Workshop on

$e^+ e^-$ in the 1-2 GeV range:
Physics and Accelerator Prospects

K decays & Flavor Physics

Gino Isidori [INFN−Frascati]

- Introduction
  - The Flavor Saga
- Rare *K* decays & flavor physics
  - The flavor problem
  - $K \to \pi\nu\nu$ decays
  - Rare *K* decays and the UT
  - $K \to ll(\pi)$ decays
- Semileptonic modes & precision low−energy physics
- Conclusions

The Flavor Saga:

'60–'70: golden age of kaon physics

'80 first B−physics era

2nd generation of ϵ'/ϵ measurements

'90 second B−physics era

'99–'01 direct CPV in the kaon system

'01–'03 CPV in the B system

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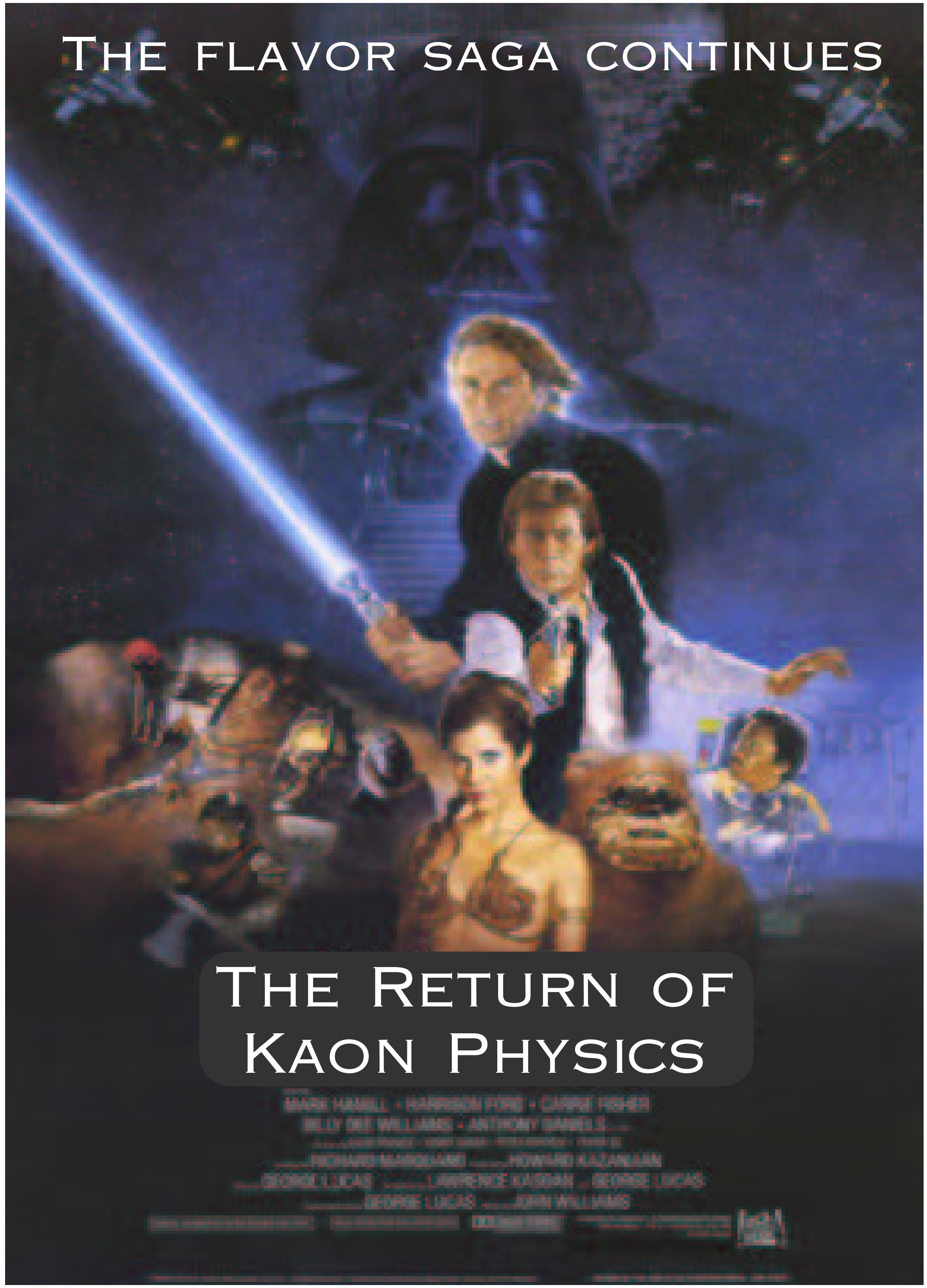
... theoretically−clean and experimentally−easy observables at B factories almost exhausted...

⬇

renewed interest in kaon physics


The flavor saga continues
The Return of Kaon Physics

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The Return of Kaon Physics:

- Search of NP in flavor dynamics via rare K decays
- Tests of CPT at unprecedented level of precision ($\sim M_K/M_{Planck}$)
- Improved understanding of low−energy QCD (CHPT vs. Lattice−QCD) & precise determination of fundamental SM couplings ($m_{u,d,s}$, V_{us} , $\langle qq \rangle$, ...)

Rare K decays & Flavor Physics

The SM can be considered as the *renormalizable part* of an effective field theory, valid up to a (still undetermined) cut–off scale Λ:

$$\mathcal{L} = \mathcal{L}_{\text{gauge}}(A_i, \psi_i) + \mathcal{L}_{\text{Higgs}}(\phi, \psi_i, v) + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)} + \ldots$$

? (relation between v and Λ)

Only 3 couplings
- simple
- tested with high precision

More than 15 coupl.
- complicated
- not very well known yet

2 +... Higgs Potential

3 +... Lepton's Yukawa coupl.

10 Quark's Yukawa coupl.

[FLAVOR PHYSICS]

Quark–flavor mixing is a key ingredient to understand the symmetry–breaking sector of the SM and, possibly, to provide an indirect indication about the value of Λ

➡ Rare decays

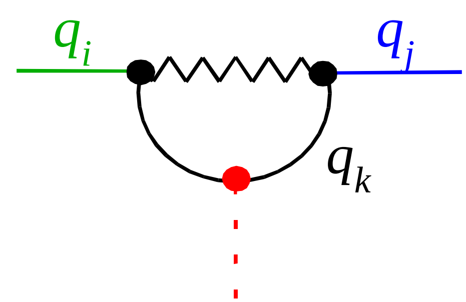
Rare processes are interesting when the suppression of the transition is associated to some (hopefully broken...) conservation law [e.g.: $\not B \Leftrightarrow p$ decay, $\not L \Leftrightarrow 2\beta 0\nu$, ...]

Flavor Changing Neutral Currents

$$q_i \to q_j + \gamma,\ l^+ l^-, \bar{\nu}\nu$$

[especially $\not{CP}$–FCNC]

are the ideal candidates to study in detail the breaking of the (approximate) flavor symmetry of the SM



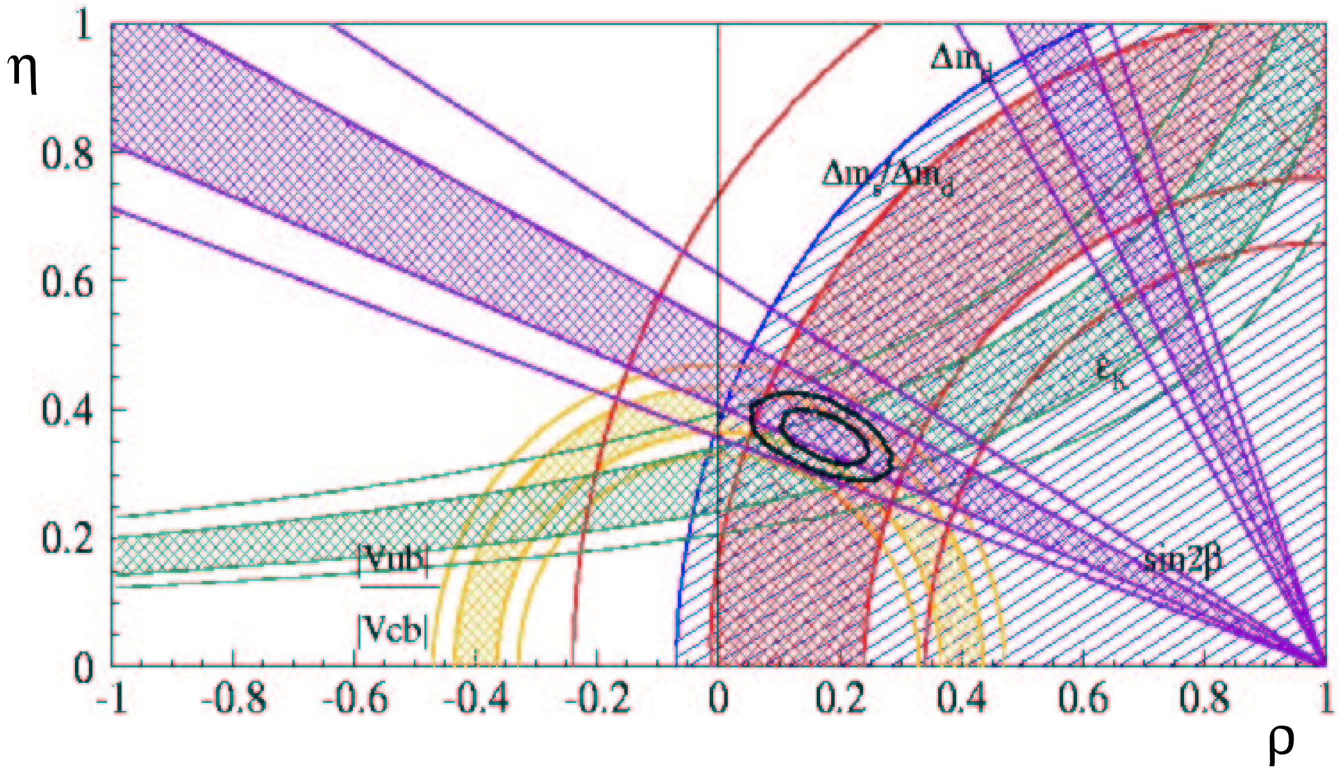
- no tree–level contribution within the SM
- likely to be dominated by short–distance dynamics [*key point*]

precise determination of flavor mixing within the SM [e.g.: V_{td}]

enhanced sensitivity to physics beyond the SM [$O^{(6)} \Rightarrow \Lambda$]

The Flavor Problem:

Available data on $\Delta F=2$ FCNC amplitudes (meson−antimeson mixing) already provides serious constraints on the scale of New Physics...



e.g.:

$K^0-\bar{K}^0$ mixing

$\Downarrow$

$\Lambda \gtrsim 100$ TeV

for $O^{(6)} \sim (\bar{s}d)^2$

much more severe than bounds on the scale of flavor−conserving operators from e.w. precision data

...while a natural stabilization of the Higgs potential $\Rightarrow$ $\Lambda \sim 1$ TeV

After the recent precise data from *B* factories, it is more difficult [although not impossible...] to believe that this is an accident

Two possible solutions:

- *pessimistic* [very unnatural]: $\Lambda > 100$ TeV
  $\Rightarrow$ almost nothing to learn from other FCNC processes
  (but also very difficult to find evidences of NP at LHC...)

- *natural*: $\Lambda \sim 1$ TeV + flavor–mixing protected by additional symmetries
  $\Rightarrow$ still a lot to learn from *rare decays*

- Present fit of the CKM unitarity triangle involve only two types of amplitudes sensitive to NP: *K*–*K* mixing and *B*–*B* mixing (ΔF=2 transitions only) $\Rightarrow$ we known very little yet about ΔF=1 transitions

- Present CKM fits provide only a consistency check of the SM hypothesis but do not provide a bound on the NP parameter space $\Rightarrow$ only with the help of rare decays we can study the underlying flavor symmetry in a model−independent way

$$\mathscr{L} = \mathscr{L}_{\text{gauge}}(A_i, \psi_i) + \mathscr{L}_{\text{Higgs}}(\phi, \psi_i, v) + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)} + \ldots$$

Anatomy of a typical $O_i^{(6)}$ relevant to FCNC rare decays:

$$Q_\gamma^{bs} = W_\gamma^{bs} \, \underbrace{D_R^{\ b} \, \sigma_{\mu\nu} F^{\mu\nu} H \, Q_L^{\ s}} \sim m_b \, b_R \, \sigma_{\mu\nu} F^{\mu\nu} s_L$$

flavor coupling

[e.g.: $W_\gamma^{bs} \sim y_b \, y_t^{\,2} V_{tb}^{\ *} V_{ts}$
for the SM short−distance contr.]

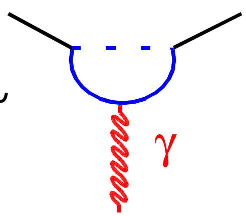
The most restrictive choice is
the so−called MFV hypothesis
[= same CKM/Yukawa suppress. as in the SM]
it cannot be worse than this without
serious fine−tuning problems

[Chivukula & Georgi, ’89; Buras *et al.* ’00;
D’Ambrosio, Giudice, G.I., Strumia ’02]

flavor−blind structure

Limited number of independent
terms once we impose
$SU(3)_c \times SU(2)_L \times U(1)_Y$
gauge invariance

[closely related to specific
loop topologies, e.g.:

$D_R \sigma_{\mu\nu} F^{\mu\nu} H Q_L \sim$ 

]

	$b \to s$	$b \to d$	$s \to d$
$\Delta F=2$ box	ΔM_{Bs} $A_{CP}(B_s \to \psi\phi)$	ΔM_{Bd} $A_{CP}(B_d \to \psi K)$	ΔM_K, ε_K
$\Delta F=1$ 4−quark box	$B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to \pi\pi$, $B_d \to \rho\pi$, ...	ε'/ε, $K \to 3\pi$, ...
gluon penguin	$B_d \to X_s \gamma$, $B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to X_d \gamma$, $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 l^+ l^-$, ...
γ penguin	$B_d \to X_s l^+ l^-$, $B_d \to X_s \gamma$ $B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to X_d l^+ l^-$, $B_d \to X_d \gamma$ $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 l^+ l^-$, ...
Z^0 penguin	$B_d \to X_s l^+ l^-$, $B_s \to \mu\mu$ $B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to X_d l^+ l^-$, $B_d \to \mu\mu$ $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 l^+ l^-$, $K \to \pi\nu\nu$, $K \to \mu\mu$, ...
H^0 penguin	$B_s \to \mu\mu$	$B_d \to \mu\mu$	$K_{L,S} \to \mu\mu$

decreasing SM contrib. →

decrea-sing SM contrib. ↓

	$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
$\Delta F=2$ box	ΔM_{Bs} $A_{CP}(B_s \to \psi\phi)$	ΔM_{Bd} $A_{CP}(B_d \to \psi K)$	ΔM_K, ε_K
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H^0 penguin	$B_s \to \mu\mu$	$B_d \to \mu\mu$	$K_{L,S} \to \mu\mu$

Theoretical errors $\lesssim$ 10%

decreasing SM contrib. →

decrea–sing SM contrib. ↓

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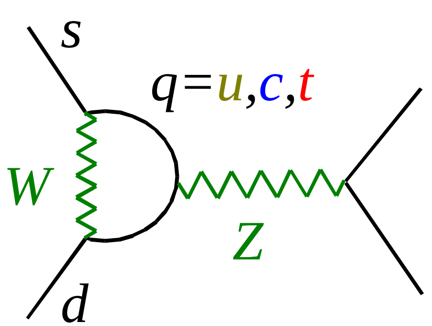
(shaded) = exp. error ~ 10%   (open) = exp. error ~ 100%

$K \to \pi\nu\nu$ *decays*:

I. Theoretical predictions within the SM

Thanks to the so−called *"hard"* GIM mechanism these decays are largely dominated by short−distance dynamics:



$$+\ box \Rightarrow A_q \sim m_q^2 \underbrace{V_{qs}^* V_{qd}}_{\lambda_q} \sim \begin{cases} \Lambda_{QCD}^2 \lambda & (u) \\ m_c^2 \lambda + i\, m_c^2 \lambda^5 & (c) \\ m_t^2 \lambda^5 + i\, m_t^2 \lambda^5 & (t) \end{cases}$$

Genuine $\Delta S=1$ $O(G_F^2)$ transition

[$\lambda = \sin\theta_c$]

$$\mathcal{H}_{eff} = \frac{G_F \alpha}{2\sqrt{2}\pi s_W^2} \left[\lambda_c X_c + \lambda_t X_t\right] (\bar{s} d)_{V-A} (\bar{\nu}\nu)_{V-A}$$

X_i @ NLO:

Buchalla & Buras '94
Misiak & Urban '99

N.B.: the hadronic matrix element $\langle \pi | (sd)_{V-A} | K \rangle$ is known from K_{l3} with excellent accuracy

Marciano & Parsa, '96

K^+

Th. error dominated by the charm contribution
[NNLO perturbative corr. (+ d=8 terms)]

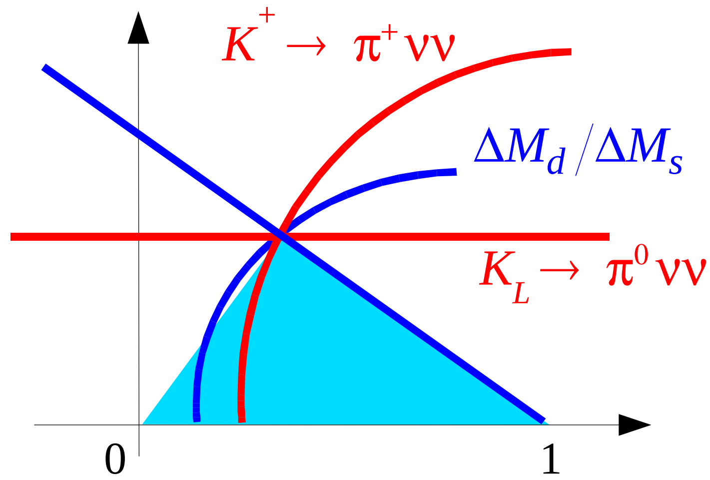
Lu & Wise '94
Buchalla & Buras '97
Falk *et al.* '00

$$BR(K^+)^{(SM)} = C\,|V_{cb}|^4\,[(\bar{\rho}-\rho_c)^2 + (\sigma\bar{\eta})^2] = (7.7 \pm 1.1)\times 10^{-11}$$

$\rho_c = 1.40 \pm 0.06$

$\Rightarrow$ 0.04 error on ρ around the origin of the UT plane

Present error still dominated by CKM uncertainties



K_L

Charm contribution suppressed by CP
[The $\bar{\nu}\nu$ state produced by $\mathcal{H}_{eff}$ is a *CP* eigenstate]

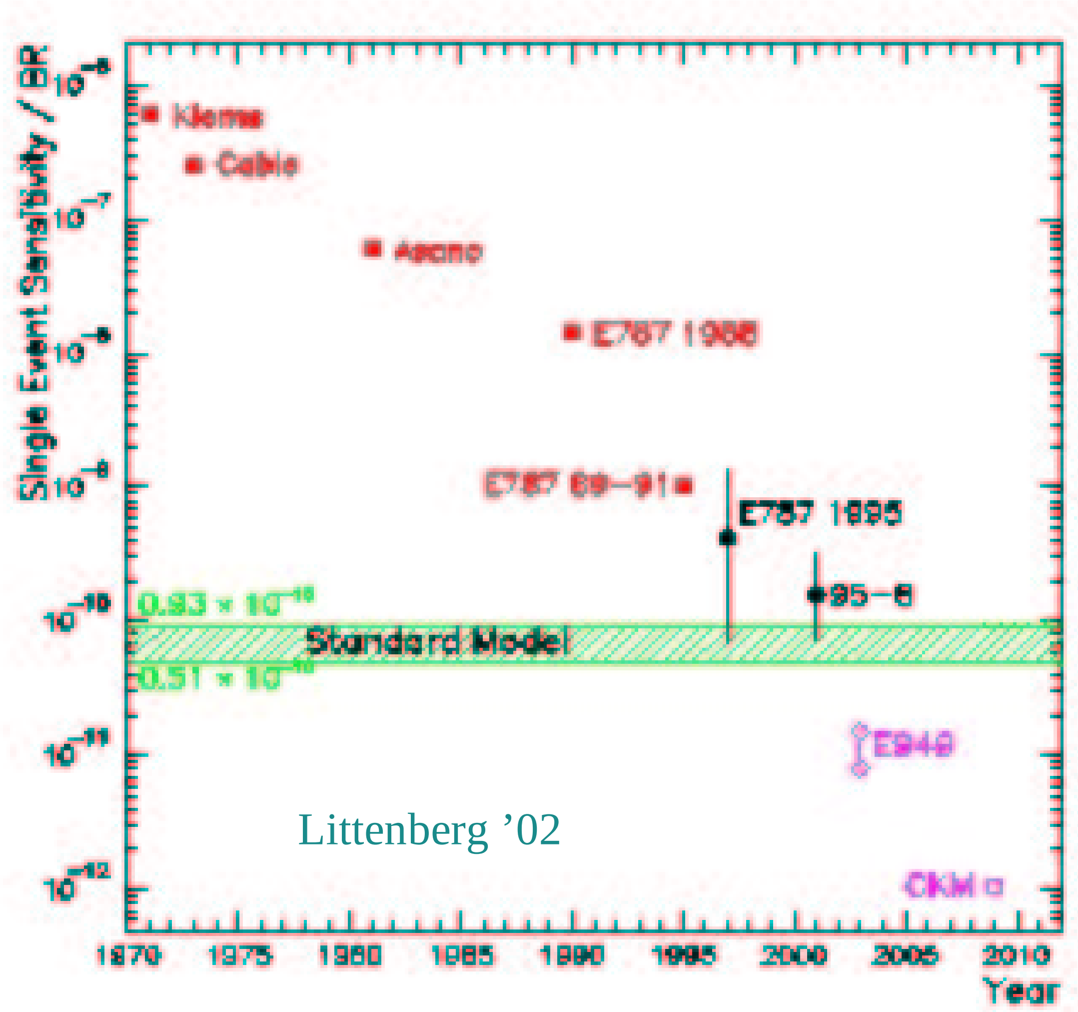
Littenberg, '89
Buchalla & Buras '97
Buchalla & G.I. '98

$$BR(K_L)^{(SM)} = 1.48\times 10^{-11}\left(\frac{m_t(m_t)}{166\ GeV}\right)^{2.3}\left[\frac{\Im(V_{ts}^* V_{td})}{10^{-4}}\right]^2 = (2.6 \pm 0.5)\times 10^{-11}$$

th. error ~ 2% !

Area of the (full) UT

II. Status of $\Gamma(K \to \pi\nu\nu)$ measurements



$$B(K^+ \to \pi^+ \nu \bar{\nu}) = \left(1.57\,^{+1.75}_{-0.82}\right) \times 10^{-10}$$

- 2 events observed by BNL–E787 (with 0.15 bkg.)
- result compatible with SM expectations (central value $2\times$SM...)

- No dedicated experiment on $K_L \to \pi^0\nu\nu$ has started yet

present best limit: $B(K_L \to \pi^0\nu\nu) < 0.59 \times 10^{-6}$ KTeV '99 [using $\pi^0 \to \gamma e^+ e^-$]

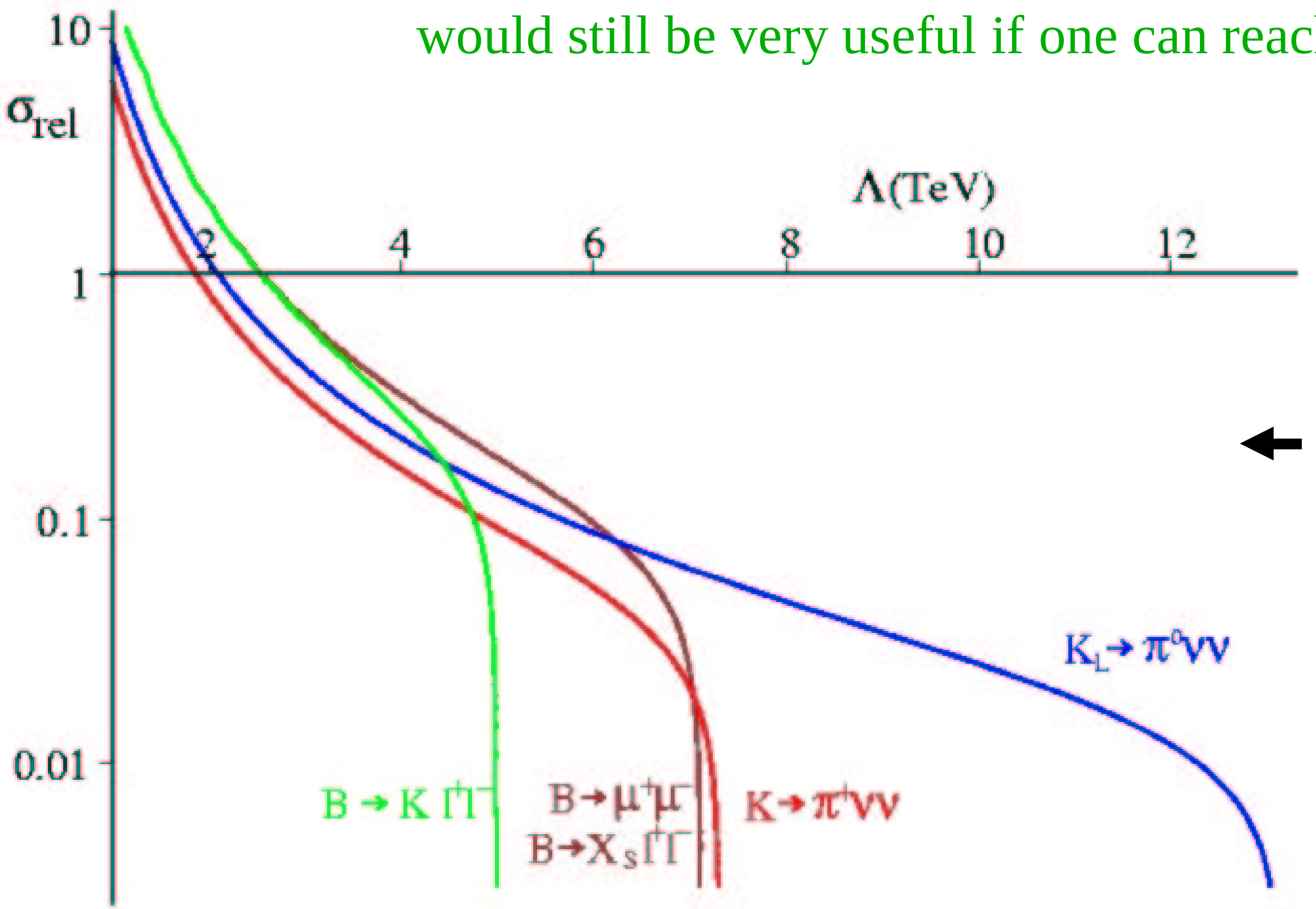
III. $K \to \pi\nu\nu$ beyond the SM

Two basic scenarios:

A) Models with Minimal Flavor Violation [the pessimistic perspective...]

$\Rightarrow$ same CKM suppression as in the SM [$A(s\to d\nu\nu) \propto V_{ts}V_{td} \sim \lambda^5$]

Within this framework the effects are naturally not very large (maximal ehancements up to ~ 50−60%) but B($K\to \pi\nu\nu$) measur. would still be very useful if one can reach the SM level:

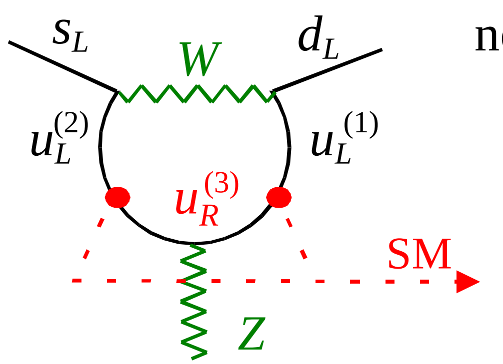


Sensitivity to the scale of new−physics (within MFV models) of future rare−decay experiments

[D’Ambrosio, Giudice, G.I. & Strumia, ’02]

B) Models with new sources of flavor mix. ➡ large effects posssible [no λ^5 suppression] in several specific frameworks.

[the optimistic perspective]



e.g.: MSSM with non−universal A terms

$(V_{ts}^* m_t)\times(V_{td} m_t)$

Nir & Worah, '97
Buras, Silvestrini & Romanino, '97
Colangelo & G.I, '98

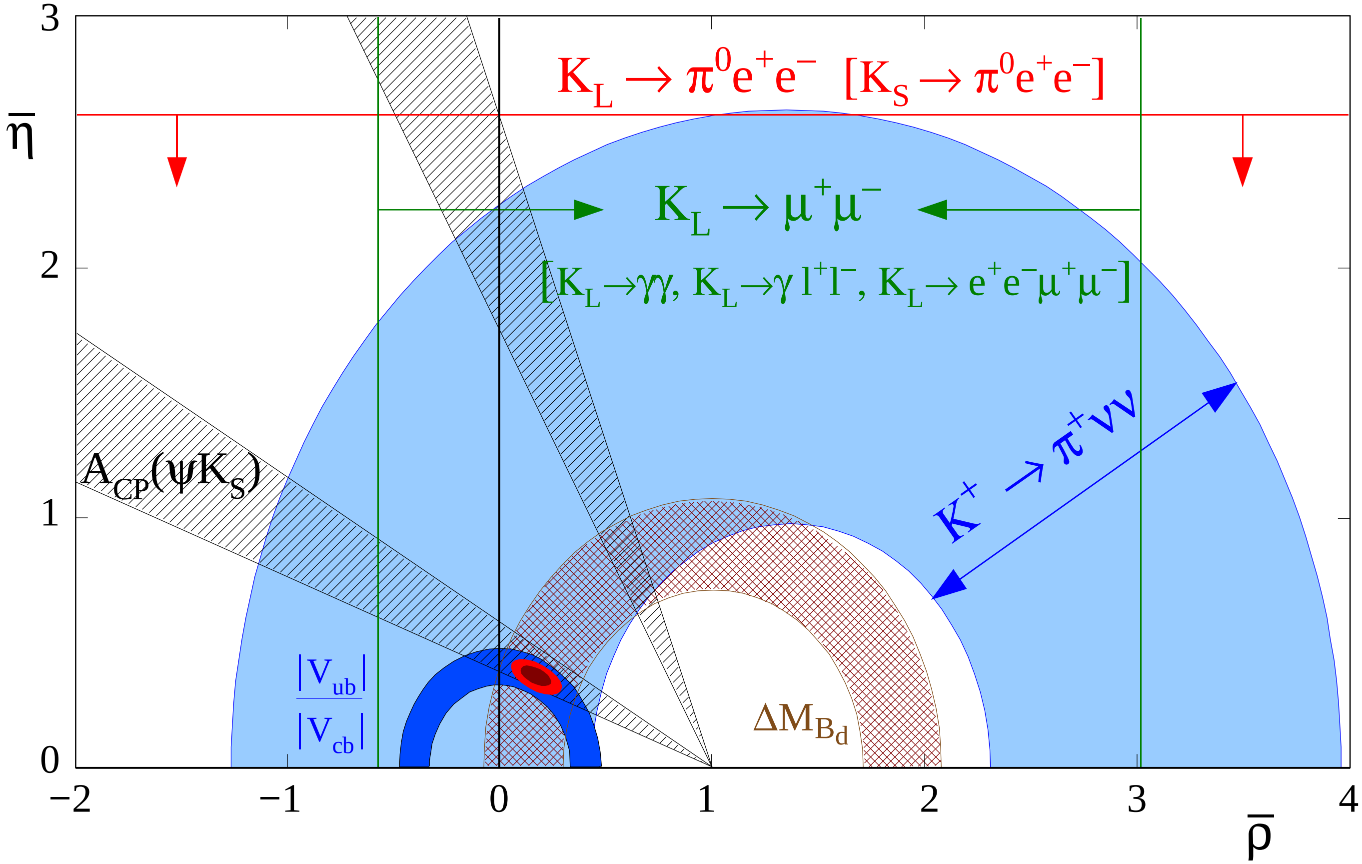
Model–independent bound: $\Gamma(K_L \to \pi^0 \nu\nu) < \Gamma(K^+ \to \pi^+ \nu\nu)$

[Grossman & Nir, '97]

➡ $B(K_L \to \pi^0 \nu\nu) < 1.8\times10^{-9}$ [90% C.L.]

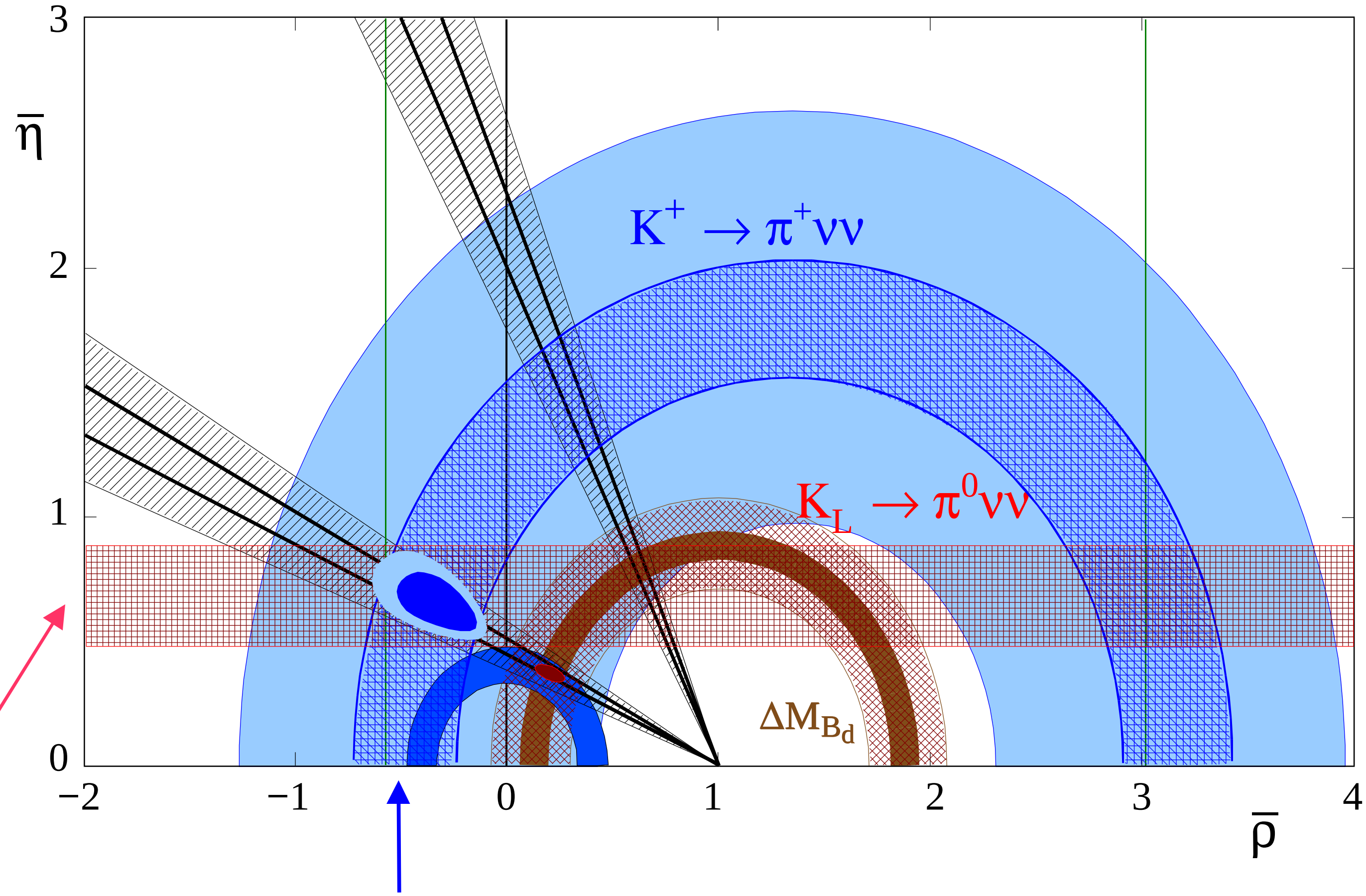
Two orders of magnitudes above the SM: a wide unexplored region of possible exciting new phenomena...

Rare K decays & the Unitarity Triangle:



Summer 2003 Status.

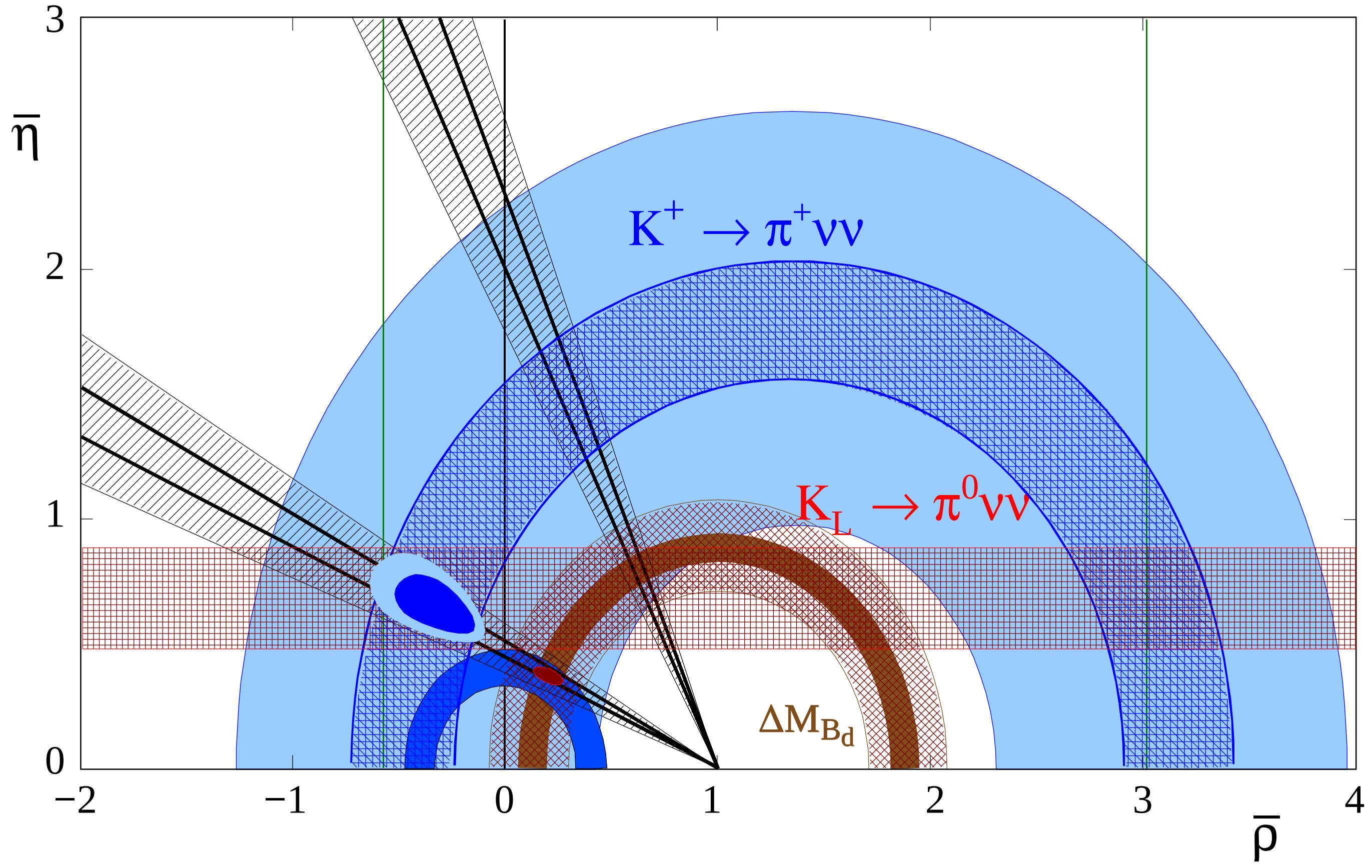
Possible future evolution (if we are lucky enough...)



$B(K^+ \to \pi^+ \nu\nu) = (1.7 \pm 0.3) \times 10^{-10}$ ≈ 2 × SM

$B(K_L \to \pi^0 \nu\nu) = (1.1 \pm 0.3) \times 10^{-10}$ ≈ 4 × SM ⇐ even exp. searches with SES ~ 10^{-10} would be very welcome & useful !

A scenario of this type is far from being excluded at present:



- it could become a rather probable scenario if Belle's hint of a huge difference between $A_{CP}(B \to \phi K_S)$ and $A_{CP}(B \to \psi K_S)$ is confirmed....
- but it would remain an open possibility even in absence of significant NP effects at *B* factories

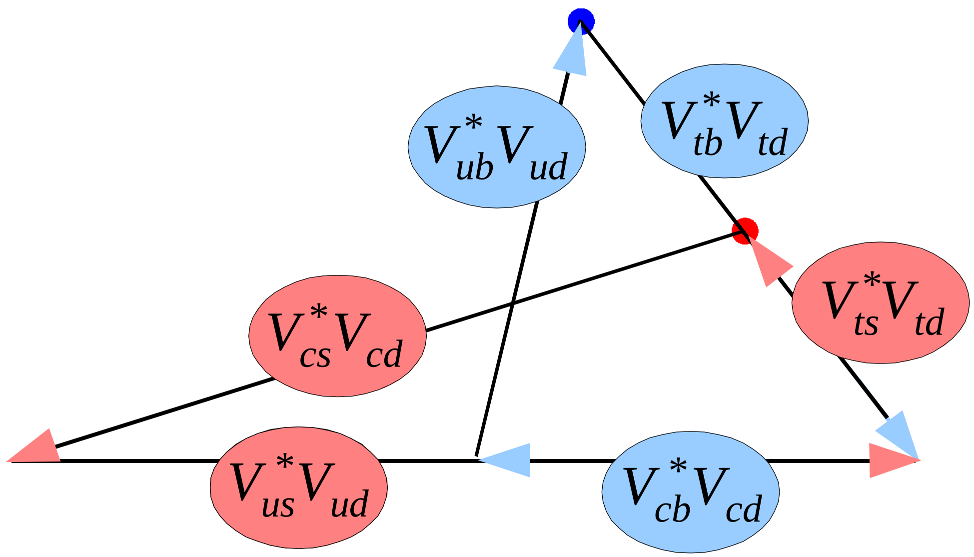
The significance of rare–kaon–decay measurements becomes even more clear if we look at CKM unitarity triangles from a different perspective:

The (usual) $b \to d$ triangle:

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

The (kaon) $s \to d$ triangle:

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0$$

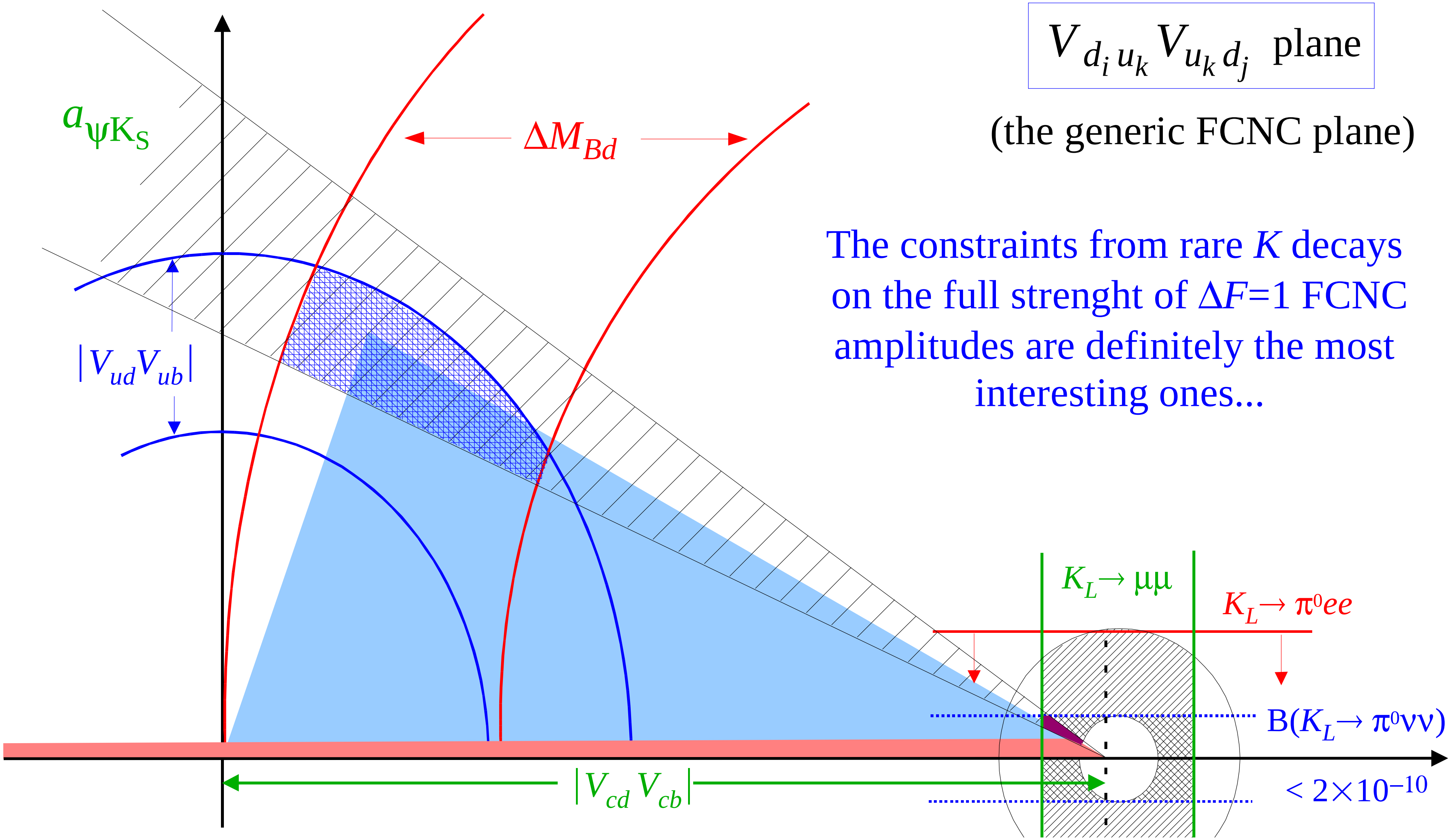


Same area (not in scale !)

$b \to d$ & $s \to d$ unitarity triangles on the same scale

$V_{d_i u_k} V_{u_k d_j}$ plane

(the generic FCNC plane)

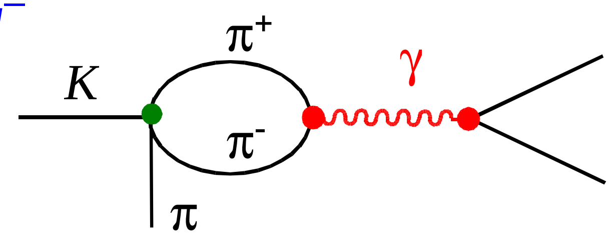


The constraints from rare K decays on the full strenght of ΔF=1 FCNC amplitudes are definitely the most interesting ones...

$K \to l^+ l^- (\pi)$ *decays*

General comment: dangerous e.m. long–distance effecs with respect to νν modes:

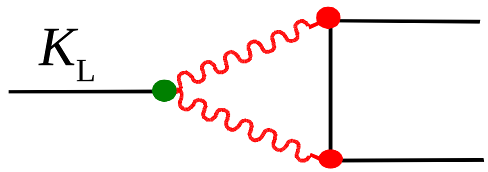
["*XL*": 1γ] $K^{\pm}(K_S) \to \pi^{\pm}(\pi^0) l^+ l^-$



hopeless to disentangle short–distance effects

$A_{short}/A_{long} \sim 10^{-2}$

["*L*": 2γ, J=0] $K_L \to \mu^+\mu^-$



$A_{short}/A_{long} \sim 1$

$$B(K_L \to \mu^+\mu^-) = |\Im A_{\gamma\gamma}|^2 + |\Re A_{\gamma\gamma} + \Re A_{short}|^2 = (7.18 \pm 0.17) \times 10^{-9}$$

fixed by $\Gamma(K_L \to \gamma\gamma)$
$B_{abs} = (7.07 \pm 0.18) \times 10^{-9}$

determined by the $K_L \to \gamma^* \gamma^*$ form factor (at all energies)

known @ NLO
$B_{s.d.} = 0.9 \times 10^{-9} \times (1.2 - \rho)^2$

perturbative QCD + CHPT helps us to put bound on the $K_L \to \gamma^* \gamma^*$ form factor:

⇒ large negative values of ρ [$\rho \lesssim -0.5$] are certainly disfavoured

⇒ very difficult to improve these limits

["*S*": 2γ, J=2] $K_L \to \pi^0 e^+ e^-$

Long−distance effects small & under control thanks to recent NA48 results ⇒ realistic hope to disentangle the short−distance CP−violating dynamics

The 3 componennts of the $K_L \to \pi^0 e^+ e^-$ amplitude:

[long−distance 1γ–exchange suppressed by CP]

A. direct CPV amplitude ⟷ **B. indirect CPV**

short−distance dominated,
very similar to $K_L \to \pi^0 \nu\nu$

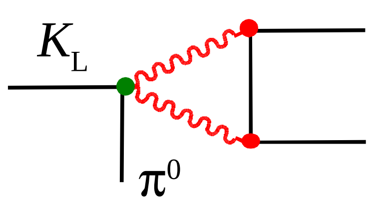
determined by $B(K_S \to \pi^0 e^+ e^-) = 5\times 10^{-9}\,|a_S|$

$a_S \sim O(1)$ from naïve dim. analysis

$$B_{CPV} = \left[16\,|a_S|^2 \pm 6.2\,|a_S| \left(\frac{\Im\lambda_t}{10^{-4}}\right) + 2.4\left(\frac{\Im\lambda_t}{10^{-4}}\right)^2 \right] \times 10^{-12}$$

$$(\Im\lambda_t)_{SM} = \Im(V_{ts}^* V_{td}) \approx 1.3\times 10^{-4}$$

C. CPC amplitude



no interference; different Dalitz Plot;
strong constraints from $K_L \to \pi^0\gamma\gamma$ @ low $M_{\gamma\gamma}$

$$B_{CPC} \sim 10^{-12}$$

The 3 componennts of the $K_L \to \pi^0 e^+ e^-$ amplitude:

[long−distance 1γ–exchange suppressed by CP]

A. direct CPV amplitude ⟷ B. indirect CPV

short−distance dominated,
very similar to $K_L \to \pi^0 \nu\nu$

determined by $B(K_S \to \pi^0 e^+ e^-) = 5\times10^{-9}\,|a_S|$

$$B(K_S \to \pi^0 e^+ e^-) = (5.8\,^{+2.8}_{-2.3} \pm 0.3 \pm 0.8)\times10^{-9}$$

NA48 ’03

- large interf. between direct & indirect CPV
- positive interf. strongly favoured
- CPC component negligible

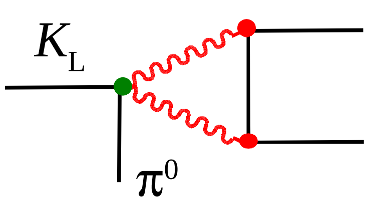
$$B_{SM} = B_{CPV} = 3.2\,^{+1.2}_{-0.8}\times10^{-11}$$

[Buchalla, D’Ambrosio, G.I ’03]

$B(K_L \to \pi^0 e^+ e^-) < 2.8\times10^{-10}$ [90% CL]

KTeV ’03 (prelim.)

C. CPC amplitude

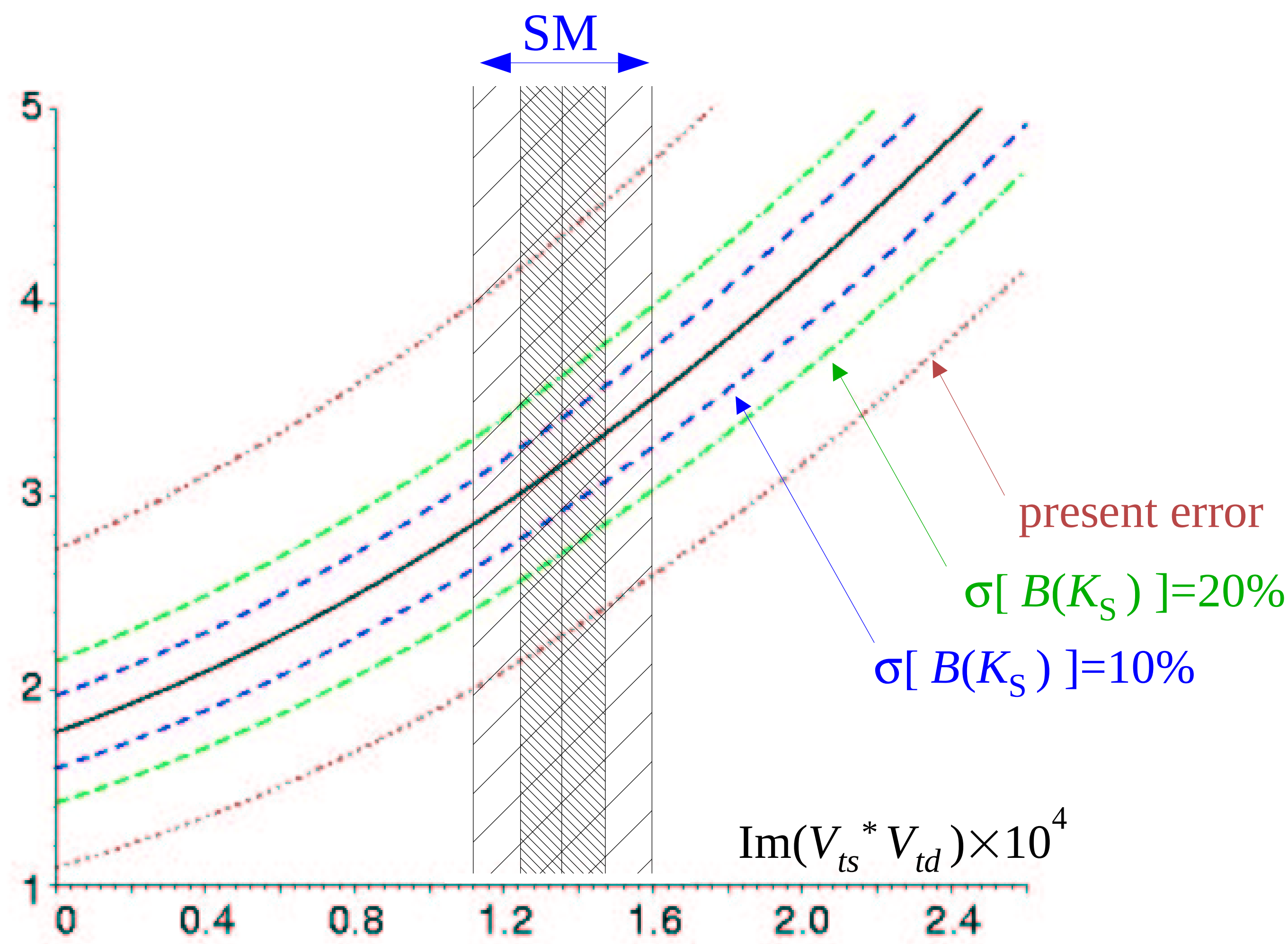


no interference; different Dalitz Plot;
strong constraints from $K_L \to \pi^0\gamma\gamma$ @ low $M_{\gamma\gamma}$

$$B(K_L \to \pi^0\gamma\gamma,\ M_{\gamma\gamma} < 110\text{ MeV}) < 0.9\times10^{-8} \quad [90\%\text{ CL}]$$

NA48 ’02

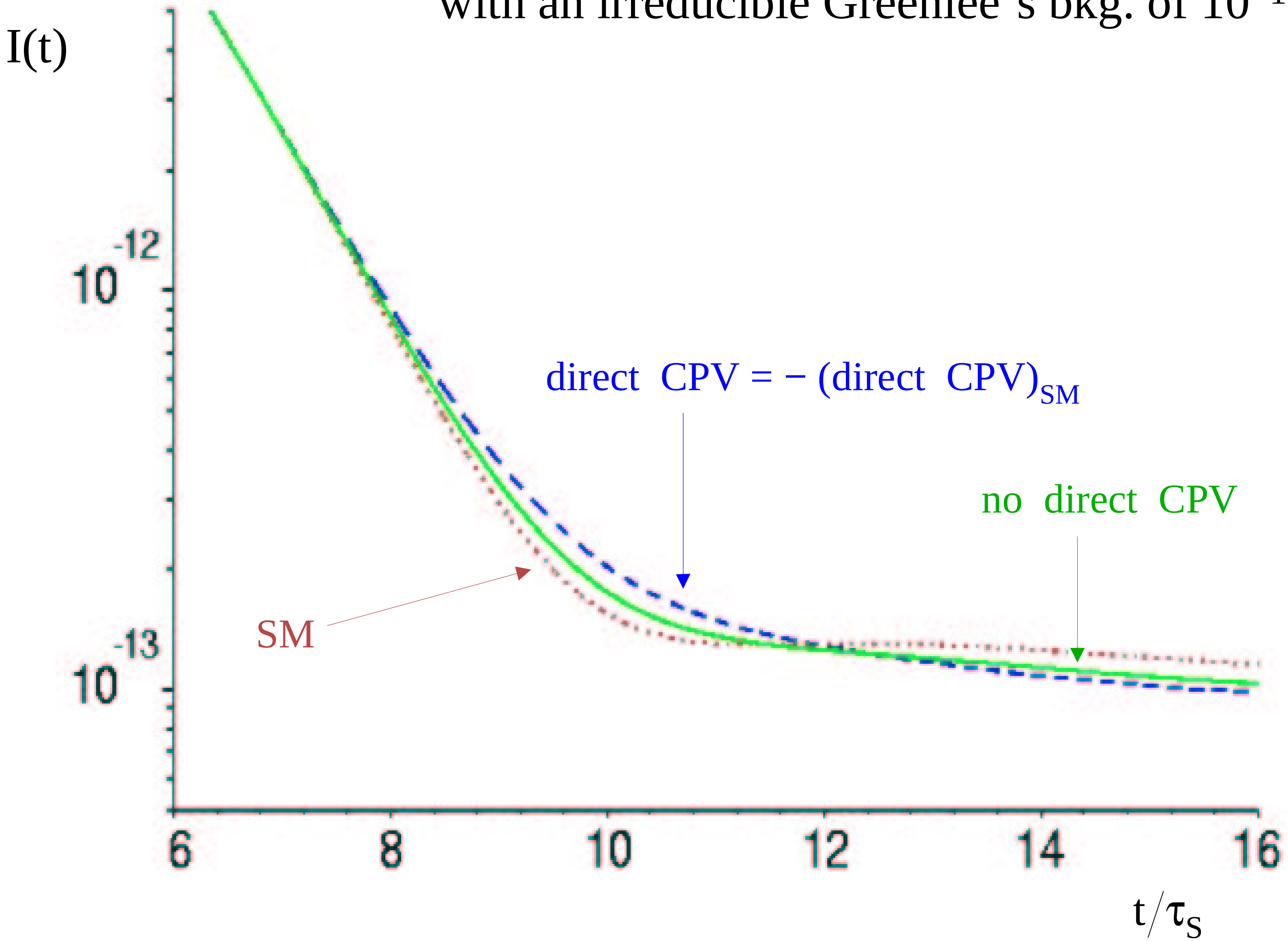
$$B_{CPC} < 3\times10^{-12}$$



This mode represents an interesting alternative for precision tests of $\Delta F=1$ $s \to d$ FCNCs:

- Irreducible th. error ~ 10% [not as clean as $K_L \to \pi^0 \nu\nu$, but still very interesting]
- Different sensitivity to NP with respect to $K_L \to \pi^0 \nu\nu$
- Clean exp. signature, but irreducible physics bkg from $K_L \to e^+ e^- \gamma\gamma$ [⇒ KTeV]
- $K_{L,S} \to \pi^0 e^+ e^-$ time−interf. ⇒ useful handle against Greenle's bkg.

Probability distribution of $K^0 \to e^+e^-(\gamma\gamma)_{\pi^0}$ events
with an irreducible Greenlee's bkg. of 10^{-10}



Semileptonic modes & precision low−energy physics

Kaon decays and, in particular, the semileptonic modes $K \to (n\pi)+l\nu$ offer an ideal framework for precision measurements of fundamental SM couplings such as light−quark masses, the CKM angle V_{us} , the quark condensate and, more in general, for precision studies of the low−energy realization of QCD

⇒ The 2nd Daϕne Physics Handbook

Two examples: K_{l3} & K_{l4} decays

I. K_{l3} decays and the Cabibbo angle

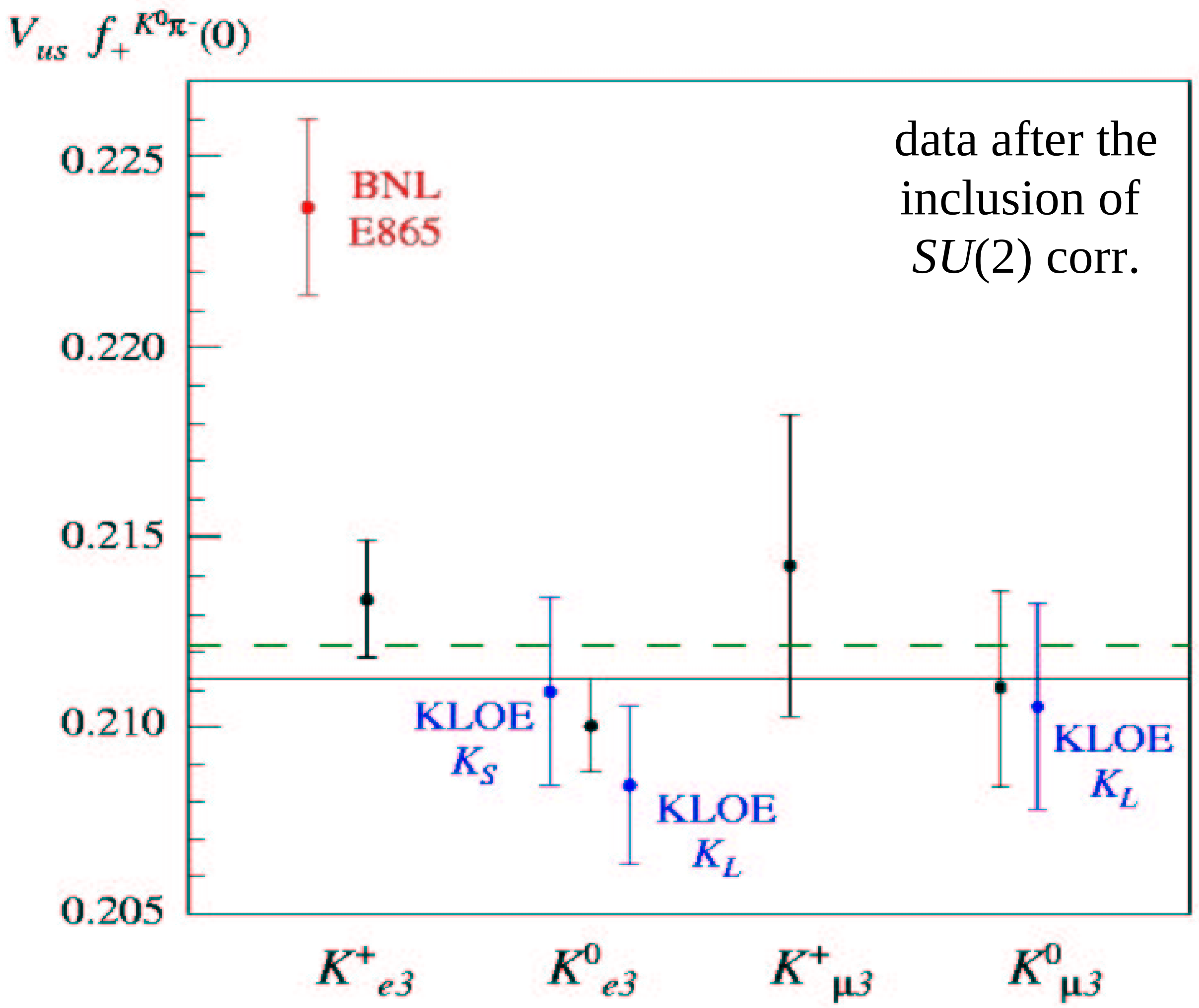
$$\Gamma = G_F^2 M_K^5 \times |V_{us}|^2 \times |f_+(0)|^2 \times I(df/dt)$$

vector form factor at zero momentum transfer [$t=(p'-p)^2=0$]

kinematical integral: mild sensitivity to df_+/dt (and f_-/f_+ for $l=\mu$) and e.m. corrections

CVC ⇒ $f_+(0) = 1$ in the $SU(3)$ limit $m_s = m_u = m_d$

The extraction of $|V_{us}|$: $(\Delta V_{us})_{today} = (\sim 1\%)_{exp} + (0.8)\%_{th.-f(0)}$



The present situation
is rather confused
[large SU(2) breaking=
wrong th. corrections,
or bad data?]...

...but in a short−time,
[with the help of KLOE
data on both modes],
we shoud be able
to clarify it.

↓

uncertainty dominated
by the th. error on *f(0)*?

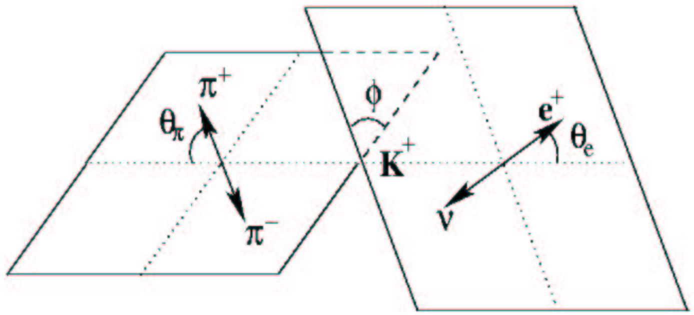
With a substantial increase of statistics (~10×) the error on *f* (0)
could be controlled by means of the quadratic slopes of $K_{\mu 3}$ modes

Bijens & Talavera, 03

II. K_{l4} and ππ phase shifts

$K^+ \to (\pi^+\pi^-) l^+ \nu$ form factors: $F_i(s) = f_i^o(s)\, e^{i\delta_0^0(s)} + \ldots$ ← strong ππ phases

possible to isolate the contribution of the δ's by looking at the *asymmetry* in the distribution of the angle between ππ and $l\nu$ planes



ππ phase shifts near thresholds [⇔ a_J^I scattering lengths] are among the most precise observables we can compute in CHPT, and also among the most interesting ones [a_0^0 strongly depends from the beahaviour of $\langle 0|\bar{q}q|0\rangle$ in the chiral limit]:

$$\delta_0^0(s) \Leftrightarrow a_0^0 = \begin{cases} 0.16 & O(p^2) \\ 0.20 \pm 0.01 & O(p^4) \\ 0.220 \pm 0.005 & O(p^6) \end{cases}$$

- 0.16 — $O(p^2)$ — Weinberg '79
- 0.20 ± 0.01 — $O(p^4)$ — Gasser & Leutwyler '83
- 0.220 ± 0.005 — $O(p^6)$ — Bijens, Colangelo, Ecker, Gasser & Leutw. '99; Ananthanarayan *et al.* '01

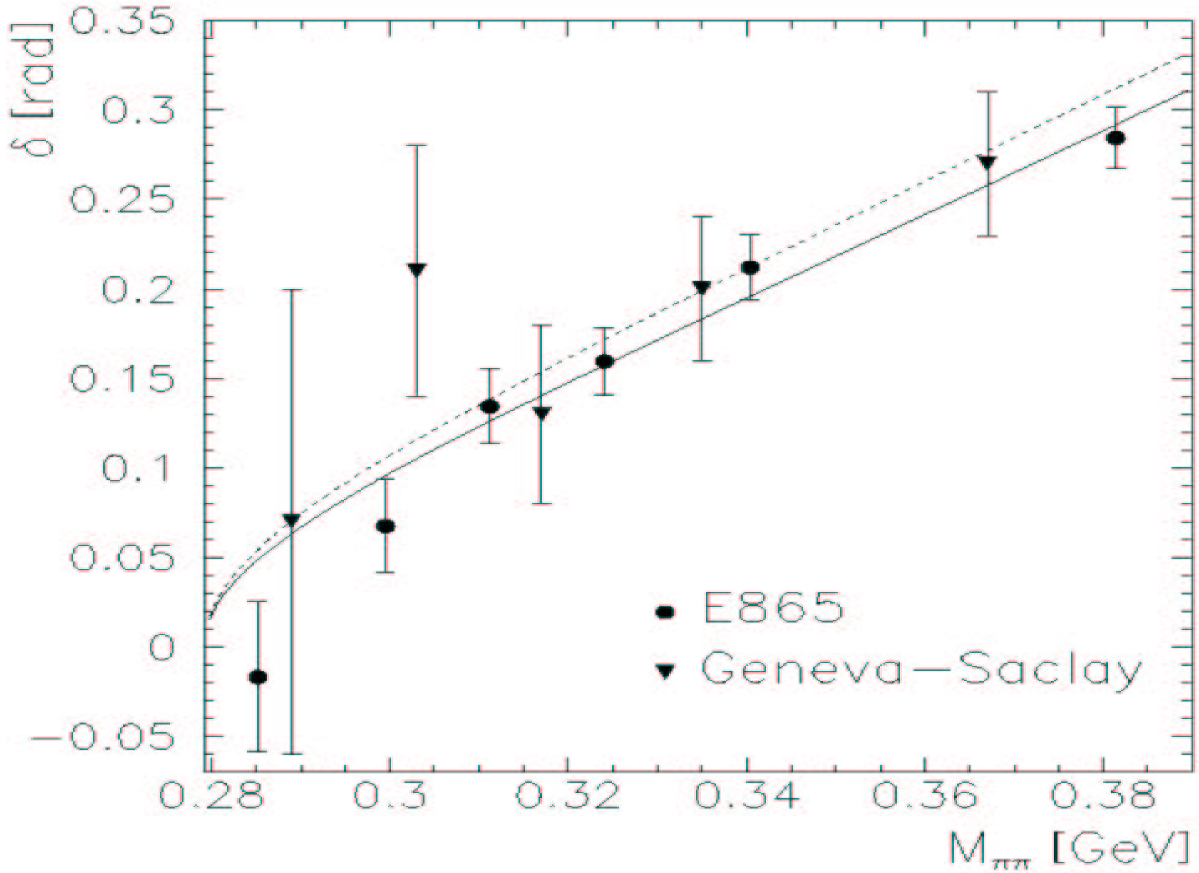
A recent measurement by BNL−E865 [hep−hp/0301040] as provided an important check of CHPT expectations:

$$a_0^0 = 0.216 \pm 0.013$$

BNL−E865 [+ th. contsr. on a_2]

$$a_0^0 = 0.220 \pm 0.005$$

CHPT [+ disp. relations]



but the precison of the theory could allow even more significant tests...

Conclusions

if it was not clear yet...

I'm strongly in favor of the high−luminosity option!

Highlights of the kaon−physics program @ Φ−factory vs. luminosity:

10^0 fb^{-1} [≈ 10^9 $K\bar{K}$]

≈ KLOE now

V_{us} from K_{l3} @ 10^{-3} (CKM);
rare K_S decays down to BR~10^{-8} (CHPT/CPT);
10^{-2} bounds on $K_S \to \pi l \nu$ charge asym. (CPT)
⋮

10^1 fb^{-1} [≈ 10^{10} $K\bar{K}$]

original KLOE program

Re(ε'/ε) @ 10^{-4} (direct CPV);
$K_{L,S}$ interf. ⇒ Im(ε'/ε) @10^{-2} (CPT);
ππ phases from K_{l4} @ % level (QCD vacuum)
⋮

10^2 fb^{-1} [≈ 10^{11} $K\bar{K}$]

CPT tests @ uprecedented level of precision via rare K_S & $K_{L,S}$ interferences;
search for exotic direct CPV in $K^{\pm}$ asym. and rare K_L decays
⋮

10^3 fb^{-1} [≈ 10^{12} $K\bar{K}$]

frontier of flavor physics

sensitivity to $K_L \to \pi^0 \nu\nu$ (& $K_L \to \pi^0 ee$) at the SM level:

region of high discovery potential for non−standard sources of CPV via new tests of the CKM mech. in the kaon system

⇒very interesting also in a long−term perspective⇐

10^4 fb^{-1}

⋮ ⋮

Conclusions

I’m strongly in favor of the high−luminosity option!

and if the option is realistic

I’m ready to defend it...