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

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New Trends in High-Energy Physics, 2-8 October 2016

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Outline

\rightarrow Introduction

- $\rightarrow~K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in the Standard Model
- $\rightarrow\,$ Supersymmetry, non-minimal flavor violation and its impact on the branching ratio
- \rightarrow Numerical analysis
- \rightarrow Conclusions

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

 $\rightarrow \text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}))_{\text{exp}} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}, \text{ Adler et al.}$ (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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- $\rightarrow \langle \pi^+ \nu \bar{\nu} | \bar{s} \gamma_\mu P_L d | K^+ \rangle \approx \sqrt{2} \langle \pi^0 e^+ \nu_e | \bar{s} \gamma_\mu P_L u | K^+ \rangle.$ Gaillard and Lee (1974); Marciano and Parsa (1996)

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



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

Inami and Lim (1981)

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

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Standard model

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

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

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(Buras et al., 2015).

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

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Supersymmetry and flavor violation

 \rightarrow CKM matrix (Minimal Flavour Violation)

Supersymmetry and flavor violation

- $\rightarrow\,$ CKM matrix (Minimal Flavour Violation)
- $\rightarrow\,$ Squark mass matrices and their off-diagonal elements

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

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

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Mass insertion approximation



Colangelo and Isidori (1998)



Blažek and Maták (2014)

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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
$\left \delta^{12}_{\tilde{u}LL}\right $	$D^0 - \bar{D}^0$	$0.10~({\rm Refs.}~28~{\rm and}~29)$	< 1.0	< 1.0
		0.14 (Ref. 28)	0.5	1.0
		0.06 (Refs. 23, 28 and 30)	< 0.6	< 0.6
$\left \delta^{12}_{\tilde{d}LL} \right $	$K^0 - \bar{K}^0$	0.14 (Ref. 18)	< 1.0	< 2.0
$\left \operatorname{Re}\left(\delta_{\tilde{d}LL}^{12}\right)\right $		$0.03~({\rm Refs.}~23~{\rm and}~30)$	< 0.6	< 0.6
$\left \operatorname{Im} \left(\delta^{12}_{\tilde{d}LL} \right) \right $		0.003 (Ref. 23)	0.5	0.5
$\left \operatorname{Re}\left(\delta_{\tilde{d}LL}^{13}\right)\right $	$\Delta M_d, S_{\psi K_S}$	0.1 (Refs. 23 and 30)	< 0.6	< 0.6
$\left \operatorname{Im} \left(\delta^{13}_{\tilde{d}LL} \right) \right $		0.03 (Ref. 30)	< 0.6	< 0.6
			\tilde{m}	M_2
$\delta^{13}_{\tilde{d}LL}$	$B \to X_s \gamma, X_s l \bar{l}$	0.24 (Ref. 31)	0.5	0.6
$\left \delta^{23}_{\tilde{d}LL} \right $		0.11 (Ref. 31)	0.5	0.6
$\left \operatorname{Re}\left(\delta_{\tilde{d}LL}^{23}\right)\right $		0.1 (Ref. 30)	< 0.6	< 0.16
$\left {\rm Im}\!\left(\!\delta^{23}_{\tilde{d}LL}\right)\right $		0.2 (Ref. 30)	< 0.6	< 0.16

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Today's sparticle mass limits

 $\sqrt{s} \equiv 7, 8$

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016 Model e, μ, τ, γ Jets $E_{\tau}^{\min} f \mathcal{L} d(n^{-1})$ Mass limit Mass limit

	ATLAS Preliminary $\sqrt{s} = 7, 8, 13 \text{ TeV}$			
TeV √s = 13 TeV	Reference			
million III	1507.05525			
n(3)<200 GeV. m(1" equ.4)cm(2" equ.4)	ATLAS-CONF-2016-078			
mij)-m(l)/:><5GeV	1604.07773			
⇒ (²) +0 GeV	ATLAS-CONF-2016-078			

	USCHRACUSSM	0-3 v. jert-2 T	2-10 9980.3 6	Yes	20.3	67	1,05 TeV	w H(mar N)	1907.09649	
	44.4-422	•	2-6 jets	Ves	13.3	4	1.35 TeV	m(8'_1)<200 GeV, m(1" gas.4)cm(2"" gcs.4)	ATLAS-CONF-2016-078	
8	ş q , q → q ξ j (compressed)	mono jet	1-3 jets	Yes	3.2	4 618 GeV		mkj)-m(i'j)<5GeV	1604.07775	
5	22.3-+99Ki	0	2-0 jets	Yes	13.3	1	1.86 TeV	m(47)+0 GeV	ATLAS-CONF-2016-078	
6	22. 3-++++++++++++++++++++++++++++++++++++	0	2-6 jets	Yes	13.3	ì	1.83 TeV	m(P1)<400 GeV, m(P1)=0.5(m(P1)+m(2))	ATLAS-CONF-2016-078	
	22.3- +++ ((()vy)81	س م ال	4 jets		13.2	ì	1.7 TeV	m(²))<400 GaV	ATLAS-CONF-2016-037	
	22.2-499WZR1	2 r. µ (SS)	D-3 jets	Yes	13.2	8	1.6 TeV	m(4 ²) <500 GeV	ATLAS-CONF-2016-037	
3	GMSB (2 NLSP)	1-27+0-1	{ 0-2 jets	Yes	3.2	2	2.0 Te	V	1607.05979	
5	GGM (bine NLSP)	2 %		Ves	3.2	i	1.05 TeV	cz (MLSP)<0.1 mm	1606.09150	
g	GGM (higgsino-bino NLSP)	7	1.6	Yes	20.3	i de la companya de la	1.37 TeV	m[i ²])<950 GeV, cr(NLSP]<0.1mm, µ<0	1507.05493	
-	GGM (higgsino-bino NLSP)	7	2 jets	Yes	13.3	2	1.8 TeV	mil(1)-880 GeV. cr/NLSPI<0.1mm, u>0	ATLAS-CONF-2016-086	
	GGM (hiocsino NLSP)	$2 \epsilon \cdot \mu(Z)$	2 ints	Ves	20.3	2 980 GeV	_	mINLSPI>430 GeV	1503.03290	
	Gravitino LSP	0	mono-iet	Ves	20.3	F ^{1/2} main 805 GeV		mK7(>1.8 × 10 ⁻¹ eV.m(2)-m(3)-1.5 TeV	1502.01518	
P.a.t.							-			
00	22. 2-+66X1	0	31-	Yes	14.8	1	1.89 TeV	m(K_1)+0 GeV	ATLAS-CONF-2016-052	
"E	22.3-+#2()	0-1 e. p	31	Yes	14.8	1	1.89 leV	== ((7)+0 GeV	ATLAS-CONF-2016-052	
50 180	22. 2-+121	0-1 <i>×.µ</i>	31	Yes	20.1	i i i i i i i i i i i i i i i i i i i	1.37 TeV	m(²)<300 GeV	1407.0600	
	11.1.1.18	0	24	Ver	3.2	1 840 GeV		mil ⁰ ic1000eV	1000.00772	
28	5.4. 5 NP ⁴	2 r. a (SS)	1.6	Men	13.2	5 723-001 GeV		mil(2)+150 GeV m(2) = m(2)+100 GeV	ATL AR. CONE. 2016.037	
10	LL L	0.2 + 4	1.3.5	New	4 2/12 2	217-176 GeV		milita math militate and	1200 2112 ATLASJOOME.2016.077	
55	101 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	0.2 - 4	0.2144/1.23	- Mare	4 7/10.0	00 100 Cell		night to h	1506 POSTE ATLAS COME SILLE OFF	
2.8	1111 A - Wales Wills	0 2.1.0	o a jour i a i	. 105	4.7713.3	1 99-196 Gev		mp / c roav	10010010, 81040-0011 4010-017	
8. 11	$L_1L_1, L_2 \rightarrow cE_1$ $L_2 / contrard CM02C0$	2000	nonorjet	Nes.	20.2	100 000 CeV		m(k,)-m(r,)+b UseV	1004/07/75	
2 2	101 (matche Gwater)	A 10. JA (A.)		100	20.3	1		mp10150GeV	140.3 (56.56	
2 1	1212, 12 - 11 1 X	30.00(2)	1.0	105	13.3	200700 GeV		m[4])<300 GeV	ALCAS-CONF-2016-036	
	$1_2I_2, I_2 \rightarrow I_1 + k$	14,4	0 jets + 2 8	105	20.3	13 320-620 GeV		m(r_1)+0 GeV	1506.08816	
	$i_{i,k}i_{i,k}$, $i \rightarrow i_{i}^{0}$	2 e. µ	0	Yes	20.3	7 90-335 GeV		m(#1):0 GeV	1403.5294	
	$\hat{x}_1 \hat{x}_1, \hat{x}_1 \rightarrow \hat{c} \pi \hat{c} \hat{p}_1$	2	0	Yes	13.3	χ [*] 640 GeV	m(²)	IGeV.ml2.91:0.5(m)?", \wm(?",1)	ATLAS-CONF-2016-036	
	$\hat{X}_1 \hat{X}_1, \hat{X}_1 \rightarrow \hat{\tau} \pi(\tau \bar{\tau})$	27		Ves	14.8	3 580 GeV		million Gal m(# it-0 Simili amili)	ATLAS-CONF-2016-003	
- N	St. Beach at little take later	3	0	New	12.3	1.0 Te	mili in	roll, 1 milling, mill the Simili lam(1)	ATLAS.CONF.2016.009	
Nº 2	Sition Wilde	2.3 4.4	D-2 jets	Yes	20.3	10.10 425 GeV		mill lamill, milling, released	1403.5294, 1402.7029	
A. A.	P.P. W. W.P. L.P. Lattimeter	100 44.4	0.2 6	Mes	20.3	270 GeV		millionniki) million (decounted	1501.071.10	
	2020 ST	4		Nee	20.2	435 GeV	- 10 ¹⁰ 1-	- (1 ⁰) - (1 ⁰)-0 - (2 ¹)-0 (1 ⁰)-(1 ⁰)	1405 5085	
	GGM (wine NI SP) week need	1 - 4 - 2		New	20.3	110 000 CeV	metta-	und in the line of the second of the line of the	1507.05495	
	OCM (kine NLRP) week good			100	20.3	in the and dev		and and	4507.05400	
_	dow (or or rear) weak proc.	* 7		105	20.3	* 550 GeV		62 S. I PRES	1007.00490	
	Direct \$1.51 prod., long-lived \$1	Disapp. trk	1 jet	Yes	20.3	x [*] 270 GeV		$m(\tilde{t}_1^+) er(\tilde{t}_2^+) \sim 100 \text{ MeV}, r(\tilde{t}_1^+) = 0.2 \text{ ns}$	1310.3675	
	Direct. St Ki prod., long-lored St	dE/dx trk		Yes	18.4	3 495 GeV		m(x ₁ [*])/m(x ₂ [*])~160 MaY, r(x ₁ [*])<15 na	1506.05332	
0	Stable, stopped § R-hadron	0	1-5 jets	Yes	27.9	2 850 GeV		m(k ⁰ ₁)=100 GeV, 10 µa <r(z)<1000 a<="" td=""><td>1310.6584</td></r(z)<1000>	1310.6584	
2.2	Stable 2 R-hadron	#k			3.2	i i	1.58 TeV		1606.05129	
6.7	Metastable 2 R-hadron	dE/dx trk			3.2	i i	1.57 TeV	mil ² 11:100 GeV, r>10 ms	1604.04520	
5 3	GMSB, stable 7, £ →7(2, 2)+7(-	κ.μ) 1-2 μ			19.1	x 537 GeV		10 <tan 0<50<="" td=""><td>1411.0795</td></tan>	1411.0795	
-1 -1	GMSB. 8°→>0, long-lived 8°	2 %		Yes	20.3	440 GeV		1 <r(x<sup>2)<3 na. SPS8 model</r(x<sup>	1409.5542	
	22 E-may low land	displ. ev/ep/s	- 14		20.3	1.0 Te	V	7 <cr></cr> ccr0(1)<740 mm, m(2)=1.3 TeV	1504.05162	
	GGM 22, 81 →207	displ. vtx + je	ets -		20.3	x 1.0 Te	V.	8 <cr(3) 480="" <="" m(2):1.1="" mm,="" td="" tev<=""><td>1504.05162</td></cr(3)>	1504.05162	
	104	-1.5			2.0		107-1	X -011.1	1007.05970	
	Disease ODV CMPPH			No.	3.2	2	1.9 TeV	and a state of the	1007.06079	
	et et et united	z r. ji (33)	0.3 8	105	40.3	24	THE TOTAL	and the state of t	1404 2500	
	$X_1X_1, X_1 \rightarrow WU_1, X_1 \rightarrow eet, epit, p$	4×.4		105	13.3	1.1	Tev	mp110400007, Arat#0 (k = 1, 2)	ALLAS-CONF-2016-075	
>	$X_1X_1, X_1 \rightarrow wx_1, X_1 \rightarrow vv_{\ell}, ev_{\ell}$		a brance to be	105	20.3	450 GeV		mitri bozonici 3 Autri	1403.5085	
<u>0</u> ,	58-8-999	0 4	ro ange R je	B '	14.8	1.08	lev	any/conjujconjujco%	ATLAS-CONF-2016-057	
ас 2	22.2→94X1.X1 → 944	0 4	to arge 8 je	s ·	14.8	1	1.55 TeV	m(4);s00 GeV	ATLAS-CONF-2016-057	
	$\underline{22}, \underline{3} \rightarrow \exists \widehat{\chi}_1^*, \widehat{\chi}_1^* \rightarrow qqq$	ک تر ۱۰	8-10 jetsi0-4	6 T.	14.8	i i	1.75 TeV	m(8))=700 GeV	ATLAS-CONF-2016-034	
	22. 3-+11. 11-+ba	1.00	0-10 jets/0-4	b -	14.0	2	1.4 TeV	825 GeV <m(j<sub>4)<850 GeV</m(j<sub>	ATLAS-CONF-2018-004	
	$\tilde{z}_1 \tilde{s}_1, \tilde{s}_1 \rightarrow \tilde{b}_2$	0	2 jets + 2 i		15.4	i 410 GeV 450-510 GeV			ATLAS-CONF-2016-022, ATLAS-CONF-2016-084	
	$\tilde{I}_1 \tilde{I}_1, \tilde{I}_1 \rightarrow b t$	2 e. µ	25		20.3	i, 0.4-1.0 Te	v.	BPs(/, → 8x/,a)>20%	ATLAS-CONF-2015-015	
Other	Scalar charm 2-3-10	0	2.	Vec	20.3	5 510 GeV	_	mil ⁰ 1/2006aV	1501.01325	
Con ler					22.0		ī.			
	*Chily a selection of the available mass limits on new 10 ⁻¹ 1 Mass scale [TeV]									

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Numerical analysis

- \rightarrow SUSY_FLAVOR 2.54 Crivellin et al. (2013); Rosiek (2015); Rosiek et al. (2010)
- $\rightarrow\,$ 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,
- $\rightarrow \ \tan\beta \in \langle 3, 10 \rangle, \, |A_t| \in \langle 2.5, 3.5 \rangle$ TeV,

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

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

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

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FCNC constraints

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

- → BR($B \rightarrow X_s \gamma$) = (3.12 ± 0.23) × 10⁻⁴ Abdesselam et al. (2016)
- → BR($B^0 \to \mu^+ \mu^-$) = (3.9 ± 1.6) × 10⁻¹⁰ Amhis et al. (2014); Bobeth et al. (2014)
- → BR($B^0 \to \mu^+ \mu^-$) = (3.1 ± 0.5) × 10⁻⁹ Amhis et al. (2014); Khachatryan et al. (2015)
- $\rightarrow \Delta M_d = 0.506 \pm 0.090 \text{ ps}^{-1} \text{ Amhis et al. (2014)}$ $\Delta M_s = 17.757 \pm 2.37 \text{ ps}^{-1} \text{ Amhis et al. (2014)}$

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Conclusions

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Conclusions

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Thank you for your attention!

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