Flavour physics with a 4th generation

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Outline

A. Buras, B. Duling, T. Feldmann, T.H., C. Promberger, S. Recksiegel 1002.2126
1004.4565
(Without S.R) 1006.5356

Why a fourth Generation?

Why a fourth Generation?

Why not?

The SM4 highlights

- Consider a fourth, sequential generation of quarks (t', b')
- The CKM matrix has to be generalised to a four generation model, thereby the model is described by a set of 10 parameters

$$\theta_{12}\,,\ \theta_{13}\,,\ \theta_{14}\,,\ \theta_{23}\,,\ \theta_{24}\,,\ \theta_{34}\,,\ \delta_{13}\,,\ \delta_{14}\,,\ \delta_{24}\,,\ m_{t'}$$

- The operator structure does not change
- Currently there are the following (rough) bounds on the new parameters

$$s_{14} \leq 0.04\,, \qquad s_{24} \leq 0.17\,, \qquad s_{34} \leq 0.27\,,$$

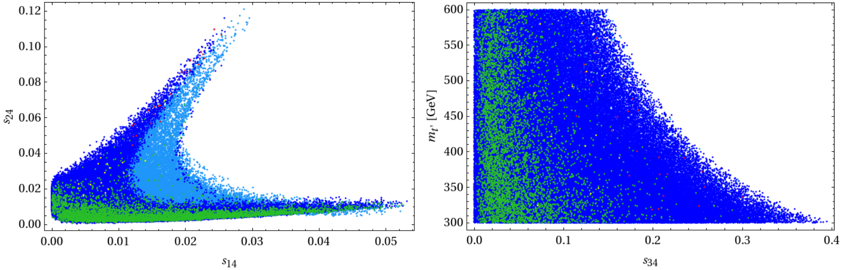
$$300\text{GeV} \leq m_{t'} \leq \text{Min}\left(600\text{GeV}, M_W/|s_{34}|\right)$$

Chanowitz et. al. Phys. Rev. D 79 (2009) 113008

More sophisticated bounds on the mixing angles

EBERHARD ET AL. (2010)

Take into account all contributions to the S and T parameters



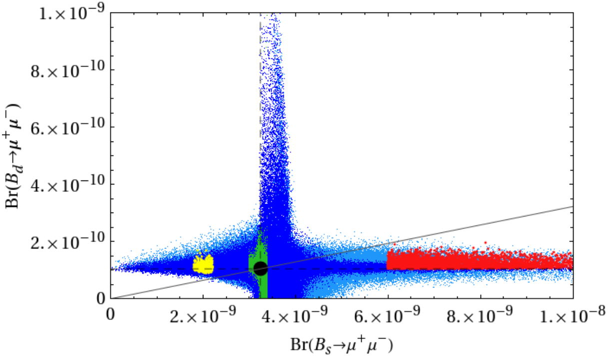
- Strong correlation between s_{14} and s_{24} from FCNC constraints
- Correlation between s_{34} and $m_{t'}$ from EWPT

Colour-Coding

	BS1 (yellow)	BS2 (green)	BS3 (red)
$S_{\psi\phi}$	0.04 ± 0.01	0.04 ± 0.01	≥ 0.4
$\mathrm{Br}(B_s \to \mu^+\mu^-)$	$(2 \pm 0.2) \cdot 10^{-9}$	$(3.2 \pm 0.2) \cdot 10^{-9}$	$\geq 6 \cdot 10^{-9}$

light blue stands for $\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) > 2 \cdot 10^{-10}$
dark blue stands for $\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) \leq 2 \cdot 10^{-10}$

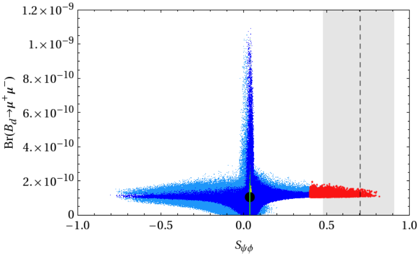
A first look at rare B decays, $\mathrm{Br}(B_q \to \mu^+\mu^-)$

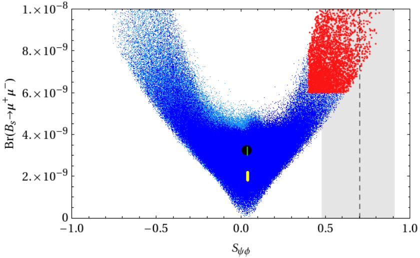


- Big enhancements in $\mathrm{Br}(B_q \to \mu^+\mu^-)$ possible but not simultaneously
- non-CMFV nature of the SM4 clearly seen in this correlation
- Maximal deviations possible if one of $\mathrm{Br}(B_q \to \mu^+\mu^-)$ is SM3 like

$\mathrm{Br}(B_q \to \mu^+\mu^-)$ vs. $S_{\psi\phi}$

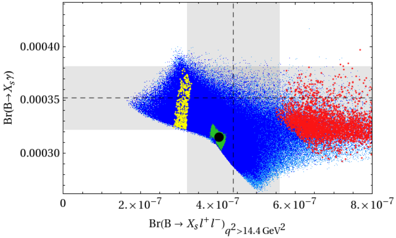
$$\varphi_{B_s}^{\text{tot}} = -(0.39^{+0.18}_{-0.14}) \quad [-(1.18^{+0.14}_{-0.18})]$$ (HFAG)





- Enhancement of $S_{\psi\phi} > 0.5$ implies enhancement of $\mathrm{Br}(B_s \to \mu^+\mu^-)$ together with $\mathrm{Br}(B_d \to \mu^+\mu^-) \sim (1-2)\cdot 10^{-10}$
- For small $S_{\psi\phi}$ a suppression of $\mathrm{Br}(B_s \to \mu^+\mu^-)$ is also possible

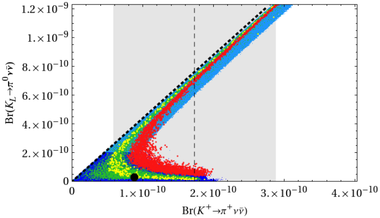
$B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$



- $\mathrm{Br}(B \to X_s\gamma)$ was calculated at LO for $\mu_{\mathrm{eff}} = 3.22\mathrm{GeV}$ to have the LO formula mimic the NNLO result
- $\mathrm{Br}(B \to X_s\ell^+\ell^-)$ was calculated at NLO and rescaled to mimic the corresponding (partial) NNLO result

The correlation is not as strong as for other observables, but the measurement of $\mathrm{Br}(B_s \to \mu^+\mu^-)$ would highly constrain the allowed area.

$\text{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$ vs. $\text{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$



- Enhancement by orders of magnitude possible!
- Only mild correlation with the B system

- For big enhancements of $\text{Br}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$, $\text{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$ is enhanced too, but the reverse is not true
- The lower branch is tightly constrained through $\text{Br}\left(K_L \to \mu^+\mu^-\right)_{\text{SD}}$

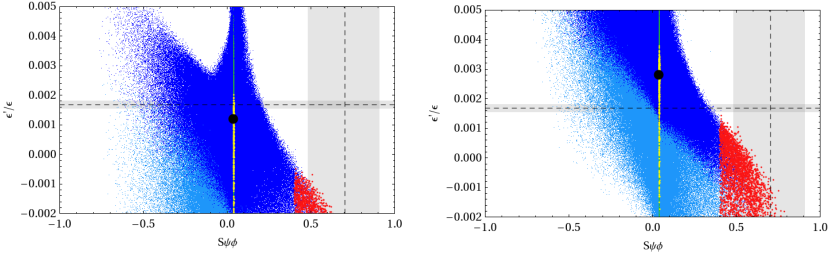
$$\text{Br}\left(K^+ \to \pi^+ \nu\bar{\nu}\right)_{\text{exp.}} = \left(17.3^{+11.5}_{-10.5}\right) \cdot 10^{-11}$$

E949 Collab., Phys. Rev. Lett. 101 (2008) 191802

ε'/ε and $S_{\psi\phi}$ ... there is a connection after all

- ε'/ε very well measured
- Theoretically demanding due to the importance of non-pert. corrections.

ε'/ε vs. $S_{\psi\phi}$ for different scenarios of the non-pert. parameters R_6 and R_8



$(R6, R8) = (1.0, 1.0)$ $(R6, R8) = (1.5, 0.5)$

- In general the SM4 can satisfy ε'/ε for any set of hadronic parameters
- For $S_{\psi\phi} > 0.4$ we need special values of $R6$ and $R8$ in order to reproduce the data

Taking ε'/ε as a constraint: Preliminaries

What happens if we take ε'/ε as a constraint?

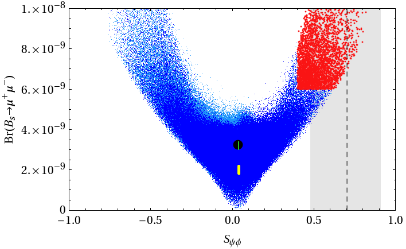
Procedure:

- Turn the argument around and assume one of our scenarios for $R6, R8$ to be correct.
- Take a very conservative error for ε'/ε and use ε'/ε as a constraint.
- Colour code:

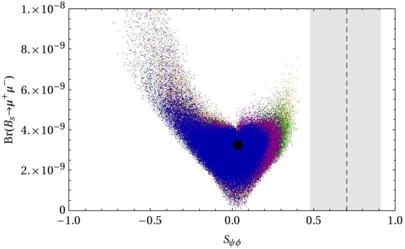
R_6	R_8	
1.0	1.0	dark blue
1.5	0.8	purple
2.0	1.0	green
1.5	0.5	orange

ε'/ε as a constraint

- For $S_{\psi\phi} > 0$ the t and t' contributions (Z penguins) are both negative and cancel out the QCD penguins
- $B8 < 1$ lessens the influence of the Z penguin, while $B6 > 1$ strengthens the QCD penguins



before ε'/ε

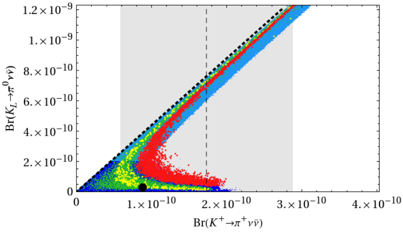


after ε'/ε

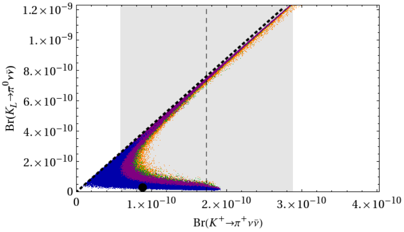
- ε'/ε constrains $S_{\psi\phi}$ asymmetrical
- For ε'/ε to agree with the data concurrently with $S_{\psi\phi} \gg 0$, we need $R6 > 1$, $R8 < 1$ and $R6/R8 \sim 3$.

ε'/ε as a constraint II

- As anticipated ε'/ε poses a constraint on $K \to \pi\nu\nu$, but much milder than usual
- Close to the GN bound spectacular enhancements of $\mathrm{Br}(K_L \to \pi\nu\bar{\nu})$ are still possible



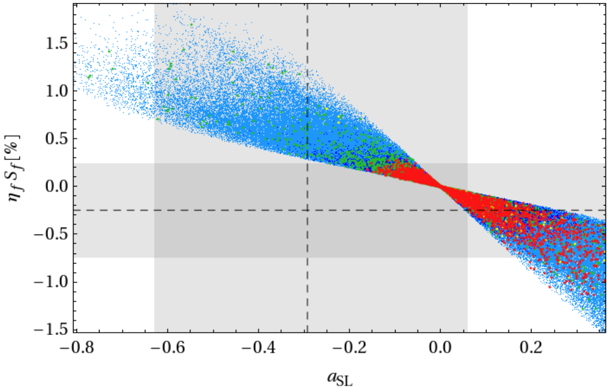
before ε'/ε



after ε'/ε

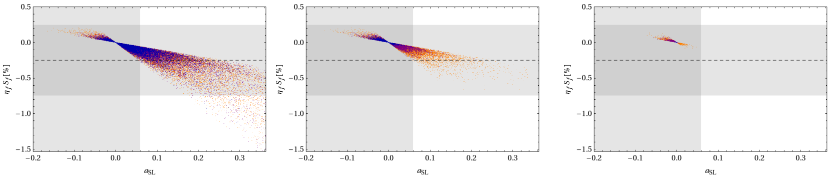
- Reminder: Operator structure not changed, but CKM elements might differ their SM values, esp. V_{ts} and V_{td}
- $\mathrm{Im}\lambda_t^{(K)}$ can be enhanced, which helps to circumvent bounds from ε'/ε

CP Violation in $D^0 - \bar{D}^0$ ($\eta_f S_f^D$ vs. $a_{\rm SL}^D$)



- Big deviations from the SM3 prediction (close to zero for both) are possible
- three-way correlation between $\eta_f S_f^D$, $a_{\rm SL}^D$ and $\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu})$

ε'/ε and $S_{\psi\phi}$ or how to kill CP-violation in $D^0 - \bar{D}^0$

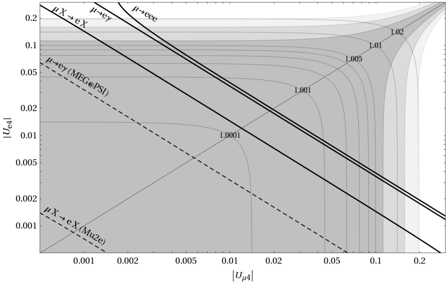


$S_{\psi\phi}$ free $\quad$ $S_{\psi\phi} > 0$ $\quad$ $S_{\psi\phi} > 0.2$

- With ε'/ε as a constraint, from left to right the possible CPV vanishes
- ε'/ε clearly diminishes CPV in the D^0 system, even without a constraint coming from $S_{\psi\phi}$
- Imposing different $S_{\psi\phi}$ constraints further shrinks the possible CPV in the D^0 system, however it is still by orders of magnitude above the SM prediction.

LFV mixing & constraints

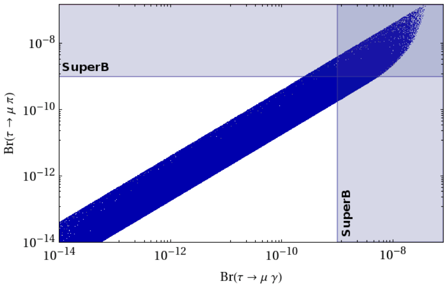
Lacker & Menzel '10



- Lepton universality: $|U_{e4}| \sim |U_{\mu 4}|$
- Radiative decays: $|U_{e4}U^*_{\mu 4}|$ small

- Lepton universality (shaded areas) provides a stringent bound on the matrix elements U_{e4} and $U_{\mu 4}$
- The radiative decays provide an orthogonal set of constraints
- Future experiments on $\mu \to e\gamma$ and $X\mu \to Xe$ can push both matrix elements below 1%

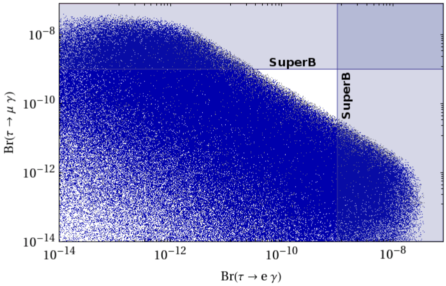
LFV: prospects I



- Both decays are $|U^*_{\tau 4} U_{\mu 4}|$ and m_{ν_4} dependent
- The additional CKM dependence of $\mu\pi$ turns out to be small

- Strong correlation, saturates current bounds.
- If was measured the other would have to be around the same order of magnitude

LFV: prospects II



- $\tau \to \mu\gamma$: $|U^*_{\tau 4} U_{\mu 4}|$ and m_{ν_4} dependent
- $\tau \to e\gamma$: $|U^*_{\tau 4} U_{e 4}|$ and m_{ν_4} dependent

- Mild correlation between $\tau \to \mu\gamma$ and $\tau \to e\gamma$ through $\mu \to e\gamma$ and lepton universality
- Future and current bounds are saturated

Messages and Conclusions

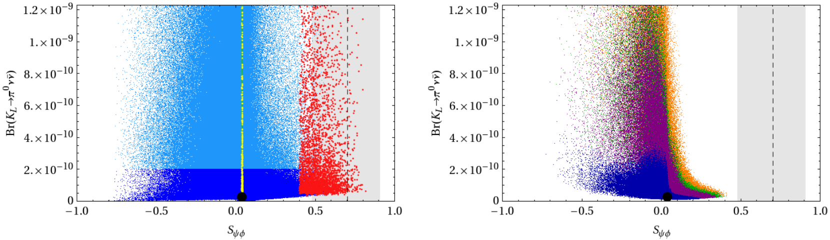
The SM4 provides a set of interesting features

- Both $\mathrm{Br}(B_s \to \mu^+\mu^-)$ and $\mathrm{Br}(B_d \to \mu^+\mu^-)$ can be increased/decreased compared to the SM3 but not simultaneously
- For $S_{\psi\phi} \gg 0$ an enhancement of $\mathrm{Br}(B_s \to \mu^+\mu^-)$ is needed
- A suppression of $\mathrm{Br}(B_s \to \mu^+\mu^-)$ is possible for $S_{\psi\phi}$ SM3 like
- In $Br(K_L \to \pi^0\nu\bar{\nu})$ and $Br(K^+ \to \pi^+\nu\bar{\nu})$ there is, independently of the B system, still much room for big enhancements
- ε'/ε could become a very important constraint, if $R6$ and $R8$ were known to moderate accuracy
- CP violation in the $D^0 - \bar{D}^0$ system can be drastically diminished through the interplay of ε'/ε and $S_{\psi\phi}$
- LFV with a fourth generation is highly predictive due to the very small number of parameters

Thank you for your attention!

Backup

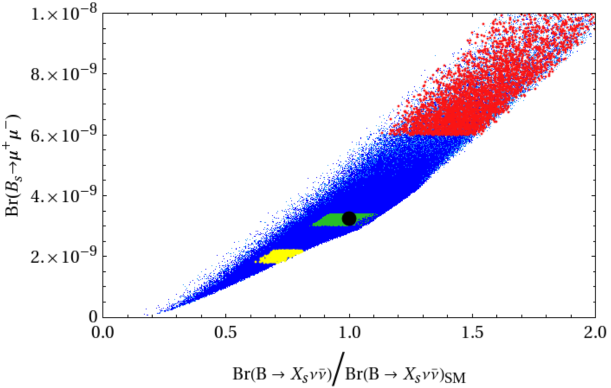
ε'/ε as a constraint III



before ε'/ε after ε'/ε

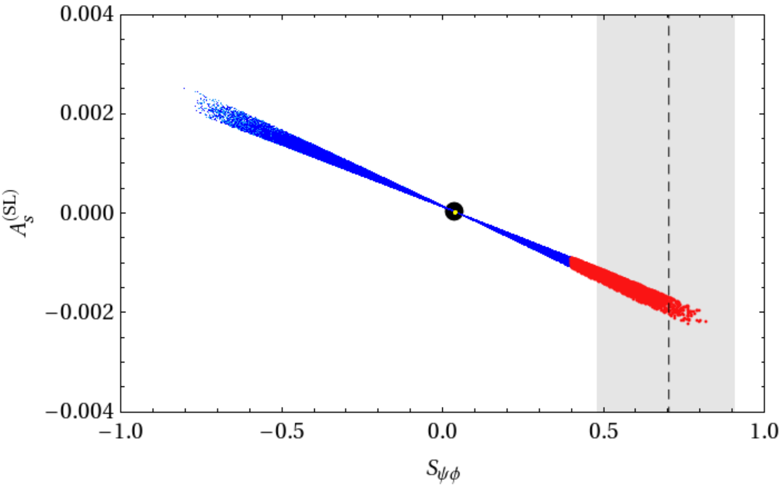
- From no correlation to a strong correlation (for $S_{\psi\phi} > 0$)
- For $S_{\psi\phi} \gg 0$ no big enhancements of $\mathrm{Br}(K_L \to \pi\nu\bar{\nu})$

$B \to X_s \nu\bar{\nu}$ and $B_s \to \mu^+\mu^-$

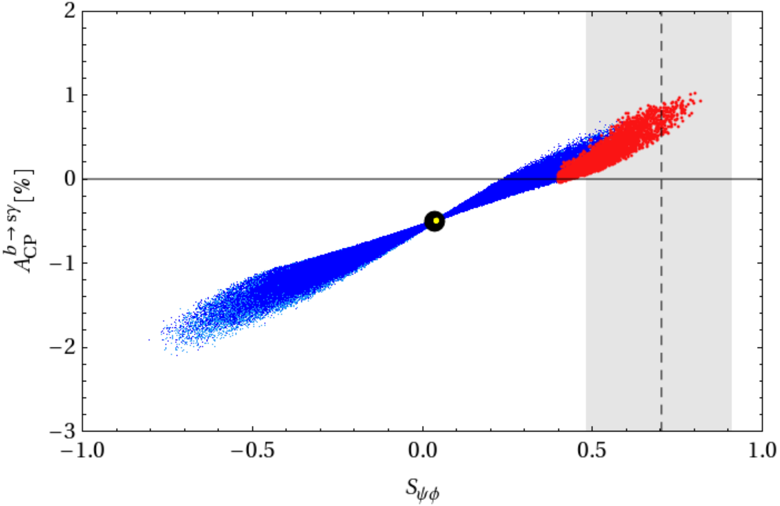


- $B \to X_s \nu\bar{\nu}$ and $B_s \to \mu^+\mu^-$ are strongly correlated
- A similar correlation between $B \to X_s \nu\bar{\nu}$ and $B \to X_s \ell^+\ell^-$ exists

Semileptonic asymmetry $a_{\mathrm{SL}}^{(s)}$ in B_s



CP violation in $b \to s\gamma$



Time-dependent CP Asymmetries Preliminaries

G. Buchalla, G. Hiller, Y. Nir, G. Raz, JHEP 09 (2005) 074

$$A_f = A_f^c \left(1 + a_f^u e^{i\gamma} + \sum_i \left(b_{fi}^c + b_{fi}^u e^{i\gamma}\right) C_i^{\mathrm{NP}}\left(M_W\right)\right)$$

$$|A_f| e^{i\varphi_f} \approx A_f^c \left(1 + r_f \frac{\lambda_{t'}^{(s)}}{\lambda_t^{(s)}}\right)$$

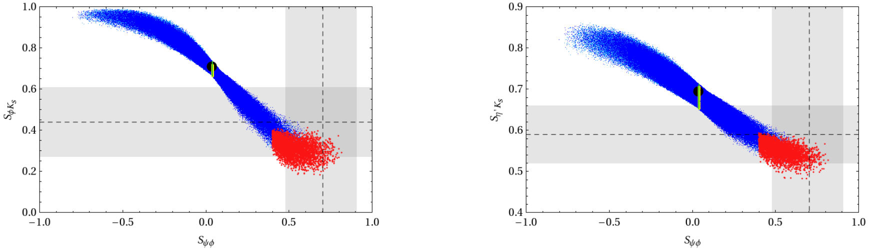
- b_{fi}^c, b_{fi}^u from non-pert. QCD
- ratio a_f^u of SM amplitudes

$$r_{\phi K_S} = -0.248\ Y_0(x_{t'}) + 0.004\ X_0(x_{t'}) + 0.075\ Z_0(x_{t'}) - 0.7\ E_0'(x_{t'})$$

$$S_f = -\eta_f \sin\left[2\left(\varphi_{B_d}^{\mathrm{tot}} + \varphi_f\right)\right]$$

S_{fK_S} as a function of $S_{\psi\phi}$

The SM4 provides the 'right' correlation to accommodate the most recent measurements for S_{fK_S} and $S_{\psi\phi}$

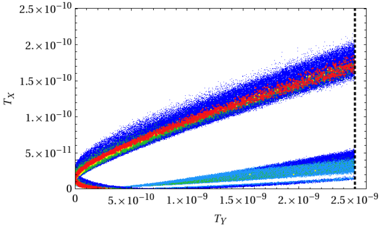


- LO approximation of the hadronic parameters involved, no strong phase.
- Enhancement of $S_{\psi\phi}$ is always accompanied by a suppression of both $S_{\phi K_S}$ and $S_{\eta' K_S}$.
- A more detailed analysis of the involved hadronic parameters would be desirable.

Constraining $\mathrm{Br}(K \to \pi\nu\bar{\nu})$ through $\mathrm{Br}\left(K_L \to \mu^+\mu^-\right)_{\mathrm{SD}}$

$$T_Y \equiv \mathrm{Br}(K_L \to \mu^+\mu^-)_{\mathrm{SD}}$$

$$T_X \equiv \mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu}) - \frac{\kappa_+}{\kappa_L}\mathrm{Br}(K_L \to \pi^0\nu\bar{\nu})$$



- T_Y and T_X are strongly correlated
- $\mathrm{Br}(K_L \to \pi^0\nu\bar{\nu})$ does not get directly constrained

$\mathrm{Br}\left(K_L \to \mu^+\mu^-\right)_{\mathrm{SD}} < 2.5 \cdot 10^{-9}$ G. Isidori et. al. JHEP 01 (2004) 009

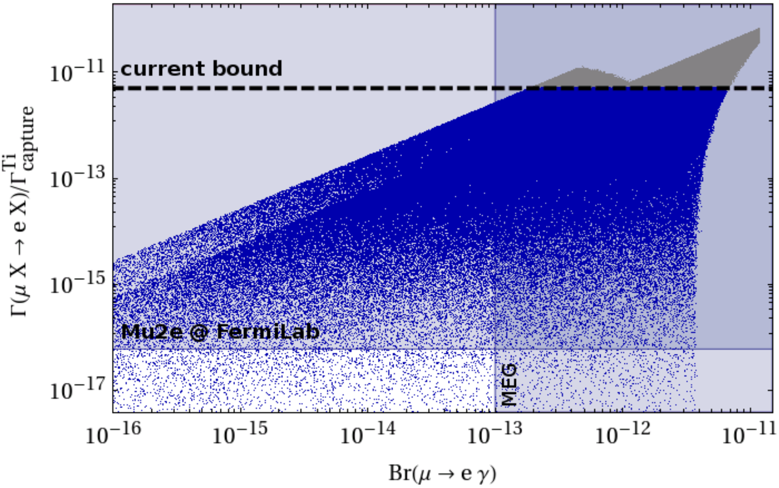
Full formulae

$$S_i = S_0(x_t) + \frac{\eta^{(i)}_{t't'}}{\eta^{(i)}_{tt}} \left(\frac{\lambda^{(i)}_{t'}}{\lambda^{(i)}_t}\right)^2 S_0(x_{t'}) + 2\,\frac{\eta^{(i)}_{tt'}}{\eta^{(i)}_{tt}} \left(\frac{\lambda^{(i)}_{t'}}{\lambda^{(i)}_t}\right) S_0(x_t, x_{t'})$$
$$+ 2\,\frac{\eta^{(i)}_{ct'}}{\eta^{(i)}_{tt}} \left(\frac{\lambda^{(i)}_c \lambda^{(i)}_{t'}}{\lambda^{(i)2}_t}\right) S_0(x_{t'}, x_c)$$

$$T_Y \equiv \mathrm{Br}(K_L \to \mu^+\mu^-)_{\mathrm{SD}} = 2.08 \cdot 10^{-9} \left(\frac{\mathrm{Re}\lambda^{(K)}_c}{|V_{us}|} P_c(Y_K) + \frac{\mathrm{Re}(\lambda^{(K)}_t Y_K)}{|V_{us}|^5}\right)^2$$

$$\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}(\lambda^{(K)}_t X^\ell_K)}{|V_{us}|^5}\right)^2 + \left(\frac{\mathrm{Re}\lambda^{(K)}_c}{|V_{us}|} P^\ell_c(X) + \frac{\mathrm{Re}(\lambda^{(K)}_t X^\ell_K)}{|V_{us}|^5}\right)^2\right]$$

$$T_X = \text{red part}$$


current bound
Mu2e @ FermiLab
MEG
10^{-11}
10^{-13}
10^{-15}
10^{-17}
$\Gamma(\mu\,X \to e\,X)/\Gamma^{Ti}_{capture}$
10^{-16}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
$Br(\mu \to e\,\gamma)$