Search for new physics beyond the SM

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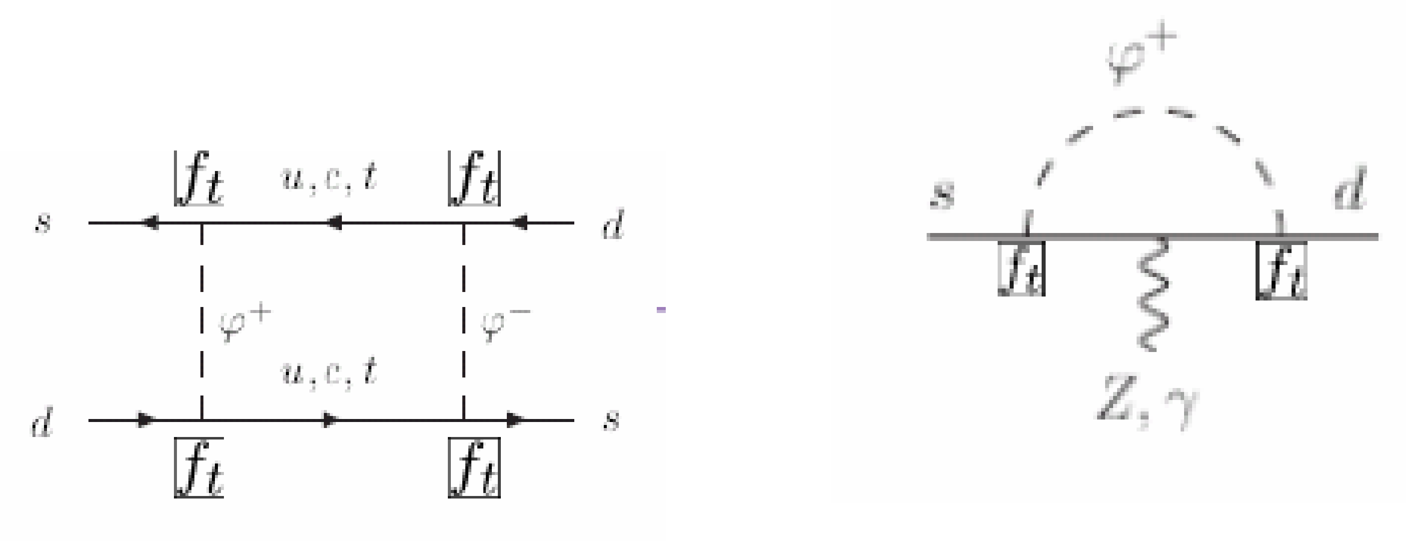
- Introduction
- $K\text{->}\pi\nu\nu$
- Lepton universality
- T violation
- Light boson search
- Test of fundamental principles

Early ’80 vs. Now

- C.S. Lim’s opening talk reminded us of the situation in early 1980’s.

Top quark was anticipated, but the mass and the flavor mixing was unknown.

- Inami and Lim showed that Flavor Changing Neutral Current processes were sensitive to these unknown quantities.



Non-decoupling loop effects of the top quark.

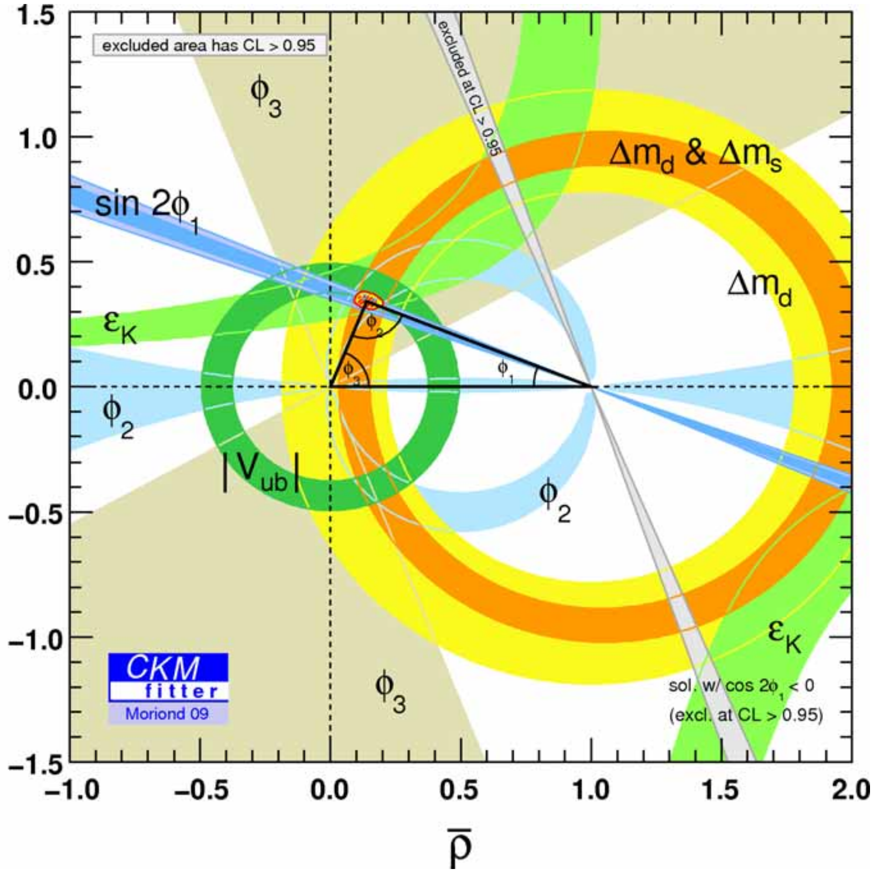
After a quarter of a century, we now know

- the top quark is heavy (mt~ 173 GeV) and
- the Cabibbo-Kobayashi-Maskawa (CKM) matrix has a hierarchical structure.

Energy frontier and Flavor Physics

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\sim \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



Now, we are anticipating something new at the TeV scale that is related to physics of the electroweak symmetry breaking.

The first hint should appear at the LHC.

We do not know what are waiting for us (new particles, new symmetry, new dimensions) except that we probably find a “Higgs”-like particle.

New physics is likely to involve new sources of flavor mixings, but the pattern of the new flavor mixing is unknown.

Various possibilities on new physics effects

(1) Minimal Flavor Violation

$$M_{ij}(New) \sim (V_{3i}^{*} V_{3j}) X(m_{new})$$

New physics contributions to flavor changing amplitudes are essentially governed by the CKM matrix.
Characteristic relation between B and K observables.

(2) Generic

$$M_{ij} = M_{ij}(SM) + M_{ij}(New)$$

No particular relation between SM and new physics contributions.
New physics effects are more likely to appear in processes where the SM contributions have severe suppression.

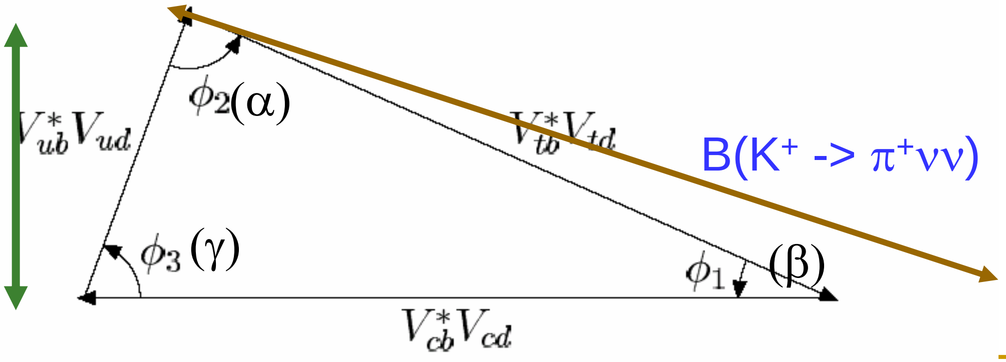
ϵ_K a severe constraint

$B(K \to \pi \nu \bar{\nu})$ A promising signal

ϵ' / ϵ a severe constraint/ a signal if theory is improved.

K_L->$\pi\nu\nu$, K^+->$\pi\nu\nu$

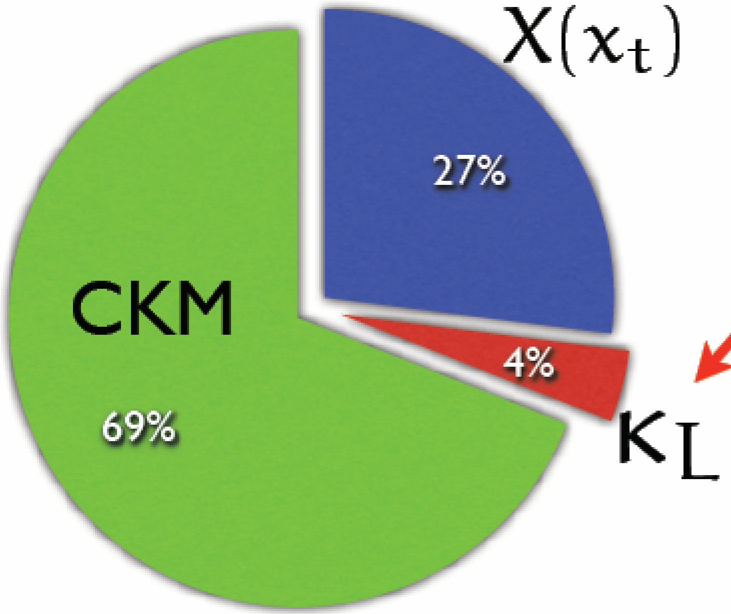
- Theoretically clean processes. Ideal to search for small new physics effects.
- NNLO calculations (M.Gorbahn)
- Long distance effects (C. Smith)



B(K^0->$\pi^0\nu\nu$)

B(K^+ -> $\pi^+\nu\nu$)

$K_L \to \pi^0 \bar{\nu} \nu$: Theoretical Status



Matrix element extracted from K_{l3} decays. $N^{\frac{3}{2}}LO\ \chi PT$
[Mescia, Smith ´07; Bijnens, Ghorbani ´07]

No further long distance uncertainty

$$\mathcal{B}r_{K_L} = (2.6 \pm 0.4) \times 10^{-11}$$

Reduce error with 2 loop electroweak calculation

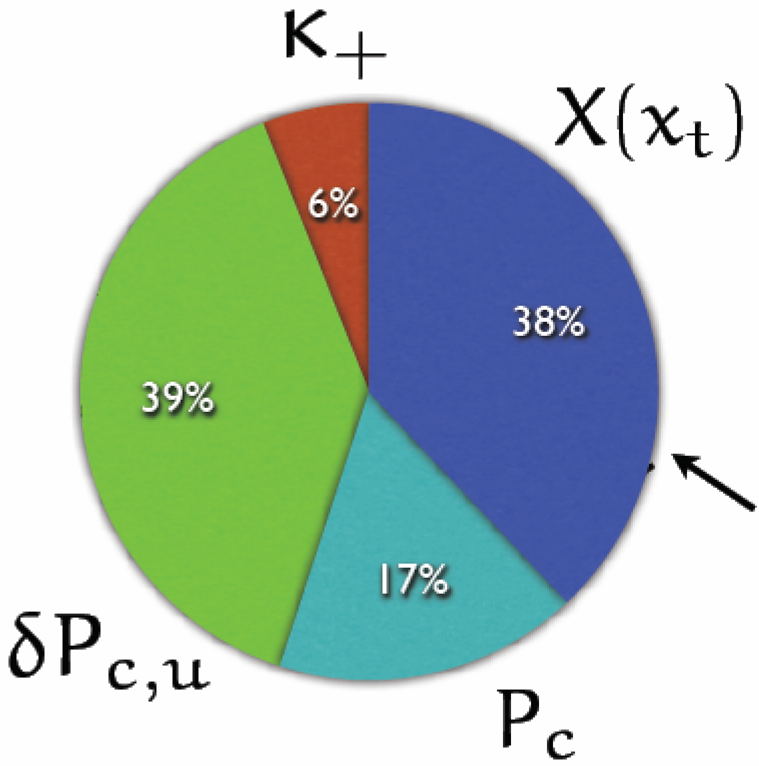
$X(x_t)$: NLO QCD calculation: ±1% error
[Misiak, Urban ´99; Buchalla, Buras ´99]

$X(x_t)$: Electroweak (EW) corrections: ±2% error
[Buchalla, Buras ´99]

M.Gorbahn

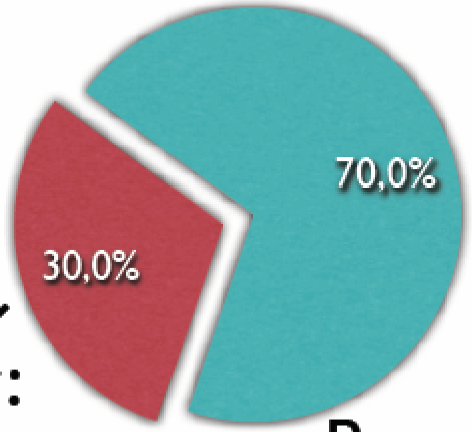
$K^+ \to \pi^+ \bar{\nu}\nu$ Error budget

Theory error budget



for $m_c(m_c) = (1286 \pm 13)MeV$
[Kühn et. al. ´07]

$$\mathcal{B}r_{K^+} = (0.85 \pm 0.07) \times 10^{-10}$$



Theory error:
10%x30% = 3%

Parametric uncertainty

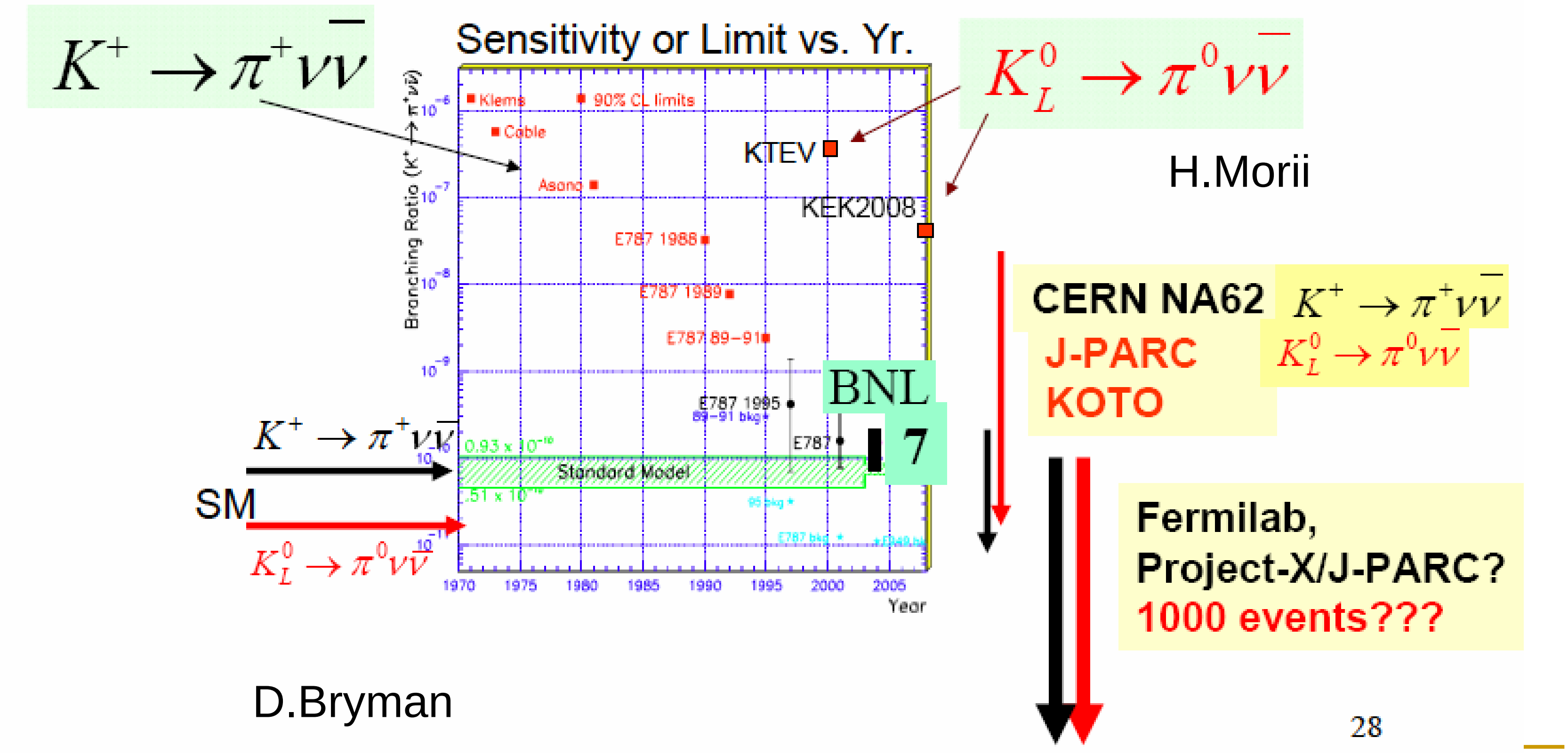
Experiment [E787, E949 ´08]

$$\mathcal{B}r_{K^+} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

M.Gorbahn

Experimental prospects

- CERN NA62 B($K^+ \to \pi\nu\nu$) 10% measurement G.Ruggiero
- J-PARC KOTO B($K_L \to \pi\nu\nu$) ~SM H.Nanjo



$K^+ \to \pi^+ \nu \bar{\nu}$

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

H.Morii

CERN NA62 $K^+ \to \pi^+ \nu \bar{\nu}$

J-PARC KOTO $K_L^0 \to \pi^0 \nu \bar{\nu}$

Fermilab, Project-X/J-PARC? 1000 events???

D.Bryman

TeV new physics example: three cases

(1) Little Higgs Model with T-parity

- Little Higgs model : a model with a composite Higgs boson.

  N.Arkani-Hamed,A.G.Cohen, E.Katz,and A.E.Nelson,2002

- New particles (heavy gauge bosons, a heavy top partner) are introduced to cancel the quadratic divergence of the Higgs mass at one loop level.

- The mass of these particles are around 1 TeV if the model is extended with “T parity”.

C.H.Cheng and I.Low,2003

At ~10 TeV, UV completion theory

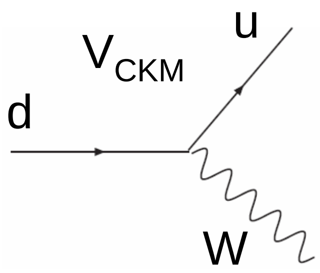
At f ~ O(1) TeV
T-odd bosons: W_H, Z_H, ϕ_{ij},
T-odd fermions: $u_{H,}d_H,l_H$
Top partners T_+, T_-

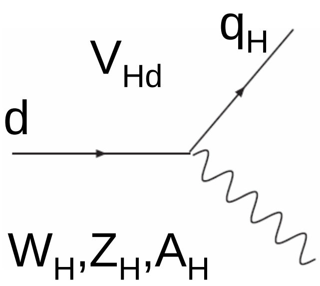
Less than ~200 GeV
T-odd heavy photon A_H
SM particles

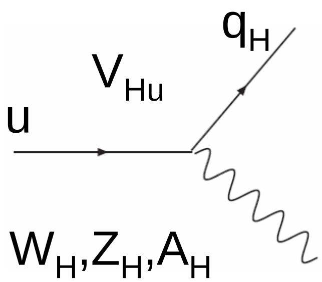
Flavor Physics in the Little Higgs model with T-parity

J.Hubisz,S.J.Lee,G.Paz, 2005

New flavor mixing from T-odd quark and lepton sectors.







Out of three mixing matrixes, two are independent.

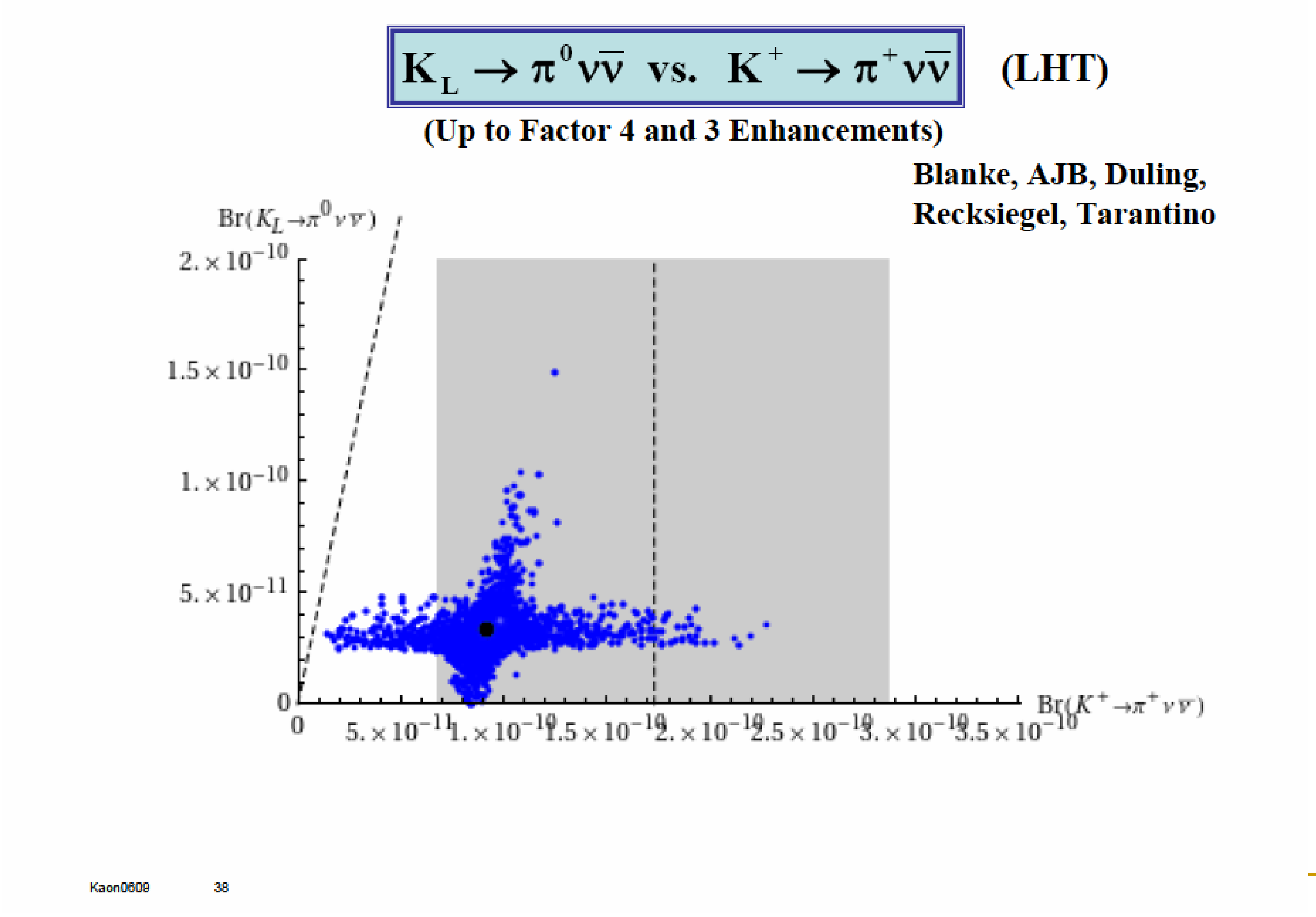
$$\boxed{V_{Hu}^{\dagger} V_{Hd} = V_{CKM}}$$

Similarly, in the lepton sector,

$$\boxed{V_{H\nu}^{\dagger} V_{Hl} = V_{PMNS}^{\dagger}}$$

These matrixes can induce a large contributions to FCNC and LFV processes.
(Non-MFV in general)

Effects of a new flavor mixing matrix: Non-MFV



$K_L \to \pi^0 \nu\bar{\nu}$ vs. $K^+ \to \pi^+ \nu\bar{\nu}$ (LHT)

(Up to Factor 4 and 3 Enhancements)

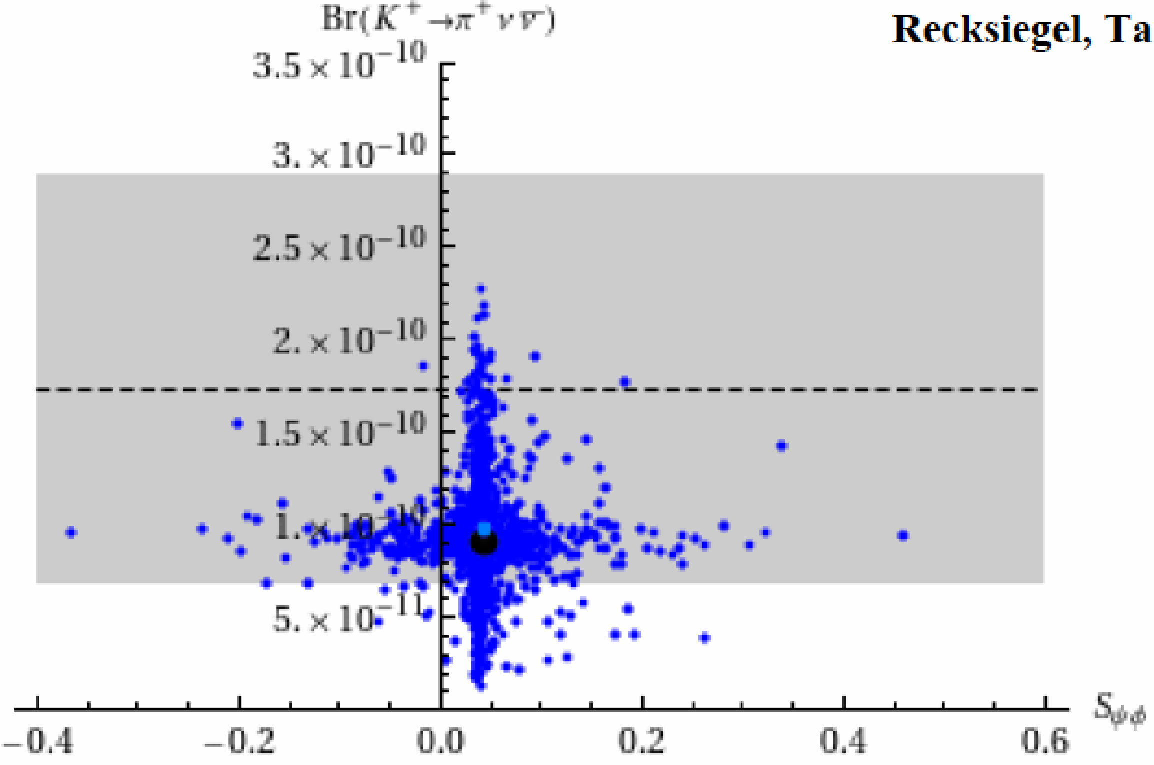
Blanke, AJB, Duling, Recksiegel, Tarantino

Kaon0609 38

$K^+ \to \pi^+ \nu\bar{\nu}$ vs. $S_{\psi\varphi}$ (LHT)

(Simultaneous Large Enhancements unlikely)

Blanke, AJB, Du Recksiegel, Tara



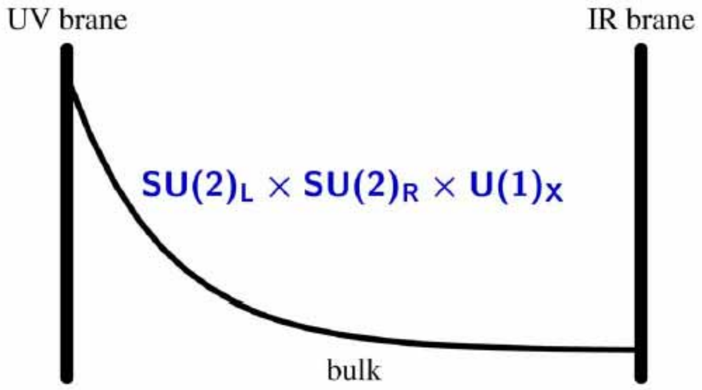
Large effects in K_L->$\pi\nu\nu$, K^+->$\pi\nu\nu$, or CP violation in Bs->$\psi\phi$

(2)Rundall Sundram model with custodial protection

A model based on a warped extra dimension. A large hierarchy between the Planck scale and the weak scale is obtained by geometry,

An interesting frame work to explain mass and flavor mixing of quarks and leptons.

FCNC processes are constraints and signals of this model.

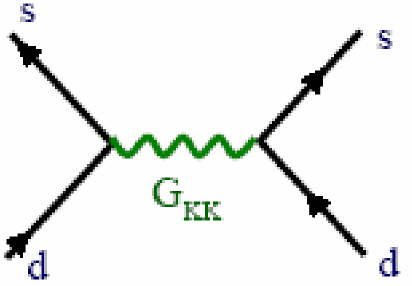


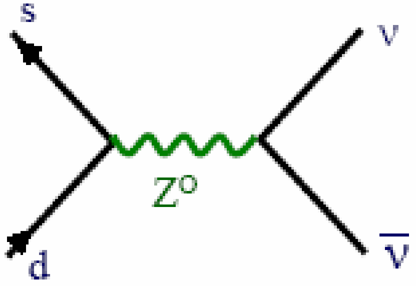
$SU(2)_R \times U(1)_X \rightarrow U(1)_Y$
by boundary conditions

$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$
by Higgs VEV

+ $(L \leftrightarrow R)$-symmetric fermion representations

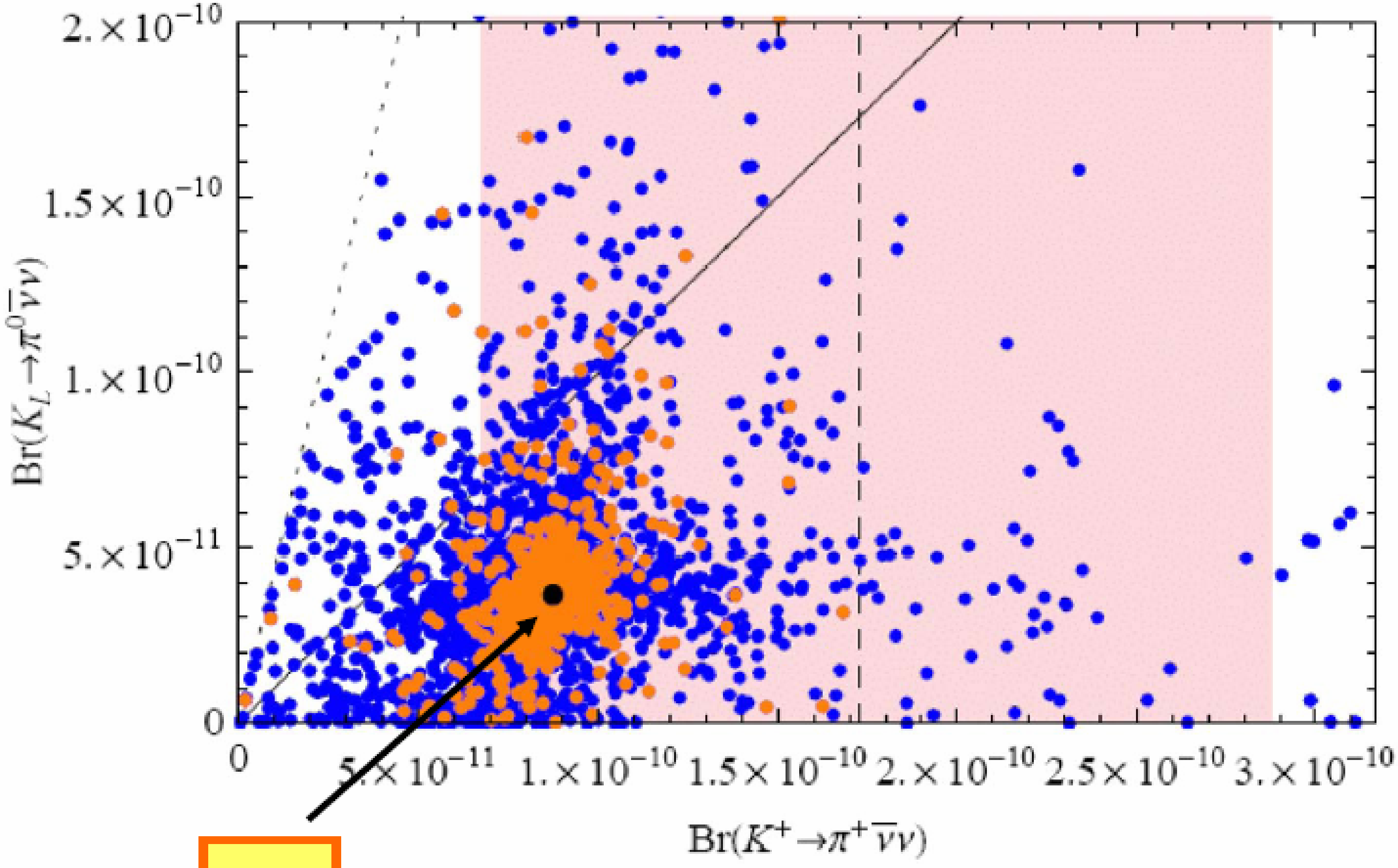
low energy theory: $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$





$K_L \to \pi^0 \nu\bar{\nu}$ vs. $K^+ \to \pi^+ \nu\bar{\nu}$ (RS)

(Up to Factor 3 and 2 Enhancements)



SM

A.Buras

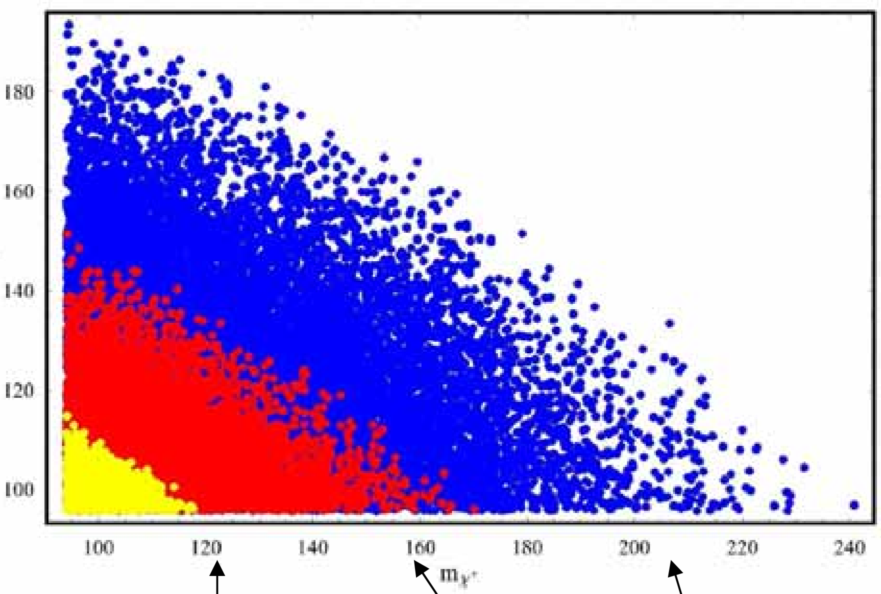
(3) SUSY and K->πνν

- There are a variety of possibilities in SUSY effects on flavor physics from MFV to generic cases.

Minimal Flavor Violation (MFV)scenario in minimal SUSY SM (MSSM)

Generic MSSM

Stop mass



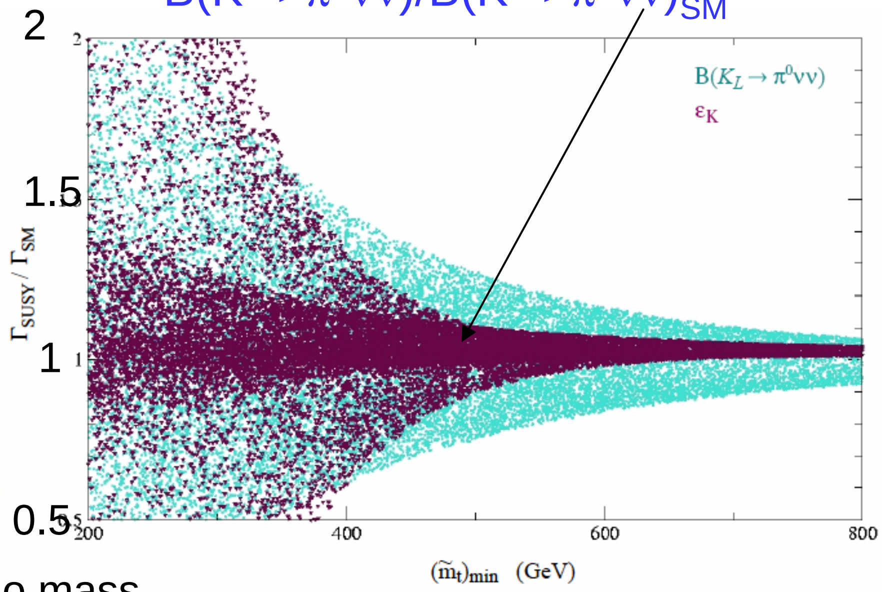
Chargino mass

>15%

>12.5%

>10%

$B(K^0\text{->}\pi^0\nu\nu)/B(K^0\text{->}\pi^0\nu\nu)_{SM}$



Stop mass

G.Isidori, et al. 2006

Anomalous W couplings to charm quark

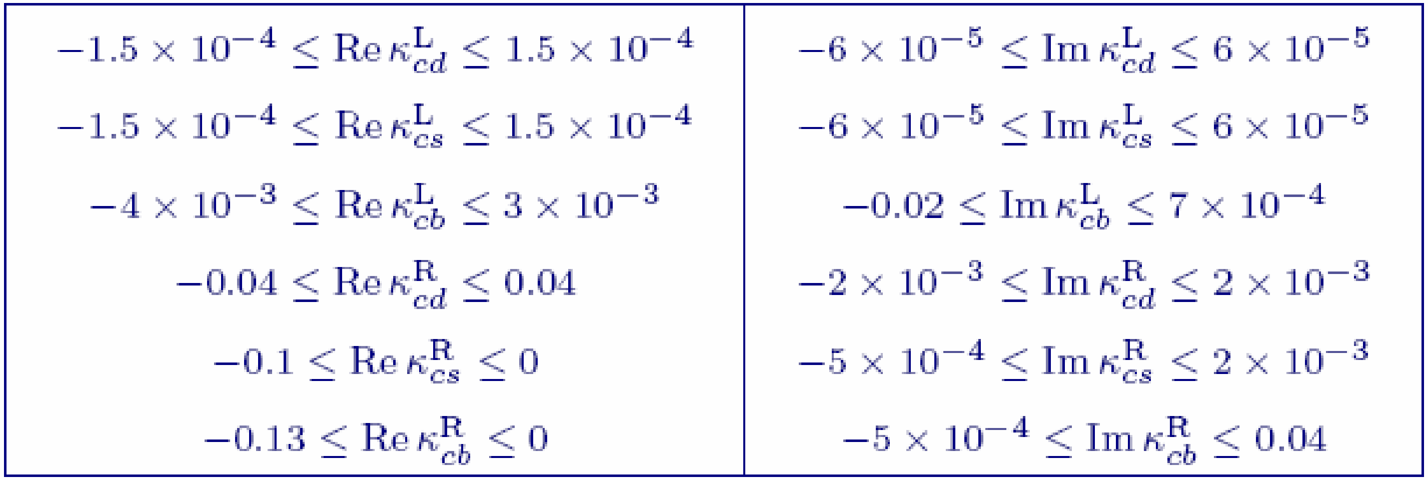
J.Tandean

$$\mathcal{L}_{UDW} = -\frac{g}{\sqrt{2}} V_{kl}\, \bar{U}_k \gamma^\mu \left[\left(1+\kappa^{\rm L}_{kl}\right) P_{\rm L} + \kappa^{\rm R}_{kl}\, P_{\rm R}\right] D_l\, W^+_\mu + {\rm H.c.}$$

Kaon processes put strong constraints especially for left-handed couplings.

For example, $\mathcal{M}(K^+ \to \pi^+ \nu\bar{\nu}) = (1+\delta)\, \mathcal{M}_{\rm SM}(K^+ \to \pi^+ \nu\bar{\nu})$,

$$\delta = \frac{V_{cd}V^*_{cs}}{V_{td}V^*_{ts}} \frac{\left(\kappa^{\rm L}_{cd} + \kappa^{\rm L*}_{cs}\right)\left[-3\ln(\Lambda/m_W) + 4X_0(x_c)\right]}{4X(x_t)} + \mathcal{O}(\kappa^2)$$



$-1.5\times10^{-4} \le {\rm Re}\,\kappa^{\rm L}_{cd} \le 1.5\times10^{-4}$	$-6\times10^{-5} \le {\rm Im}\,\kappa^{\rm L}_{cd} \le 6\times10^{-5}$
$-1.5\times10^{-4} \le {\rm Re}\,\kappa^{\rm L}_{cs} \le 1.5\times10^{-4}$	$-6\times10^{-5} \le {\rm Im}\,\kappa^{\rm L}_{cs} \le 6\times10^{-5}$
$-4\times10^{-3} \le {\rm Re}\,\kappa^{\rm L}_{cb} \le 3\times10^{-3}$	$-0.02 \le {\rm Im}\,\kappa^{\rm L}_{cb} \le 7\times10^{-4}$
$-0.04 \le {\rm Re}\,\kappa^{\rm R}_{cd} \le 0.04$	$-2\times10^{-3} \le {\rm Im}\,\kappa^{\rm R}_{cd} \le 2\times10^{-3}$
$-0.1 \le {\rm Re}\,\kappa^{\rm R}_{cs} \le 0$	$-5\times10^{-4} \le {\rm Im}\,\kappa^{\rm R}_{cs} \le 2\times10^{-3}$
$-0.13 \le {\rm Re}\,\kappa^{\rm R}_{cb} \le 0$	$-5\times10^{-4} \le {\rm Im}\,\kappa^{\rm R}_{cb} \le 0.04$

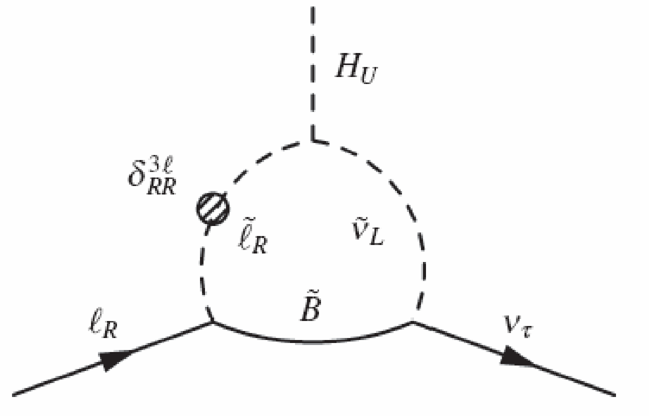
SUSY and lepton universality

P.Paradisi

- One particularly interesting case is that the right-handed slepton flavor mixing induces the violation of lepton universality in K->lν decays.

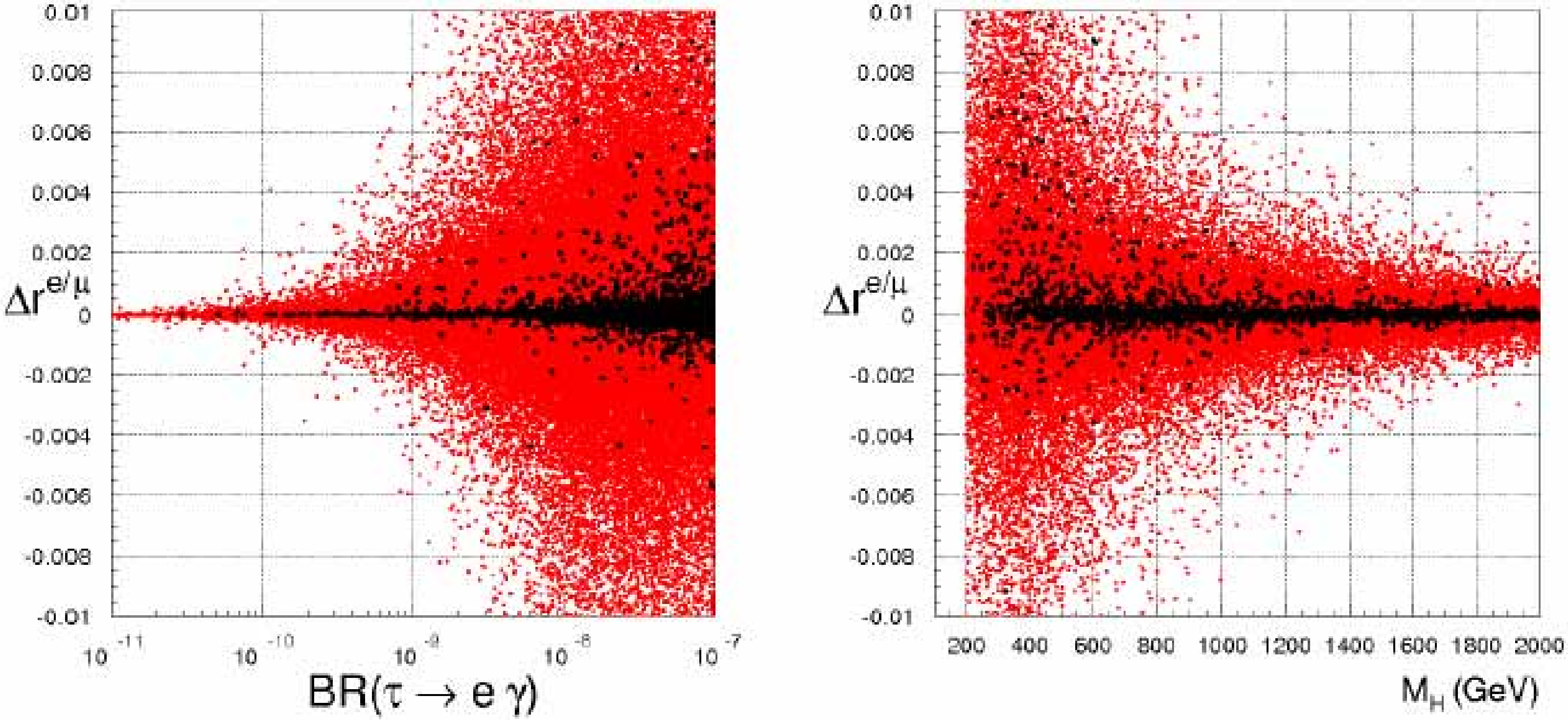
$$R_K = \Gamma(K \to e\nu_e)/\Gamma(K \to \mu\nu_\mu)$$

$$\frac{R^{LFV}_{K,\pi}}{R^{SM}_{K,\pi}} \simeq \left[\left(1 - \frac{m_\tau}{m_e}\frac{m^2_{K,\pi}}{M^2_{H\pm}}\Delta^{11}_{RL}\tan^3\beta\right)^2 + \frac{m^2_\tau}{m^2_e}\frac{m^4_{K,\pi}}{M^4_{H\pm}}|\Delta^{31}_R|^2\tan^6\beta\right]$$



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

P.Paradisi

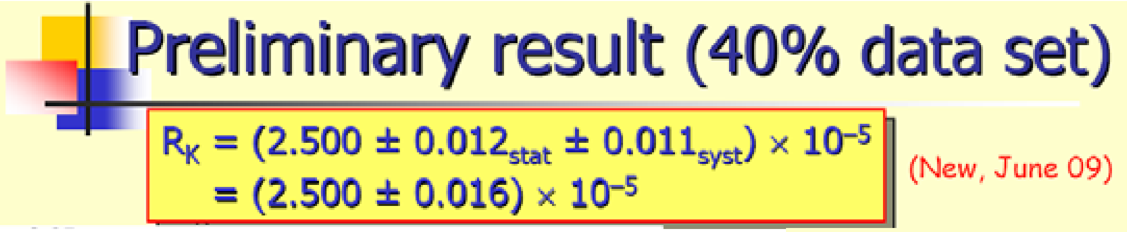


Black points explain the $(g-2)_\mu$ anomaly

Masiero, P.P., Petronzio, '08

Recent experimental results

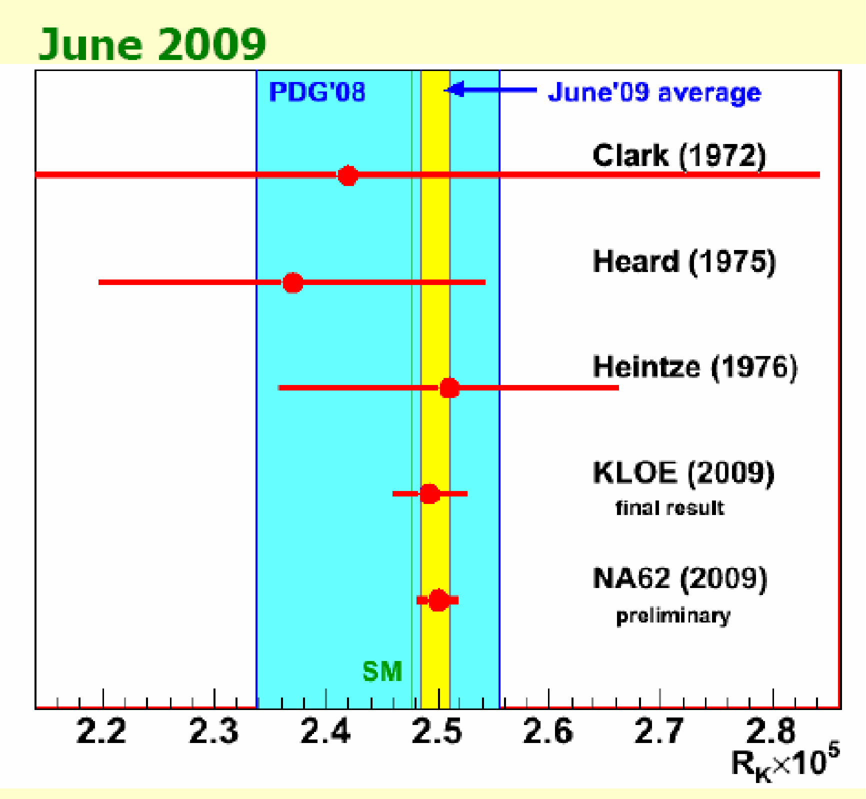
NA62 E.Goudzovski



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)



June 2009

KLOE B.Sciascia

- Using 2.2 fb^{-1} of data acquired at the ϕ peak, KLOE measured:

$R_K = (2.493 \pm 0.025_{stat} \pm 0.019_{syst}) \times 10^{-5}$

Higgs effects at large tan β in MSSM

M.Palutan, E.Passemer, Flavianet
Coupling universality with Kl2, Kl3dec

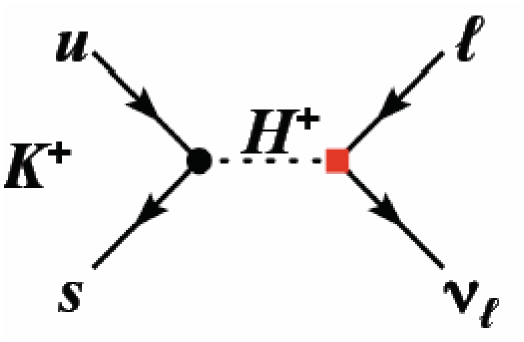
$$R_{l23} = \left| \frac{V_{us}(K_{\mu 2})}{V_{us}(K_{l3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\mu 2})} \right|$$

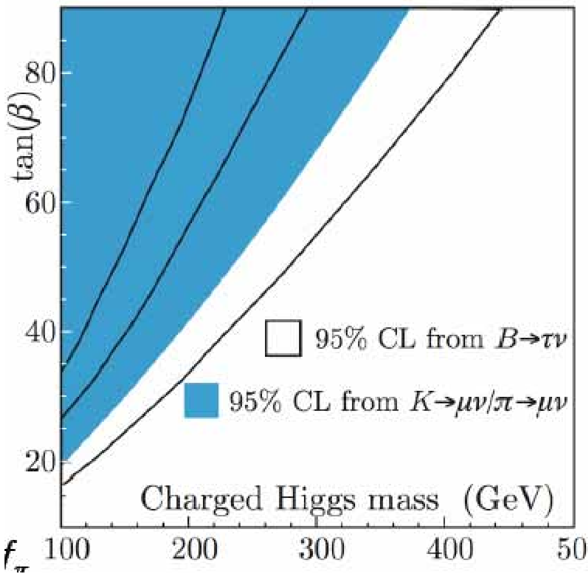
$$= \left| 1 - \frac{m_{K^+}^2}{m_{H^+}^2} \left(1 - \frac{m_{\pi^+}^2}{m_{K^+}^2} \right) \frac{\tan^2 \beta}{1 + \varepsilon_0 \tan \beta} \right|$$

(Hou, Isidori-Paradisi)

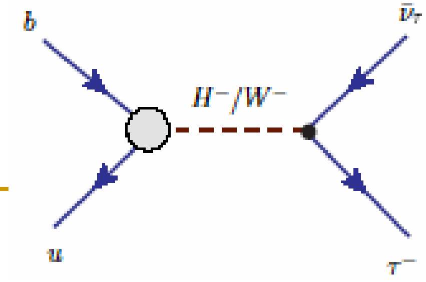
R_{l23} = 1.008 ± 0.008

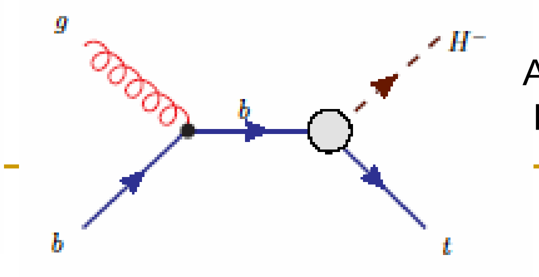
(KLOE only)





Charged Higgs coupling test with B->τν
B-Dτν and charged Higgs production at LHC





A. Cornell, A Deandrea,N.Gaur,
H.Itoh, M.Klassen, Y.O,

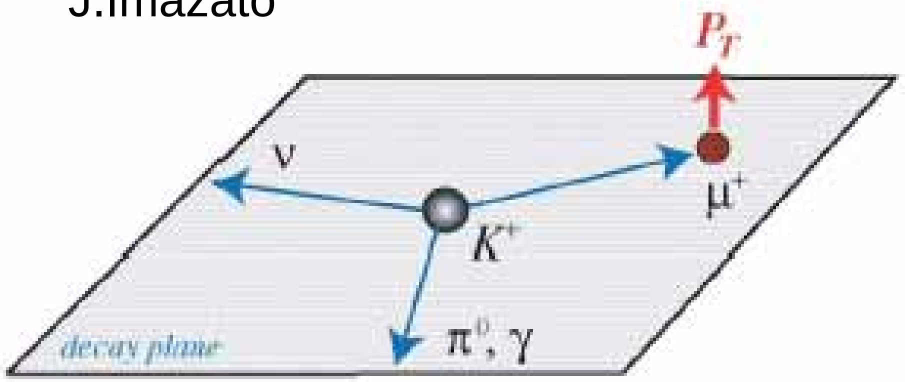
T-violation in K^+->$\pi\nu\mu$ decay

J.Imazato

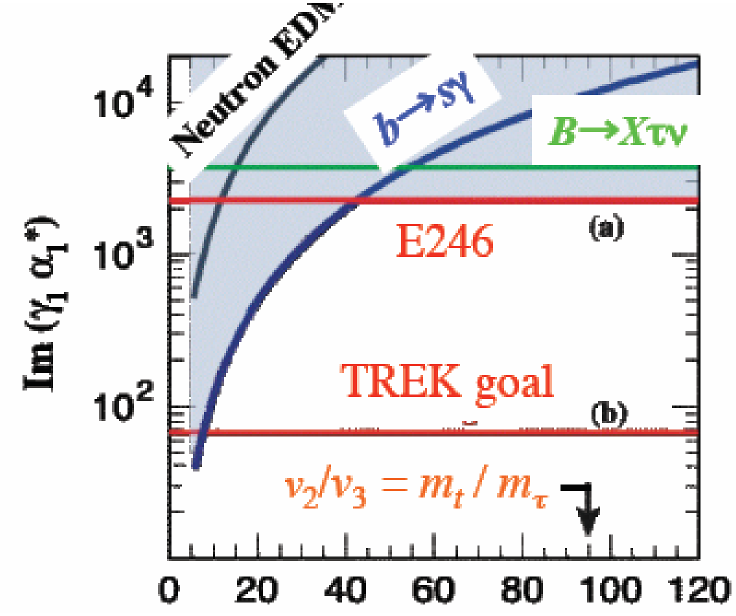
Current upper limit of the transverse muon polarization of K+->$\pi\nu\mu$ decay is given by KEK E246 exp.

$$P_T = -\,0.0017 \pm 0.0023(stat) \pm 0.0011(syst)$$

$$(\,|P_T| < 0.0050 : 90\%\ C.L.\,)$$



J-PARC TREK experiment aim to search for $\delta P_T \sim 10^{-4}$.
Sensitive, for example, to CPV couplings in multi-Higgs models.



Effective four fermion interaction

$$
\begin{aligned}
\mathcal{L} = &-\frac{G_F}{\sqrt{2}}\sin\theta_C \bar{s}\gamma_\alpha(1-\gamma_5)u\,\bar{\nu}\gamma^\alpha(1-\gamma_5)\mu \\
&+ G_S \bar{s}u\,\bar{\nu}(1+\gamma_5)\mu + G_P \bar{s}\gamma_5 u\,\bar{\nu}(1+\gamma_5)\mu \\
&+ G_V \bar{s}\gamma_\alpha u\,\bar{\nu}\gamma^\alpha(1-\gamma_5)\mu + G_A \bar{s}\gamma_\alpha\gamma_5 u\,\bar{\nu}\gamma^\alpha(1-\gamma_5)\mu \\
&+ \text{H.c.},
\end{aligned}
$$

The transverse polarization needs interference between the SM four fermion term and new contributions and a relative phase between them.

$P_\perp(K^+ \to \pi^0\mu^+\nu_\mu)\ :\ G_S$

$P_\perp(K^+ \to \gamma\mu^+\nu_\mu)\ :\ G_P,\ G_R = (G_V + G_A)/2$

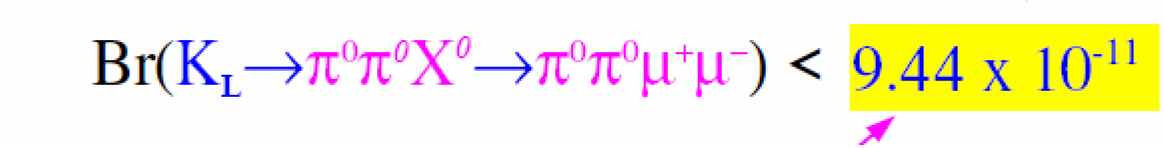
$G_L = (G_V - G_A)/2$ does not contribute to $P_\perp$ at the first order.

Light boson search

- There are proposals postulating light bosons.

  HyperCP, Dark Matter, Light U(1) gauge boson, etc.
- K decays put strong constraints.

KTeV Preliminary D.G.Phillips II

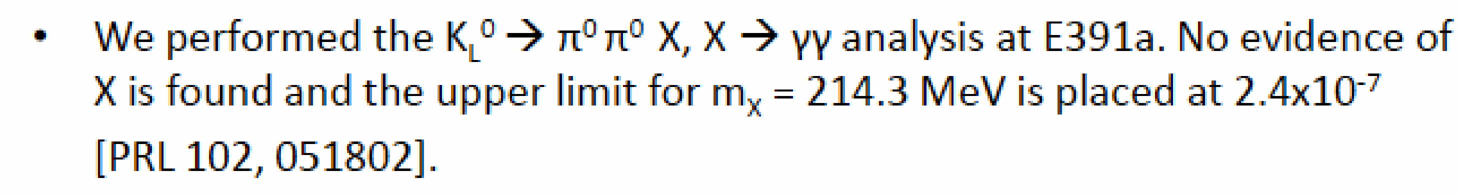


$\mathrm{Br}(K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\mu^+\mu^-) < 9.44 \times 10^{-11}$

HyperCP anomaly with pseudo scalar is excluded.

KEK E391a Y-C Tung

X sgoldstino in GMSB



- We performed the $K_L^0 \rightarrow \pi^0\pi^0 X$, $X \rightarrow \gamma\gamma$ analysis at E391a. No evidence of X is found and the upper limit for m_X = 214.3 MeV is placed at 2.4×10^{-7} [PRL 102, 051802].

Also 

$K_L^0 \rightarrow \pi^0\pi^0 X$, $X \rightarrow \mu^+\mu^-$ the upper limit is placed at 1.7×10^{-6}.

Test on fundamental principles

A.Di Domenico

- K meson system is an ideal place to test CPT invariance, Quantum Coherence, Lorentz invariance. KLOE improved previous limits.

CPT

$$\left|m_{\overline{K}^0} - m_{K^0}\right| < 4.0\times 10^{-19}\ \text{GeV at } 95\%\ \text{C.L.}$$

CPT violation in correlation

Quantum coherent

KLOE FINAL:

$$\zeta_{0\overline{0}} = \left(1.4 \pm 9.5_{\text{STAT}} \pm 3.8_{\text{SYST}}\right)\times 10^{-7}$$

L=1.5 fb^{-1}

KLOE FINAL :

$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right)\times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4}$$

$$|\omega| < 1.0\times 10^{-3}\ \text{ at } 95\%\ \text{C.L.}$$

KLOE2 can improve further.

P.Branchini

etc.

Summary

- Particle physics enters a new era from the LHC experiment.
- Energy frontier and flavor physics will be complementary to each other.
- Kaon physics will provide several opportunities which are unique in flavor physics.