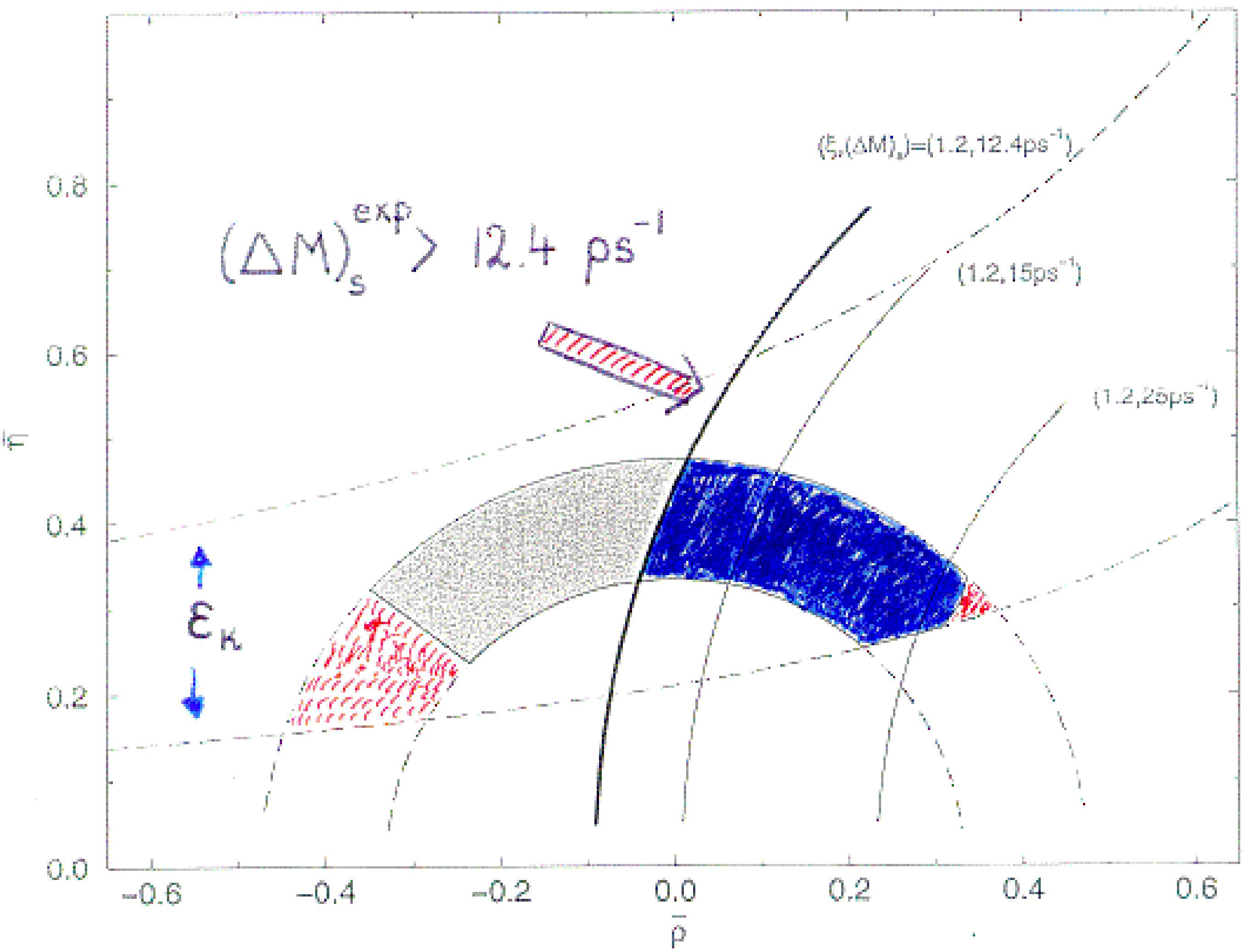
$\eta_B = 0.55 \pm 0.01$ (AJB, Jamin, Weisz)

$F_{Bd}\sqrt{B_d} = 200 \pm 40$ MeV; $\xi = 1.14 \pm 0.08$ (Q)

10% (?)

Present Unitarity Triangle

(1999 : $(\Delta M)_s^{exp} > 14.3\ ps^{-1}$ 95% C.L.)



Excluded by $B_d^0 - \bar{B}_d^0$

$66^\circ \leq \alpha \leq 113$

$18^\circ \leq \beta \leq 29^\circ$

$44^\circ \leq \gamma \leq 97^\circ$

Using

$\hat{B}_K = 0.80 \pm 0.15$

Output

$$\left|V_{td}\right| = (8.4 \pm 1.4) \cdot 10^{-3}$$

$$\mathrm{Im}\ \left(V_{td} V_{ts}^*\right) = (1.33 \pm 0.30) \cdot 10^{-4}$$

$$\sin 2\beta = 0.71 \pm 0.13$$

$$\sin \gamma = 0.85 \pm 0.15$$

CDF : February 5, 1999

$A_{CP}(J/\psi\ K_s, t) \Rightarrow \sin 2\beta = 0.79 \begin{smallmatrix} +0.41 \\ -0.44 \end{smallmatrix}$

$A_{CP}(J/\psi\ K_s) \Rightarrow \sin 2\beta = 0.71 \pm 0.63$

CP-Violation in B-Decays at 93% C.L.

Targets in the Standard Analysis of $\triangle$

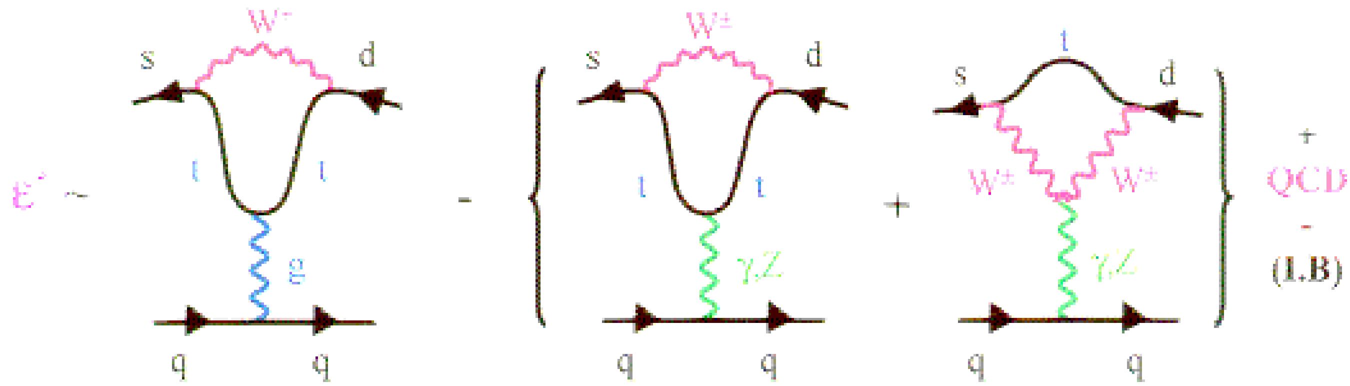
1. $\Delta M_s, \quad \xi = \dfrac{F_{B_s}\sqrt{B_s}}{F_{B_d}\sqrt{B_d}} \Rightarrow \{R_t, |V_{td}|\}$

2. $V_{cb}, \; V_{ub}, \; \hat{B}_K \Rightarrow \{\mathrm{Im}(V_{ts}^* V_{td})\}$

3. $F_{B_s}\sqrt{B_s}, \; F_{B_d}\sqrt{B_d} \Rightarrow \{|V_{ts}|, \; |V_{td}|\}$

Present Status of ε'/ε

ε'/ε in the Standard Model



QCD - Penguins

Ellis, Gaillard, Nanopoulos (76)
Gilman, Wise; Guberina
Peccei; AJB, Gérard

Electroweak - Penguins

Flynn, Randall (89)
Buchalla, AJB, Harlander (89)

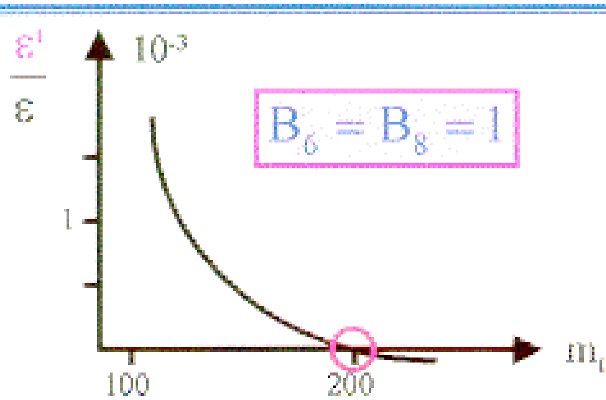
NLO: AJB, Jamin, Lautenbacher, Weisz
Ciuchini, Franco, Martinelli, Reina } (92, 93)

$\delta = \gamma$

$$\frac{\varepsilon'}{\varepsilon} = 10^{-4}\left[\frac{|V_{ub}||V_{cb}|\sin\delta}{1.34\cdot 10^{-4}}\right] F\left(m_t, \Lambda^{(4)}_{\overline{MS}}, m_s, B_6, B_8, \Omega_{\eta+\eta'}\right)$$

$$F \approx 18\cdot\left[\frac{110\ \mathrm{Mev}}{m_s(2\ \mathrm{GeV})}\right]^2 \left[\underbrace{B_6}_{P_{QCD}}(1-\Omega_{\eta+\eta'}) - \tilde{Z}(m_t)\underbrace{B_8}_{P_{EW}}\right]\left(\frac{\Lambda^{(4)}_{\overline{MS}}}{340\ \mathrm{MeV}}\right)$$

$$\tilde{Z}(m_t) \cong 0.4\left[\frac{m_t}{165\ \mathrm{GeV}}\right]^{2.5} \quad ; \quad \Omega_{\eta+\eta'} \cong 0.25$$



$\mathrm{Im}\,\lambda_t \equiv |V_{ub}||V_{cb}|\sin\delta$

Until February 24th 1999

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

After February 24th 1999

$$\frac{\varepsilon'}{\varepsilon} = \begin{cases} (28.0 \pm 4.1) \cdot 10^{-4} & \text{(KTeV)} \\ (18.5 \pm 7.3) \cdot 10^{-4} & \text{(NA48)} \\ (\qquad\qquad) \cdot 10^{-4} & \text{(KLOE)} \end{cases}$$

Grand Average: : $\frac{\varepsilon'}{\varepsilon} = (21.2 \pm 4.6) \cdot 10^{-4}$

$$(21.2 \pm 2.8) \cdot 10^{-4}$$

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

Christenson, Cronin, Fitch, Turlay (1964)

Munich 1999 Analysis

(hep-ph / 9904408)

Stefan	Bosch
Andrzej	Buras
Martin	Gorbahn
Sebastian	Jäger
Matthias	Jamin
Markus	Lautenbacher
Luca	Silvestrini

$$m_s(2\ \mathrm{GeV}) = (110 \pm 20)\ \mathrm{MeV} \qquad \Lambda^{(4)}_{\overline{MS}} = (340 \pm 50)\ \mathrm{MeV}$$

$$B_6 = 1.0 \pm 0.3 \qquad B_8 = 0.8 \pm 0.2$$

(with $B_6 \geq B_8$)

$$\Omega_{IB} = \Omega_{\eta+\eta'} = 0.25 \pm 0.08$$

$B_6^{(1/2)}$	$B_8^{(3/2)}$	$m_s(2\ \mathrm{GeV})$	Central	$\Lambda_{\overline{MS}}^{(4)} = 390\mathrm{MeV}$	Maximal
1.3	0.6	90	20.2	23.3	28.8
		110	12.8	14.8	18.3
		130	8.5	9.9	12.3
1.3	0.8	90	18.1	20.8	26.0
		110	11.3	13.1	16.4
		130	7.5	8.7	10.9
1.3	1.0	90	15.9	18.3	23.2
		110	9.9	11.5	14.5
		130	6.5	7.6	9.6
1.0	0.6	90	13.7	15.8	19.7
		110	8.4	9.8	12.2
		130	5.4	6.4	7.9
1.0	0.8	90	11.5	13.3	16.9
		110	7.0	8.1	10.4
		130	4.4	5.2	6.6
1.0	1.0	90	9.4	10.9	14.1
		110	5.5	6.5	8.5
		130	3.3	4.0	5.2

Status of B_6, B_8

(Before Summer 99)

Method	B_6	B_8
Lattice	-	0.69 - 1.06
Large-N	0.72 - 1.10 *)	0.42 - 0.64
Chiral Quark Model	1.07 - 1.58	0.75 - 0.79

*) A higher order term $0\,(p^2/N)$ $B_6 \to 1.5 - 1.6$ (??)

Lattice: Sharpe, Kilcup, Pekurovsky, Gupta
Bhattacharaya, Martinelli & APE

Large-N: Bardeen, AJB, Gérard (87)
Hambye, Köhler, Paschos, Soldan, Bardeen (98)
(Dortmund)

Chiral Quark Model: *Bertolini, Eeg, Fabbrichesi,* Lashin (98)
(Trieste)

Final Results (Munich)

Monte Carlo

$$\boxed{\begin{array}{ll} \dfrac{\varepsilon'}{\varepsilon} = \left(7.7\,{}^{+6.0}_{-3.5}\right)\cdot 10^{-4} & (\mathrm{NDR}) \\ \dfrac{\varepsilon'}{\varepsilon} = \left(5.2\,{}^{+4.4}_{-2.6}\right)\cdot 10^{-4} & (\mathrm{HV}) \end{array}}$$

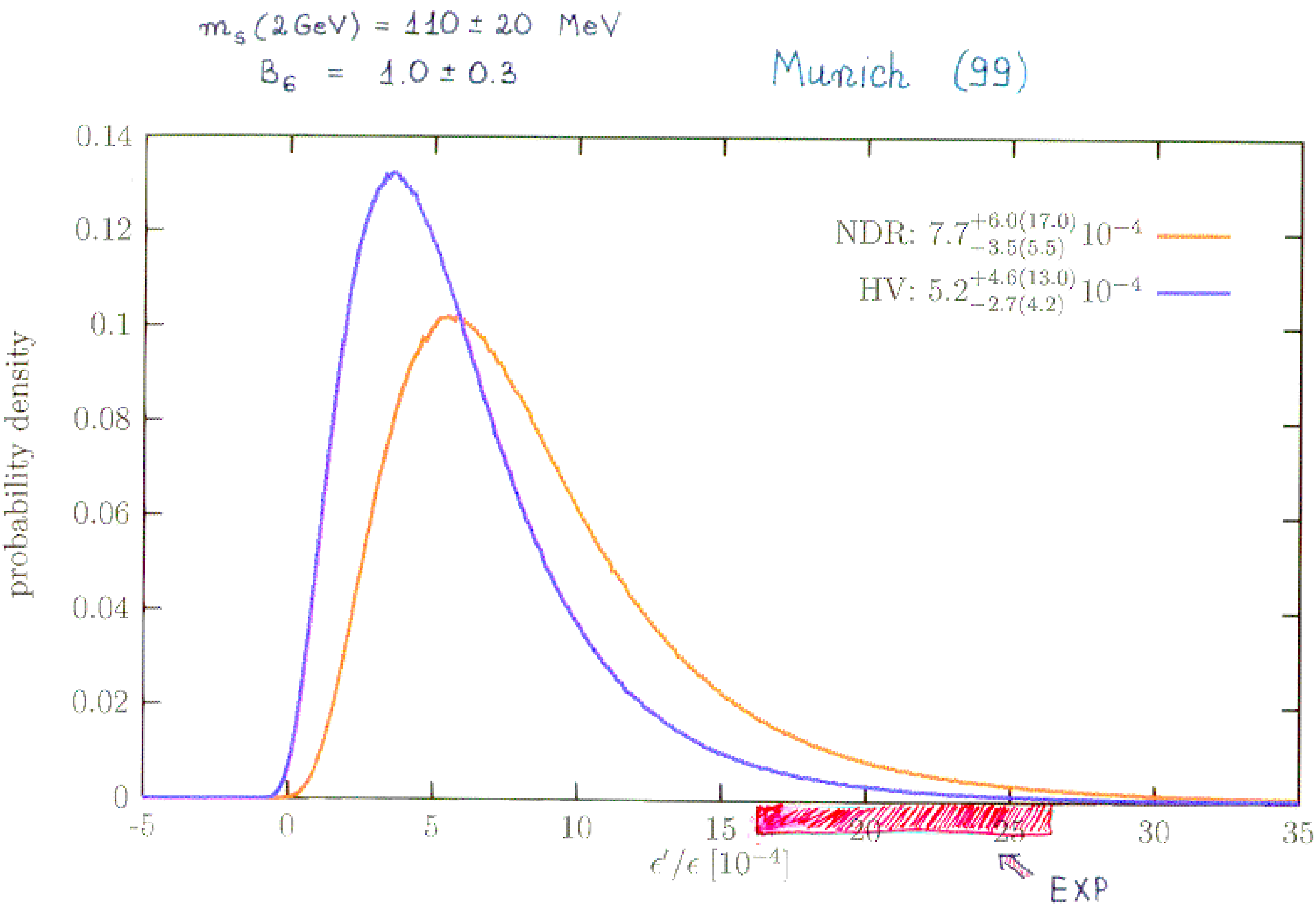
Scanning

$$\boxed{\begin{array}{ll} 1.1\cdot 10^{-4} \le \dfrac{\varepsilon'}{\varepsilon} \le 28.8\cdot 10^{-4} & (\mathrm{NDR}) \\ 0.3\cdot 10^{-4} \le \dfrac{\varepsilon'}{\varepsilon} \le 22.0\cdot 10^{-4} & (\mathrm{HV}) \end{array}}$$

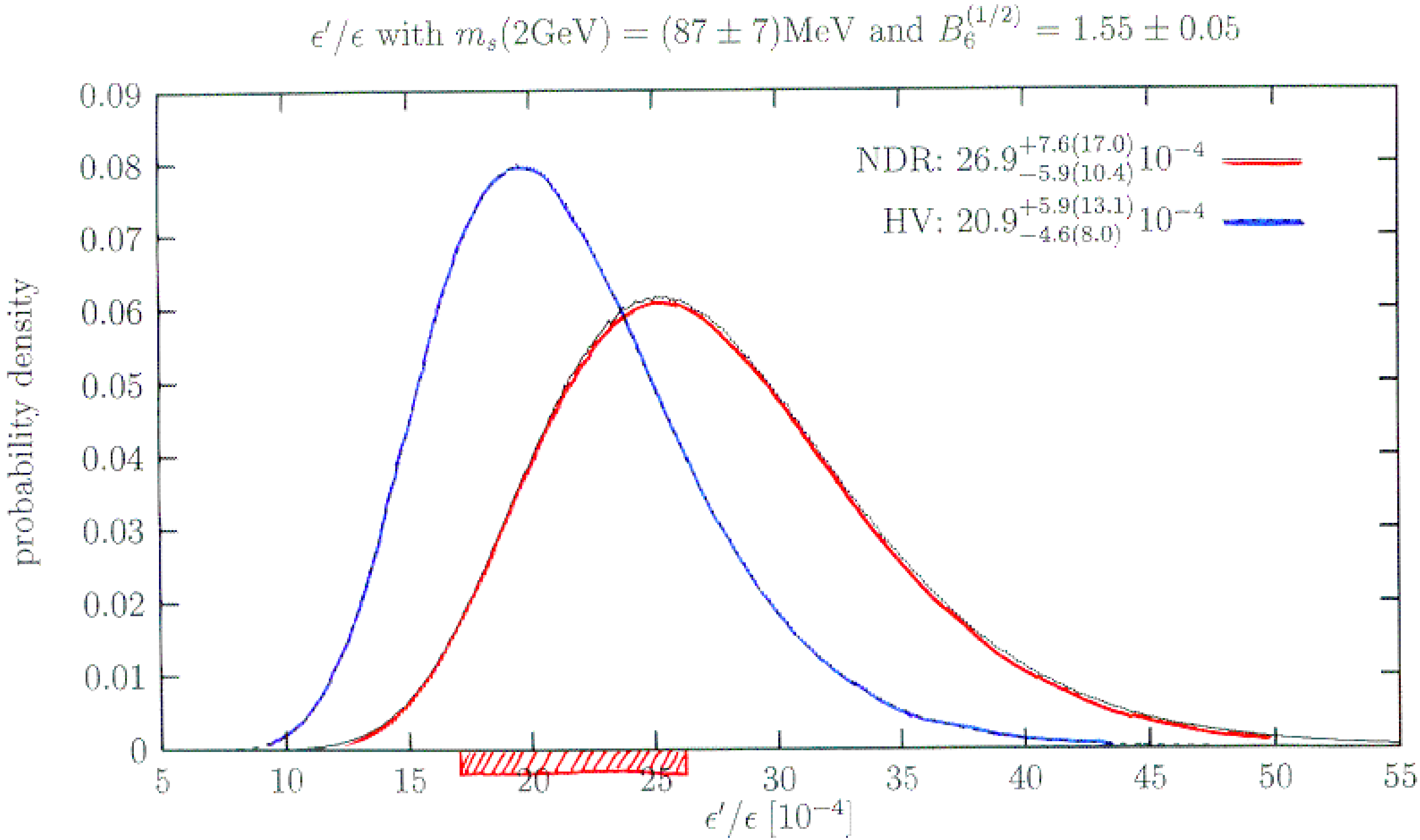
$$0.6\cdot 10^{-4} \le \varepsilon'/\varepsilon \le 26.9\cdot 10^{-4} \qquad (\mathrm{HV})^{*)}$$

Exp: $\boxed{\dfrac{\varepsilon'}{\varepsilon} = (21.2 \pm 4.6)\cdot 10^{-4}}$

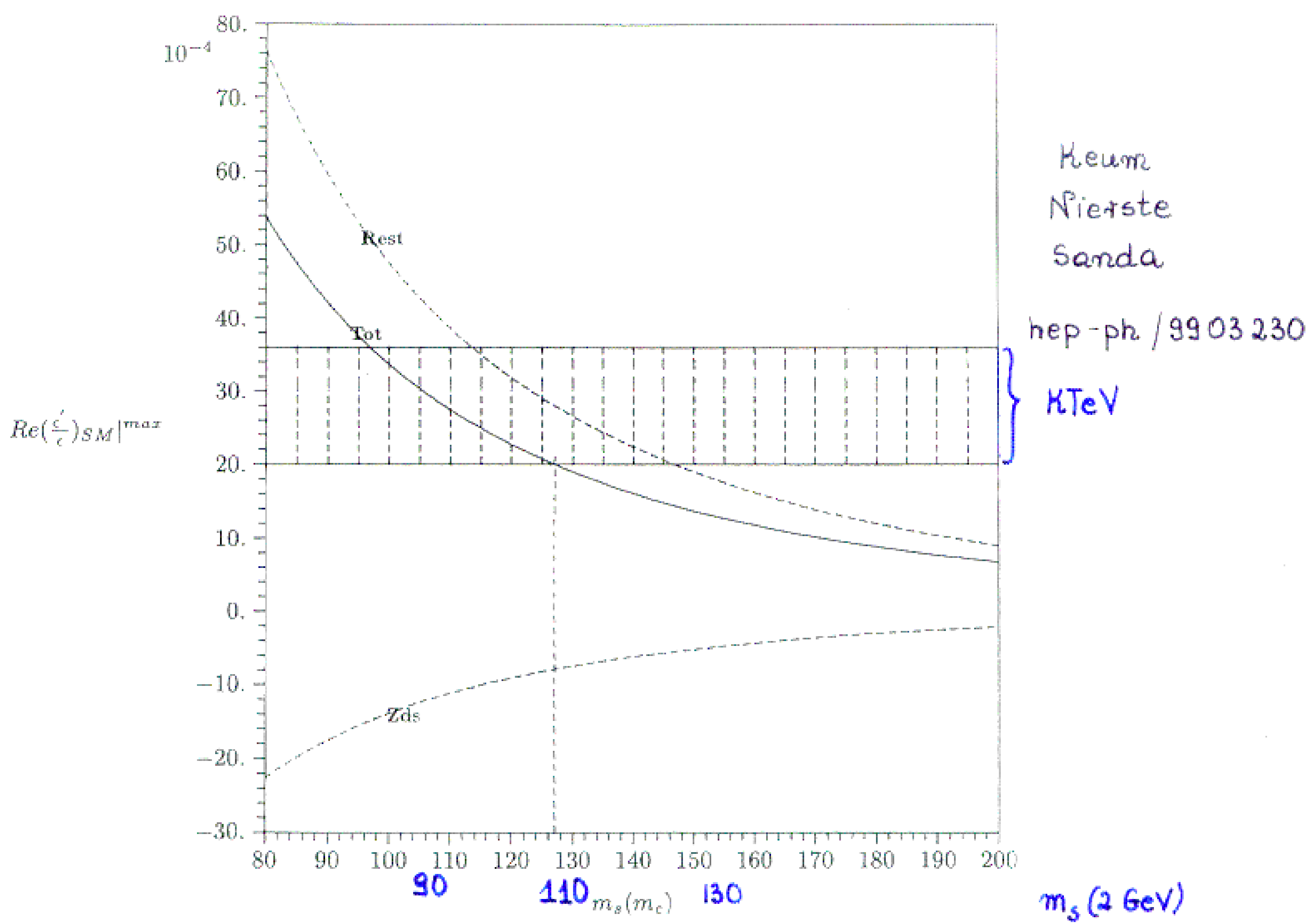
* $B_6^{HV} \cong 1.2\, B_6^{NDR} \qquad B_8^{HV} \cong 1.2\, B_8^{NDR}$



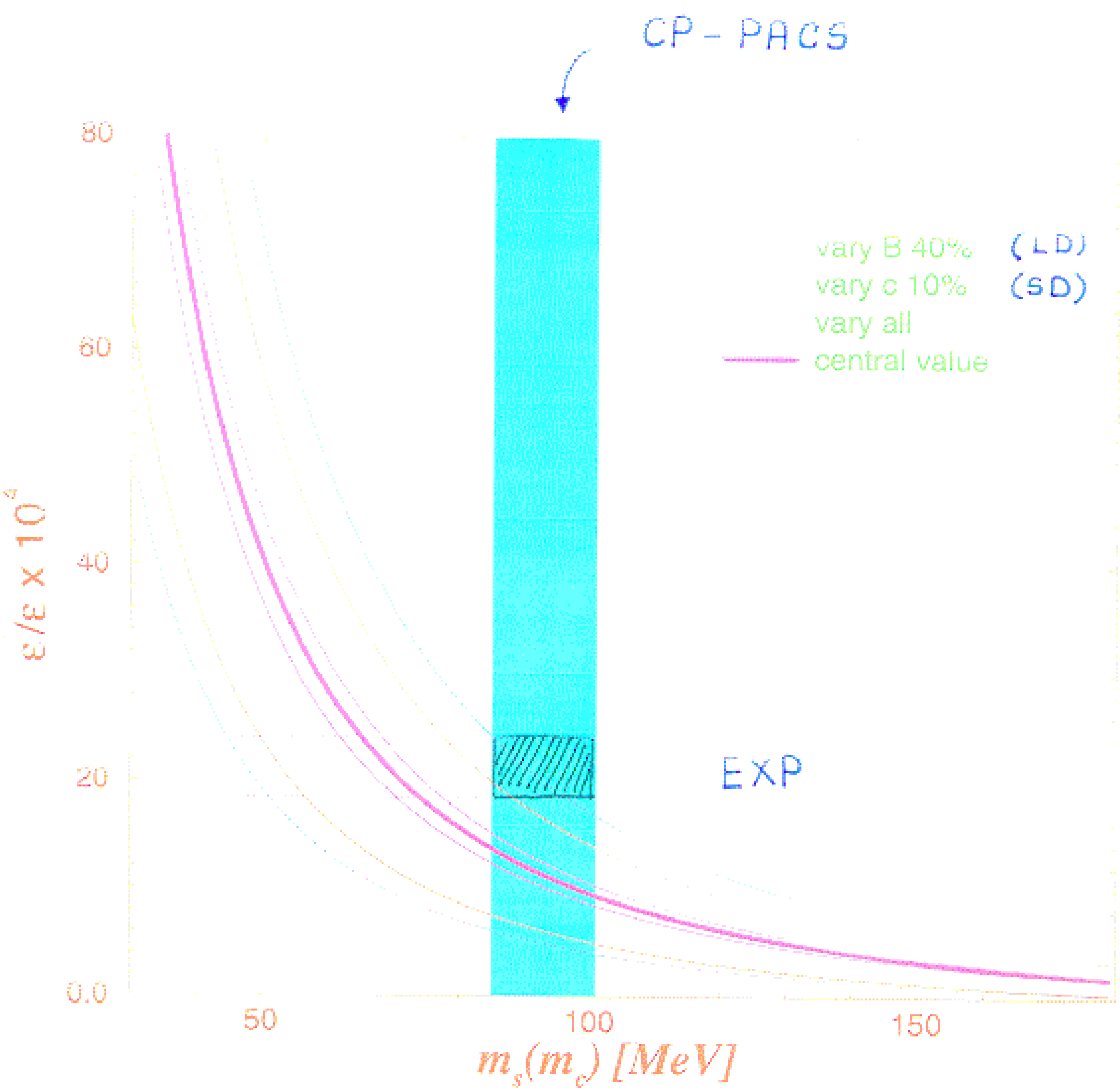
$m_s(2\,GeV) = 110 \pm 20$ MeV
$B_6 = 1.0 \pm 0.3$
Munich (99)
NDR: $7.7^{+6.0(17.0)}_{-3.5(5.5)}\,10^{-4}$
HV: $5.2^{+4.6(13.0)}_{-2.7(4.2)}\,10^{-4}$
probability density
$\epsilon'/\epsilon\ [10^{-4}]$
EXP



ϵ'/ϵ with $m_s(2\text{GeV}) = (87 \pm 7)\text{MeV}$ and $B_6^{(1/2)} = 1.55 \pm 0.05$
NDR: $26.9^{+7.6(17.0)}_{-5.9(10.4)}\,10^{-4}$
HV: $20.9^{+5.9(13.1)}_{-4.6(8.0)}\,10^{-4}$
probability density
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
5
10
15
20
25
30
35
40
45
50
55
$\epsilon'/\epsilon\ [10^{-4}]$


Keum
Nierste
Sanda
hep-ph / 9903230
KTeV
m_s (2 GeV)
90
110
130
$m_s(m_c)$
$Re(\frac{\epsilon'}{\epsilon})_{SM}|^{max}$
10^{-4}
Rest
Tot
Zds
80. 70. 60. 50. 40. 30. 20. 10. 0. −10. −20. −30.
80 90 100 110 120 130 140 150 160 170 180 190 200

S. Ryan



CP - PACS
vary B 40% (LD)
vary c 10% (SD)
vary all
central value
EXP
80
60
40
20
0.0
50
100
150
ε'/ε x 10^4
m_s(m_c) [MeV]

1999 Results from various Groups

$$\frac{\varepsilon'}{\varepsilon} = \left(7.7 {+6.0 \atop -3.5}\right) \cdot 10^{-4}$$

$$1.1 \cdot 10^{-4} \le \frac{\varepsilon'}{\varepsilon} \le 28.8 \cdot 10^{-4}$$

(Munich) (NDR)

$$\frac{\varepsilon'}{\varepsilon} = \left(4.7 {+6.7 \atop -5.9}\right) \cdot 10^{-4}$$

(Rome) (NDR)

$$2.1 \cdot 10^{-4} \le \frac{\varepsilon'}{\varepsilon} \le 26.4 \cdot 10^{-4}$$

(Dortmund) (NDR)

$(5.2 \cdot 10^{-4} \le \varepsilon'/\varepsilon \le 49.8 \cdot 10^{-4})$ $(B_6 \cong 1.5\text{-}1.7)$

$$\frac{\varepsilon'}{\varepsilon} = \left(17 {+9 \atop -7}\right) \cdot 10^{-4}$$

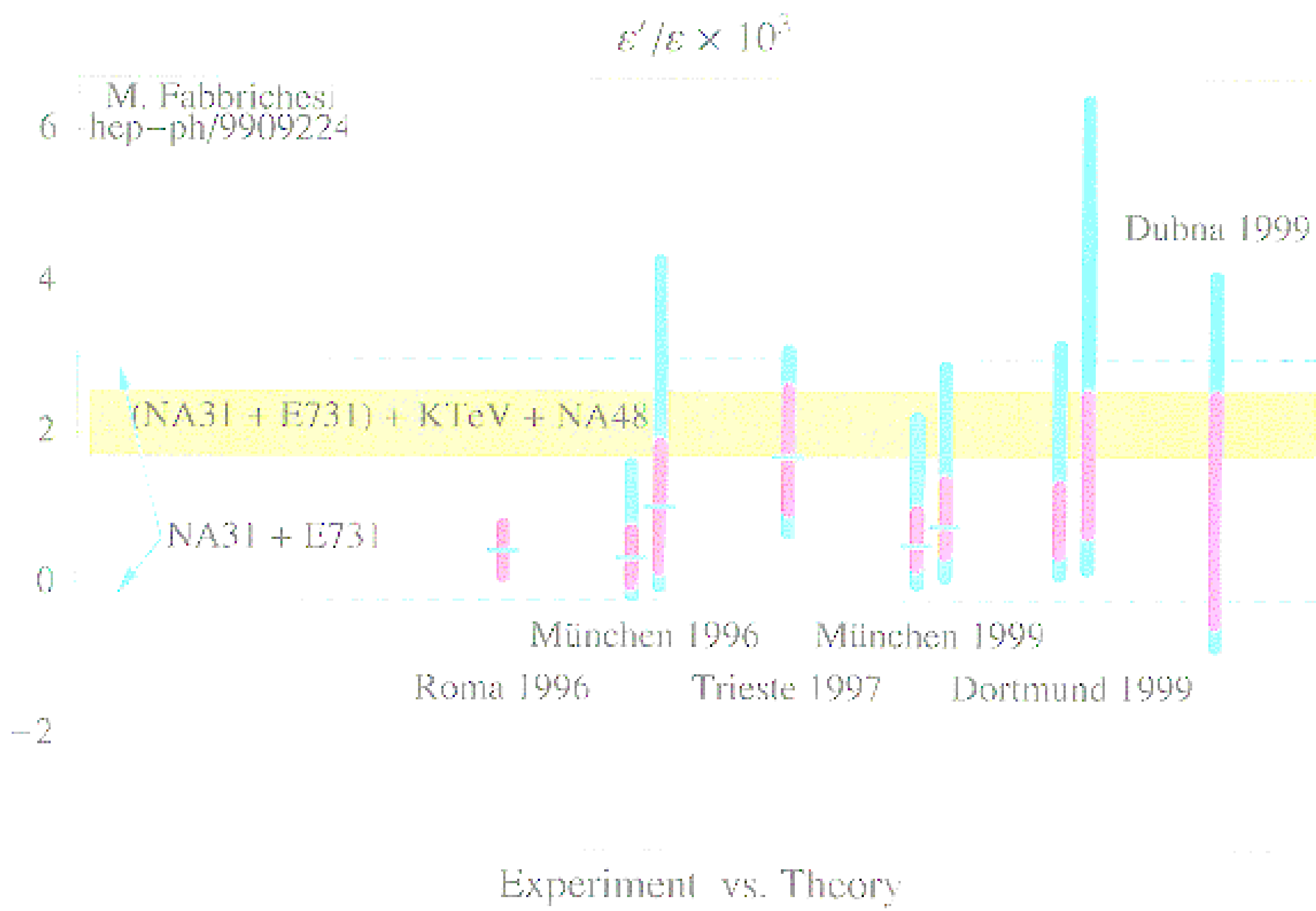
$$7 \cdot 10^{-4} \le \frac{\varepsilon'}{\varepsilon} \le 31 \cdot 10^{-4}$$

(Trieste) (1998)
New: Fall 1999

$$-3.2 \cdot 10^{-4} \le \frac{\varepsilon'}{\varepsilon} \le 3.3 \cdot 10^{-4}$$

$(B_6 = B_8 = 1)$

(Dubna
DESY-Zeuthen)
Eff. Chiral Lagr.
Approach
(Belkov et al)



$\varepsilon'/\varepsilon \times 10^3$
M. Fabbrichesi
hep−ph/9909224
6
4
2
0
−2
(NA31 + E731) + KTeV + NA48
NA31 + E731
München 1996
München 1999
Roma 1996
Trieste 1997
Dortmund 1999
Dubna 1999
Experiment vs. Theory

Present Status

$$B_6 = ?$$

$$B_8 = 0.7 \pm 0.3$$

$$m_s(2\ \mathrm{GeV}) = 110 \pm 20\ \mathrm{MeV} \quad ^{*)}$$

$$\Omega_{IB} = ?$$

$$\Lambda^{(4)}_{\overline{MS}} = (340 \pm 50)\ \mathrm{MeV}$$

*) New Results:

106±7	JLQCD	Quenched
97±4	ALPHA/UKQCD	Quenched
105±4	QCDSF	Quenched
84±7	CP-PACS	Unquenched

New Developments

(After Summer 99)

$\left\{ \begin{array}{l} \text{ENJL model} \\ \text{combined with} \\ \text{Large-N} \\ \text{techniques} \end{array} \right\}$: $B_6 \cong 2.2 \pm 0.5$ (Enhancement from Higher order CHPT) $\left\{ \begin{array}{l} \text{Bijnens} \\ \text{Prades} \end{array} \right\}$

$\left\{ \begin{array}{l} \text{Lattice with} \\ \text{domain wall} \\ \text{fermions} \end{array} \right\}$: $B_6 \cong -6.5 \pm 0.6$, $B_8 \cong 0.42 \pm 0.02$ $\left\{ \begin{array}{l} \text{RIKEN-BNL} \\ \text{-Columbia} \\ \text{Collaboration} \end{array} \right\}$

Higher order $0(p^4)$ Isospin breaking corrections

(Gardner, Valencia): $\Omega_{\eta+\eta'} \Rightarrow \Omega_{IB}$

$\{\Omega_{\eta+\eta'} \cong 0.25 \pm 0.08\} \Rightarrow \{-0.6 \le \Omega_{IB} \le 0.2\}$

Donoghue, Golowich, Holstein
A.J.B. + Gérard
Cheng; Lusignoli

Very uncertain
(Model dependence)

{Enhancement of ε'/ε possible}

Status of ε'/ε

1. If $B_6 \approx 1.0 \pm 0.3 \quad B_8 \approx 0.8 \pm 0.2$

$m_s(2\text{GeV}) \approx 110\text{MeV} \pm 20\text{MeV}$

$$\boxed{\left(\frac{\varepsilon'}{\varepsilon}\right)_{SM} \approx \frac{1}{(1-3)}\left(\frac{\varepsilon'}{\varepsilon}\right)_{exp}}$$

$\Omega_{IB} \approx \Omega_{\eta+\eta'} \cong 0.25$

2. If $B_6 \approx 1.5\text{-}2.5 \qquad \Omega_{IB} < 0.2$

$$\boxed{\left(\frac{\varepsilon'}{\varepsilon}\right)_{SM} \approx (3 \pm 2) \cdot 10^{-3}}$$

Consistent with Experiment

3. If $B_6 \cong -6.5 \pm 0.6$ (RIKEN-BNL-Columbia)

$$\boxed{\left(\frac{\varepsilon'}{\varepsilon}\right)_{SM} \approx -(12 \pm 7) \cdot 10^{-3}}$$

??

Spectacular Signal of New Physics
in NA31, KTeV, NA48 data

A Lot of Room for New Physics

1. Models with new CP-violating phases can give large contributions to ε'/ε

- General supersymmetric models (Gabbiani, Gabrielli, Masiero, Silvestrini; Masiero, Murayama; Babu, Dutta, Mohapatra) BCIRS; Neubert, Kagan; Barbieri, Contino, Strumia; Eyal, Masiero, Nir, Silvestrini; Beak, Jang, Ko, Park
- Models with new fermions and gauge bosons (Agrawal, Frampton)
- Models with anomalous gauge couplings (He)
- Models with modified sdZ vertex (AJB, Silvestrini, Colangelo, Isidori, Romanino)
- Models with enhanced chromomagnetic Penguins (Keum, Nierste, Sanda; BCIRS, Martinelli et al)

Unfortunately : {Many Parameters}

{Not predictive}

2. These Models can be constrained through interplay of ε'/ε with rare K-decays (AJB, Colangelo, Isidori, Romanino, Silvestrini)

Targets for ε'/ε

1. $\Delta(\varepsilon'/\varepsilon)_{exp} = (1.-2.)\cdot 10^{-4}$
   (KTeV, NA48, KLOE)

2. B_6, B_8, m_s, $\mathrm{Im}\lambda_t$

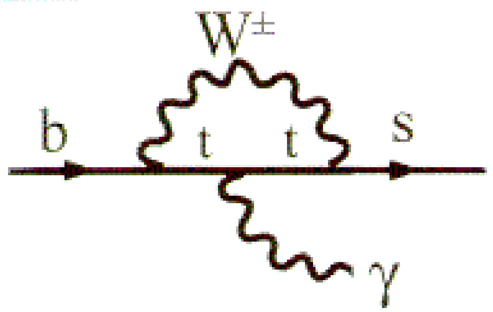
3. $\Omega_{\eta+\eta'}$, $\Lambda^{(4)}_{\overline{MS}}$

Rare B-Decays

$$B \to X_s \gamma \qquad B \to X_s \nu\bar{\nu}$$

$$B \to X_s \mu\bar{\mu} \qquad B \to \mu\bar{\mu}$$

$B \to X_s\gamma$ (Magnetic Penguins)



+ Large SD QCD Corrections

Bertolini et al. (87)
Deshpande et al (87)

Long Distance Effects: few %
Short Distance Enhancement: ~ factor 3

$\left\{ \begin{matrix} \text{Large } \mu_b \\ \text{Dependence} \\ \text{at LO} \end{matrix} \right\}$: $\left\{ \begin{matrix} \text{LO} \\ \pm 20\% \end{matrix} \right\} \Rightarrow \left\{ \begin{matrix} \text{NLO} \\ \pm 4\% \end{matrix} \right\}$

(Ali, Greub; AJB, Misiak, Münz, Pokorski)

	Standard Model		Experiment	
		(93)		(CLEO, 94)
LO:	$(2.8 \pm 0.6 \pm 0.4)\cdot 10^{-4}$ (scale) (par)		$(2.32 \pm 0.57 \pm 0.35)\cdot 10^{-4}$	

	Standard Model		Experiment	
		(98)		(CLEO,ALEPH 98)
NLO:	$(3.30 \pm 0.15 \pm 0.26)\cdot 10^{-4}$ (scale) (par)		$(3.15 \pm 0.35 \pm 0.41)\cdot 10^{-4}$ $(3.11 \pm 0.80 \pm 0.72)\cdot 10^{-4}$	
	$\Downarrow$		$\Downarrow$	
	$(3.30 \pm 0.30)\cdot 10^{-4}$	$\Leftrightarrow$	$(3.14 \pm 0.48)\cdot 10^{-4}$	

$B \to X_s \gamma$ at Leading Order

Grinstein, Springer, Wise (87-89)
Ciuchini, Franco, Martinelli, Reina, Silvestrini (93)
Cella, Curci, Ricciardi, Viceré (94); Misiak (93-94)

$B \to X_s \gamma$ at NLO

Initial Conditions

Adel, Yao (93); Greub, Hurth (97);
AJB, Kwiatkowski, Pott (97)
Ciuchini, Degrassi, Gambino, Giudice (97)

Renormalization Group Evolution

Misiak, Münz (94)	(Two Loop)
Chetyrkin, Misiak, Münz (96)	(Three Loop)

Matrix Elements

Ali, Greub (93); Pott (95)	(One-Loop)
Greub, Hurth, Wyler (96)	(Two-Loop)

Two-Loop Electroweak Corrections

Czarnecki, Marciano (98); Strumia (98)
Kagan, Neubert (98)

$B \to X_s \gamma$ in 2 Higgs Doublet Models

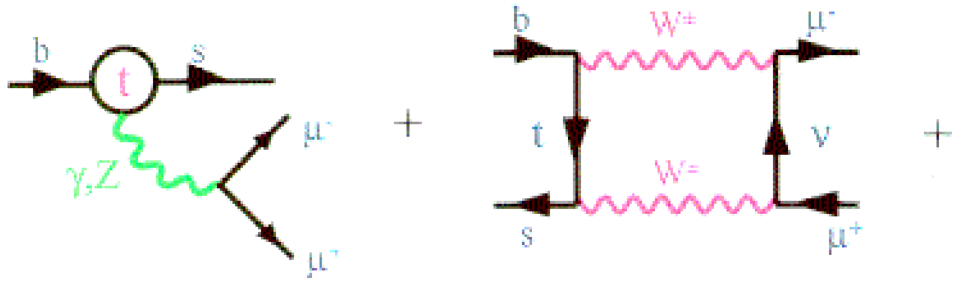
NLO:
- Ciuchini, Degrassi, Gambino, Giudice (98)
- Ciafaloni, Romanino, Strumia (98)
- Borzumati, Greub (98)

$B \to X_s \gamma$ in SUSY

NLO: Ciuchini, Degrassi, Gambino, Giudice (98)

$B \to X_s \mu^+ \mu^-$

Hou, Willey, Soni (87)



Smaller Magnetic Penguins

LO: Grinstein et al.; Deshpande et al.; Lim et al. Ali et al.; Greub et al.; Burdman; Hewett; Krüger, Sehgal; Falk et al.;

NLO: Misiak (94); AJB + Münz (94);

$$\boxed{Br\left(B \to X_s \mu^+ \mu^-\right)_{NR} \cong 6.2 \cdot 10^{-6} \frac{|V_{ts}|^2}{|V_{cb}|^2} \left[\frac{\overline{m}_t(m_t)}{170\ \text{GeV}}\right]^2}$$

$\left(\text{for } Br(B \to X_c e \nu) = 10.4\%\right)$

$\left\{\begin{matrix}\mu \\ \text{Uncertainty} \\ \text{in Br}\end{matrix}\right\} : \left\{\begin{matrix}\text{LO} \\ \pm 20\%\end{matrix}\right\} \Rightarrow \left\{\begin{matrix}\text{NLO} \\ \pm 4\%\end{matrix}\right\}$

SM Expectation

$\boxed{(5.7 \pm 0.9) \cdot 10^{-6}}$

Intensive Studies:

LD: Buchalla, Isidori, Rey; Kim, Morozumi, Sanda; Ali, Hiller

New Physics: Hewett; Ali, Mannel, Morozumi

Experiment

$\boxed{< 5.8 \cdot 10^{-5}}$ CLEO

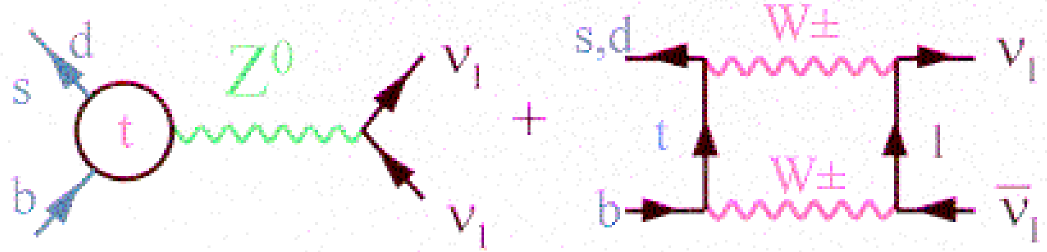
Should be measured at Run II

Useful for $\left|\frac{V_{td}}{V_{ts}}\right|$ in combination with $B \to X_d \mu^+ \mu^-$

$B \to X_{d,s} \nu\bar{\nu}$

$|V_{ts}|$ $|V_{td}|$ (very clean)

$\sum_{\nu_l}$



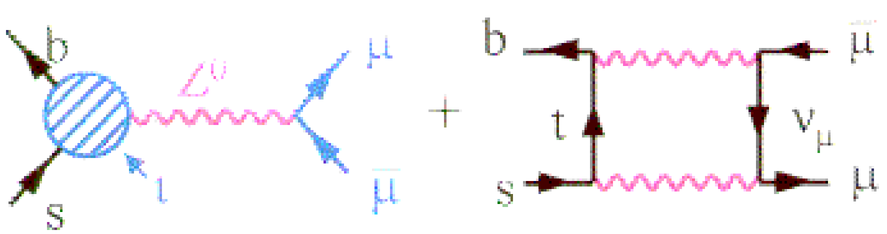
$$Br\left(B \to X_s \nu\bar{\nu}\right) = \begin{cases} (3.5 \pm 0.7)\cdot 10^{-5} & \text{(SM)} \\ < \ 7.7\cdot 10^{-4} & \text{(ALEPH)} \end{cases}$$

(90% C.L.)

$$\bigstar \quad \frac{Br\left(B \to X_d \nu\bar{\nu}\right)}{Br\left(B \to X_s \nu\bar{\nu}\right)} = \frac{|V_{td}|^2}{|V_{ts}|^2}$$

Cleanest Measurement of this Ratio

$B_s \to \mu\bar{\mu}$



\+ QCD Corrections

$$\frac{Br\left(B_d \to \mu\bar{\mu}\right)}{Br\left(B_s \to \mu\bar{\mu}\right)} = 0.98\,\frac{\tau(B_d)}{\tau(B_s)}\,\frac{F_{Bd}^2}{F_{Bs}^2}\,\frac{|V_{td}|^2}{|V_{ts}|^2}$$

SM Expectation

$$(3.2 \pm 1.5)\cdot 10^{-9}$$

Run II : $\sim 0\ (10^{-8})$; LHC-B

Experiment (CDF)

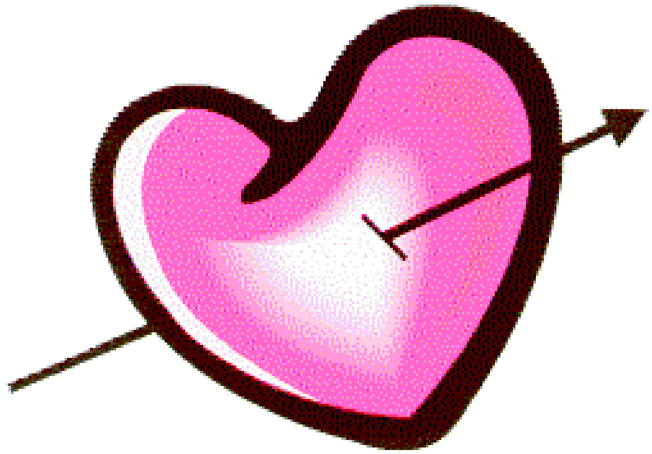
$$Br\left(B_s \to \mu\bar{\mu}\right) < 2.6\cdot 10^{-6}$$

$$Br\left(B_d \to \mu\bar{\mu}\right) < 8.6\cdot 10^{-7}$$

Rare K-Decays

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

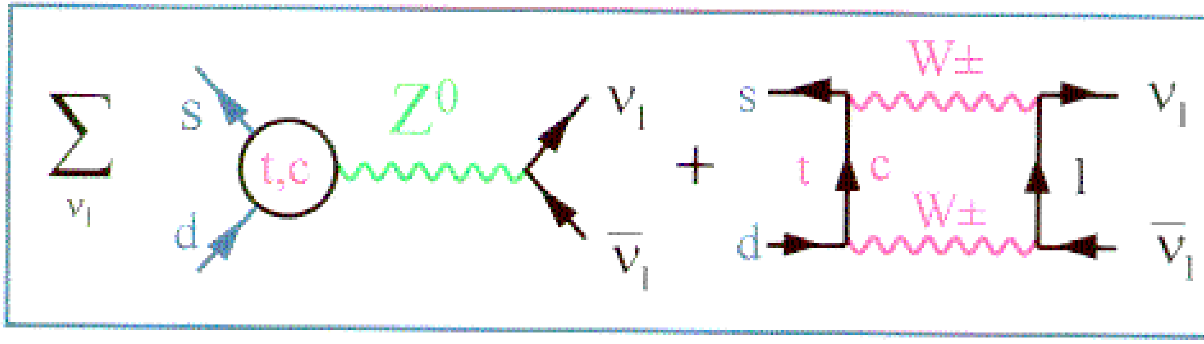
$$K_L \to \pi^0 e^+ e^-$$



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

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

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



V_{td}

QCD Corrections: Dib, Dunietz, Gilman LO (91)

Buchalla + AJB NLO (94)

"Isospin Breaking": (relation to $K^+ \to \pi^0 e^+ \nu$) Marciano + Parsa (-10%) (95)

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) = 0.7 \cdot 10^{-10} \left\{ \left[\frac{|V_{td}|}{0.01}\right]^2 \left[\frac{|V_{cb}|}{0.04}\right]^2 \left[\frac{\overline{m}_t(m_t)}{170\,\mathrm{GeV}}\right]^{2.3} + \begin{matrix} cc \\ tc \end{matrix} \right\}$$

		LO		NLO
$\left\{ \begin{matrix} \mu \\ \text{Uncertainty} \\ \text{in} \quad \mathrm{Br}, \quad \lvert V_{td} \rvert \end{matrix} \right\}$:	$\begin{matrix} \mathrm{Br} \\ \lvert V_{td} \rvert \end{matrix}$	$\left\{ \begin{matrix} \pm 23\% \\ \pm 14\% \end{matrix} \right\}$	⇒	$\left\{ \begin{matrix} \pm 7\% \\ \pm 4\% \end{matrix} \right\}$

$\{\overline{m}_t(\mu_t), \overline{m}_c(\mu_c)$: $100\,\mathrm{Gev} \le \mu_t \le 300\,\mathrm{Gev}$; $1\,\mathrm{Gev} \le \mu_c \le 3\,\mathrm{Gev}\}$

SM Expectation

$$\boxed{(7.9 \pm 3.1) \cdot 10^{-11}}$$

LD Effects < 1%
Rein, Sehgal
Hagelin, Littenberg
Lu, Wise; Fajfer

Experiment

$$\boxed{\left(4.2^{+9.7}_{-3.5}\right) \cdot 10^{-10}}$$ (1997)

E787 (Brookhaven)

(No new events) ⇓ (1999)

$$\boxed{\left(1.7^{+3.9}_{-1.4}\right) \cdot 10^{-10}}$$ (my estimate)

Upper Bound on $Br(K^+ \to \pi^+ \nu\bar{\nu})$ from $(\Delta M)_s$

Buchalla + AJB (99)

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{max} = 3.9 \cdot 10^{-11} \left[P_C + \frac{A^2}{\lambda} X(m_t) \xi \sqrt{\frac{\Delta M_d}{\Delta M_s}} \right]^2$$

$$\xi = \frac{F_{Bs}\sqrt{B_{Bs}}}{F_{Bd}\sqrt{B_{Bd}}} \qquad |V_{cb}| = A\lambda^2 \qquad \lambda = 0.22$$

$$\left\{ \begin{array}{lll} A < 0.89 & X(m_t) < 1.57 & \sqrt{\dfrac{\Delta M_d}{\Delta M_s}} < 0.2 \\ P_c < 0.48 & & \end{array} \right\}$$

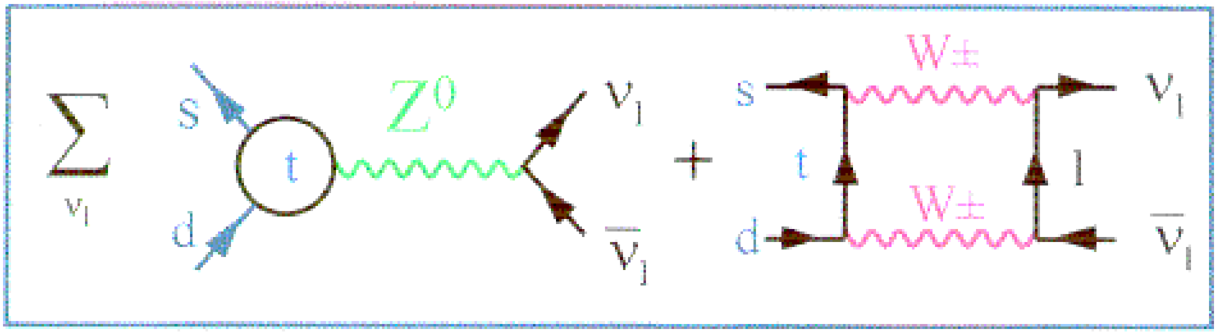
$$\left(\Delta M_s > 14.3\ \mathrm{ps}^{-1}\right)$$

⇓

ξ	$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{max} \left[10^{-10}\right]$
1.4	1.67 (1.47)
1.3	1.49 (1.32)
1.25	1.40 (1.24)
1.20	1.32 (1.17)

$$\xi_{Lattice} = 1.14 \pm 0.08 \qquad Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{exp} = \left(4.2 \pm {}^{9.7}_{3.5}\right) \cdot 10^{-10}$$

$$\boxed{K_L \to \pi^0 \nu\bar{\nu}}$$ Direct $\cancel{CP}$ (Littenberg)



$\boxed{\eta}$

NLO-QCD (Buchalla+AJB) ➡ ±1% Scale Uncertainties
(Misiak+Urban)

Isospin Breaking: Marciano, Parsa (-5.6% reduction)

Long distance: Negligible (Buchalla, Isidori)

$$Br(K_L \to \pi^0 \nu\bar{\nu}) = 3.0 \cdot 10^{-11} \left[\frac{\eta}{0.39}\right]^2 \left[\frac{|V_{cb}|}{0.040}\right]^4 \left[\frac{\bar{m}_t(m_t)}{170\text{GeV}}\right]^{2.3}$$

Standard Model:	$(2.8 \pm 1.1) * 10^{-11}$

Exp: $\boxed{<5.9 \cdot 10^{-7}}$ ➡ $\boxed{\sim 10^{-8}}$ ➡ $2 \cdot 10^{-12}$ single event sensitivity

KTeV (99) — KTEV — BNL E926 (KAMI, KEK)

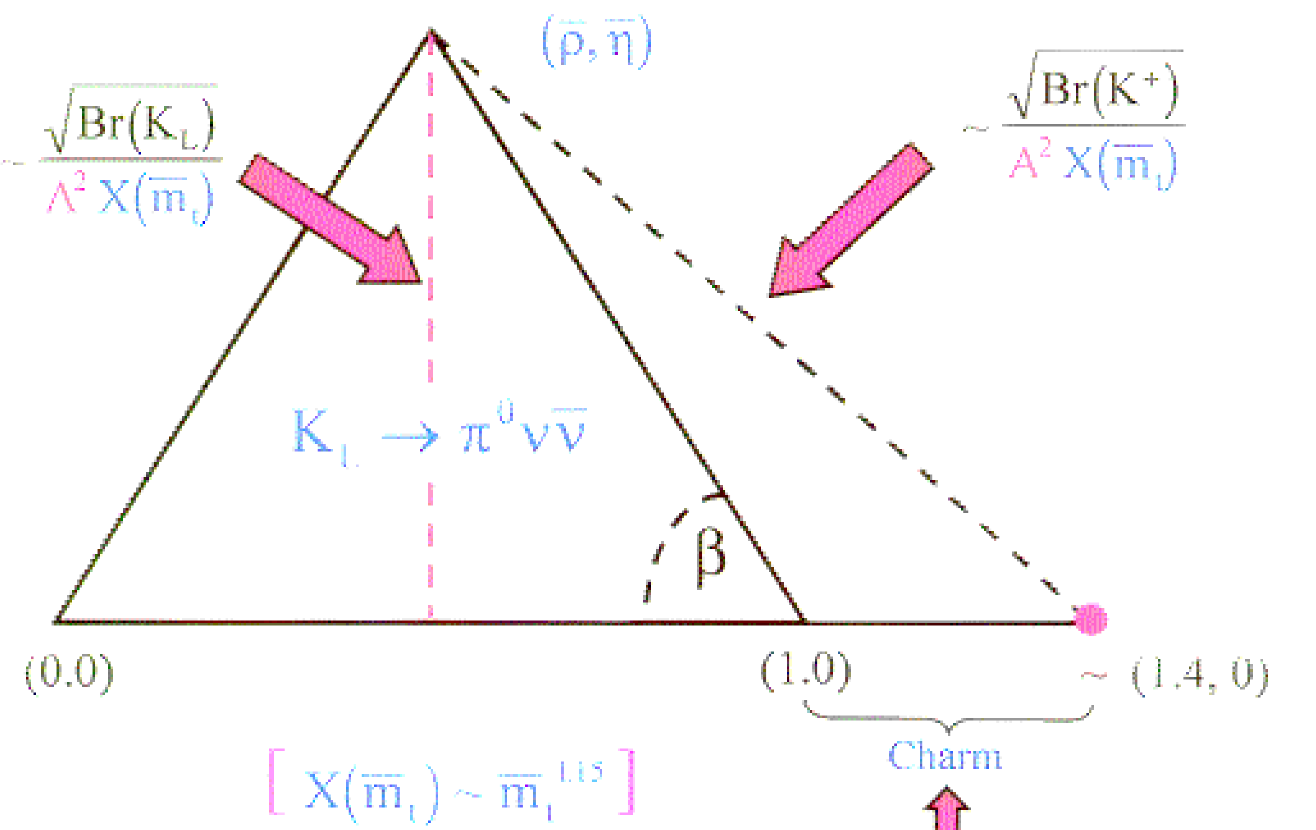
Model Independent Bound:

$$\boxed{Br(K_L \to \pi^0 \nu\bar{\nu}) < 4.4\, Br(K^+ \to \pi^+ \nu\bar{\nu})} < \boxed{1 \cdot 10^{-9}}$$

Grossman, Nir

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

Buchalla
AJB



$$\sim \frac{P_c}{A^2 X(\bar{m}_t)} \qquad P_c \leftarrow (0.42 \pm 0.06)$$

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

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

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

$\sin 2\beta$ $(K \to \pi \nu \bar{\nu})$	$\Leftrightarrow$	$\sin 2\beta$ $(B \to J/\psi K_s)$ $\to \varphi K_s$

K - Physics $\Leftrightarrow$ B - Physics

Test of SM and Beyond

Master Formulae

$$\mathrm{Im}\,\lambda_t = 1.36\cdot 10^{-4}\sqrt{\frac{Br(K_L\to\pi^0\nu\bar{\nu})}{3\cdot 10^{-11}}}\left[\frac{170\mathrm{Gev}}{\overline{m}_t(m_t)}\right]^{1.15}$$

$$\sin 2\beta = \frac{2r_s}{1+r_s^2} \qquad r_s = \frac{\sqrt{B_1 - B_2} - P_c}{\sqrt{B_2}}$$

$$B_1 \equiv \frac{Br(K^+\to\pi^+\nu\bar{\nu})}{4.11\cdot 10^{-11}} \qquad B_2 \equiv \frac{Br(K_L\to\pi^0\nu\bar{\nu})}{1.80\cdot 10^{-10}}$$

$$P_c = 0.42 \pm 0.06 \Leftarrow (m_c, \Lambda_{\overline{MS}}, \mu_c)$$

$$|V_{cb}| = 40\cdot 10^{-3}\sqrt{\frac{0.39}{\eta}}\left[\frac{170\mathrm{GeV}}{\overline{m}_t(m_t)}\right]^{0.575}\left[\frac{Br(K_L\to\pi^0\nu\bar{\nu})}{3\cdot 10^{-11}}\right]^{\frac{1}{4}}$$

(AJB)

Cleanest Determination of $|V_{cb}|$

{From CP-B Asymmetries}

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

$\Delta\,Br\,(K^+) = \Delta\,Br\,(K_L) = \pm 10\%$

$\Delta\,m_t = \pm 3$ GeV $\quad \Delta\,m_c = \pm 50\ (100)$ MeV

	$\Delta V_{cb} = \pm 0.002$	$\Delta V_{cb} = \pm 0.001$	Present	Future
$\Delta\lvert V_{td}\rvert$	$\pm$ 10% ($\pm$ 12%)	$\pm$ 9% ($\pm$ 11%)	$\pm$ 17%	$\pm$ 7%
$\Delta\bar{\rho}$	$\pm$ 0.16 ($\pm$ 0.18)	$\pm$ 0.11 ($\pm$ 0.13)	$\pm$ 0.20	$\pm$ 0.08
$\Delta\bar{\eta}$	$\pm$ 0.04	$\pm$ 0.03	$\pm$0.12	$\pm$0.03
$\Delta \sin 2\beta$	$\pm$ 0.05 ($\pm$ 0.06)	$\pm$ 0.05 ($\pm$ 0.06)	$\pm$ 0.13	$\pm$ 0.05
$\mathrm{Im}\,\lambda_t$	$\pm$ 5%	$\pm$ 5%	$\pm$ 23%	$\pm$ 8%

$K \to \pi\nu\bar{\nu}$ $\qquad$ Standard Analysis

$$(\Delta \sin 2\beta)_{\text{Scale Uncertainty}} = \begin{cases} \pm 0.02 & \text{NLO} \\ \pm 0.05 & \text{LO} \end{cases}$$

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

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

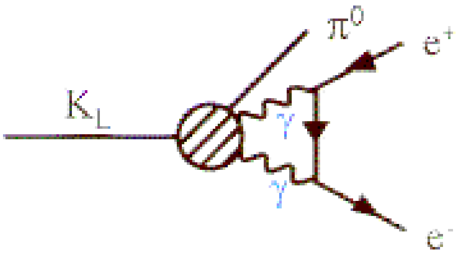
$K_L \to \pi^+\pi^- e^+e^-$

Beautiful confirmation of the TH predictions
(Seghal, Wanninger, Heiliger)

	TH	KTeV
Br	$3.1 * 10^{-7}$	$(3.32 \pm 0.14 \pm 0.28) \cdot 10^{-7}$
$A_{\not{C}\not{P}\not{T}}$	$\approx 14\%$	$(13.6 \pm 2.5 \pm 1.2)\ \%$

$K_L \to \pi^0 e^+ e^-$ (3 contributions)

① $K_L \to \pi^0\gamma\gamma \to \pi^0 e^+ e^-$ ⇐ CP conserving

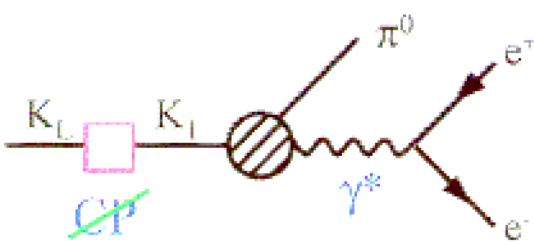


$$\boxed{B_1^{th} = (1-4)\cdot 10^{-12}}$$ (Using KTeV (99) $K_L \to \pi\gamma\gamma$)

Donoghue, Holstein, Valencia, Ecker, Pich, de Rafael, Flynn, Randall, Seghal, Heiliger, Fajfer (95)
Cohen, Ecker, Pich (93)
Donoghue, Gabbiani (95)
Ambrosio, Portoles (97)

② $K_L \xrightarrow{K_1} \pi^0\gamma^* \to \pi^0 e^+ e^-$ ⇐ indirect $\cancel{CP}$

★ ($K_S \to \pi^0 e^+ e^-$ will help!)

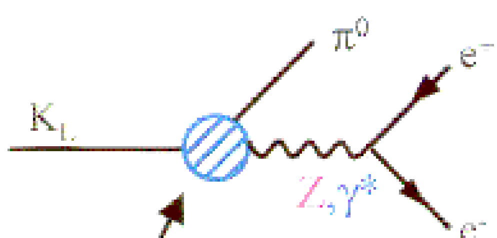


$$\boxed{B_2^{th} \approx (1-5)\cdot 10^{-12}}$$

Ecker, Pich, de Rafael (91)
Heiliger, Seghal (93)
Donoghue, Gabbiani (95)
Fajfer (95)

③ $K_L \xrightarrow{K2} \pi^0\gamma^* \to \pi^0 e^+ e^-$ ⇐ direct $\cancel{CP}$

★ (TH very clean!)



The action of Z^0, γ Penguins

$$\boxed{B_3^{th} = (4.7 \pm 1.9)\cdot 10^{-12}}$$

LO: Dib, Dunietz, Gilman; Flynn, Randall; Buchalla, AJB, Harlander

NLO: AJB, Lautenbacher, Misiak, Münz (94)

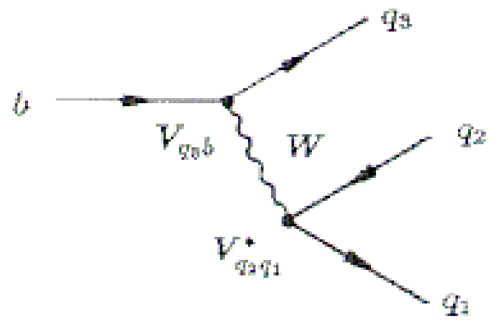
KTeV (99): $\boxed{\left[Br\left(K_L \to \pi^0 e^+ e^-\right)\right]_{Exp} \le 5.6\cdot 10^{-10}}$

Problematic background: $K_L \to e^+ e^- \gamma\gamma$

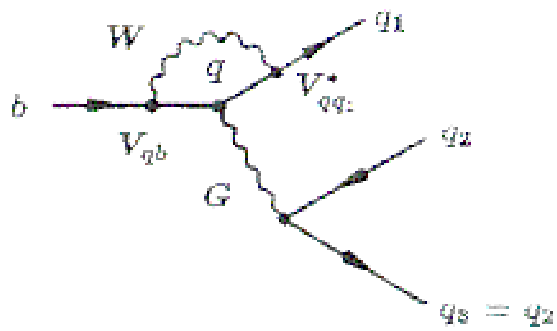
CP Violation in B-Decays

(Asymmetries and Other Strategies)

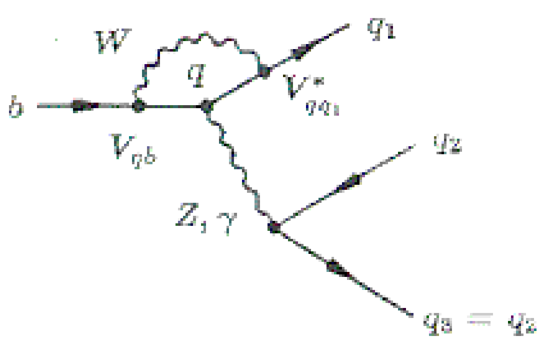
Tree Diagrams:

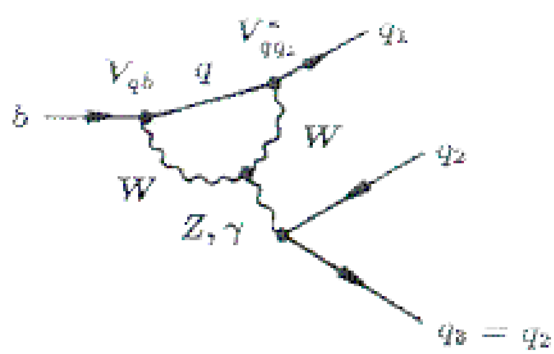


QCD Penguin Diagrams:



EW Penguin Diagrams:





Basic Diagrams in CP-B

CP Asymmetries in B-Decays

$$A_{CP}(f) = \frac{\Gamma(B \to f) - (\overline{B} \to \bar{f})}{\Gamma(B \to f) + (\overline{B} \to \bar{f})} \qquad B = \{B^{\pm}, B_d^0, B_s^0\}$$

Most promising:

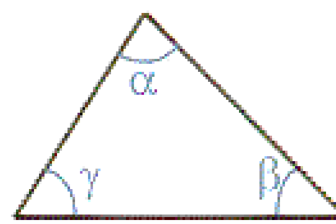
Free of
Hadronic Uncertainties

Mixing induced A_{CP}
in B^0 decays dominated
by a single CKM amplitude

Particularly simple:

f = CP eigenstate

⇒ Weak Phases can be measured directly !



Example: $B_d \to \psi K_s$

$$A_{CP}(\psi K_s, t) = -\sin((\Delta M)_d t)\sin 2\beta$$

However: $B_d \to \pi^+\pi^-$

$$A_{CP}(\pi^+\pi^-, t) = -\sin((\Delta M)_d t)\sin(2\alpha + \theta_P)$$

"Penguin pollution"

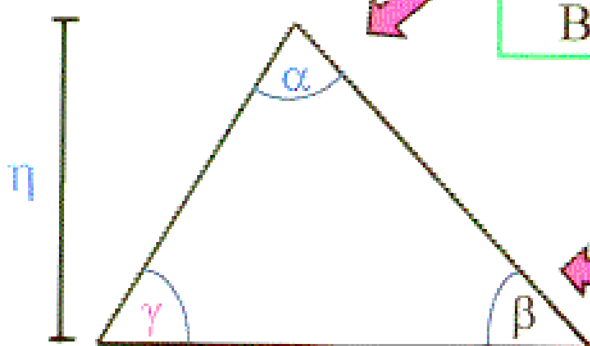
Theoretically Clean Determinations of (α,β,γ)

Very small Asymmetry

TD = Time dependent

$\overset{(-)}{B}_s \to J/\psi\, \varphi$

$\overset{(-)}{B}_d \to \pi^+\pi^-$ (Gronau + >London)
+ Isospin Analysis (TD)
$B^\pm \to \pi^\pm\pi^0$
$B \to \pi^0\pi^0 \leq 10^{-6}$



$\overset{(-)}{B}_d \to J/\psi\, K_s$ (TD)
(Bigi + Sanda)

$(B_d \to \varphi\, K_s,\ D^+D^-)$

Free of Penguins

$\overset{(-)}{B}_s \to D_s^\pm K^\pm$ (Aleksan, Dunietz, Kayser) (TD)

$B^\pm \to D^0_{CP} K^\pm, \ldots$ (Gronau, Wyler)* } Rates only

$B^0 \to \overline{D}^0 K^{*0}$ etc. (Dunietz)

Direct ~~CP~~

* Atwood, Dunietz, Soni

Rest: $B^0 - \overline{B}^0$ mixing induced ~~CP~~

Tagging required : distinction between unmixed B^0 and $\overline{B}^0$ at t=0 (hard task)

Decays to CP Eigenstates

Single Tree Diagram:

$$A_{CP}(f) = \overbrace{\chi_{CP}(f)}^{\pm 1}\ \sin(2\varphi_D - 2\varphi_M)\ \frac{x_{d,s}}{1+x_{d,s}^2}$$

$$x_{d,s} \equiv \frac{(\Delta M)_{d,s}}{\Gamma_{B_{d,s}}}$$

$$\varphi_D = \begin{cases} \gamma & b \to u \\ 0 & b \to c \end{cases} \qquad \varphi_M = \begin{cases} -\beta & B_d \\ 0 & B_s \end{cases}$$

(Decay) (Mixing)

$\sin(2\varphi_D - 2\varphi_M)$

☺ B_d decays $(b \to c)$: $\boxed{\sin 2\beta}$

$B_d \to \psi K_s$ (very clean) ($Br \sim 10^{-4}$)

☺ B_s decays $(b \to c)$: $\boxed{2\lambda^2\eta}$

$B_s \to \psi\varphi$ (clean but small) ($Br \sim 10^{-3}$)

☹ B_d decays $(b \to u)$: $\boxed{\sin 2\alpha}$

$B_d \to \pi^+\pi^-$ (Need Isospin Analysis to remove P) (Gronau London)

$$Br(B^0 \to \pi^+\pi^-) = (4.7 \pm 1.6 \pm 0.6)\cdot 10^{-6}$$
$$Br(B^0 \to \pi^+\pi^0) < 12 \cdot 10^{-6}$$
$$Br(B^0 \to \pi^0\pi^0) < 10^{-6}$$

(CLEO)

$\boxed{\alpha}$

- $\{A_{CP}(\pi^+\pi^-) + \text{Isospin}\}$ Gronau + London
  (Difficult to realize : Br $(B^0 \to \pi^0\pi^0) < 10^{-6}$)

- $B \to \rho\pi$ etc. Quinn, Snyder
  (Rather involved)

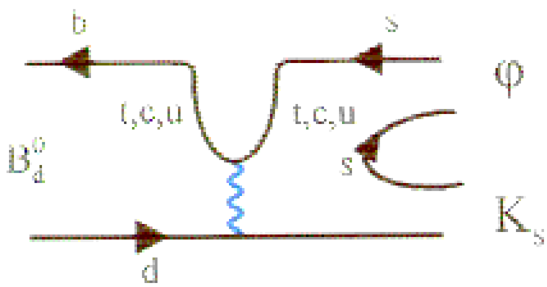
- $A_{CP}(\pi^+\pi^-)$, $A_{CP}(K^0\bar{K}^0)$ AJB + Fleischer
  (Limitations from SU(3) breaking)

- $A_{CP}(\pi^+\pi^-)$, $B \to \pi^{\pm}K^{\pm}$, $B^{\pm} \to K_S\pi^{\pm}$ Digh, Gronau, Rosner
  (Limitations from u-, c-penguins)

- $$\left\{\begin{matrix} A_{CP}^{dir}\left(B_d \to \pi^+\pi^-\right),\ Br\left(B^+ \to \pi^+K^0\right) \\ A_{CP}^{mix-ind}\left(B_d \to \pi^+\pi^-\right),\ Br\left(B^+ \to \pi^+\pi^0\right) \end{matrix}\right\} \Rightarrow \left\{\Delta\alpha_{TH} = \pm 3\%\right\}$$

  Fleischer, Mannel

$\boxed{B_d^0 \to \varphi\, K_s}$ (Pure Penguin Decay)



$$\underbrace{V_{ts}V_{tb}^* \quad + \quad V_{cs}V_{cb}^*} \Rightarrow \boxed{\varphi_D \cong 0}$$

$$\Rightarrow \boxed{\sin[2\varphi_D - 2\varphi_M] = \sin 2\beta}$$

$\{$Pure Loop Decay$\}$ ⇒ Sensitivity to
New Physics
(London, Peccei;
Fleischer;
Grossman, Isidori, Worah)

<u>Comment:</u> u-penguin at $O(\lambda^4)$ carries
$\varphi_D = \gamma$ (small correction)

γ from $B \to \pi K$

Penguin dominated decays:

CLEO

$$Br\left(\overset{(-)}{B}{}^0 \to \pi^{\mp} K^{\pm}\right) = (1.9 \pm 0.3 \pm 0.1) \cdot 10^{-5}$$

$$Br\left(B^{\pm} \to \pi^{\pm} K^0\right) = (1.8 \pm 0.4 \pm 0.2) \cdot 10^{-5}$$

$$Br\left(B^{\pm} \to \pi^0 K^{\pm}\right) = (1.2 \pm 0.3 \pm 0.2) \cdot 10^{-5}$$

$$Br\left(B^0 \to \pi^0 K^0\right) = (1.5 \pm 0.6 \pm 0.3) \cdot 10^{-5}$$

$\Rightarrow$ γ

Uncertainties from:

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

Recent Studies:

Fleischer, Mannel
Fleischer; Gronau, Rosner
Neubert, Rosner;
(General Parametrization) $\to$ AJB, Fleischer; Neubert
Gronau, Pirjol

In particular:

Fleischer - Mannel Bound

Neubert-Rosner Bound

Recent work of Beneke, Buchalla, Neubert, Sachrajda (Non-factorizable contributions) could be useful here.

Two new Strategies

$(s \leftrightarrow d)$

Fleischer (99)

No FSI problems
Limited by U-spin breaking effects

$$\begin{Bmatrix} B_s \to I/\psi\, K_s \\ B_d \to I/\psi\, K_s \end{Bmatrix} \Rightarrow \{\gamma\}$$

$$\begin{Bmatrix} B_s \to K^+K^- \\ B_d \to \pi^+\pi^- \end{Bmatrix} \Rightarrow \{\beta,\gamma\}$$

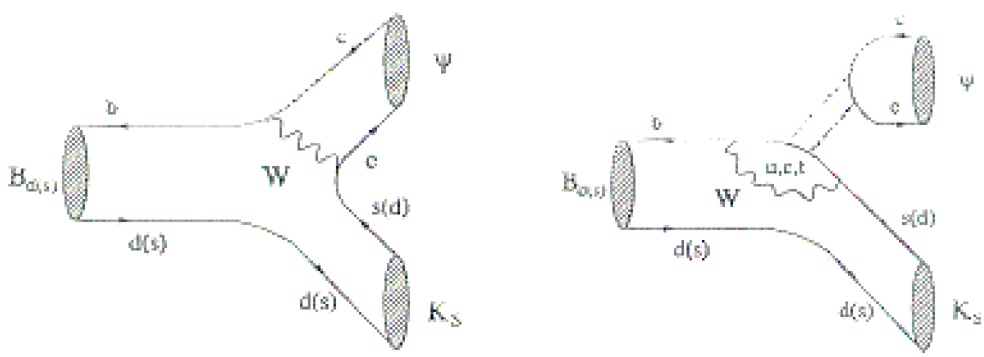


Figure 7: Feynman diagrams contributing to $B_{d(s)} \to J/\psi\, K_S$. The dashed lines in the penguin topology represent a colour-singlet exchange.

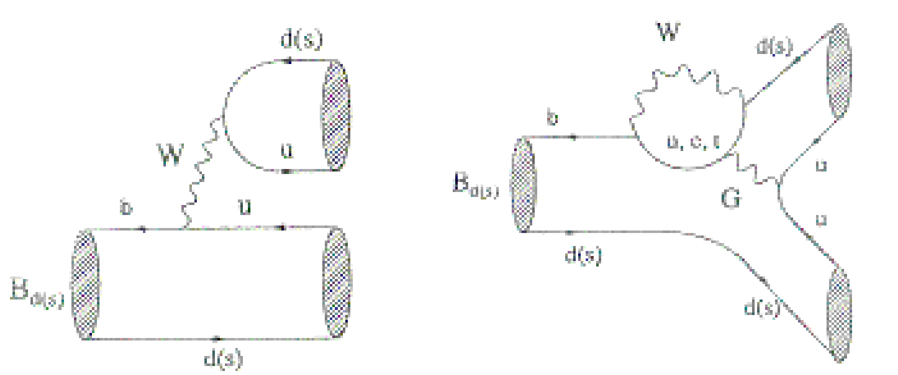
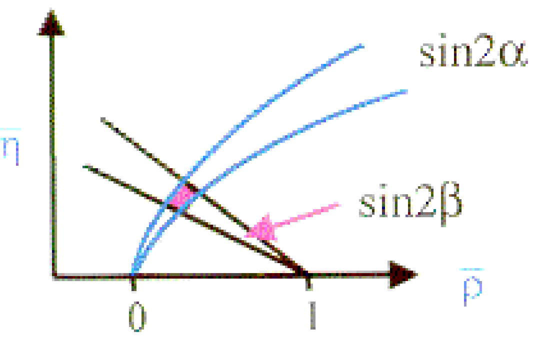


Figure 8: Feynman diagrams contributing to $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$.

$$\boxed{(\bar{\rho}, \bar{\eta}) \text{ from } (\sin 2\alpha, \sin 2\beta)}$$



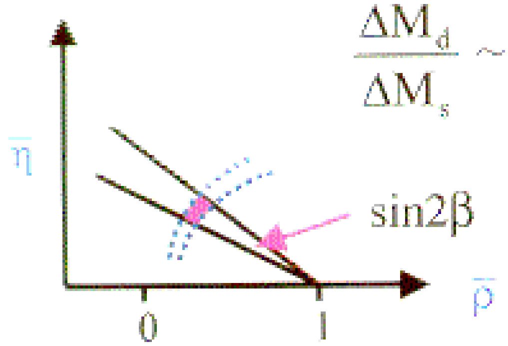
$a \equiv \sin 2\alpha$

$b \equiv \sin 2\beta$

$$\bar{\rho} = 1 - \bar{\eta} r_+(b) \qquad \bar{\eta} = \frac{r_-(a) + r_+(b)}{1 + r_+^2(b)}$$

$$r_\pm(z) = \frac{1}{z}\left[1 \pm \sqrt{1 - z^2}\right] \qquad z = a,\ b$$

$$\boxed{(\bar{\rho}, \bar{\eta}) \text{ from } (R_t,\ \sin 2\beta)}$$



$$\bar{\eta} = \eta(1 - \lambda^2/2)$$

$$\bar{\rho} = \rho(1 - \lambda^2/2)$$

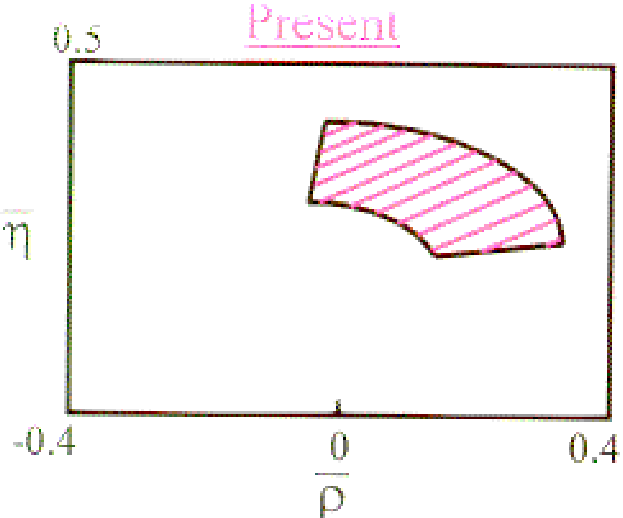
$$\bar{\rho} = 1 - \bar{\eta} r_+(b) \qquad \bar{\eta} = \frac{R_t}{\sqrt{2}}\sqrt{b r_-(b)}$$

Progress in △

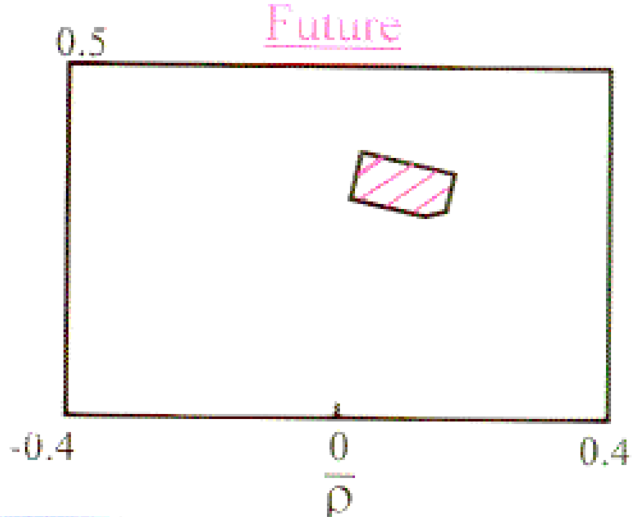
Standard Analysis

$(\bar{\rho}, \bar{\eta})$

Present

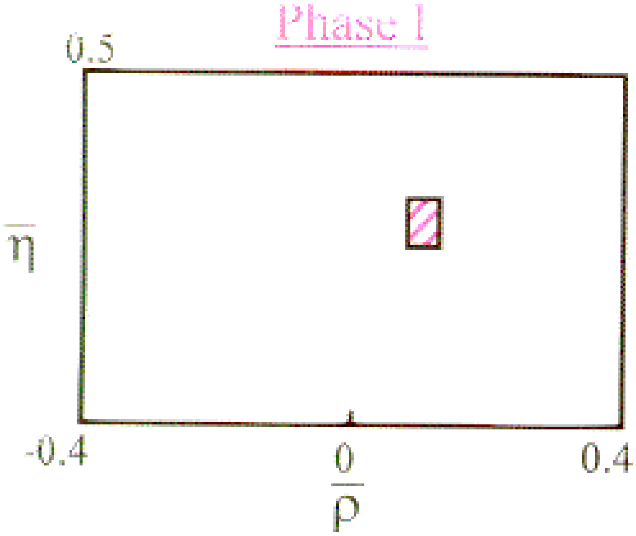


Future

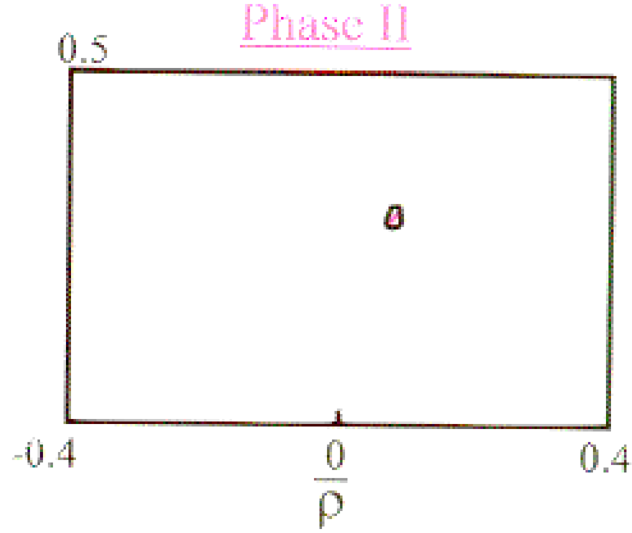


$\not{CP}$ Asymmetries (B Decays)

Phase I



Phase II



$\sin 2\alpha = 0.40 \pm 0.10$
$\sin 2\beta = 0.60 \pm 0.06$
(BABAR, HERA-B, BELLE)
CLEO III, CDF, DØ

$\sin 2\alpha = 0.40 \pm 0.04$
$\sin 2\beta = 0.60 \pm 0.02$
(LHC-B, BTeV)

$$\begin{Bmatrix} K_L \to \pi^0 \nu\bar{\nu} \\ K^+ \to \pi^+ \nu\bar{\nu} \end{Bmatrix} \Leftrightarrow \begin{Bmatrix} \cancel{CP} - B \ \text{Decays} \\ (\sin 2\alpha, \ \sin 2\beta) \end{Bmatrix}$$

(Buchalla, AJB 96)

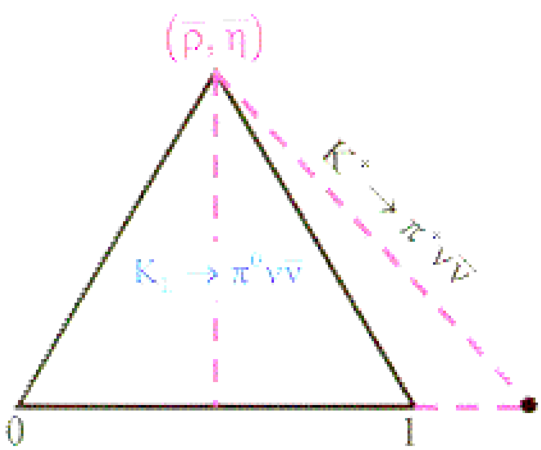
$\Delta Br = \pm 10\%$

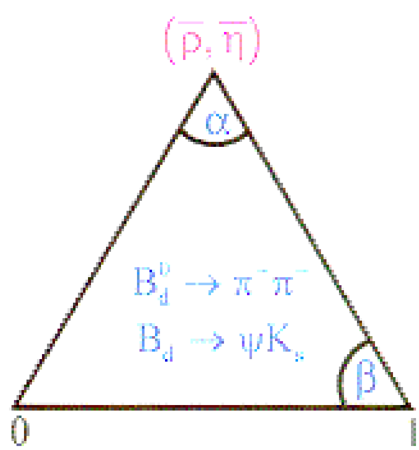
$\Delta m_t = \pm 3 \text{ GeV}$

$\Delta V_{cb} = \pm\, 0.002\ (0.001)$

Present: ± 0.003

Errors	$K \to \pi\nu\bar{\nu}$	Phase I	Phase II
$\Delta \lvert V_{td} \rvert$	$\pm$ 10% (9%)	$\pm$ 5.5% (3.5%)	$\pm$ 5.0% (2.5%)
$\Delta\ \bar{\rho}$	$\pm$ 0.16 (0.11)	$\pm$ 0.03	$\pm$ 0.01
$\Delta\ \bar{\eta}$	$\pm$ 0.04 (0.03)	$\pm$ 0.04	$\pm$ 0.01
$\Delta \sin 2\beta$	$\pm$ 0.05	$\pm$ 0.06	$\pm$ 0.02
$\Delta\, \mathrm{Im}\lambda_t$	$\pm$ 5%	$\pm$ 14% (11%)	$\pm$ 10% (6%)





$$\begin{Bmatrix} K_L \to \pi^0 \nu\bar{\nu} \\ \sin 2\alpha, \ \sin 2\beta \end{Bmatrix} \Leftrightarrow \begin{Bmatrix} \Delta V_{cb} = \pm 0.001 \\ \Delta \left| \dfrac{V_{ub}}{V_{cb}} \right| = \pm 0.003 \end{Bmatrix}$$

Future Targets

$\Delta V_{cb} = \pm 0.001$	$\Delta \lvert V_{ub} / V_{cb} \rvert = \pm 0.01$
$\Delta(\varepsilon'/\varepsilon)_{exp} = \pm 1 - 2 \cdot 10^{-4}$	Improved $(\varepsilon'/\varepsilon)_{th.}$
$K_L \to \pi^0 \nu\bar{\nu}$	$K^+ \to \pi^+ \nu\bar{\nu}$
$\sin 2\beta$	α, γ from $CP - B$
$B_S^0 - \bar{B}_S^0$ Mixing	$K_{L,S} \to \pi^0 e^+ e^-$
$B \to X_S \mu^+ \mu^-$	Improved $B \to X_S \gamma$
Electric Dipole Moments	$\mu \to e\gamma$

The Future until 2011 should be very exciting