SUSY effects in Kaon physics: Lepton Universality tests and rare decays

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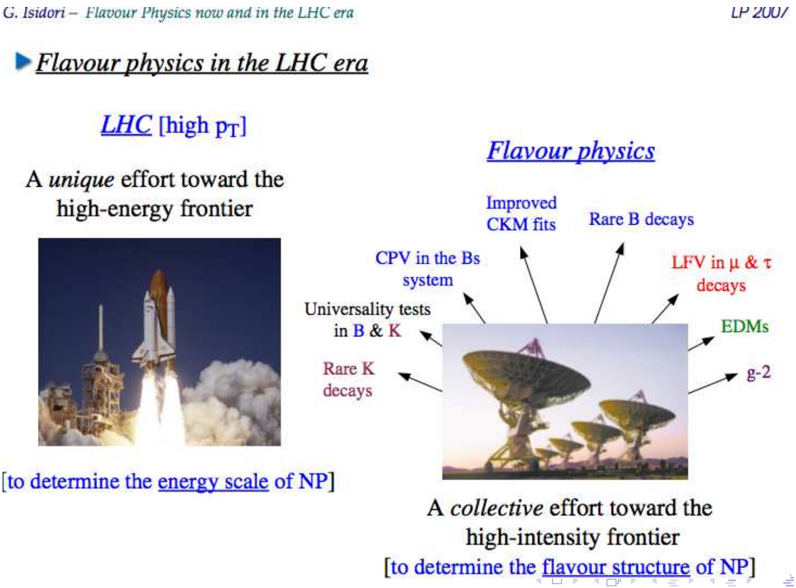
General Considerations

Flavor Physics in the LHC era

- **High energy experiments** are the key tool to determine the **energy scale Λ** by direct production of NP particles.
- **Low energy experiments** are a fundamental ingredient to determine the **symmetry properties** of the new d.o.f. via their virtual effects in precision observables.

General Considerations



G. Isidori – *Flavour Physics now and in the LHC era* LP 2007

Flavour physics in the LHC era

LHC [high p_T]

A *unique* effort toward the high-energy frontier

[to determine the energy scale of NP]

Flavour physics

Improved CKM fits

Rare B decays

CPV in the Bs system

LFV in μ & τ decays

Universality tests in B & K

EDMs

Rare K decays

g-2

A *collective* effort toward the high-intensity frontier

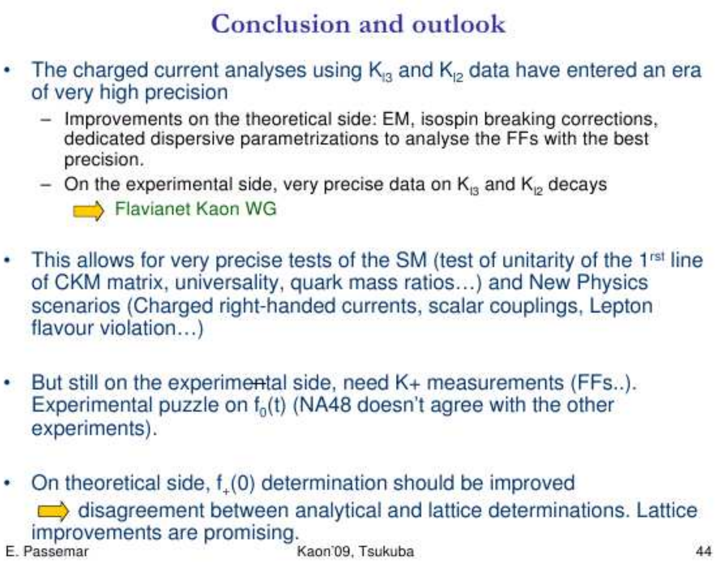
[to determine the flavour structure of NP]

NP search strategies

Where to look for New Physics?

- **Processes very suppressed or even forbidden in the SM**
  - FCNC processes ($\mu \to e\gamma$, $\tau \to \mu\gamma$, $B^0_{s,d} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$)
  - CPV effects (electron/neutron EDMs, $d_{e,n}$....)
  - CPV in $B_{s,d}$ decay/mixing amplitudes
- **Processes predicted with high precision in the SM**
  - EWPO as $\Delta\rho$, $(g-2)_\mu$....
  - LU tests in $R_M^{e/\mu} = \Gamma(K(\pi) \to e\nu)/\Gamma(K(\pi) \to \mu\nu)$

LU tests with $K\ell3$ and $k\ell2$ modes



Conclusion and outlook

- The charged current analyses using K_{l3} and K_{l2} data have entered an era of very high precision
  - Improvements on the theoretical side: EM, isospin breaking corrections, dedicated dispersive parametrizations to analyse the FFs with the best precision.
  - On the experimental side, very precise data on K_{l3} and K_{l2} decays

    ⇒ Flavianet Kaon WG
- This allows for very precise tests of the SM (test of unitarity of the 1^{rst} line of CKM matrix, universality, quark mass ratios…) and New Physics scenarios (Charged right-handed currents, scalar couplings, Lepton flavour violation…)
- But still on the experimental side, need K+ measurements (FFs..). Experimental puzzle on $f_0(t)$ (NA48 doesn't agree with the other experiments).
- On theoretical side, $f_+(0)$ determination should be improved

  ⇒ disagreement between analytical and lattice determinations. Lattice improvements are promising.

$\mu - e$ universality in $R_K = \Gamma(K \to e\nu_e)/\Gamma(K \to \mu\nu_\mu)$

	$(R_K^{e/\mu})_{exp.}$ $[10^{-5}]$
PDG 2006	2.45 ± 0.11
NA48/2 '03 prel.	$2.416 \pm 0.043 \pm 0.024$
NA48/2 '04 prel.	$2.455 \pm 0.045 \pm 0.041$
KLOE prel.	$2.55 \pm 0.05 \pm 0.05$
SM prediction	2.477 ± 0.001

$$(R_K^{e/\mu})_{exp.} = (2.457 \pm 0.032) \times 10^{-5}$$

- A dedicated run (of 4 month) for R_K by **P326/NA62** (former **NA48**) has been performed @ the **CERN**. Goal: the error @ **0.3%!**
- $R_\pi^{exp.} = (1.230 \pm 0.004) \cdot 10^{-4}$ PDG

SM prediction for $R_{K,\pi}$

- $R_K^{SM} = (2.472 \pm 0.001) \cdot 10^{-5}$ SM
- $R_\pi^{SM} = (1.2354 \pm 0.0002) \cdot 10^{-4}$ SM

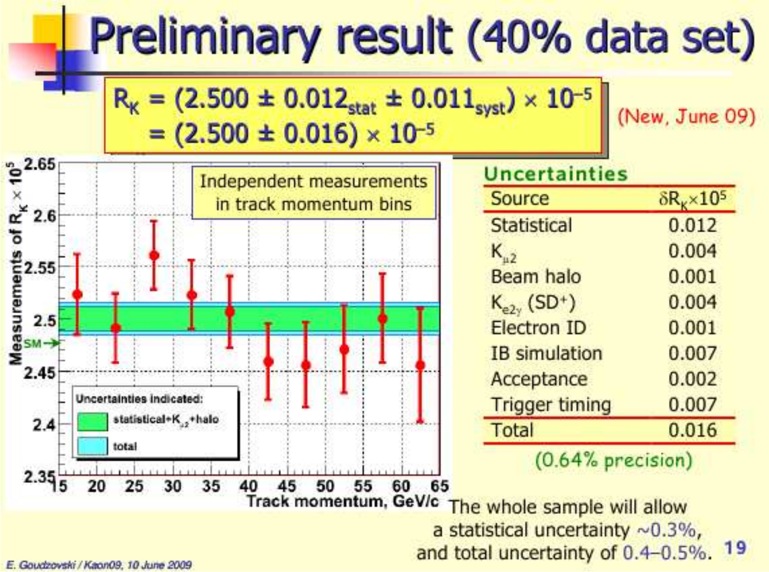
Marciano Sirlin '93, Finkemeyer '96

- $R_K^{SM} = (2.477 \pm 0.001) \cdot 10^{-5}$ SM
- $R_\pi^{SM} = (1.2352 \pm 0.0001) \cdot 10^{-4}$ SM

Cirigliano Rossell '07

The total errors in $R_{K,\pi}$ are dominated by the EXP. ERRORS!!!

R_K @ NA62



Preliminary result (40% data set)

$$R_K = (2.500 \pm 0.012_{stat} \pm 0.011_{syst}) \times 10^{-5}$$
$$= (2.500 \pm 0.016) \times 10^{-5}$$

(New, June 09)

Independent measurements in track momentum bins

Uncertainties

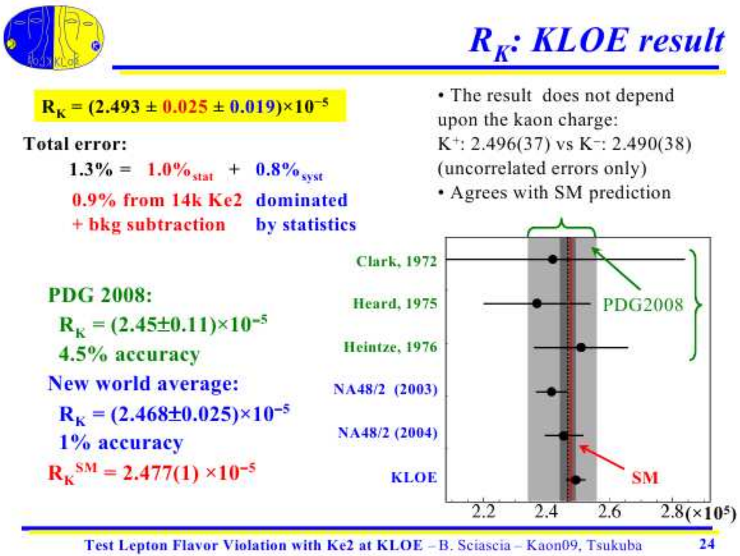
Source	$\delta R_K \times 10^5$
Statistical	0.012
$K_{\mu2}$	0.004
Beam halo	0.001
$K_{e2\gamma}$ (SD⁺)	0.004
Electron ID	0.001
IB simulation	0.007
Acceptance	0.002
Trigger timing	0.007
Total	0.016

(0.64% precision)

The whole sample will allow a statistical uncertainty ~0.3%, and total uncertainty of 0.4–0.5%.

E. Goudzovski / Kaon09, 10 June 2009

R_K @ KLOE



R_K: KLOE result

$R_K = (2.493 \pm 0.025 \pm 0.019)\times10^{-5}$

Total error:

$1.3\% = 1.0\%_{stat} + 0.8\%_{syst}$

0.9% from 14k Ke2 + bkg subtraction **dominated by statistics**

- The result does not depend upon the kaon charge: K^+: 2.496(37) vs K^-: 2.490(38) (uncorrelated errors only)
- Agrees with SM prediction

PDG 2008:

$R_K = (2.45\pm0.11)\times10^{-5}$

4.5% accuracy

New world average:

$R_K = (2.468\pm0.025)\times10^{-5}$

1% accuracy

$R_K^{SM} = 2.477(1) \times10^{-5}$

Test Lepton Flavor Violation with Ke2 at KLOE – B. Sciascia – Kaon09, Tsukuba 24

$\mu - e$ universality in $M \to l\nu$

- Any deviation from the SM expectation for $R_{K,\pi}$ due to NP can be written as

$$R_{K,\pi} = R_{K,\pi}^{SM}\left(1 + \Delta r_{K,\pi\,NP}^{e-\mu}\right),$$

- Violations of **LU** in **CCI** can be classified as
  - i) **Corrections** to $(V-A)\times(V-A)$ interaction through $W\ell\nu_\ell$ vertex correction induced by a loop of NP particles

$$\Delta r_{SUSY}^{e-\mu} \sim \frac{\alpha_2}{4\pi}\left(\frac{\tilde{m}_\mu^2 - \tilde{m}_e^2}{\tilde{m}_\mu^2 + \tilde{m}_e^2}\right)\frac{m_W^2}{M_{SUSY}^2} \leq 10^{-4}$$

  - ii) **New Lorentz Structures**, i.e. **scalar CCI** with

$$H\ell\nu \sim m_\ell \tan\beta$$

$\mu - e$ universality in $M \rightarrow l\nu$

- Four-Fermi interaction for $M \to \ell\nu$ induced by $W^\pm$, $H^\pm$

$$\frac{4G_F}{\sqrt{2}} V_{ud}\left[(\overline{u}\gamma_\mu P_L d)(\bar{\ell}\gamma^\mu P_L \nu_\ell) - t_\beta^2\left(\frac{m_d\, m_\ell}{m_{H^\pm}^2}\right)(\overline{u}P_R d)(\bar{\ell}P_L\nu_\ell)\right]$$

- PCAC's
  - $< 0|\overline{u}\gamma_\mu\gamma_5 d|M >= if_M p_M^\mu \qquad < 0|\overline{u}\gamma_5 d|M >= -if_M \frac{m_M^2}{m_d+m_u}$

- $H^\pm$ ($\mathbf{W}^\pm$) amplitude is proportional to m_ℓ because of the Yukawa coupling (**helicity suppression**)

$$\frac{\Gamma^{H^\pm + W^\pm}(M \to \ell\nu)}{\Gamma^{W^\pm}(M \to \ell\nu)} = r_M = \left[1 - t_\beta^2\ \left(\frac{m_d}{m_u + m_d}\right)\frac{m_M^2}{m_{H^\pm}^2}\right]^2 .$$

Tree level $H^\pm$ effects (r_M) are lepton flavour blind

$\mu - e$ universality in $M \rightarrow l\nu$

WHAT ARE WE MISSING ?..........

$$R_K^{EXP.} = \frac{\Gamma(K \rightarrow e\nu_e) + \Gamma(K \rightarrow e\nu_\mu) + \Gamma(K \rightarrow e\nu_\tau)}{\Gamma(K \rightarrow \mu\nu_\mu) + \Gamma(K \rightarrow \mu\nu_e) + \Gamma(K \rightarrow \mu\nu_\tau)}$$

..........EXPERIMENTALLY THE NEUTRINO FLAVOUR IS UNDETERMINED !!

Masiero, Paradisi, Petronzio, '06

$\mu - e$ universality in $M \to l\nu$

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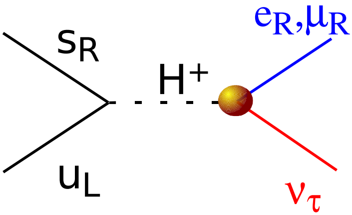
R_K^{LFV} in SUSY

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



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

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

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

$$\Downarrow$$

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

$$\Delta r_{K\,SUSY}^{e-\mu} \approx 10^{-2} \quad \Longrightarrow \quad Br^{th.(exp.)}(\tau \to eX) \leq 10^{-10(-7)}$$

R_K^{LFV} in SUSY

Which is the sign of $\Delta r_{NP}^{e-\mu}$?

- LFV effects to LFC channels in R_M

$$\ell H^{\pm}\nu_\ell \rightarrow \frac{g_2}{\sqrt{2}}\frac{m_\ell}{M_W}\tan\beta\left(1+\frac{m_\tau}{m_\ell}\Delta_{RL}^{\ell\ell}\tan\beta\right) \qquad (\ell = e,\mu)$$

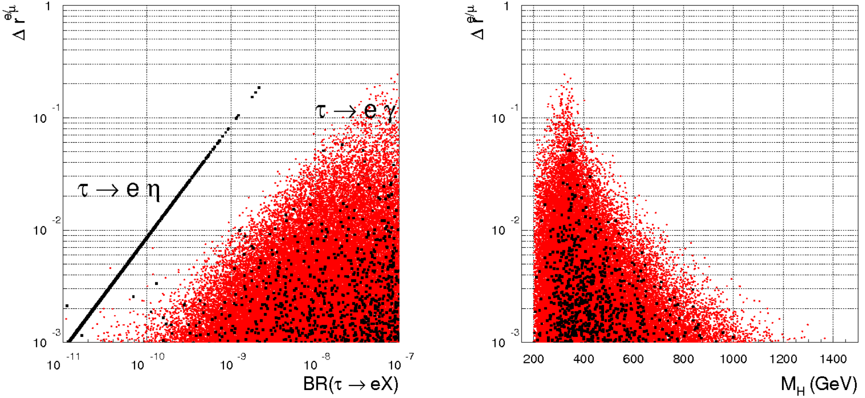
$$\Delta_{RL}^{\ell\ell} \sim \frac{\alpha_1}{4\pi}\delta_{RR}^{\ell 3}\delta_{LL}^{3\ell} f_{loop} \leq 10^{-4}$$

- Deviations from $\mu - e$ universality in K_{l2} and π_{l2}

$$\frac{R_{K,\pi}^{LFV}}{R_{K,\pi}^{SM}} \simeq \left[\left(1-\frac{m_\tau}{m_e}\frac{m_{K,\pi}^2}{M_{H^\pm}^2}\Delta_{RL}^{11}\tan^3\beta\right)^2+\frac{m_\tau^2}{m_e^2}\frac{m_{K,\pi}^4}{M_{H^\pm}^4}|\Delta_R^{31}|^2\tan^6\beta\right]$$

$$R_K^{LFV} \simeq R_K^{SM}(1-0.032)\,, \qquad R_\pi^{LFV} \simeq R_\pi^{SM}(1-0.0021)$$

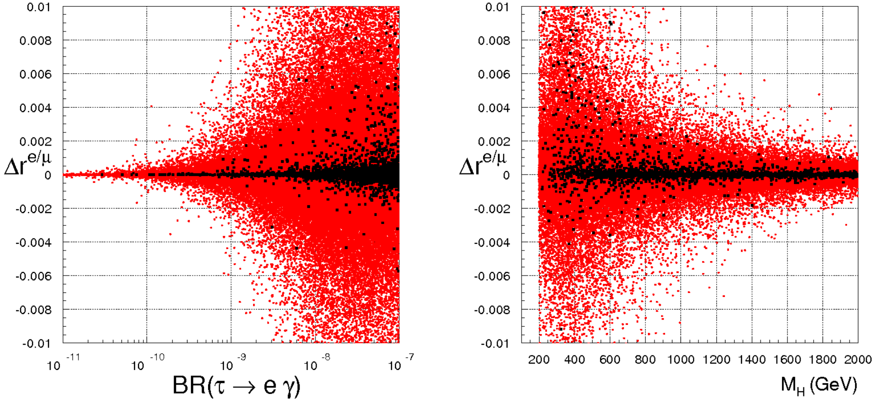
R_K^{LFV} in SUSY



Black points explain the $(g-2)_\mu$ anomaly

Masiero, P.P., Petronzio, '08

R_K^{LFV} in SUSY



Black points explain the $(g-2)_\mu$ anomaly

Masiero, P.P., Petronzio, '08

LU at a (Super)B factories

- $R_\tau^{\mu/e} = \Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\tau \to e\nu\bar{\nu})$

$$R_\tau^{\mu/e} \simeq 1 - 10^{-3} \left(\frac{t_\beta}{50}\right)^2 \left(\frac{200\mathrm{GeV}}{M_{H^\pm}}\right)^2$$

Mursula et al. '83

- $R_{B\to D}^{\tau/\ell} = \Gamma(B \to D\tau\nu)/\Gamma(B \to D\ell\nu)$

Hou '92, **Tanaka '95**, **Kiers & Soni '97**

$$\frac{R_{B\to D}^{\tau/\mu}}{R_{B\to D}^{\tau/\mu}|_{SM}} \simeq 1 - 0.3 \left(\frac{t_\beta}{50}\right)^2 \left(\frac{200\mathrm{GeV}}{M_{H^\pm}}\right)^2$$

Nierste et al.'08, **Kamenik & Mescia '08**

SUSY MFV scenario @ large tan β

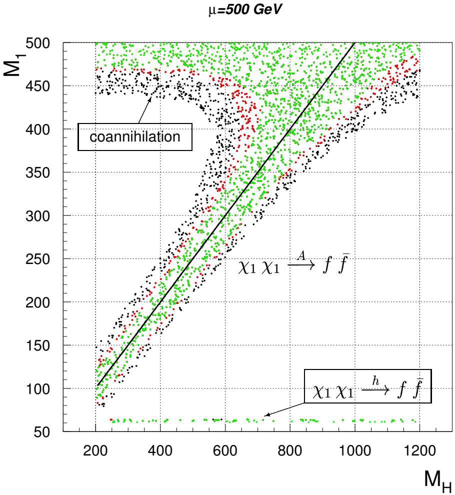
How natural is the MFV SUSY scenario @ large tan β?

- Top-Bottom Yukawa unification in GUT ⇒ $\tan\beta = (m_t/m_b)$
- $m_h > 114\mathrm{GeV}$ constraint better satisfied
- $\Delta a_\mu = (g-2)_\mu/2 = (3 \pm 1) \times 10^{-9}$ naturally explained
- WMAP constraints **"naturally"** satisfied **Ellis et al.**
- Correlations between $\mathrm{BR(B \to \tau\nu)}$ and $\mathrm{BR(B \to X_s\gamma)}$, ΔM_{B_s},$\mathrm{BR(B_{s,d} \to \ell^+\ell^-)}$, $(g-2)_\mu$ and m_{h^0}

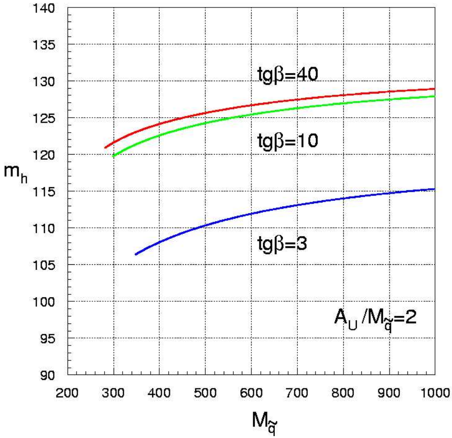
Isidori, P.P., '06

Lightest Higgs boson mass WMAP & $(g-2)_\mu$

$$\Delta a_\mu \simeq 3 \times 10^{-9} \left(\frac{400\mathrm{GeV}}{\tilde{m}}\right)^2 \left(\frac{t_\beta}{50}\right) \mathit{sign}\,\mu$$



$t_\beta = 20\,(\mathit{green}), 30\,(\mathit{red}), 50\,(\mathit{black})$

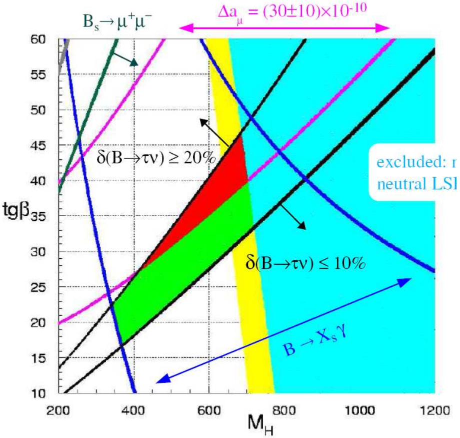


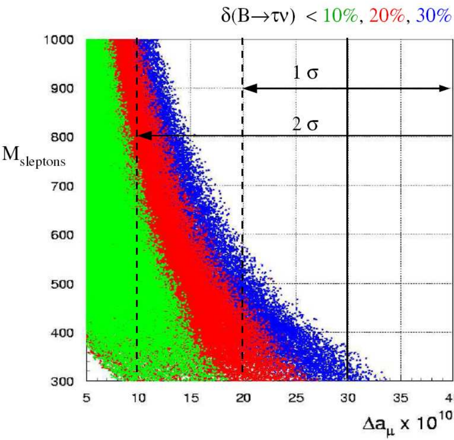
Isidori et al., 06','07

Constraints

- $\mathbf{B \to X_s}\gamma$: $[1.01 < \mathbf{R_{Bs\gamma}} < 1.24]$
- $\mathbf{a}_\mu$: $[2 < 10^{-9}(\mathbf{a}_\mu^{\rm exp} - \mathbf{a}_\mu^{\rm SM}) < 4]$
- $\mathbf{B} \to \mu^+\mu^-$: $[\mathcal{B}^{\rm exp} < 8.0 \times 10^{-8}]$
- ΔM_{B_s} : $[\mathbf{\Delta M_{B_s}} = 17.35 \pm 0.25 \ {\rm ps}^{-1}]$
- $B \to \tau\nu$: $[0.8 < \mathbf{R_{B\tau\nu}} < 0.9]$

B-physics & $(g-2)_\mu$ under WMAP constraints





$M_H \sim 2M_1$

Isidori, Mescia, P.P., Temes, 07

$K \longrightarrow \pi\nu\bar{\nu}$ in the SM

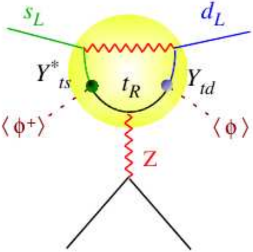
- $K \rightarrow \pi\nu\bar{\nu}$ processes offer a unique possibility in probing the underlying flavour mixing mechanism:
  - No SM tree-level contributions (FCNC decays);
  - One-loop SM contributions CKM-suppressed ($V^*_{ts}V_{td} \sim \lambda^5$);
  - High precision of the SM prediction thanks to short distance (e.w.) dynamics dominance:

$$\mathcal{H}^{(s.d.)}_{\rm eff} = \sum_{l=e,\mu,\tau} V^*_{ts}V_{td}\left[X_L(\bar{s}d)_{V-A} + X_R(\bar{s}d)_{V+A}\right](\bar{\nu}_l\nu_l)_{V-A}$$

$$Br(K \rightarrow \pi\nu\bar{\nu}) \sim (X = X_L + X_R)^2$$

$$X \sim c_{SM}\frac{y_t^2 V^*_{ts}V_{td}}{16\pi^2 M_W^2}$$

$$X_L^{\rm SM} = 1.464 \pm 0.041\ ,\quad X_R^{\rm SM} = 0$$



$K \to \pi\nu\bar{\nu}$ and NP

- $K \to \pi\nu\bar{\nu}$ has a **high sensitivity to NP** effects of many theories as SUSY, LHT, Z' models.....

$$X(s \to d)_{\rm FCNC} \sim c_{\rm SM}\frac{y_t^2 V_{ts}^* V_{td}}{16\pi^2 M_W^2} + c_{\rm NP}\frac{\delta_{21}}{16\pi^2 \Lambda_{NP}{}^2}$$

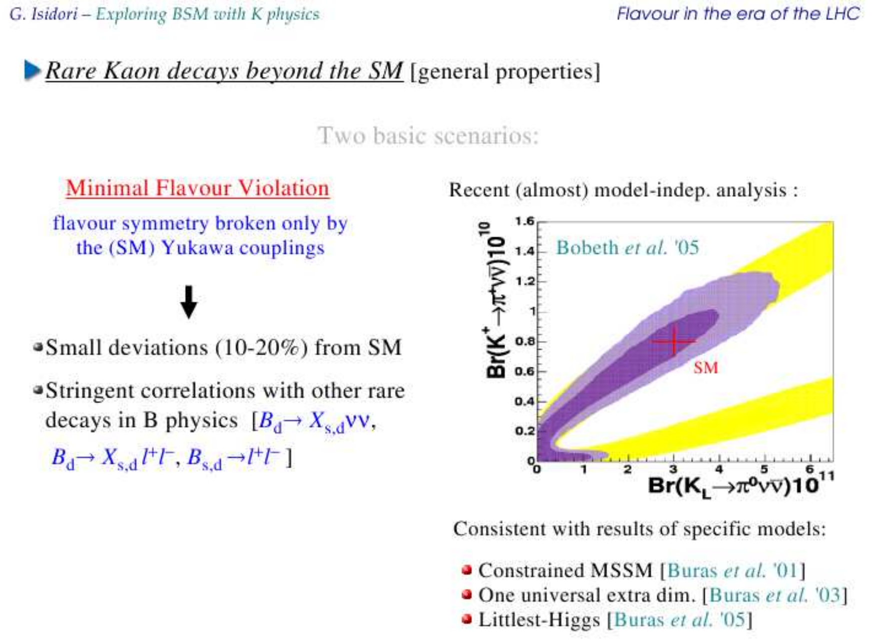
$$Br(K \to \pi\nu\bar{\nu}) \sim (X = X_L + X_R)^2$$

$$X_L = X_L^{\rm SM} + X_L^{\rm NP}\,, \qquad X_R = X_R^{\rm NP}$$

- Large **NP** effects only if $\delta_{21} \nsim V_{ts}^* V_{td}$ (beyond MFV)

see the talk by Buras

$K \to \pi\nu\bar{\nu}$ in MFV



G. Isidori – *Exploring BSM with K physics* Flavour in the era of the LHC

Rare Kaon decays beyond the SM [general properties]

Two basic scenarios:

Minimal Flavour Violation

flavour symmetry broken only by the (SM) Yukawa couplings

↓

- Small deviations (10-20%) from SM
- Stringent correlations with other rare decays in B physics [$B_d \to X_{s,d}\nu\nu$, $B_d \to X_{s,d}\, l^+l^-$, $B_{s,d} \to l^+l^-$]

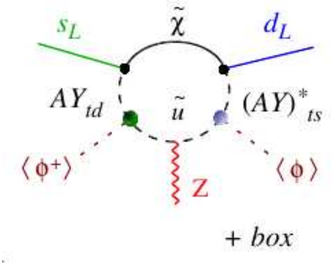
Recent (almost) model-indep. analysis :

Consistent with results of specific models:

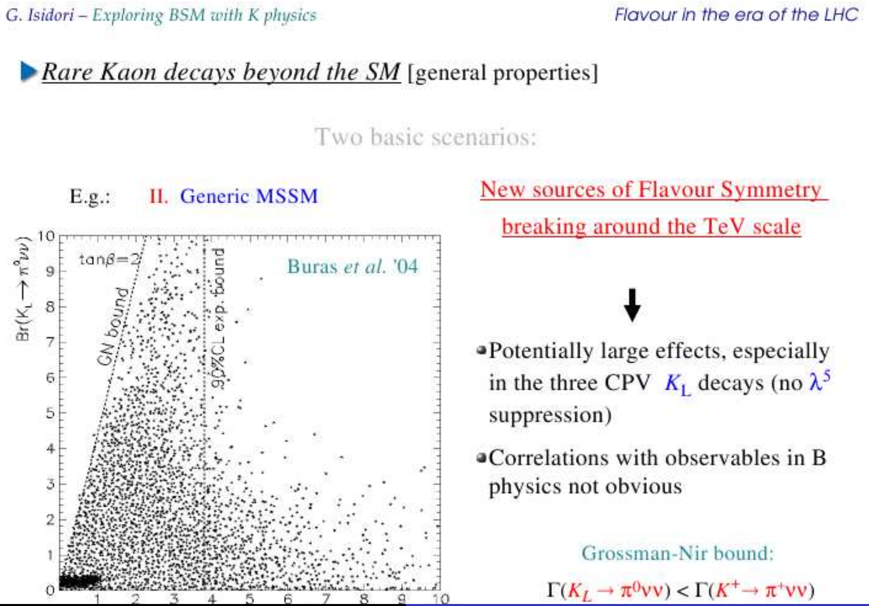
- Constrained MSSM [Buras *et al.* '01]
- One universal extra dim. [Buras *et al.* '03]
- Littlest-Higgs [Buras *et al.* '05]

Gaugino mediated $K \to \pi\nu\bar{\nu}$

- The dominant effects to $K \to \pi\nu\bar{\nu}$ arise from $\tilde{\chi}/\tilde{u}$ diagrams with double-MIA [Colangelo, Isidori '98].
- Gluino-type amplitudes (LL, RR and LR-down squarks type mixings) essentially negligible contrary to ϵ_K, $b \to s\gamma$, $B^0 - \bar{B}^0$
- Minor effects within pure MFV.
- The maximal sensitivity to the up-type trilinear terms is obtained for
  - Light stop and charginos
  - small $\tan\beta$



$K \rightarrow \pi \nu \bar{\nu}$ in SUSY beyond MFV



G. Isidori – Exploring BSM with K physics

Flavour in the era of the LHC

Rare Kaon decays beyond the SM [general properties]

Two basic scenarios:

E.g.: **II. Generic MSSM**

New sources of Flavour Symmetry breaking around the TeV scale

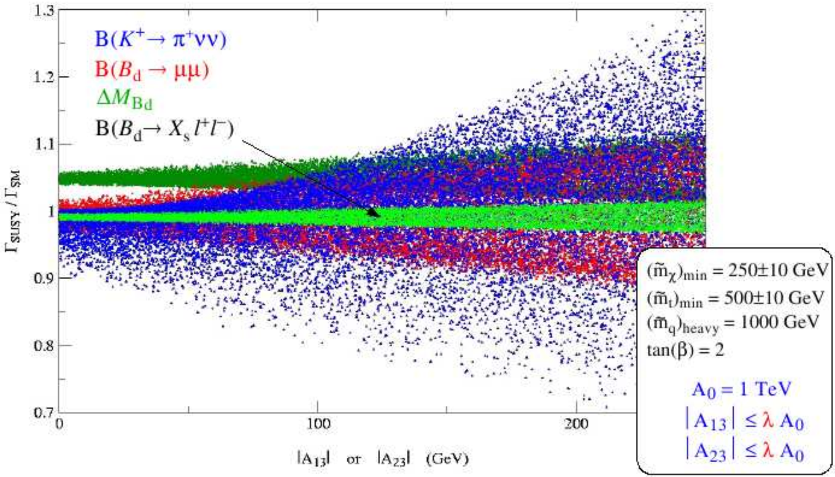
↓

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

Grossman-Nir bound:

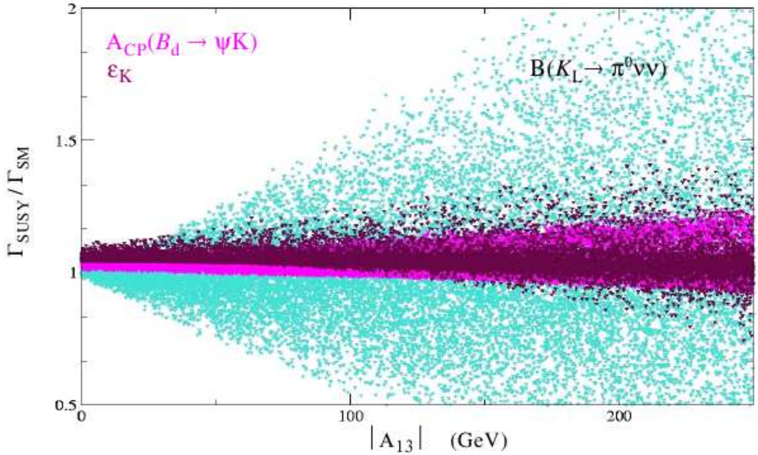
$$\Gamma(K_L \rightarrow \pi^0 \nu\nu) < \Gamma(K^+ \rightarrow \pi^+ \nu\nu)$$

Chargino mediated $K \to \pi\nu\bar{\nu}$



G.Isidori, F.Mescia, P.P., C.Smith, S.Trine, '06

Chargino mediated $K \to \pi\nu\bar{\nu}$



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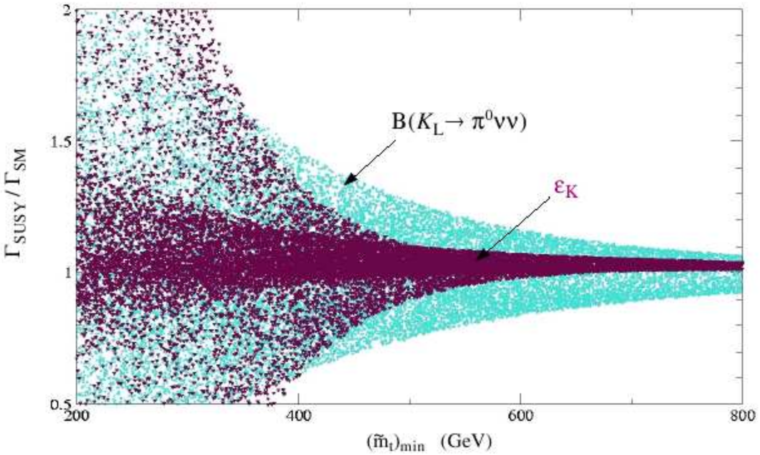
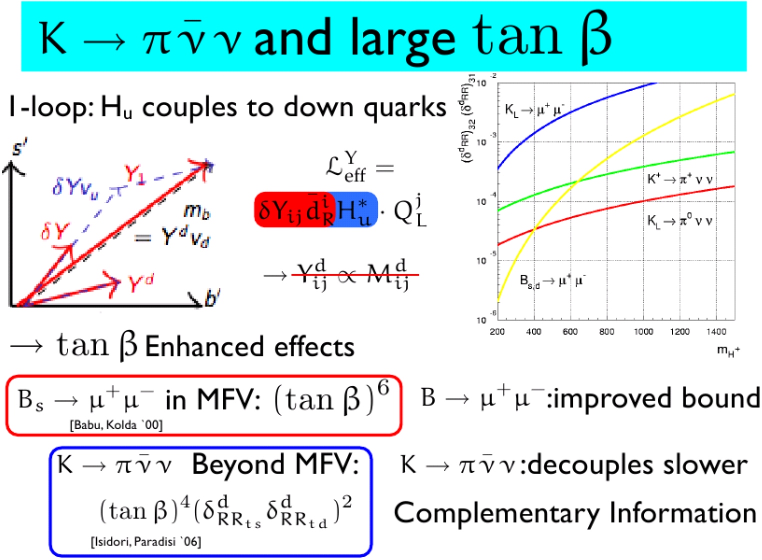


G.Isidori, F.Mescia, P.P., C.Smith, S.Trine, '06

Higgs mediated $K \to \pi\nu\bar{\nu}$



$K \to \pi\bar{\nu}\nu$ and large $\tan\beta$

1-loop: H_u couples to down quarks

$$\mathcal{L}^{Y}_{\rm eff} = \delta Y_{ij}\bar{d}^i_R H^*_u \cdot Q^j_L$$

$$\to \cancel{Y^d_{ij} \propto M^d_{ij}}$$

$\to \tan\beta$ Enhanced effects

$B_s \to \mu^+\mu^-$ in MFV: $(\tan\beta)^6$

[Babu, Kolda `00]

$B \to \mu^+\mu^-$:improved bound

$K \to \pi\bar{\nu}\nu$ Beyond MFV:

$$(\tan\beta)^4(\delta^d_{RR_{ts}}\delta^d_{RR_{td}})^2$$

[Isidori, Paradisi `06]

$K \to \pi\bar{\nu}\nu$:decouples slower

Complementary Information

Conclusion

Where to look for New Physics?

- LU breaking @ % in $R_K^{e/\mu}$ from SUSY LFV effects
- LU breaking @ % in $R_K^{e/\mu}$ implies $M_{H^\pm} < 1\mathrm{TeV}$ and it can be compatible with the $(g-2)_\mu$ anomaly
- LU breaking @ % in $R_K^{e/\mu}$ $\Rightarrow \mathrm{BR}(\tau \to \mathrm{e}\gamma) > 10^{-9}$
- The relevant SUSY parameter space for $R_K^{e/\mu}$ @ % is allowed by the constraints of rare LFV decays, **B**-physics observables and **D**ark **M**atter

$$\Downarrow$$

$R_K^{e/\mu}$ **offers a great chance to probe SUSY LFV .**

Conclusion

Where to look for New Physics?

- $K \to \pi\nu\overline{\nu}$ is a **golden channel** where to look for **NP** because:
  - $K \to \pi\nu\overline{\nu}$ is predicted with high resolution in the SM
  - $K \to \pi\nu\overline{\nu}$ has a **high sensitivity to NP** effects of many theories as SUSY, LHT, Z' models.....

$$\Downarrow$$

Kaon Physics will play a major role in the LHC ERA to unveil and to understand NP