

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

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# Outline

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

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

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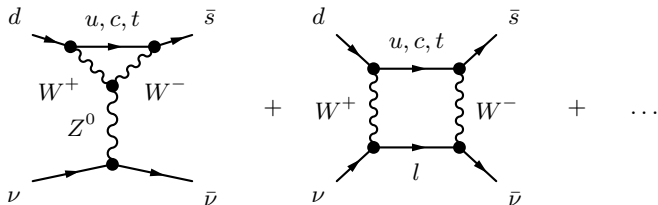
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→  $\langle \pi^+ \nu \bar{\nu} | \bar{s} \gamma_\mu P_L d | K^+ \rangle \approx \sqrt{2} \langle \pi^0 e^+ \nu_e | \bar{s} \gamma_\mu P_L u | K^+ \rangle$ . Gaillard and Lee (1974); Marciano and Parsa (1996)



# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ amplitude



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

Inami and Lim (1981)

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

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

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Mescia and Smith (2007)

$$(5.173 \pm 0.025) \times 10^{-11} \left[ \frac{\lambda}{0.225} \right]^8$$

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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  $\bar{B} \rightarrow \pi l^- \bar{\nu}$ ,  
Amhis et al. (2014)),  
 $|V_{cb}| = (38.94 \pm 0.76) \times 10^{-3}$  (exclusive from  $\bar{B} \rightarrow D^* l^- \bar{\nu}$ ,  
Amhis et al. (2014)),  
 $\gamma = (73.2_{-7.0}^{+6.3})^\circ$ , (Charles et al., 2015),
- $X(x_t) = \eta_X X_0(x_t) = 1.481 \pm 0.005_{\text{th}} \pm 0.008_{\text{exp}}$  (Buras et al., 2015).

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

# Supersymmetry and flavor violation

→ CKM matrix (Minimal Flavour Violation)

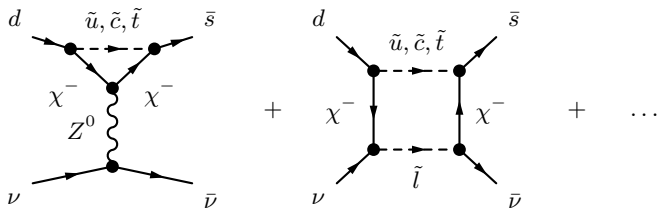


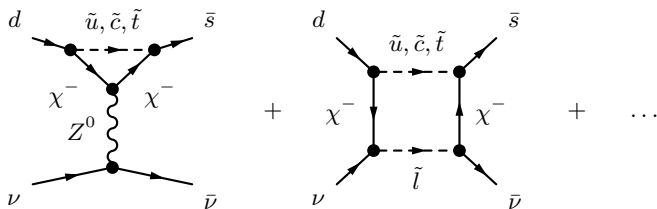
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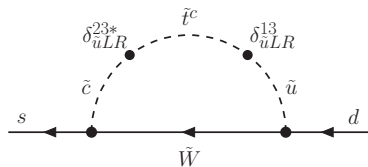
→ Squark mass matrices and their off-diagonal elements

$$M_{\tilde{q}}^2 = \begin{pmatrix} M_{\tilde{q},LL}^2 & M_{\tilde{q},LR}^2 \\ M_{\tilde{q},LR}^{2\dagger} & M_{\tilde{q},RR}^2 \end{pmatrix},$$
$$\delta_{\tilde{q}XY}^{ij} = \frac{(M_{\tilde{q},XY}^2)^{ij}}{\sqrt{(M_{\tilde{q},XX}^2)^{ii} (M_{\tilde{q},YY}^2)^{jj}}}.$$

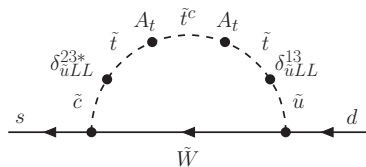




## Mass insertion approximation



Colangelo and Isidori (1998)



Blažek and Maták (2014)

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

$\delta_{\tilde{q}LL}^{ij}$	Constraining observables	Upper bound	$\tilde{m}$	$M_3$	
$ \delta_{\tilde{u}LL}^{12} $	$D^0 - \bar{D}^0$	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	
$ \delta_{\tilde{d}LL}^{12} $	$K^0 - \bar{K}^0$	0.14 (Ref. 18)	< 1.0	< 2.0	
		$ \text{Re}(\delta_{\tilde{d}LL}^{12}) $	0.03 (Refs. 23 and 30)	< 0.6	< 0.6
		$ \text{Im}(\delta_{\tilde{d}LL}^{12}) $	0.003 (Ref. 23)	0.5	0.5
$ \text{Re}(\delta_{\tilde{d}LL}^{13}) $	$\Delta M_d, S_{\psi K_S}$	0.1 (Refs. 23 and 30)	< 0.6	< 0.6	
		$ \text{Im}(\delta_{\tilde{d}LL}^{13}) $	0.03 (Ref. 30)	< 0.6	< 0.6
			$\tilde{m}$	$M_2$	
$ \delta_{\tilde{d}LL}^{13} $	$B \rightarrow X_s \gamma, X_s \bar{l}l$	0.24 (Ref. 31)	0.5	0.6	
		$ \delta_{\tilde{d}LL}^{23} $	0.11 (Ref. 31)	0.5	0.6
$ \text{Re}(\delta_{\tilde{d}LL}^{23}) $		0.1 (Ref. 30)	< 0.6	< 0.16	
$ \text{Im}(\delta_{\tilde{d}LL}^{23}) $		0.2 (Ref. 30)	< 0.6	< 0.16	

# Today's sparticle mass limits

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13$  TeV

Model	$\epsilon, \mu, \tau, \gamma$	Jets	$E_{T}^{\text{miss}}$	$f_{\mathcal{L}} d(B^{-1})$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference
Inclusive Searches	MSUGRA/CMSSM	$0 < \mu, \tau, \gamma < 2$	$2-10$ jets/3 $\beta$	Yes	20.3	4.8	1.89 TeV	$m(\tilde{g})=0$
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	2-6 jets	Yes	13.3	1.35 TeV	816 GeV	$m(\tilde{g})=230$ GeV, $m(\tilde{q})=m(\tilde{u}_L)=m(\tilde{d}_L)$
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$ (compressed)	monojet	1-3 jets	Yes	3.2			$m(\tilde{g})=m(\tilde{q})=15$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	2-6 jets	Yes	13.3			$m(\tilde{g})=0$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g} \rightarrow q\bar{q}W\tilde{g}$	0	2-6 jets	Yes	3.2			1.83 TeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g} \rightarrow q\bar{q}W\tilde{g}$	$3 \leq \mu, \tau, \gamma < 4$	4 jets	-	13.2			$m(\tilde{g})=480$ GeV, $m(\tilde{q})=1.55m(\tilde{t}_1)=m(\tilde{b}_1)$
	$\tilde{g} \rightarrow q\bar{q}\tilde{g} \rightarrow q\bar{q}W\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	8-9 jets	Yes	13.2			1.7 TeV
	GMSB (bino NLSP)	$1.2 < \mu < 1$	8-9 jets	Yes	3.2			1.6 TeV
	GGM (bino NLSP)	$2\gamma$	-	Yes	3.2			2.0 TeV
	GGM (higgsino-bino NLSP)	$\gamma$	1-6 jets	Yes	3.2			1.85 TeV
	GGM (higgsino-bino NLSP)	$\gamma$	2 jets	Yes	13.3			1.37 TeV
	GGM (higgsino NLSP)	$2 \leq \mu < 2$	2 jets	Yes	20.3			1.8 TeV
Gravitino LSP	0	monojet	Yes	20.3	980 GeV 895 GeV		$m(\tilde{g})=180$ GeV, $m(\tilde{q})=0.1$ mm, $m(\tilde{g})=1.8 \times 10^{11} \text{ eV}$ , $m(\tilde{g})=m(\tilde{g})=1.5$ TeV	
3 $\beta$ jets	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	3 $\beta$	Yes	14.8			$m(\tilde{g})=0$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$0 < \mu, \tau, \gamma < 1$	3 $\beta$	Yes	14.8			$m(\tilde{g})=0$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$0 < \mu, \tau, \gamma < 1$	3 $\beta$	Yes	20.1			$m(\tilde{g})=330$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	2 $\beta$	Yes	3.2			1.29 TeV
3 $\beta$ jets + monojet	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	2 $\beta$	Yes	3.2			$m(\tilde{g})=180$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	2 jets (SS)	Yes	13.2			$m(\tilde{g})=180$ GeV, $m(\tilde{q})=m(\tilde{u}_L)=m(\tilde{d}_L)=180$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$0 < \mu, \tau, \gamma < 1$	1-2 $\beta$	Yes	4.7/13.3	11178 GeV	325-665 GeV 200-726 GeV	$m(\tilde{g})=2$ TeV, $m(\tilde{q})=35$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$ or $\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$0 < \mu, \tau, \gamma < 1$	2 jets (SS) + 1 $\beta$	Yes	4.7/13.3	91-190 GeV	206-630 GeV	$m(\tilde{g})=0$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	monojet	Yes	3.2			$m(\tilde{g})=m(\tilde{q})=5$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$ (natural GMSB)	$2 \leq \mu, \tau, \gamma < 1$	1 $\beta$	Yes	20.3			$m(\tilde{g})=180$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$3 \leq \mu, \tau, \gamma < 4$	1 $\beta$	Yes	13.3			$m(\tilde{g})=330$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$1 \leq \mu, \tau, \gamma < 2$	6 jets + 2 $\beta$	Yes	20.3			$m(\tilde{g})=0$ GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	2 jets	Yes	20.3			90-535 GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	2 jets	Yes	13.3			840 GeV
EW direct	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	0	Yes	20.3			180 GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	0	Yes	14.8			980 GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	0	Yes	13.3			1.0 TeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	0	Yes	20.3			270 GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	0	Yes	20.3			435 GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	0	Yes	20.3			119-370 GeV
	GGM (bino NLSP) weak prod.	$1 \leq \mu, \tau, \gamma < 2$	0	Yes	20.3			535 GeV
	GGM (bino NLSP) weak prod.	$2\gamma$	0	Yes	20.3			590 GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	0	Yes	20.3			$m(\tilde{g})=m(\tilde{q})=150$ GeV, $m(\tilde{g})=0.2$ ns
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	0	Yes	20.3			$m(\tilde{g})=m(\tilde{q})=180$ GeV, $m(\tilde{g})=1.800$ s
Long-lived particles	Dimuon $\tilde{g}$ prod., long-lived $\tilde{g}$	dilepton trk	1 jet	Yes	20.3			$m(\tilde{g})=100$ GeV, $\tau > 10$ ns
	Dimuon $\tilde{g}$ prod., long-lived $\tilde{g}$	dilepton trk	0	Yes	18.4			10-lepton-6 $\beta$
	Stable stopped $\tilde{g}$ R-hadron	trk	1-5 jets	Yes	27.9			$\tau > 100$ GeV, $10 \leq \tau < 1800$ s
	Stable $\tilde{g}$ R-hadron	trk	0	Yes	3.2			1.58 TeV
	Unstoppable $\tilde{g}$ R-hadron	dilepton trk	-	3.2				1.57 TeV
	GMSB, stable $\tilde{g}$ , $\tilde{g} \rightarrow \tilde{g} + \tilde{g}$	1 $\beta$	0	Yes	19.1			537 GeV
	GMSB, $\tilde{g} \rightarrow \tilde{g}$ , long-lived $\tilde{g}$	2 $\beta$	0	Yes	20.3			446 GeV
	$\tilde{g} \rightarrow \tilde{g} + \tilde{g}$	displ. vtx	0	Yes	20.3			1.0 TeV
	GGM $\tilde{g} \rightarrow \tilde{g} + \tilde{g}$	displ. vtx + jets	0	Yes	20.3			1.0 TeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$0 \leq \mu, \tau, \gamma < 1$	0	Yes	3.2			1.9 TeV
RPV	bilinear RPV CMSSM	$2 \leq \mu, \tau, \gamma < 3$	0-3 $\beta$	Yes	20.3			$\tilde{A}_{11} \leq 0.11$ , $\tilde{A}_{22} \leq 0.07$
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$4 \leq \mu, \tau, \gamma < 5$	0	Yes	13.3			$m(\tilde{g})=0$ , $\tilde{A}_{11} \leq 0.1$
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$3 \leq \mu, \tau, \gamma < 4$	0	Yes	20.3			$m(\tilde{g})=480$ GeV, $\tilde{A}_{11} \leq 0.1$
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$0 < \mu, \tau, \gamma < 1$	0	Yes	14.8			$m(\tilde{g})=480$ GeV, $\tilde{A}_{11} \leq 0.1$
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$0 < \mu, \tau, \gamma < 1$	4-5 large- $\beta$ jets	-	14.8			1.38 TeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$0 < \mu, \tau, \gamma < 1$	4-5 large- $\beta$ jets	-	14.8			1.35 TeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$1 \leq \mu, \tau, \gamma < 2$	8-10 jets+0-4 $\beta$	-	14.8			1.75 TeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$1 \leq \mu, \tau, \gamma < 2$	8-10 jets+0-4 $\beta$	-	14.8			1.4 TeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	2 jets + 2 $\beta$	-	15.4			418 GeV
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	$2 \leq \mu, \tau, \gamma < 3$	2 jets + 2 $\beta$	-	20.3			820 GeV+10 $\beta$ +1850 GeV
Other	Scalar charm, $\tilde{g} \rightarrow c\bar{c}\tilde{g}$	0	2 $\beta$	Yes	20.3			910 GeV

\*Only a selection of the available mass limits on new states or phenomena is shown.

10<sup>-1</sup>

1

Mass scale [TeV]

## 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,
- $\delta_{\tilde{u}LL}^{ij} \in \langle -0.4, 0.4 \rangle$ ,
- $\delta_{\tilde{q}LR}^{ij}$  - CCB and UFB bounds from scalar potential Casas and Dimopoulos (1996); Jager (2009)

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

## FCNC constraints

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

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

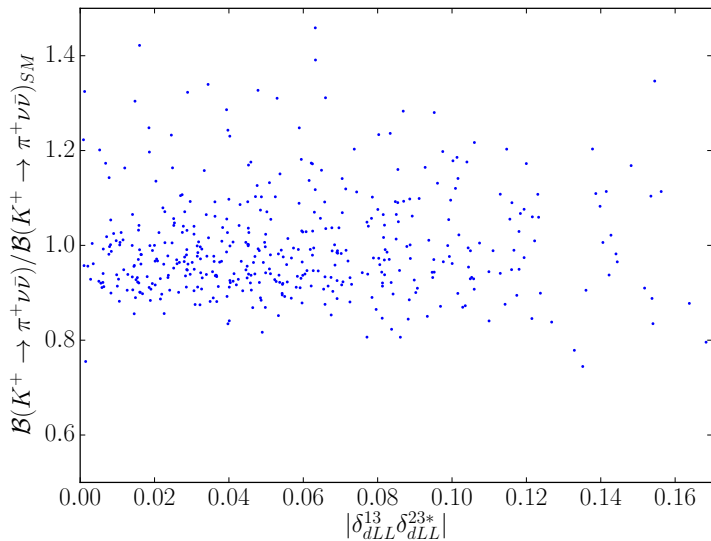
$$\rightarrow \text{BR}(B^0 \rightarrow \mu^+ \mu^-) = (3.9 \pm 1.6) \times 10^{-10} \text{ Amhis et al. (2014); Bobeth et al. (2014)}$$

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

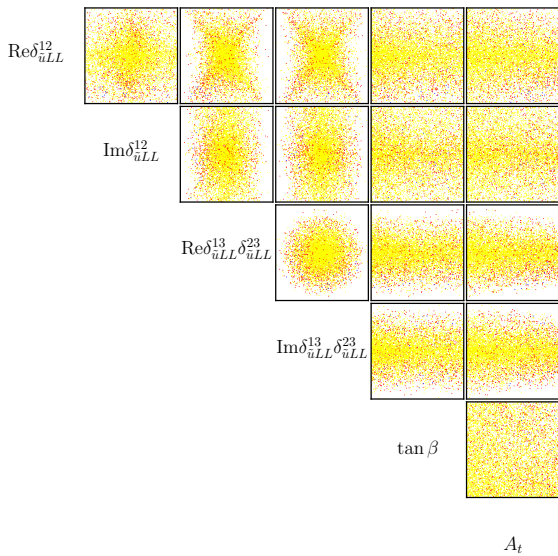
$$\rightarrow \Delta M_d = 0.506 \pm 0.090 \text{ ps}^{-1} \text{ Amhis et al. (2014)}$$

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

## Results







## Conclusions

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  should not be overlooked when thinking about supersymmetry,
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- possible deviations of the branching ratio can be explained in terms of large left-left squark mixing and large stop trilinear coupling constant.

Thank you for your attention!

## References I

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