THEORETICAL INTERPRETATION OF ε'/ε

MATTER-ANTIMATTER ASYMMETRY

XIVth RENCONTRES DE BLOIS

16th - 22nd June 2002

BLOIS JUNE 18th 2002

Guido Martinelli

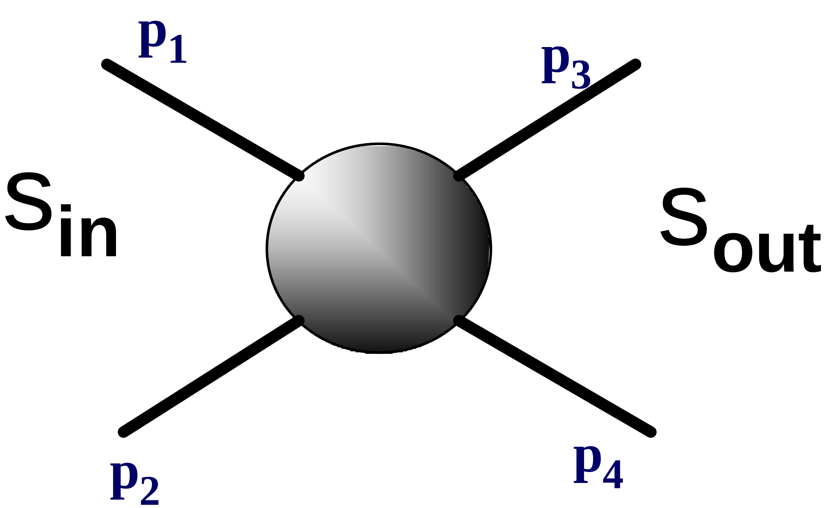
Plan of the talk

- General Theoretical Framework;
- ε'/ε in the Standard Model ;
- The operators of the Effective Weak Hamiltonian;
- Calculation of the operator matrix elements;
- ε'/ε Beyond the SM;
- Conclusions and outlook.

General Considerations: Consequences of a Symmetry

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

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 a=0 or b=0

$\not{CP}$ Violation in the Neutral Kaon System

Expanding in several "small" quantities

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

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

$$\left| \frac{\eta^{+-}}{\eta^{00}} \right|^2 \sim 1 + 6\,\mathrm{Re}\,(\varepsilon'/\,\varepsilon)$$

Conventionally:

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

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

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

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

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

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

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

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

In the Standard Model

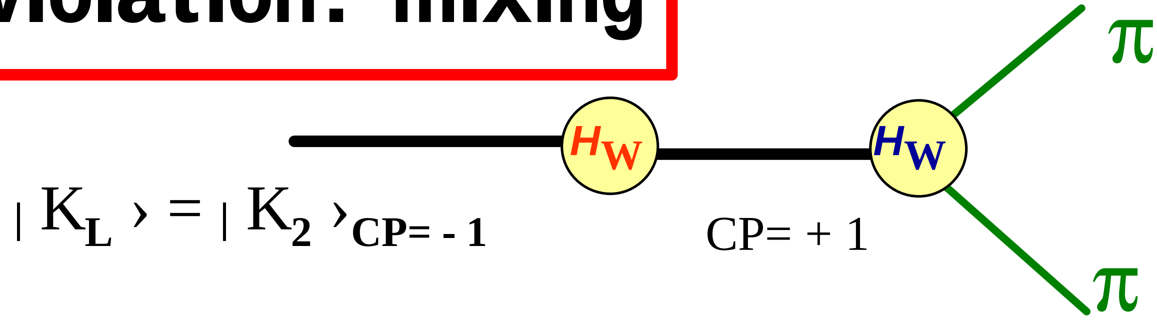
$\lambda_t = V_{td} V_{ts}^{*}$

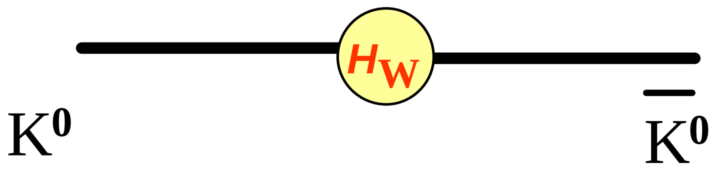
$r = G_F \, \omega / (2 \, |\varepsilon| \, \mathrm{Re} \, A_0)$

Extracting the phases:

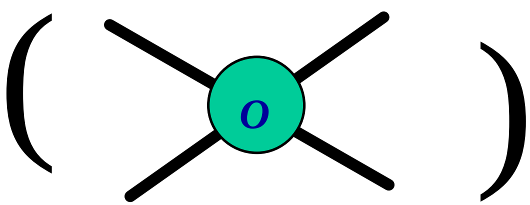
$$\varepsilon' / \varepsilon = \mathrm{Im} \, \lambda_t \, e^{\, i \, (p/2 + d_2 - d_0 - f_e)} \; r \; \left[|A_0| - \frac{1}{\omega} \, |A_2| \right]$$

Indirect CP violation: mixing





DS=2

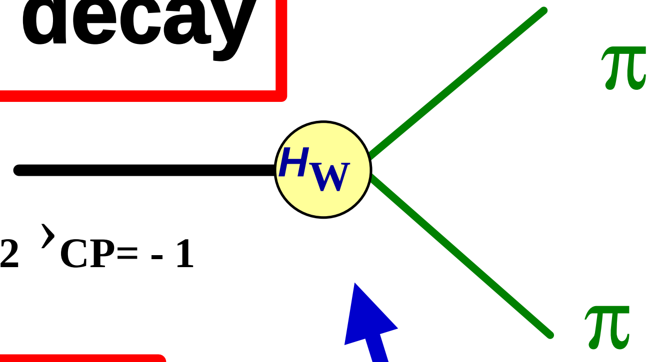


Complex DS=2 **effective coupling**

LOCAL OPERATOR

$H_W = C(\mu)\, O(\mu)$

Direct CP violation: decay



CP= + 1

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

Complex DS=1 effective coupling

Effective Hamiltonian expressed in terms of

LOCAL OPERATORS

$$H_W = ?\ C_i(\mu)\ O_i\ (\mu)$$

GENERAL FRAMEWORK

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

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

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

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

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

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

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

+ Chromomagnetic end electromagnetic operators
to be discussed in the following

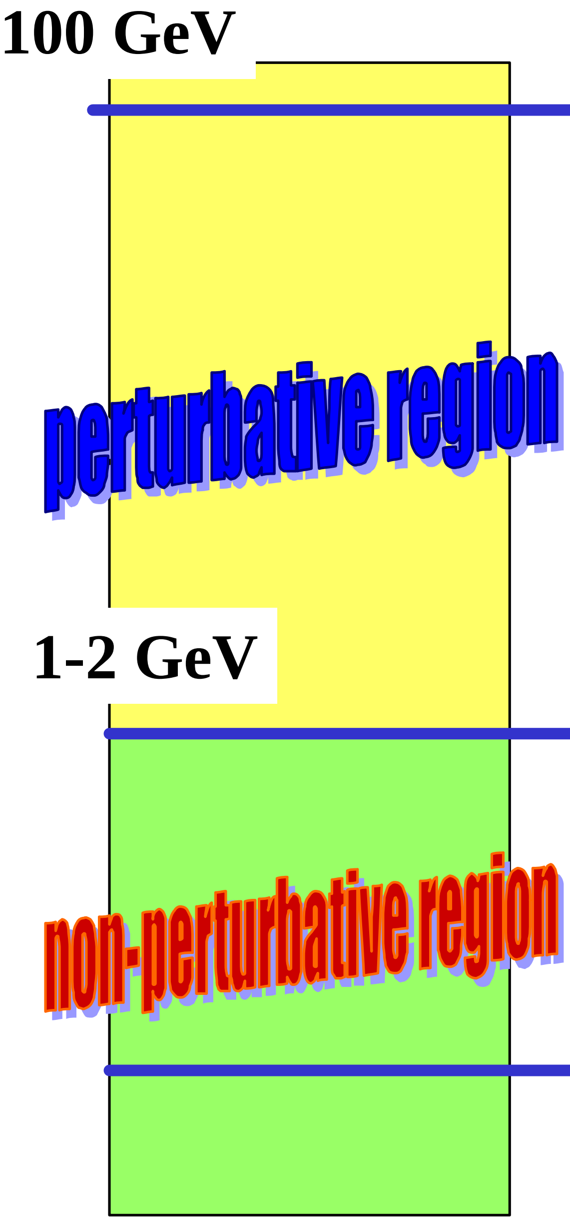
$$A_0 = ?_i\ C_i(\mu)\ \langle (p\ p) | Q_i(\mu) | K \rangle_{I=0}\ (1 - \Omega_{IB})$$

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

ISOSPIN BREAKING

$$A_2 = ?_i\ C_i(\mu)\ \langle (p\ p) | Q_i(\mu) | K \rangle_{I=2}$$

Ω_{IB} = 0.25± 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 μ > 2-4 GeV

VACUUM SATURATION & B-PARAMETERS

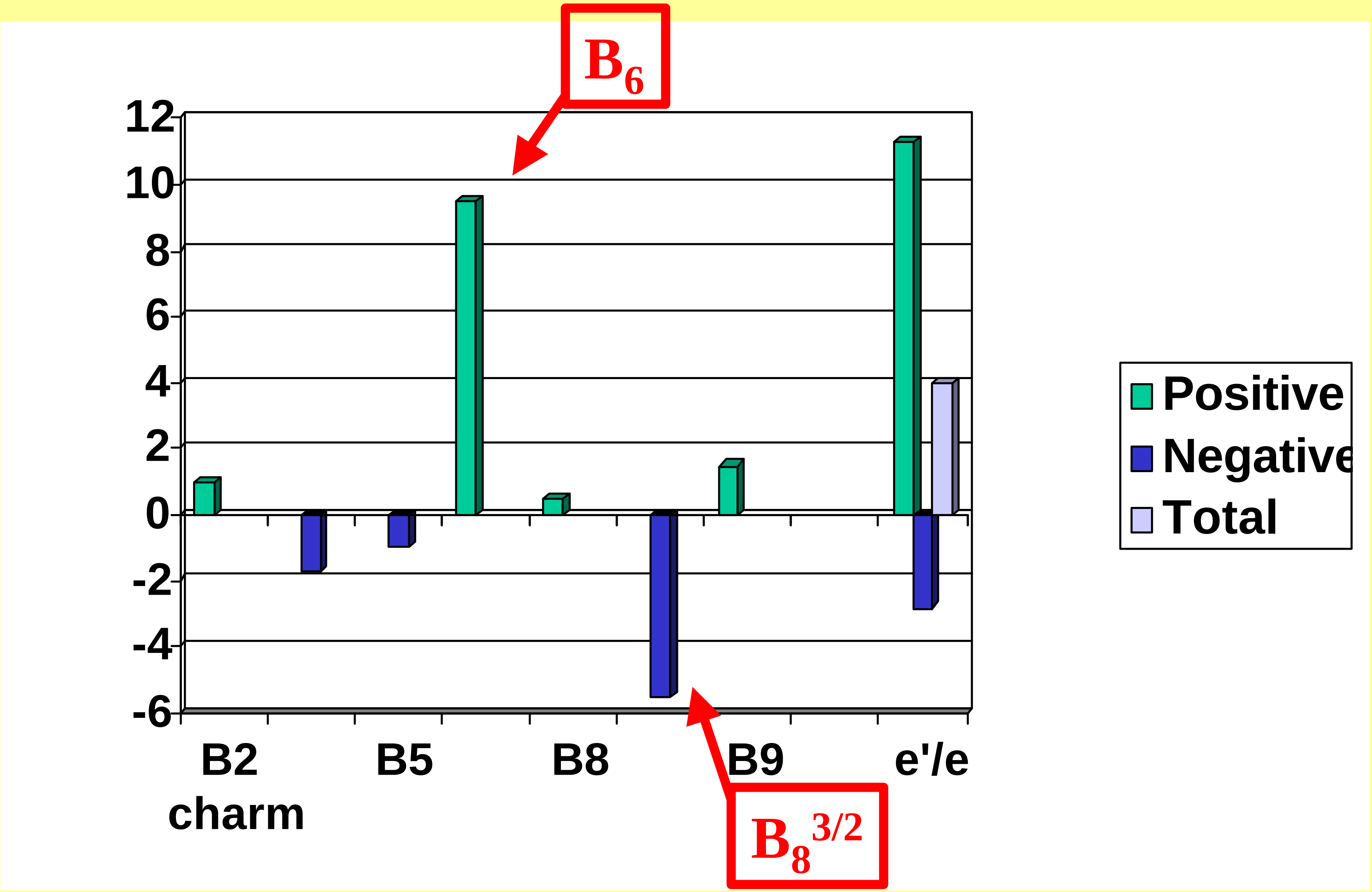
$$A = ?_{i} \; C_{i}(\mu) \; \langle (p\ p) | Q_{i} (\mu) | K \rangle$$

$$\langle (p\ p) | Q_{i} (\mu) | K \rangle = \langle (p\ p) | Q_{i} | K \rangle_{VIA} \; B(\mu)$$

μ -dependence of VIA matrix elements is not consistent
With that of the Wilson coefficients
e.g. $\langle (p\ p) | Q_{9} | K \rangle_{I=2,VIA} = 2/3\, f_{p} \,(M^{2}_{K} - M^{2}_{p})$

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

$$\lambda_t = V_{td} V_{ts}^* = (1.1 \pm 0.2)\, 10^{-4}$$

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

a value of B_6 **MUCH LARGER** than 1 (2 ÷ 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 $<Q_6>$ ☹
- Fenomenological Approach **Munich** **A.Buras & al.**
- NLO Accuracy and consistent matching ☺
- no results for $<Q_{6,8}>$ which are taken elsewhere ☹
- Chiral quark model **Trieste** **S.Bertolini & al.**
- all ME computed with the same method ☺
- model dependence, quadratic divergencies,matching ☹

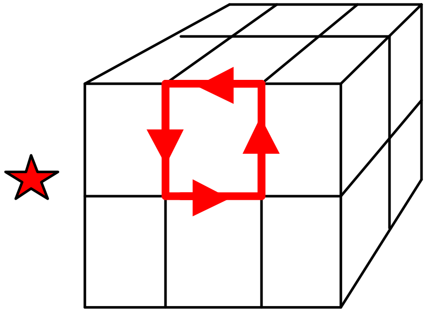
Theoretical Methods for the Matrix Elements (ME)

- 1/N expansion+ χPT **Munich, Dortmunt, Valencia,…**
- $< Q_{6,8} >$ are computed ☺
- 1/N corrections only partially computed 😐
- quadratic divergencies,matching ☹

Model calculations suggest that the enhancement of $< Q_6 >$ may come from large higher-order corrections in the chiral expansion, typical of **I=0 pp states** (Q_1 and Q_2 ?)

A related physical effect is given the large Final State Interactions expected in I=0 channels, which are taken into account only at the lowest orders of the chiral expansion. A strong enhancement can be obtained from resummation (and unitarization) of FSI using the Omnès-Mushkelishvili approach (Truong, Pich & Pallante); quantitave results controversial (Buras & al., Colangelo & al. etc. etc.)

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)

Theoretical Novelties

- ‹ p p IQ_iI K › on finite volumes
  L. Lellouch & M. Luscher Commun. Math. Phys. 219 (2001) 31 (LL) **and D.Lin, G.M., C. Sachrajda and M. Testa hep-lat/0104006** (LMST)
- Chiral Perturbation Theory for ‹ $Q_{+,1,2,7,8}$› **V. Cirigliano and E. Golowich Phys. Lett. B475 (2000) 351**; **M. Golterman and E. Pallante JHEP 0008 (2000) 023; D.Lin, G.M., E. Pallante, C. Sachrajda and G. Villadoro, Rome prep. 1337 (quenched,unquenched, finite and infinite volumes) and in preparation.**
- FSI and extrapolation to the physical point
  Truong, E. Pallante and A. Pich (PP) Phys. Rev. Lett. 84 (2000) 2568; see also A. Buras at al. Phys. Lett. B480 (2000) 80;

<u>The IR problem</u> 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 ⌫ p p 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

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

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

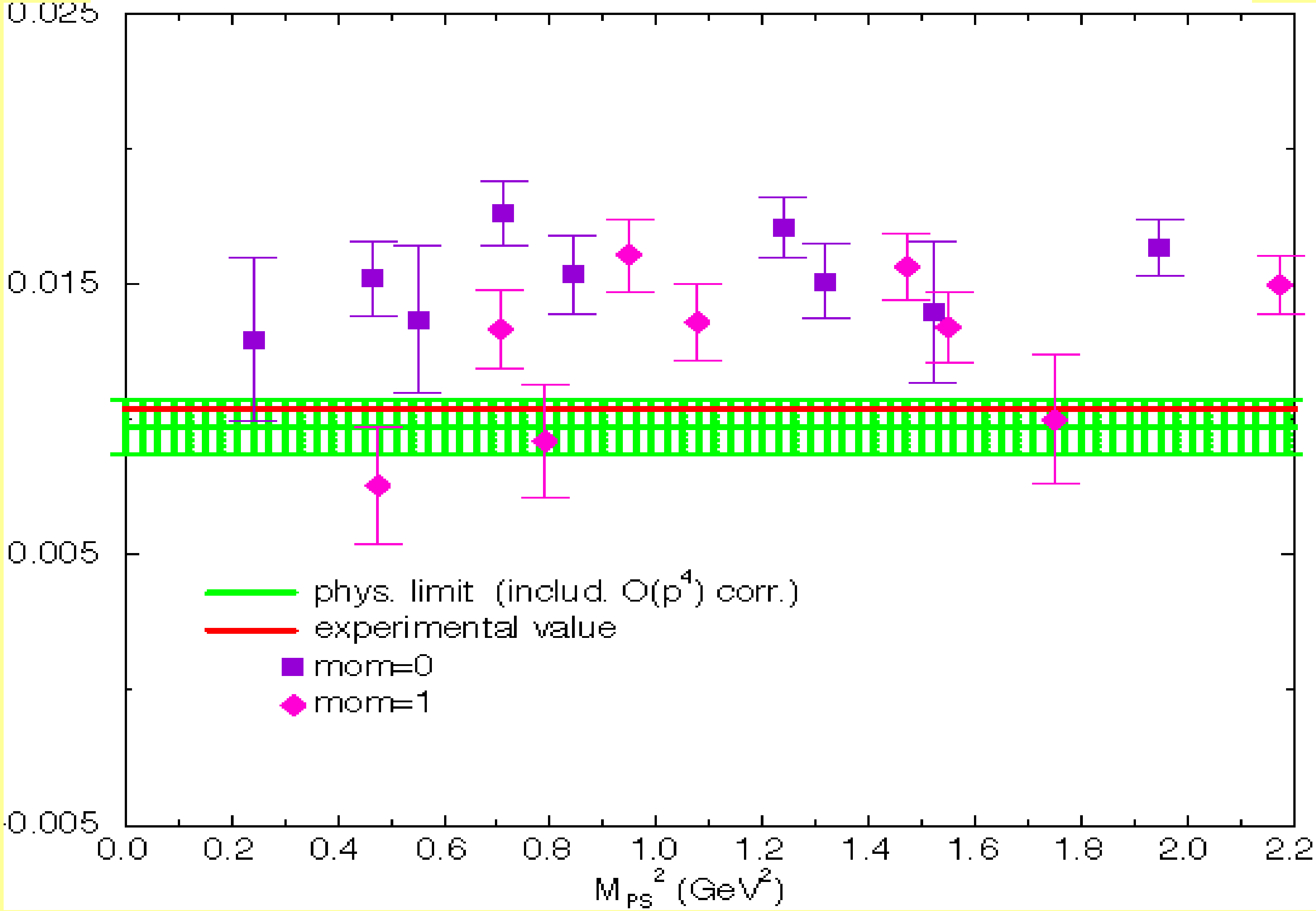
$\rho_V(E) = (q\,\phi'(q) + k\,\delta'(k))/4\,\pi\, k^2$ is the expression which one would heuristically derive by interpreting $\rho_V(E)$ as the density of states in a finite volume (D. Lin, G.M., C. Sachrajda and M. Testa)

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):

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

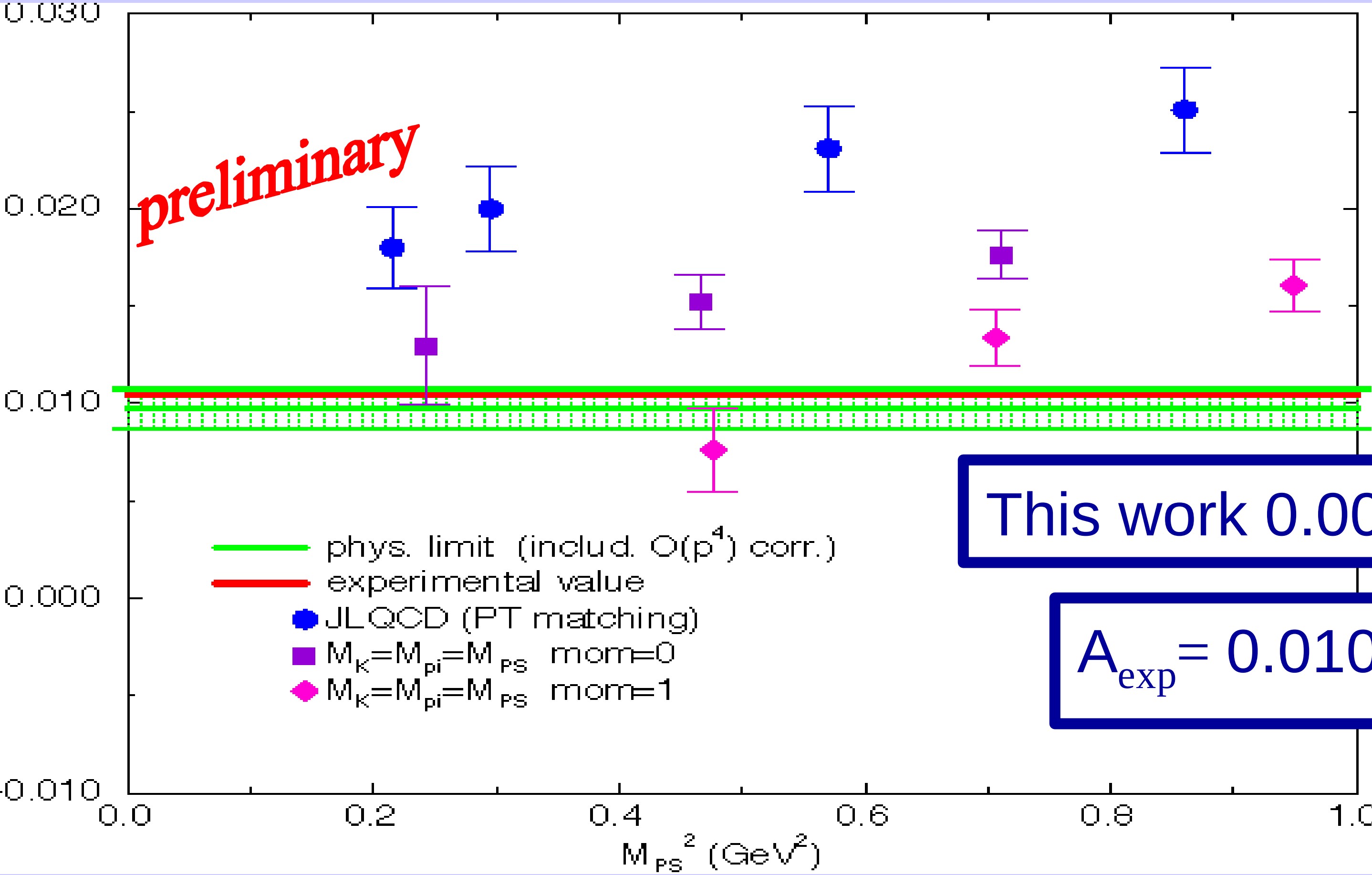
THE CHIRAL BEHAVIOUR FOR ‹p p |Q $_4$| K ›



for the chiral behaviour of ‹Q $_4$› see for example Pallante and Golterman and Lin;
chiral logs and extra operators not yet included; cos δ(E) ˜ 1

THE CHIRAL BEHAVIOUR OF ‹p p |H_W| K ›$_{I=2}$ by the $SPQ_{cd}R$ Collaboration and a comparison with JLQCD **Phys. Rev. D58 (1998) 054503**

no chiral logs included yet, analysis under way

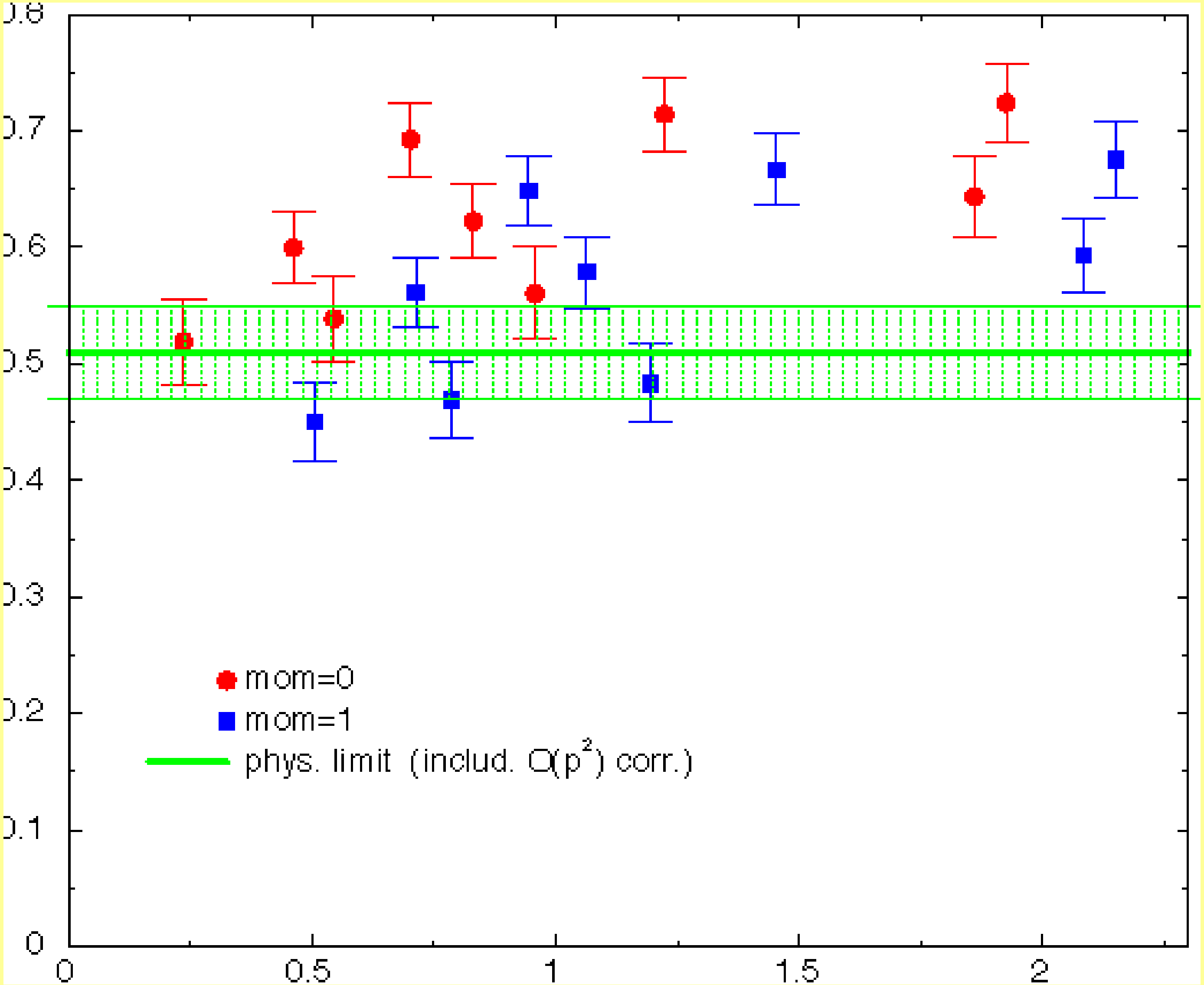


This work 0.0097(10) GeV^3

A_{exp}= 0.0104098 GeV^3

Lattice QCD finds B_K = 0.86 and a value of ‹p p |H_W| K ›$_{I=2}$ compatible with exps

THE CHIRAL BEHAVIOUR FOR $\langle \pi \pi | Q_8 | K \rangle_{I=2}$



for $\langle Q_{7,8} \rangle$ formulae by V. Cirigliano and E. Golowich and Lin+gm+Pallante+Sachrajda+Villadoro

Results for $Q_{7,8}$ and comparison with other determinations ($\overline{MS}$)

Lattice RBC ~ 0.9
CPPACS ~ 0.8

χQM
0.75 ± 0.03

GeV^3

results out of the Table at different scales; from S. Bertolini review

	$\langle Q_8 \rangle$	$\langle Q_7 \rangle$
K ' š š (SPQ$_{cd}$R) NEW!!	0.53 ± 0.06	0.02 ± 0.01
J. Donoghue and E. Golowich	2.2 ± 0.7	0.22 ± 0.05
M. Knecht, S. Peris and E. De Rafael	3.5 ± 1.1	0.11 ± 0.03
Donini et al. (Rome)	0.5 ± 0.1	0.11 ± 0.04
D. Becirevic et al. (SPQ$_{cd}$R) NEW!!	0.49 ± 0.06	0.10(2)(1)

preliminary

Bijnens & Prades 1.2 ± 0.5 Hambye (1/N) ~ 0.36 -> 0.63

from K ⌫ p

Lattice results for the operators contributing to A_0

For A_2 the result for the strong interaction phase-shift $\delta_2(k)$ is in agreement with the experimental value, and the dependence on masses and momenta is that expected in χPT (Papinutto, $SPQ_{cd}R$ Collaboration at Lattice 2001)

For A_0 the result for $\delta_0(k)$ is in TOTAL DISAGREEMENT with the experimental value, and the dependence on masses and momenta is NOT that expected in χPT

??????

I=0 pp 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 in preparation.

There could be a way-out …..

ΔI=1/2 and ε′/ε

- K ⌫ p p from K ⌫ p and K ⌫

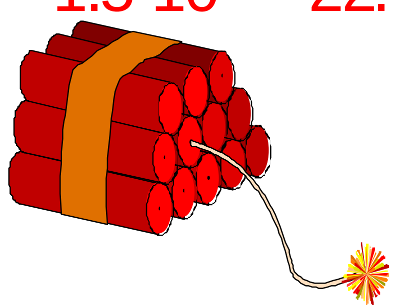
- Direct K … calculation

- ΔI=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

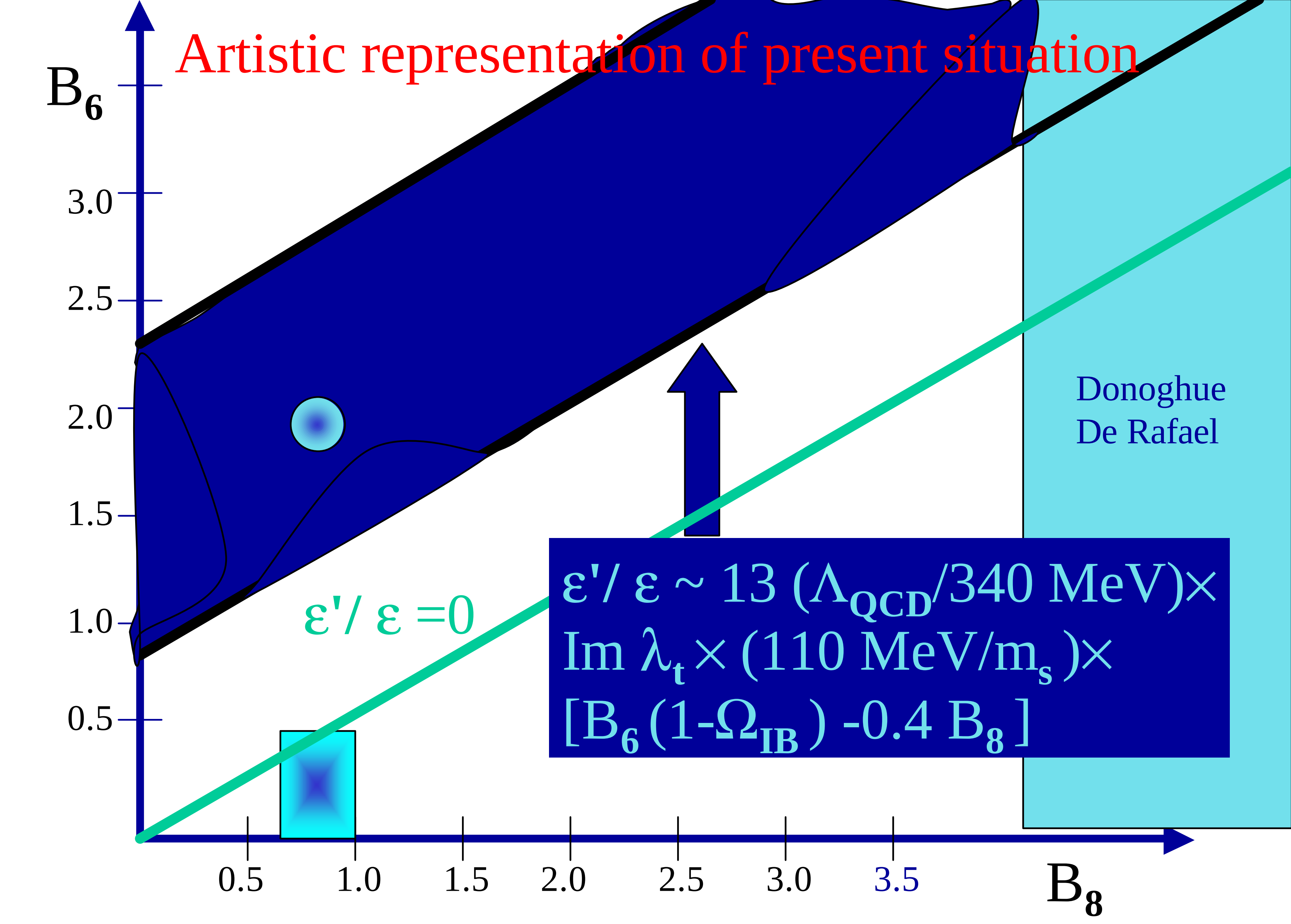
	$Re(A_0)$	$Re(A_2)$	$Re(A_0)/Re(A_2)$	ε'/ε
RBC	$29 \div 31 \; 10^{-8}$	$1.1 \div 1.2 \; 10^{-8}$	$24 \div 27$	$-4 \div -8 \; 10^{-4}$
CP PACS	$16 \div 21 \; 10^{-8}$	$1.3 \div 1.5 \; 10^{-8}$	$9 \div 12$	$-2 \div -7 \; 10^{-4}$
EXP	$33.3 \; 10^{-8}$	$1.5 \; 10^{-8}$	22.2	$17.2 \pm 1.8 \; 10^{-4}$



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

Physics Results from RBC and CP-PACS

talks by Mawhinney,Calin,Blum and Soni (RBC)

Noaki (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}
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}

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

Even by doubling O_6 one cannot agree with the data

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

Chromomagnetic operators vs ε'/ ε and ε

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

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

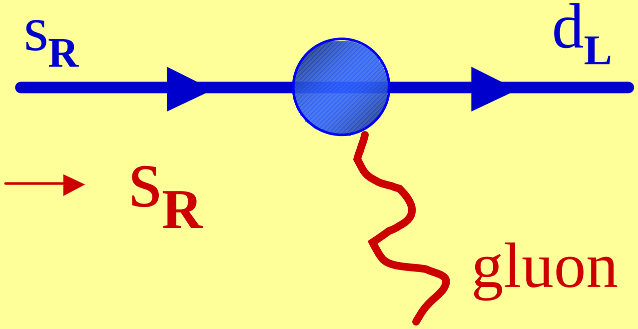
- It contributes also in the Standard Model (but it is chirally supressed $\propto m_K^4$)
- Beyond the SM can give important contributions to ε' (Masiero and Murayama)
- It is potentially dangerous for ε (Murayama et. al., D'Ambrosio, Isidori and G.M.)
- It enhances CP violation in $K \rightarrow \pi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

(‹ p^0 | Q_g^+ | K^0 › computed by D. Becirevic et al. , The $SPQ_{cd}R$ Collaboration, Phys.Lett. B501 (2001) 98)

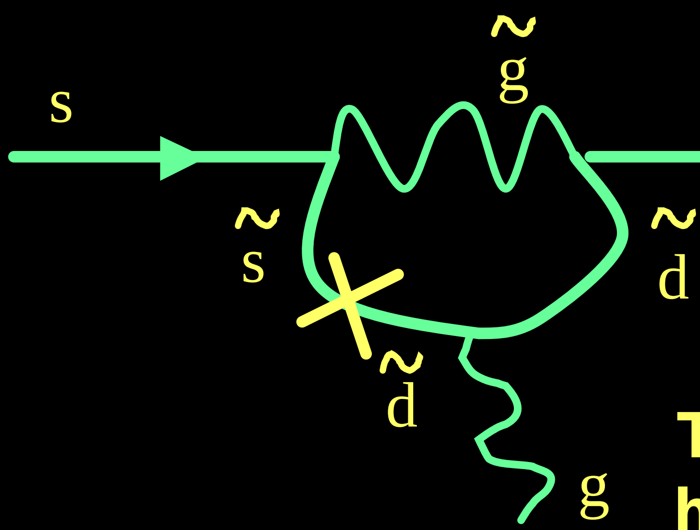
The Chromomagnetic operator

$$O_S = m_s \, \bar{d}_L \, \sigma_{mn} \, t^a \, s_R \, G^{mna}$$

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



$$\langle \pi\pi | \, O_s \, | \, K \rangle \sim O(M_K^4) \qquad [\langle \pi\pi | \, H_W \, | \, K \rangle \sim O(M_K^2)\,]$$

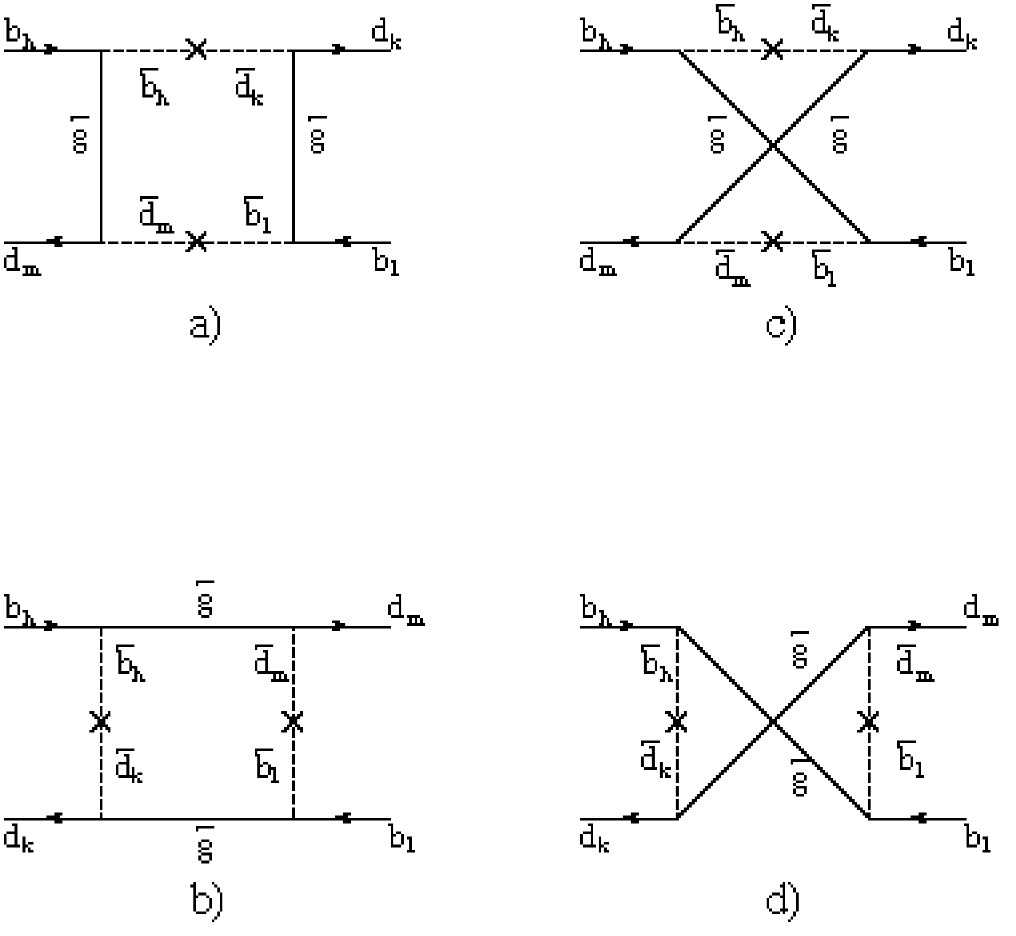


Masiero-Murayama

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 e'/e



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

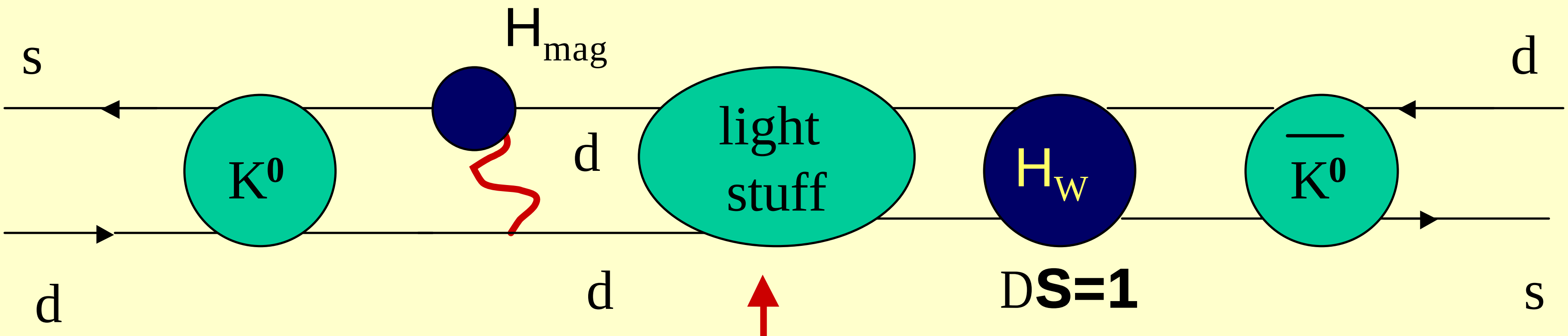
$\not{CP}$ from SUSY flavour mixing

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

$\delta_+ \rightarrow$		$K \rightarrow \pi$
		$K \rightarrow 3\pi$
parity even		$K_L \rightarrow \pi^0 e^+ e^-$

$\delta_- \rightarrow$	$K \rightarrow 2\pi$
parity odd	

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



π^0, η, η', etc.

$A^{SUSY}(K^0 \longrightarrow \bar{K}^0) =$

$A_{boxes} + A_{1mag} + A_{2mag}$

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

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

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

Boxes		$\mathrm{Im}(d^2_+)$ or $\mathrm{Im}(d^2_-)$
1-mag		$\mathrm{Im}(d_+)$
2-mag		$\mathrm{Im}(d^2_+)$
K_L	$p^0 e^+ e^-$	$\mathrm{Im}(d^2_+)^2$
e'/ e $\longrightarrow$		$\mathrm{Im}(d_-)$

If the K-factor K_1 is not too small,
the strongest limits on $\mathrm{Im}(d_+)$ 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

Conclusions and Outlook

MANY PROGRESSES

1) The possibility of computing the physical K ⌫ p p amplitude has been demonstrated by LL (see also LMST);

2) For the first time there is a signal for K ⌫ p p penguin-like contractions of $\mathbf{Q_{1,2,6}}$. More work is needed to reduce the uncertainties (QUENCHING !!!);

3) The new results with Domain Wall Fermions for K ⌫ p amplitudes are really puzzling;

4) The chiral extrapolation to the physical point (quenched, unquenched, infinite and finite volumes) is <u>critical;</u>

4) The extension of LL/LMST to non-leptonic B-decays (e.g. B ⌫ K p), for which the two light mesons are above the inelastic threshold, remains an open problem worth being investigated.