CP Violation and Rare Decays in K Mesons

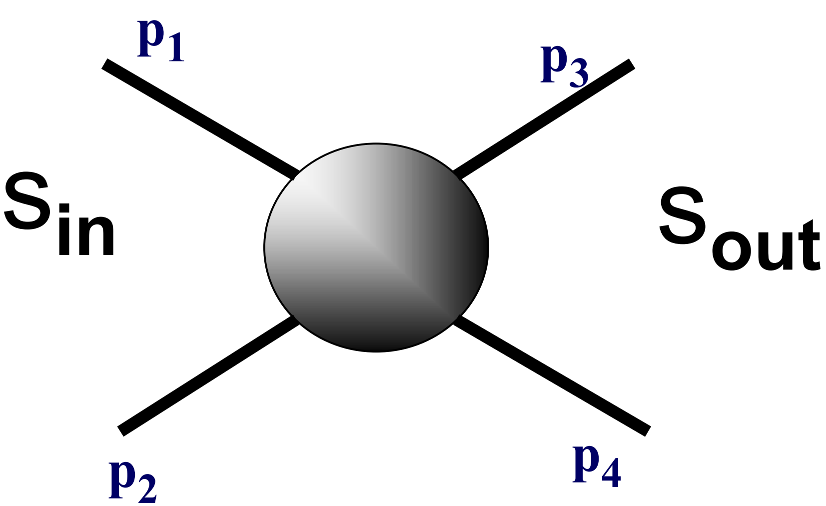
- $\not{CP}$ Violation in Kaon Systems in the Standard Model
- CP Violation in Kaon Systems Beyond the SM
- Why rare decays
- Which rare decays
- Conclusions

Dipartimento di Fisica di Roma I Guido Martinelli Paris June 5th 2003

Consequences of a Symmetry

$$[S, H] = 0 \rightarrow |E, \mathbf{p}, \mathbf{s}\rangle$$

We may find states which are simultaneously eigenstates of S and of the Energy



$$CP\,|K_1^0\rangle = +\,|K_1^0\rangle$$

$$CP\,|K_2^0\rangle = -\,|K_2^0\rangle$$

$$\langle\pi\pi|K_1^0\rangle \neq 0$$

$$\langle\pi\pi|K_2^0\rangle = 0$$

$$|K_{S,L}^0\rangle = \alpha\,|K_1^0\rangle + \beta\,|K_2^0\rangle$$

if *CP* is conserved either $\alpha=0$ or $\beta=0$

$\not{C}\not{P}$ Violation in the Neutral Kaon System

Expanding in several "small" quantities

$$\eta^{00} = \frac{\langle \pi^0\pi^0 | H_W | K_L \rangle}{\langle \pi^0\pi^0 | H_W | K_S \rangle} \sim \varepsilon - 2\,\varepsilon'$$

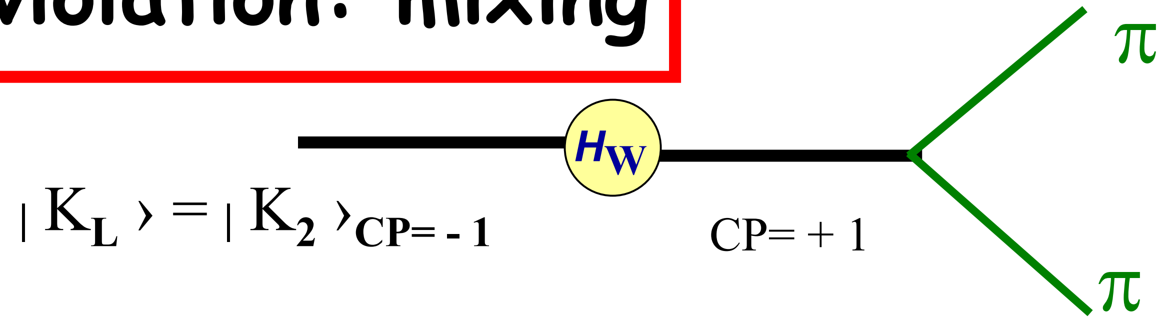
$$\eta^{+-} = \frac{\langle \pi^+\pi^- | H_W | K_L \rangle}{\langle \pi^+\pi^- | H_W | K_S \rangle} \sim \varepsilon + \varepsilon'$$

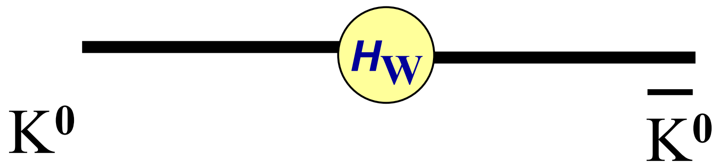
Conventionally:

$$| K_S \rangle = | K_1 \rangle_{CP=+1} + \varepsilon\, | K_2 \rangle_{CP=-1}$$

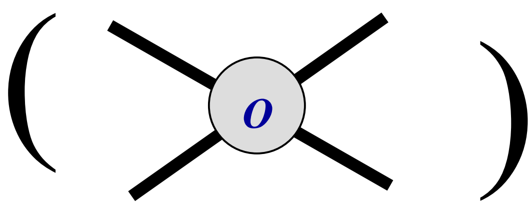
$$| K_L \rangle = | K_2 \rangle_{CP=-1} + \varepsilon\, | K_1 \rangle_{CP=+1}$$

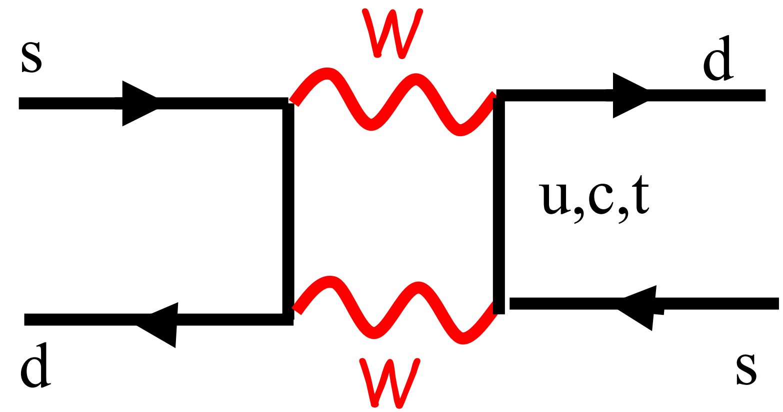
Indirect CP violation: mixing





ΔS=2





Box diagrams:
They are also responsible for $B^0 - \overline{B}^0$ mixing
$\Delta m_{d,s}$

Complex ΔS=2 effective coupling

$$|\varepsilon| \sim C_\varepsilon A^2 \lambda^6 \sigma \sin\delta \{F(x_c, x_t) + F(x_t)[A^2 \lambda^4 (1 - \sigma\cos\delta)] - F(x_c)\} B_K$$

Inami-Lin Functions + QCD Corrections (NLO)

$$\eta = \sigma \sin\delta \quad \rho = \sigma \cos\delta$$

$$C_\varepsilon = \frac{G_F^2 M_W^2 M_K f_K^2}{6\sqrt{2}\,\pi^2 \Delta M_K}$$

$$\langle \overline{K^0} | (\bar{s}\gamma_\mu (1-\gamma_5) d)^2 | K^0 \rangle = 8/3\, f_K^2 M_K^2 B_K$$

K^0-$\bar{K}^0$ mixing in the Standard Model (and beyond)

$$\langle \bar{K}^0 | (\bar{s}_L^A \gamma_\mu d_L^A)(\bar{s}_L^B \gamma_\mu d_L^B) | K^0 \rangle =$$

$$8/3\ f^2_K M^2_K B_K(\mu)$$

NEW RESULTS FOR B_K

	$B^{NDR}_K(2\ \text{GeV})$	$\hat{B}_K$
World Average by L.Lellouch at Lattice 2000 and GM 2001	0.63 ± 0.04 ±0.10	0.86 ±0.06 ±0.14
CP-PACS perturbative renorm. (quenched) DWF	0.575 ±0.006 0.5746(61)(191)	0.787 ±0.008
RBC non-perturbative renorm. (quenched) DWF	0.538 ±0.008	0.737 ±0.011

Lattice 2002 preliminary

	$B^{NDR}_K(2\ \text{GeV})$	$\hat{B}_K$
$SPQ_{cd}R$ Wilson Improved NP renorm.	0.66 ± 0.07	0.90 ±0.10
NNC-HYP Overlap Fermions perturbative	0.66 ± 0.04	0.90 ±0.06
Garron & al. Overlap Fermions Non-perturbative	0.61 ± 0.07	0.83 ±0.10

K-$\bar{K}$-mixing: summary (2)

Final number

$$B_K^{NDR}(2\,\mathrm{GeV}) = 0.628(42)(99) \longrightarrow \hat{B}_K^{NLO} = 0.86(6)(14)$$

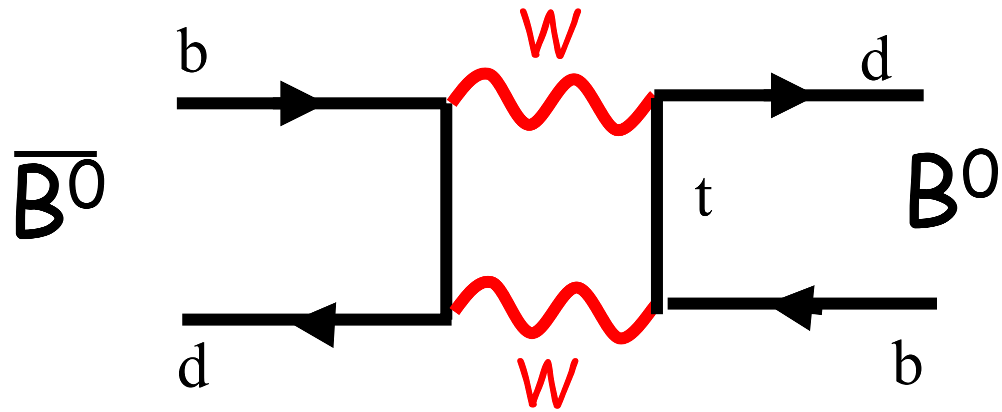
with $\hat{B}_K^{NLO}$ two-loop RGI B-parameter

- Same result as in LL, Lattice 2000
- Clarify situation regarding DW results
- Need unquenched studies to reduce the 15% quenching error in order to maintain impact of indirect CPV in the kaon system on UT (talk by Parodi)

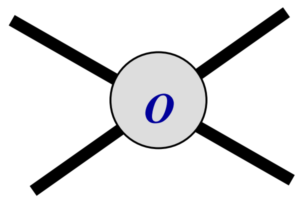
B^0 - B^0 mixing

$$H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}$$

ΔB=2 Transitions



$H_{eff}^{\Delta B=2} =$



$$\propto \left(\overline{\mathbf{d}}\, \gamma_\mu (\mathbf{1} - \gamma_5)\, \mathbf{b} \right)^2$$

CKM

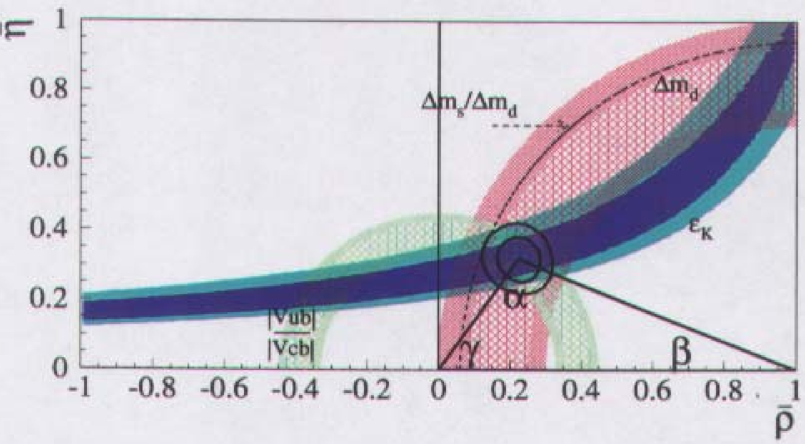
Hadronic matrix element

$$\Delta m_{d,s} = \frac{G^2_F\, M^2_W}{16\, \pi^2}\, A^2 \lambda^6\, F_{tt}\left(\frac{m^2_t}{M^2_W}\right) \langle\, O\, \rangle$$

Unitarity Triangle

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

$$\overline{AC} = \frac{1-\lambda^2/2}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right| \qquad \overline{AB} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$



Measurement	V_{CKM} ×other	Constraint
$b \to u / b \to c$	$\lvert V_{ub}/V_{cb}\rvert^2$	$\bar\rho^2 + \bar\eta^2$
Δm_d	$\lvert V_{td}\rvert^2 f_{B_d}^2 B_{B_d} f(m_t)$	$(1-\bar\rho)^2 + \bar\eta^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\left\lvert\frac{V_{td}}{V_{ts}}\right\rvert^2 \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}}$	$(1-\bar\rho)^2 + \bar\eta^2$
ϵ_K	$f(A, \bar\eta, \bar\rho, B_K)$	$\propto \bar\eta(1-\bar\rho)$

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

sin 2β is measured directly from $B \to J/\psi\, K_s$ decays at Babar & Belle

$$A_{J/\psi\, K_s} = \frac{\Gamma(B_d^0 \to J/\psi\, K_s, t) - \Gamma(\bar{B}_d^0 \to J/\psi\, K_s, t)}{\Gamma(B_d^0 \to J/\psi\, K_s, t) + \Gamma(\bar{B}_d^0 \to J/\psi\, K_s, t)}$$

$$A_{J/\psi\, K_s} = \sin 2\beta \quad \sin(\Delta m_d\, t)$$

from the study: CKM Triangle Analysis

A critical review with updated experimental inputs and theoretical parameters

M. Ciuchini et al . 2000 (& 2001)

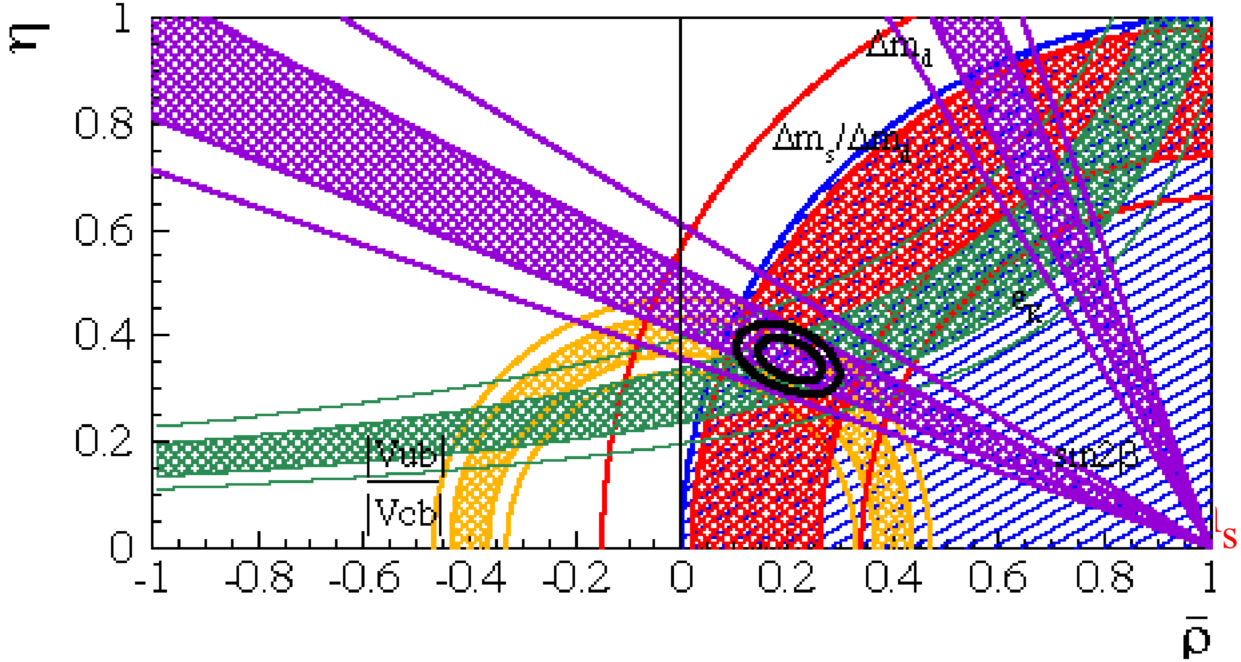
upgraded for ICHEP 2002-presented by A. Stocchi

see also the CERN Yellow Book (CKM Workshop)

similar results from Hoecker et al. 2000-2001

Results for ρ and η & related quantities

Allowed regions in the ρ-η plane (contours at 68% and 95% C.L.)



$\rho = 0.178 \pm 0.046$ [0.085 - 0.265]

$\eta = 0.341 \pm 0.028$ [0.288 - 0.397]

at 95% C.L.

$\sin 2\alpha = -0.19 \pm 0.25$ [-0.62 - +0.33]

$\sin 2\beta = 0.695 \pm 0.056$ [0.68 - 0.79]

Comparison of $\sin 2\beta$ from direct measurements (Aleph, Opal, Babar, Belle and CDF) and UTA analysis

$\sin 2\beta_{measured} = 0.734 \pm 0.054$ [0.68 - 0.79] 95%C.L.

$\sin 2\beta_{UTA} = 0.695 \pm 0.056$ [0.54 - 0.79] 95%C.L.

Very good agreement
no much room for physics beyond the SM !!

Grand average $0.705 ^{+0.042}_{-0.032}$

CKM YELLOW BOOK

Rfit Method			
Parameter	$\leq$ 5% CL	$\leq$ 1% CL	$\leq$ 0.1% CL
$\bar{\rho}$	0.015 - 0.334	-0.016 - 0.355	-0.049 - 0.377
$\bar{\eta}$	0.274 - 0.448	0.262 - 0.465	0.250 - 0.484
$\sin 2\beta$	0.647 - 0.813	0.616 - 0.836	0.581 - 0.860
γ^{o}	41.3 - 87.7	38.9 - 92.0	36.8 - 97.1

OPTIMIST ?

Bayesian Method			
Parameter	5% CL	1% CL	0.1% CL
$\bar{\rho}$	0.079 - 0.262	0.047 - 0.294	0.005 - 0.336
$\bar{\eta}$	0.303 - 0.408	0.287 - 0.425	0.268 - 0.444
$\sin 2\beta$	0.658 - 0.787	0.658 - 0.806	0.609 - 0.826
γ^{o}	50.5 - 78.5	45.9 - 83.2	40.4 - 89.4

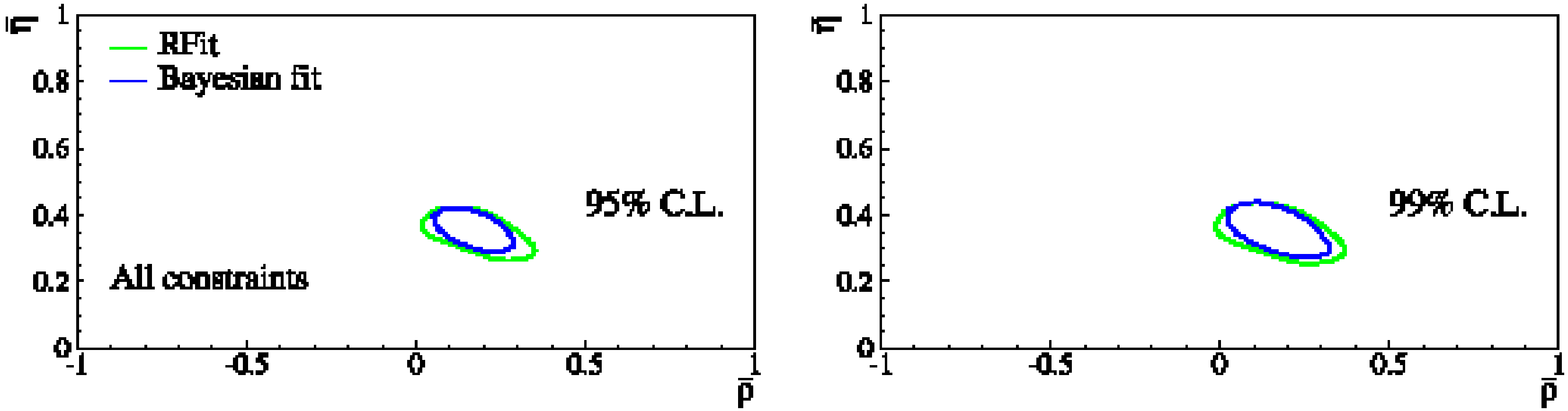
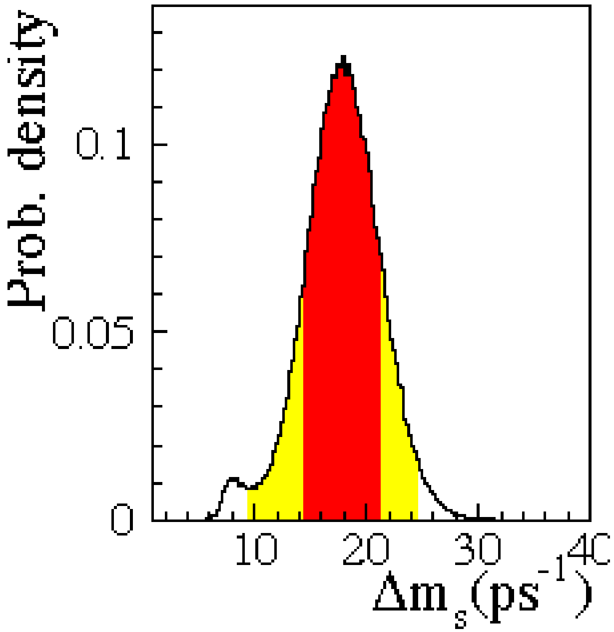


Fig. 5.15: **Comparison Bayesian/RFit Methods** *Allowed regions for $\bar{\rho}$ and $\bar{\eta}$ at 95% (left plot) and 99% (right plot) using the measurements of $|V_{ub}| / |V_{cb}|$, ΔM_d, the amplitude spectrum for including the information from the $B_s^0 - \bar{B}_s^0$ oscillations, $|\varepsilon_K|$ and the measurement of sin 2β.*

Parameter	5% CL	1% CL	0.1% CL
$\bar{\rho}$	1.30	1.17	1.03
$\bar{\eta}$	1.03	0.96	0.90
$\sin 2\beta$	1.20	1.21	1.21
γ°	1.34	1.22	1.15

Table 5.4: **Comparison** *Ratio for confidence levels Rfit/Bayesian using the distributions as obtained from Rfit to account for the information on input quantities*

Δm_s Probability Density

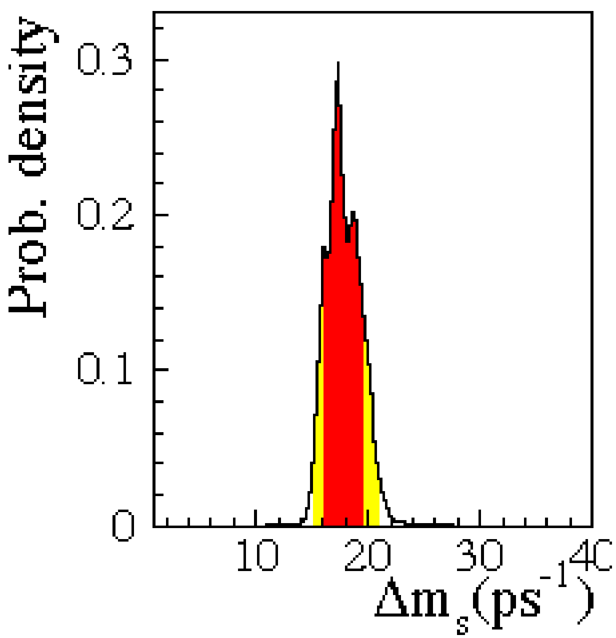


Without the constraint from Δm_s

$$\Delta m_s = (17.8^{+3.4}_{-3.2})\ ps^{-1}$$

[9.4 - 24.4] ps^{-1} at 95% C.L.

$\Delta m_s = (17.8 \pm 3.4)\ ps^{-1}$



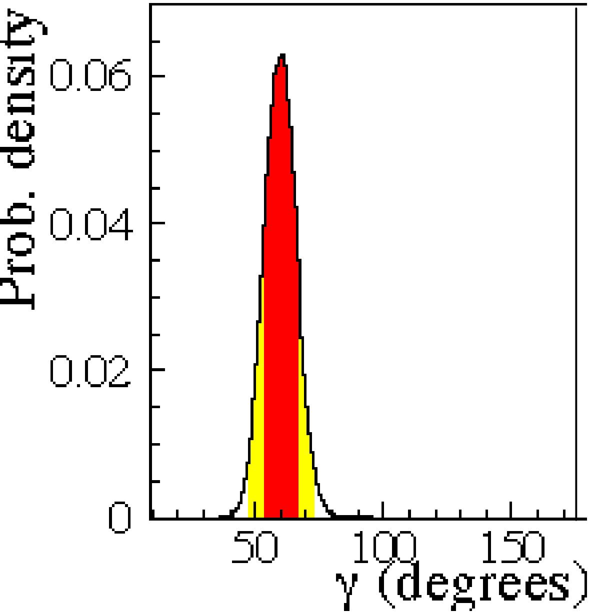
With the constraint from Δm_s

$$\Delta m_s = (17.6^{+2.0}_{-1.3})\ ps^{-1}$$

[15.2 - 20.9] ps^{-1} at 95% C.L.

$\Delta m_s = (17.3^{+1.5}_{-0.7})\ ps^{-1}$

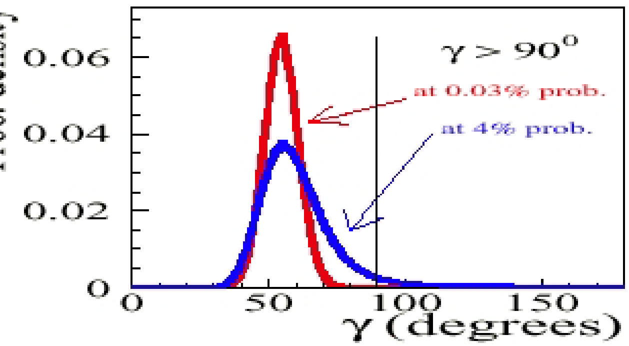
The angle γ



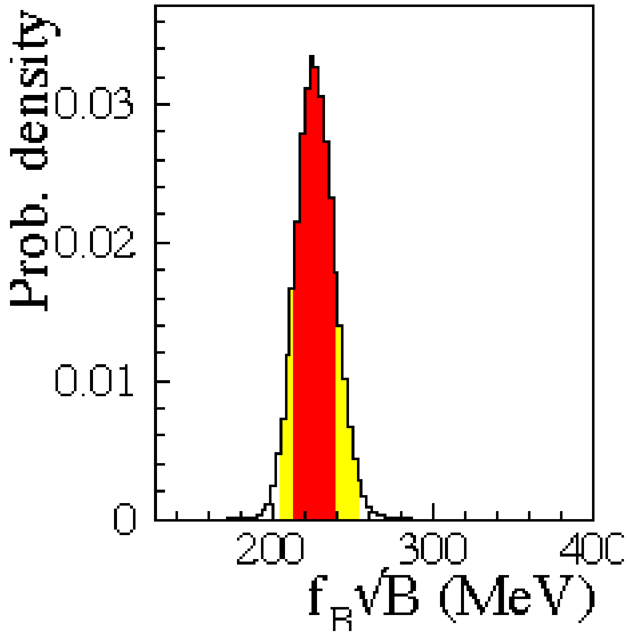
$$\gamma = (59.5^{+6.5}_{-5.5})^0$$

$[49 - 72]^0$ at 95% C.L.

With (red) and without (blue) the constraint from Δm_s



Δm_s fundamental for constraining γ



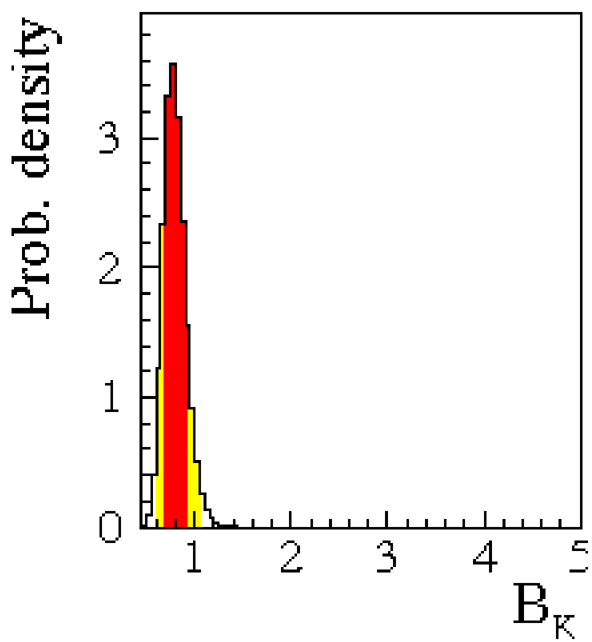
Hadronic parameters

$$f_{Bd}\sqrt{B_{Bd}} = 232 \pm 30^{(+0)}_{(-20)}\ \text{MeV}$$ **gm**

$$f_{Bd}\sqrt{B_{Bd}} = 235 \pm 33^{(+0)}_{(-24)}\ \text{MeV}$$

lellouch

$$f_{Bd}\sqrt{B_{Bd}} = 228^{(+14)}_{(-11)}\ \text{MeV}$$ **UTA**

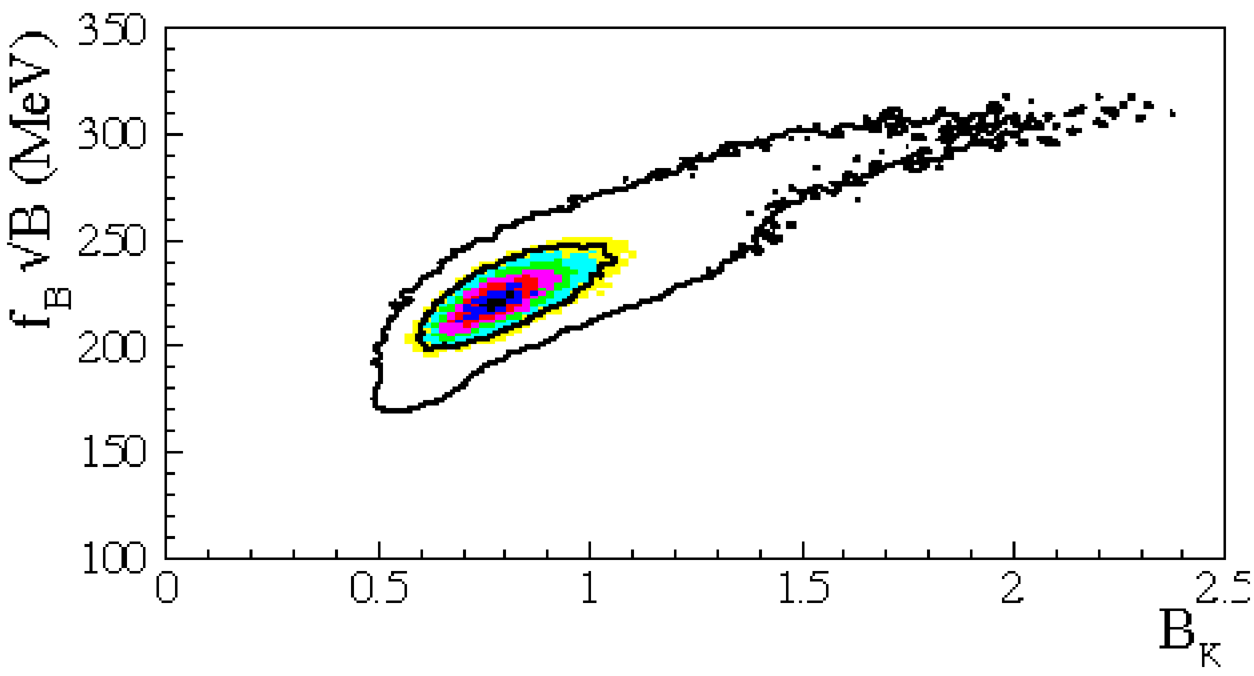


$$B_K = 0.86 \pm 0.06 \pm 0.14$$

lellouch &gm
rather conservative

$$B_K = 0.78^{(+0.14)}_{(-0.08)}$$ **UTA**

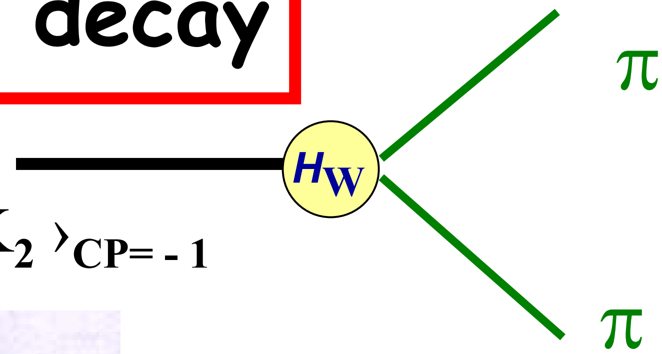
Hadronic parameters



95% C.L. **UTA**

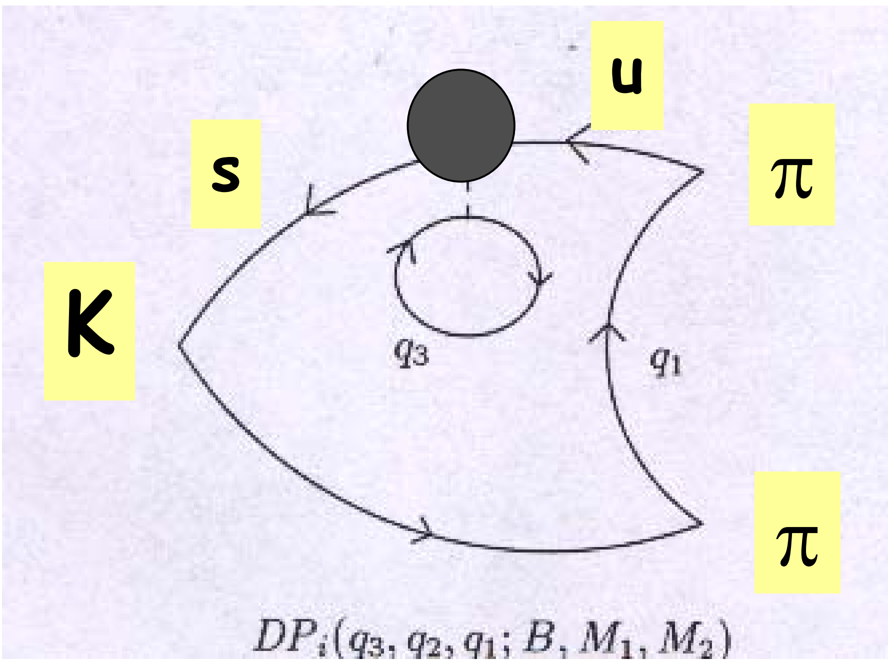
$B_K > 0.5$ $f_{Bd} \sqrt{B_{Bd}} > 150$ MeV

Direct CP violation: decay



CP= + 1

$|K_L\rangle = |K_2\rangle_{CP=-1}$



S

Complex ΔS=1 effective coupling

$$A_0 e^{i\delta_0} = \langle (\pi\,\pi)_{I=0} | H_W | K^0 \rangle$$

$$A_2 e^{i\delta_2} = \langle (\pi\,\pi)_{I=2} | H_W | K^0 \rangle$$

Where $\delta_{0,2}$ is the strong interaction phase (Watson theorem) and the weak phase is hidden in $A_{0,2}$

$$\not{C}\not{P} \quad \text{if} \quad \mathrm{Im}[A_0^* A_2] \neq 0$$

$$\varepsilon' = i \frac{e^{i(\delta_2 - \delta_0)}\,\omega}{\sqrt{2}} \left[\frac{\mathrm{Im}\, A_2}{\mathrm{Re}\, A_2} - \frac{\mathrm{Im}\, A_0}{\mathrm{Re}\, A_0} \right]$$

$$\omega = \mathrm{Re}\, A_2 / \mathrm{Re}\, A_0 \sim 1/22$$

In the Standard Model

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

$r = G_F \, \omega / (2 \, |\varepsilon| \, \mathrm{Re} \, A_0)$

Extracting the phases:

$$\varepsilon'/\varepsilon = \mathrm{Im} \, \lambda_t \, e^{i(\pi/2 + \delta_2 - \delta_0 - \phi_\varepsilon)} \, r \left[|A_0| - \frac{1}{\omega} |A_2| \right]$$

GENERAL FRAMEWORK

$$H^{\Delta S=1} = G_F/\sqrt{2}\, V_{ud}\, V_{us}^{*}\Big[\, (1-\tau)\, \Sigma_{i=1,2}\, z_i\, (Q_i - Q^c_i) + \tau\, \Sigma_{i=1,10}\, (\, z_i + y_i\,)\, Q_i\ \Big]$$

Where y_i and z_i are short distance coefficients, which are known in perturbation theory at the NLO (Buras et al. + Ciuchini et al.)

$$\tau = -V_{ts}^{*} V_{td} / V_{us}^{*} V_{ud}$$

We have to compute $A^{I=0,2}_{i} = \langle\, (\pi\, \pi)_{I=0,2}\, | Q_i |\, K \,\rangle$ with a non perturbative technique (lattice, QCD sum rules, 1/N expansion etc.)

New local four-fermion operators are generated

$Q_1 = (\bar{s}_L^{\ A} \gamma_\mu u_L^{\ B}) (\bar{u}_L^{\ B} \gamma_\mu d_L^{\ A})$ Current-Current

$Q_2 = (\bar{s}_L^{\ A} \gamma_\mu u_L^{\ A}) (\bar{u}_L^{\ B} \gamma_\mu d_L^{\ B})$

$Q_{3,5} = (\bar{s}_R^{\ A} \gamma_\mu d_L^{\ A}) \sum_q (\bar{q}_{L,R}^{\ B} \gamma_\mu q_{L,R}^{\ B})$ Gluon

$Q_{4,6} = (\bar{s}_R^{\ A} \gamma_\mu d_L^{\ B}) \sum_q (\bar{q}_{L,R}^{\ B} \gamma_\mu q_{L,R}^{\ A})$ Penguins

$Q_{7,9} = 3/2(\bar{s}_R^{\ A} \gamma_\mu d_L^{\ A}) \sum_q e_q (\bar{q}_{R,L}^{\ B} \gamma_\mu q_{R,L}^{\ B})$ Electroweak

$Q_{8,10} = 3/2(\bar{s}_R^{\ A} \gamma_\mu d_L^{\ B}) \sum_q e_q (\bar{q}_{R,L}^{\ B} \gamma_\mu q_{R,L}^{\ A})$ Penguins

+ Chromomagnetic end electromagnetic operators
to be discussed in the following

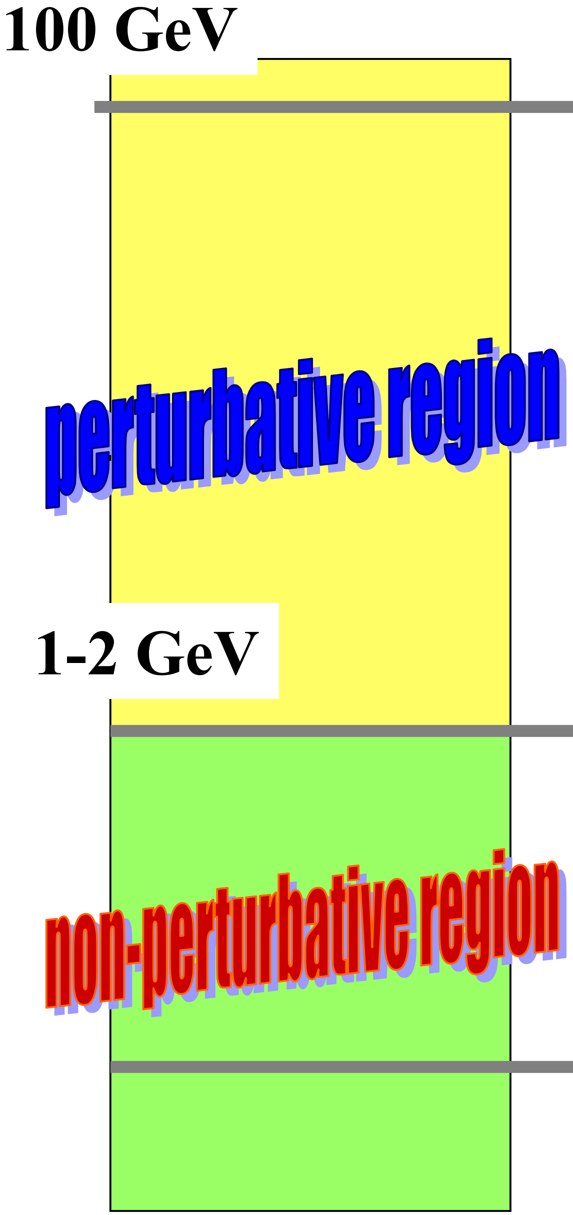
$$A_0 = \sum_i \; C_i(\mu) \; \langle (\pi\,\pi) | Q_i(\mu) | K \rangle_{I=0} \; (1 - \Omega_{IB})$$

μ = renormalization scale
μ-dependence cancels if operator matrix elements are consistently computed

ISOSPIN BREAKING

$$A_2 = \sum_i \; C_i(\mu) \; \langle (\pi\,\pi) | Q_i(\mu) | K \rangle_{I=2}$$

$\Omega_{IB} = 0.25 \pm 0.08$ (Munich from Buras & Gerard)
0.25 ± 0.15 (Rome Group) 0.16 ± 0.03 (Ecker et al.)
0.10 ± 0.20 Gardner & Valencia, Maltman & Wolf, Cirigliano & al.



Large mass scale: heavy degrees of freedom (m_t, M_W, M_s) are removed and their effect included in the Wilson coefficients

renormalizazion scale μ (inverse lattice spacing $1/a$); this is the scale where the quark theory is matched to the effective hadronic theory

Scale of the low energy process $\Lambda \sim M_W$

THE SCALE PROBLEM: Effective theories prefer low scales, Perturbation Theory prefers large scales

if the scale μ is too low
problems from higher dimensional operators

(Cirigliano, Donoghue, Golowich)

- it is illusory to think that the problem is solved by using dimensional regularization

on the lattice this problem is called

DISCRETIZATION ERRORS

(reduced by using improved actions and/or scales $\mu > 2\text{-}4$ GeV

VACUUM SATURATION & B-PARAMETERS

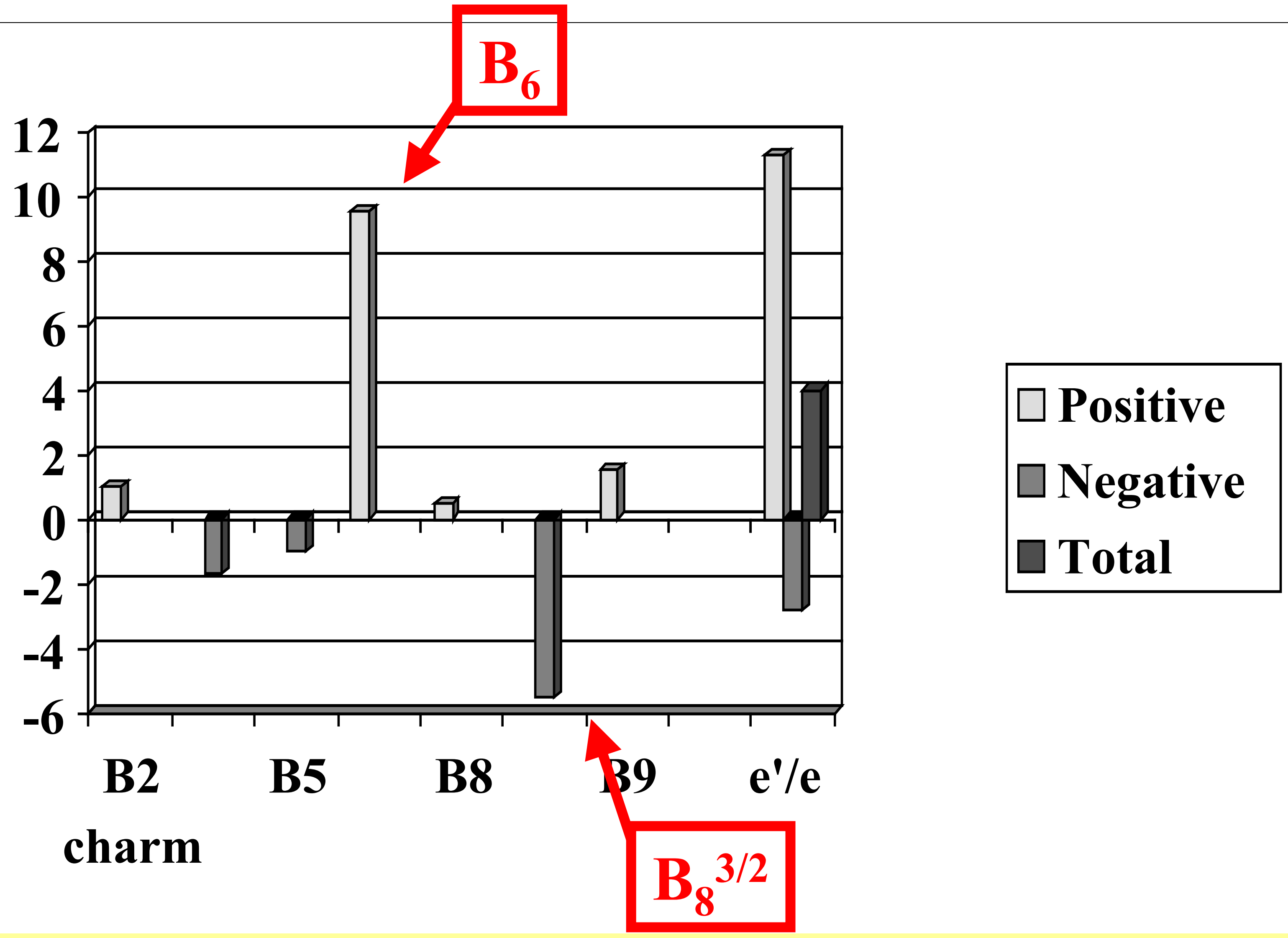
$$A = \sum_i \; C_i(\mu) \; \langle (\pi\,\pi)\, | Q_i(\mu) | \, K \rangle$$

$$\langle (\pi\,\pi)\, | Q_i(\mu) | \, K \rangle = \langle (\pi\,\pi)\, | Q_i | \, K \rangle_{VIA} \; B(\mu)$$

μ -dependence of VIA matrix elements is not consistent
With that of the Wilson coefficients
e.g. $\langle (\pi\,\pi)\, | Q_9 | \, K \rangle_{I=2,VIA} = 2/3 \; f_\pi \,(M^2_K - M^2_\pi)$

In order to explain the $\Delta I=1/2$ enhancement
the B-parameters of
Q_1 and Q_2 should be of order 4 !!!

Relative contribution of the OPS



The Buras Formula that should NOT be used but is presented by everyone

$$(\varepsilon'/\varepsilon)_{EXP} = (\ 17.2 \pm 1.8\ )\ 10^{-4}$$

$$\lambda_t = V_{td} V_{ts}^* = (\ 1.31 \pm 1.0\ )\ 10^{-4}$$

$$\varepsilon'/\varepsilon = 13\ \mathrm{Im}\,\lambda_t \left[\frac{110\ \mathrm{MeV}}{m_s(\mu)}\right]^2 [B_6(1-\Omega_{IB}) - 0.4\ B_8]$$

a value of B_6 **MUCH LARGER** than 1 $(2 \div 3)$ is needed to explain the experiments

The situation worsen if also B_8 is larger than 1

Theoretical Methods for the Matrix Elements (ME)

- Lattice QCD **Rome Group, M. Ciuchini & al.**
- NLO Accuracy and consistent matching ☺
- χPT (now at the next to leading order) and quenching 😐
- no realistic calculation of $\langle Q_6 \rangle$ ☹
- Fenomenological Approach **Munich A.Buras & al.**
- NLO Accuracy and consistent matching ☺
- no results for $\langle Q_{6,8} \rangle$ which are taken elsewhere ☹
- Chiral quark model **Trieste S.Bertolini & al.**
- all ME computed with the same method ☺
- model dependence, quadratic divergencies,matching ☹

From
S. Bertolini

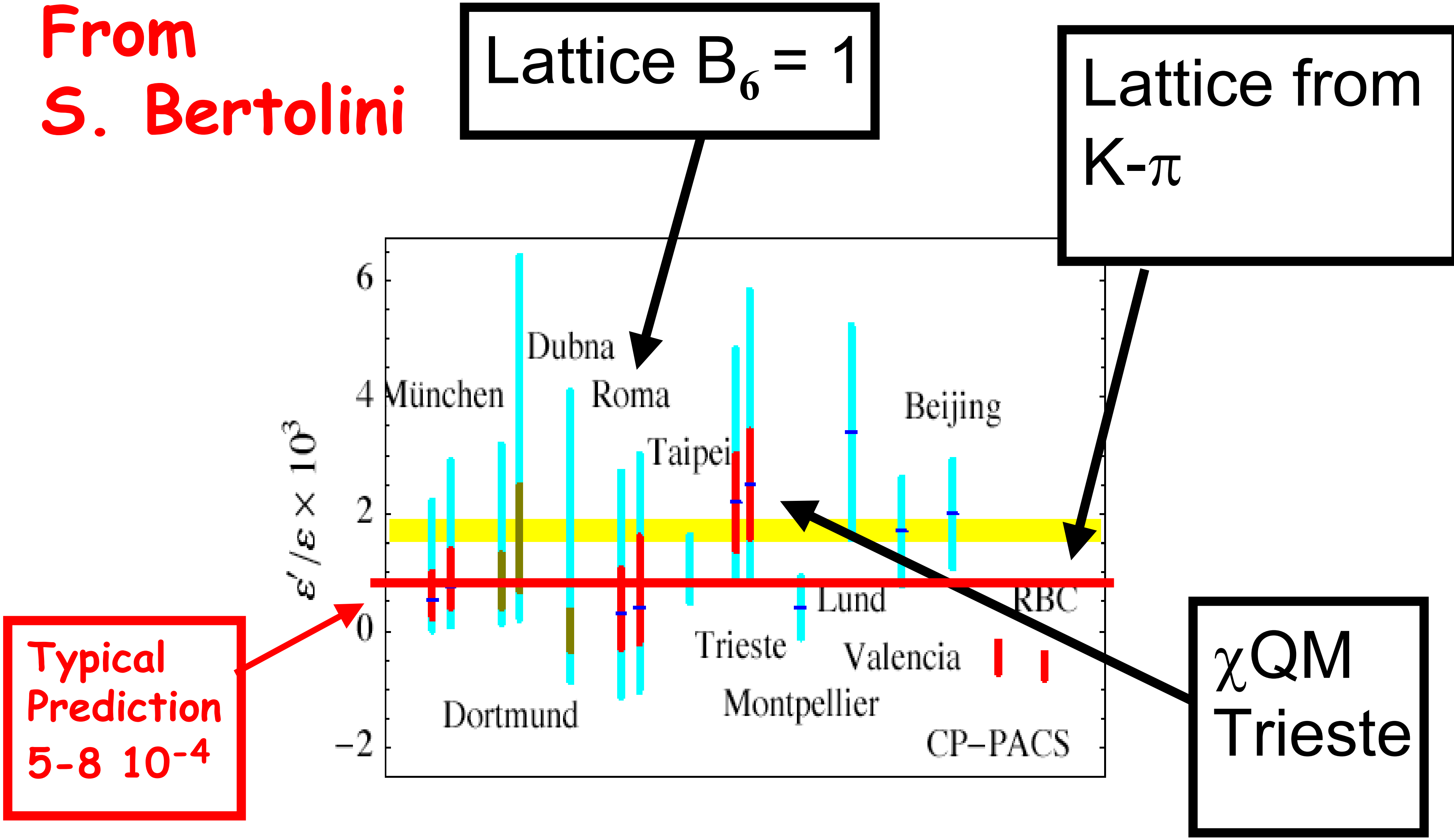
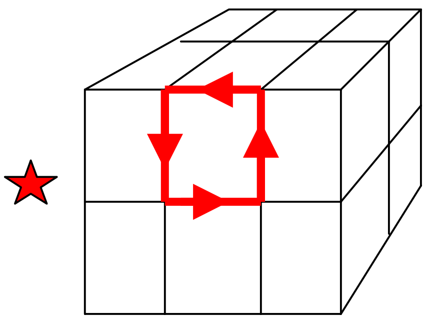


Figure 3: Recent theoretical calculations of ε'/ε are compared with the combined 1-σ average of the NA31, E731, KTeV and NA48 results ($\varepsilon'/\varepsilon = 17.2 \pm 1.8 \times 10^{-4}$), depicted by the [ ] horizontal band.

In my opinion only the Lattice approach will be able to give quantitative answers with controlled systematic errors



Quenching for $\Delta I=1/2$ transitions !

Gladiator The $SPQ_{cd}R$ Collaboration & APE

(Southapmton, Paris, Rome,Valencia)

The IR problem arises from two sources:

- The (unavoidable) continuation of the theory to Euclidean space-time (Maiani-Testa theorem)
- The use of a finite volume in numerical simulations

An important step towards the solution of the IR problem has been achieved by L. Lellouch and M. Lüscher (LL), who derived a relation between the $K \to \pi\,\pi$ matrix elements in a finite volume and the physical amplitudes

presented by L. Lellouch at Latt2000

Commun.Math.Phys.219:31-44,2001
e-Print Archive: **hep-lat/0003023**

Here I discuss an alternative derivation based on the behaviour of correlators of local operator when $V \to \infty$

D. Lin, G.M., C. Sachrajda and M. Testa hep-lat/0104006 (LMST)

The finite-volume Euclidean matrix elements are related to the absolute values of the **Physical Amplitudes** $|\langle \pi\pi\, E\, |Q(0)|\, K \rangle|$

by comparing, at large values of V, finite volume correlators to the infinite volume ones

$$|\langle \pi\pi\, E\, |Q(0)|\, K \rangle| \quad = \quad \sqrt{F} \quad \langle \pi\pi\, n\, |Q(0)|\, K \rangle_V$$

$F = 32\, \pi^2\, V^2\, \rho_V(E)\, E\, m_K / k(E)$ where $k(E) = \sqrt{E^2/4 - m^2_\pi}$ and

$\rho_V(E) = (q\, \phi'(q) + k\, \delta'(k))/4\, \pi\, k^2$ is the expression which one would heuristically derive by interpreting $\rho_V(E)$ as the density of states in a finite volume (D. Lin, G.M., C. Sachrajda and M. Testa)

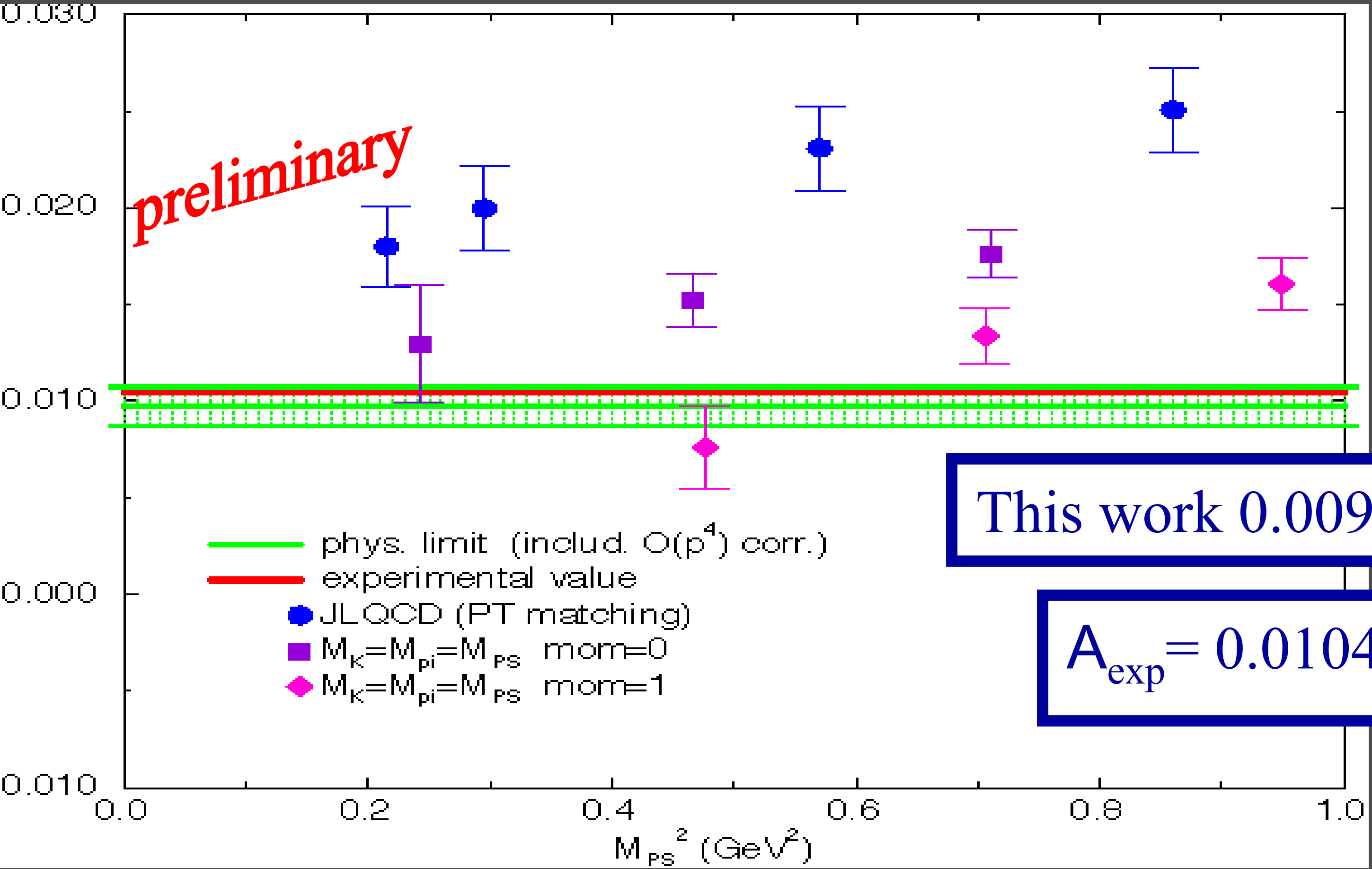
the corrections are exponentially small in the volume

On the other hand the phase-shift can be extracted from the two-pion energy according to (Lüscher):

$$W_n = 2\sqrt{m^2_\pi + k^2} \qquad\qquad n\,\pi - \delta(k) = \phi(q)$$

THE CHIRAL BEHAVIOUR OF $\langle \pi\, \pi\, |H_W|\, K \rangle_{I=2}$ by the $SPQ_{cd}R$ Collaboration and a comparison with JLQCD **Phys. Rev. D58 (1998) 054503**

no chiral logs included yet, analysis under way



This work 0.0097(10) GeV^3

A_{exp} = 0.0104098 GeV^3

Lattice QCD finds B_K = 0.86 and a value of $\langle \pi\, \pi\, |H_W|\, K \rangle_{I=2}$ compatible with exps

I=0 ππ States in the Quenched Theory (Lack of Unitarity)

1) the final state interaction phase is not universal, since it depends on the operator used to create the two-pion state. This is not surprising, since the basis of Watson theorem is unitarity;

2) the Lüscher quantization condition for the two-pion energy levels does not hold. Consequently it is not possible to take the infinite volume limit at constant physics, namely with a fixed value of W ;

3) a related consequence is that the LL relation between the absolute value of the physical amplitudes and the finite volume matrix elements is no more valid;

4) whereas it is usually possible to extract the lattice amplitudes by constructing suitable time-independent ratios of correlation functions, this procedure fails in the quenched theory because the time-dependence of correlation functions corresponding to the same external states is not the same

D. Lin, G.M., E. Pallante, C. Sachrajda and G. Villadoro

There could be a way-out …..

$\Delta I = 1/2$ and ε'/ε

- $K \rightarrow \pi\,\pi$ from $K \rightarrow \pi$ and $K \rightarrow 0$

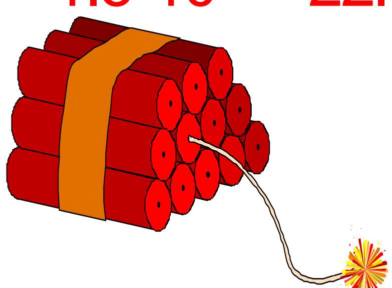
- Direct $K \rightarrow \pi\,\pi$ calculation

- $\Delta I = 1/2$ decays and Q_2)
- ε'/ε electrope ns (Q_7 and Q_8)
- ε'/ε strong pe ins (Q_6)

Physics Results from RBC and CP-PACS

no lattice details here

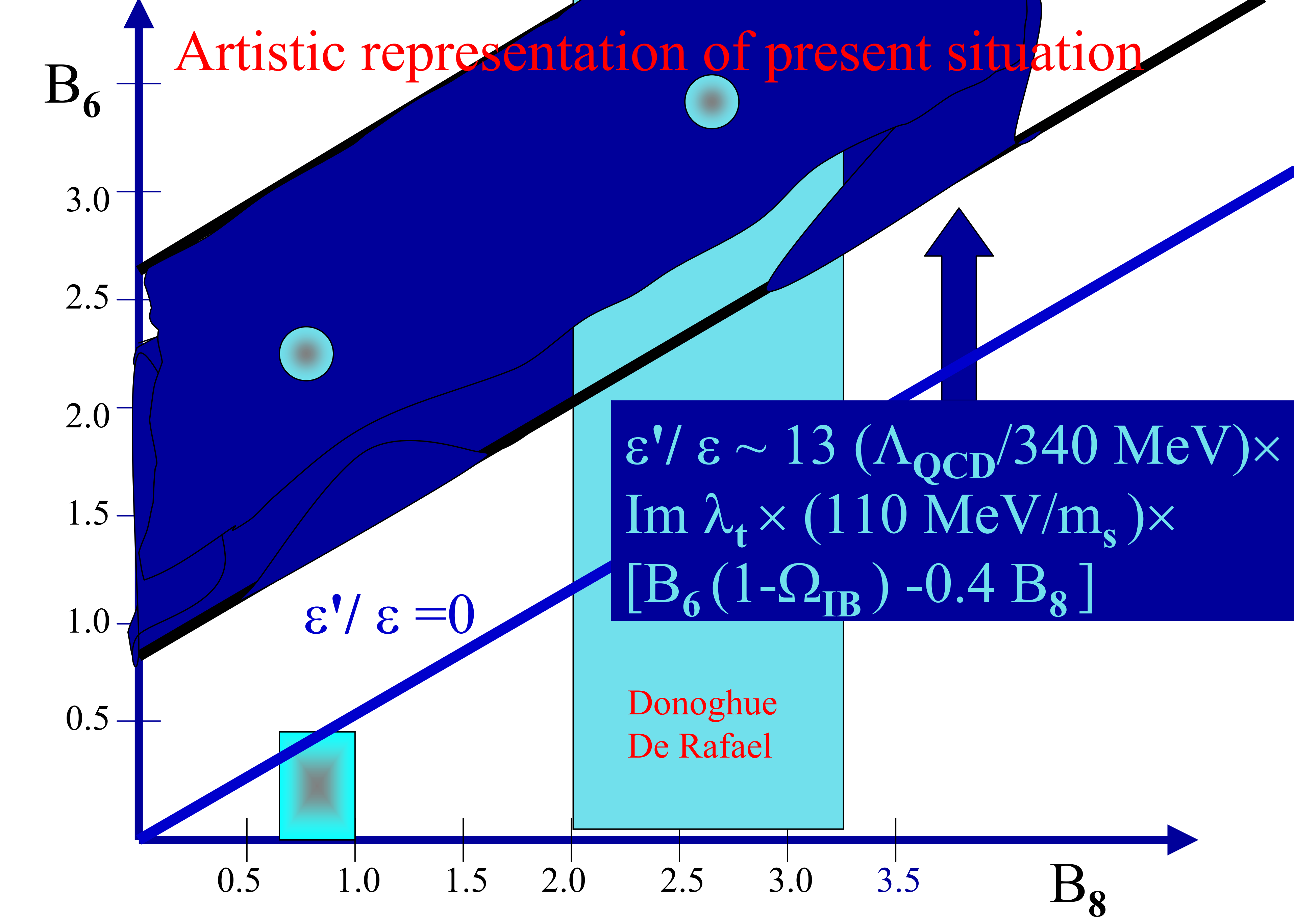
	Re(A_0)	Re(A_2)	Re(A_0)/Re(A_2)	ε'/ε
RBC	29÷31 10^{-8}	1.1 ÷1.2 10^{-8}	24÷27	-4 ÷ -8 10^{-4}
CP PACS	16÷21 10^{-8}	1.3÷1.5 10^{-8}	9÷12	-2 ÷ -7 10^{-4}
EXP	33.3 10^{-8}	1.5 10^{-8}	22.2	17.2 ± 1.8 10^{-4}



Total Disagreement with experiments ! (and other th. determinations)

Opposite sign !

New Physics?


Artistic representation of present situation
B6
3.0
2.5
2.0
1.5
1.0
0.5
ε'/ ε =0
ε'/ ε ~ 13 (ΛQCD/340 MeV)×
Im λt × (110 MeV/ms)×
[B6 (1-ΩIB) -0.4 B8]
Donoghue
De Rafael
0.5
1.0
1.5
2.0
2.5
3.0
3.5
B8

Physics Results from RBC and CP-PACS

	Re(A_0)	Re(A_2)	Re(A_0)/ Re(A_2)	ε'/ε
RBC	29÷31 10^{-8}	1.1 ÷1.2 10^{-8}	24÷27	-4 ÷ -8 10^{-4}
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EXP	33.3 10^{-8}	1.5 10^{-8}	22.2	17.2 ± 1.8 10^{-4}

- **Chirality**
- **Subtraction**
- **Low Ren.Scale**
- **Quenching**
- **FSI**
- **New Physics**
- **A combination ?**

Even by doubling O_6 one cannot agree with the data

$K \to \pi\,\pi$ and Staggered Fermions (Poster by W.Lee) will certainly help to clarify the situation I am not allowed to quote any number

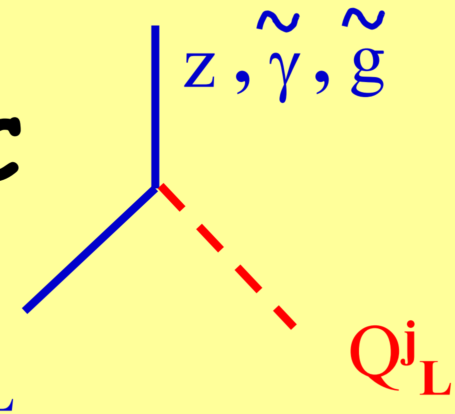
~~CP~~ beyond the SM (Supersymmetry)

SM			SUSY partners		
Spin 1/2	Quarks	q_L , u_R , d_R	Spin 0	SQuarks	Q_L , U_R , D_R
	Leptons	l_L , e_R		SLeptons	L_L , E_R
Spin 1	Gauge bosons	W , Z , γ , g	Spin 1/2	Gauginos	w , z , $\tilde{\gamma}$, $\tilde{g}$
Spin 0	Higgs bosons	H_1 , H_2	Spin 1/2	Higgsinos	$\tilde{H}_1$, $\tilde{H}_2$

In general the mixing mass matrix of the SQuarks (SMM) is not diagonal in flavour space analogously to the quark case

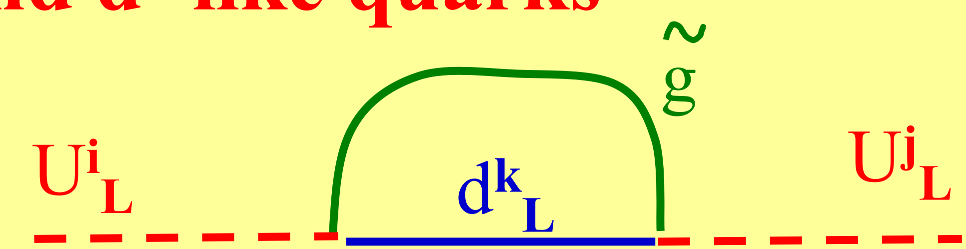
We may either **Diagonalize the SMM**

FCNC

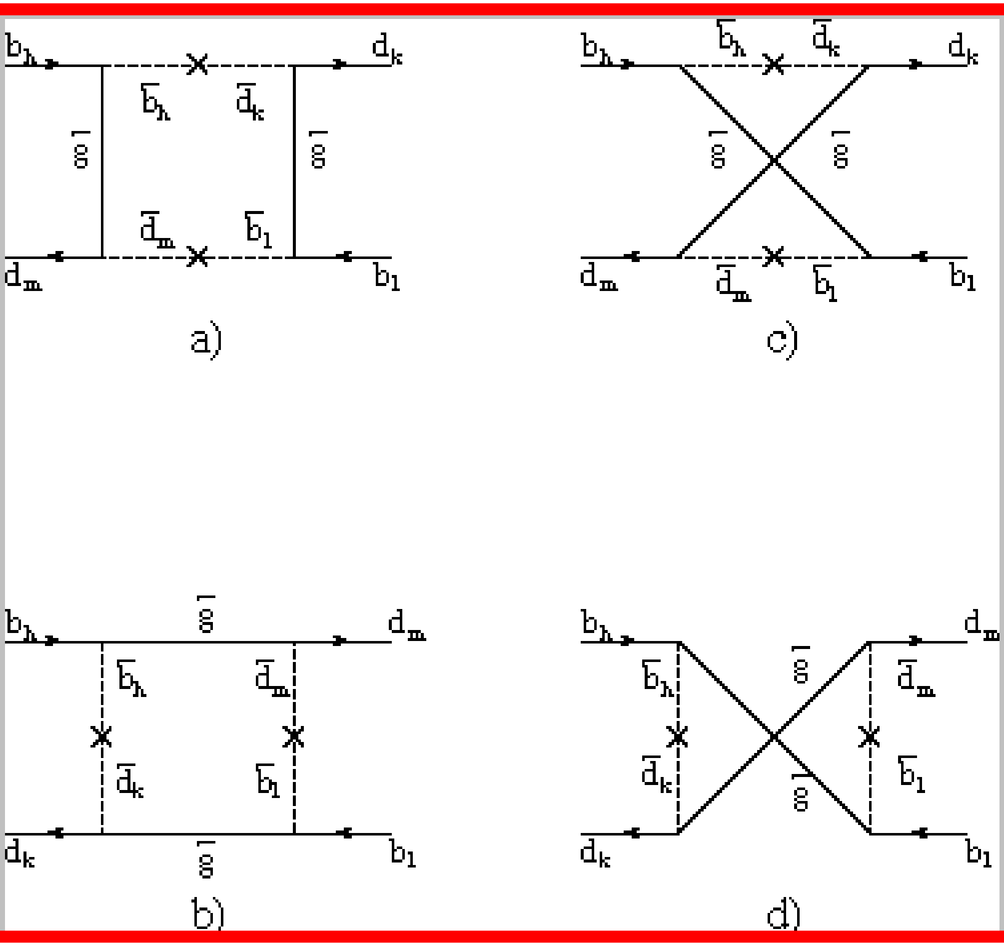


or **Rotate by the same matrices the SUSY partners of the u- and d- like quarks**

$(Q^j_L)' = U^{ij}_L \, Q^j_L$



In the latter case the Squark Mass Matrix is not diagonal



$$(m^2_Q)_{ij} = m^2_{average}\, \mathbf{1}_{ij} + \Delta m_{ij}^2 \qquad \delta_{ij} = \Delta m_{ij}^2 / m^2_{average}$$

New local four-fermion operators are generated

$Q_1 = (\bar{s}_L{}^A \gamma_\mu d_L{}^A)(\bar{s}_L{}^B \gamma_\mu d_L{}^B)$ SM

$Q_2 = (\bar{s}_R{}^A d_L{}^A)(\bar{s}_R{}^B d_L{}^B)$

$Q_3 = (\bar{s}_R{}^A d_L{}^B)(\bar{s}_R{}^B d_L{}^A)$

$Q_4 = (\bar{s}_R{}^A d_L{}^A)(\bar{s}_L{}^B d_R{}^B)$

$Q_5 = (\bar{s}_R{}^A d_L{}^B)(\bar{s}_L{}^B d_R{}^A)$

+ those obtained by $L \leftrightarrow R$

Similarly for the b quark e.g.

$(\bar{b}_R{}^A d_L{}^A)(\bar{b}_R{}^B d_L{}^B)$

$$L_{SM}^{\Delta F=2} = \Sigma_{ij=d,s,b} (V_{td_i} V^*_{td_j})^2\ C\ [\bar{d}_i \gamma_\mu (1-\gamma_5) d_j]^2$$

$$L^{\Delta F=2}_{general} = \Sigma_\alpha \Sigma_{ij=d,s,b} C^{ij}_\alpha Q^{ij}_\alpha$$

α = different Lorentz structures L×L, L ×R etc.

C^{ij}_α =complex coefficients from perturbation theory

$\langle \bar{K} | Q^{ij}_\alpha | K \rangle$ from lattice QCD (APE Collaboration Allton et al., Donini et al., Becirevic et al.)

APE & $SPQ_{cd}R$ Collaboration
(Becirevic et. al.)
also $\langle \bar{B} | Q^{ij}_\alpha | B \rangle$

In the kaon case matrix elements of LR operators have a large enhancement as can be guessed by their value in the VSA

$$\frac{\langle \overline{K}^{\mathbf{0}} | Q_{\mathbf{2\text{-}5}} | K^{\mathbf{0}} \rangle}{\langle \overline{K}^{\mathbf{0}} | Q_{\mathbf{1}} | K^{\mathbf{0}} \rangle} \sim \left(\frac{M^2_K}{(m_s + m_d)} \right)^2$$

This enhancement is confirmed by explicit lattice calculations (APE & SPQR)

lattice operators are renormalized in a scheme suitable for a consistent NLO calculation of the physical amplitude

Tree level coefficients computed by Gabbiani, Masiero, Gabrielli and Silvestrini, …..

LO coefficients computed by Bagger, Matchev and Zhang

The QCD corrections have large effects !

NLO corrections of $O(\alpha_s)$ to the Wilson coefficients known only in few cases, their effect is expected to be rather small $\alpha_s = \alpha_s\,(M_{SUSY})$

NLO coefficients computed by Ciuchini, Franco, Lubicz, Scimemi, Silvestrini, G.M.; Buras, Misiak, Urban

Phenomenological analyses Gabbiani et al., Ciuchini et al. + Masiero; Ali and London; Ali and Lunghi; Buras et al.; Bartl et al. etc. etc. ………………...

TYPICAL BOUNDS FROM ΔM_K AND ε_K

$x = m^2_{\tilde{g}} / m^2_{\tilde{q}}$

$x = 1$ $\qquad m_{\tilde{q}} = 500$ GeV

$$\sqrt{|\mathrm{Re}\,(\delta_{12}{}^2)_{LL}|} < 3.9 \times 10^{-2}$$

$$\sqrt{|\mathrm{Re}\,(\delta_{12}{}^2)_{LR}|} < 2.5 \times 10^{-3}$$

$$\sqrt{|\mathrm{Re}\,(\delta_{12})_{LL}\,(\delta_{12})_{RR}|} < 8.7 \times 10^{-4}$$

from ΔM_K

from ε_K

$x = 1 \quad m_{\tilde{q}} = 500$ GeV

$$\sqrt{|\mathrm{Im}\,(\delta_{12}^{2})_{LL}|} < \mathbf{5.8 \times 10^{-3}}$$

$$\sqrt{|\mathrm{Im}\,(\delta_{12}^{2})_{LR}|} < \mathbf{3.7 \times 10^{-4}}$$

$$\sqrt{|\mathrm{Im}\,(\delta_{12})_{LL}\,(\delta_{12})_{RR}|} < \mathbf{1.3 \times 10^{-4}}$$

ΔM_B and $A(B \to J/\psi K_s)$

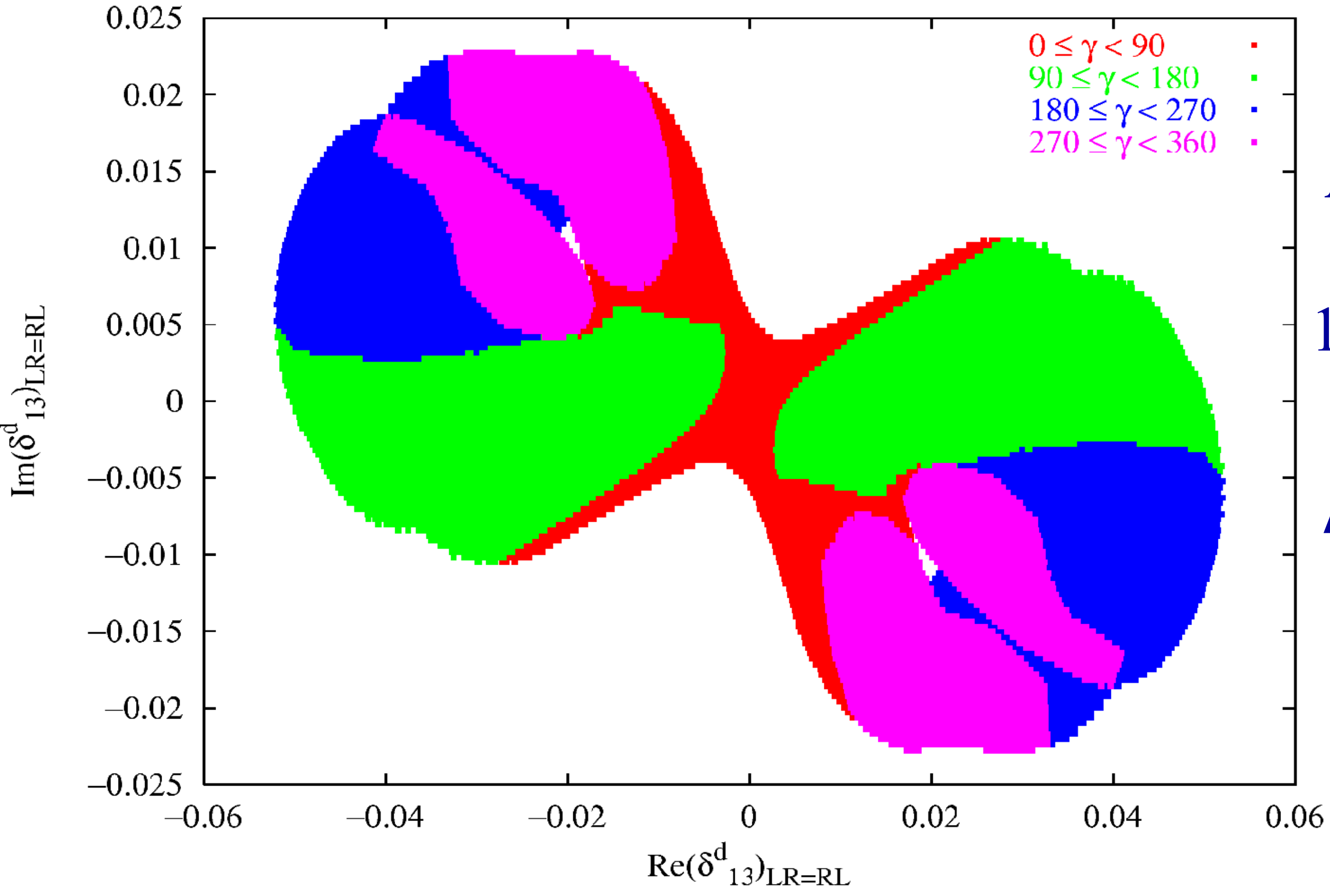
$$\Delta M_{B_d} = 2\,\mathrm{Abs}\,|\langle \overline{B}_d | H^{\Delta B=2}_{\mathrm{eff}} | B_d \rangle|$$

$$A(B \to J/\psi K_s) = \sin 2\beta_{\mathrm{eff}} \quad \sin \Delta M_{B_d} t$$

$$2\beta_{\mathrm{eff}} = \mathrm{Arg}\,|\langle \overline{B}_d | H^{\Delta B=2}_{\mathrm{eff}} | B_d \rangle|$$

$\sin 2\beta = 0.79 \pm 0.10$ from exps
BaBar & Belle & others

TYPICAL BOUNDS ON THE δ-COUPLINGS



A, B =LL, LR, RL, RR

1,3 = generation index

$$A_{SM} = A_{SM}(\delta_{SM})$$

$$\langle B^0 | H_{eff}^{\Delta B=2} | B^0 \rangle = \mathrm{Re}\, A_{SM} + \mathrm{Im}\, A_{SM}$$
$$+ A_{SUSY}\, \mathrm{Re}(\delta_{13}{}^{d})_{AB}{}^{2} + i\, A_{SUSY}\, \mathrm{Im}(\delta_{13}{}^{d})_{AB}{}^{2}$$

TYPICAL BOUNDS ON THE δ-COUPLINGS

$\langle B^0 | H_{eff}^{\Delta B=2} | B^0 \rangle = \mathrm{Re}\, A_{SM} + \mathrm{Im}\, A_{SM}$
$+ A_{SUSY}\, \mathrm{Re}(\delta_{13}^{d})_{AB}^{2} + i\, A_{SUSY}\, \mathrm{Im}(\delta_{13}^{d})_{AB}^{2}$

Typical bounds:

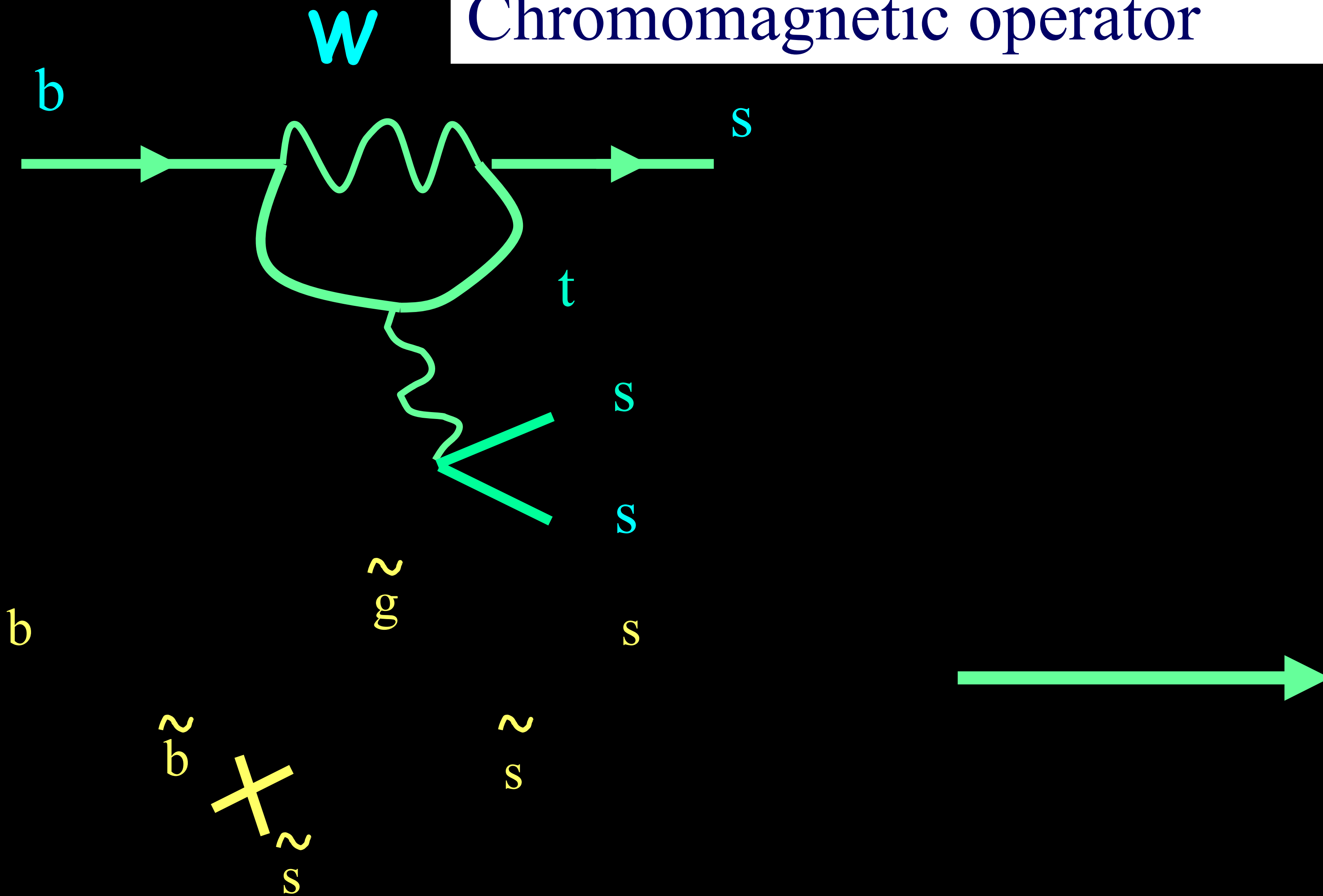
$$\mathrm{Re},\mathrm{Im}(\delta_{13}^{d})_{AB} \leq 1 \div 5 \times 10^{-2}$$

Note: in this game δ_{SM} is not determined by the UTA

From Kaon mixing: $\mathrm{Re},\mathrm{Im}(\delta_{12}^{d})_{AB} \leq 1 \times 10^{-4}$

SERIOUS CONSTRAINTS ON SUSY MODELS

SUSY Penguins & the Magnetic and Chromomagnetic operator



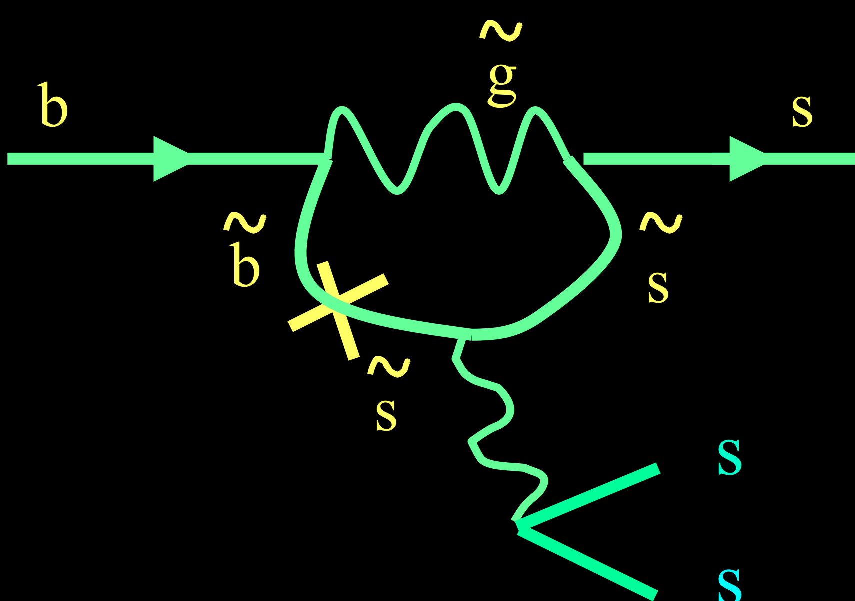
SUSY Penguins & the Magnetic and Chromomagnetic operator

W

b

s

t



Recent analyses by G. Kane and collaborators, Murayama and Ciuchini et al.

Also Higgs (h,H,A) contributions

Chromomagnetic operators vs ε'/ε and ε

$$H_g = C^+_g O^+_g + C^-_g O^-_g$$

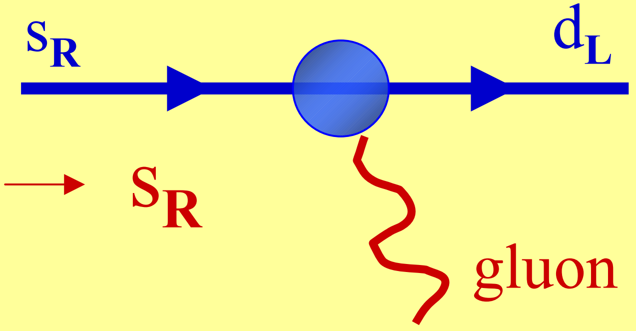
$$O^{\pm}_g = \frac{g}{16\pi^2} \left(s_L \sigma^{\mu\nu} t^a d_R G_{\mu\nu}^a \pm s_R \sigma^{\mu\nu} t^a d_L G_{\mu\nu}^a \right)$$

- It contributes also in the Standard Model (but it is chirally supressed $\propto m_K^4$)
- Beyond the SM can give important contributions to ε' (Masiero and Murayama)
- It is potentially dangerous for ε (Murayama et. al., D'Ambrosio, Isidori and G.M.)
- It enhances CP violation in $K \to \pi\pi\pi$ decays (D'Ambrosio, Isidori and G.M.)
- Its cousin $O^{\pm}_{\gamma}$ gives important effects in $K_L \to \pi^0 e^+ e^-$

($\langle \pi^0 | Q_{\gamma}^+ | K^0 \rangle$ computed by D. Becirevic et al. , The SPQ$_{cd}$R Collaboration, Phys.Lett. B501 (2001) 98)

The Chromomagnetic operator

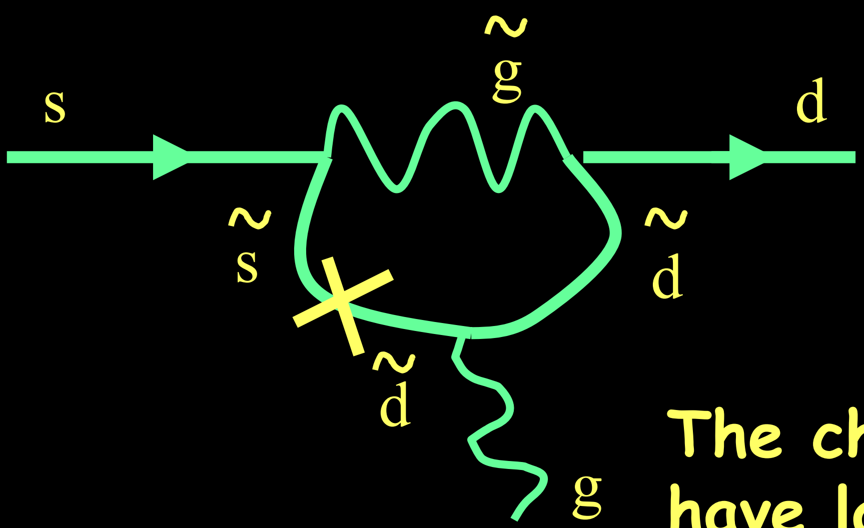
$O_\sigma = m_s \, \bar{d}_L \, \sigma_{\mu\nu} \, t^a \, s_R \, G^{\mu\nu a}$



mass term necessary to the helicity flip $S_L \longrightarrow S_R$

$\langle \pi\pi | O_\sigma | K \rangle \sim O(M_K^4)$ $\quad [\langle \pi\pi | H_W | K \rangle \sim O(M_K^2)]$

Masiero-Murayama



m_s

$\alpha_s \; \delta^{12}{}_{LR} \, (M^2_W / m^2_{\tilde{q}}) \;\; m_{\tilde{g}}$

The chromomagnetic operator may have large effects in ε'/ε

$\not{CP}$ from SUSY flavour mixing

define $\delta_{\pm} = \delta^{21}{}_{LR} \pm (\delta^{12}{}_{LR})^{*}$ then

δ_{+} → $K \to \pi$

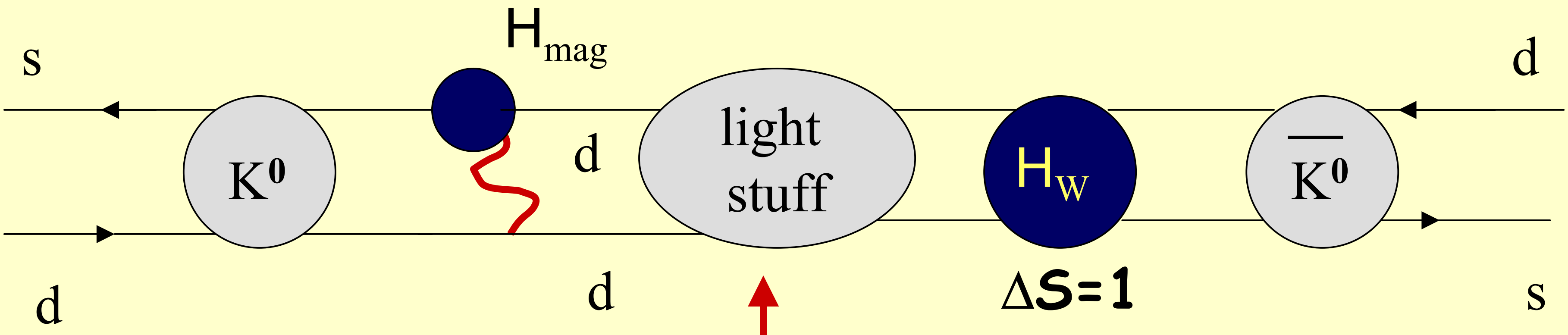
$K \to 3\pi$

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

δ_{-} → $K \to 2\pi$

parity odd

$K \to \pi$ in $K^0 - \overline{K^0}$ mixing (see next page)



π^0, η, η', etc.

$$A^{SUSY}(K^0 \rightarrow \overline{K}^0) = A_{boxes} + A_{1mag} + A_{2mag}$$

$$A_{1mag} = \frac{2 \langle \overline{K}^0 | H_W | \pi^0 \rangle \langle \pi^0 | H_{mag} | K^0 \rangle}{M^2_K - M^2_\pi}$$

$$\propto \ \mathrm{Im}(\delta_+) \times \ 4.8\ 10^{-13}\ \mathrm{GeV}^2\ \ K_1$$

The K-factor K_1 accounts for other contributions besides the π^0, as the etas, more particle states, etc.

Boxes		$\mathrm{Im}(\delta^2_+)$ or $\mathrm{Im}(\delta^2_-)$
1-mag		$\mathrm{Im}(\delta_+)$
2-mag		$\mathrm{Im}(\delta^2_+)$
K_L	$\pi^0 e^+ e^-$	$\mathrm{Im}(\delta^2_+)^2$
$\varepsilon'/\varepsilon \rightarrow$		$\mathrm{Im}(\delta_-)$

If the K-factor K_1 is not too small,
the strongest limits on $\mathrm{Im}(\delta_+)$ come
from A_{1mag} in $K^0 - \overline{K}^0$ mixing ($10^{-4} - 10^{-5}$) !!
D'Ambrosio, Isidori and G.M.; X-G He, Murayama, Pakvasa and Valencia

GENERAL FRAMEWORK

$$H^{\Delta B=1} = G_F/\sqrt{2}\, \sum_{p=u,c} V_{pb}\, V_{ps}{}^{*} [C_1\, Q_1{}^p + C_2\, Q_2{}^p +$$

$$\sum_{i=1,10} C_i\, Q_i + C_{7\gamma}\, Q_{7\gamma} + C_{8g}\, Q_{8g}\ ]$$

penguin ops

Where the C_i are short distance coefficients, the evolution of which is known in perturbation theory at the NLO (Buras et al. + Ciuchini et al.)

The coefficients of the penguin operators are modified by the SUSY penguins with mass insertions

Rare Kaon Decays

- Why rare decays
- Which rare decays
-

WHY RARE DECAYS ?

Rare decays are a manifestation of broken (accidental) symmetries e.g. of physics beyond the Standard Model

Proton decay	**baryon and lepton number conservation**
$\mu \rightarrow e + \gamma$ $\nu_i \rightarrow \nu_k$	**lepton flavor number**

RARE DECAYS WHICH ARE ALLOWED IN THE STANDARD MODEL

FCNC:

$q_i \;\text{->}\; q_k + \nu\,\bar{\nu}$

$q_i \;\text{->}\; q_k + l^+\,l^-$

$q_i \;\text{->}\; q_k + \gamma$

THUS THEY ARE SENSITIVE TO NEW PHYSICS

these decays occur only via loops because of GIM and are suppressed by CKM

Why we like $K \to \pi \nu \bar{\nu}$?

For the same reason as $A_{J/\psi K_S}$:

1) Dominated by short distance dynamics

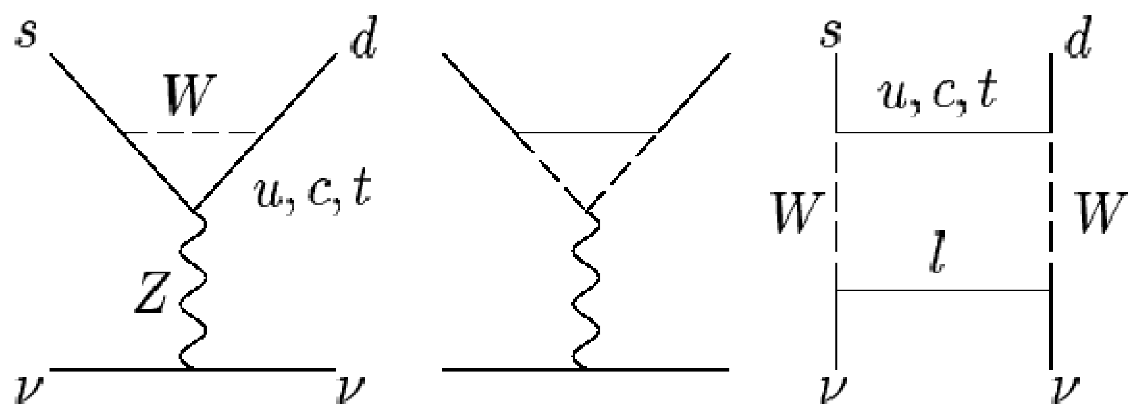
(hard GIM suppression, calculable in pert. theory)

2) Negligible hadronic uncertainties

(matrix element known)

$O(G_F^2)$ Z and W penguin/box $s \to d \nu \bar{\nu}$ diagrams

SM Diagrams



$$H_{eff} = G^2_F\, \alpha / (2\sqrt{2}\pi\, s^2_W)[\, V_{td} V_{ts}^* X_t + V_{cd} V_{cs}^* X_c\,] \times (\bar{s}\gamma_\mu (1 - \gamma_5)\, d)\, (\bar{\nu}\gamma^\mu (1 - \gamma_5)\, \nu\,)$$

☺ NLO QCD corrections to $X_{t,c}$ and $O(G^3_F\, m^4_t)$ contributions known

☺ the hadronic matrix element $\langle\, \pi\, |\, s\, \gamma_\mu (1 - \gamma_5)\, d\, |\, K \rangle$ is known with very high accuracy from Kl3 decays

☺ sensitive to $V_{td}\, V_{ts}^*$ and expected large $\not{CP}$

$A(s \to d \nu \bar{\nu})$

$O(\lambda^5 m^2_t) + i\, O(\lambda^5 m^2_t)$ CKM suppressed

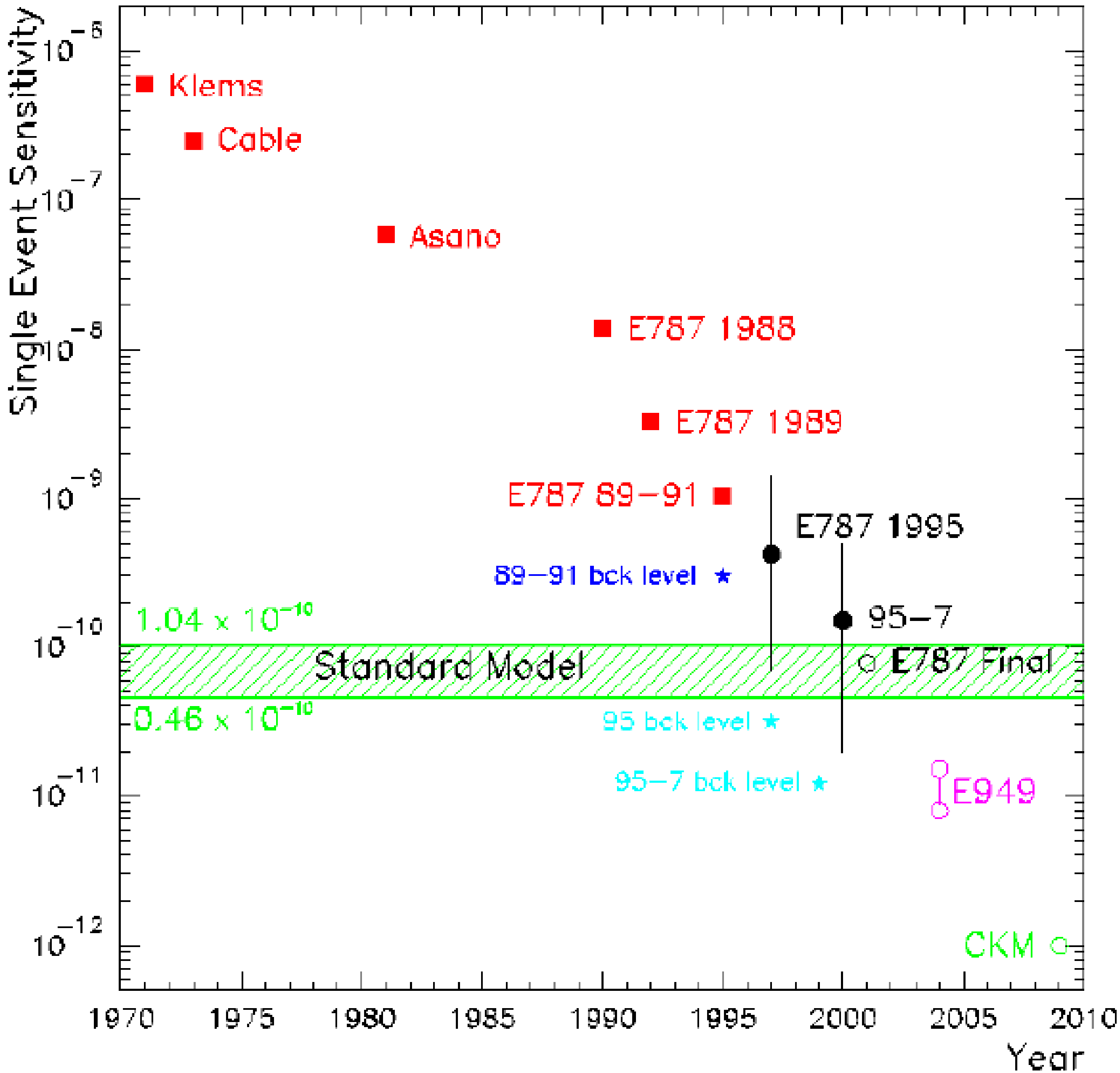
$O(\lambda\, m^2_c) + i\, O(\lambda^5 m^2_c)$

$O(\lambda\, \Lambda^2_{QCD})$ GIM

CP conserving: error of $O(10\%)$ due to NNLO corrections in the charm contribution and CKM uncertainties **$BR(K^+)_{SM} = (7.2 \pm 2.0) \times 10^{-11}$**

$BR(K^+)_{EXP} = (15.7^{+17.5}_{-8.2}) \times 10^{-11}$

- 2 events observed by E787
- central value about 2 the value of the SM
- E949 10-20 events in 2 years



Single Event Sensitivity
Year
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
1970
1975
1980
1985
1990
1995
2000
2005
2010
Klems
Cable
Asano
E787 1988
E787 1989
E787 89−91
E787 1995
89−91 bck level
95−7
1.04×10^{-10}
Standard Model
E787 Final
0.46×10^{-10}
95 bck level
95−7 bck level
E949
CKM

CP Violating

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

$O(\lambda^5 m_t^2) + i\, O(\lambda m_t^2)$

$O(\lambda m_c^2) + i\, O(\lambda^5 m_c^2)$

$O(\lambda \Lambda_{QCD}^2)$

dominated by the top quark contribution -> short distances (or new physics)

theoretical error ~ 2 %

$BR(K^+)_{SM} = 4.30 \times 10^{-10} (m_t(m_t)/170GeV)^{2.3} \times (Im(V_{ts}^* V_{td})/\lambda^5)^2 = (2.8 \pm 1.0) \times 10^{-11}$

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

One gets $BR(K_L \to \pi^0 \nu\bar{\nu}) < 1.8 \times 10^{-9}$ (90% C.L.)

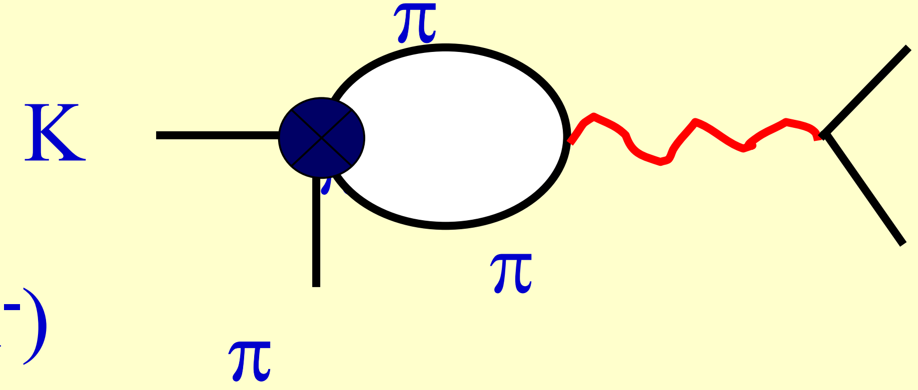
2 order of magnitude larger than the SM expectations

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

KEK E931 ~ 10^{-9} KOPIO 10^{-13} (50 events)

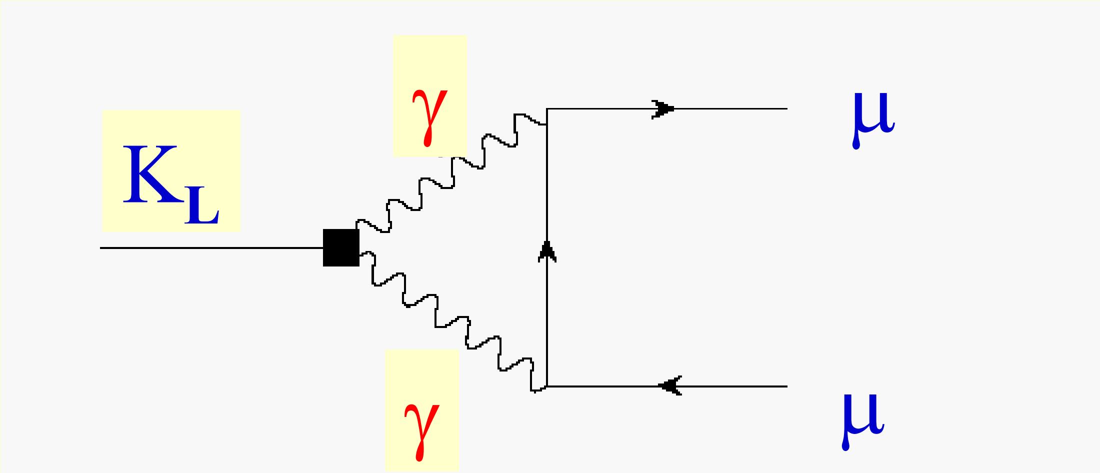
Other interesting decays
(but with long important long distance effects):

$K^+ \to \pi^+ l^+ l^-$ ($K_S \to \pi^0 l^+ l^-$)



LONG DISTANCES DOMINATE

$K_L \to \mu^+ \mu^-$



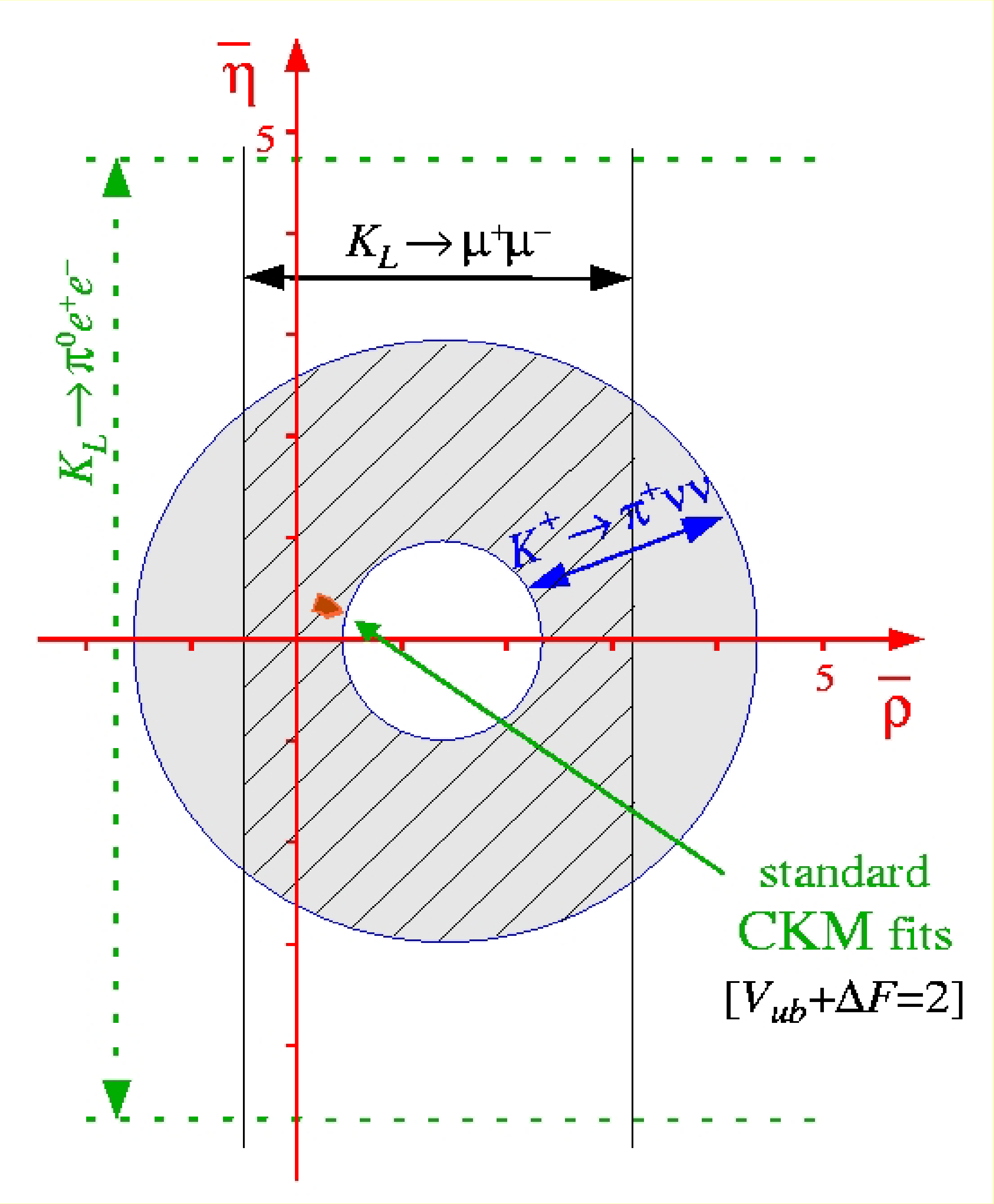
BNL E871

$BR(K_L \to \mu^+ \mu^-) = (7.18 \pm 0.17) \times 10^{-9}$

Almost saturated by the absorptive 2 photon contribution

$BR_{abs}(K_L \to \mu^+ \mu^-) = (7.07 \pm 0.18) \times 10^{-9}$

LONG AND SHORT DISTANCES COMPARABLE



Still a long way to go but worth to be continued and improved

Any measurement above the SM should satisfy other exp constraints

Conclusions and Outlook

1) Since their discovery in 1947
KAONS HAVE BEEN THE PROTAGONIST OF EXTRAORDINARY EXPERIMENTAL (UNEXPECTED) DISCOVERIES AND THEORETICAL PROGRESSES IN OUR UNDERSTANDING OF FUNDAMENTAL INTERACTIONS AND COSTITUENTS
(strangeness, θ-τ puzzle, CP violation, GIM to mention only the main ones)

2) KAON PHYSICS CONTINUE TO BE A FUNDAMENTAL TESTING GROUND FOR WEAK INTERACTIONS, FLAVOUR PHYSICS AND CP VIOLATION

3) KAON DECAYS MAY ALSO BE (HOPEFULLY) ONE OF THE LOW ENERGY WINDOWS FOR THE PHYSICS BEYOND THE STANDARD MODEL