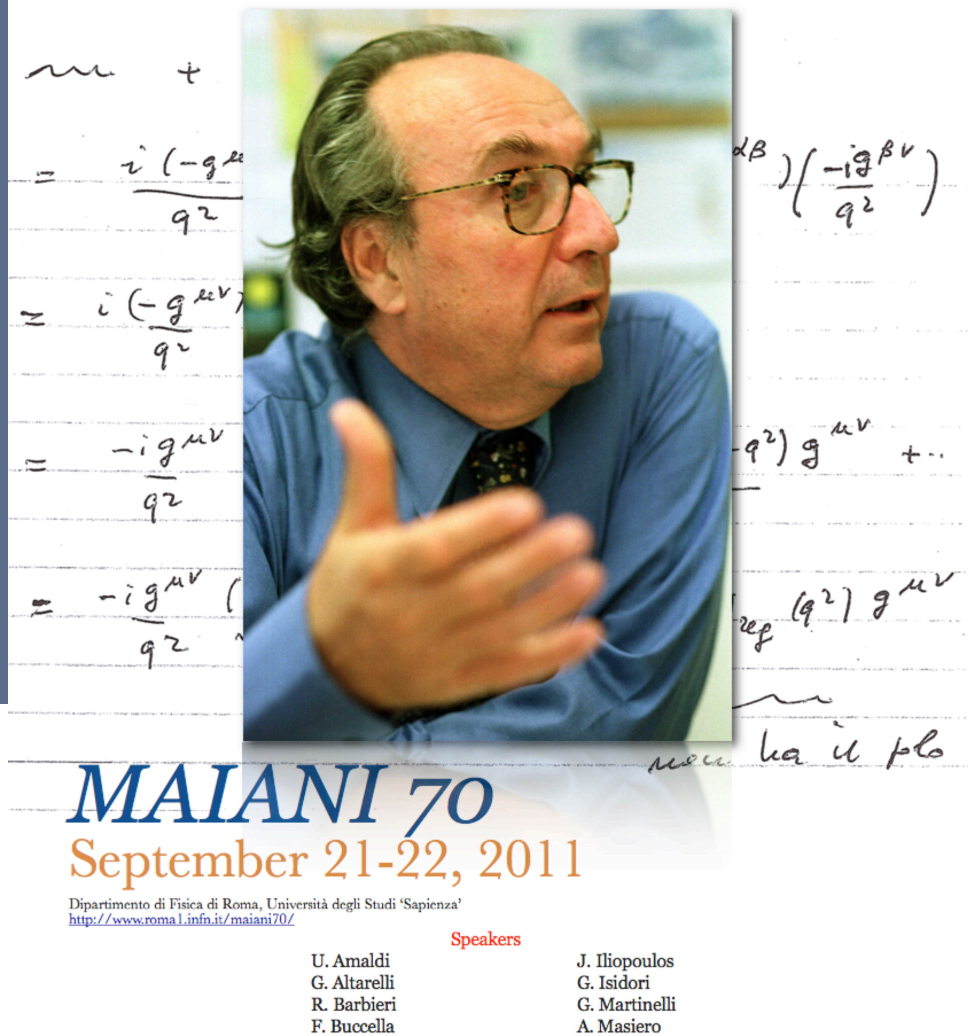
Isospin Breaking in Hadron Physics



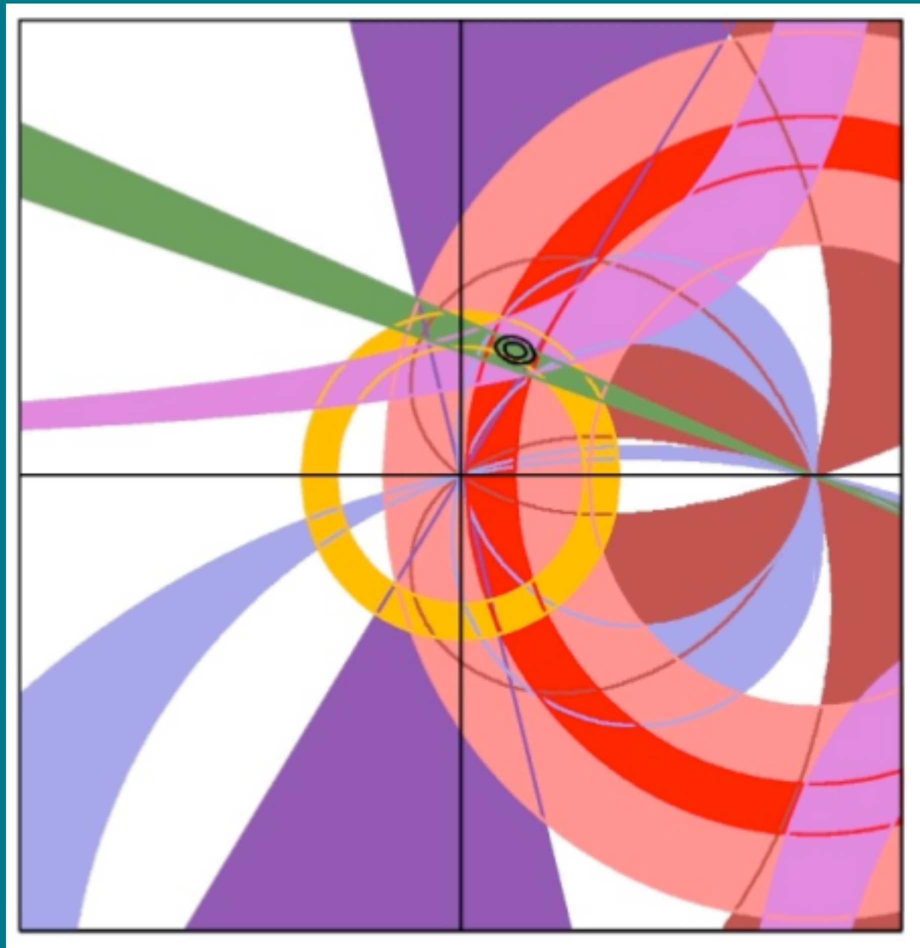
La Sapienza Roma

September 21st 2011

Guido Martinelli

From the Standard Model to Dark Matter and beyond: Symmetries, Masses and Misteries

Guido Martinelli
SISSA & INFN



NIS, Serbia 29/08/2011

Mixing and CP violation in K- and B-mesons:
a lattice QCD point of view

Maurizio Lusignoli, **Luciano Maiani**, Guido Martinelli, Laura Reina,

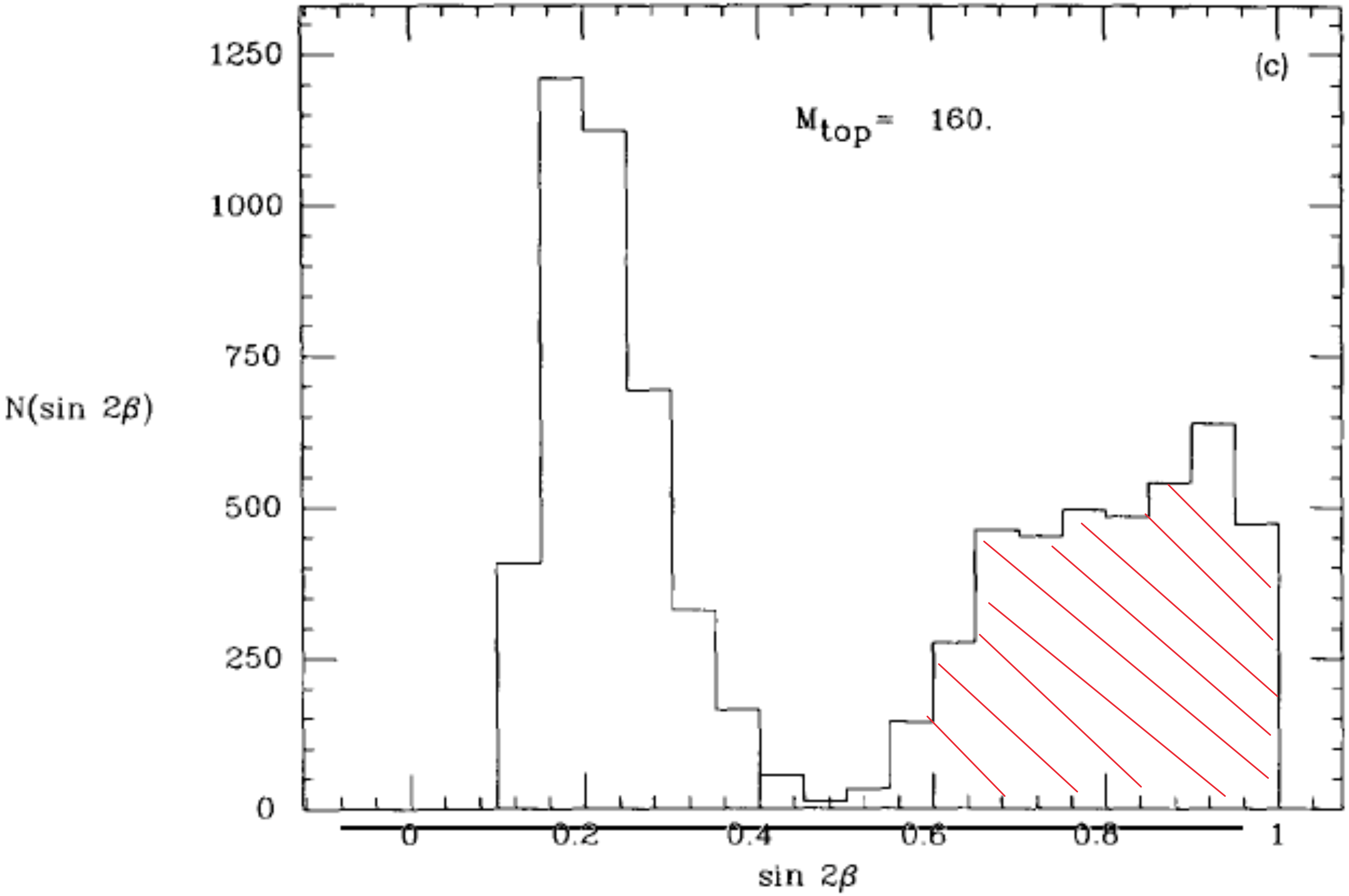
Received 11 March 1991; revised 4 July 1991;
Accepted 5 August 1991. Available online 18 October 2002.

Abstract

We have analyzed K^0 - $\underline{K}^0$ and B^0 - $\underline{B}^0$ mixing on the basis of the most recent experimental results and theoretical lattice determination of the relevant matrix elements. We find that a top mass larger than 140 GeV and $f_B \geq 200$ MeV, as suggested by recent lattice calculations, imply a CP-violating asymmetry in $B \rightarrow J/\Psi + Ks$ decays much larger than previously estimated. We also report the corresponding theoretical prediction for ε'/ε, for which rather large experimental and theoretical uncertainties still exist.

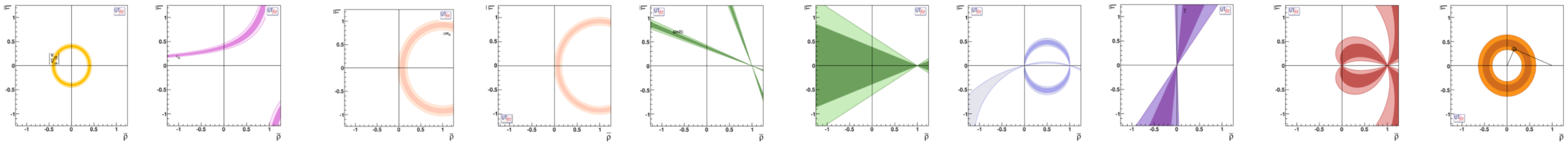
The average values of $\sin(2\beta)$ and $\sin(2\alpha)$ in correspondence to the different m_t and f_B ranges are listed in table 7 in sect. 8. Absolute lower bounds can be read from figs. 3 and 4. For large f_B, eq. (2.3a), we find

$$\sin(2\beta) \geqslant 0.55(0.45,\, 0.40), \quad \text{for} \quad m_t = 140(160,\, 200)\ \text{GeV}. \tag{2.14}$$

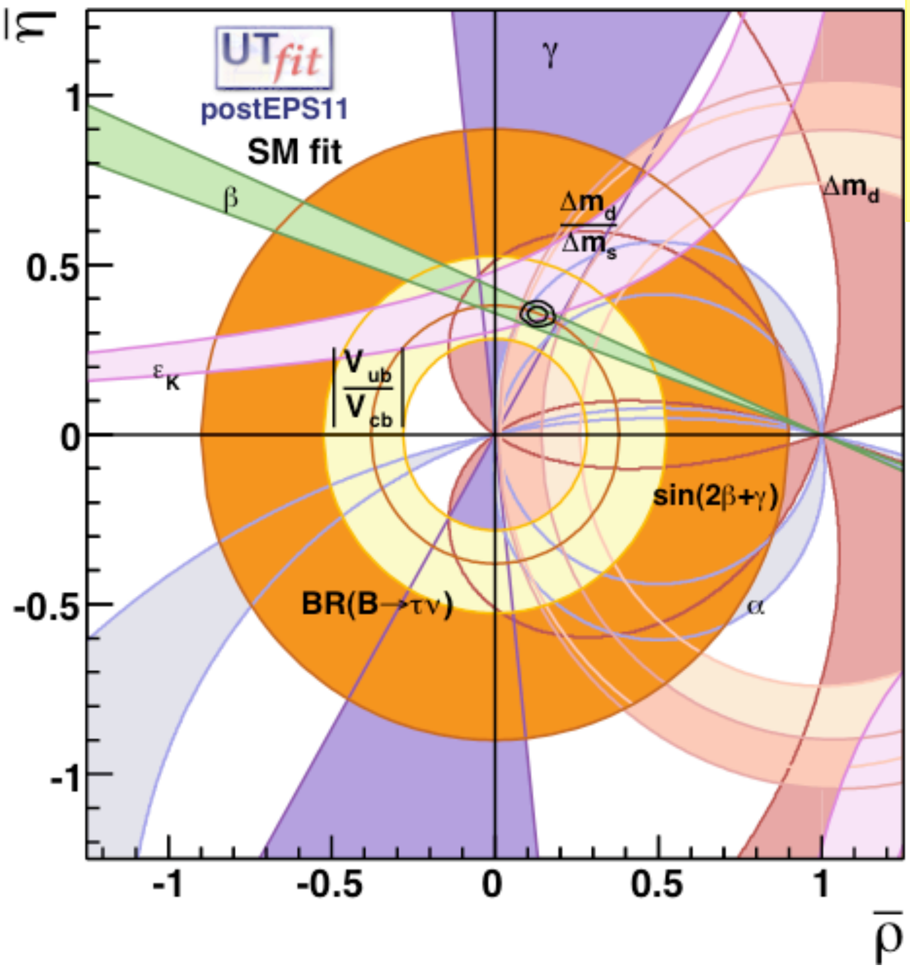


Global Fit within the SM

SM Fit



In the hadronic sector, the SM CKM pattern represents the principal part of the flavour structure and of CP violation



Consistence on an over constrained fit of the CKM parameters

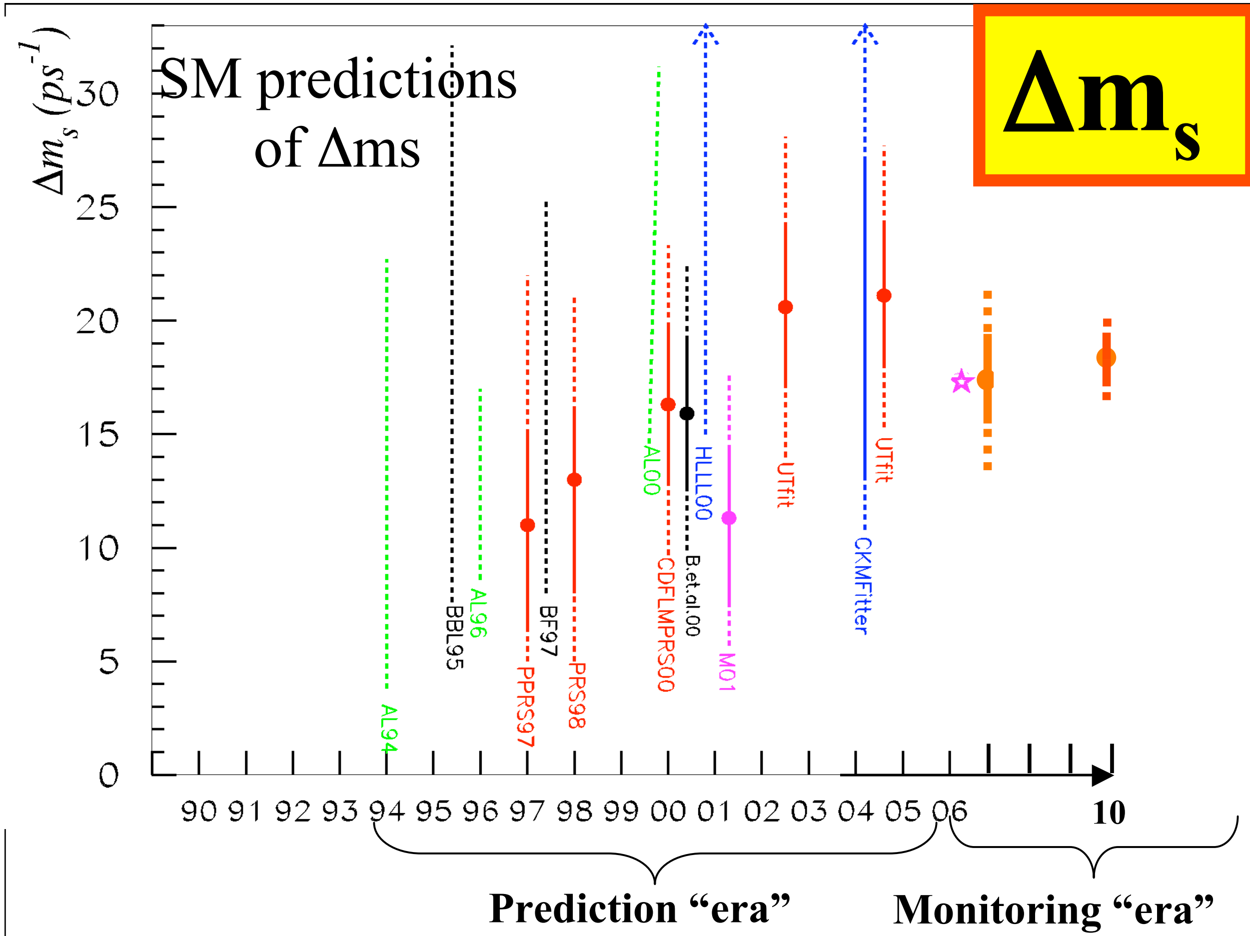
$\rho = 0.132 \pm 0.020$

$\eta = 0.353 \pm 0.014$

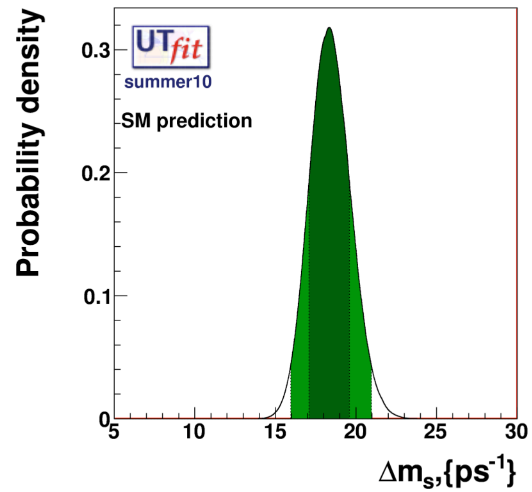
$\alpha = (88 \pm\ 3)^0$
$\sin 2\beta = 0.695 \pm 0.025??$
$\beta = (22 \pm 1)^0$
$\gamma = (69 \pm\ 3)^0$

CKM matrix is the dominant source of flavour mixing and CP violation

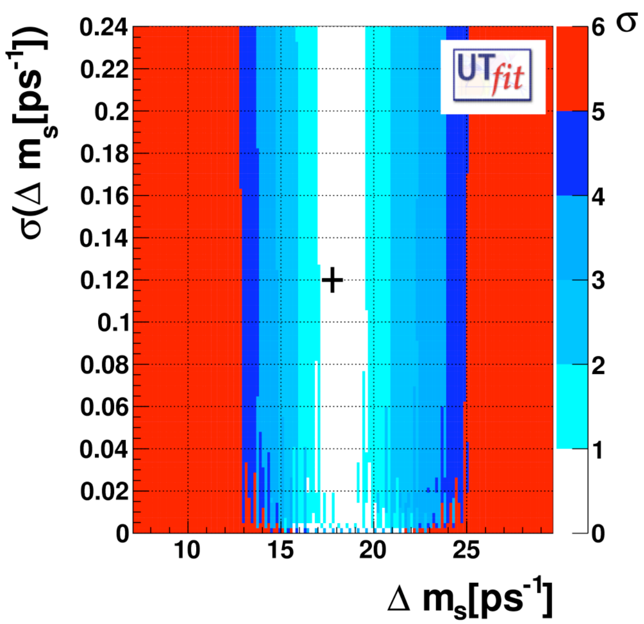
Δm_s



SM expectation
$\Delta m_s = (18.3 \pm 1.3\ )\ ps^{-1}$



Exp
$\Delta m_s = (17.77 \pm 0.12\ \ )\ ps^{-1}$



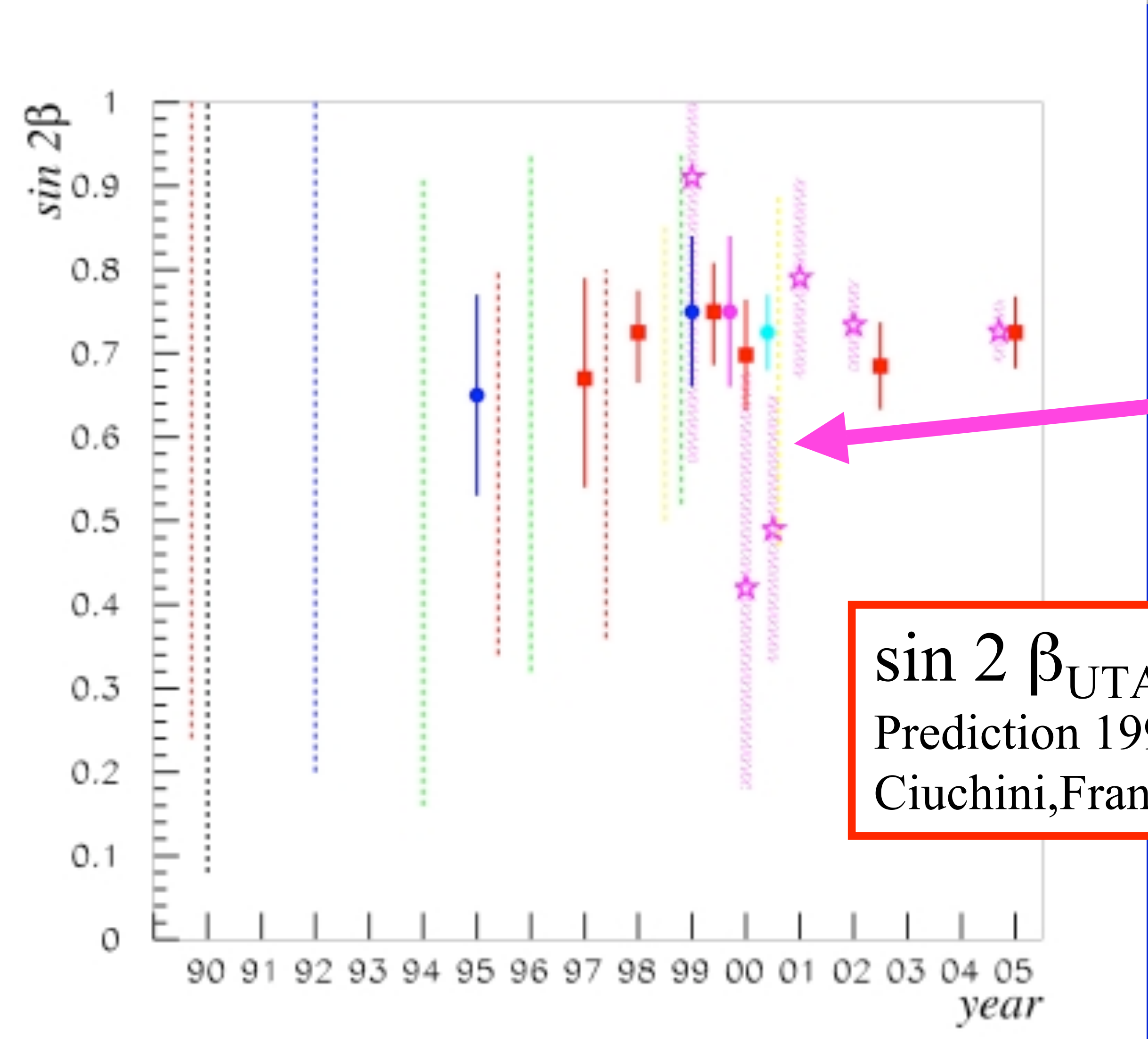
Legenda

agreement between the predicted values
and the measurements at better than :

1σ 3σ 5σ

2σ 4σ 6σ

Theoretical predictions of Sin 2 β in the years



predictions exist since '95

experiments

$\sin 2\beta_{UTA} = 0.65 \pm 0.12$

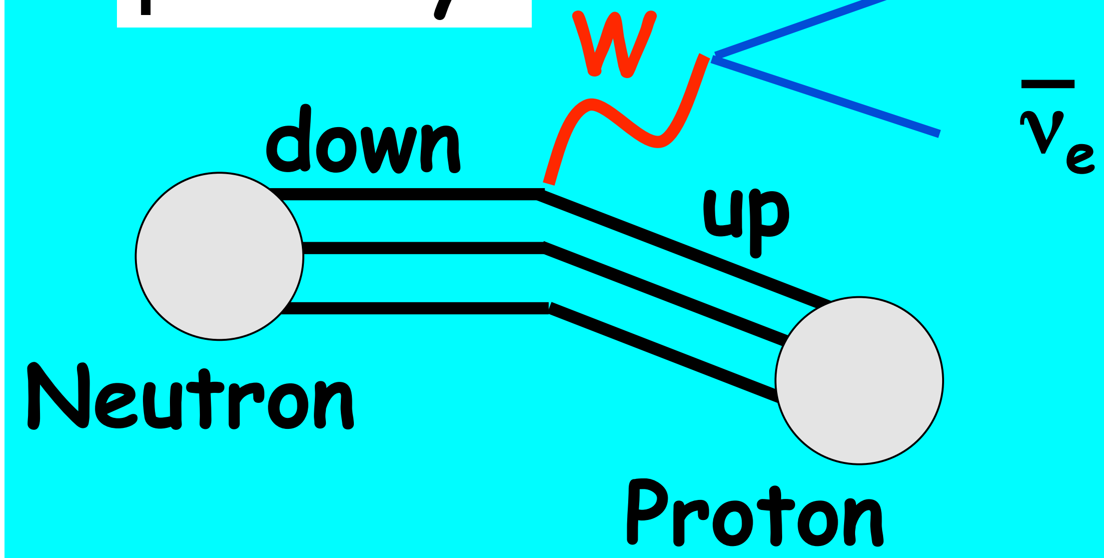
Prediction 1995 from Ciuchini,Franco,G.M.,Reina,Silvestrini

Quark masses & Generation Mixing

V_{ud}	V_{us}	V_{ub}
V_{cd}	V_{cs}	V_{cb}
V_{td}	V_{ts}	V_{tb}

GIM

β-decays



$|V_{ud}|$

$|V_{ud}| = 0.9735(8)$

$|V_{us}| = 0.2196(23)$

$|V_{cd}| = 0.224(16)$

$|V_{cs}| = 0.970(9)(70)$

$|V_{cb}| = 0.0406(8)$

$|V_{ub}| = 0.00409(25)$

$|V_{tb}| = 0.99(29)$

(0.999)

Form factor, decay constants and unitarity

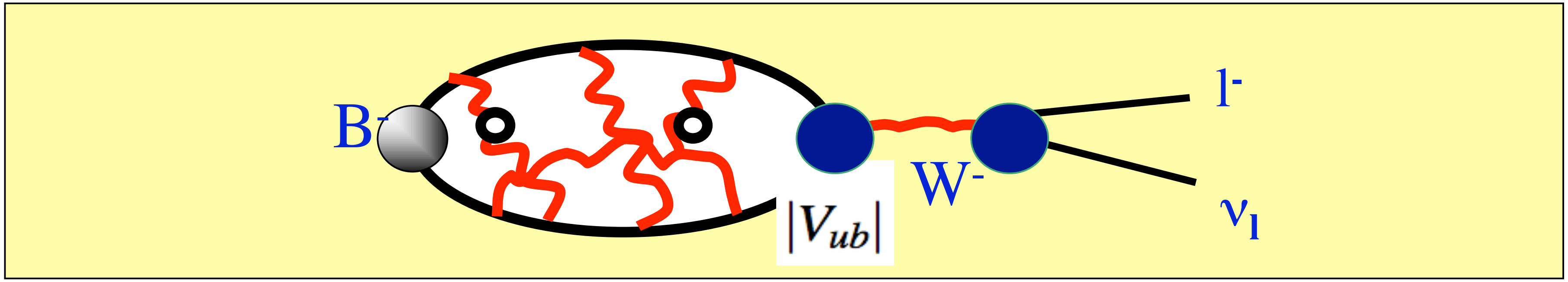
- unitarity: $$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$
- experiment: $$|V_{ub}| = 3.93\,(36)\cdot 10^{-3}$$

via non pert. quantities

- Kaon decays: $$|V_{us}|\ f_+(0) = \mathbf{0.2163(5)}$$

$$\left|\frac{V_{us} f_K}{V_{ud} f_\pi}\right| = \mathbf{0.2758(5)}$$

- 3 expressions, 4 unknowns; need one more input



Form factor, decay constants and unitarity

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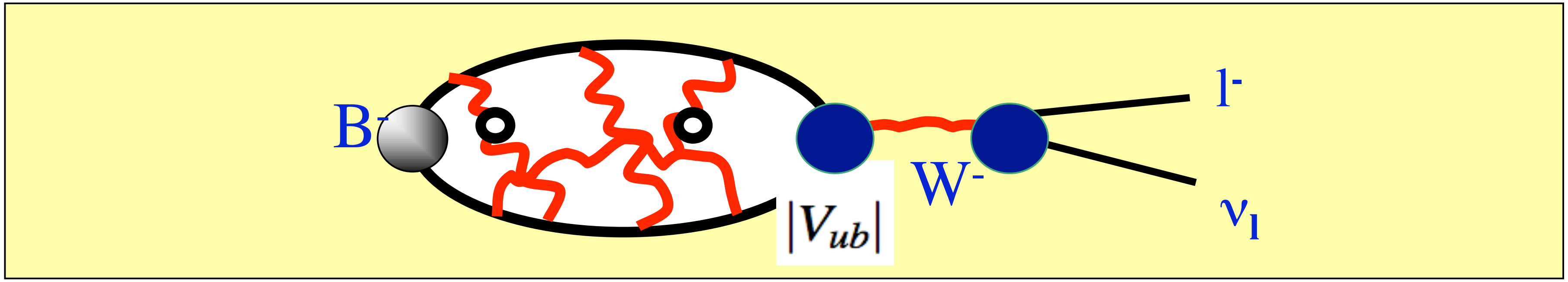


Form factor, decay constants and unitarity

$$f_+(0) = 0.964\ (3)\ (4) \qquad (N_f = 2+1)$$
$$f_+(0) = 0.956\ (6)\ (6) \qquad (N_f = 2)$$

2010

blication status | iral extrapolation | ite volume errors | tinuum extrapolation

Precision at the per mille level !!

The K -> pi vector form-factor at zero momentum transfer on the lattice.
D. Becirevic, G. Isidori, V. Lubicz, G. Martinelli,
F. Mescia, S. Simula, C. Tarantino, G. Villadoro Published in Nucl.Phys. B705 (2005) 339-362

Table 1: Colour code for the data on $f_+(0)$.

$$f_K/f_\pi = 1.190\ (2)\ (10) \qquad (N_f = 2+1)$$
$$f_K/f_\pi = 1.210\ (6)\ (17) \qquad (N_f = 2)$$

2010

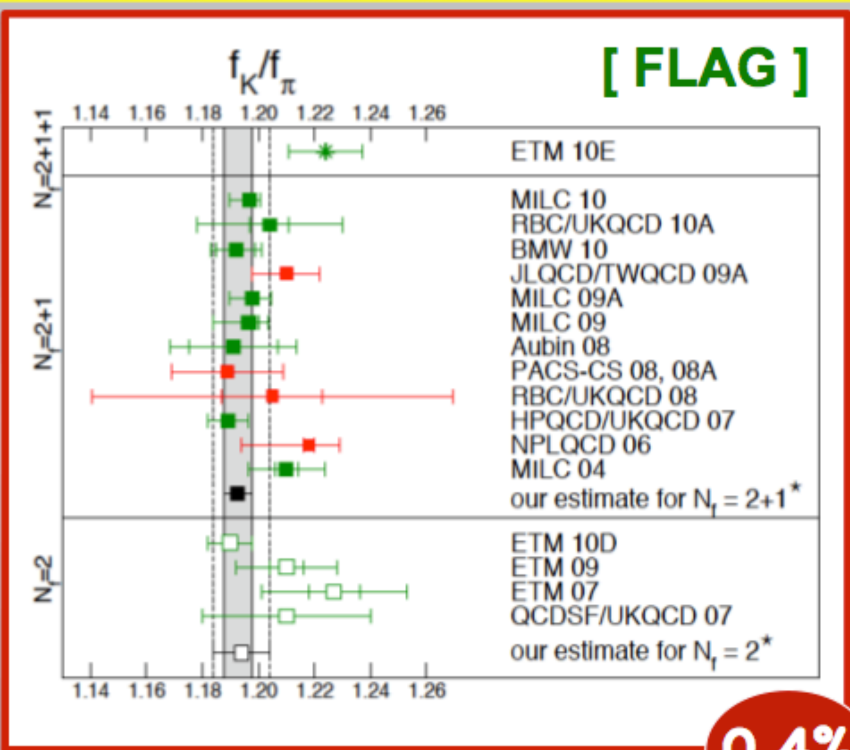
most systematics OK

Collaboration	N_f	publication status	chiral extrapolation	finite volume errors	continuum extrapolation	f_K/f_π
MILC 09A	2+1	C	★	★	★	$1.198(2)(^{+6}_{-8})$
MILC 09	2+1	P	★	★	★	$1.197(3)(^{+6}_{-13})$
ALVdW 08	2+1	C	★	●	●	1.191(16)(17)
PACS-CS 08, 08B	2+1	A	★	■	■	1.189(20)
BMW 08	2+1	C	★	★	★	1.18(1)(1)
HPQCD/UKQCD 08	2+1	A	★	●	★	1.189(2)(7)
RBC/UKQCD 08	2+1	A	●	★	■	1.205(18)(62)
NPLQCD 06	2+1	A	●	■	■	$1.218(2)(^{+11}_{-24})$
ETM 09	2	A	●	●	★	1.210(6)(15)(9)
QCDSF/UKQCD 07	2	C	●	★	●	1.21(3)

Table 1: Colour code for the data on f_K/f_π.

LATTICE RESULTS FOR f_K/f_π & $f_+(0)$

Lubicz LP2011

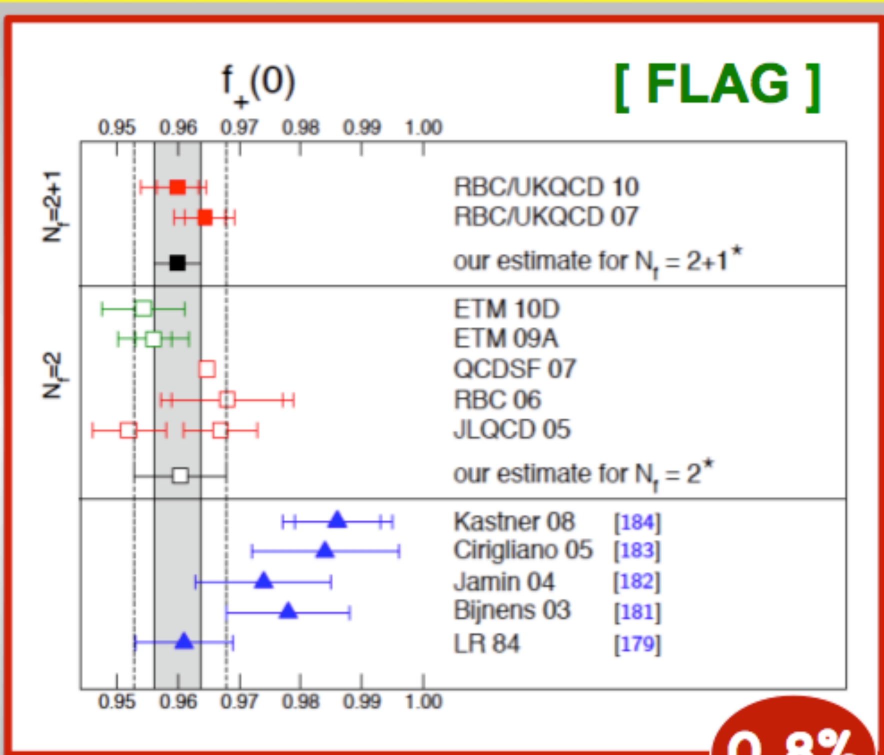


0.4%

$f_K/f_\pi = 1.193(5)$ (Nf=2+1)

$f_K/f_\pi = 1.210(18)$ (Nf=2)

First result with Nf=2+1+1 available



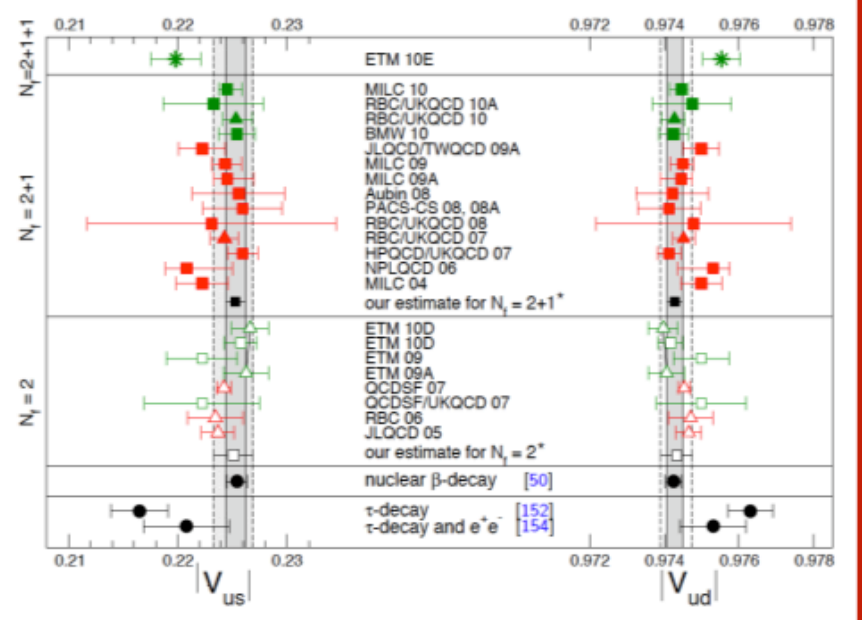
0.8%

$f_+(0) = 0.956(8)$ (Nf=2 & 2+1)

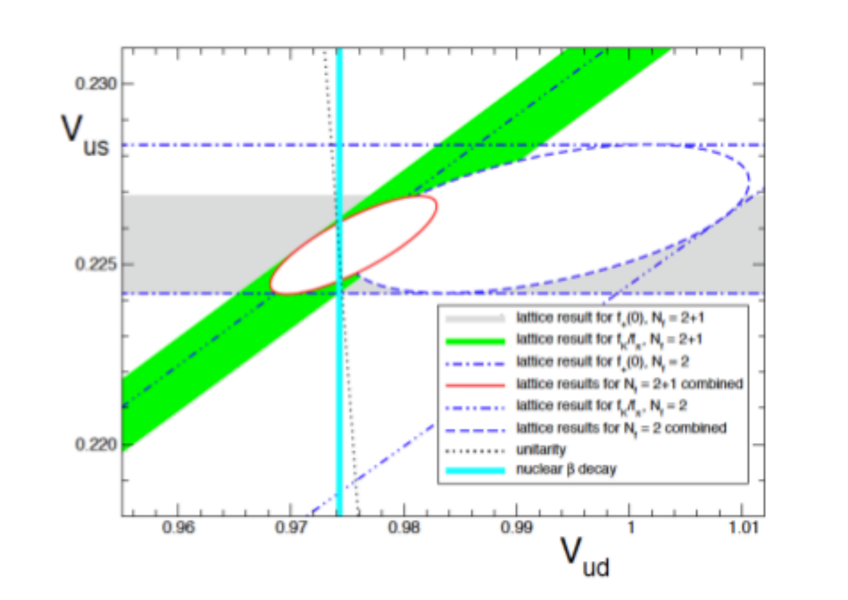
Predictions of analytical model tends to be larger than lattice results

First row V_{CKM} Unitarity Test

Lubicz LP2011



Results from f_K/f_π [squares] and $f_+(0)$ [triangles]



The 1st row unitarity plot [FLAG]

From Kl2 and Kl3 decays

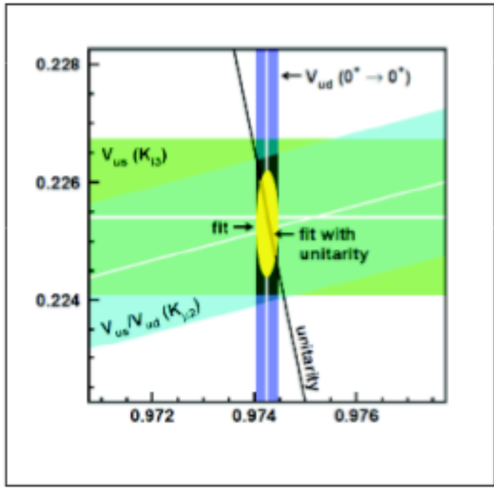
• $|V_{ud}| = 0.9743(2)$ • $|V_{us}| = 0.2254(9)$

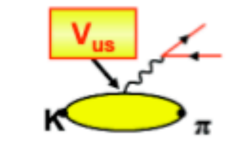
Combining with $|V_{ud}|$ from nuclear β decays:

$$\Delta_{CKM} = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (0 \pm 7)\cdot 10^{-4}$$

F. Sanfilippo ETMC @ Lattice2011

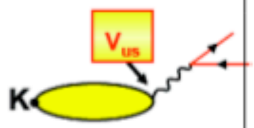
Examples: IB effects in Unitary triangle analysis - V_{us}





Semi-leptonic decays of K to π

$$\Gamma_{K\to\pi l\nu} = C\underbrace{|V_{us}|^2 \left|f_+^{K\pi}(0)\right|^2}_{experiments}$$



Leptonic decays of K and π

$$\frac{\Gamma_{K\to\mu\bar{\nu}_\mu(\gamma)}}{\Gamma_{\pi\to\mu\bar{\nu}_\mu(\gamma)}} = C\underbrace{\frac{|V_{us}|^2}{|V_{ud}|^2}\left(\frac{f_K}{f_\pi}\right)^2}_{experiments}$$

Lattice:
$$f_+^{K\pi}(0) = 0.956(8)$$
$$f_K/f_\pi = 1.193(5)$$
in the **isospin simmetric** limit.

$\rightarrow$ At current precision (0.5–1%), IB corrections **not negligible** $\leftarrow$

Indeed $Ch-PT$ estimates of effects are:

$\left(f_+^{K^+\pi^0}/f_+^{K^-\pi^+}-1\right)^{QCD}$=2.9(4)%	$\left(\frac{f_{K^+}/f_{\pi^+}}{f_K/f_\pi}-1\right)^{QCD}$=−0.22(6)%
A. Kastner, H. Neufeld (EPJ C57 2008)	V. Cirigliano, H. Neufeld (arXiv:1102.0563)

RM123 collaboration:

F. Sanfilippo:	La Sapienza	(ROMA 1)
G.deDivitiis, P.Dimopoulos, R.Frezzotti, R.Petronzio, G.Rossi, N.Tantalo:	Tor Vergata	(ROMA 2)
V. Lubicz, S. Simula, C. Tarantino:	Roma Tre	(ROMA 3)
G. Martinelli:	Renegade @ SISSA	

Ahhh the modern PhD students !!!

Motivations

Sources of Isospin Breaking (in SM)

Electro-magnetic: quarks have different charge $Q_{Up} \neq Q_{Down}$,
$O(\alpha_{em}) \simeq 1/100$

Strong: quarks have different mass, $m_{Up} \neq m_{Down}$,
$O((m_{Down} - m_{Up}) / \Lambda_{QCD}) \simeq 1/100$

We concentrated on **strong** effects: we left EM for the (near) future.

Current situation

- Lattice tipically neglect these effects
- Important corrections at current precision in flavour physics
- Tipically estimated with $Ch - PT$ but
  - not always possible (e.g. nucleon mass splitting) or reliable
  - not from first principles

A new strategy: $m_d - m_u$ expansion

Separate mass lagrangian in **two contributions:**

$$\mathcal{L}_{mass} = \underbrace{\left(\frac{m_d + m_u}{2}\right)}_{m_{ud}} (\bar{u}u + \bar{d}d) - \underbrace{\left(\frac{m_d - m_u}{2}\right)}_{\delta m} (\bar{u}u - \bar{d}d)$$

Split action in **two parts**:

$$S = S_0 - \delta m \hat{S}, \qquad \begin{cases} S_0 & \text{isospin simmetric action} \\ \hat{S} & \text{perturbation} = \sum_x (\bar{u}u - \bar{d}d) \end{cases}$$

Expand functional integral:

$$\langle O \rangle = \frac{\int D\psi O e^{-S_0 + \delta m \hat{S}}}{\int D\psi e^{-S_0 + \delta m \hat{S}}} \stackrel{1st}{\simeq} \frac{\int D\psi O e^{-S_0} \left(1 + \delta m \hat{S}\right)}{\int D\psi e^{-S_0} \left(1 + \delta m \hat{S}\right)} \simeq \frac{\langle O \rangle_0 + \delta m \left\langle O \hat{S} \right\rangle_0}{1 + \delta m \cancel{\left\langle \hat{S} \right\rangle_0}}$$

Isospin correction determination

One can determine relative correction to an observable O as:

$$\frac{\delta \langle O \rangle}{\langle O \rangle_0} \equiv \frac{\langle O \rangle - \langle O \rangle_0}{\langle O \rangle_0} \simeq \delta m \frac{\langle \hat{S} O \rangle_0}{\langle O \rangle_0}, \qquad \hat{S} = \sum_x (\bar{u}u - \bar{d}d)$$

Advantages

- **No need** for new gauge configurations
- Matrix elements are **large** (correction are small due to δm)
- Advantage from **statistical correlations** between $\langle \hat{S} O \rangle$ and $\langle O \rangle$.

Diagrammatically

After fixing δm this method can be applied in principle to any observable.

Numerical analysis

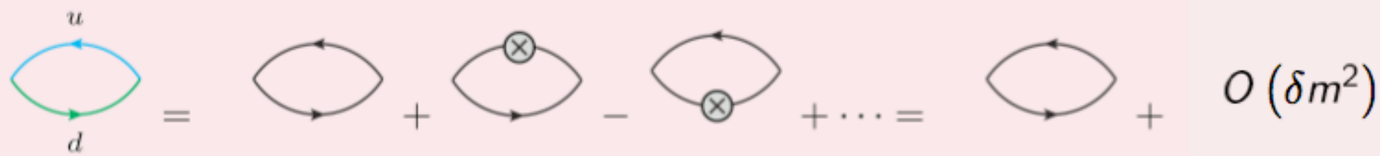
Focus

- Applicability of the method
- First observable chosen: f_K/f_π.

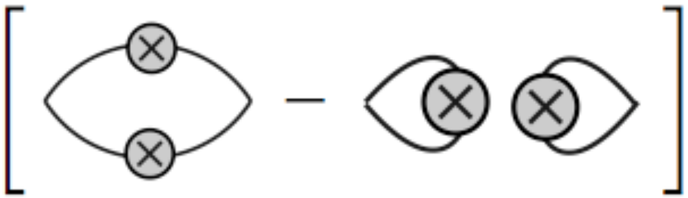
Lattice data

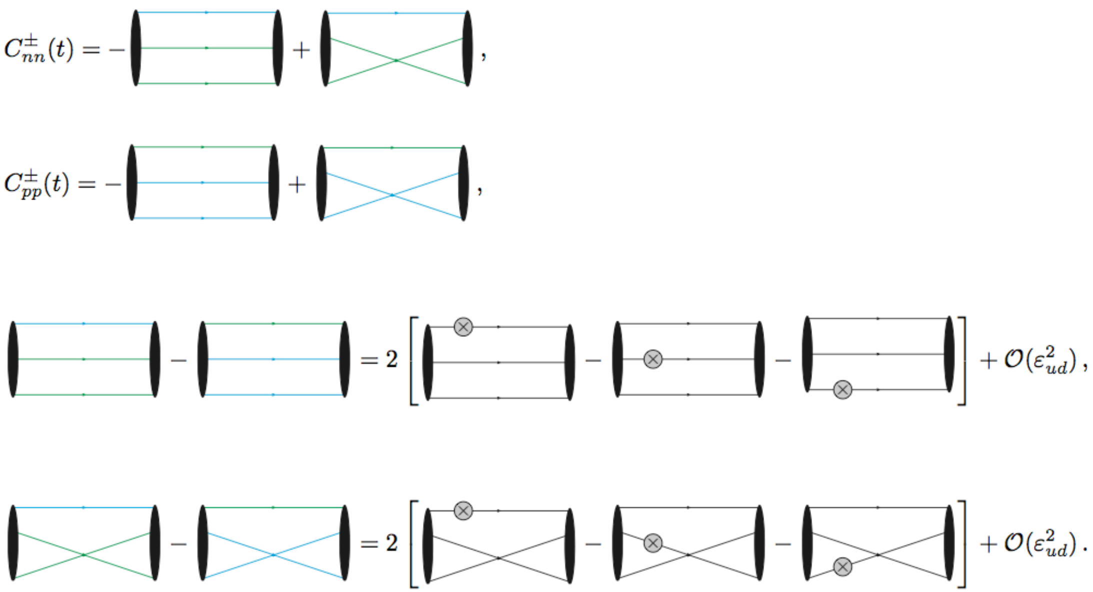
- $N_f = 2$ twisted mass configuration provided by ETMC
- m_{ud}, $\mathfrak{a}$ already determined (arxiv:1010.3659)
- We fix δm from $M_{K_0} - M_{K_+}$
- Electromagnetic corrections are taken from *FLAG*.

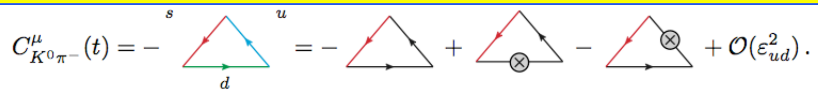
Pion effects start at second order in δm (also for π^0)



$$C_{\pi^0\pi^0}(t) - C_{\pi^+\pi^-}(t) = -4\left[\ \cdots\ \right] + \mathcal{O}(\varepsilon_{ud}^3)$$

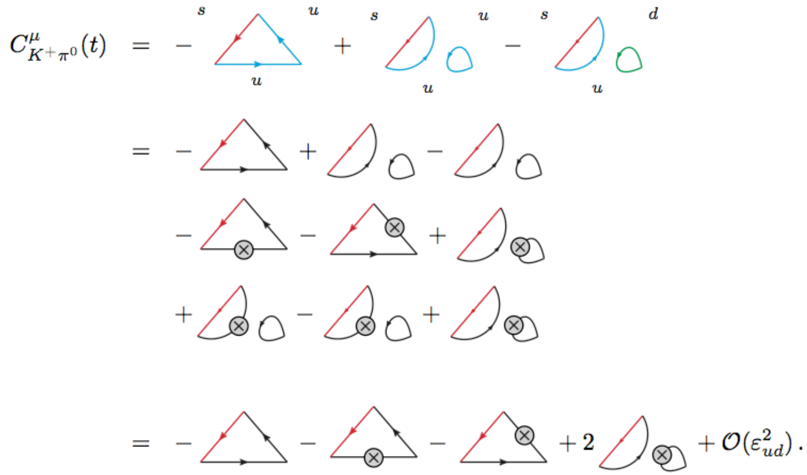






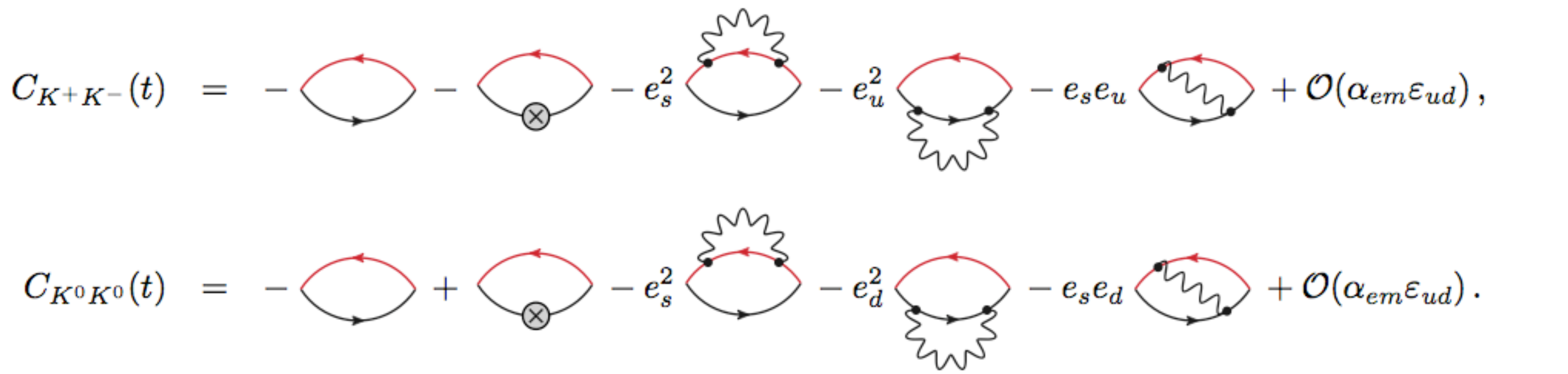
(20)

In order to derive the correction in the $K^+ \to \pi^0 l^+ \nu$ case, in accordance to our general recipe outlined in the previous section, we start from the correlation function $C^{\mu}_{K^+\pi^0}(t)$ in the full theory, that has disconnected diagrams, and expand all the light quark propagators in powers of ε_{ud}, namely



(21)

Electromagnetic and ``strong" QCD IB corrections



The electromagnetic corrections are logarithmically divergent, corresponding to the renormalization of the up and down quark masses (or $\bar{q}q$ or $\bar{q}\tau_3 q$)

Using Dashen theorem:

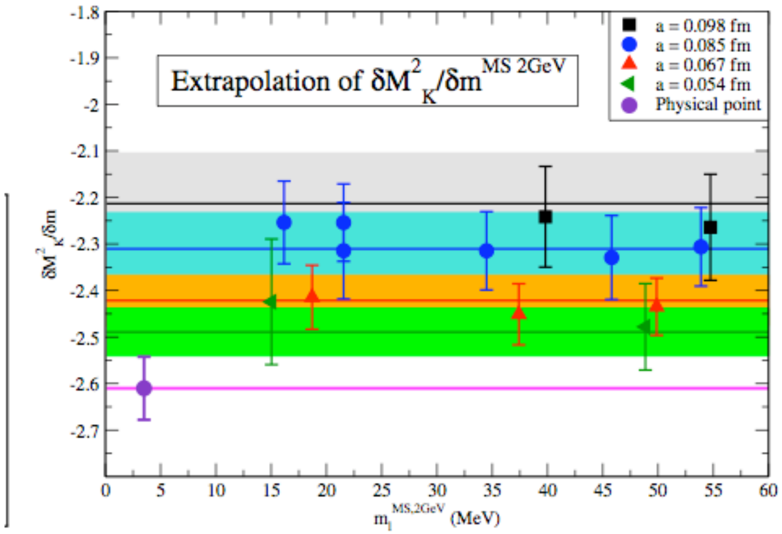
$$\left[M^2_{K^0} - M^2_{K^+}\right]^{QCD} = \left[M^2_{K^0} - M^2_{K^+}\right]^{exp} - (1+\varepsilon_\gamma)\left[M^2_{\pi^0} - M^2_{\pi^+}\right]^{exp}$$

FLAG

Eur. Phys. J. C71 (2011) 1695

$$\varepsilon_\gamma = 0.7(5)\,,$$

$$\left[M^2_{K^0} - M^2_{K^+}\right]^{QCD} = 6.05(63) \times 10^3 \text{ MeV}$$



No details on the lattice analysis only a bunch of (preliminary) results

$$[m_d - m_u]^{QCD}\,(\overline{MS}, 2GeV) \;=\; 2.29(5)(24)\ \text{MeV} \;\times\; \frac{[M^2_{K^0} - M^2_{K^+}]^{QCD}}{6.05\times 10^3\ \text{MeV}},$$

Cirigliano Neufeld -0.0022(6)

$$\left[\frac{F_{K^+}/F_{\pi^+}}{F_K/F_\pi} - 1\right]^{QCD} \;=\; -0.00376(29)(4) \;\times\; \frac{[M^2_{K^0} - M^2_{K^+}]^{QCD}}{6.05\times 10^3\ \text{MeV}},$$

$$[M_n - M_p]^{QCD} \;=\; 2.8(8)(3)\ \text{MeV} \;\times\; \frac{[M^2_{K^0} - M^2_{K^+}]^{QCD}}{6.05\times 10^3\ \text{MeV}},$$

$$\left[\frac{f_+^{K^0\pi^-}(0) - f_+^{K\pi}(0)}{f_+^{K\pi}(0)}\right]^{QCD} \;=\; 1.9(4)(2)\times 10^{-4} \;\times\; \frac{[M^2_{K^0} - M^2_{K^+}]^{QCD}}{6.05\times 10^3\ \text{MeV}}.$$

?

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
$\mu \to e + \gamma$ $\nu_i \to \nu_k$	lepton flavor number

RARE DECAYS WHICH ARE ALLOWED IN THE STANDARD MODEL

FCNC :

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

$q_i \;\; -> \;\; q_k \; + \;\; l^+ \; l^-$

$q_i \;\; -> \;\; q_k \; + \;\; \gamma$

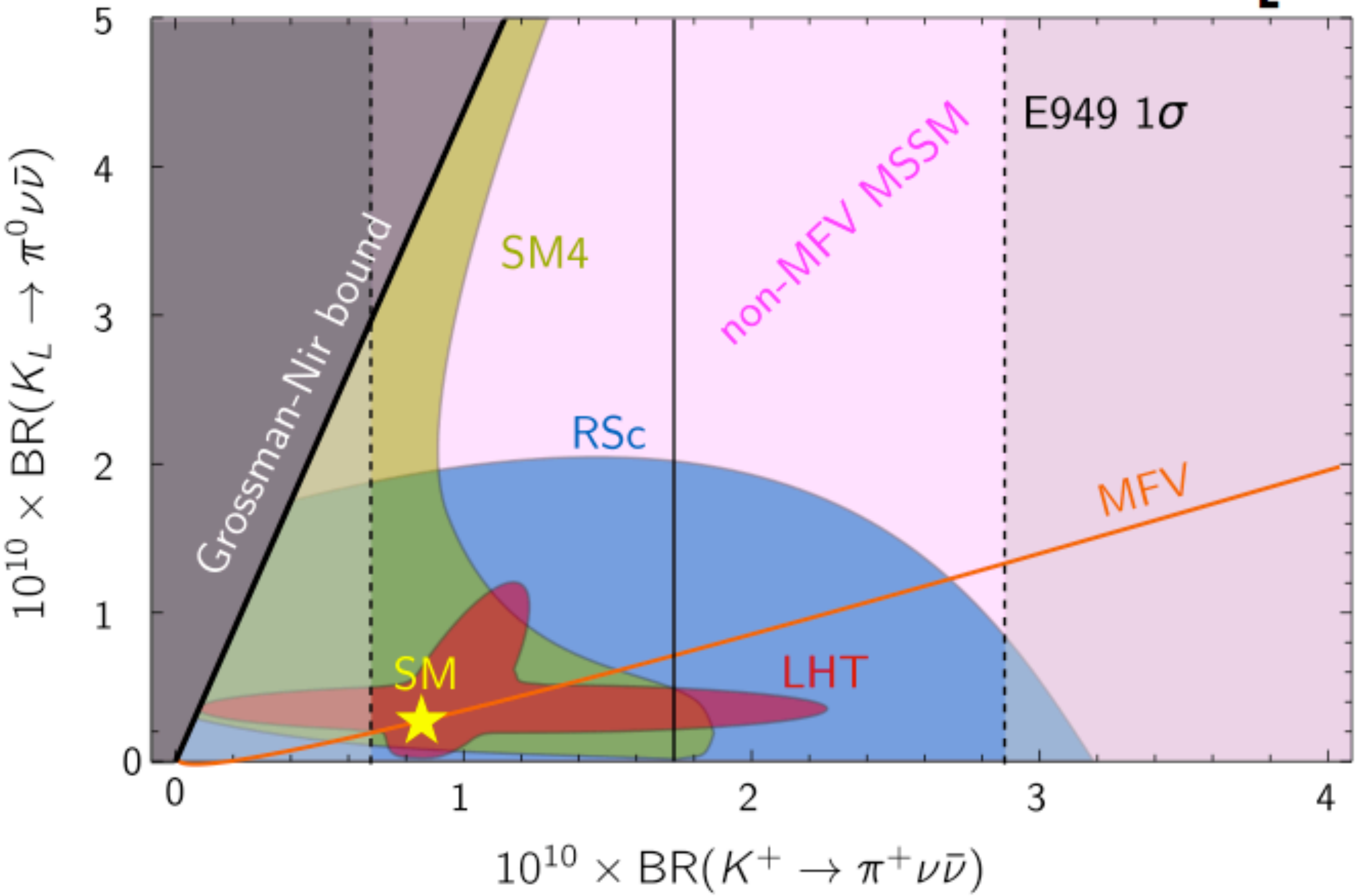
these decays occur only via loops because of GIM and are suppressed by CKM

THUS THEY ARE SENSITIVE TO NEW PHYSICS

Rare Decays as Probes of NP models

FCNC in rare K decays

[Straub]



- While only a schematic picture :
  - Correlation between different measurements a powerful probe of NP models
  - Large number of potential channels ... will talk only about a few
  - RD have a bright future: final data sets from B-factories, LHCb, Super Flavour Factories, Kaon experiments...

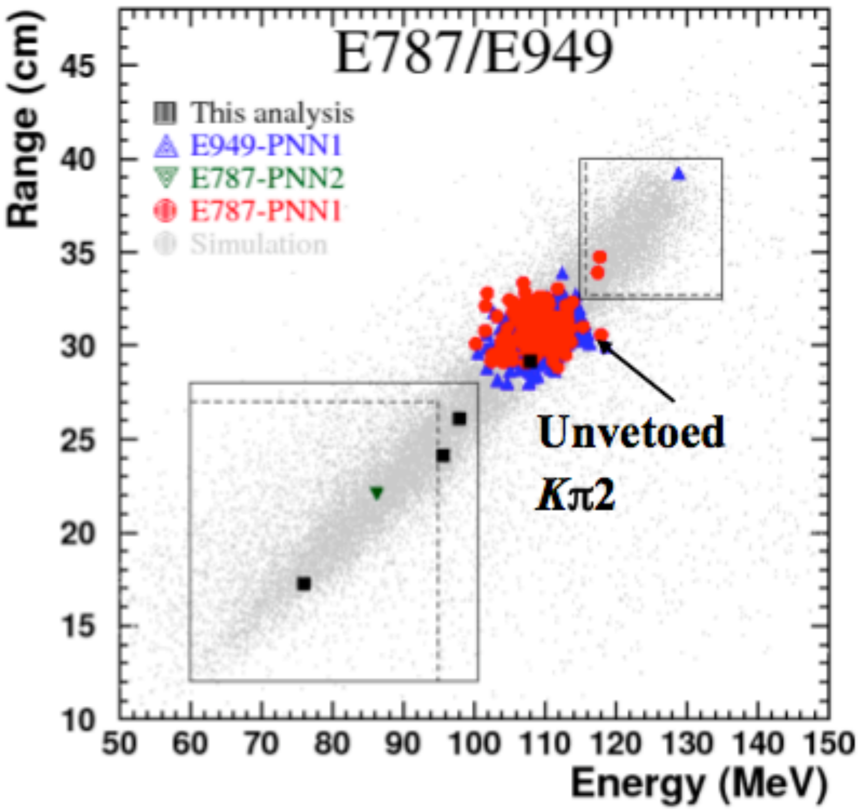
K^+ -> pi^+nunu - Experiment

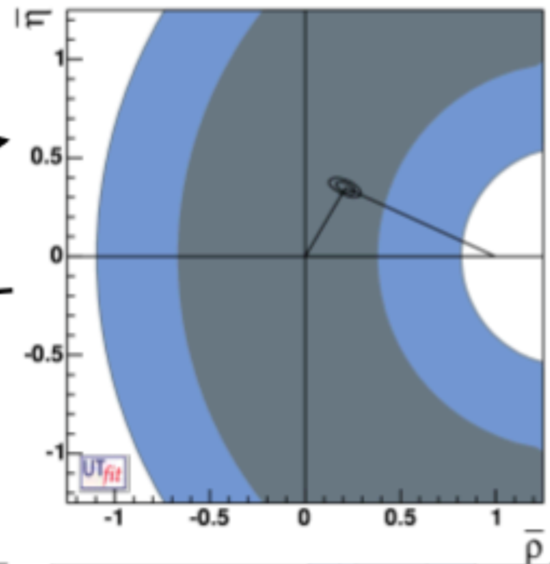
[Spadaro]

Final results from E787/E949 (2008)

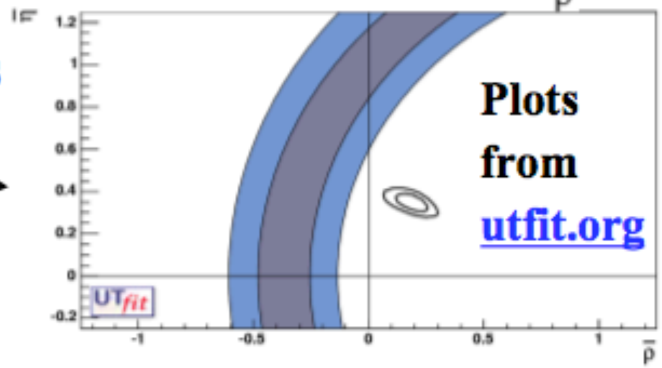
Combined results, from E787 (1995-8 runs) & E949 (12-weeks run in 2001)

$BR(K^+ \to \pi^+ \nu\nu) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$





Same central value, 100 evts



Plots from utfit.org

Prob. all 7 obs. evts are bkg is ~10^{-3}

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

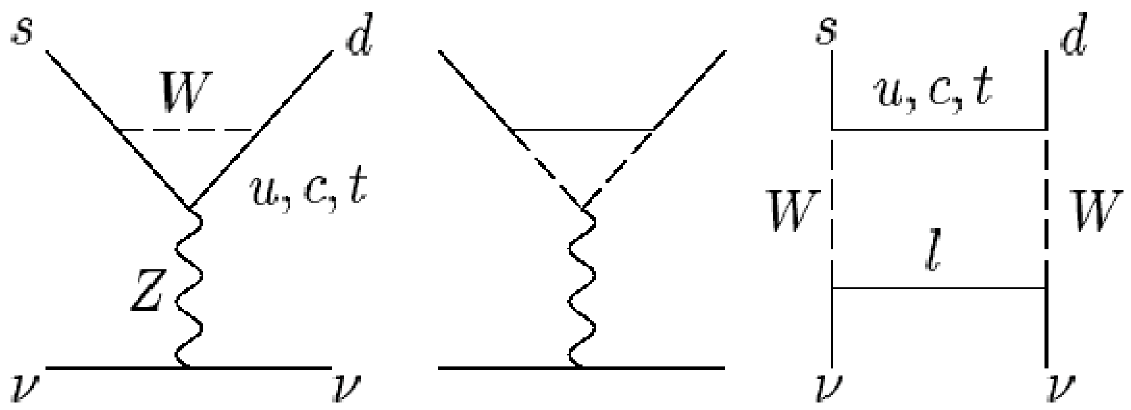
(hard GIM suppression, calculable in pert. theory)

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 K13 decays

☺ Sensitive to $V_{td} V_{ts}^*$ and expected large ~~CP~~

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

$O(\lambda^5\, m_t^2) + i\, O(\lambda\, m_t^2)$
$O(\lambda\, m_c^2) + i\, O(\lambda^5\, m_c^2)$
$O(\lambda\, \Lambda^2_{QCD})$

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

theoretical error ~ 2 %

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

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

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

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

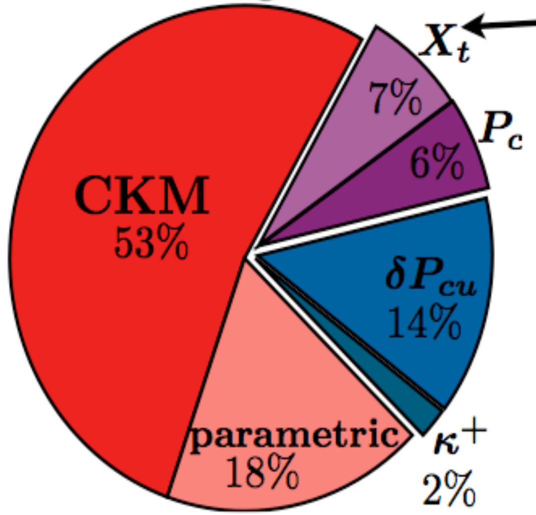
$O(\lambda\, m^2_c) + i\, O(\lambda^5 m^2_c)$

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

CP conserving: error of $O(10\%)$ due to NNLO corrections in the charm contribution and

Error can be halved by LQCD !!

K^+ -> pi^+nunu - error budget



Improved theory prediction

$$\mathrm{Br}^{exp} = 1.73^{+1.15}_{-1.05} \times 10^{-10}$$

$$\mathrm{Br}^{the} = 8.22^{+0.74}_{-0.65} \pm 0.29 \times 10^{-10}$$

[Brod, Gorbahn, ES 10]

[22] L. Maiani, G. Martinelli, M. L. Paciello, B. Taglienti, Nucl. Phys. **B293** (1987) 420.

Citation summary results	All papers	Published only
Total number of citable papers analyzed:	20	16
Total number of citations:	2,177	2,169
Average citations per paper:	108.8	135.6
Breakdown of papers by citations:		
Renowned papers (500+)	1	1
Famous papers (250-499)	1	1
Very well-known papers (100-249)	4	4
Well-known papers (50-99)	4	4
Known papers (10-49)	5	5
Less known papers (1-9)	4	1
Unknown papers (0)	1	0
Additional Citation Metrics [?]		
h-index [?]	15	15

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(799) Guido Altarelli, N. Cabibbo, G. Corbo, L. Maiani (Rome U. & INFN, Rome), G. Martinelli (Frascati). ROME-302-1982. Jun 1982. 30 pp.
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1. **Chiral Symmetry on the Lattice with Wilson Fermions.**
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Massimo Testa (INFN, Rome). ROME-452-1985. Mar 1985. 45 pp.
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Published in **Nucl.Phys. B306 (1988) 677**


Blois '87 (1987)

Luciano writing a paper
with Massimo Giancarlo Marco and Guido M.

&

The sign of ε (or the missed dinner !!)

SUMMARY

WORK IN PROGRESS