Flavour correlations in the RS_c model

based on

P. Biancofiore, F. De Fazio, PC: PRD 89 (2014) 09501
P. Biancofiore, F. De Fazio, E. Scrimieri, PC: EPJ C 75 (2015) 134

Pietro Colangelo
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Portoroz, Slovenia, 10 April 2015

small tensions in flavour observables

$$B\left(B_s^0 \to \mu^+\mu^-\right) = \left(2.8^{+0.7}_{-0.6}\right)\times 10^{-9}$$
$$B\left(B_d^0 \to \mu^+\mu^-\right) = \left(3.9^{+1.6}_{-1.4}\right)\times 10^{-10}$$

LHCb & CMS
1411.4413

$$\overline{B}\left(B_s^0 \to \mu^+\mu^-\right)_{SM} = \left(3.65 \pm 0.23\right)\times 10^{-9}$$
$$B\left(B_d^0 \to \mu^+\mu^-\right)_{SM} = \left(1.06 \pm 0.09\right)\times 10^{-10}$$

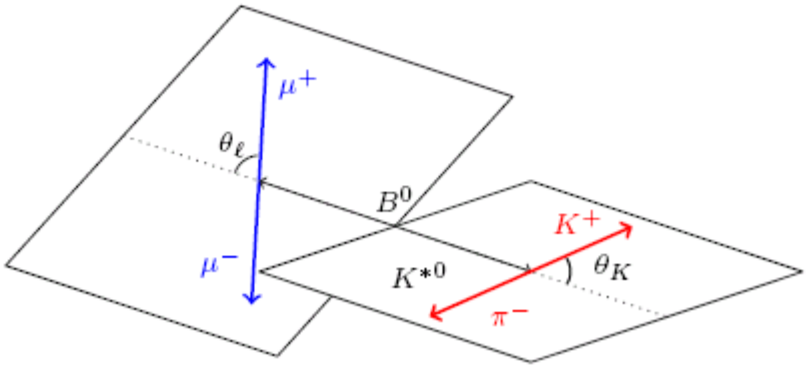
Bobeth et al,
PRL 112 (2014) 101801

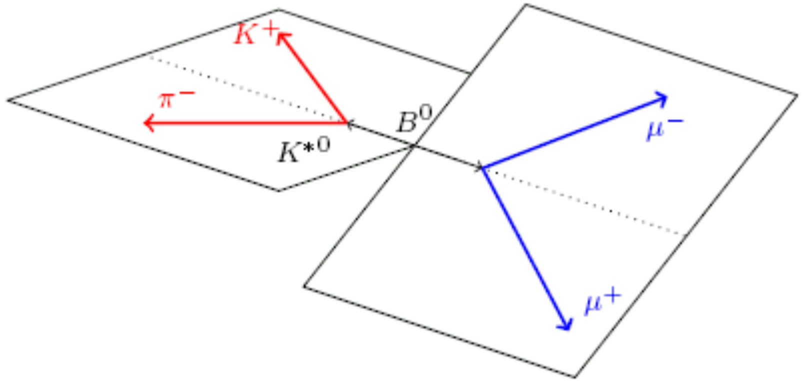
***B*(B$_d$ → μ$^+$ μ$^-$)** higher than in SM ?

R_K, $B(B_s \to \phi\, \mu^+ \mu^-)$ discussed at this workshop — not in this talk

$B(B \to D^* \tau \nu)/B(B \to D^* \mu \nu)$ $B(B \to D \tau \nu)/B(B \to D \mu \nu)$ S. Fajfer, J. Kamenik et al.

angular distributions in B → K* μ+ μ-





$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

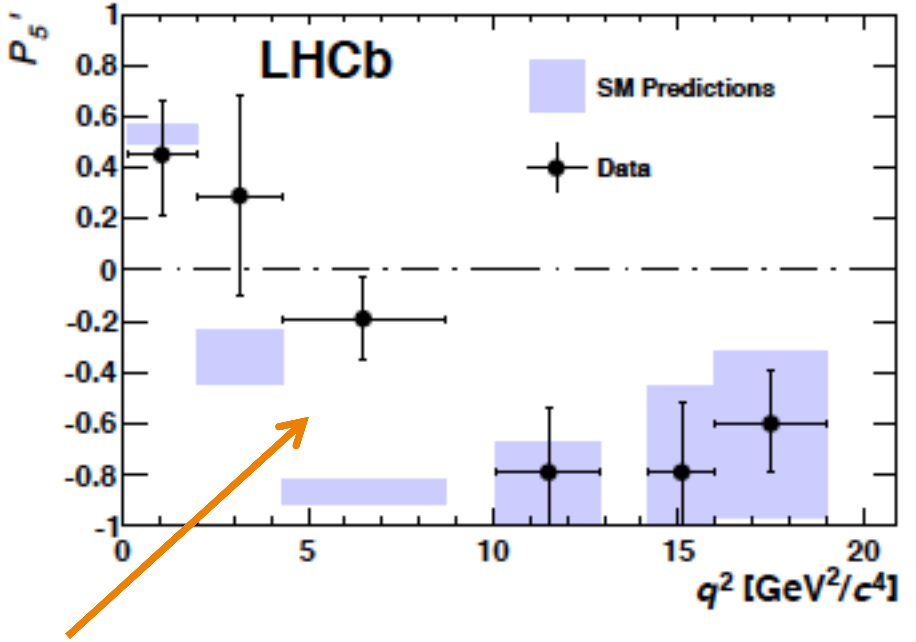
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

mild (?) form factor dependence

Descotes, Matias, Virto, …

observables in $B \to K^* \mu^+ \mu^-$

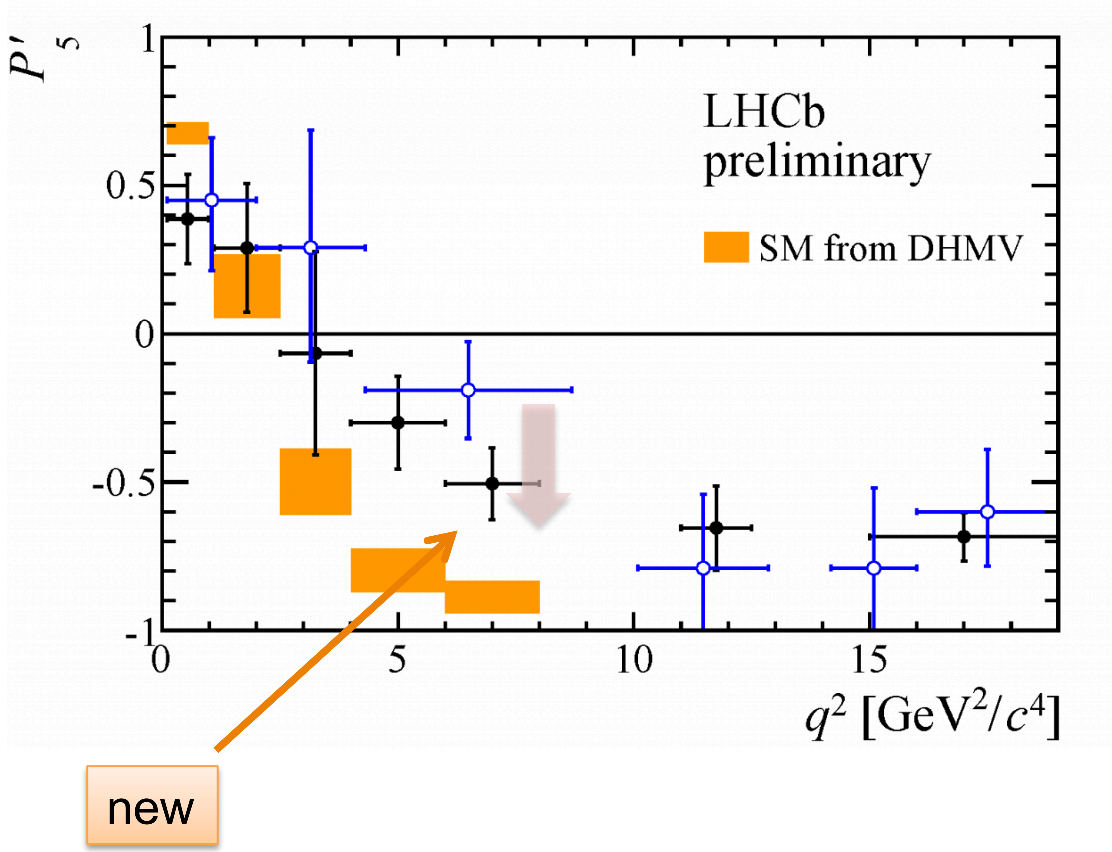
LHCb
PRL 111 (2013) 191801



discrepancy in two bins of q^2

observables in $B \to K^* \mu^+ \mu^-$

LHCb
Moriond 2015



$B \to K^* \mu^+ \mu^-$

$$H^{eff} = -4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left\{ C_1 O_1 + C_2 O_2 + \sum_{i=3,..,6} C_i O_i + \sum_{i=7,..,10,P,S} [C_i O_i + C_i' O_i'] \right\}$$

mostly relevant

$$O_7 = \frac{e}{16\pi^2} m_b (\bar{s}_{L\alpha} \sigma^{\mu\nu} b_{R\alpha}) F_{\mu\nu}$$
$$O_7' = \frac{e}{16\pi^2} m_b (\bar{s}_{R\alpha} \sigma^{\mu\nu} b_{L\alpha}) F_{\mu\nu}$$

$$O_9 = \frac{e^2}{16\pi^2} (\bar{s}_{L\alpha} \gamma^\mu b_{L\alpha})\, \bar{\ell} \gamma_\mu \ell$$
$$O_9' = \frac{e^2}{16\pi^2} (\bar{s}_{R\alpha} \gamma^\mu b_{R\alpha})\, \bar{\ell} \gamma_\mu \ell$$
$$O_{10} = \frac{e^2}{16\pi^2} (\bar{s}_{L\alpha} \gamma^\mu b_{L\alpha})\, \bar{\ell} \gamma_\mu \gamma_5 \ell$$
$$O_{10}' = \frac{e^2}{16\pi^2} (\bar{s}_{R\alpha} \gamma^\mu b_{R\alpha})\, \bar{\ell} \gamma_\mu \gamma_5 \ell$$

if the anomaly is due to NP, how large should be the NP contributions to the relevant Wilson coefficients?

many talks at this workshop

consider other NP realizations

extra-dimensions option

main motivation: hierarchy

RS_c model

concrete models -> precise correlations among observables

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RS_c model

not of a simple model

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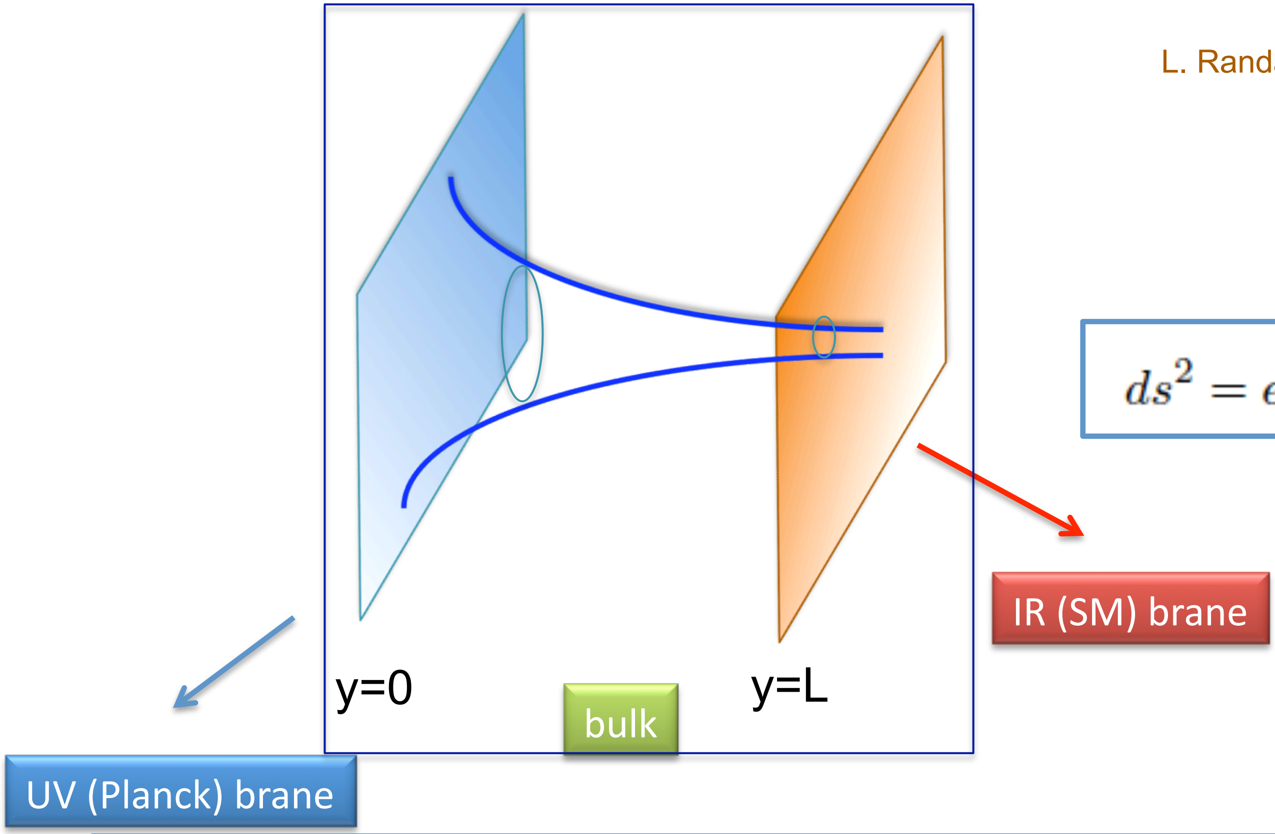
concrete models -> precise correlations among observables

a few correlations found in RS_c

geometry of the RS model



L. Randall, R. Sundrum, PRL 83 (99) 8370

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

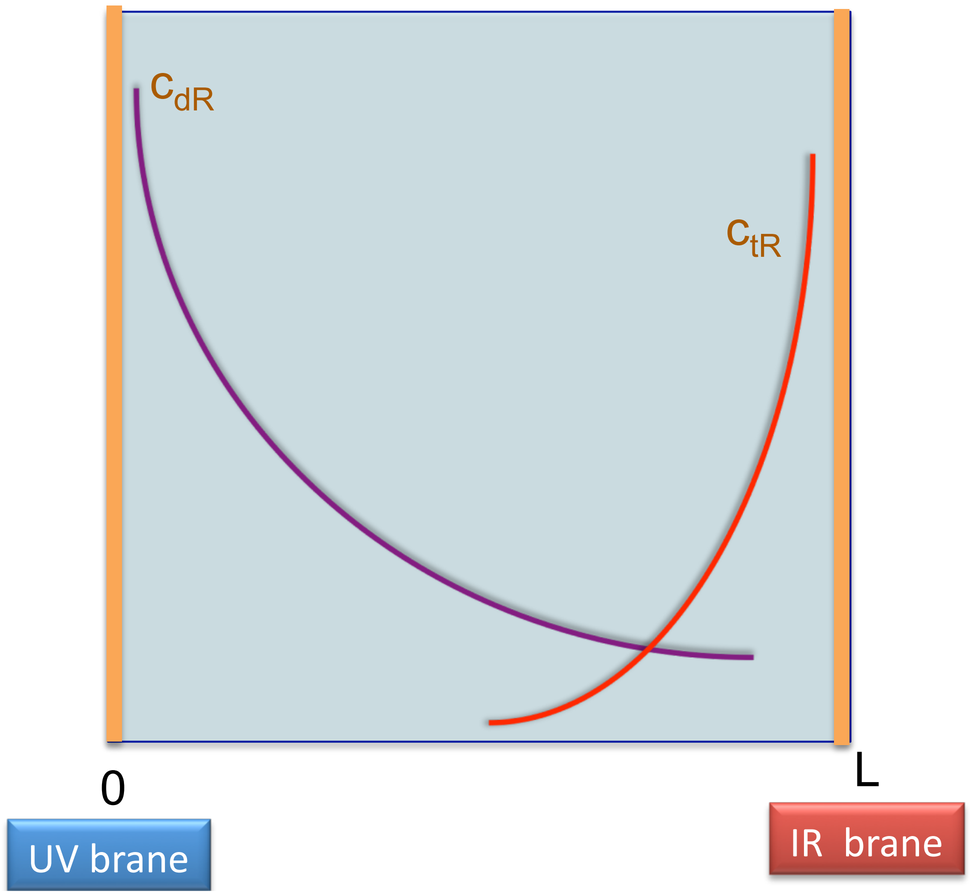
$$k \approx O(M_{Pl})$$

$$k\, e^{-kL} \approx O(TeV)$$

$$kL = Log\left(\frac{M_{Pl}}{M_{EW}}\right) \approx 37$$

- all fields propagate in the bulk, Higgs localized close to or on the IR brane
- solution of the hierarchy problem via geometry
- produces patterns in fermion masses and mixing

bulk Higgs considered, eg, in Archer et al, JHEP 1501 (2015) 060



fermion localization in the extra dimension depends exponentially on O(1) bulk mass parameters c

overlap with a Higgs localized on IR exponentially small for light quarks O(1) for top

custodially protected RS_c

Agashe et al PLB641 (06) 62
Carena et al NPB 759 (06) 202
Cacciapaglia et al PRD75 (07) 015003
Blanke et al JHEP 0903 (09) 001
Casagrande et al JHEP 1009 (09) 014

enlarged gauge group $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{L,R}$

implies a mirror action of the two SU(2) groups

Pros:

- prevents large Z couplings to left-handed fermions
- consistent with electroweak precision observables without large fine-tuning
- masses of KK of a few TeV (within the LHC reach)

compact ED -> tower of KK excitatios for each particle

SM particles identified with zero-modes

boundary conditions on the branes distinguish particles with a SM counterpart from those without it

Neumann BC on both branes (++) -> zero-modes (SM states)

Neumann BC on the IR brane + Dirichlet BC on the UV brane-> no zero-modes

extended gauge group -> new gauge bosons

$SU(2)_L \longrightarrow W_L^{a,\mu}$

$SU(2)_R \longrightarrow W_R^{a,\mu}$

$U(1)_X \longrightarrow X^{\mu}$

charged

$$W^{\pm}_{L(R)\mu} = \frac{W^1_{L(R)\mu} \mp i W^2_{L(R)\mu}}{\sqrt{2}}$$

neutral: two-step mixing

$W_R^3 + X$

$$Z_{X\mu} = c_\phi W^3_{R\mu} - s_\phi X_\mu$$
$$B_\mu = s_\phi W^3_{R\mu} + c_\phi X_\mu$$

$$c_\phi = \cos\phi = \frac{g}{\sqrt{g^2 + g_X^2}}$$
$$s_\phi = \sin\phi = \frac{g_X}{\sqrt{g^2 + g_X^2}}$$

$W_L^3 + B$

$$Z_\mu = c_\psi W^3_{L\mu} - s_\psi B_\mu$$
$$A_\mu = s_\psi W^3_{L\mu} + c_\psi B_\mu$$

$$c_\psi = \cos\psi = \frac{1}{\sqrt{1 + s_\phi^2}}$$
$$s_\psi = \sin\psi = \frac{s_\phi}{\sqrt{1 + s_\phi^2}}$$

gauge bosons after mixing

- gluons $G_\mu(++)$
- charged bosons $W_L^\pm(++)$ and $W_R^\pm(-+)$
- neutral bosons $A(++)$, $Z(++)$ and $Z_X(-+)$

+ KK towers

further mixing occurs between zero-modes and higher KK states

$$\begin{pmatrix} W^\pm \\ W_H^\pm \\ W'^\pm \end{pmatrix} = \mathcal{G}_W \begin{pmatrix} W_L^{\pm(0)} \\ W_L^{\pm(1)} \\ W_R^{\pm(1)} \end{pmatrix}$$

$$\begin{pmatrix} Z \\ Z_H \\ Z' \end{pmatrix} = \mathcal{G}_Z \begin{pmatrix} Z^{(0)} \\ Z^{(1)} \\ Z_X^{(1)} \end{pmatrix}$$

fermions

ordinary fermions in suitable representations of the enlarged gauge group together with new massive fermions

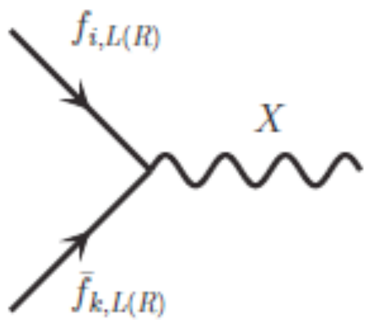
quark mass eigenstates obtained upon rotation of the flavour eigenstates

4 rotation matrices:
$U_{L,R}$ $D_{L,R}$ for up left- (right-) and down left- (right-) type quarks

$$V_{CKM} = \mathscr{U}_L^\dagger \mathscr{D}_L$$

one of the 4 matrices can be eliminated in favour of the CKM
the others enter in the Feynman rules of neutral and charged current interactions

tree-level FCNC in RS$_c$ model

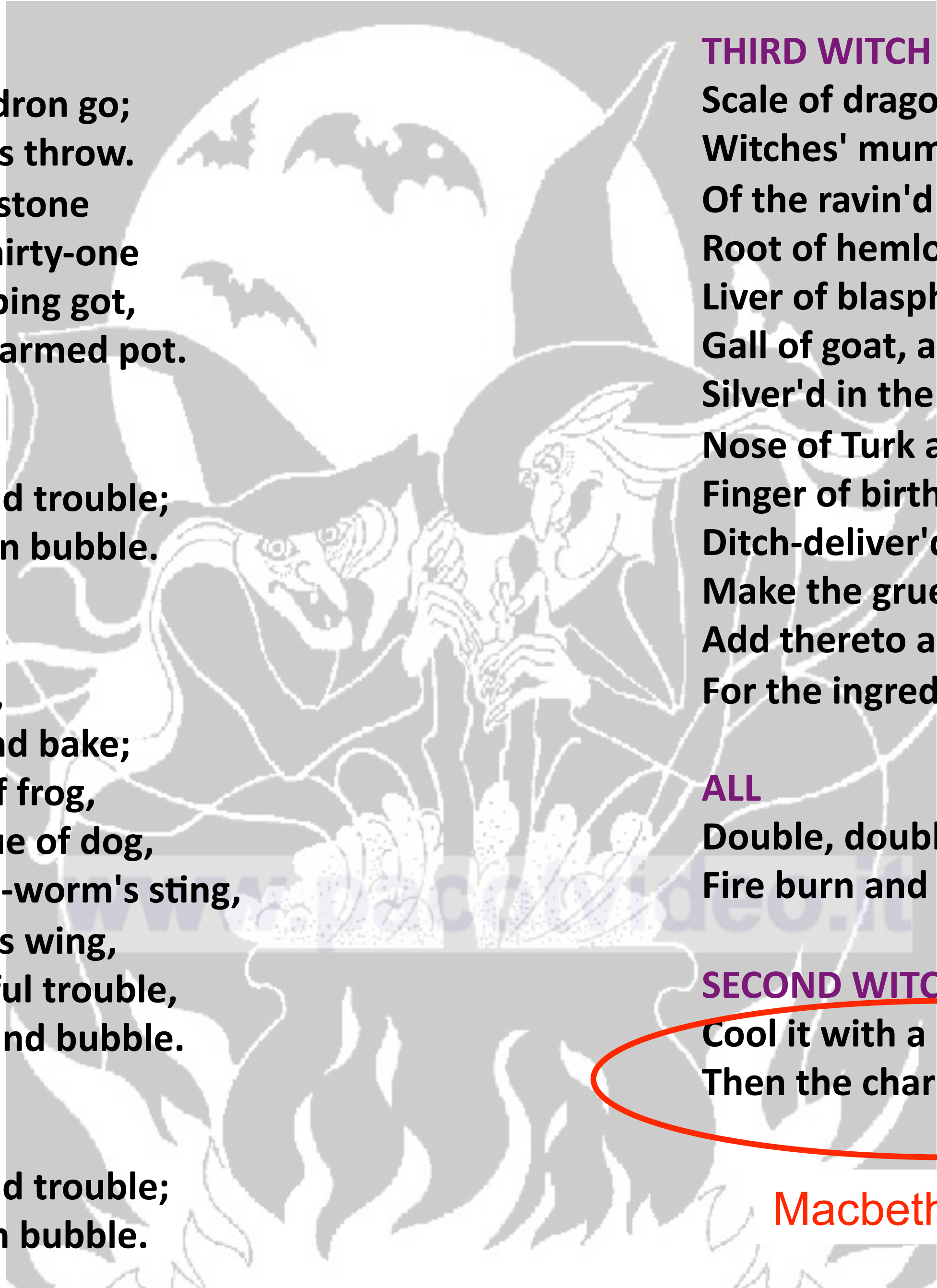


$$-i\bar{f}_k \Delta^{ik}_{L(R)} \gamma_\mu P_{L(R)} f_i X^\mu$$

X= A$^{(1)}$ (1st KK of the γ)
Z, Z$_H$, Z' (from mixing of 0- and 1-modes)
G$^{(1)}$ (1st KK of the g)

FCNC involving quarks other than top suppressed

many ingredients



FIRST WITCH

Round about the cauldron go;
In the poison'd entrails throw.
Toad, that under cold stone
Days and nights has thirty-one
Swelter'd venom sleeping got,
Boil thou first i' the charmed pot.

ALL

Double, double toil and trouble;
Fire burn, and cauldron bubble.

SECOND WITCH

Fillet of a fenny snake,
In the cauldron boil and bake;
Eye of newt and toe of frog,
Wool of bat and tongue of dog,
Adder's fork and blind-worm's sting,
Lizard's leg and owlet's wing,
For a charm of powerful trouble,
Like a hell-broth boil and bubble.

ALL

Double, double toil and trouble;
Fire burn and cauldron bubble.

THIRD WITCH

Scale of dragon, tooth of wolf,
Witches' mummy, maw and gulf
Of the ravin'd salt-sea shark,
Root of hemlock digg'd i' the dark,
Liver of blaspheming Jew,
Gall of goat, and slips of yew
Silver'd in the moon's eclipse,
Nose of Turk and Tartar's lips,
Finger of birth-strangled babe
Ditch-deliver'd by a drab,
Make the gruel thick and slab:
Add thereto a tiger's chaudron,
For the ingredients of our cauldron.

ALL

Double, double toil and trouble;
Fire burn and cauldron bubble.

SECOND WITCH

Cool it with a baboon's blood,
Then the charm is firm and good.

Macbeth, act 4, scene 1

modified Wilson coefficients in RS_c model

$$\Delta C_9 = \left[\frac{\Delta Y_s}{\sin^2(\theta_W)} - 4\Delta Z_s\right]$$

$$\Delta C_9' = \left[\frac{\Delta Y_s'}{\sin^2(\theta_W)} - 4\Delta Z_s'\right]$$

$$\Delta C_{10} = -\frac{\Delta Y_s}{\sin^2(\theta_W)} ,$$

$$\Delta C_{10}' = -\frac{\Delta Y_s'}{\sin^2(\theta_W)} ,$$

$$\Delta Y_s = -\frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_L^{\ell\ell}(X) - \Delta_R^{\ell\ell}(X)}{4M_X^2 g_{SM}^2}\Delta_L^{bs}(X) ,$$

$$\Delta Y_s' = -\frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_L^{\ell\ell}(X) - \Delta_R^{\ell\ell}(X)}{4M_X^2 g_{SM}^2}\Delta_R^{bs}(X) ,$$

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Blanke et al, JHEP 0903 (09) 108
Albrecht et al, JHEP 0909 (09) 064

modified Wilson coefficients in RS$_c$ model

$$\Delta C_9 = \left[\frac{\Delta Y_s}{\sin^2(\theta_W)} - 4\Delta Z_s\right]$$

$$\Delta C'_9 = \left[\frac{\Delta Y'_s}{\sin^2(\theta_W)} - 4\Delta Z'_s\right]$$

$$\Delta C_{10} = -\frac{\Delta Y_s}{\sin^2(\theta_W)} \,,$$

$$\Delta C'_{10} = -\frac{\Delta Y'_s}{\sin^2(\theta_W)} \,,$$

$$\Delta Y_s = -\frac{1}{V_{tb}V^*_{ts}} \sum_X \frac{\Delta_L^{\ell\ell}(X) + \Delta_R^{\ell\ell}(X)}{4M_X^2 g_{SM}^2} \Delta_L^{bs}(X) \,,$$

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couplings to leptons

Blanke et al, JHEP 0903 (09) 108
Albrecht et al, JHEP 0909 (09) 064

modified Wilson coefficients in RS_c model

$$\Delta C_9 = \left[\frac{\Delta Y_s}{\sin^2(\theta_W)} - 4\Delta Z_s\right]$$

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$$\Delta C_{10} = -\frac{\Delta Y_s}{\sin^2(\theta_W)} \,,$$

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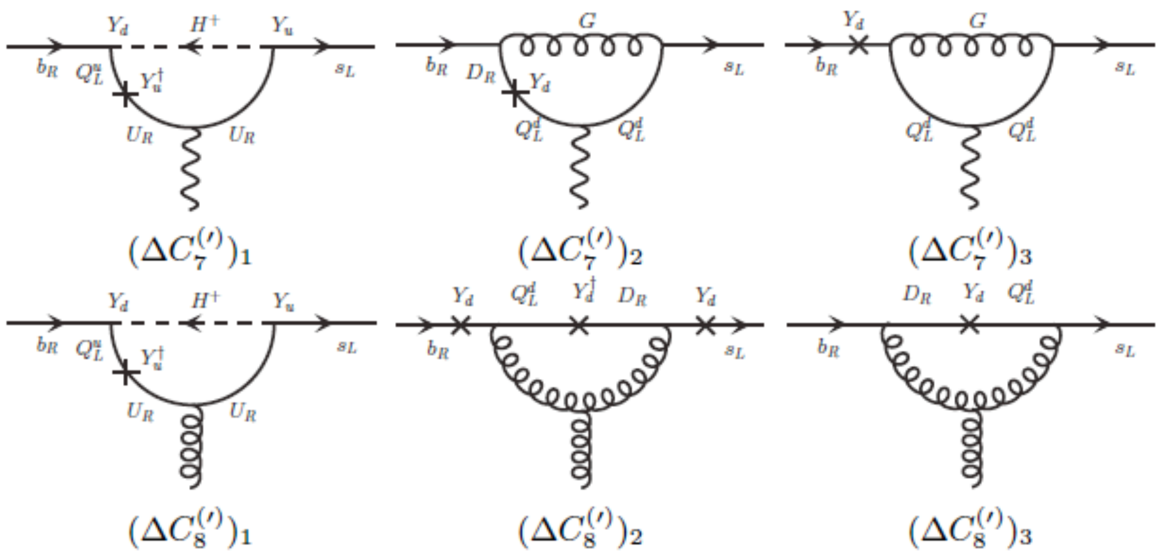
Blanke et al, JHEP 0903 (09) 108
Albrecht et al, JHEP 0909 (09) 064

couplings to leptons

couplings to quarks

modified Wilson coefficients in RS_c

contributions to $C_{7,8}$



Blanke et al. in 5D
Biancofiore, De Fazio, PC, in the effective 4D theory

parameters

KK decomposition:

$$F(x,y) = \frac{1}{\sqrt{L}} \sum_k F^{(k)}(x) f^{(k)}(y)$$

4D fields

5D profiles

fermion profiles (0-mode)

$$f^{(0)}(y,c) = \sqrt{\frac{(1-2c)kL}{e^{(1-2c)kL}-1}}\, e^{-cky}$$

bulk mass

bulk mass parameters are the same for left-handed fermions of the same generation
$(u\ d)_L$ $(c\ s)_L$ $(t\ b)_L$ $(e\ \nu_e)_L$ $(\mu\ \nu_\mu)_L$ $(\tau\ \nu_\tau)_L$

parameters

4D Yukawas

$$Y_{ij}^{u(d)} = \frac{1}{\sqrt{2}} \frac{1}{L^{3/2}} \int_0^L dy\, \lambda_{ij}^{u(d)} f^{(0)}_{q_L^i}(y) f^{(0)}_{u_R^j(d_R^j)}(y) h(y)$$

5D Yukawa matrices

constraints:
$\lambda^{u,d}$ should reproduce
- quark masses
- CKM elements

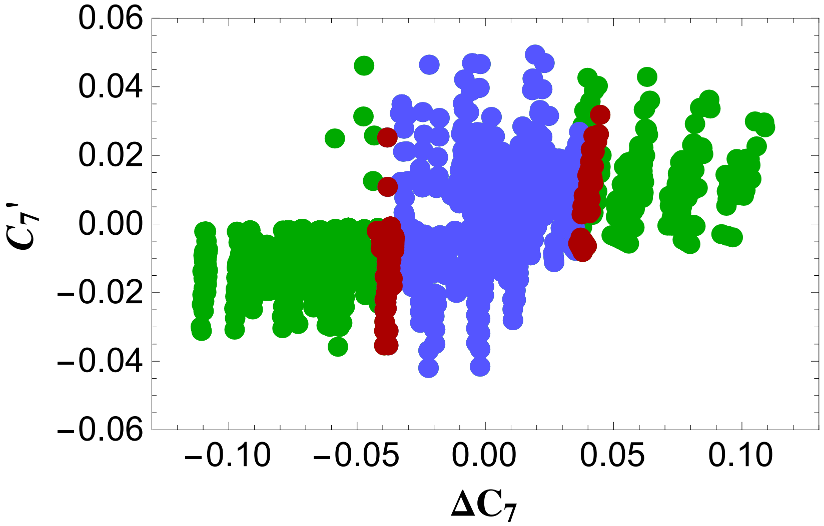
$$m_u = \frac{v}{\sqrt{2}} \frac{det(\lambda^u)}{\lambda^u_{33}\lambda^u_{22} - \lambda^u_{23}\lambda^u_{32}} \frac{e^{kL}}{L} f_{u_L} f_{u_R}$$

$$m_c = \frac{v}{\sqrt{2}} \frac{\lambda^u_{33}\lambda^u_{22} - \lambda^u_{23}\lambda^u_{32}}{\lambda^u_{33}} \frac{e^{kL}}{L} f_{c_L} f_{c_R}$$

$$m_t = \frac{v}{\sqrt{2}} \lambda^u_{33} \frac{e^{kL}}{L} f_{t_L} f_{t_R} \ ,$$

quark rotation matrices depend on $\lambda^{u,d}$

additional contraints with respect to previous analyses



constraints from V_{us} and V_{ub}

constraints from V_{cb} and V_{ub}

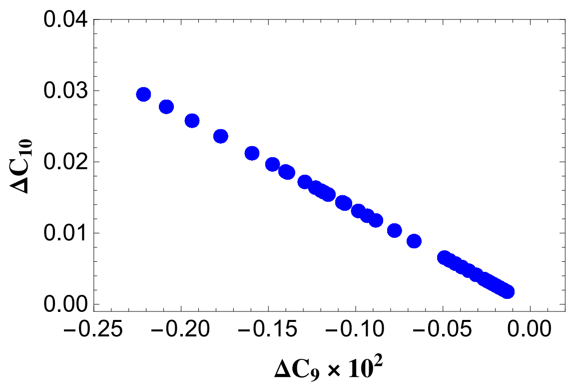
constraints from Brs

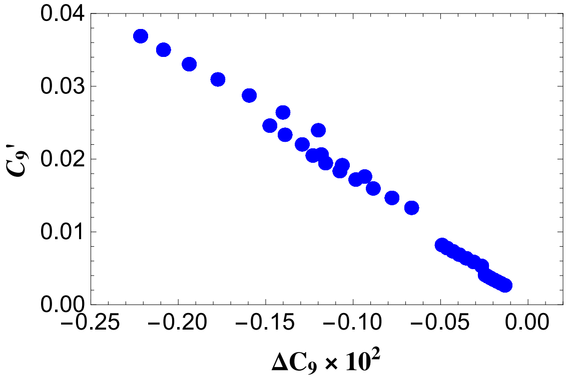
$$B\left(B \to X_s\gamma\right)_{\exp} = \left(3.43 \pm 0.21 \pm 0.07\right) \times 10^{-4}$$

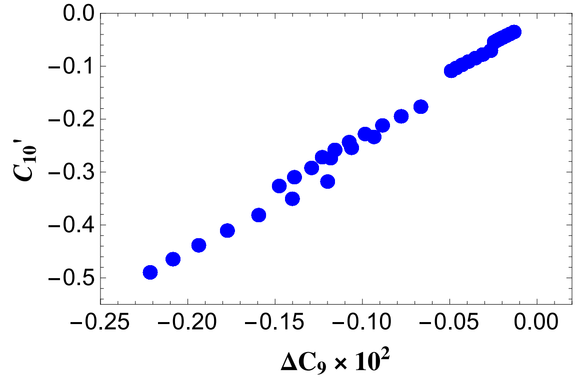
$$B\left(B \to K^* \mu^+ \mu^-\right)_{\exp} = \left(1.02^{+0.14}_{-0.13} \pm 0.05\right) \times 10^{-6}$$

HFAG 2015

results



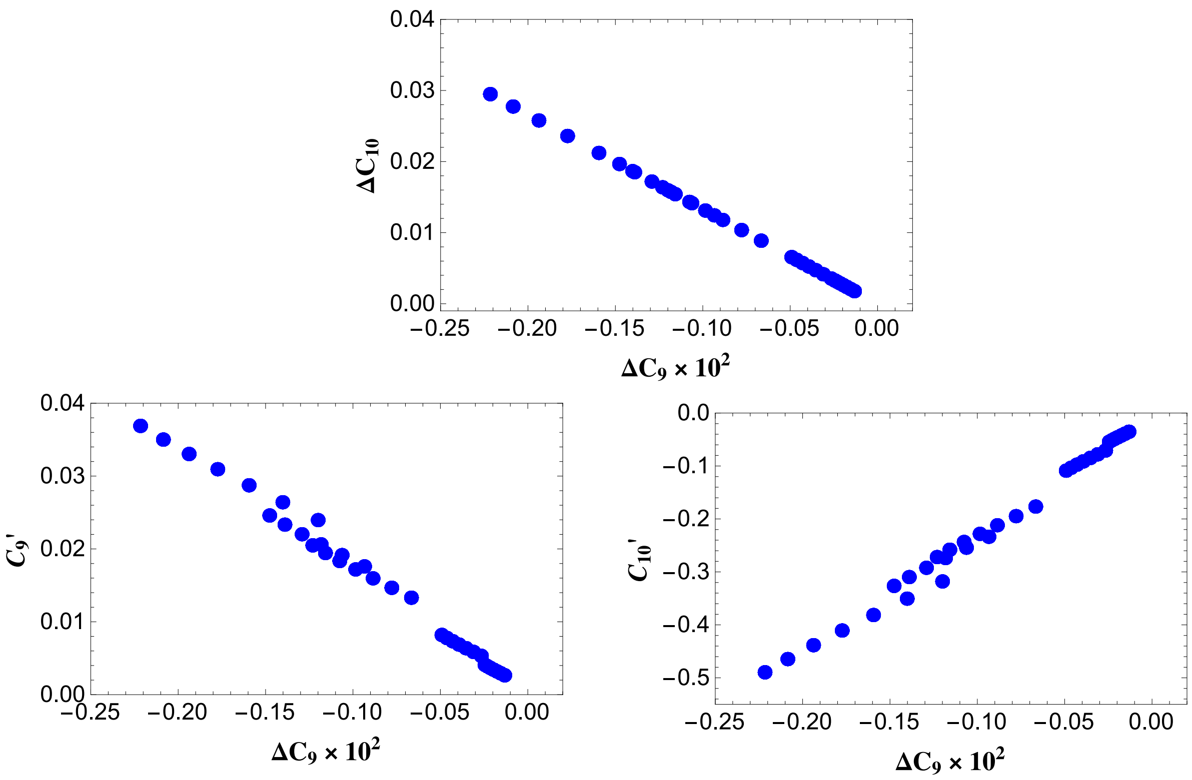




largest deviations from SM:

$$|\Delta C_7|_{max} \simeq 0.046$$
$$|\Delta C_7'|_{max} \simeq 0.05$$
$$|\Delta C_9|_{max} \simeq 0.0023$$
$$|\Delta C_9'|_{max} \simeq 0.038$$
$$|\Delta C_{10}|_{max} \simeq 0.030$$
$$|\Delta C_{10}'|_{max} \simeq 0.50$$

results



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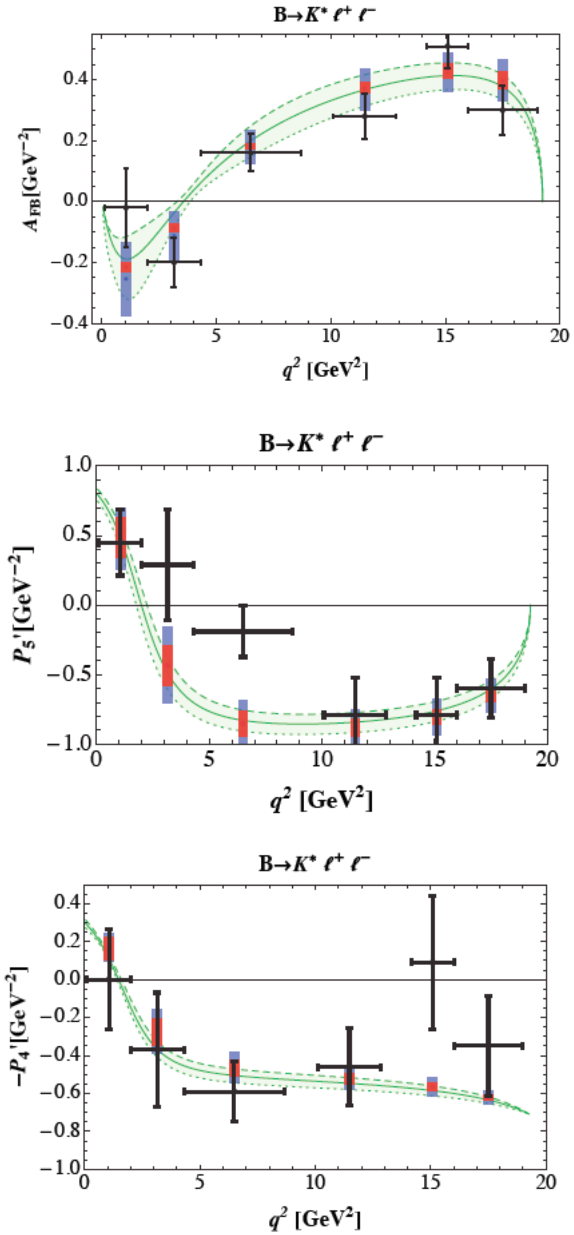
not enough

Althmannshofer at this workshop

Results for B → K^* μ^+ μ^-



SM
including uncertainty on FF

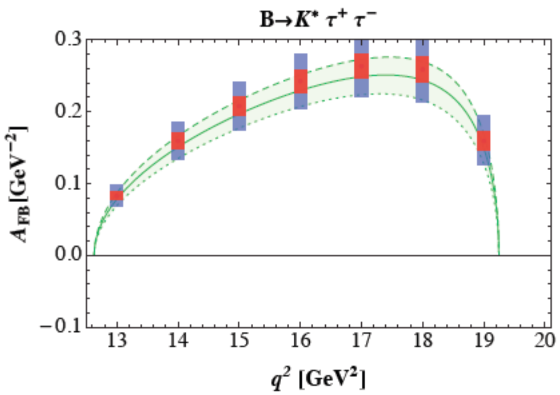
RS_c
uncertainty reflects only
the variation of input parameters

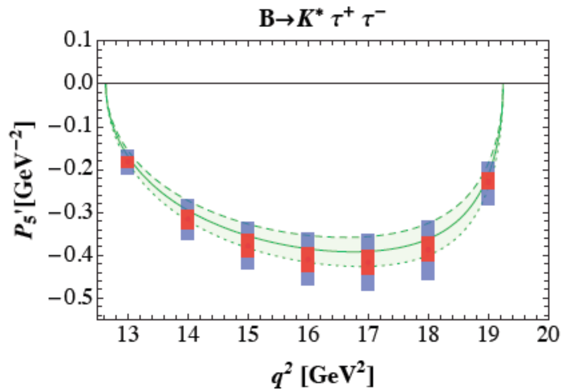
RS_c
uncertainty from
the variation of input parameters & FF

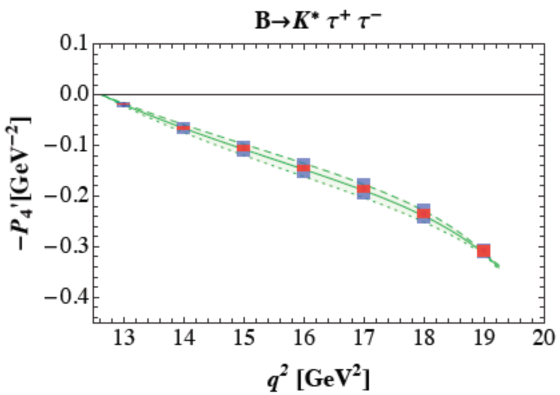
LHCb

- deviations from SM hidden
  by the hadronic uncertainties
- anomaly in P'_5 distribution not explained

τ in the final state

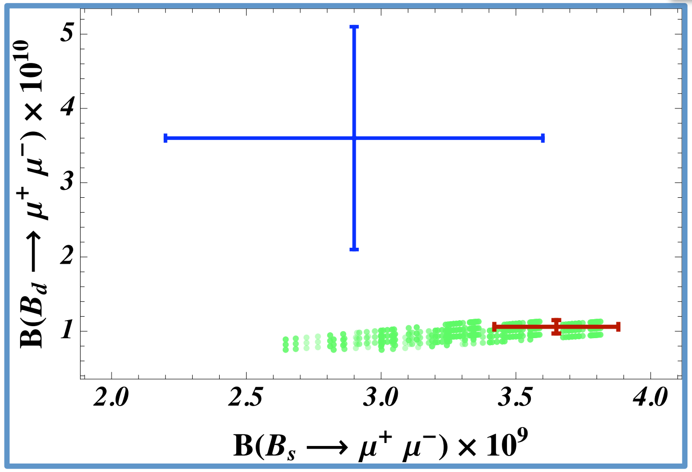






more results

modification versus SM: C_{10} -> C_{10} - C_{10}'



RS_c

SM

data

- in a region of the parameter space the SM result is reproduced
- the allowed range in RS_c is larger than in SM

$$B(B_s \to \mu^+\mu^-)\big|_{RS} \in [2.64 - 3.83] \times 10^{-9}$$

$$B(B_d \to \mu^+\mu^-)\big|_{RS} \in [0.70 - 1.16] \times 10^{-10}$$

- BR for B_d still lower than exp

B -> K$^{(*)}$ $\nu\bar{\nu}$

$$H_{eff} = C_L O_L + C_R O_R$$

$$O_L \;=\; (\bar{b}s)_{V-A}(\bar{\nu}\nu)_{V-A}$$

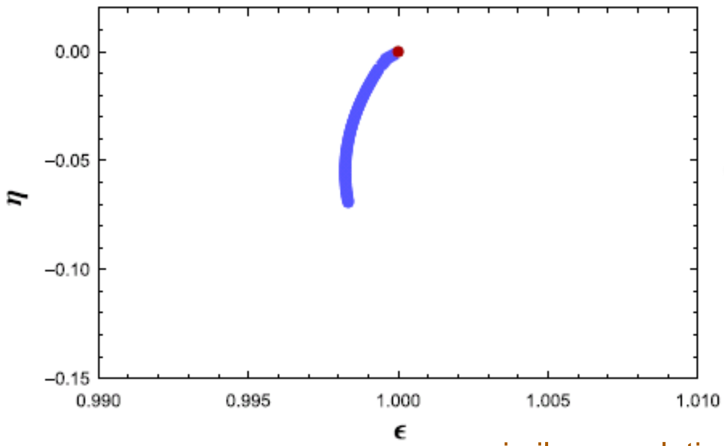
$$O_R \;=\; (\bar{b}s)_{V+A}(\bar{\nu}\nu)_{V-A}$$

the relative weight
can be assessed using

$$\epsilon^2 = \frac{|C_L|^2 + |C_R|^2}{|C_L^{SM}|^2}\,, \qquad \eta = -\frac{\mathrm{Re}\,(C_L C_R^*)}{|C_L|^2 + |C_R|^2}$$

SM: $(\epsilon,\, \eta)_{SM} = (1, 0)$

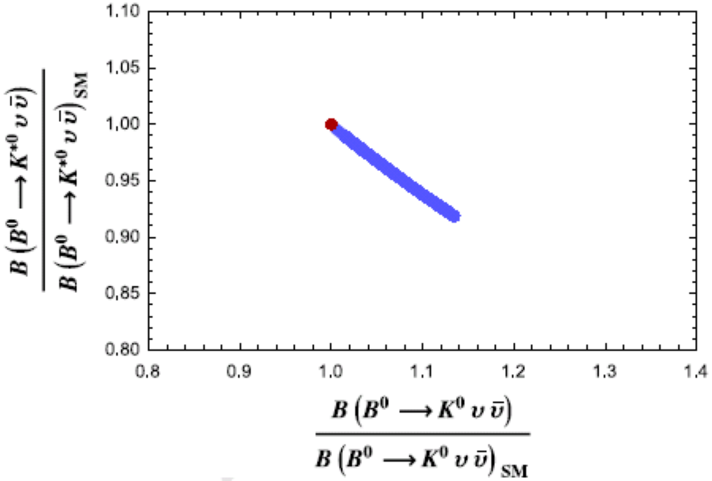
RSc:

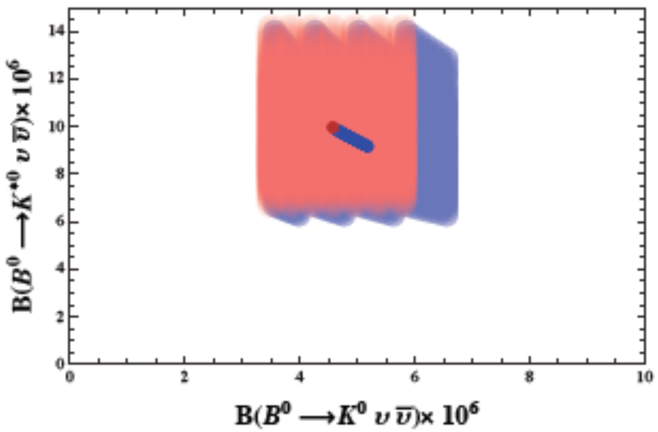


→ η deviates from 0

similar correlation in Buras, De Fazio, Girrbach, JHEP 1302 (2013) 116
Buras et al., JHEP 1502 (2015) 184

B -> $K^{(*)} \nu \bar{\nu}$





$$\mathcal{B}(B^0 \to K^0 \nu\bar{\nu})_{SM} = (4.6 \pm 1.1) \times 10^{-6}$$

$$\mathcal{B}(B^0 \to K^0 \nu\bar{\nu})_{RS} \in [3.45 - 6.65] \times 10^{-6}$$

$$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})_{SM} = (10.0 \pm 2.7) \times 10^{-6}$$

$$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})_{RS} \in [6.1 - 14.3] \times 10^{-6}$$

Belle

$$\begin{aligned} \mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) &< 5.5 \times 10^{-5} \\ \mathcal{B}(B^0 \to K^0_S \nu\bar{\nu}) &< 9.7 \times 10^{-5} \\ \mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu}) &< 4.0 \times 10^{-5} \\ \mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu}) &< 5.5 \times 10^{-5} . \end{aligned}$$

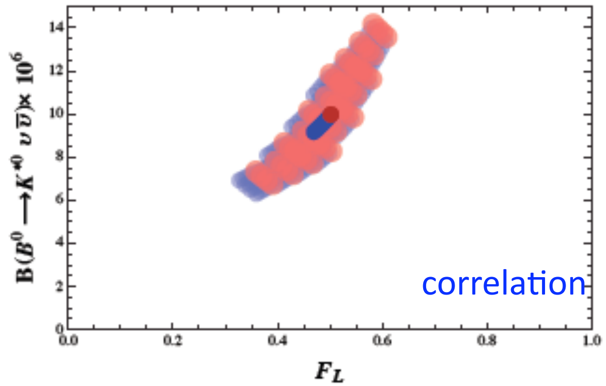
BaBar

$$\begin{aligned} \mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) &< 1.6 \times 10^{-5} \\ \mathcal{B}(B^0 \to K^0 \nu\bar{\nu}) &< 4.9 \times 10^{-5} \\ \mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu}) &< 6.4 \times 10^{-5} \\ \mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu}) &< 12 \times 10^{-5} , \end{aligned}$$

observables in B -> $K^{(*)} \nu \bar{\nu}$

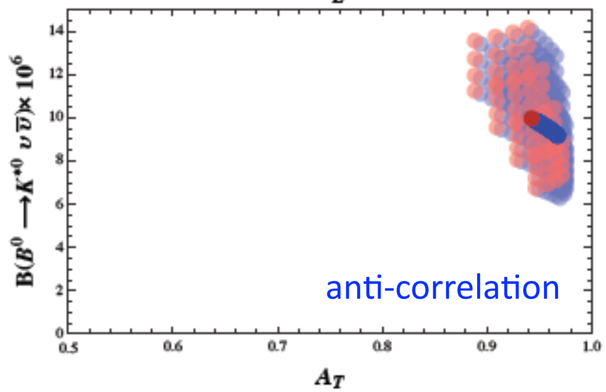
integrated K* polarization fractions

$$F_{L,T} = \frac{1}{\Gamma} \int_0^{1-\bar{m}_{K^*}^2} ds_B \frac{dF_{L,T}}{ds_B} .$$



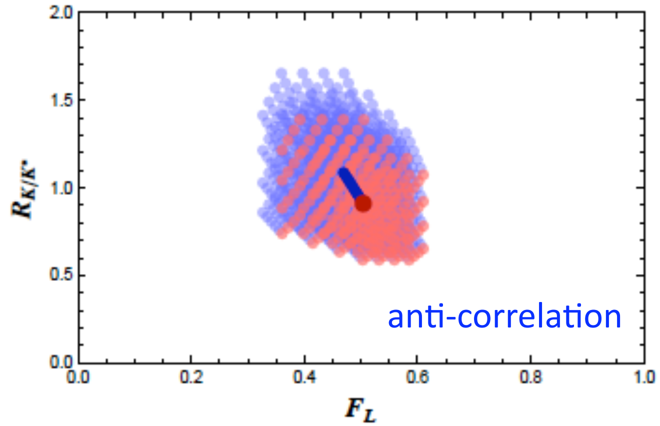
ratio of BRs of K mode and K* mode with transversely polarized K*

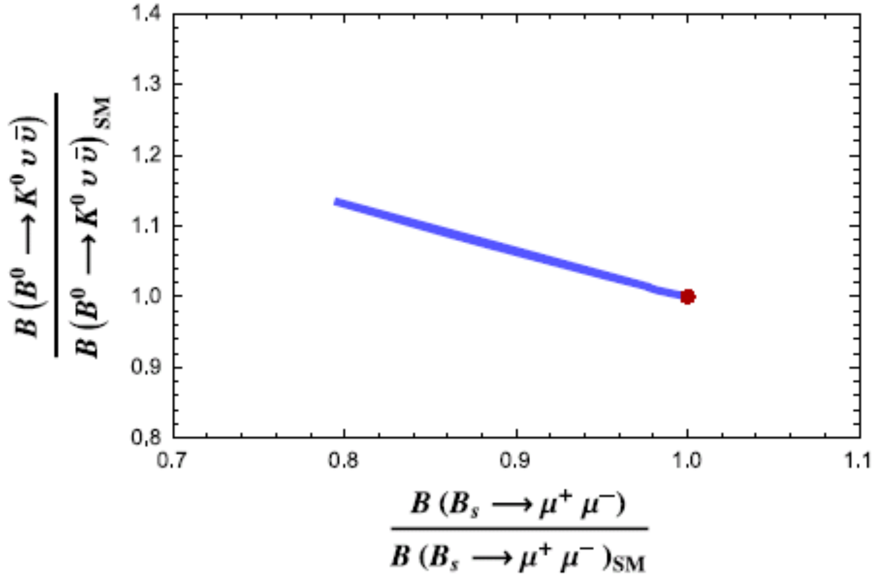
$$R_{K/K^*} = \frac{\mathcal{B}(B \to K \nu\bar{\nu})}{\mathcal{B}(B \to K^*_{h=-1} \nu\bar{\nu}) + \mathcal{B}(B \to K^*_{h=+1} \nu\bar{\nu})}$$

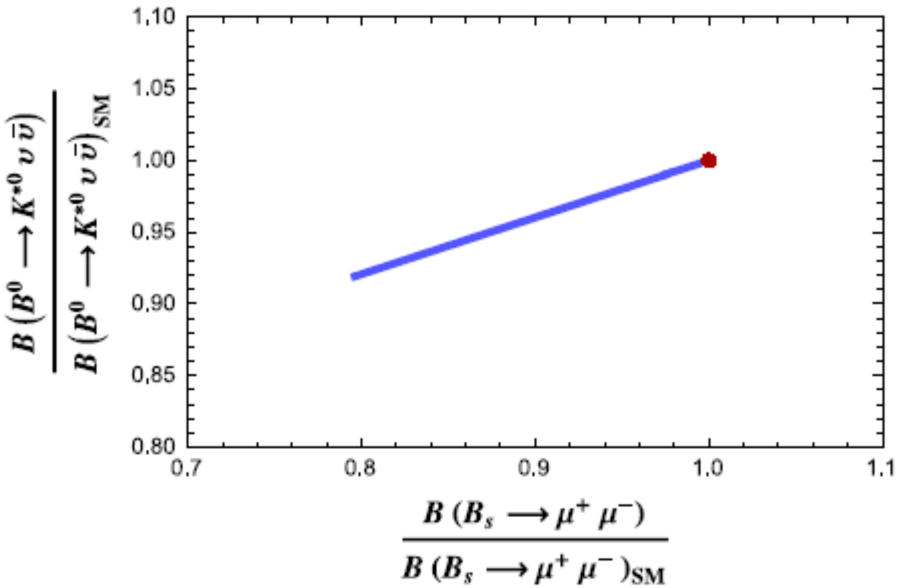


transverse asymmetry

$$A_T = \frac{\mathcal{B}(B \to K^*_{h=-1} \nu\bar{\nu}) - \mathcal{B}(B \to K^*_{h=+1} \nu\bar{\nu})}{\mathcal{B}(B \to K^*_{h=-1} \nu\bar{\nu}) + \mathcal{B}(B \to K^*_{h=+1} \nu\bar{\nu})} ,$$



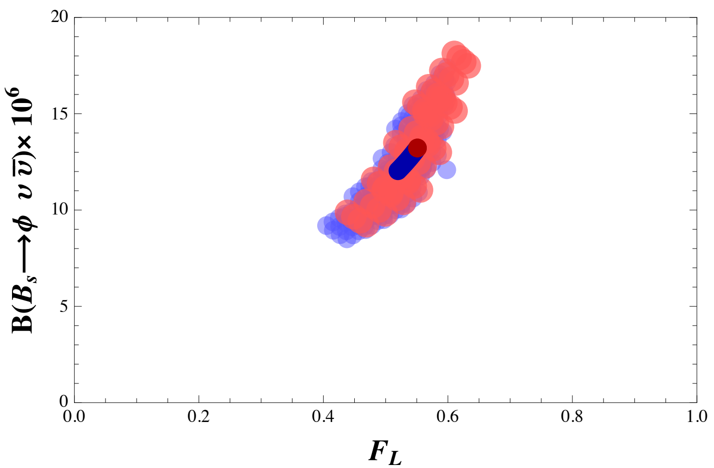

1,4
1,3
1,2
1,1
1,0
0,9
0,8
0.7
0.8
0.9
1.0
1.1
$\frac{B(B^0 \to K^0 \nu \bar{\nu})}{B(B^0 \to K^0 \nu \bar{\nu})_{SM}}$
$\frac{B(B_s \to \mu^+ \mu^-)}{B(B_s \to \mu^+ \mu^-)_{SM}}$


1,10
1,05
1,00
0,95
0,90
0,85
0,80
0.7
0.8
0.9
1.0
1.1
$\frac{B(B^0 \to K^{*0} \nu \bar{\nu})}{B(B^0 \to K^{*0} \nu \bar{\nu})_{SM}}$
$\frac{B(B_s \to \mu^+ \mu^-)}{B(B_s \to \mu^+ \mu^-)_{SM}}$

$B_s \to \phi \nu \bar{\nu}$

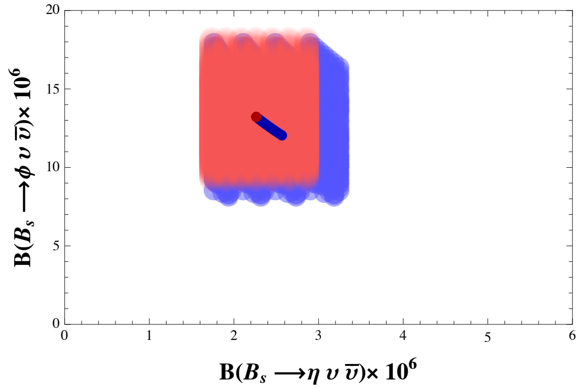
integrated ϕ polarization fractions

$$F_{L,T} = \frac{1}{\Gamma} \int_0^{1-\hat{m}^2_{K^*}} ds_B \, \frac{dF_{L,T}}{ds_B} \, .$$

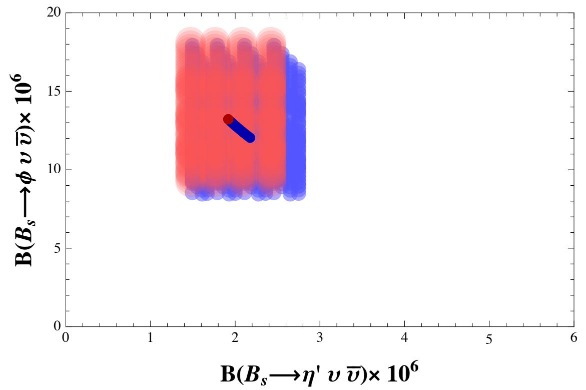


B_s -> (ϕ, η, η' , f_0) $\nu \bar{\nu}$

$$\mathcal{B}(B_s \to \eta\nu\bar{\nu})_{SM} = (2.3 \pm 0.5) \times 10^{-6}$$
$$\mathcal{B}(B_s \to \eta'\nu\bar{\nu})_{SM} = (1.9 \pm 0.5) \times 10^{-6}$$
$$\mathcal{B}(B_s \to \phi\nu\bar{\nu})_{SM} = (13.2 \pm 3.3) \times 10^{-6}$$

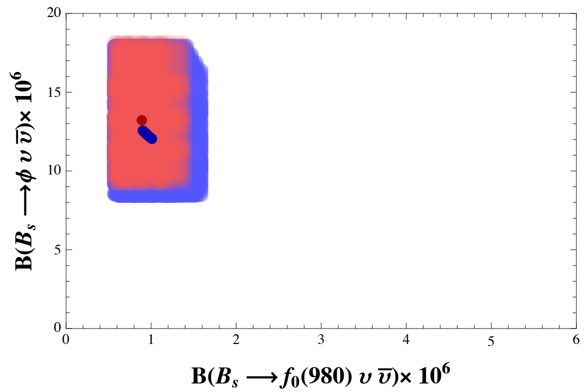


$$\mathcal{B}(B_s \to \eta\nu\bar{\nu})_{RS} \in [1.7 - 3.3] \times 10^{-6}$$
$$\mathcal{B}(B_s \to \eta'\nu\bar{\nu})_{RS} \in [1.5 - 2.8] \times 10^{-6}$$
$$\mathcal{B}(B_s \to \phi\nu\bar{\nu})_{RS} \in [8.4 - 18.0] \times 10^{-6} \ .$$



important role of $f_0(980)$ in rare $B_{(s)}$ decays

$$\mathcal{B}(B_s \to f_0(980)\nu\bar{\nu})_{SM} = (8.95 \pm^{2.9}_{2.5}) \times 10^{-7}$$
$$\mathcal{B}(B_s \to f_0(980)\nu\bar{\nu})_{RS} \in [5 - 17] \times 10^{-7} \ .$$



$B_{(s)}$ -> $f_0(980)$ FF by LCSR

De Fazio, Wang, PC, PRD 81 (2010) 074001

Conclusions

small deviations of the Wilson coefficients in RS_c

not enough to accommodate the present tensions

modes with τ important

multiple correlation patterns among observables, e.g. in neutrino modes