Left-left squark mixing in $K^+ \to \pi^+ \nu\bar{\nu}$ decay

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Outline

→ Introduction

→ $K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

→ Supersymmetry, non-minimal flavor violation and its impact on the branching ratio

→ Numerical analysis

→ Conclusions

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

$\to$ $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}))_{\mathrm{exp}} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$, Adler et al. (2000); Anisimovsky et al. (2004); Artamonov et al. (2008)

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→ The NA62 experiment is running at CERN, expected to observe $\mathcal{O}(10^2)$ rare kaon decays.

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In the Standard Model (Buras et al., 2008; Isidori et al., 2005)

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{c,\text{eff}} + \frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_W} \lambda_t \sum_{l=e,\mu,\tau} (X_L \mathcal{O}_L + X_R \mathcal{O}_R).$$

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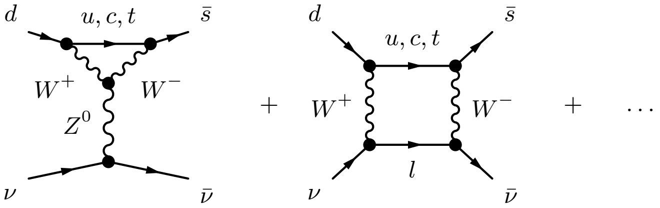
→ $\langle \pi^+ \nu\bar{\nu} | \bar{s}\gamma_\mu P_L d | K^+ \rangle \approx \sqrt{2} \langle \pi^0 e^+ \nu_e | \bar{s}\gamma_\mu P_L u | K^+ \rangle$. Gaillard and Lee (1974); Marciano and Parsa (1996)

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



$$\to X_0(x_t) = \frac{x_t}{8}\left[\frac{x_t + 2}{x_t - 1} + \frac{3x_t - 6}{(x_t - 1)^2}\ln x_t\right], x_t = \frac{m_t^2}{M_W^2}$$

Inami and Lim (1981)

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

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ (1 + \Delta_{EM}) \left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X \right)^2 + \left(\frac{\mathrm{Re}\lambda_c}{\lambda} (P_c + \delta P_{c,u}) + \frac{\mathrm{Re}\lambda_t}{\lambda^5} X \right)^2 \right]$$

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Buras et al. (2005)
$(0.37 \pm 0.04) \left[\frac{0.2248}{\lambda}\right]^4$

Isidori et al. (2005)
$(0.04 \pm 0.02) \left[\frac{0.2248}{\lambda}\right]^4$

Standard model

→ $|V_{us}| = 0.2253 \pm 0.0008$ (Olive et al., 2014),
$|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$ (exclusive from $\bar{B} \to \pi l^- \bar{\nu}$, Amhis et al. (2014)),
$|V_{cb}| = (38.94 \pm 0.76) \times 10^{-3}$ (exclusive from $\bar{B} \to D^* l^- \bar{\nu}$, Amhis et al. (2014)),
$\gamma = (73.2^{+6.3}_{-7.0})^\circ$, (Charles et al., 2015),

→ $X(x_t) = \eta_X X_0(x_t) = 1.481 \pm 0.005_{\mathrm{th}} \pm 0.008_{\mathrm{exp}}$ (Buras et al., 2015).

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$$\text{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{SM}} = (7.44 \pm 0.70) \times 10^{-11}$$

Supersymmetry and flavor violation

$\rightarrow$ CKM matrix (Minimal Flavour Violation)

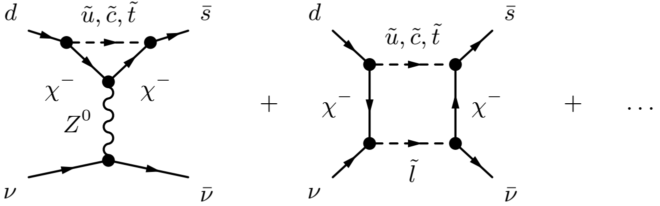
Supersymmetry and flavor violation

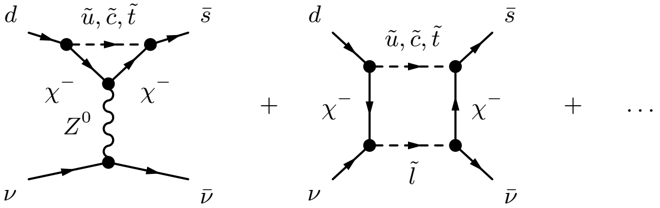
→ CKM matrix (Minimal Flavour Violation)

→ Squark mass matrices and their off-diagonal elements

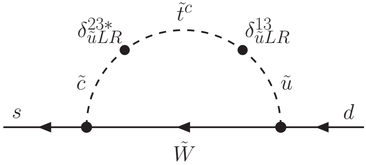
$$M^2_{\tilde{q}} = \begin{pmatrix} M^2_{\tilde{q},LL} & M^2_{\tilde{q},LR} \\ M^{2\dagger}_{\tilde{q},LR} & M^2_{\tilde{q},RR} \end{pmatrix},$$

$$\delta^{ij}_{\tilde{q}XY} = \frac{(M^2_{\tilde{q},XY})^{ij}}{\sqrt{(M^2_{\tilde{q},XX})^{ii}(M^2_{\tilde{q},YY})^{jj}}}.$$

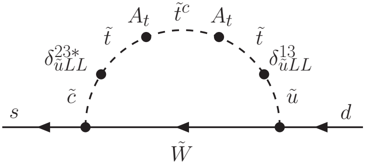

d
$\tilde{u}, \tilde{c}, \tilde{t}$
$\bar{s}$
χ^-
χ^-
Z^0
ν
$\bar{\nu}$
+
d
$\tilde{u}, \tilde{c}, \tilde{t}$
$\bar{s}$
χ^-
χ^-
$\tilde{l}$
ν
$\bar{\nu}$
+ $\cdots$



Mass insertion approximation



Colangelo and Isidori (1998)

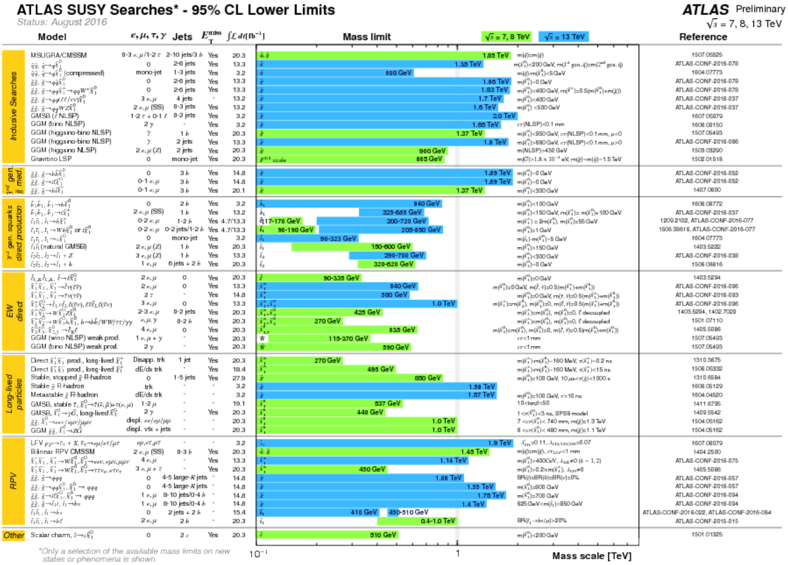


Blažek and Maták (2014)

Constraints on $\delta^{ij}_{\tilde{q}LL}$ (from Blažek and Maták (2014))

$\delta^{ij}_{\tilde{q}LL}$	Constraining observables	Upper bound	$\tilde{m}$	M_3
$\lvert\delta^{12}_{\tilde{u}LL}\rvert$	$D^0 - \bar{D}^0$	0.10 (Refs. 28 and 29)	< 1.0	< 1.0
		0.14 (Ref. 28)	0.5	1.0
		0.06 (Refs. 23, 28 and 30)	< 0.6	< 0.6
$\lvert\delta^{12}_{\tilde{d}LL}\rvert$	$K^0 - \bar{K}^0$	0.14 (Ref. 18)	< 1.0	< 2.0
$\lvert\mathrm{Re}(\delta^{12}_{\tilde{d}LL})\rvert$		0.03 (Refs. 23 and 30)	< 0.6	< 0.6
$\lvert\mathrm{Im}(\delta^{12}_{\tilde{d}LL})\rvert$		0.003 (Ref. 23)	0.5	0.5
$\lvert\mathrm{Re}(\delta^{13}_{\tilde{d}LL})\rvert$	ΔM_d, $S_{\psi K_S}$	0.1 (Refs. 23 and 30)	< 0.6	< 0.6
$\lvert\mathrm{Im}(\delta^{13}_{\tilde{d}LL})\rvert$		0.03 (Ref. 30)	< 0.6	< 0.6
			$\tilde{m}$	M_2
$\lvert\delta^{13}_{\tilde{d}LL}\rvert$	$B \to X_s\gamma$, $X_s l\bar{l}$	0.24 (Ref. 31)	0.5	0.6
$\lvert\delta^{23}_{\tilde{d}LL}\rvert$		0.11 (Ref. 31)	0.5	0.6
$\lvert\mathrm{Re}(\delta^{23}_{\tilde{d}LL})\rvert$		0.1 (Ref. 30)	< 0.6	< 0.16
$\lvert\mathrm{Im}(\delta^{23}_{\tilde{d}LL})\rvert$		0.2 (Ref. 30)	< 0.6	< 0.16

Today's sparticle mass limits



Numerical analysis

→ `SUSY_FLAVOR 2.54` Crivellin et al. (2013); Rosiek (2015); Rosiek et al. (2010)

→ Sparticle masses fixed at $M_3 = 3.0$ TeV, $M_2 = 700$ GeV, $\mu = 700$ GeV, $m_{\tilde{Q}} = m_{\tilde{q}} = 1.3$ TeV,

→ $\tan\beta \in \langle 3, 10\rangle$, $|A_t| \in \langle 2.5, 3.5\rangle$ TeV,

→ $\delta^{ij}_{\tilde{u}LL} \in \langle -0.4, 0.4\rangle$,

→ $\delta^{ij}_{\tilde{q}LR}$ - CCB and UFB bounds from scalar potential Casas and Dimopoulos (1996); Jager (2009)

$$(M^2_{\tilde{u},LR})^{ij} < m_{u_k}\sqrt{m^2_{\tilde{Q}_i} + m^2_{\tilde{u}_j} + \min\{m^2_{H_u}, m^2_{\tilde{L}_i} + m^2_{\tilde{l}_j}\}}.$$

FCNC constraints

→ $\epsilon_K = (2.23 \pm 0.25) \times 10^{-3}$ Buras et al. (2015); Olive et al. (2014)

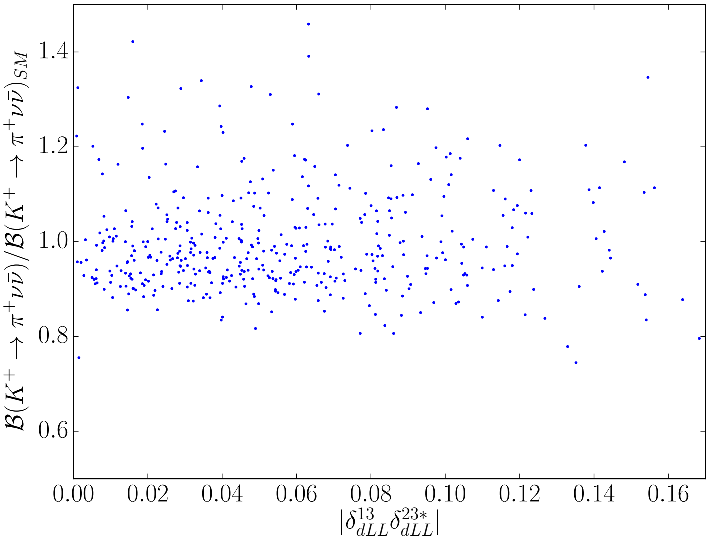
→ $\mathrm{BR}(B \to X_s \gamma) = (3.12 \pm 0.23) \times 10^{-4}$ Abdesselam et al. (2016)

→ $\mathrm{BR}(B^0 \to \mu^+ \mu^-) = (3.9 \pm 1.6) \times 10^{-10}$ Amhis et al. (2014); Bobeth et al. (2014)

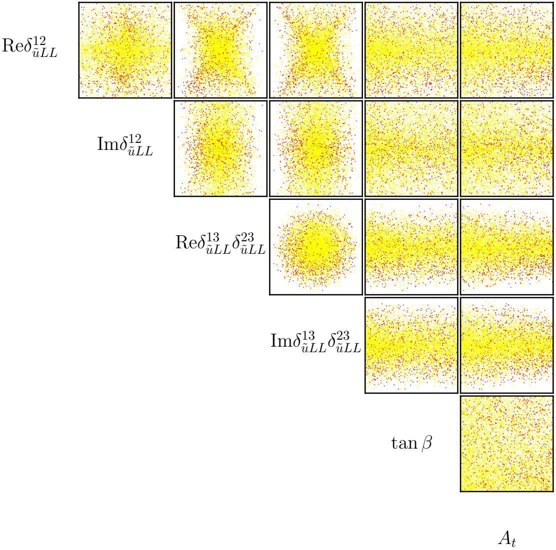
→ $\mathrm{BR}(B^0 \to \mu^+ \mu^-) = (3.1 \pm 0.5) \times 10^{-9}$ Amhis et al. (2014); Khachatryan et al. (2015)

→ $\Delta M_d = 0.506 \pm 0.090 \text{ ps}^{-1}$ Amhis et al. (2014)
$\Delta M_s = 17.757 \pm 2.37 \text{ ps}^{-1}$ Amhis et al. (2014)

Results



$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})/\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{SM}$
1.4
1.2
1.0
0.8
0.6
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
$|\delta^{13}_{dLL}\delta^{23*}_{dLL}|$


$\mathrm{Re}\delta^{12}_{\tilde{u}LL}$
$\mathrm{Im}\delta^{12}_{\tilde{u}LL}$
$\mathrm{Re}\delta^{13}_{\tilde{u}LL}\delta^{23}_{\tilde{u}LL}$
$\mathrm{Im}\delta^{13}_{\tilde{u}LL}\delta^{23}_{\tilde{u}LL}$
$\tan\beta$
A_t

Conclusions

→ $K^+ \to \pi^+ \nu\bar{\nu}$ should not be overlooked when thinking about supersymmetry,

→ possible deviations of the branching ratio can be explained in terms of large left-left squark mixing and large stop trilinear coupling constant.

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Thank you for your attention!

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