Probing SUSY effects in $K_S^0 \to \mu^+\mu^-$

Miriam Lucio

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V. Chobanova, G. D'Ambrosio, T. Kitahara, M. Lucio Martinez,
D. Martinez Santos, I. Suarez Fernandez, K. Yamamoto

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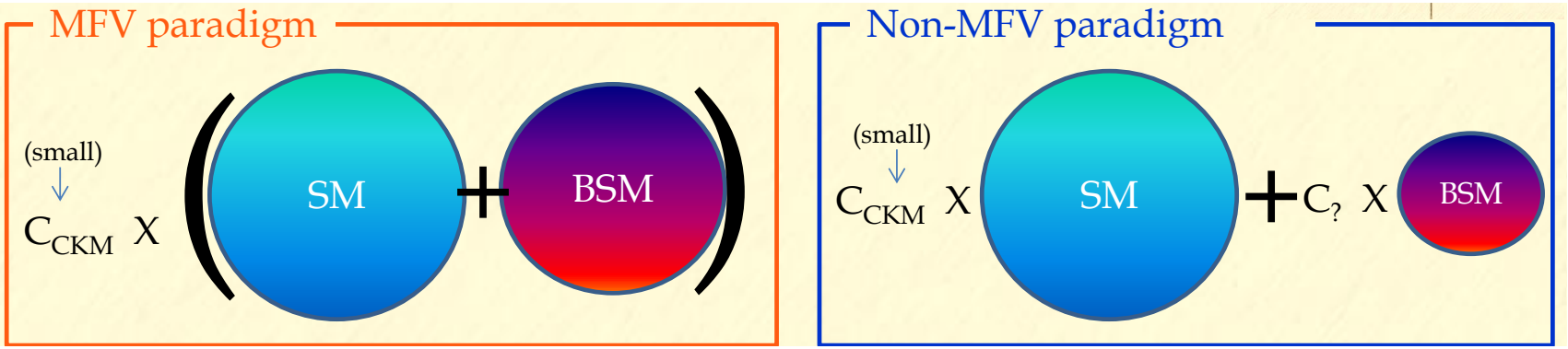
Motivation

- $P \to l^+ l^-$ decays very sensitive to the Higgs sector of MSSM ($\propto \tan^6 \beta / M_A^4$)
- If BSM Physics is at energies $> \mathcal{O}(\mathrm{TeV})$, the only possibility to see it in quark flavour physics is if it has new sources of Flavour Violation: **non-MFV**, not originating from the CKM Matrix

	$<$ 1 TeV	few TeV	$>$ few TeV
Direct searches	Reachable @ 8 TeV	Reachable @ 14 TeV	Not reachable
Quark flavour			
Anarchic structure	$> \mathcal{O}(1)$ effects	$\mathcal{O}(1)$ effects	$\mathcal{O}(1)$ effects
Small misalignment	$\mathcal{O}(1)$ effects	$\mathcal{O}(10\%)$ effects	$\mathcal{O}(1\text{-}10\%)$ effects
MFV	$\mathcal{O}(10\%)$ effects	$\mathcal{O}(1\%)$ effects	Invisible

Motivation

- **Minimal Flavour Violation:** $B_s^0 \to \mu^+\mu^-$ is the dominant constraint
- **New sources for Flavour Violation:** $B_{s(d)}^0 \to \mu^+\mu^-$, $K_{S(L)}^0 \to \mu^+\mu^-$ carry **complementary** information



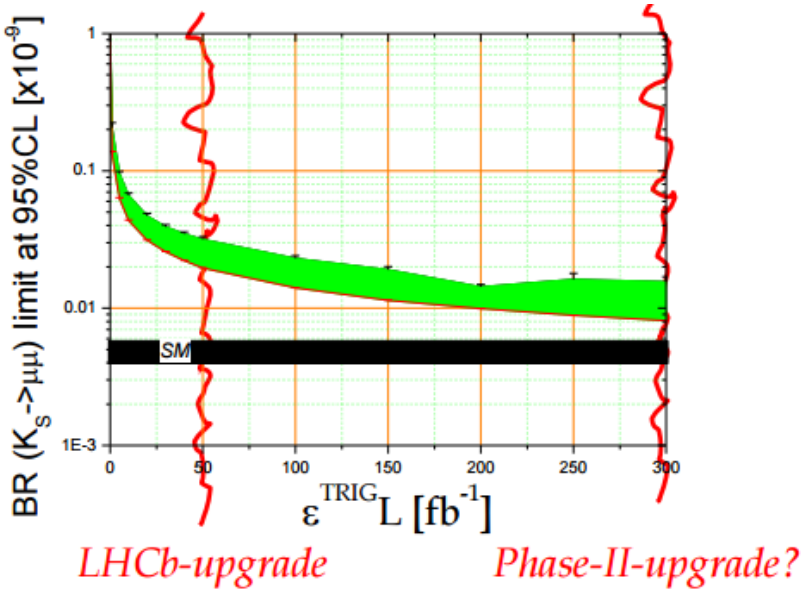
$C \sim 1 \Rightarrow$ bounds from kaon physics go up to a scale of $10^5\,\mathrm{TeV}$

$K_S^0 \to \mu^+\mu^-$

$K_S^0 \to \mu^+\mu^-$

$$\mathcal{B}_{SM}(K_S^0 \to \mu^+\mu^-) = (5.18 \pm 1.50_{\rm LD} \pm 0.02_{\rm SD}) \times 10^{-12}$$

[Nucl. Phys. B366 (1991) 189], [JHEP 01 (2004) 009]



- Strongly suppressed decay in the SM

LHCb Run1 data (EPJ C (678) 77)

$$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 0.8(1.0) \times 10^{-9}$$

90%, 95% CL

- Good prospects for LHCb to enter the most interesting region in the future

- Dispersive treatment of $K_S^0 \to \gamma\gamma$ and $K_S^0 \to \gamma l^+ l^-$ [EPJ C76 (2016) 604]: $K_S^0 \to \gamma\gamma$, $K_S^0 \to \gamma\mu^+\mu^-$, $K_S^0 \to \mu^+\mu^-\mu^+\mu^-$, $K_S^0 \to \mu^+\mu^- e^+ e^-$ (measurable @ LHCb) are relevant to improve LD prediction

Formalism

Mass Insertion Approximation (MIA)

[Nucl. Phys. B830 (2010) 17–94], [arXiv:hep-ph/9511250]

- MI terms as phenomenological parameters at the SUSY scale, $\mu^{\rm SUSY} = \sqrt{\tilde{m}_Q M_3}$

$$\left(\delta_d^{LL}\right)_{ij} = \frac{\left[\left(\mathcal{M}_D^2\right)_{LL}\right]_{ij}}{\tilde{m}_Q^2} = \frac{(m_Q^2)_{ji}}{\tilde{m}_Q^2},$$
$$\left(\delta_d^{RR}\right)_{ij} = \frac{\left[\left(\mathcal{M}_D^2\right)_{RR}\right]_{ij}}{\tilde{m}_d^2} = \frac{(m_D^2)_{ij}}{\tilde{m}_d^2},$$

- $\mathcal{M}_{D,U}^2$: 6x6 squark mass matrices; $\tilde{m}_Q^2, \tilde{m}_d^2, \tilde{m}_u^2$: average of the Q, D, and U-squark masses

Observables

$\mathcal{B}(\mathbf{K_S^0} \to \mu^+\mu^-)$:

- Relation between $\mathcal{B}(K_S^0 \to \mu^+\mu^-)$ and $\mathcal{B}(K_L^0 \to \mu^+\mu^-)$ different for **left-handed** and **right-handed** new physics scenarios
  1. **left-handed**: $C_P = C_S$ (P: pseudoscalar, S: scalar)
  2. **right-handed**: $C_P = -C_S$ (P: pseudoscalar, S: scalar)
  3. **right-handed** + **left-handed**
  - $\mathcal{B}(K_L^0 \to \mu^+\mu^-)^{\mathrm{EXP}}$ upper bound on $\mathcal{B}(K_S^0 \to \mu^+\mu^-)$ for 1 and 2, alleviated for 3

$\mathcal{B}(\mathbf{K_S^0} \to \mu^+\mu^-)_{\mathrm{eff}}$

- Includes and interference contribution with $K_L^0 \to \mu^+\mu^-$

Direct CP asymmetry

$$A_{CP}(K_S^0 \to \mu^+\mu^-)_{D,D'} = \frac{\mathcal{B}(K_S^0 \to \mu^+\mu^-)_{\mathrm{eff}}(D) - \mathcal{B}(K_S^0 \to \mu^+\mu^-)_{\mathrm{eff}}(D')}{\mathcal{B}(K_S^0 \to \mu^+\mu^-)_{\mathrm{eff}}(D) + \mathcal{B}(K_S^0 \to \mu^+\mu^-)_{\mathrm{eff}}(D')}$$

D, D': initial K^0–$\overline{K}^0$ asymmetry, using K^- and K^+ tagging

Observables

- MSSM contribution to $\mathcal{B}(K_S^0 \to \mu^+\mu^-) \propto [(\delta_d^{LL(RR)})_{12}\mu \tan^3\beta M_3/M_A^2]^2$

Observable	Constraint
$\mathcal{B}(K_S^0 \to \mu^+\mu^-)^{\mathrm{EXP/SM}}$	unconstrained
$\mathcal{B}(K_L^0 \to \mu^+\mu^-)^{\mathrm{EXP/SM}}$ (*)	1.00 ± 0.12 $(+)$ [PRL 119 (2017) 201802], 0.84 ± 0.16 $(-)$ [hep-ph/9411439]
$\Delta M_K^{\mathrm{EXP/SM}}$	1 ± 1
$\varepsilon_K^{\mathrm{EXP/SM}}$	1.05 ± 0.10 [1710.06614], [JHEP 04 (2018) 019]
$\Delta(\varepsilon'_K/\varepsilon_K)^{\mathrm{EXP-SM}}$	$[15.5 \pm 2.3(\mathrm{EXP}) \pm 5.07(\mathrm{TH})] \times 10^{-4}$
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)^{\mathrm{EXP/SM}}$	0.91 ± 0.22 [PDG]
$\mathcal{B}(K^+ \to \mu^+\nu_\mu)^{\mathrm{EXP/SM}}$	1.0004 ± 0.0095 [PDG]
ΔC_7	-0.02 ± 0.02 [JHEP 6 (2016) 92]
$\tan\beta$:M_A plane	ATLAS limits for hMSSM scenario [1709.07242]
LSP	Lightest neutralino
B_G	$1 \pm 3(\mathrm{TH})$ [NPB 566], [NPB 578]

- (*) due to unknown sign in long-distance S-wave contribution
- Consider degenerate Higgs masses: $M_H \approx M_A$

Observables

- **Large** $\tan\beta$ **regime**

$\varepsilon'_K/\varepsilon_K$	ε_K
• Hadronic matrix elements from lattice e.g. [PRL 115 (2015) 212001] $\left(\frac{\varepsilon'_K}{\varepsilon_K}\right)^{\rm SUSY} \simeq \left(\frac{\varepsilon'_K}{\varepsilon_K}\right)_{\rm box+pen} + \left(\frac{\varepsilon'_K}{\varepsilon_K}\right)_{\rm chromo}$ [JHEP 12 (2016) 078]	• Controversial SM prediction for ε_K • $(\varepsilon_K^{\rm SM})_{\rm SD} \propto \lvert V_{cb}\rvert^4$ [PRD 92 (2015) 034510] • 4.1 σ discrepancy between measured value using inclusive and exclusive decays [1710.06614], [HFLAV] • Require $Re(\varepsilon_K) > 0$ [JHEP 12 (2006) 011]

Parameter scan

- `Ipanema`-β framework [arXiv:1706.01420], GPU GeForce GTX 1080
- Flat scans + scans based on genetic algorithms
  [IEEE Transactions on Evolutionary Computation 10 (2006) 646–657]

Scenarios

Scenario A : universal gaugino masses + no DM relic density constraint

- Mostly Bino-like LSP, with some points with Higgsino LSP

Scenario B : universal gaugino mass + relic density function of the LSP mass: $m_{\chi_1^0} \approx 1\ \mathrm{TeV}$ e.g. [EPJ C78 (2018) 158] fulfills the measured value [Astronomy & Astrophysics 594 no. A1]

- motivated by scenarios with Higgsino LSP

Scenario C : relic density function of the LSP mass: $m_{\chi_1^0} \approx 3\ \mathrm{TeV}$ ([EPJ C77 (2017) 268], [PLB 646 (2007) 34-38])

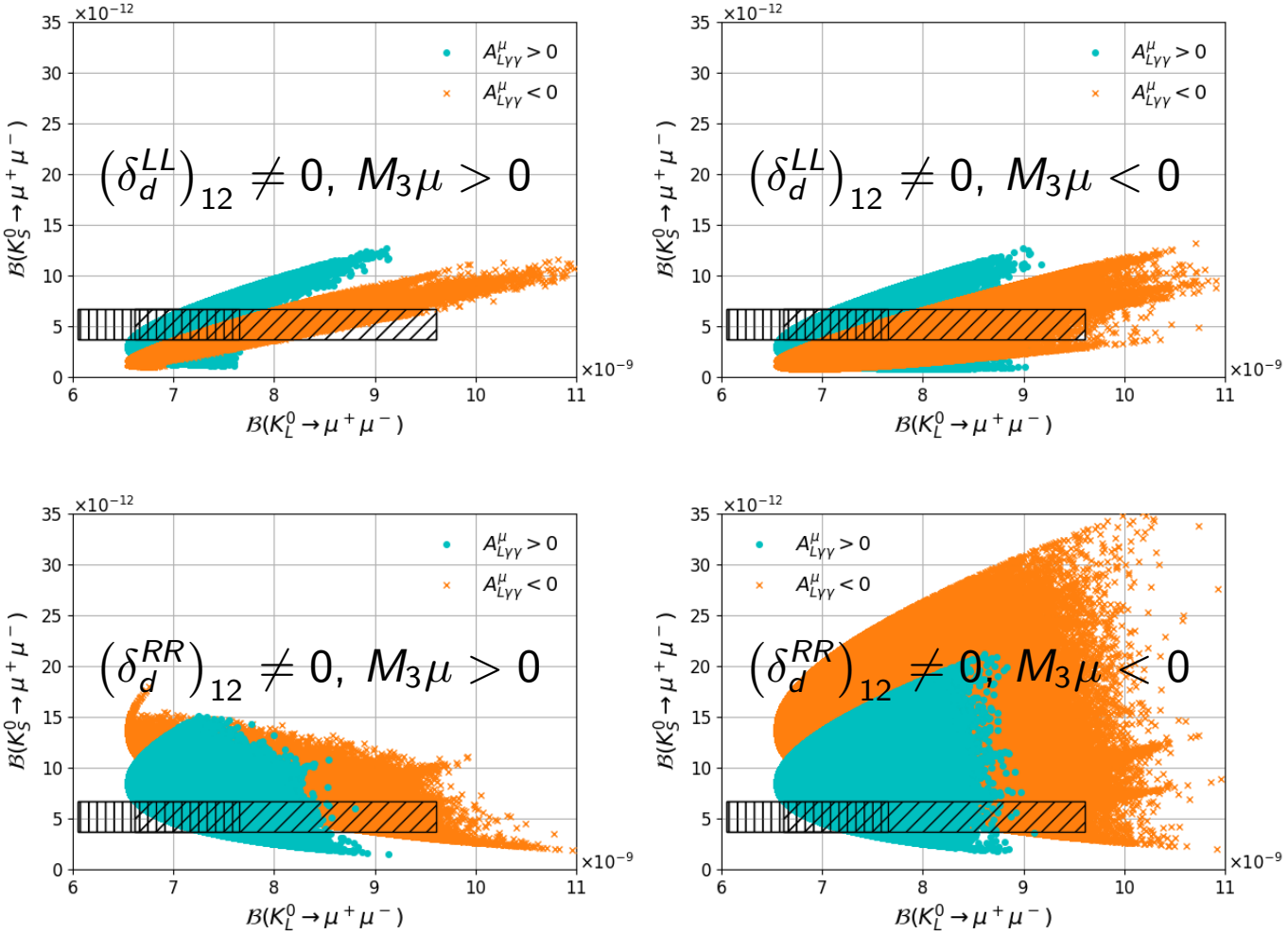
- motivated by scenarios with Wino LSP (mAMSB, pMSSM)
- nearly degenerate lightest neutralino and lightest chargino

Parameter scan

Parameter	Scenario A	Scenario B	Scenario C
$\tilde{m}_Q$	[2, 10]	[2, 10]	[4, 10]
$\tilde{m}_Q^2/\tilde{m}_d^2$	[0.25, 4]	[0.25, 4]	[0.25, 4]
M_3	[2, 10]	[4.5, 15]	[4, 15]
$\tan\beta$	[10, 50]	[10, 50]	[10, 50]
M_A	[1, 2]	[1, 2]	[1, 2]
$\lvert\mu\rvert$	[1, 10]	1	[5, 20]
M_1	$\frac{\alpha_1(\mu^{SUSY})}{\alpha_3(\mu^{SUSY})}M_3$	$\frac{\alpha_1(\mu^{SUSY})}{\alpha_3(\mu^{SUSY})}M_3$	5
M_2	$\frac{\alpha_2(\mu^{SUSY})}{\alpha_3(\mu^{SUSY})}M_3$	$\frac{\alpha_2(\mu^{SUSY})}{\alpha_3(\mu^{SUSY})}M_3$	3
B_G	[-2, 4]	[-2, 4]	[-2, 4]
$\mathrm{Re}\left[(\delta_d^{LL(RR)})_{12}\right]$	[-0.2, 0.2]	[-0.2, 0.2]	[-0.2, 0.2]
$\mathrm{Im}\left[(\delta_d^{LL(RR)})_{12}\right]$	[-0.2, 0.2]	[-0.2, 0.2]	[-0.2, 0.2]

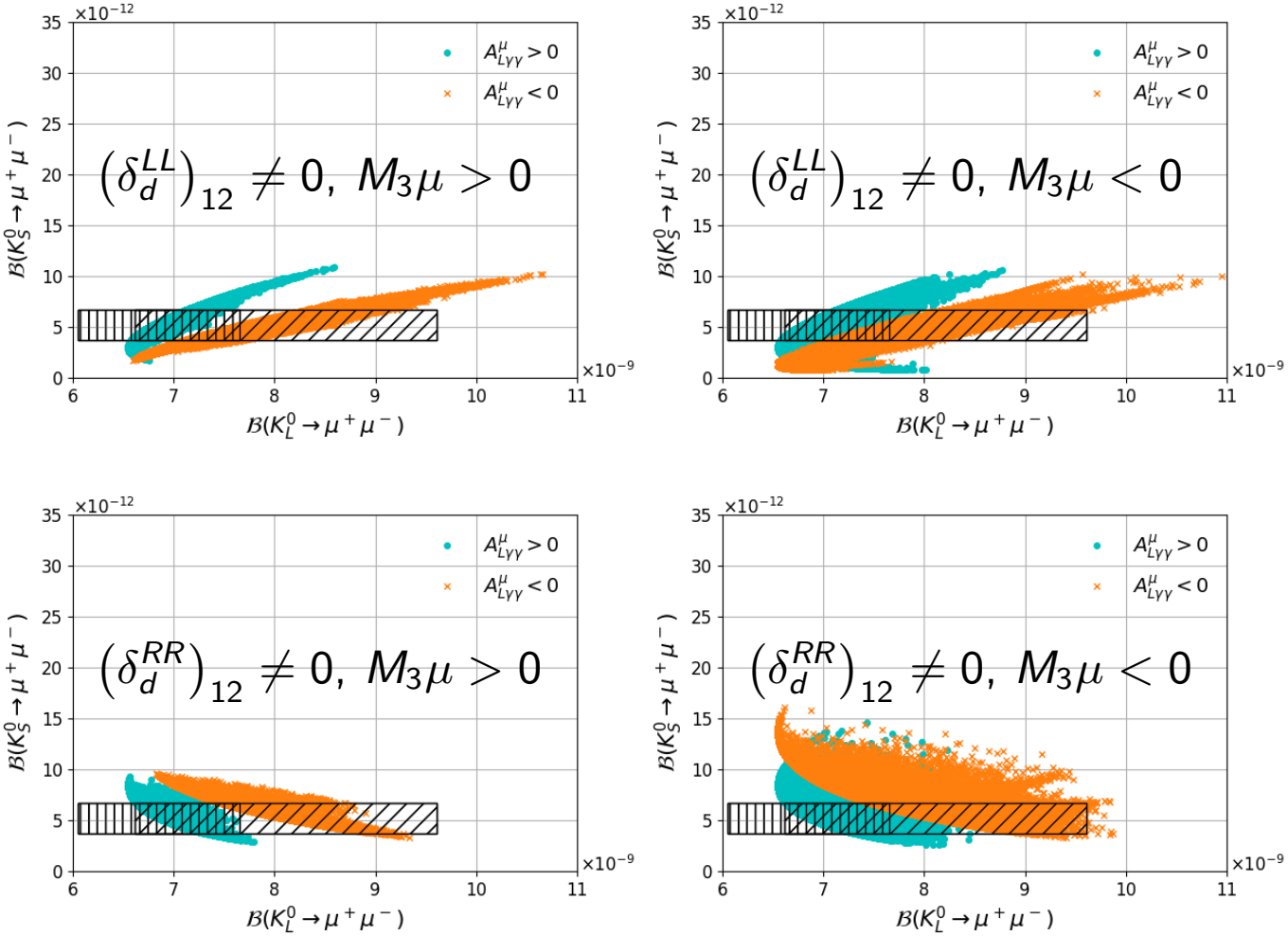
- Trilinear couplings and the MIs other than $\left(\delta_d^{LL(RR)}\right)_{12}$ and $\left(\delta_u^{LL}\right)_{12}$ set to **zero**
- $\tilde{m}_Q = \tilde{m}_u \neq \tilde{m}_d$

Results: floating $\left(\delta_d^{LL(RR)}\right)_{12}$ separately



- **A & C**: 95 % CL allowed regions for $\mathcal{B}(K_S^0 \to \mu^+\mu^-)$:
  $[0.78, 14] \times 10^{-12}$ (LL), $[1.5, 35] \times 10^{-12}$ (RR)

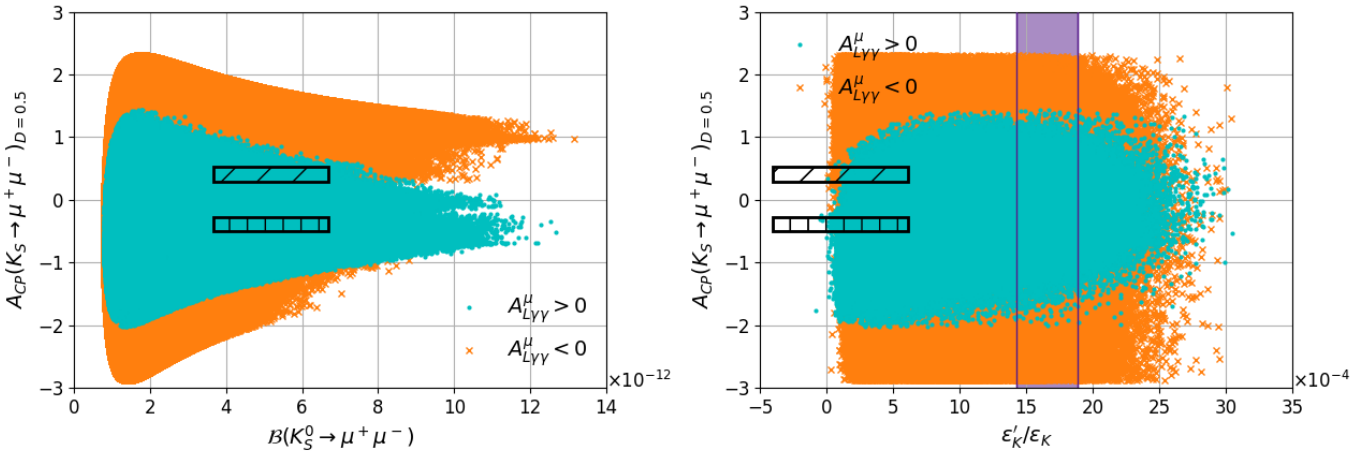
Results: floating $\left(\delta_d^{LL(RR)}\right)_{12}$ separately



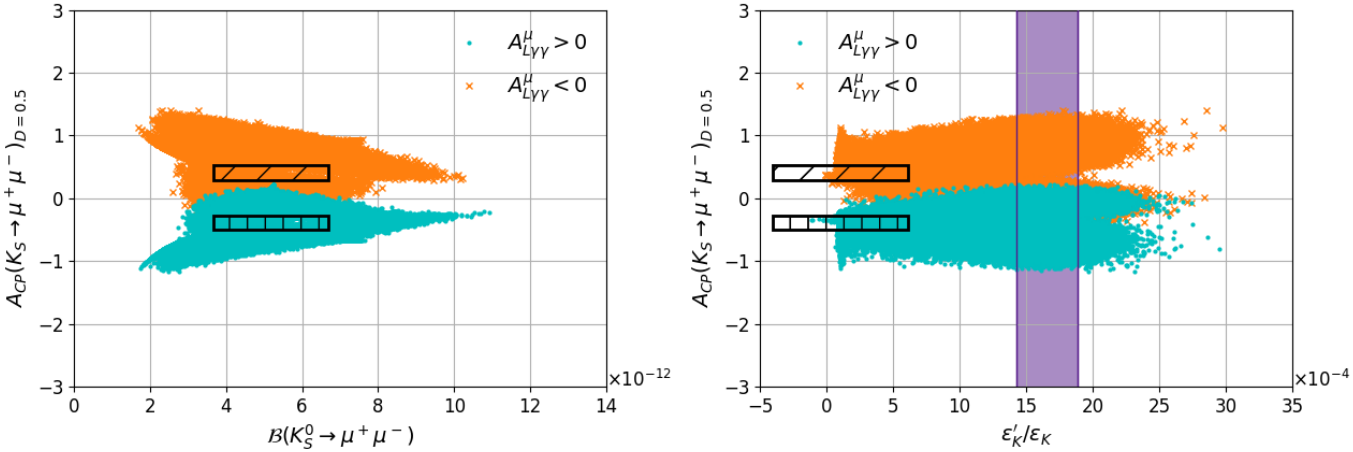
- **B**: smaller deviation of $\mathcal{B}(K_S^0 \to \mu^+\mu^-)$ from the SM ($C_{S,P} \propto \mu$, μ is small relative to squark and gluino masses)

Results: floating $\left(\delta_d^{LL(RR)}\right)_{12}$ separately

Scenario A, $\left(\delta_d^{LL}\right)_{12} \neq 0$ and $(M_3 \cdot \mu) < 0$, $D = -D' = 0.5$

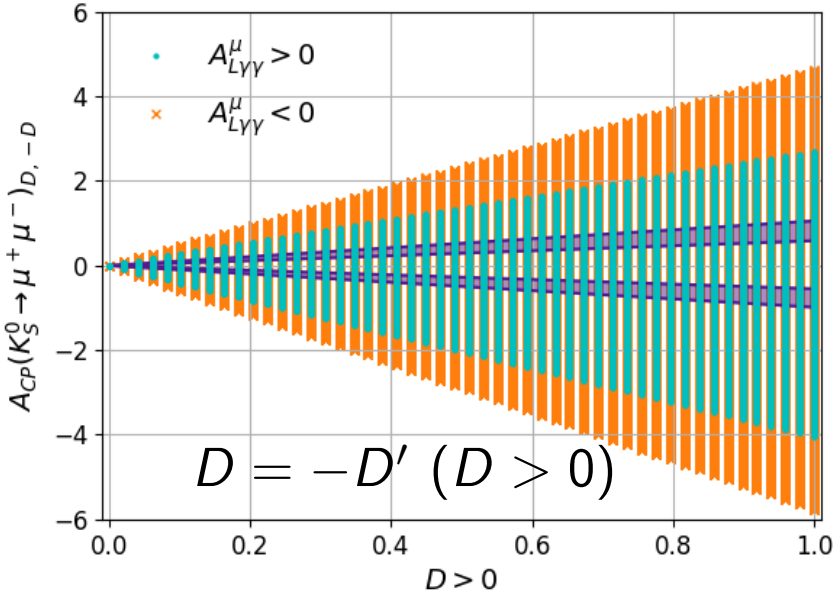


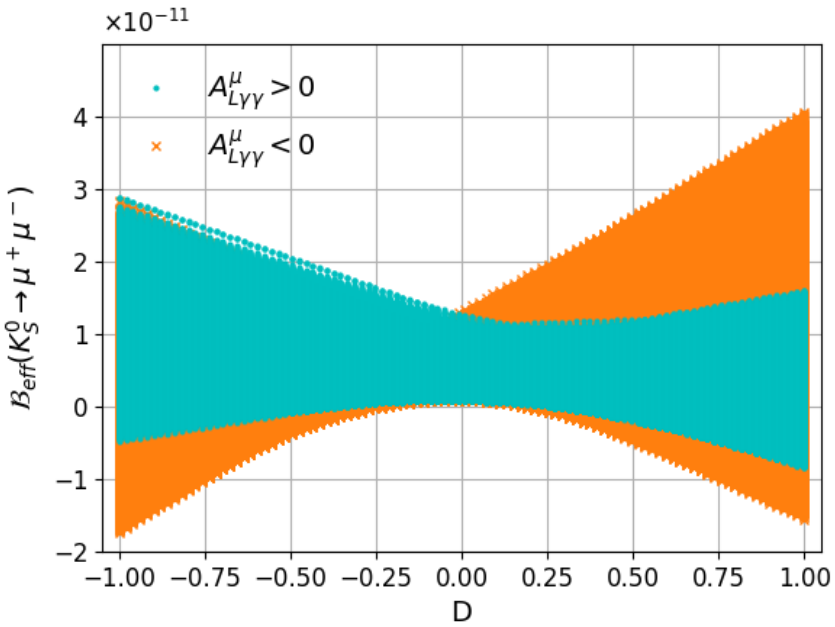
Scenario B, $\left(\delta_d^{LL}\right)_{12} \neq 0$ and $(M_3 \cdot \mu) > 0$, $D = -D' = 0.5$



Results: floating $\left(\delta_d^{LL(RR)}\right)_{12}$ separately

Scenario A, $\left(\delta_d^{LL}\right)_{12} \neq 0$ and $(M_3 \cdot \mu) < 0$

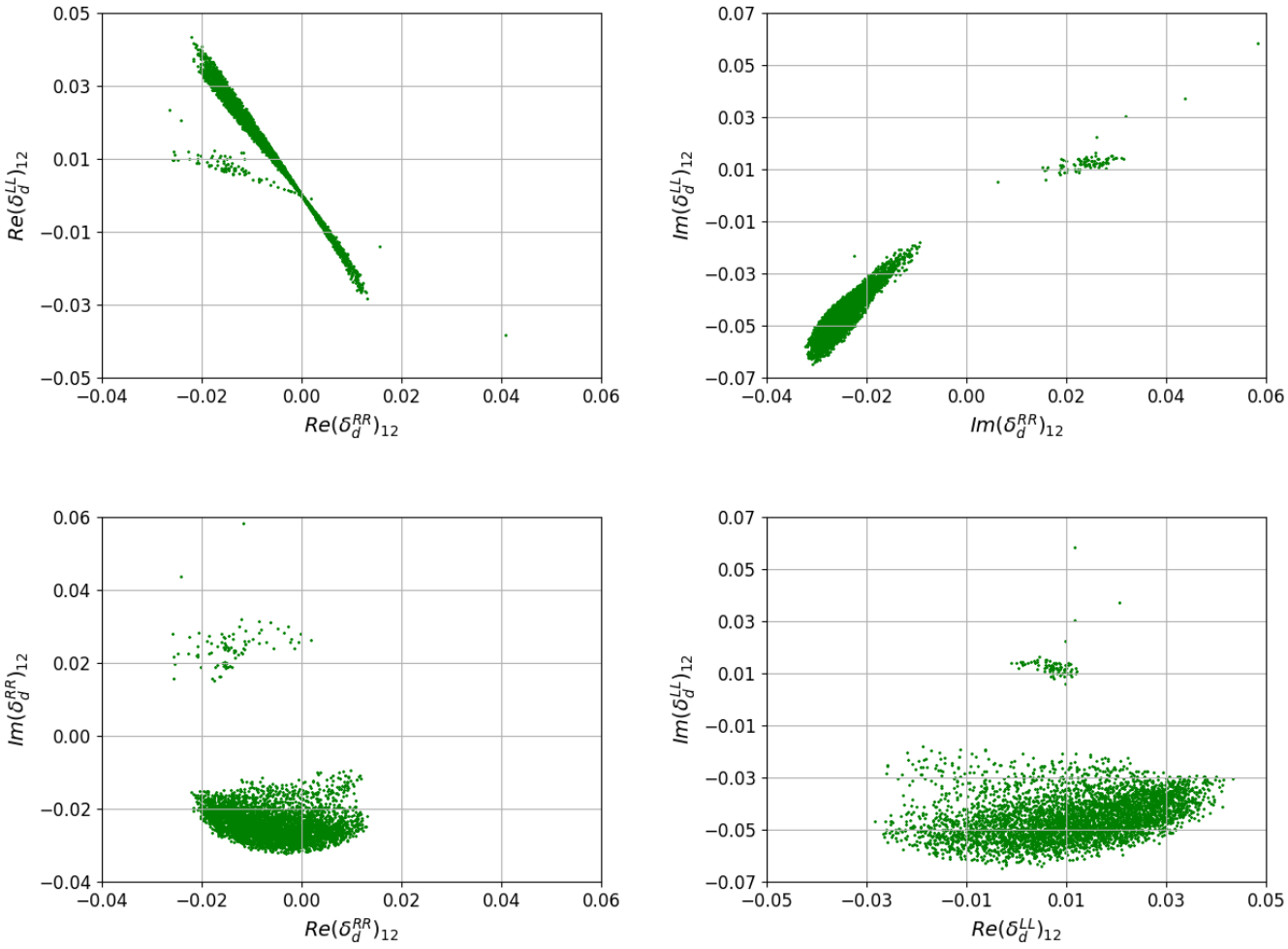




- CP asymmetries can be up to ≈ 6 (at $D = 1$) $\Rightarrow 8 \times$ SM
- Largest effects in left-handed scenarios

Results: floating LL and RR MIs simultaneously

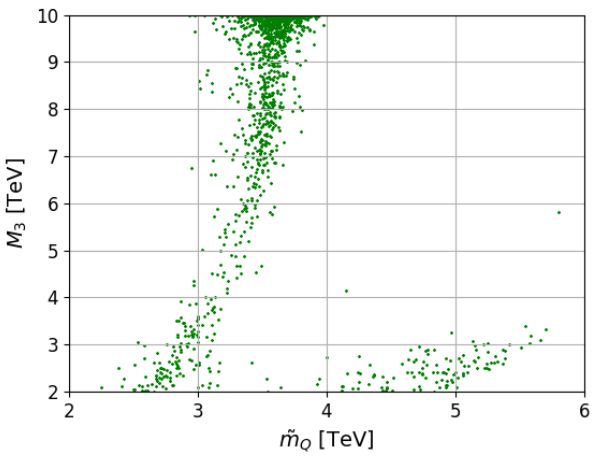
Scenario C $\mathcal{B}(K_S^0 \to \mu^+\mu^-) > 2 \times 10^{-10}$



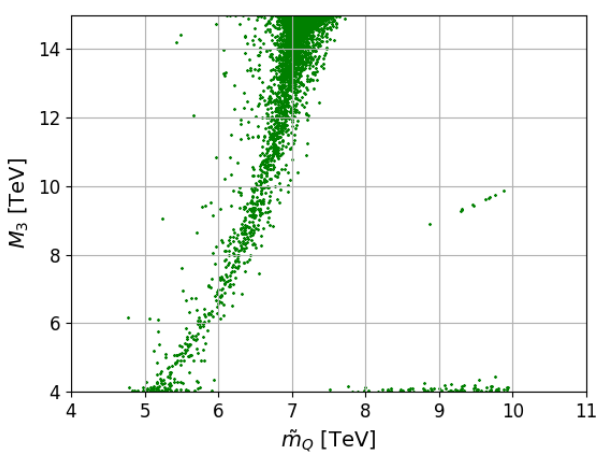
- Scenario A shows similar pattern

Results: floating *LL* and *RR* MIs simultaneously

Scenario A



Scenario C



- $\mathcal{B}(K_S^0 \to \mu^+\mu^-) > 2 \times 10^{-10}$
- Region where $|(\delta_d^{LL})_{12}| \approx 2|(\delta_d^{RR})_{12}| \sim 0.03$, $arg\left[(\delta_d^{LL})_{12}\right] \approx -arg\left[(\delta_d^{RR})_{12}\right] + \pi$ particularly favorable
- Higher chances of finding regions with $\mathcal{B}(K_S^0 \to \mu^+\mu^-) > 10^{-10}$ using $\varepsilon_K^{\mathrm{EXP/SM}} = 1.41 \pm 0.16(\mathrm{TH})$ (from exclusive decays)

Conclusions

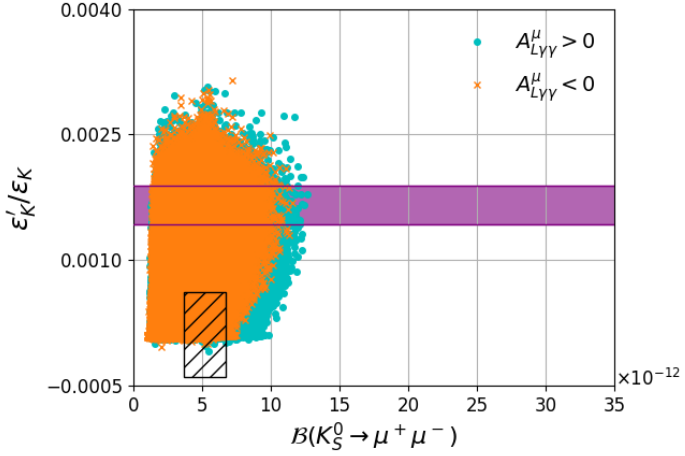
- $\mathcal{B}(K_S^0 \to \mu^+\mu^-)$ can surpass the SM contributions by a factor of 7 within the MSSM (**large** $\tan\beta$ **regime**)
  - even for large SUSY masses
  - with no conflict with experimental (LHCb) data
- Fine-tuned regions can bring $\mathcal{B}(K_S^0 \to \mu^+\mu^-)$ above the 10^{-10} level
  - largest deviations from SM at $|(\delta_d^{LL})_{12}| \approx 2|(\delta_d^{RR})_{12}| \sim 0.03$ and $arg\left[(\delta_d^{LL})_{12}\right] \approx -arg\left[(\delta_d^{RR})_{12}\right] + \pi$ for large squark and gluino masses
- CP asymmetry of $K^0 \to \mu^+\mu^-$ can be significantly modified by MSSM contributions
- If $M_H \neq M_A$ (small $\tan\beta$) $\Rightarrow$ looser constraints
  - regions $\mathcal{B}(K_S^0 \to \mu^+\mu^-) > 10^{-10}$ for mass differences of $\mathcal{O}(33\%)$ or larger without fine-tuning the MIs

Thanks for your attention!

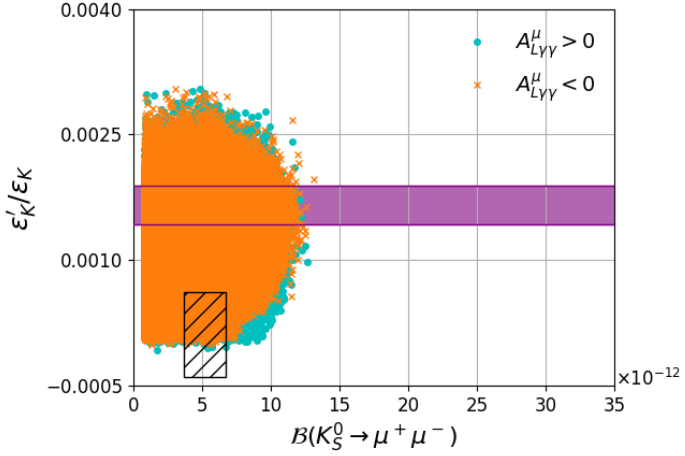
BACKUP

Scenario A

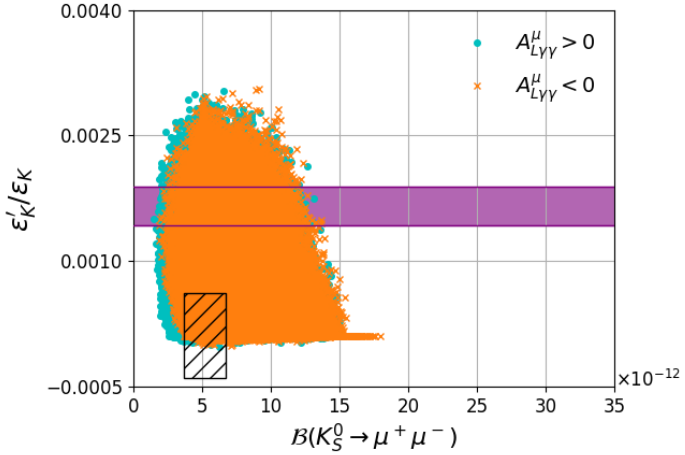
$\left(\delta_d^{LL}\right)_{12} \neq 0,\ M_3\mu > 0$



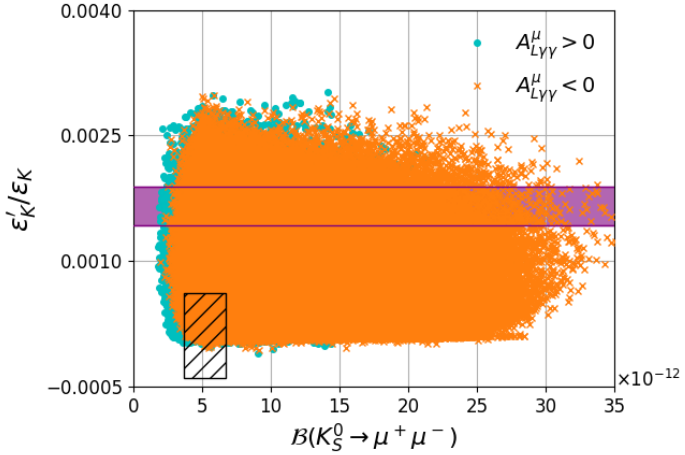
$\left(\delta_d^{LL}\right)_{12} \neq 0,\ M_3\mu < 0$



$\left(\delta_d^{RR}\right)_{12} \neq 0,\ M_3\mu > 0$

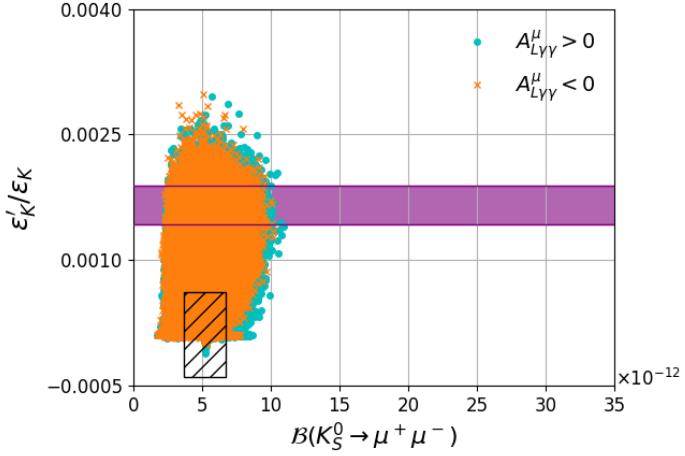


$\left(\delta_d^{RR}\right)_{12} \neq 0,\ M_3\mu < 0$

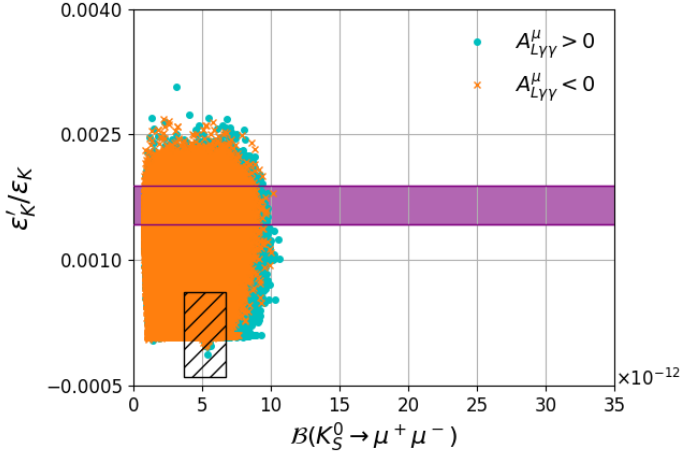


Scenario B

$\left(\delta_d^{LL}\right)_{12} \neq 0,\ M_3\mu > 0$



$\left(\delta_d^{LL}\right)_{12} \neq 0,\ M_3\mu < 0$



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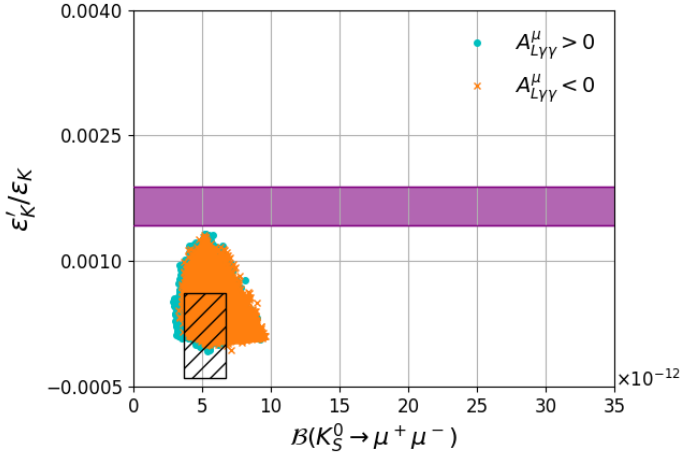
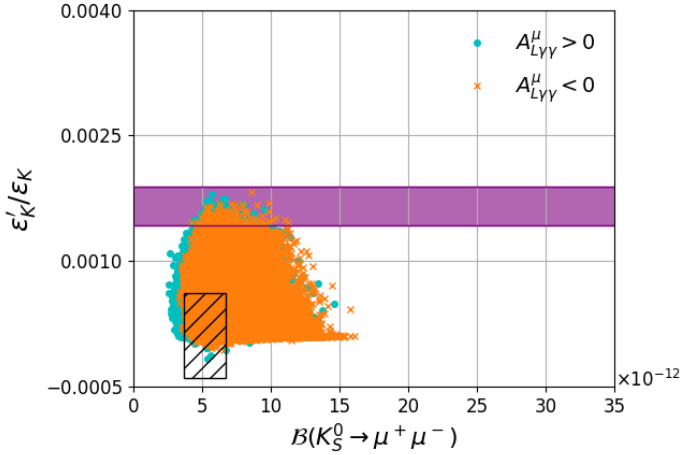
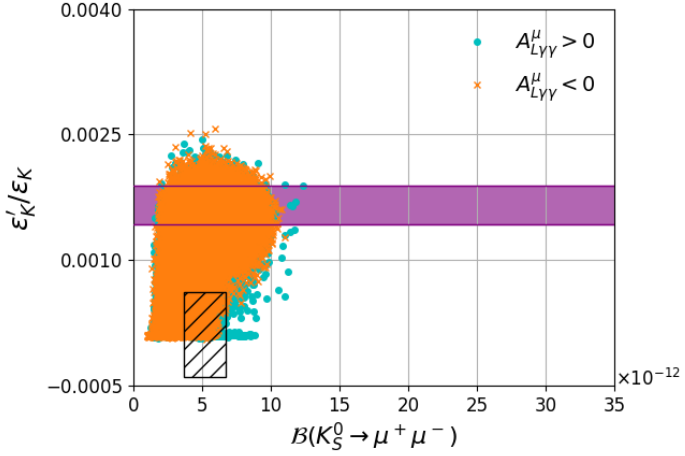


$\left(\delta_d^{RR}\right)_{12} \neq 0,\ M_3\mu < 0$

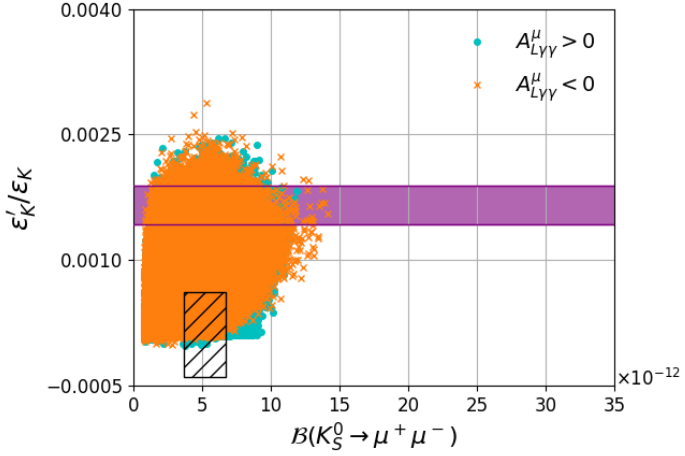


Scenario C

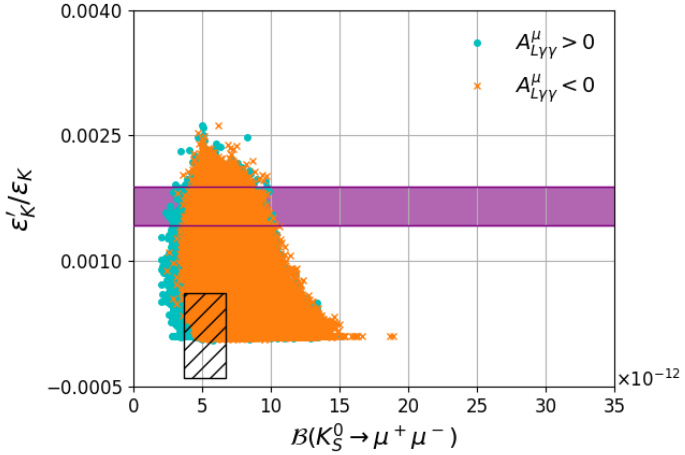
$\left(\delta_d^{LL}\right)_{12} \neq 0,\ M_3\mu > 0$



$\left(\delta_d^{LL}\right)_{12} \neq 0,\ M_3\mu < 0$



$\left(\delta_d^{RR}\right)_{12} \neq 0,\ M_3\mu > 0$



$\left(\delta_d^{RR}\right)_{12} \neq 0,\ M_3\mu < 0$