Cosners forum on Heavy Flavour Physics

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Recent results & future perspectives in Kaon Physics

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FlaviA net

Introduction

Despite K mesons have been discovered more than 50 years ago, Kaon physics is still a very active and interesting field (as demonstrated by the interesting talks and lively discussion we recently had at Kaon 2007...)

For reasons of time, in this talk I will briefly overview status & prospects only in two sectors of this interesting field:

- K_{l3} & K_{l2} decays [V_{us}, lepton universality]
  present & near future from the exp. point of view

- Rare FCNC decays [NP searches via $K \to \pi\nu\nu$]
  the mid/long-term perspective

Part I

Recent progress in K_{l3} & K_{l2} decays

Motivation

What's behind precise measurements of K_{l2} & K_{l3} decays?

$$\mathscr{L}_{\rm eff} = \underline{\mathscr{L}_{\rm gauge}(A_i, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi_i, A_i, \psi_i)}$$

$$\downarrow$$

$$\mathscr{L}_{\rm c.c.} = (g/\sqrt{2})\, W_\mu^+ \; \bar{u}_L^{\,i}\, (V_{\rm CKM})_{ij}\, \gamma^\mu\, d_L^{\,j} + {\rm h.c.}$$

The universality of g & the unitarity of $V_{\rm CKM}$ holds also beyond the SM if the gauge symmetry is respected [Appelquist-Carrazone]

• Motivation

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$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm gauge}(A_i, \psi_i) + \mathcal{L}_{\rm Higgs}(\phi_i, A_i, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\,d}(\phi_i, A_i, \psi_i)$$

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The universality of g & the unitarity of $V_{\rm CKM}$ holds also beyond the SM if the gauge symmetry is respected [Appelquist-Carrazone]

However, thanks to the s.s.b. of the SU(2)×U(1) group, what we measure at low energy is *not necessarily* only the gauge coupling of the W boson:

$$\mathcal{L}_{\rm c.c.\text{-}eff.} = G_{\rm eff}\ (u^i\, \Gamma_A\, d^j)\, (l^k\, \Gamma_B\, \nu^l) + \text{h.c.}$$

eff. dimensional coupling
potentially sensitive to NP

$$G_{\rm eff} \sim \frac{g^2 V_{ij}\, \delta^{kl}}{M_W^{\,2}} + \frac{c_n}{\Lambda^2}$$

The comparison of different effective Fermi couplings (G_{eff}) is a way to probe/constrain NP effects:

$\mu \to e$	$G_\mu = 1.166371(6)\times 10^{-5}\ \text{GeV}^{-2}$
$\tau \to \mu$	$G_\tau = 1.1678(26)\times 10^{-5}\ \text{GeV}^{-2}$
$\alpha + M_W + s_W$ [e.w. precision tests]	$G_{e.w.} = 1.1655(12)\times 10^{-5}\ \text{GeV}^{-2}$
$u \to d,s,b$ [CKM unitarity]	$G_{CKM} = 1.1658(04)\times 10^{-5}\ \text{GeV}^{-2}$

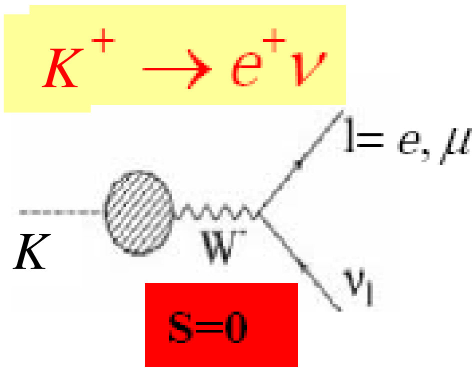
$$\sim G_\mu \left(|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \right)^{1/2}$$

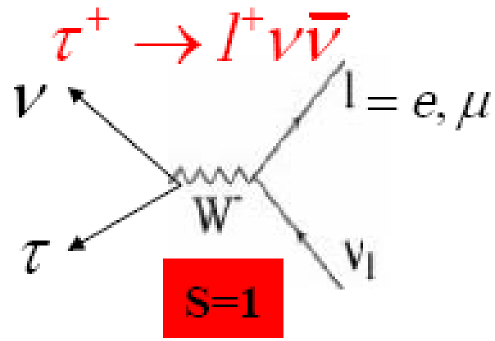
error assuming $\sigma(V_{us}) = 0.5\%$

Vus @ below 1% compettive with e.w. precision tests !

Marciano @ Kaon '07

The most popular/exciting NP scenario which could affect c.c. semileptonic decays is the possibility of LFV effects modifying the μ/e ratio in K_{l2}

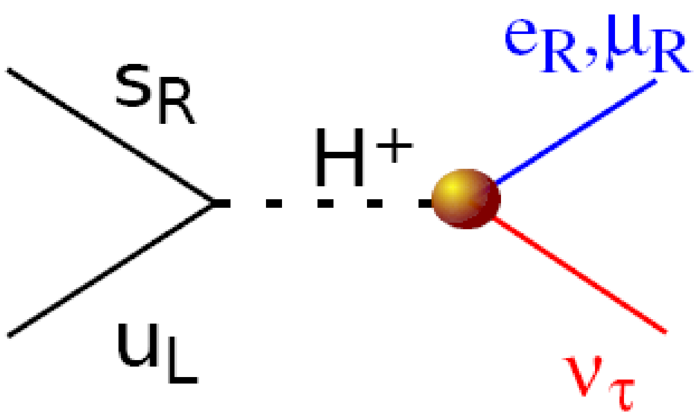




probe of the
s.s.b. sector of the SM

The most popular/exciting NP scenario which could affect c.c. semileptonic decays is the possibility of LFV effects modifying the μ/e ratio in K_{l2}

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)} \ , \quad i = e, \mu, \tau$$



$$eH^\pm\nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$

$$\Delta_R^{31} \sim \frac{\alpha_2}{4\pi} \delta_{RR}^{31}$$

$$\Delta_R^{31} \sim 5 \cdot 10^{-4} \quad t_\beta = 40 \quad M_{H^\pm} = 500\text{GeV}$$

$$\Downarrow$$

$$\Delta r_{K\ SUSY}^{e-\mu} \simeq \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right) |\Delta_R^{31}|^2 \tan^6\beta \approx 10^{-2}$$

Masiero Paradisi Petronzio '06

key ingredeints for visible effects in SUSY:

- Large $\tan\beta$, $M_H < 1\,TeV$
- Large LFV slepton minxings, $\delta_{3j} \sim \mathcal{O}(1)$, ($m_{SUSY} \geq 1\text{TeV}$)

• The determination of Vus

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 I_{Kl}(\lambda) (1+2\Delta_K^{SU(2)}+2\Delta_{Kl}^{EM})$$

with $K = K^+, K^0$; $l = e, \mu$ and C_K^2 = 1/2 for K^+, 1 for K^0

Inputs from theory:

- S_{EW} — Universal short distance EW correction (1.0232) → SU(2)xU(1) pert. theory — Marciano & Sirlin
- $f_+^{K^0\pi}(0)$ — Hadronic matrix element at zero momentum transfer (t=0) → Lattice (+CHPT) — Most delicate point !
- $\Delta_K^{SU(2)}$ — Form factor correction for strong SU(2) breaking → CHPT
- Δ_{Kl}^{EM} — Long distance EM effects → CHPT

CHPT: Knecht et al. '00; Cirigliano et al. '02-'04; Andre '04; Gatti '05; Moussalam et al. '06; Neufeld prelim. '07

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Inputs from experiment:

- $\Gamma(K_{l3(\gamma)})$ — **Branching ratios** with well determined treatment of radiative decays; **lifetimes**
- $I_{Kl}(\lambda)$ — Phase space integral: λs parameterize form factor dependence on t:
  - K_{e3} : *only* λ_+ (or λ_+' λ_+'')
  - $K_{\mu3}$: *need* λ_+ *and* λ_0

Several new results in the last 2 years

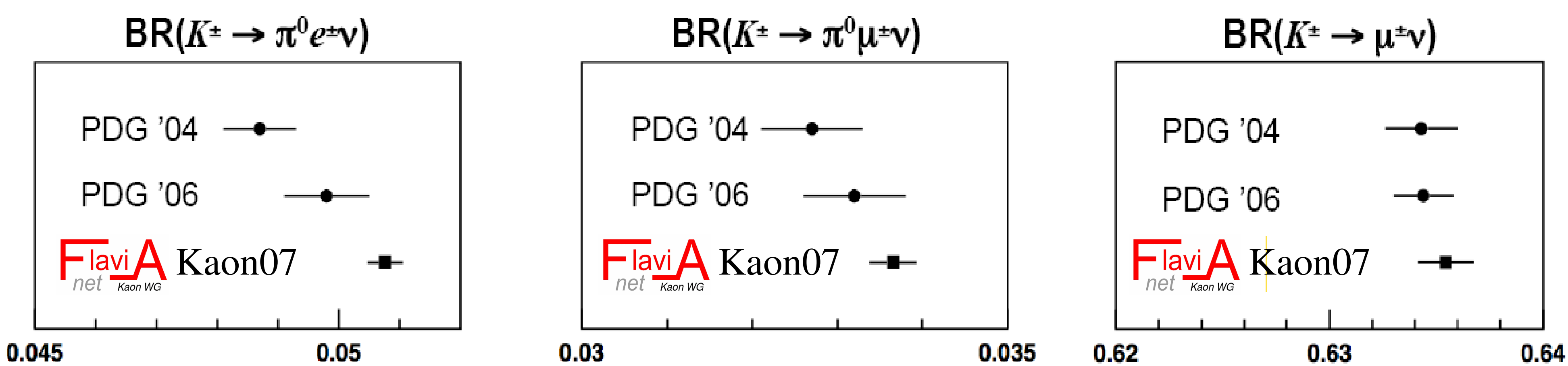
KTeV KLOE NA48 ISTRA+ E865

Several experimental inputs contribute to the determination of $V_{us} f_+(0)$

[semileptonic BR's + lifetime's + all leading BR's to check BR's unitarity
+ various sets of slopes]

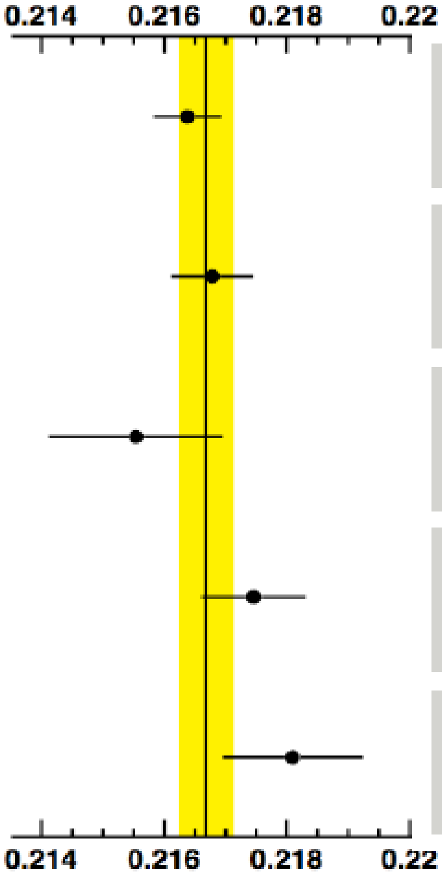
These measurements have non-trivial correlation which is crucial to take into account $\Rightarrow$ *Flavianet Kaon WG* [analog of HFAG for B physics]

e.g.: Evolution of $K^\pm$ BRs



FlaviAnet Kaon WG

$|V_{us}| f_+(0)$ from K_{l3} data



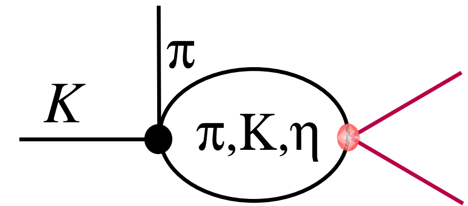
		% err	Approx. contrib. to % err from: BR	τ	Δ	Int
$K_L e3$	0.21638(55)	0.25	0.09	**0.19**	0.10	0.10
$K_L \mu 3$	0.21678(67)	0.31	0.10	**0.18**	0.15	0.15
$K_S e3$	0.21554(142)	0.66	**0.65**	0.03	0.10	0.10
$K^\pm e3$	0.21746(85)	0.39	**0.29**	0.09	**0.24**	0.09
$K^\pm \mu 3$	0.21810(114)	0.52	**0.42**	0.09	**0.26**	0.15

Average: $|V_{us}| f_+(0)$ = 0.21668(45) χ^2/ndf = 2.74/4 (60%)

$\Delta^{SU(2)}_{exp}$ = 2.86(38)% → success of CHPT calculations [$\Delta^{SU(2)}_{th}$ = 2.31(22)%]

What do we know about $[f_+(0) - 1]$?

- no linear corrections in $(m_s - m_u)$ [Ademollo-Gatto, '64]
- Within CHPT: $f_+(0) = 1 + f_4 + f_6 + \ldots$



$O(p^4)$: finite non-polynomial term induced by meson loops
$[\sim m_P \log m_P \Rightarrow \sim (m_s - m_u)^2 / m_s]$
small compared to naïve expectations: $f_4 = -2.3\ \%$

Leutwyler & Roos '84

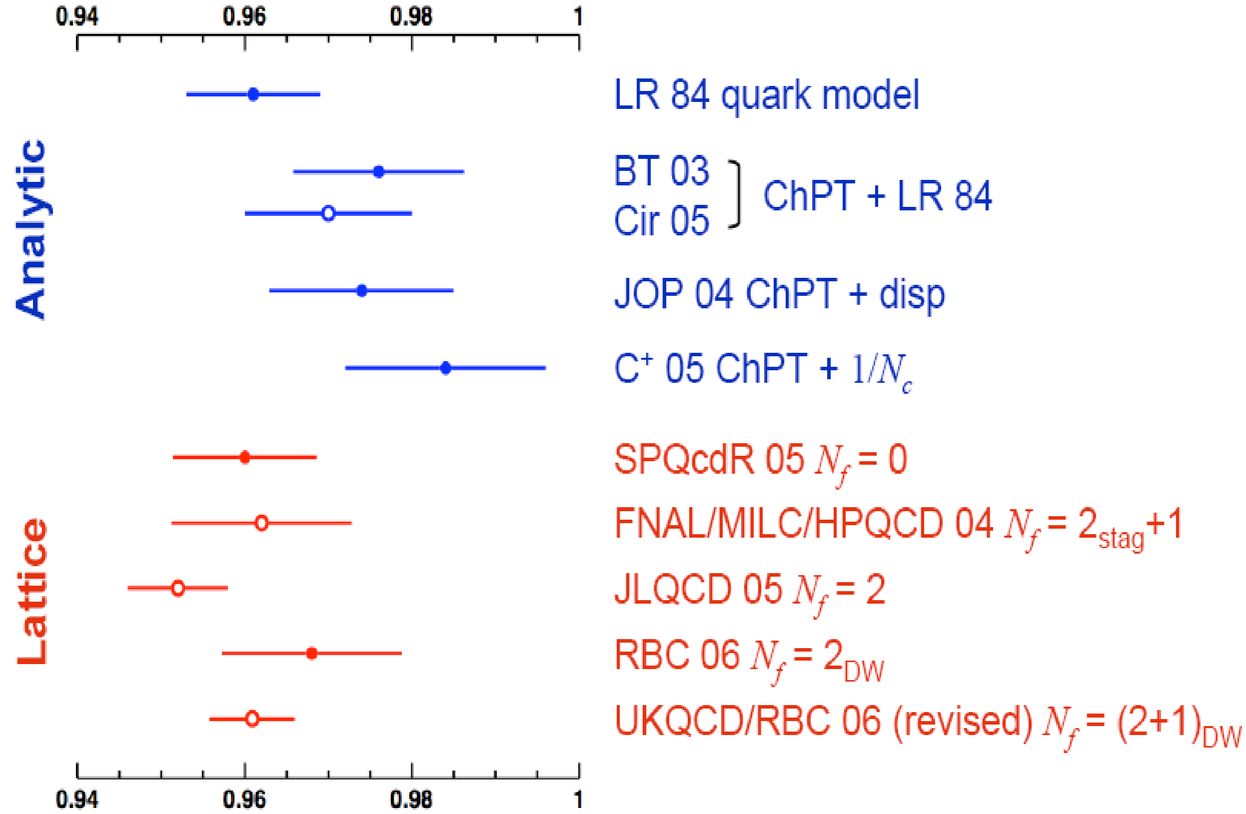
$O(p^6)$: appearance of $(m_s - m_u)^2 / \Lambda^4_\chi$ (unknown) local terms → irreducible error for analytic approaches [Bijnens Talavera '03, Cirigliano et al. '05]

↓

Possible to reach errors < 1% with Lattice QCD measuring directly $[f_+(0) - 1]$ or $[f_+(0) - 1 - f_4]$

Becirevic et al. '05

$f_+(0)$



Kaneko, Juttner
@ Kaon '07

unquenched calculations:

follow strategy proposed in the quenched calculation

	N_f	action	a[fm]	L[fm]	M_{PS}[MeV]
JLQCD (2005)	2	clover	0.09	1.8	$\gtrsim 550$
RBC (2006)	2	domain-wall	0.12	1.9	$\gtrsim 490$
MILC (2005)	3	KS (d=clover)	0.12	2.5	$\gtrsim 500$
RBC+UKQCD (2007)	3	domain-wall	0.12	1.9, 2.9	$\gtrsim 300$

Lattice inputs play an even more important role in the extraction of V_{us} from K_{l2} :

$$\frac{\Gamma(K_{\mu 2+n\gamma})}{\Gamma(\pi_{\mu 2+n\gamma})} = \left|\frac{V_{us}}{V_{ud}}\right|^2 \times \left|\frac{f_K}{f_\pi}\right|^2 \times \frac{M_K^2 (1-m_\mu^2/M_K^2)}{M_\pi^2 (1-m_\mu^2/M_\pi^2)} \times [\, 1 + \delta_{e.m.} \,]$$

- Non-trivial to reach 1% accuracy [no Ademollo-Gatto protection] → $\frac{\sigma[\text{SU(3)-brk}]}{[\text{SU(3)-brk}]} \sim 5\ \%$
- No competition from non-Lattice approaches

$f_K/f_\pi = 1.208(2)(^{+7}{}_{-14})$

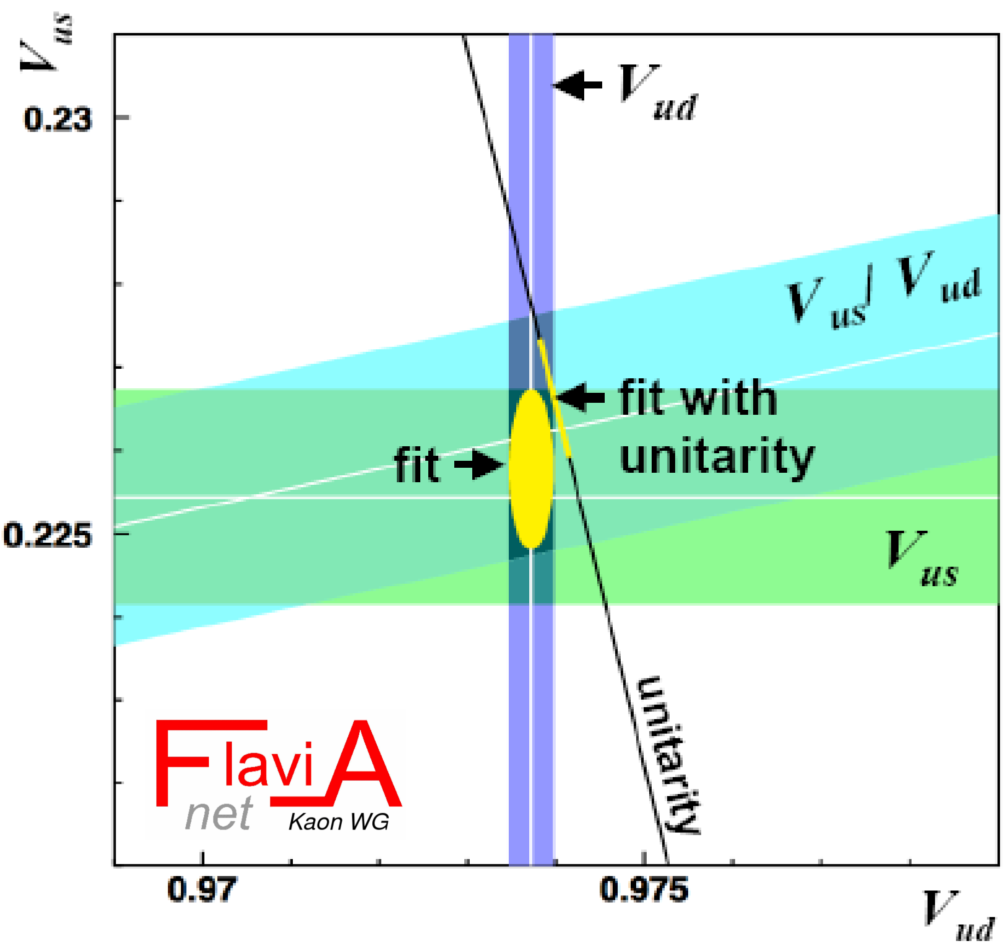
MILC '05

$f_K/f_\pi = 1.189(7)$

UKQCD+HPQCD '07

→ $N_f = (2+1)_{stag}$ [MILC]

$f_+(0)$ from UKQCD/RBC '06
$|V_{us}| = 0.2254(13)$ from $Kl3$



Fit results, no constraint:

$V_{ud} = 0.97372(26)$
$V_{us} = 0.2258(10)$
$\chi^2/\text{ndf} = 0.142/1\ (70\%)$

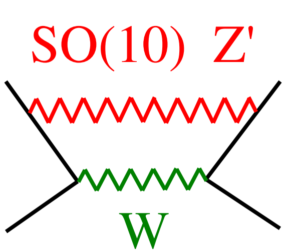
Fit results, unitarity constraint:

$V_{ud} = 0.97398(17)$
$V_{us} = 0.2266(7)$
$\chi^2/\text{ndf} = 1.92/2\ (38\%)$

Agreement with unitarity 0.9σ

This is a highly non-trivial constraint for NP models...

E.g.:



→ $M_{Z'} > 1.2$ TeV

• The lepton-universality tests in K_{l2}

Two new preliminary results on the rare K_{e2} mode:

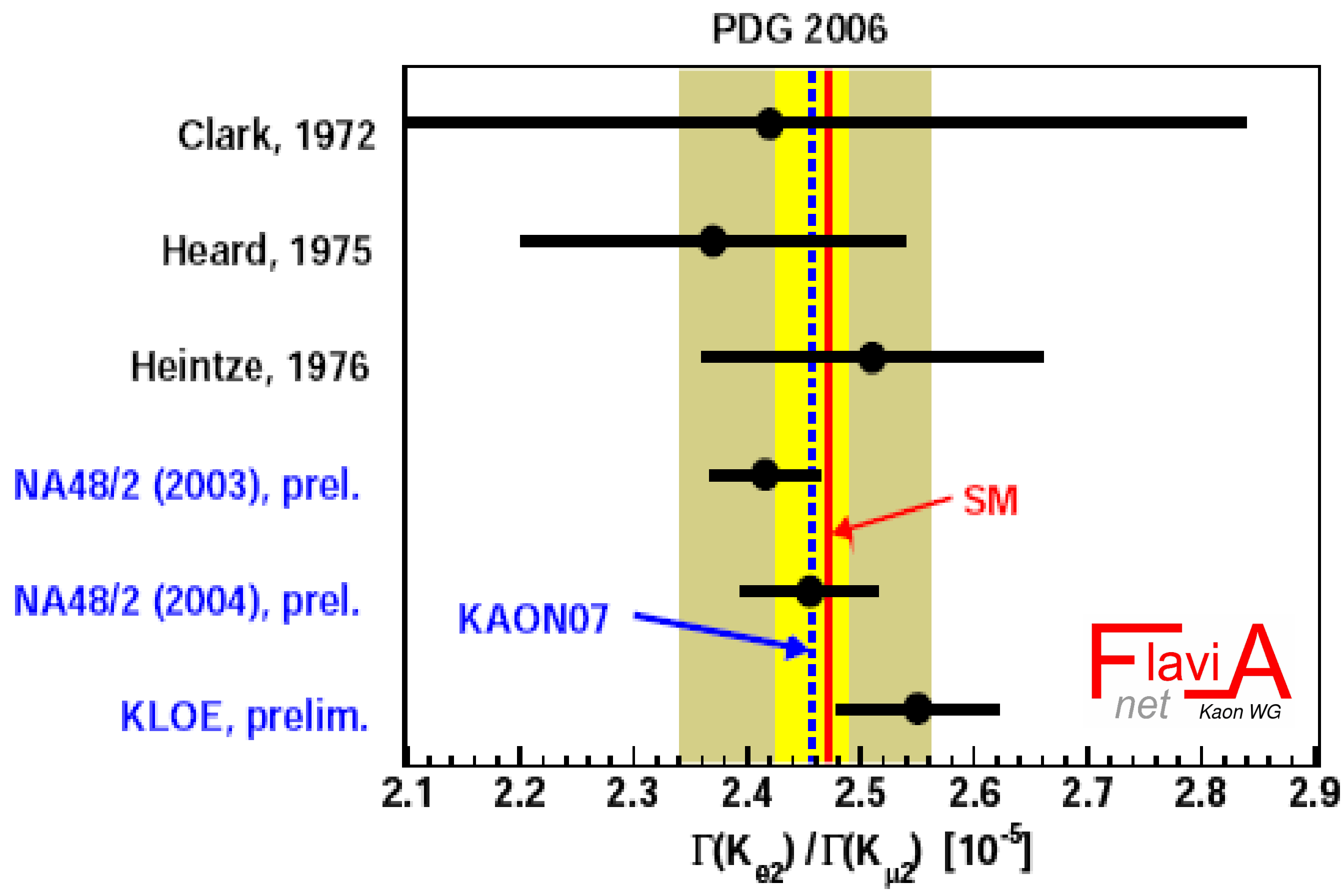
- **NA48/2 (2004 data), presented at KAON07:**
  - About 4000 signal events from special minimum bias trigger.
  - Small systematics, except background.
    (measured from data → large statistical uncertainty in syst. error.)
  - Completely uncorrelated with 2003 measurement.

$$\Gamma(K_{e2})/\Gamma(K_{\mu 2}) = (2.455 \pm 0.045 \pm 0.041) \times 10^{-5}$$

- **KLOE, presented at KAON07:**
  - About 8000 signal events from 1.7 fb^{-1}.
  - Statistics dominated by MC, conservative systematics estimation.

$$\Gamma(K_{e2})/\Gamma(K_{\mu 2}) = (2.55 \pm 0.05 \pm 0.05) \times 10^{-5}$$

It is a difficult measurement (dangerous backgrounds from $K_{\mu 2}$ & $K_{e2\gamma}$) which already provides interesting constraints on (realistic) NP models:



It is a difficult measurement (dangerous backgrounds from $K_{\mu 2}$ & $K_{e2\gamma}$) which already provides interesting constraints on (realistic) NP models:

Limit on LFV in $H^\pm$ coupling:

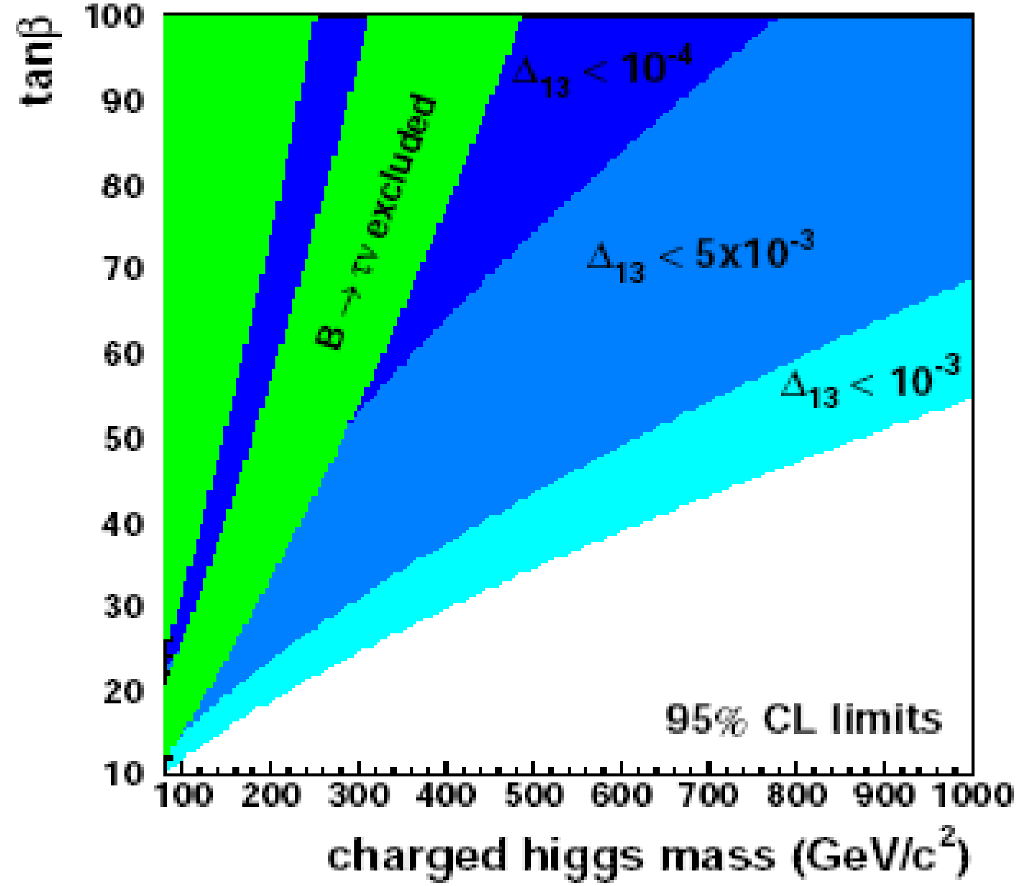
(Masiero, Paradisi, Petronzio, PRD 74, 2006)

LFV Yukawa coupling:

$$l H^\pm \nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_{13} \tan^2 \beta$$

$$\Delta_{3j} \sim \frac{\alpha_2}{4\pi} \delta_{3j}$$

slepton flavour-mixing angle



More stringent than present constraints from B→τν if $|\delta_{3j}| > 0.1$

The near-future prospects are very promising:

KLOE

- Has $\sim 20\%$ more data on tape.
- Another ~ 3000 events with other reconstruction method.
- Improve MC statistics & systematics

$\Longrightarrow$ Should arrive at $\sigma_{\text{rel}}(\mathbf{R_K}) \sim \pm 1\%$.

P-326: (also known as NA48/3)

- Similar setup as for NA48/2 (2004) prel. measurement, use of most parts of existing NA48 apparatus.
- Plan: 4 months (June-October 2007) run period
  $\Longrightarrow$ Collect $\sim 150\,000\ K_{e2}$ decays.

$\Longrightarrow$ Goal to reach $\sigma_{\text{rel}}(\mathbf{R_K}) \sim \pm \mathbf{0.3}\%$.

Wanke @ Kaon '07

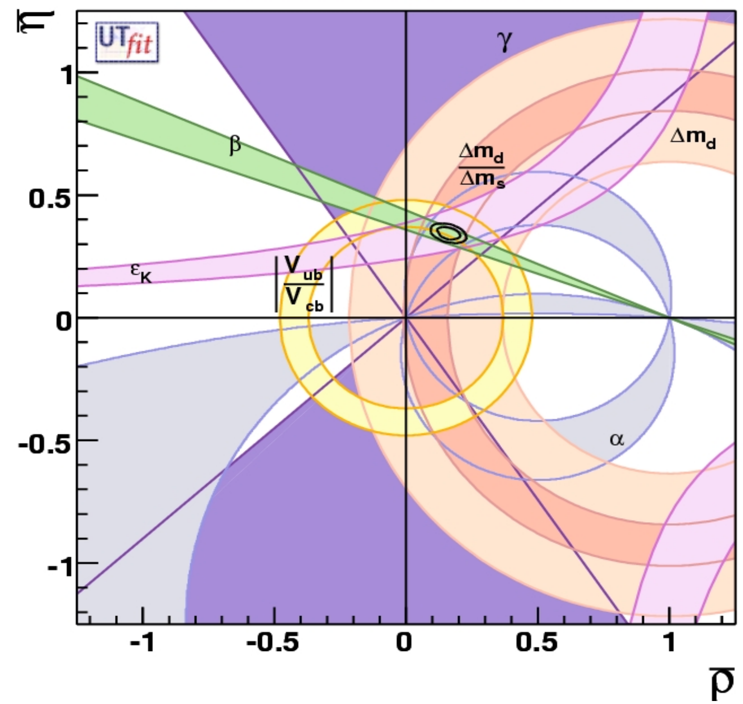
Part II

Rare FCNC decays

Motivation

Why are we (still) interested in rare K decays?

- Neither to measure again CKM matrix elements [already well determined from other processes]



- Nor to find direct evidences of new particles [very likely that there are new particles in additions to the SM ones, but they are naturally around or a above the TeV scale]

The information coming form rare K decays is a key element to understand the *flavour structure* of *physics beyond the SM*

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_i, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi_i, A_i, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\,d}(\phi_i, A_i, \psi_i)$$

While we know quite well the flavour strucutre of the SM (or the low-energy limit of the theory), we have only started to investigate the flavour structure of the new degrees of freedom (which realistically will show up around the TeV scale).

This strucutre is highly non generic (otherwise we would have already seen NP effects), but the mechanism which protect flavour symmetry breaking beyond the SM is still unknown

MFV

approximate MFV

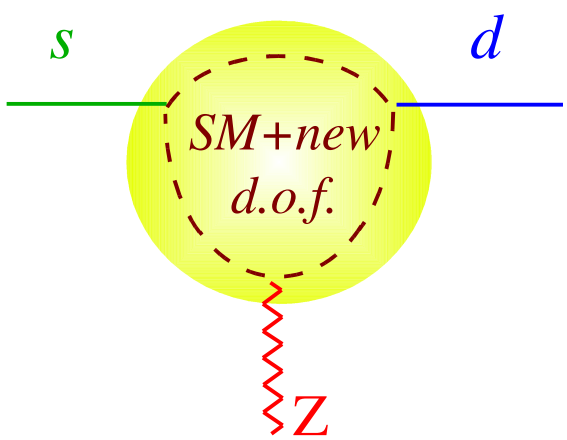
non-MFV only in specific flavour structures [e.g. large b→s coupl.]

non-MFV only in specific e.w. structures [e.g. large scalar currents]

effective heavy Λ for flavour physics [e.g. split SUSY]

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_i, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi_i, A_i, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\,d}(\phi_i, A_i, \psi_i)$$

- Rare FCNC decays [$q_i \to q_j + \gamma, l^+l^-, \nu\nu$] are ideal probes of possible new terms:



- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Predicted with high precision within the SM at the short-distance level

$$A(s \to d)_{\rm short} \sim c_{\rm SM} \frac{y_t^2\, V_{ts}^* V_{td}}{16\,\pi^2 M_W^2} + c_{\rm new} \frac{\Delta_{sd}}{\Lambda^2}$$

Enhanced sensitivity to the *flavour structure* of *physics beyond the SM*

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}}(A_i, \psi_i) + \mathcal{L}_{\text{Higgs}}(\phi_i, A_i, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\,d}(\phi_i, A_i, \psi_i)$$

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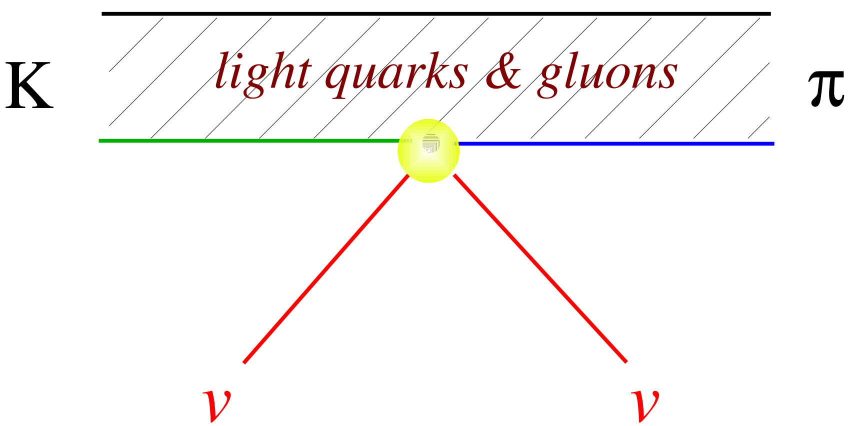


- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Predicted with high precision within the SM at the short-distance level

$$A(K \to \pi\nu\nu) = f\left(c_{SM} \frac{y_t^2 V_{ts}^* V_{td}}{16\pi^2 M_W^2} + c_{new} \frac{\Delta_{sd}}{\Lambda^2} \; ; \; \delta_{long} \right)$$

Sensitivity to new-physics controlled by:

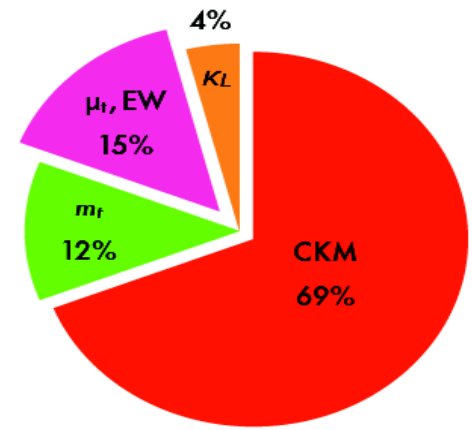
- How precisely we can compute the hadronic amplitude
- How much the amplitude is determined by dynamics around the electroweak scale (short distances)

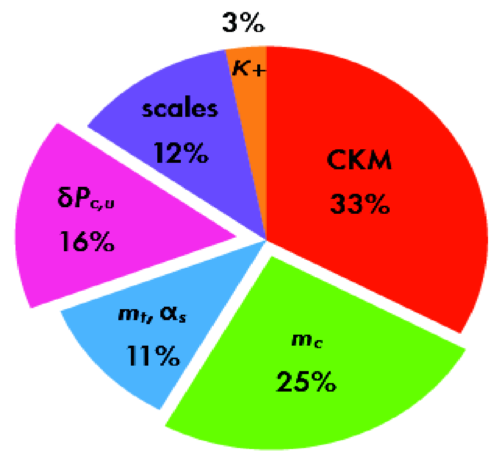
The two $K \to \pi\nu\nu$ modes represent a unique opportunity which has almost no analog in B physics:

	short-distance (e.w.) contrib. to the total rate $(\Gamma - \Gamma_{\text{no s.d.}}) / \Gamma$	
$K_L \to \pi^0 \nu\nu$	> 99%	$BR_{SM} = (2.54 \pm 0.35) 10^{-11}$
$K^+ \to \pi^+ \nu\nu$	88%	$BR_{SM} = (7.90 \pm 0.67) 10^{-11}$
$K_L \to \pi^0 e^+ e^-$	38%	
$K_L \to \pi^0 \mu^+ \mu^-$	28%	

Anatomy of the present SM error:

Haisch @ Kaon'07





Intense recent th. activity:

Buras et al. '05 [NNLL dim.6]
G.I., Mescia, Smith '05 [dim.8]
Mescia, Smith, '07 [isospin]

Rare K decays beyond SM

Two basic scenarios:

Minimal Flavour Violation

flavour symmetry broken only by the (SM) Yukawa couplings

New sources of Flavour Symmetry breaking around the TeV scale

Rare K decays beyond SM

Two basic scenarios:

Minimal Flavour Violation

flavour symmetry broken only by the (SM) Yukawa couplings

New sources of Flavour Symmetry breaking around the TeV scale

⬇

- Small deviations (10-20%) from the SM
- Stringent correlations among the two $K \to \pi\nu\nu$ modes and a few rare B decays [$B \to K\nu\nu$, $B_{s,d} \to l^+l^-$]

$$\Gamma(K^+ \to \pi^+ \nu\nu) = |(c_{SM} + c_{NP}) V_{ts}^* V_{td} + \delta_{long}|^2$$

$$\Gamma(K_L \to \pi^0 \nu\nu) = \mathrm{Im}[(c_{SM} + c_{NP}) V_{ts}^* V_{td} + \delta_{long}]^2 = (c_{SM} + c_{NP})^2 \, \mathrm{Im}[V_{ts}^* V_{td}]^2$$

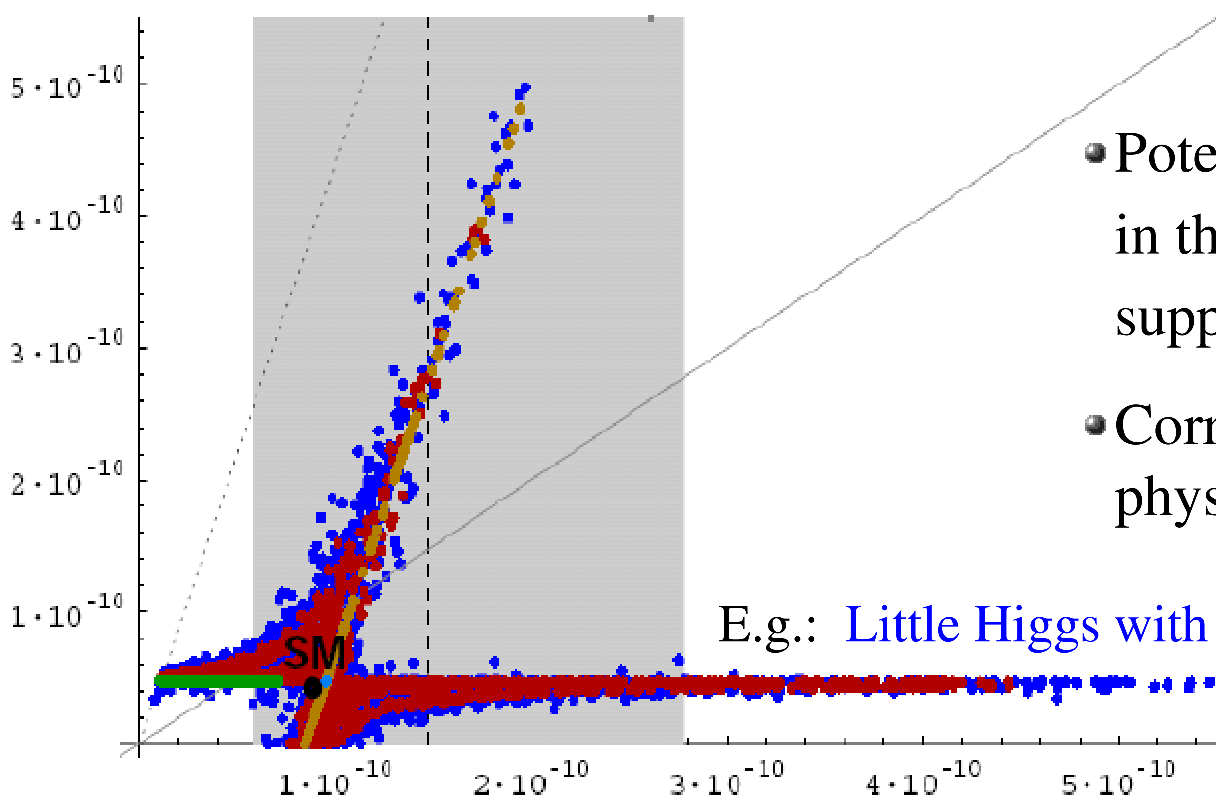
Rare K decays beyond SM

Two basic scenarios:

Minimal Flavour Violation

New sources of Flavour Symmetry breaking around the TeV scale

$B(K_L \to \pi^0 \nu\nu)$



$B(K^+ \to \pi^+ \nu\nu)$

E.g.: Little Higgs with T parity

Buras et al. '06

- Potentially large effects, especially in the three CPV K_L decays (no λ^5 suppression)
- Correlations with observables in B physics not obvious

Rare K decays beyond SM

Two basic scenarios:

Minimal Flavour Violation

flavour symmetry broken only by the (SM) Yukawa couplings

↓

- Small deviations (10-20%) from SM
- Stringent correlations among the two $K \to \pi\nu\nu$ modes and a few rare B decays [$B \to K\nu\nu$, $B_{s,d} \to l^+l^-$]

A precise exp. info on one of the two $K \to \pi\,\nu\nu$ modes is a key ingredient to verify or disproof the MFV hypothesis

New sources of Flavour Symmetry breaking around the TeV scale

↓

- Potentially large effects, especially in the three CPV K_L decays (no λ^5 suppression)
- Correlations with observables in B physics not obvious

In presence of sizable non-MFV couplings mandatory to explore also the $K_L \to \pi\, ll$ modes

Rare K decays beyond SM

A specific (popular) example: $K \to \pi\nu\nu$ in the MSSM.

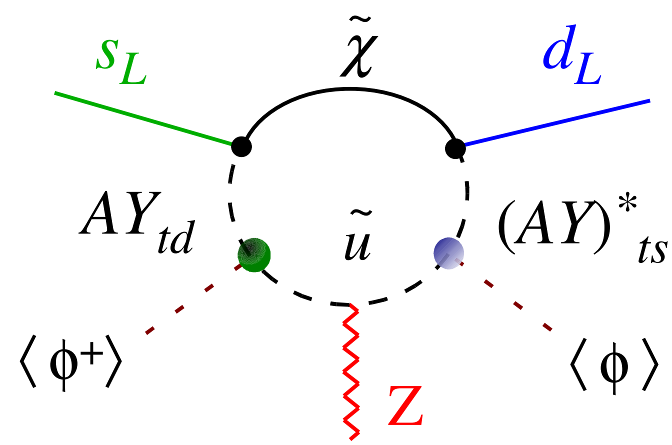
Main features:

- Gluino-type amplitudes essentially negligible ⇒ reduced sensitivity to LL, RR and LR-down type mixings [contrary to ε_K, $B \to X_s\gamma$, ΔM_{Bd}]
- Appreciable deviations from SM induced only by chargino -- up-squark diagrams

⬇

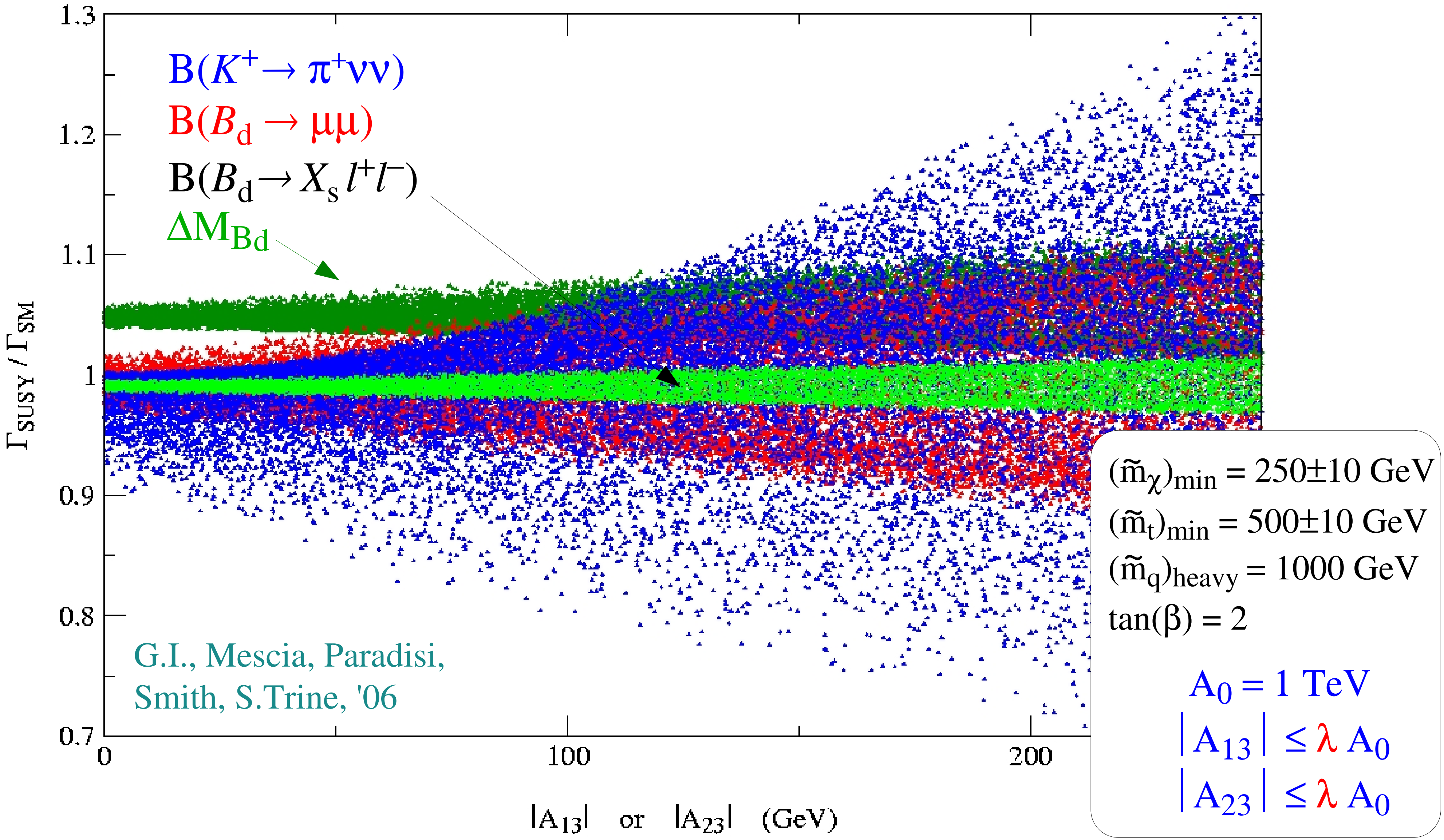
$K \to \pi\nu\nu$ decays are the *best probe* of the flavour structure of the up-type trilinear terms *which are still largely unknown:*

$$\mathscr{L}_{soft} \subset (A^U Y^U)_{ij}\, \tilde{Q}_L{}^i\, \tilde{U}_R{}^j\, \phi$$

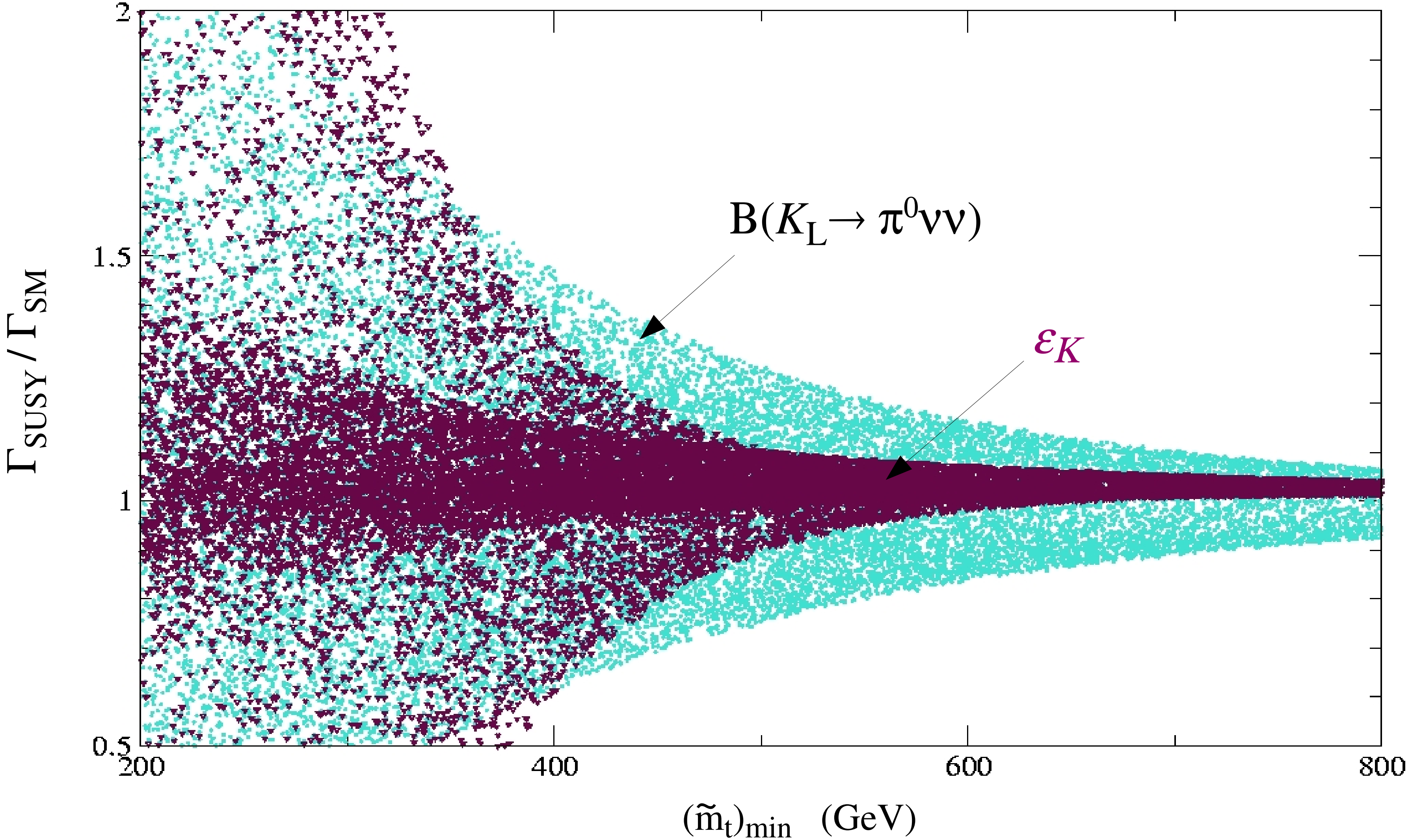


+ *box*

- Non-standard effects induced by chargino-squarks amplitudes largely dominant in $K \to \pi\nu\nu$ with respect to similar effects in B physics
- The A terms are still largely unconstrained



- At fixed magnitude of the A terms, there is a larger room for deviations from the SM in the CPV observables ⇒ great interest of $K_L \to \pi^0 \nu\nu$
- Slower decoupling of penguins ($K \to \pi\nu\nu$) with respect to boxes ($\Delta F=2$)



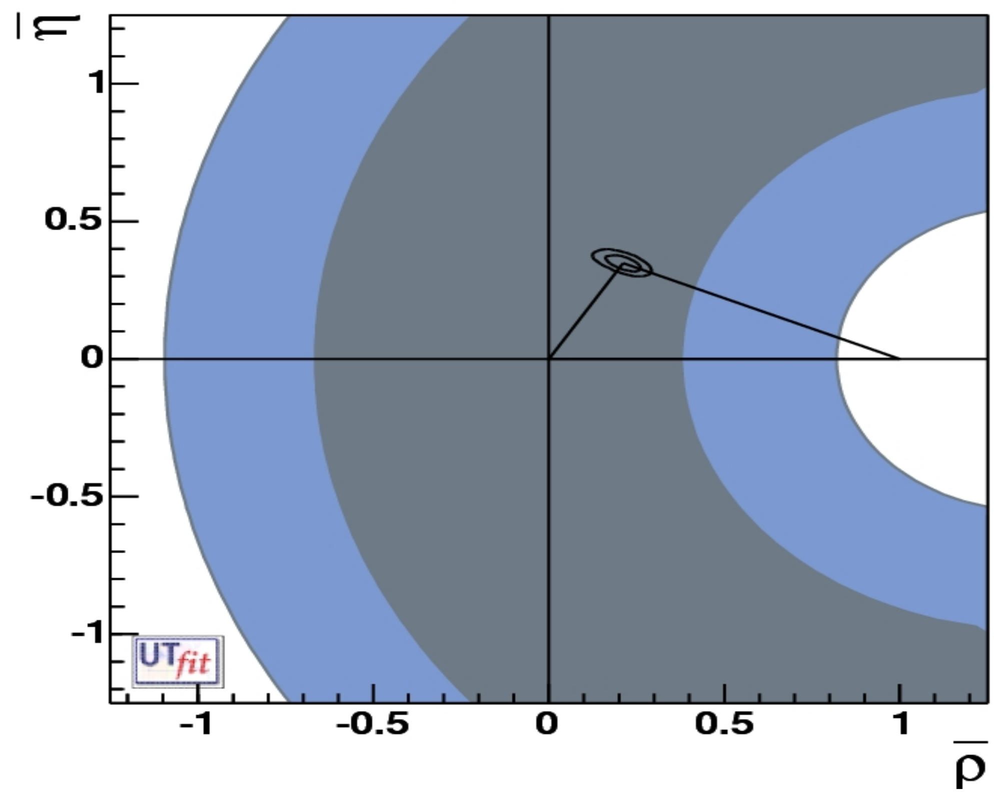
Experimental prospects

Unfortunately the present experimental knowledge of these decay modes is still very limited:

$$\mathrm{BR}(K^+ \to \pi^+ \nu\nu)^{\mathrm{exp}} = (1.47\,^{+1.30}_{-0.89}) \times 10^{10}$$

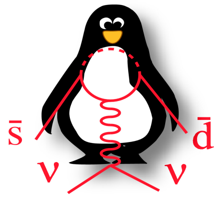
3 events
[BNL E787/E949]

It's shame for the flavour physics community that essentially no progress on this measurement has occurred since 2002...

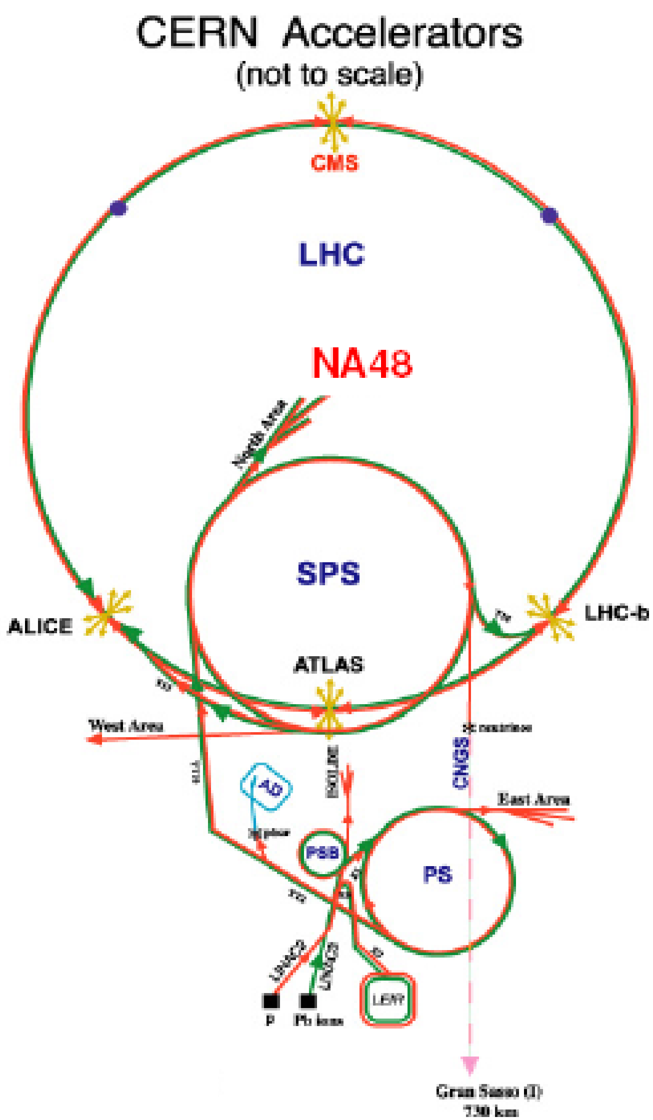


Hopefully, the situation should substantially improve with the CERN proposal on $K^+ \to \pi^+\nu\nu$ ...

P326



- P-326 experiment: Measurement of the $B(K^+ \to \pi^+\nu\nu)$ with a ~10% accuracy (+ other physics opportunities)
- General design: Mostly defined. Overall simulation and performances under review.
- R&D program: Well advanced: construction of detector prototypes and test in progress (in some cases completed). Important results by the end of 2007.
- We propose a new experiment able to reach a ~10^{-12} sensitivity per event at an existing machine and employing the infrastructures of an existing experiment. [CERN-SPSC-P-326, 11/ 06/ 2005]



Ruggiero, Ceccucci @ Kaon'07

Hopefully, the situation should substantially improve with the CERN proposal on $K^+ \to \pi^+\nu\nu$ ...and the JPARC proposal on $K_L \to \pi^0\nu\nu$

- J-PARC E14 experiment aims at First Observation of $K_L \to \pi^0\nu\nu$ (upgrade of KEK-E391a detector)
- E14 submitted a proposal to PAC (program advisory committee).
  - 1st-stage scientific approval.
  - 2nd stage process is in progress

Schedule

2007:
- Engineering design of beam-line completed.
- KTeV CsI's will be started to move to J-PARC.
- Many R&D's are in progress.

2008: beam-line construction will be scheduled.
- Dec, 2008: First commissioning of slow beam extract. measuring the beam-line performances

2008-2009
- Assembling of Detector system.

2010: First Engineering Run or/and Physics Run.

Conclusions

I briefly illustrated some relevant aspects of kaon physics,

but the field is much more rich

[ππ phase shifts & QCD vacuum, search for T and/or CPT violations, tests of Lattice & CHPT...]

↓

future kaon programs centered on rare K decays offers one of the most interesting future perspective in flavour physics