Patterns of Flavour Violation in the Presence of a Fourth Generation of Quarks

Tillmann Heidsieck

Technical University of Munich (TUM)

Workshop
Indirect Searches for New Physics at the time of LHC
Florence, February 23, 2010

Outline

A. Buras, B. Duling, T. Feldmann, T.H., C. Promberger, S. Recksiegel, 1002.2126

Why a fourth Generation?

Why a fourth Generation?

Why not?

Why a fourth Generation?

- The Standard Model with a 4G (SM4) could explain the $S_{\psi\phi}$ and $S_{\phi K_S}$ anomaly

  Soni et al., Phys.Lett.B 683 302-305 (2010)

- A fourth generation (4G) could trigger dynamic breaking of the electroweak symmetry

  B. Holdom (1986), C. T. Hill et. al. (1991), S. F. King (1990), Hung et. al. (2009)

- Electroweak baryogenesis might be viable in the presence of a 4G

  W.-S. Hou et. al. (2009), Y. Kikukawa et. al. (2009), R. Fok et. al. (2008)

- see also various papers by for example

  Herrera, Chanowitz, Kribs, ...

The SM4 highlights

- We consider a fourth, sequencial generation of quarks (t', b')
- The model is described by a set of 10 parameters

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

$+$ known quark masses etc.

- The CKM matrix can be generalized to a four generation model
- The operator structure does not change
- Currently there are the following 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

The CKM4 matrix

$c_{12}c_{13}c_{14}$	$c_{13}c_{14}s_{12}$	$c_{14}s_{13}e^{-i\delta_{13}}$	$s_{14}e^{-i\delta_{14}}$
$-c_{23}c_{24}s_{12} - c_{12}c_{24}s_{13}s_{23}e^{i\delta_{13}}$ $-c_{12}c_{13}s_{14}s_{24}e^{i(\delta_{14}-\delta_{24})}$	$c_{12}c_{23}c_{24} - c_{24}s_{12}s_{13}s_{23}e^{i\delta_{13}}$ $-c_{13}s_{12}s_{14}s_{24}e^{i(\delta_{14}-\delta_{24})}$	$c_{13}c_{24}s_{23}$ $-s_{13}s_{14}s_{24}e^{-i(\delta_{13}+\delta_{24}-\delta_{14})}$	$c_{14}s_{24}e^{-i\delta_{24}}$
$-c_{12}c_{23}c_{34}s_{13}e^{i\delta_{13}} + c_{34}s_{12}s_{23}$ $-c_{12}c_{13}c_{24}s_{14}s_{34}e^{i\delta_{14}}$ $+c_{23}s_{12}s_{24}s_{34}e^{i\delta_{24}}$ $+c_{12}s_{13}s_{23}s_{24}s_{34}e^{i(\delta_{13}+\delta_{24})}$	$-c_{12}c_{34}s_{23} - c_{23}c_{34}s_{12}s_{13}e^{i\delta_{13}}$ $-c_{12}c_{23}s_{24}s_{34}e^{i\delta_{24}}$ $-c_{13}c_{24}s_{12}s_{14}s_{34}e^{i\delta_{14}}$ $+s_{12}s_{13}s_{23}s_{24}s_{34}e^{i(\delta_{13}+\delta_{24})}$	$c_{13}c_{23}c_{34}$ $-c_{13}s_{23}s_{24}s_{34}e^{i\delta_{24}}$ $-c_{24}s_{13}s_{14}s_{34}e^{i(\delta_{14}-\delta_{13})}$	$c_{14}c_{24}s_{34}$
$-c_{12}c_{13}c_{24}c_{34}s_{14}e^{i\delta_{14}}$ $+c_{12}c_{23}s_{13}s_{34}e^{i\delta_{13}}$ $+c_{23}c_{34}s_{12}s_{24}e^{i\delta_{24}} - s_{12}s_{23}s_{34}$ $+c_{12}c_{34}s_{13}s_{23}s_{24}e^{i(\delta_{13}+\delta_{24})}$	$-c_{12}c_{23}c_{34}s_{24}e^{i\delta_{24}} + c_{12}s_{23}s_{34}$ $-c_{13}c_{24}c_{34}s_{12}s_{14}e^{i\delta_{14}}$ $+c_{23}s_{12}s_{13}s_{34}e^{i\delta_{13}}$ $+c_{34}s_{12}s_{13}s_{23}s_{24}e^{i(\delta_{13}+\delta_{24})}$	$-c_{13}c_{23}s_{34}$ $-c_{13}c_{34}s_{23}s_{24}e^{i\delta_{24}}$ $-c_{24}c_{34}s_{13}s_{14}e^{i(\delta_{14}-\delta_{13})}$	$c_{14}c_{24}c_{34}$

Generalized Wolfenstein Parametrization

$$\lambda \equiv s_{12}\,, \quad s_{23} \equiv A\lambda^2\,, \quad s_{13}e^{i\delta_{13}} \equiv A\lambda^3(\rho + i\eta) \equiv A\lambda^3\, z_\rho$$

$$s_{14}e^{i\delta_{14}} = \lambda^{n_1} z_\tau\,, \quad s_{24}e^{i\delta_{24}} = \lambda^{n_2} z_\sigma\,, \quad s_{34} = \lambda^{n_3} B\,,$$

For the maximally allowed mixing $s_{14} \sim \lambda^2, s_{24} \sim \lambda, s_{34} \sim \lambda$ we obtain the following approximation up to $\mathcal{O}(\lambda^3)$

$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 A z_\rho^* & \lambda^2 z_\tau^* \\ -\lambda & 1-\frac{\lambda^2}{2}\left(1+|z_\sigma|^2\right) & \lambda^2 A & \lambda z_\sigma^* \\ \lambda^3 A(1-z_\rho) & -\lambda^2\left(A + B z_\sigma\right) & 1-\frac{\lambda^2}{2}B^2 & \lambda B \\ \lambda^2\left(-z_\tau + z_\sigma\right) & -\lambda z_\sigma & -\lambda B & 1-\frac{\lambda^2}{2}\left(|z_\sigma|^2 + B^2\right) \end{pmatrix}$$

$$+\lambda^3 \begin{pmatrix} 0 & 0 & 0 & 0 \\ \frac{1}{2}\left(-2z_\tau z_\sigma^* + |z_\sigma|^2\right) & 0 & 0 & 0 \\ B(-z_\tau + z_\sigma) & 0 & 0 & -\frac{1}{2}B|z_\sigma|^2 \\ 0 & \frac{1}{2}\left(z_\sigma(1+B^2) + 2AB - 2z_\tau\right) & -Az_\sigma & 0 \end{pmatrix}$$

Generalized Loop Functions

similar to Blanke et. al., JHEP 01 (2007) 666

We introduced generalized Inami-Lim functions

$$I_0 \to I_i = |I_i| e^{i\theta_I^i}$$

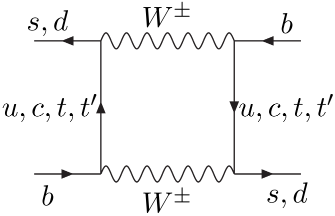
for $I = S, X, Y, \ldots$ and $i = K, s, d$

- in contrast to the std. ones they are non-universal and complex-valued
- enable us to study universality-violation in a systematic manner

e.g. X_0, relevant for $K \to \pi\nu\bar{\nu}$, will change as follows

$$X_i^l = X_0(x_t) + \frac{\lambda_{t'}^{(i)}}{\lambda_t^{(i)}} X(x_{t'}) + \Delta_i^l$$

$B^0_{s,d} - \overline{B^0}_{s,d}$ mixing



for $q = d, s$
$\lambda_i^{(q)} = V_{ib} V_{iq}^*$

for the K system
$\lambda_i^{(K)} = V_{id} V_{is}^*$

$$\mathcal{H}_{\text{eff}}^q = \frac{G_F^2}{16\pi^2} M_W^2 \eta_B \left(\lambda_t^{(q)}\right)^2 S_q \left[\alpha_s^{(5)}\right]^{-6/23} \left[1 + \frac{\alpha_s^{(5)}}{4\pi} J_5\right] Q^q(\Delta B = 2)$$

$$S_q = S_0(x_t) + \frac{\eta_{tt'}^{(q)}}{\eta_{tt}^{(q)}} \left(\frac{\lambda_{t'}^{(q)}}{\lambda_t^{(q)}}\right)^2 S_0(x_{t'}) + 2\,\frac{\eta_{tt'}^{(q)}}{\eta_{tt}^{(q)}} \left(\frac{\lambda_{t'}^{(q)}}{\lambda_t^{(q)}}\right) S_0(x_t, x_{t'})$$

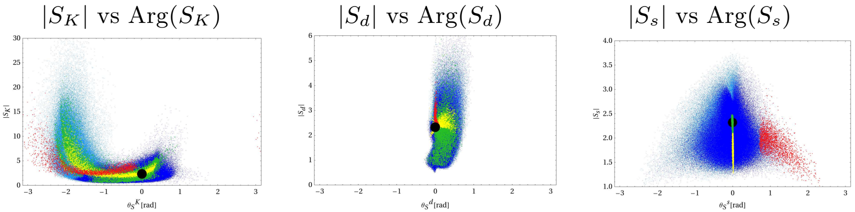
For the B system we can neglect all the charm contributions

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 $\mathrm{Br}(K_L \to \pi^0\nu\bar{\nu}) \leq 2 \cdot 10^{-10}$

$\Delta F = 2$ master functions



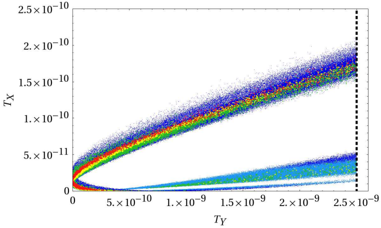
- hierachic effects in $|S_i|$ resulting from the hierachy in $|\lambda_t^{(i)}|$
- $\theta_S^K < 0$ preferred as a solution to the ε_K anomaly in the SM3
- θ_S^d constrained through $S_{\psi K_S}$ but $\theta_S^d > 0$ is preferred
- θ_S^s currently not directly constrained, however $S_{\psi\phi} > 0.4$ would require a substantial phase

ε_K and ΔM_K only put relatively mild constraints on the SM4!

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

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

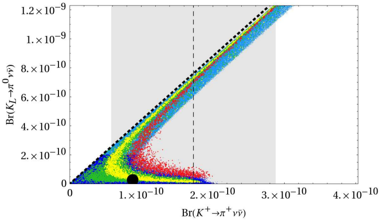
$$T_X \equiv \mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu}) - \frac{\kappa_+}{\kappa_L}\mathrm{Br}(K_L \to \pi^0\nu\bar{\nu})$$



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

$\mathrm{Br}\left(K_L \to \mu^+\mu^-\right)_{\mathrm{SD}} < 2.5\cdot10^{-9}$ G. Isidori et. al. JHEP 01 (2004) 009

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



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

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

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

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

Time-dependent CP Asymmetries Preliminaries

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

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

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

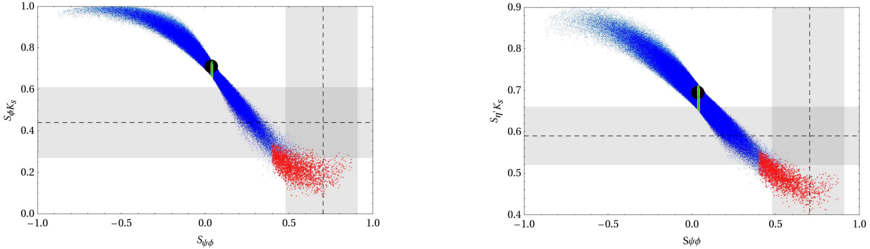
- b_{fi}^c, b_{fi}^u from non-pert. QCD
- ratio a_f^u of SM amplitudes

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

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

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 $S_{\psi\phi}$

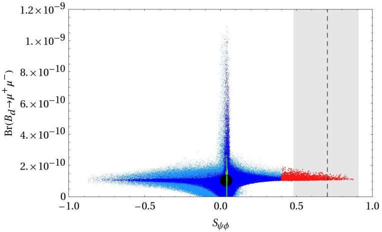


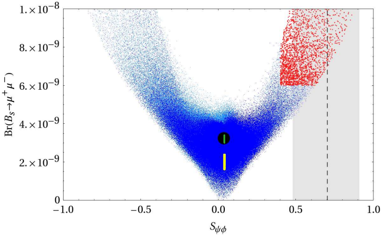
- Enhancement of $S_{\psi\phi}$ is always accompanied by a suppression of both $S_{\phi K_S}$ and $S_{\eta' K_S}$.
- For $S_{\psi\phi} > 0.7$ all the points 'miss' the 1σ range of $S_{\eta' K_S}$
- A more detailed analysis of the b_{fi} parameters would be needed in order to turn the above into solid predictions.

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

$\mathrm{Br}(B_s \to \mu^+\mu^-)$ will be measured in the near future at the LHC

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

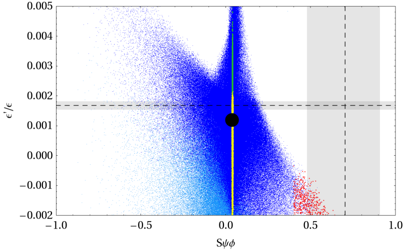




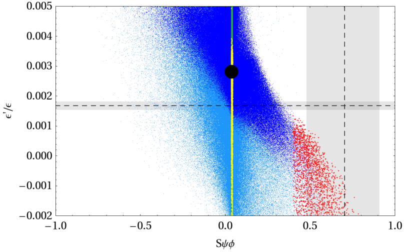
- Big enhancements in $\mathrm{Br}(B_q \to \mu^+\mu^-)$ possible but not simultaneously ($\to$ non-CMFV nature of the SM4)
- Enhancement of $S_{\psi\phi}$ above 0.5 implies enhancement of $\mathrm{Br}(B_s \to \mu^+\mu^-)$

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

$S_{\psi\phi}$ vs. ε'/ε 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 fit 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

Messages and Conclusions

- All existing tensions in the SM UT fit can be resolved simultaneously within the SM4
- In particular the $S_{\psi\phi}$ anomaly can be resolved while suppressing $S_{\phi K_S}$ in accord with the data
- The desire to explain the $S_{\psi\phi}$ anomaly implies an (spectacular) enhancement of $\mathrm{Br}(B_s \to \mu^+\mu^-)$
- In $Br(K_L \to \pi^0 \nu\bar{\nu})$ and $Br(K^+ \to \pi^+ \nu\bar{\nu})$ there is, independently from the B system, still much room for big enhancements
- ε'/ε could put the SM4 under pressure if the measurement of $S_{\psi\phi} \gg (S_{\psi\phi})_{\mathrm{SM}}$ was confirmed

Thank you for your attention!

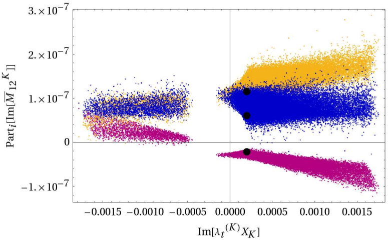
Backup Start

Backup

The constraints from ε_K on the K sector

$$\overline{M}_{12}^{K} = \lambda_c^{*(K)^2} \eta_{cc} S_0(x_c) + \lambda_t^{*(K)^2} \eta_{tt}^{(K)} S_K^{*} + 2\eta_{ct}^{(K)} \lambda_t^{*(K)} \lambda_c^{*(K)} S_0(x_t, x_c)$$

$$\varepsilon_K \sim \mathrm{Im}\left(\overline{M}_{12}^{K}\right)$$

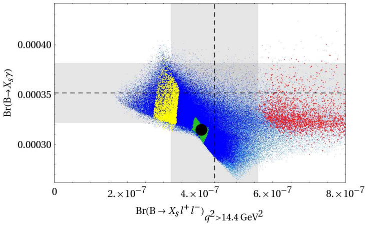


- The individual parts of $\overline{M}_{12}^{K}$ can deviate up to an order of magnitude from their SM value
- Deviations are cancelled out due to correlations between the individual parts

$\mathrm{Im}\left(\lambda_t^{(K)} X_K\right)$ can be enhanced by an order of magnitude

$\mathrm{SM} \approx 0.0002$

$B \to X_s\gamma$ 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.

Full formulae

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

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

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

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

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

Classification of the new mixing angles - Preliminaries

Following T. Feldmann, T. Mannel, JHEP 02 (2007) 067

- The SM4 is a particular realisation of the next-to-Minimal-Flavour-Violation (nMFV) framework
- The new flavour violating structures are generated by one spurion,

$$\chi_L \sim (\mathbf{3}, \mathbf{1}, \mathbf{1})_{0,0,1}$$

which is a triplet of $SU(3)_{Q_L}$ and charged under $U(1)_{Q'}$

- To preserve the SM power-counting in the CKM parameters the following consistency relation has to hold

$$\begin{aligned} |(\chi_L)_i||(\chi_L)_j| &\lesssim \theta_{ij}\,, && (i,j = 1\ldots 3) \\ \Leftrightarrow \theta_{ik}\theta_{jk} &\lesssim \theta_{ij}\,, && (i,j,k = 1\ldots 4) \end{aligned}$$

- A special way to ensure this relation is to consider a simple Froggatt-Nielsen (FN) setup

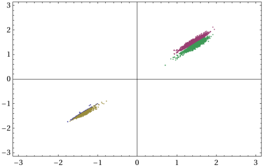
Four Benchmark Scenarios

We defined four Benchmark Scenarios, charaterized by the scaling of the three new mixing angles in terms of Wolfenstein λ

$$(4,3,1) \qquad (2,1,1) \qquad (2,3,1) \qquad (3,2,1)$$

Scenario $n_1 n_2 n_3$	(a) 431	(b) 211	(c) 231	(d) 321
$\mathrm{Im}\left[\lambda_{t'}^{(d)}/\lambda_t^{(d)}\vert_{\mathrm{SM}}\right]$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(\lambda)$
$\mathrm{Im}\left[\lambda_{t'}^{(s)}/\lambda_t^{(s)}\vert_{\mathrm{SM}}\right]$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(1)$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(\lambda)$
$\mathrm{Im}\left[\lambda_{t}^{(K)}/\lambda_t^{(K)}\vert_{\mathrm{SM}}\right]$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(\lambda)$
$\mathrm{Im}\left[\lambda_{t'}^{(K)}/\lambda_t^{(K)}\vert_{\mathrm{SM}}\right]$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(\lambda^{-2})$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\mathrm{Im}\left[\lambda_{c}^{(K)}/\lambda_c^{(K)}\vert_{\mathrm{SM}}\right]$	$\mathcal{O}(\lambda^6)$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(\lambda^4)$	$\mathcal{O}(\lambda^4)$

Disecting δ_{14} - δ_{24} correlations



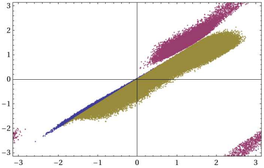
$$(2,1,1) + (2,2,1)$$

class 1a: $\delta_{14} < \delta_{24} < \delta_{14} + \frac{\pi}{8}, \quad \delta_{24} < 0.$

class 1b: $\delta_{14} - \frac{\pi}{8} < \delta_{24} < \delta_{14}, \quad \delta_{24} < 0.$

class 2a: $\delta_{14} < \delta_{24} < \delta_{14} + \frac{\pi}{8}, \quad \delta_{24} > 0.$

class 2b: $\delta_{14} - \frac{\pi}{8} < \delta_{24} < \delta_{14}, \quad \delta_{24} > 0.$

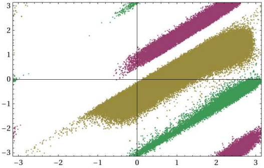


$$(3,2,1)$$

class 1a: $\delta_{14} < \delta_{24} < \delta_{14} + \frac{\pi}{8}, \quad \delta_{24} < 0.$

class 2a/3a: $\delta_{14} < \delta_{24} < \delta_{14} + \frac{3\pi}{8}, \quad \delta_{24} > 0.$

class 3b: $\delta_{14} - \frac{3\pi}{8} < \delta_{24} < \delta_{14}.$



$$(3,3,1) + (3,3,2)$$

class 3a: $\delta_{14} + \frac{\pi}{8} < \delta_{24} < \delta_{14} + \frac{\pi}{2}.$

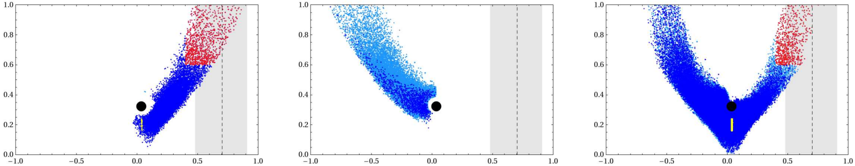
class 3b: $\delta_{14} - \frac{3\pi}{4} < \delta_{24} < \delta_{14}.$

class 4: $\delta_{14} - \frac{9\pi}{8} < \delta_{24} < \delta_{14} - \frac{3\pi}{4}.$

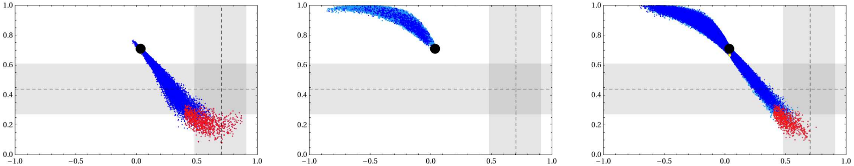
Disentangling Correlations Using Classes I

1a 2a 3b

$$10^8 \cdot \mathrm{Br}(B_s \to \mu^+\mu^-) \quad \text{vs} \quad S_{\psi\phi}$$



$$S_{\phi K_S} \quad \text{vs} \quad S_{\psi\phi}$$

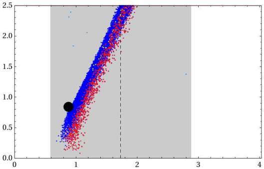


Disentangling Correlations Using Classes II

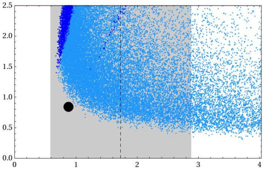
...adding K decays

$$10^9 \cdot \mathrm{Br}(K_L \to \mu^+\mu^-)_{\mathrm{SD}} \quad \text{vs.} \quad 10^{10} \cdot \mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})$$

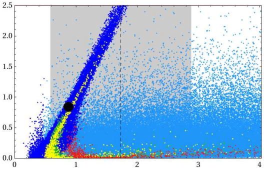
1a



2a



3b



- The different classes are responsible for different structures in the correlations
- One correlation is not enough to clearly distinguish all classes, taking into account more correlations enhances the 'resolution'