

Quark flavour observables in the flavor precision era: 331 models vs other NP scenarios

Fulvia De Fazio INFN- Bari

Vienna, March 25th 2014

Summary

- Experimental results that challenge SM predictions
- Anatomy of flavour observbles in 331 models
- deviations in angular observables in $B \rightarrow K^* \mu^+ \mu^-$

Based on works in collaborations with

- A.J. Buras, J. G Irrbach
- P. Colangelo, P. Biancofiore

Some results for flavour observables

Two scenarios

1. $|V_{ub}|$ fixed to the exclusive (smaller) value
2. $|V_{ub}|$ fixed to the inclusive (larger) value

Using $\gamma \approx 68^\circ$:

	Scenario 1:	Scenario 2:	Experiment
$ \varepsilon_K $	$1.72(22) \cdot 10^{-3}$	$2.15(32) \cdot 10^{-3}$	$2.228(11) \times 10^{-3}$
$(\sin 2\beta)_{\text{true}}$	$0.623(25)$	$0.770(23)$	$0.679(20)$
$\Delta M_s [\text{ps}^{-1}]$	$19.0(21)$	$19.0(21)$	$17.73(5)$
$\Delta M_d [\text{ps}^{-1}]$	$0.56(6)$	$0.56(6)$	$0.507(4)$
$\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$	$0.62(14) \cdot 10^{-4}$	$1.02(20) \cdot 10^{-4}$	$1.12(22) \times 10^{-4}$

$|V_{ub}|$ in scenario 1

requires NP enhancing $B(B \rightarrow \tau \nu_\tau)$
 reproduces the experimental value for $S_{J/\psi K_S}$
 suppresses ε_K w.r.t. experiment

$\Delta M_{s,d}$ agree within uncertainties, slightly preferring models predicting a small suppression

$|V_{ub}|$ in scenario 2

no NP required for $B(B \rightarrow \tau \nu_\tau)$
 $S_{J/\psi K_S}$ higher than experiment
 ε_K consistent with experiment

Recent results for flavour observables deviating from SM predictions

BR($B_s \rightarrow \mu^+ \mu^-$) close to SM while **BR($B_d \rightarrow \mu^+ \mu^-$)** higher than its SM value
(LHCb + CMS)

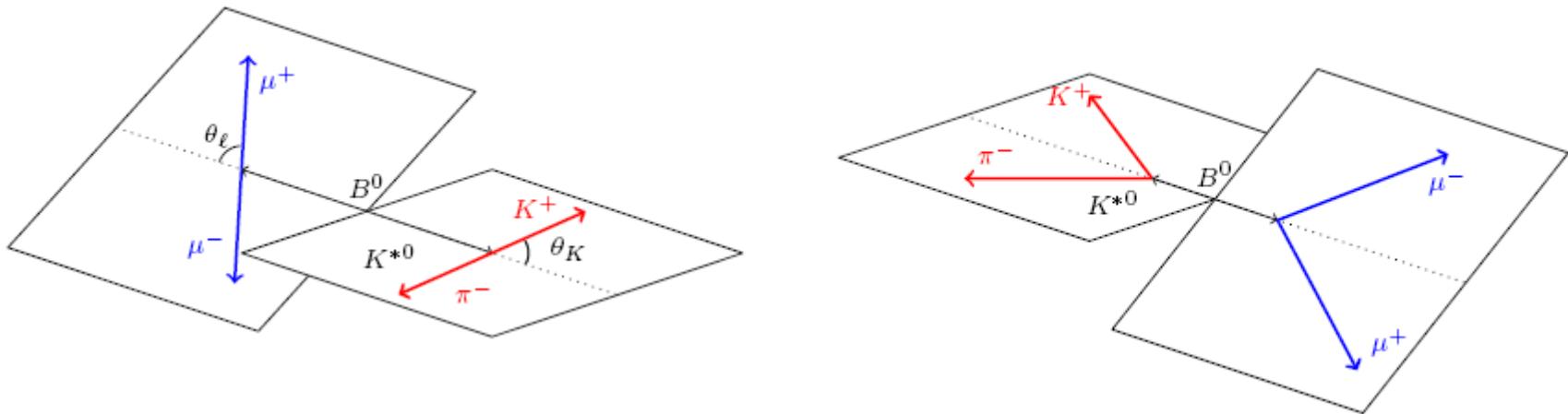
$$\bar{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$
$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) = (3.6 \pm 1.6) \times 10^{-10}$$

LHCb+
CMS

$$\bar{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-)_{SM} = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-)_{SM} = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al,
1311.0903

Bin analysis of angular observables in $\mathbf{B} \rightarrow \mathbf{K}^* \mu^+ \mu^-$ deviate from SM (LHCb)



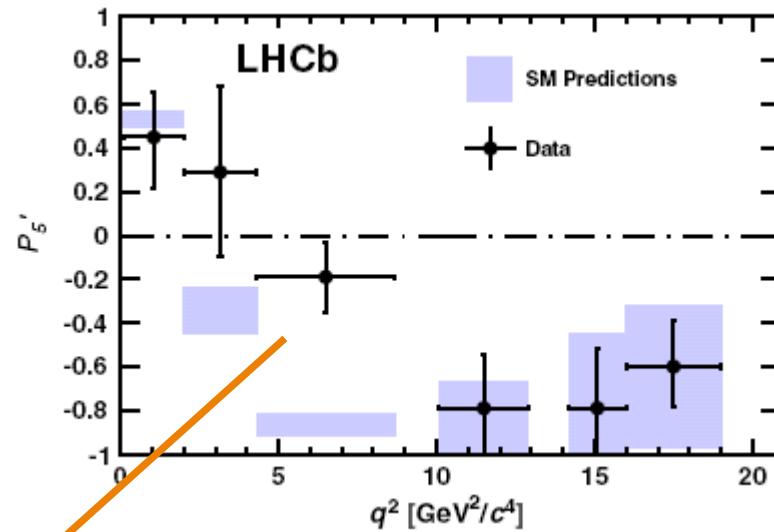
$$\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1 - F_L)\sin^2\theta_K \cos 2\theta_\ell - F_L\cos^2\theta_K \cos 2\theta_\ell + S_3\sin^2\theta_K \sin^2\theta_\ell \cos 2\phi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

Form factor (almost)
independent observables:

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

Observables in $B \rightarrow K^* \mu^+ \mu^-$: LHCb results

LHCb Collab.
PRL 111 (2013) 191801



One measurement
turns out to be discrepant



I discuss predictions for these observables

- in 331 models
- in comparison with RS model with custodial protection

A.J. Buras, J. Girrbach, M.V. Carlucci, FDF JHEP 1302 (2013) 023
A.J. Buras, J. Girrbach, FDF JHEP 1402 (2014) 112

P. Biancofiore, P. Colangelo, FDF 1403.2944



Gauge group: $SU(3)_c \times SU(3)_L \times U(1)_X$

Spontaneously broken to $SU(3)_c \times SU(2)_L \times U(1)_X$

Spontaneously broken to $SU(3)_c \times U(1)_Q$

Nice features:

- requirement of anomaly cancelation + asymptotic freedom of QCD implies number of generations = number of colors
- two quark generations transform as triplets under $SU(3)_L$, one as an antitriplet this may allow to understand why top mass is so large

Fundamental relation:

$$Q = T_3 + \beta T_8 + X$$



Key parameter: defines the variant of the model

$$\beta = \pm 1/\sqrt{3}, \pm 2/\sqrt{3}$$

- lead to interesting phenomenology
- for $\beta = \pm 1/\sqrt{3}$ the new gauge bosons have integer charge

331 Model: new particle content

New Gauge Bosons

A new heavy Z' mediates
tree level FCNC in the quark sector

Extended Higgs sector

Three $SU(3)_L$ triplets, one sextet

New heavy fermions

D, S, T new heavy quarks

$E,$ new heavy neutrinos (both L & R)

331 Models: gauge sector

SU(3)_L Gauge Bosons:
 $W^a \quad a=1, \dots, 8$

$$W_\mu = W_\mu^a T^a = \frac{1}{2} \begin{pmatrix} W_\mu^3 + \frac{1}{\sqrt{3}} W_\mu^8 & \sqrt{2} W_\mu^+ & \sqrt{2} Y_\mu^{Q_Y} \\ \sqrt{2} W_\mu^- & -W_\mu^3 + \frac{1}{\sqrt{3}} W_\mu^8 & \sqrt{2} V_\mu^{Q_V} \\ \sqrt{2} Y_\mu^{-Q_Y} & \sqrt{2} V_\mu^{-Q_V} & -\frac{2}{\sqrt{3}} W_\mu^8 \end{pmatrix}$$



Charged ones:

New Gauge Bosons,
 with charges depending on β

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp i W_\mu^2),$$

$$Y_\mu^{\pm Q_Y} = \frac{1}{\sqrt{2}}(W_\mu^4 \mp i W_\mu^5),$$

$$V_\mu^{\pm Q_V} = \frac{1}{\sqrt{2}}(W_\mu^6 \mp i W_\mu^7).$$

SM ones

Neutral ones:

W^3 and W^8

U(1)_X Gauge Boson: X

Mixing pattern among the neutral gauge bosons

$$X_\mu, W_\mu^8, W_\mu^3 \xrightarrow{\theta_{331}} Z'_\mu, B_\mu, W_\mu^3 \xrightarrow{\theta_W} Z'_\mu, Z_\mu, A_\mu.$$

$$\sin \theta_{331} = \frac{g}{\sqrt{g^2 + \frac{g_X^2 \beta^2}{6}}}.$$

$$\sin \theta_W = \frac{g_Y}{\sqrt{g^2 + g_Y^2}}.$$

g → SU(3)_L gauge coupling constant

g_x → U(1)_X gauge coupling constant

$$\frac{1}{g_Y^2} = \frac{6}{g_X^2} + \frac{\beta^2}{g^2}$$

It turns out that

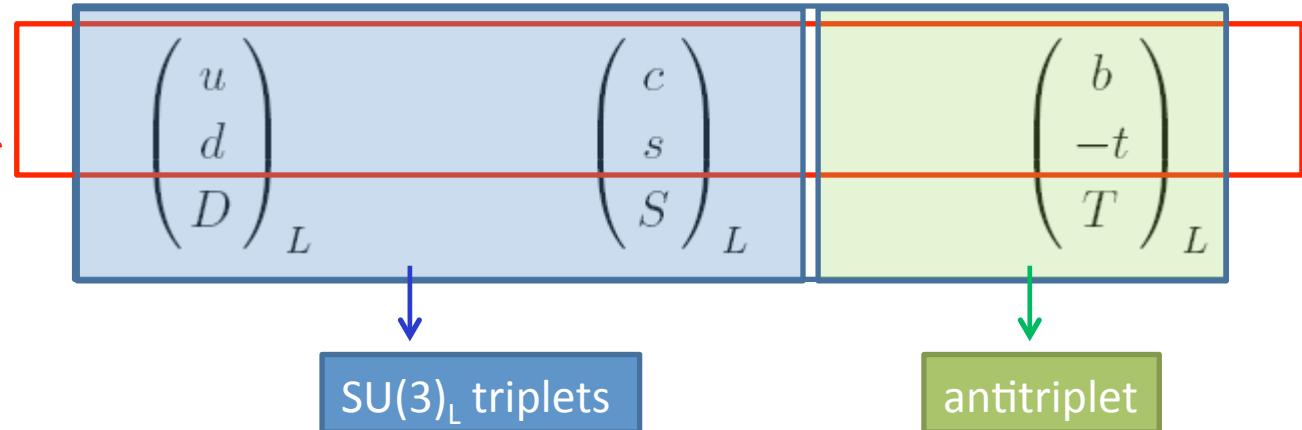
$$\frac{M_W^2}{M_Z^2} = \cos \theta_W$$

θ_W is the Weinberg angle

331 Models: Fermions

Left-handed quarks

SM quarks



Corresponding right-handed quarks are singlets

Left-handed leptons

The choice of the third component
depends on the variant of the model

$$\begin{pmatrix} e \\ -\nu_e \\ E_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ -\nu_\mu \\ E_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ -\nu_\tau \\ E_\tau \end{pmatrix}_L$$

antitriplets

331 Models: Fermions

	Arbitrary β		$\beta = \frac{1}{\sqrt{3}}$	
Fermions	Q_W	X	Q_W	X
u_L, c_L	$\frac{2}{3}$	$\frac{1}{6} - \frac{\beta}{2\sqrt{3}}$	$\frac{2}{3}$	0
u_R, c_R	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
d_L, s_L	$-\frac{1}{3}$	$\frac{1}{6} - \frac{\beta}{2\sqrt{3}}$	$-\frac{1}{3}$	0
d_R, s_R	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
D_L, S_L	$\frac{1}{6} - \frac{\sqrt{3}\beta}{2}$	$\frac{1}{6} - \frac{\beta}{2\sqrt{3}}$	$-\frac{1}{3}$	0
D_R, S_R	$\frac{1}{6} - \frac{\sqrt{3}\beta}{2}$	$\frac{1}{6} - \frac{\sqrt{3}\beta}{2}$	$-\frac{1}{3}$	$-\frac{1}{3}$
b_L	$-\frac{1}{3}$	$\frac{1}{6} + \frac{\beta}{2\sqrt{3}}$	$-\frac{1}{3}$	$\frac{1}{3}$
t_L	$\frac{2}{3}$	$\frac{1}{6} + \frac{\beta}{2\sqrt{3}}$	$\frac{2}{3}$	$\frac{1}{3}$
b_R	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
t_R	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
T_L	$\frac{1}{6} + \frac{\sqrt{3}\beta}{2}$	$\frac{1}{6} + \frac{\beta}{2\sqrt{3}}$	$\frac{2}{3}$	$\frac{1}{3}$
T_R	$\frac{1}{6} + \frac{\sqrt{3}\beta}{2}$	$\frac{1}{6} + \frac{\sqrt{3}\beta}{2}$	$\frac{2}{3}$	$\frac{2}{3}$

	Arbitrary β		$\beta = \frac{1}{\sqrt{3}}$	
Fermions	Q_W	X	Q_W	X
b_L	$-\frac{1}{3}$	$\frac{1}{6} + \frac{\beta}{2\sqrt{3}}$	$-\frac{1}{3}$	$\frac{1}{3}$
t_L	$\frac{2}{3}$	$\frac{1}{6} + \frac{\beta}{2\sqrt{3}}$	$\frac{2}{3}$	$\frac{1}{3}$
b_R	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
t_R	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
T_L	$\frac{1}{6} + \frac{\sqrt{3}\beta}{2}$	$\frac{1}{6} + \frac{\beta}{2\sqrt{3}}$	$\frac{2}{3}$	$\frac{1}{3}$
T_R	$\frac{1}{6} + \frac{\sqrt{3}\beta}{2}$	$\frac{1}{6} + \frac{\sqrt{3}\beta}{2}$	$\frac{2}{3}$	$\frac{2}{3}$
ℓ_L	-1	$-\frac{1}{2} + \frac{\beta}{2\sqrt{3}}$	-1	$-\frac{1}{3}$
ℓ_R	-1	-1	-1	-1
$\nu_{\ell L}$	0	$-\frac{1}{2} + \frac{\beta}{2\sqrt{3}}$	0	$-\frac{1}{3}$
$\nu_{\ell R}$	0	0	0	0
$E_{\ell L}$	$-\frac{1}{2} + \frac{\sqrt{3}\beta}{2}$	$-\frac{1}{2} + \frac{\beta}{2\sqrt{3}}$	0	$-\frac{1}{3}$
$E_{\ell R}$	$-\frac{1}{2} + \frac{\sqrt{3}\beta}{2}$	$-\frac{1}{2} + \frac{\sqrt{3}\beta}{2}$	0	0

331 Models: quark mixing

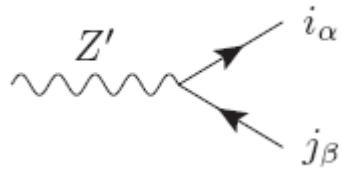
Quark mass eigenstates defined upon rotation through two unitary matrices \mathbf{U}_L & \mathbf{V}_L

$$V_{\text{CKM}} = U_L^\dagger V_L$$

In contrast to SM only one of them can be traded for VCKM,
the other one enters in Z' couplings to quarks

$$V_L = \begin{pmatrix} \tilde{c}_{12}\tilde{c}_{13} & \tilde{s}_{12}\tilde{c}_{23}e^{i\delta_3} - \tilde{c}_{12}\tilde{s}_{13}\tilde{s}_{23}e^{i(\delta_1-\delta_2)} & \tilde{c}_{12}\tilde{c}_{23}\tilde{s}_{13}e^{i\delta_1} + \tilde{s}_{12}\tilde{s}_{23}e^{i(\delta_2+\delta_3)} \\ -\tilde{c}_{13}\tilde{s}_{12}e^{-i\delta_3} & \tilde{c}_{12}\tilde{c}_{23} + \tilde{s}_{12}\tilde{s}_{13}\tilde{s}_{23}e^{i(\delta_1-\delta_2-\delta_3)} & -\tilde{s}_{12}\tilde{s}_{13}\tilde{c}_{23}e^{i(\delta_1-\delta_3)} - \tilde{c}_{12}\tilde{s}_{23}e^{i\delta_2} \\ -\tilde{s}_{13}e^{-i\delta_1} & -\tilde{c}_{13}\tilde{s}_{23}e^{-i\delta_2} & \tilde{c}_{13}\tilde{c}_{23} \end{pmatrix}$$

331 Models: Z' couplings to quarks The case of B_d, B_s, K systems



$$i\mathcal{L}_L(Z') = i \left[\Delta_L^{sd}(Z') (\bar{s}\gamma^\mu P_L d) + \Delta_L^{bd}(Z') (\bar{b}\gamma^\mu P_L d) + \Delta_L^{bs}(Z') (\bar{b}\gamma^\mu P_L s) \right] Z'_\mu$$

FCNC involve only left-handed quarks

depend only on four new parameters:

$$\tilde{s}_{13}, \quad \tilde{s}_{23}, \quad \delta_1, \quad \delta_2$$

B_d system \rightarrow only on s_{13} and δ_1

B_s system \rightarrow only on s_{23} and δ_2

K system \rightarrow on s_{13}, s_{23} and $\delta_2 - \delta_1$

Specific feature of this model
Not true in general!



stringent correlations between observables expected

$M_{Z'}$ is fixed to 3 TeV, satisfying lower bounds from LEPII and low energy constraints

331 Models: Z' couplings to leptons

$$\Delta_L^{\nu\bar{\nu}}(Z') = \frac{g}{2\sqrt{3}c_W} \sqrt{f(\beta)} \left[1 - (1 + \sqrt{3}\beta)s_W^2 \right],$$

$$\Delta_L^{\mu\bar{\mu}}(Z') = \Delta_L^{\nu\bar{\nu}}(Z'),$$

$$\Delta_R^{\mu\bar{\mu}}(Z') = \frac{-g\beta s_W^2}{c_W} \sqrt{f(\beta)}$$

$$\Delta_V^{\mu\bar{\mu}}(Z') = \frac{g}{2\sqrt{3}c_W} \sqrt{f(\beta)} \left[1 - (1 + 3\sqrt{3}\beta)s_W^2 \right],$$

$$\Delta_A^{\mu\bar{\mu}}(Z') = \frac{g}{2\sqrt{3}c_W} \sqrt{f(\beta)} \left[-1 + (1 - \sqrt{3}\beta)s_W^2 \right]$$

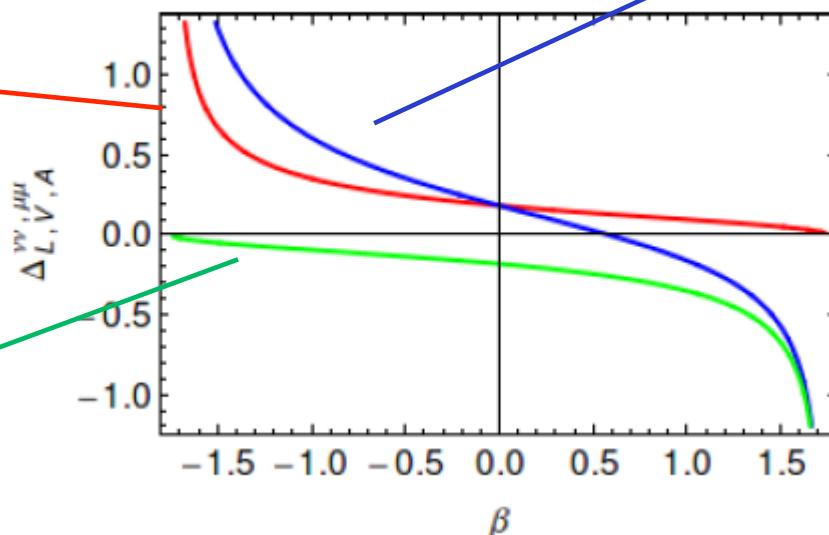
$$\Delta_V^{\mu\bar{\mu}}(Z') = \Delta_R^{\mu\bar{\mu}}(Z') + \Delta_L^{\mu\bar{\mu}}(Z'),$$

$$\Delta_A^{\mu\bar{\mu}}(Z') = \Delta_R^{\mu\bar{\mu}}(Z') - \Delta_L^{\mu\bar{\mu}}(Z').$$

$$f(\beta) = \frac{1}{1 - (1 + \beta^2)s_W^2} > 0$$

$$\boxed{\Delta_V^{\mu\bar{\mu}}(Z')}$$

$$\boxed{\Delta_L^{\nu\bar{\nu}}(Z')}$$



$$\boxed{\Delta_A^{\mu\bar{\mu}}(Z')}$$

Oases in the parameter space from $\Delta F=2$ observables

ΔM_d
Mass difference
in the $\bar{B}_d - B_d$ system

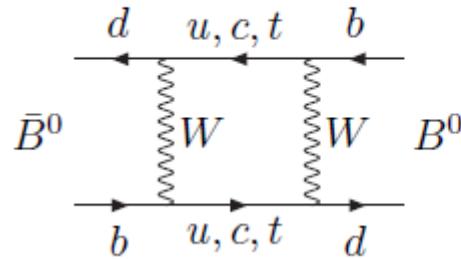
$S_{\psi K_S}$
CP asymmetry in
 $B_d \rightarrow J/\psi K_S$

ΔM_s
Mass difference
in the $\bar{B}_s - B_s$ system

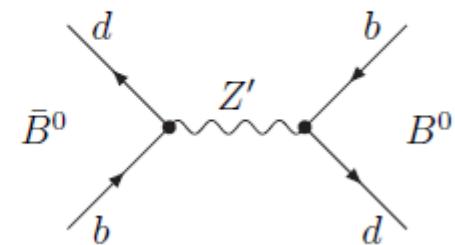
$S_{\psi \phi}$
CP asymmetry in
 $B_s \rightarrow J/\psi \phi$

Example of NP contribution:
The case of B_d mixing

SM loop contribution



tree-level NP contribution



Imposing the experimental constraints:

$$0.48/\text{ps} \leq \Delta M_d \leq 0.53/\text{ps}, \quad 0.64 \leq S_{\psi K_S} \leq 0.72.$$

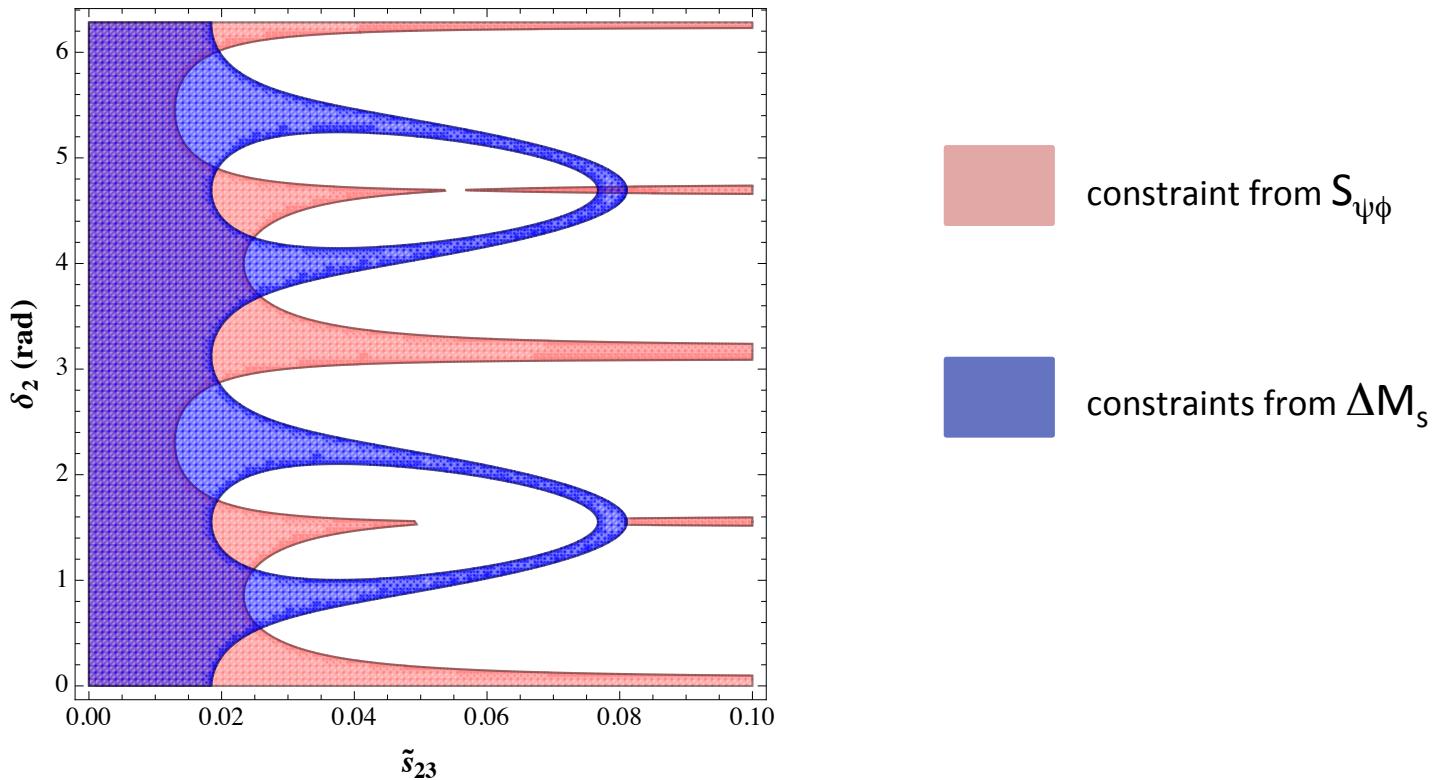
$$16.9/\text{ps} \leq \Delta M_s \leq 18.7/\text{ps}, \quad -0.18 \leq S_{\psi \phi} \leq 0.18.$$

One finds the allowed oases for the parameters

$$s_{13}, s_{23} > 0 \quad \& \quad 0 < \delta_{23} < 2\pi \quad 0 < \delta_{13} < 2\pi$$

Oases in the parameter space from $\Delta F=2$ observables

Example for $\beta=-2/\sqrt{3}$



The decays $B_{s,d} \rightarrow \mu^+ \mu^-$

SM effective hamiltonian \rightarrow one master function $Y_0(x_t)$

$$x_t = m_t^2/M_W^2$$

$$Y_0(x_t) = \frac{x_t}{8} \left(\frac{x_t - 4}{x_t - 1} + \frac{3x_t \log x_t}{(x_t - 1)^2} \right)$$



independent on the decaying meson
and on the lepton flavour

Z' contribution modifies this function to:

$$Y(B_q) = Y(x_t) + \left[\frac{\Delta_A^{\mu\bar{\mu}}(Z')}{M_{Z'}^2 g_{\text{SM}}^2} \right] \frac{\Delta_L^{qb}(Z')}{V_{tq}^* V_{tb}} \equiv |Y(B_q)| e^{i\theta_Y^q}$$

SM

$$\overline{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.65 \pm 0.23) \cdot 10^{-9}$$

EXP

$$\overline{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$$

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

The decays $B_{s,d} \rightarrow \mu^+ \mu^-$

SM effective hamiltonian \rightarrow one master function $Y_0(x_t)$

$$x_t = m_t^2/M_W^2$$

$$Y_0(x_t) = \frac{x_t}{8} \left(\frac{x_t - 4}{x_t - 1} + \frac{3x_t \log x_t}{(x_t - 1)^2} \right)$$



independent on the decaying meson
and on the lepton flavour

Z' contribution modifies this function to:

$$Y(B_q) = Y(x_t) + \left[\frac{\Delta_A^{\mu\bar{\mu}}(Z')}{M_{Z'}^2 g_{\text{SM}}^2} \right] \frac{\Delta_L^{qb}(Z')}{V_{tq}^* V_{tb}} \equiv |Y(B_q)| e^{i\theta_Y^q}$$

SM

$$\overline{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.65 \pm 0.23) \cdot 10^{-9}$$

EXP

$$\overline{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$$

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

The decays $B_{s,d} \rightarrow \mu^+ \mu^-$

SM effective hamiltonian \rightarrow one master function $Y_0(x_t)$

$$x_t = m_t^2/M_W^2$$

$$Y_0(x_t) = \frac{x_t}{8} \left(\frac{x_t - 4}{x_t - 1} + \frac{3x_t \log x_t}{(x_t - 1)^2} \right)$$



independent on the decaying meson
and on the lepton flavour

Z' contribution modifies this function to:

$$Y(B_q) = Y(x_t) + \left[\frac{\Delta_A^{\mu\bar{\mu}}(Z')}{M_{Z'}^2 g_{\text{SM}}^2} \right] \frac{\Delta_L^{qb}(Z')}{V_{tq}^* V_{tb}} \equiv |Y(B_q)| e^{i\theta_Y^q}$$

SM

$$\overline{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.65 \pm 0.23) \cdot 10^{-9}$$

EXP

$$\overline{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$$

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

The decay $B \rightarrow K^* \mu^+ \mu^-$

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

Most relevant operators

$$\begin{aligned} O_7 &= \frac{e}{16\pi^2} m_b (\bar{s}_{L\alpha} \sigma^{\mu\nu} b_{R\alpha}) F_{\mu\nu} \\ O'_7 &= \frac{e}{16\pi^2} m_b (\bar{s}_{R\alpha} \sigma^{\mu\nu} b_{L\alpha}) F_{\mu\nu} \end{aligned}$$



Magnetic penguin operators

$$\begin{aligned} O_9 &= \frac{e^2}{16\pi^2} (\bar{s}_{L\alpha} \gamma^\mu b_{L\alpha}) \bar{\ell} \gamma_\mu \ell \\ O'_9 &= \frac{e^2}{16\pi^2} (\bar{s}_{R\alpha} \gamma^\mu b_{R\alpha}) \bar{\ell} \gamma_\mu \ell \\ O_{10} &= \frac{e^2}{16\pi^2} (\bar{s}_{L\alpha} \gamma^\mu b_{L\alpha}) \bar{\ell} \gamma_\mu \gamma_5 \ell \\ O'_{10} &= \frac{e^2}{16\pi^2} (\bar{s}_{R\alpha} \gamma^\mu b_{R\alpha}) \bar{\ell} \gamma_\mu \gamma_5 \ell \end{aligned}$$



Semileptonic electroweak penguin operators

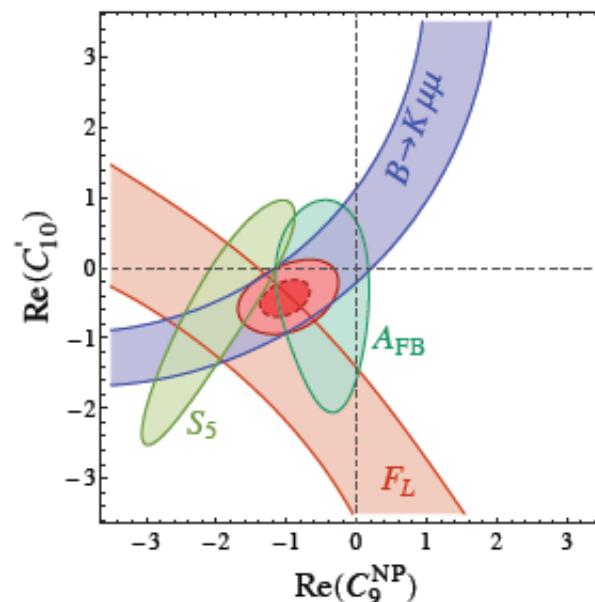
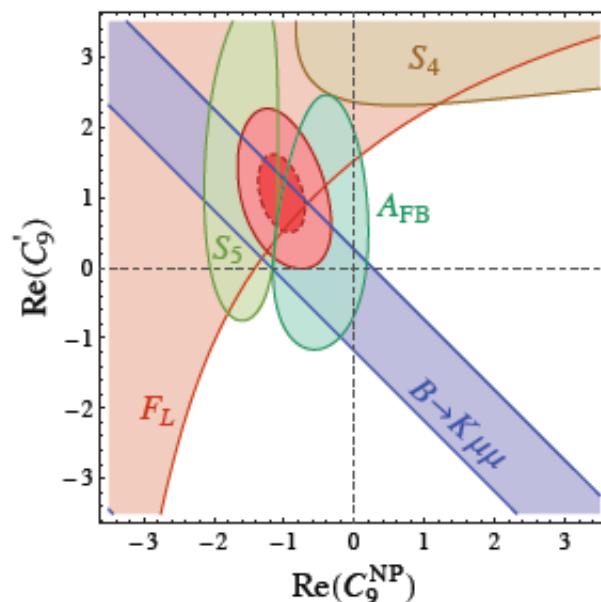
The decay $B \rightarrow K^* \mu^+ \mu^-$

How large should be the NP contributions to the relevant Wilson coefficients to explain the observed anomalies?



The result depends on how many coefficients are assumed to be affected by NP

W. Altmanshofer, D. Straub
EPJC73 (2013) 2646



Wilson coefficients C_9 and C_{10}

$$C_9 = C_9^{\text{SM}} + C_9^{\text{NP}}, \quad C_{10} = C_{10}^{\text{SM}} + C_{10}^{\text{NP}}$$

$$C_9^{\text{SM}} \approx 4.1, \quad C_{10}^{\text{SM}} \approx -4.1$$

$$\sin^2 \theta_W C_9^{\text{NP}} = -\frac{1}{g_{\text{SM}}^2 M_{Z'}^2} \frac{\Delta_L^{sb}(Z') \Delta_V^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb}}$$

$$\sin^2 \theta_W C_{10}^{\text{NP}} = -\frac{1}{g_{\text{SM}}^2 M_{Z'}^2} \frac{\Delta_L^{sb}(Z') \Delta_A^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb}}$$

Wilson coefficients C_9 and C_{10}

$$C_9 = C_9^{\text{SM}} + C_9^{\text{NP}}, \quad C_{10} = C_{10}^{\text{SM}} + C_{10}^{\text{NP}}$$

$$C_9^{\text{SM}} \approx 4.1, \quad C_{10}^{\text{SM}} \approx -4.1$$

$$\sin^2 \theta_W C_9^{\text{NP}} = -\frac{1}{g_{\text{SM}}^2 M_{Z'}^2} \frac{\Delta_L^{sb}(Z') \Delta_V^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb}}$$

$$\sin^2 \theta_W C_{10}^{\text{NP}} = -\frac{1}{g_{\text{SM}}^2 M_{Z'}^2} \frac{\Delta_L^{sb}(Z') \Delta_A^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb}}$$

The same coupling entering in ΔY
governing $B_{s,d} \rightarrow \mu^+ \mu^-$

Wilson coefficients C_9 and C_{10}

$$C_9 = C_9^{\text{SM}} + C_9^{\text{NP}}, \quad C_{10} = C_{10}^{\text{SM}} + C_{10}^{\text{NP}}$$

$$C_9^{\text{SM}} \approx 4.1, \quad C_{10}^{\text{SM}} \approx -4.1$$

$$\sin^2 \theta_W C_9^{\text{NP}} = -\frac{1}{g_{\text{SM}}^2 M_{Z'}^2} \frac{\Delta_L^{sb}(Z') \Delta_V^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb}}$$

$$\sin^2 \theta_W C_{10}^{\text{NP}} = -\frac{1}{g_{\text{SM}}^2 M_{Z'}^2} \frac{\Delta_L^{sb}(Z') \Delta_A^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb}}$$

Requires the investigation of the ratio

$$R_1 = \frac{C_9^{\text{NP}}}{C_{10}^{\text{NP}}} = \frac{\Delta_V^{\mu\bar{\mu}}(Z')}{\Delta_A^{\mu\bar{\mu}}(Z')}$$

The same coupling entering in ΔY
governing $B_{s,d} \rightarrow \mu^+ \mu^-$

The ratio R_1 :
e.g. investigating the correlation
between the $B \rightarrow K^* \mu^+ \mu^-$ anomalies and $B_s \rightarrow \mu^+ \mu^-$

$$R_1 = \frac{C_9^{\text{NP}}}{C_{10}^{\text{NP}}} = \frac{\Delta_V^{\mu\bar{\mu}}(Z')}{\Delta_A^{\mu\bar{\mu}}(Z')}$$

β	$1/\sqrt{3}$	$-1/\sqrt{3}$	$2/\sqrt{3}$	$-2/\sqrt{3}$
R_1	-0.004	-2.98	0.59	-8.87

$$C_9 \simeq 4.1 + C_9^{\text{NP}}$$

$$C_{10} \simeq -4.1 + \frac{C_9^{\text{NP}}}{R_1}$$

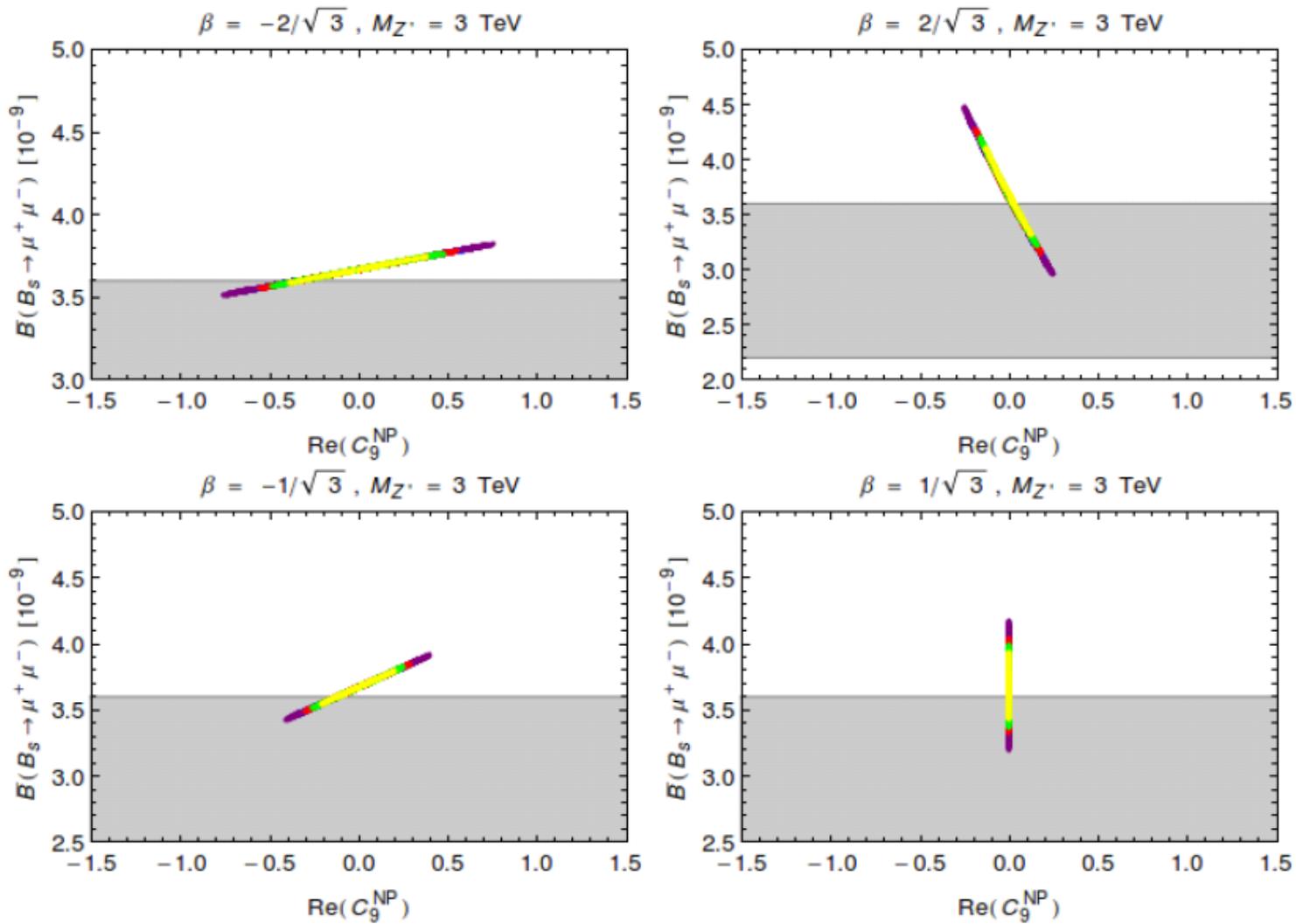
For $\beta < 0$ R_1 is negative \Rightarrow NP contributions to C_9 and $B_s \rightarrow \mu^+ \mu^-$ are correlated



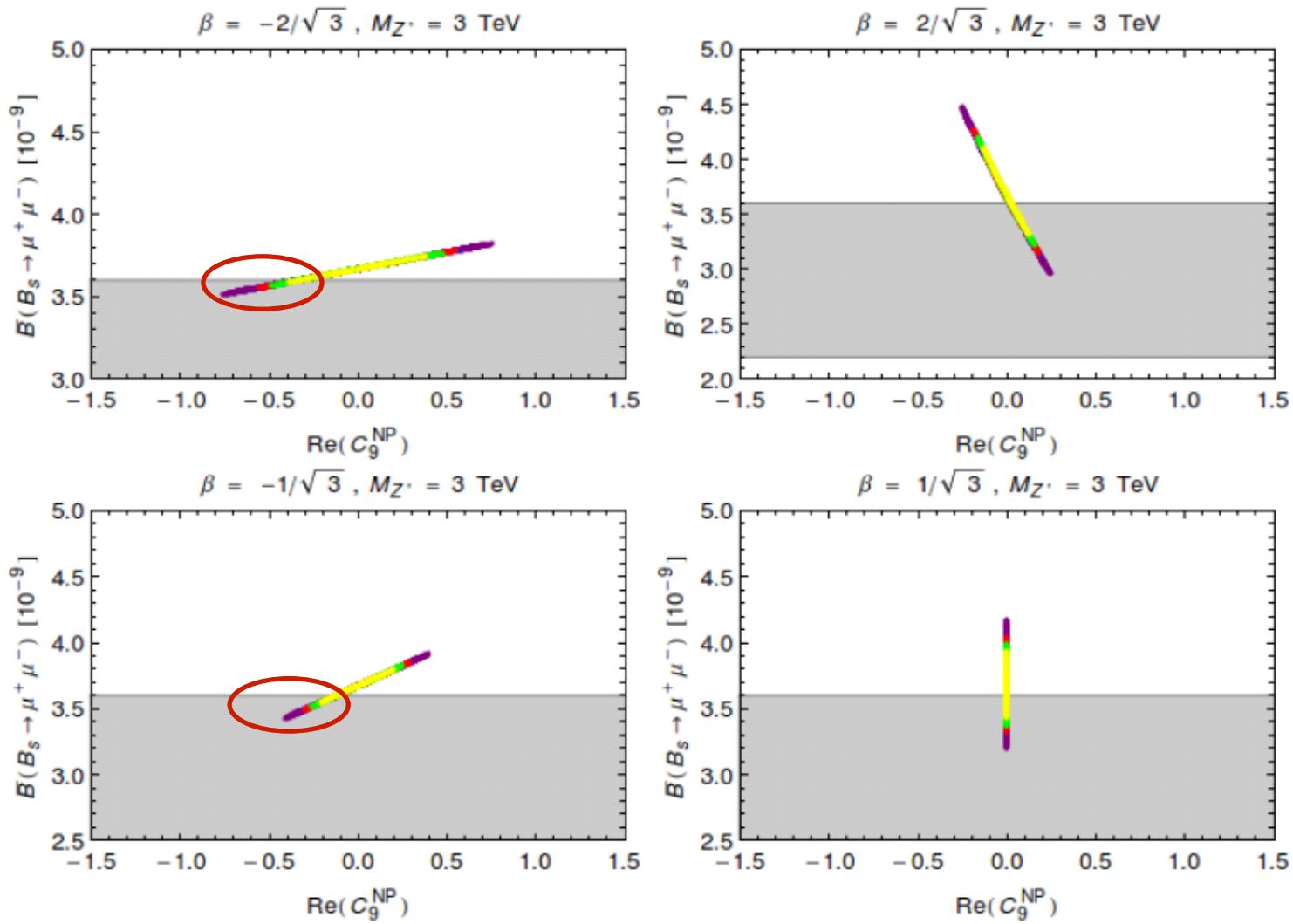
Large negative ΔC_9 required to reproduce present data in $B \rightarrow K^* \mu^+ \mu^-$ would imply a suppression of $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ as presently required by data

The opposite happens for $\beta=2/\sqrt{3}$ which might be considered if data change

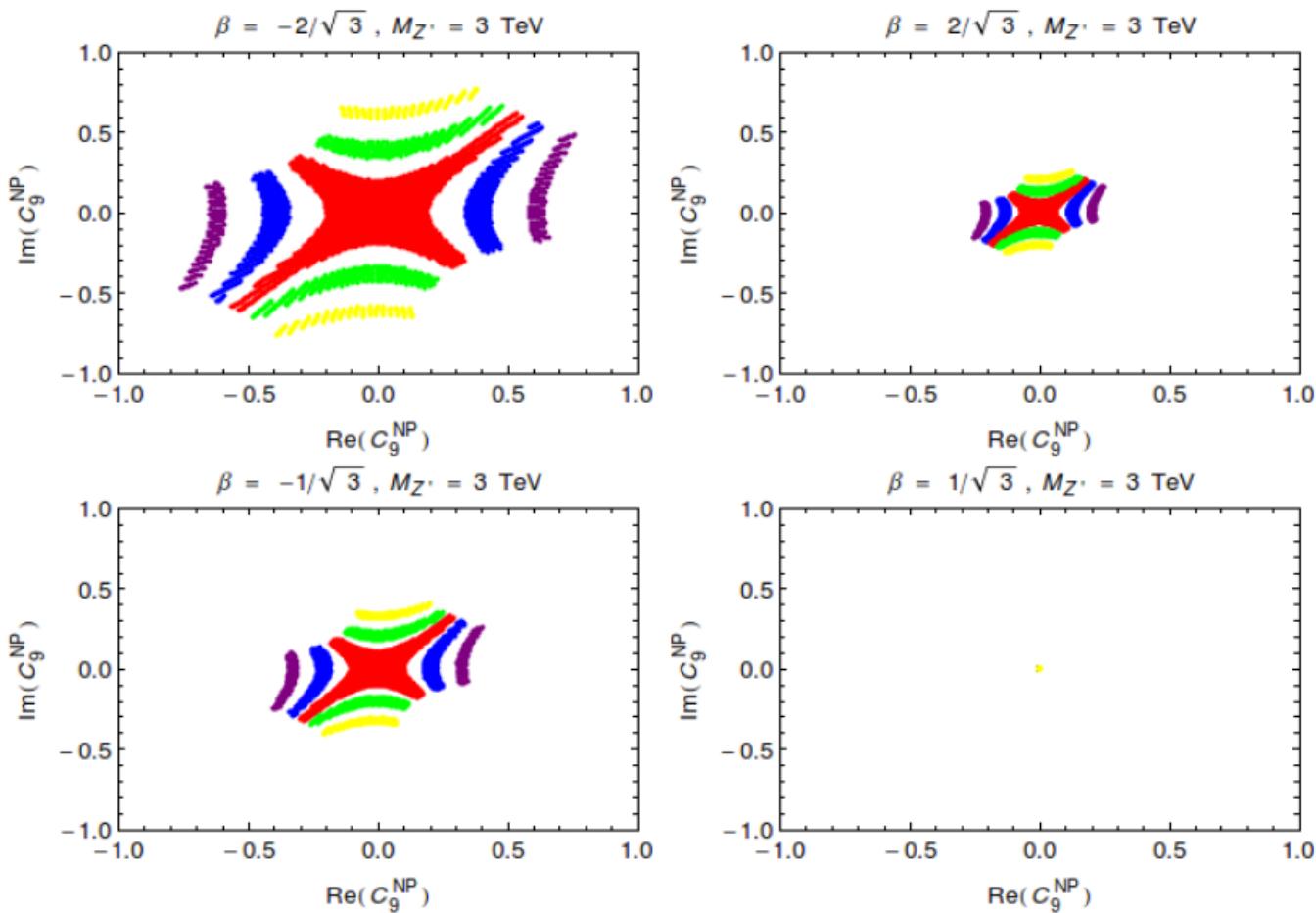
Correlation between C_9 and $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$



Correlation between C_9 and $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$

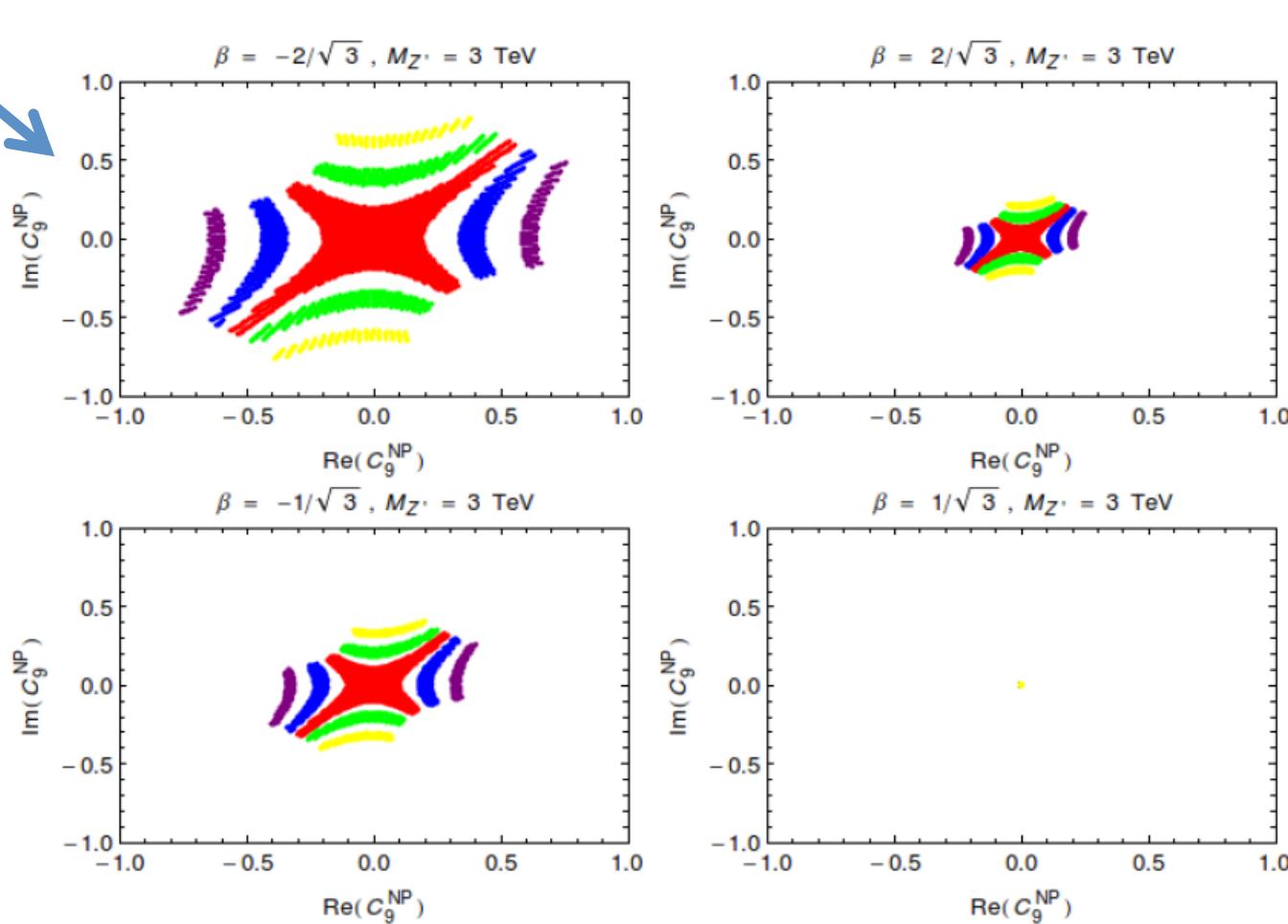


C_9

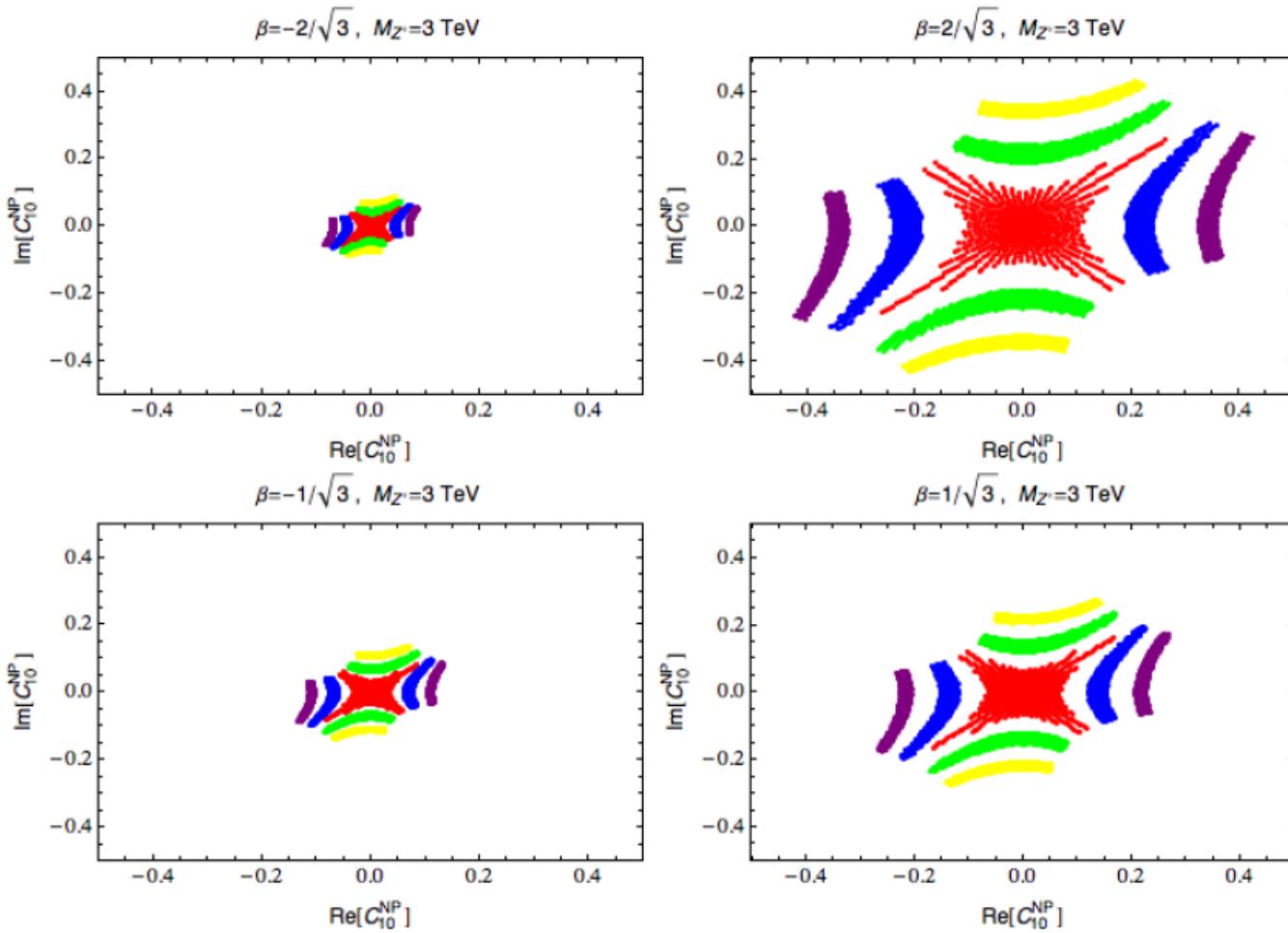


Scenario with the largest possible deviations from SM

C_9

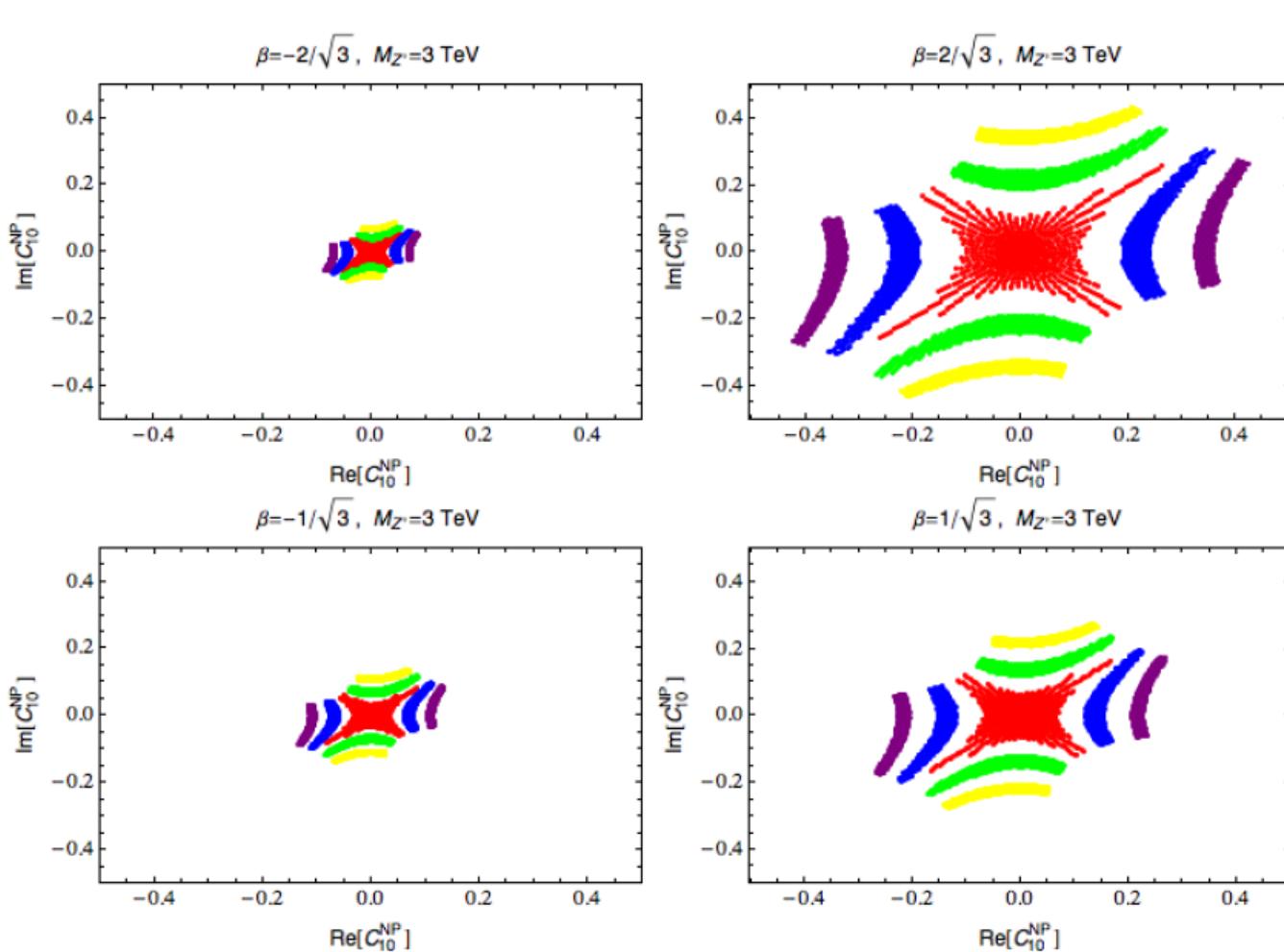


C_{10}

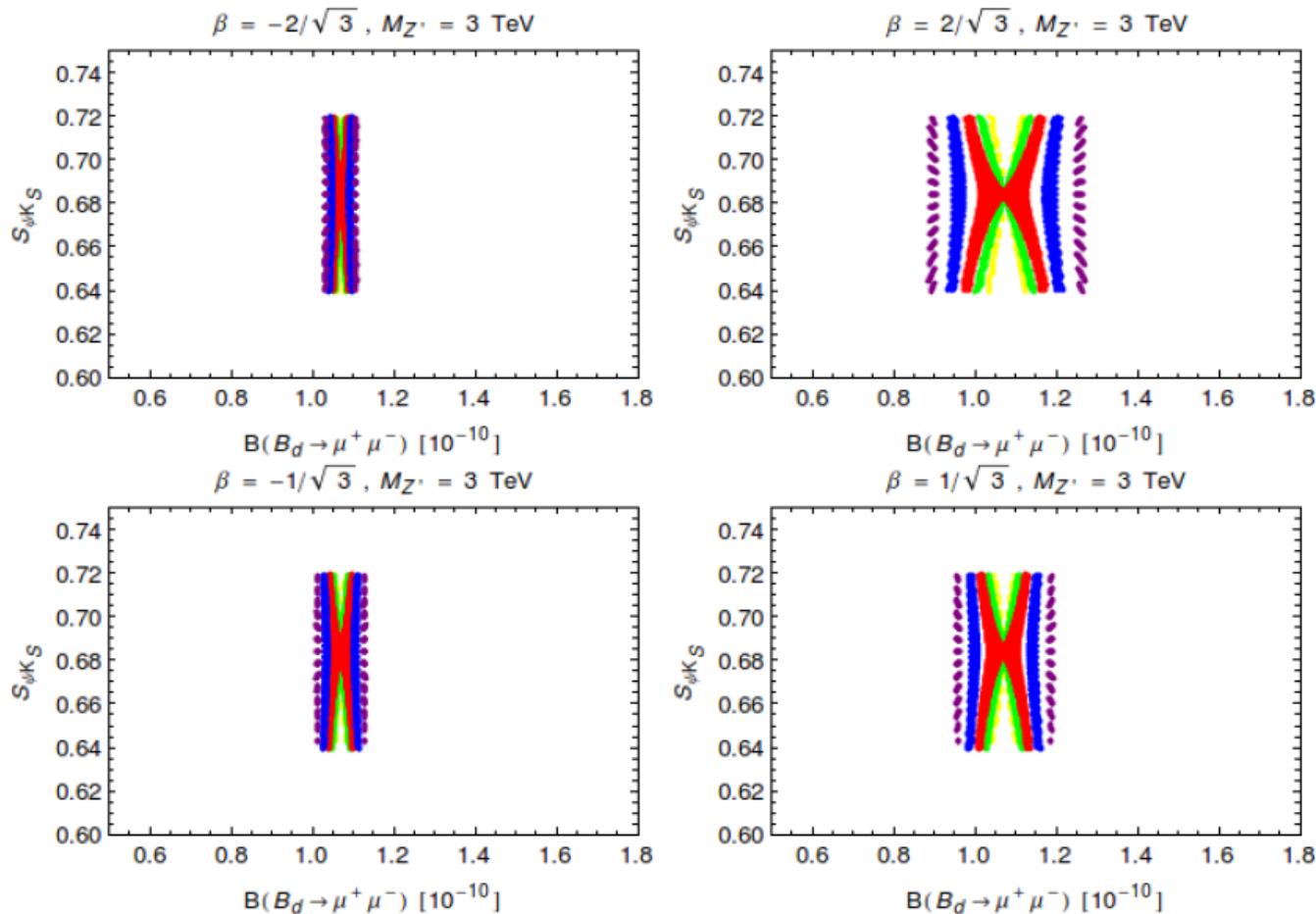


C_{10}

Scenario with the largest possible deviations from SM



BR($B_d \rightarrow \mu^+ \mu^-$)

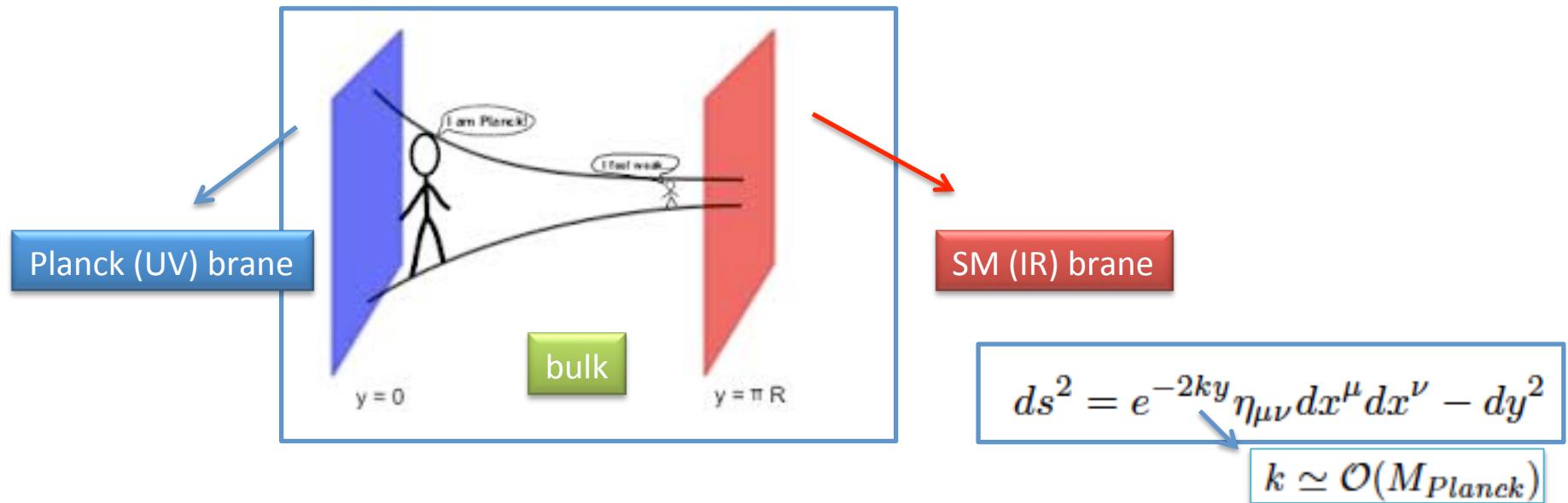


In this model independently of β the large exp result for
 $BR(B_d \rightarrow \mu^+ \mu^-)$ cannot be reproduced

The $B \rightarrow K^* \mu^+ \mu^-$ anomaly in another NP model:
 RS_c

Main features of the RS model

L. Randall, R. Sundrum, PRL83 (99) 8370



- All fields propagate in the bulk, Higgs localized close to or on the IR brane
- possibility of solving the hierarchy problem
- Explaining the observed pattern in fermion masses and mixing

Custodially protected RS_c model

Agashe et al, PLB641 (06) 62
Carena et al., NPB 759 (06) 202
Cacciapaglia et al PRD75 (07) 015003

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



Implies a mirror action
of the two $SU(2)$ groups

Benefits:

- Prevents large Z couplings to left-handed fermions
- Consistent with electroweak precision observables without large fine-tuning even for KK masses a few TeV (LHC reach)

Particle content:

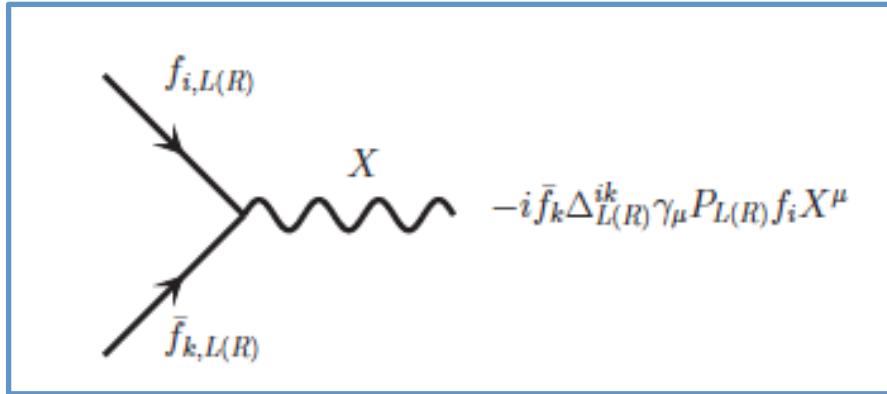
SM particles+ their KK excitations

New particles

Zero modes identified with SM fields

Boundary conditions distinguish fields with or without a zero mode

Tree level FCNC in RS_c model



$X = A^{(1)}$ (1st KK of the γ)

Z, Z_H, Z' (from mixing of 0- and 1-modes)

$G^{(1)}$ (1st KK of the g)

does not contribute to decays
to leptons



New contributions to the Wilson coefficients

Modified Wilson coefficients in RS_c model

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

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

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

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

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

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

$$\Delta Z_s = \frac{1}{V_{tb} V_{ts}^*} \sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)} \Delta_L^{bs}(X),$$

$$\Delta Z'_s = \frac{1}{V_{tb} V_{ts}^*} \sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)} \Delta_R^{bs}(X).$$

Modified Wilson coefficients in RS_c model

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

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

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

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

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

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

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

$$\Delta Z_s = \frac{1}{V_{tb} V_{ts}^*} \sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)} \Delta_L^{bs}(X),$$

$$\Delta Z'_s = \frac{1}{V_{tb} V_{ts}^*} \sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)} \Delta_R^{bs}(X).$$

Couplings to leptons

Modified Wilson coefficients in RS_c model

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

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

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

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

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

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

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

$$\Delta Z_s = \frac{1}{V_{tb} V_{ts}^*} \sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)} \Delta_L^{bs}(X),$$

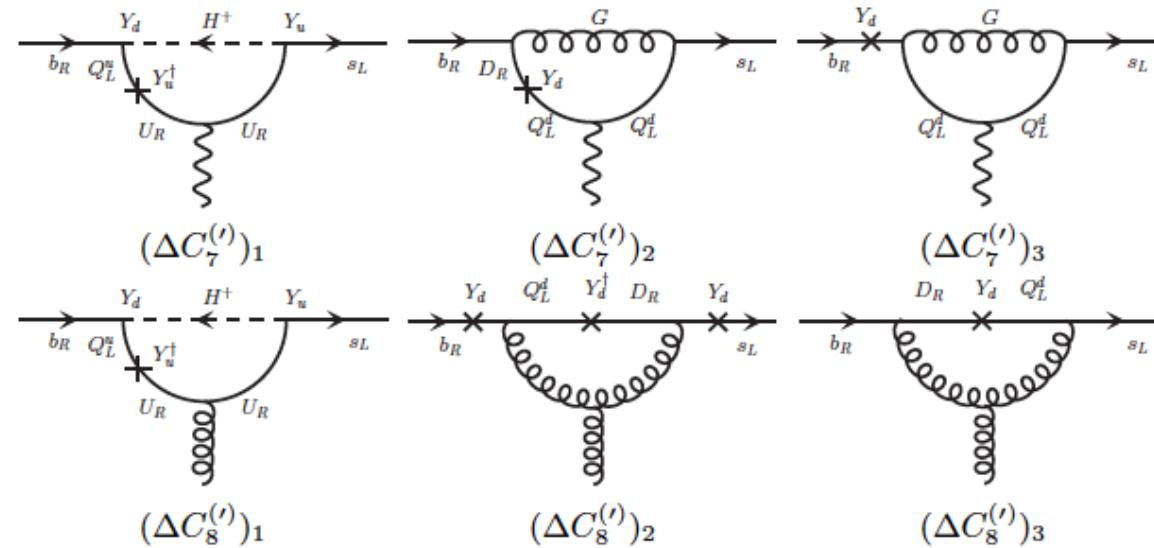
$$\Delta Z'_s = \frac{1}{V_{tb} V_{ts}^*} \sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)} \Delta_R^{bs}(X).$$

Couplings to leptons

Couplings to quarks

Modified Wilson coefficients in RS_c model

New contributions to $C_{7,8}$ are still loop induced



Parameters of the RS_c model

KK decomposition for each field:

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

effective 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 of the RS_c model

4D Yukawa couplings:

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

5D Yukawa matrices

Constraints: $\lambda^{u,d}$ should reproduce

- quark masses
- CKM elements

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

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

$$\begin{aligned} m_u &= \frac{v}{\sqrt{2}} \frac{\det(\lambda^u)}{\lambda_{33}^u \lambda_{22}^u - \lambda_{23}^u \lambda_{32}^u} \frac{e^{kL}}{L} f_{u_L} f_{u_R} \\ m_c &= \frac{v}{\sqrt{2}} \frac{\lambda_{33}^u \lambda_{22}^u - \lambda_{23}^u \lambda_{32}^u}{\lambda_{33}^u} \frac{e^{kL}}{L} f_{c_L} f_{c_R} \\ m_t &= \frac{v}{\sqrt{2}} \lambda_{33}^u \frac{e^{kL}}{L} f_{t_L} f_{t_R} , \end{aligned}$$

Parameters of the RS_c model

4D Yukawa couplings:

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

5D Yukawa matrices

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

$$V_{CKM} = U_L^\dagger D_L$$

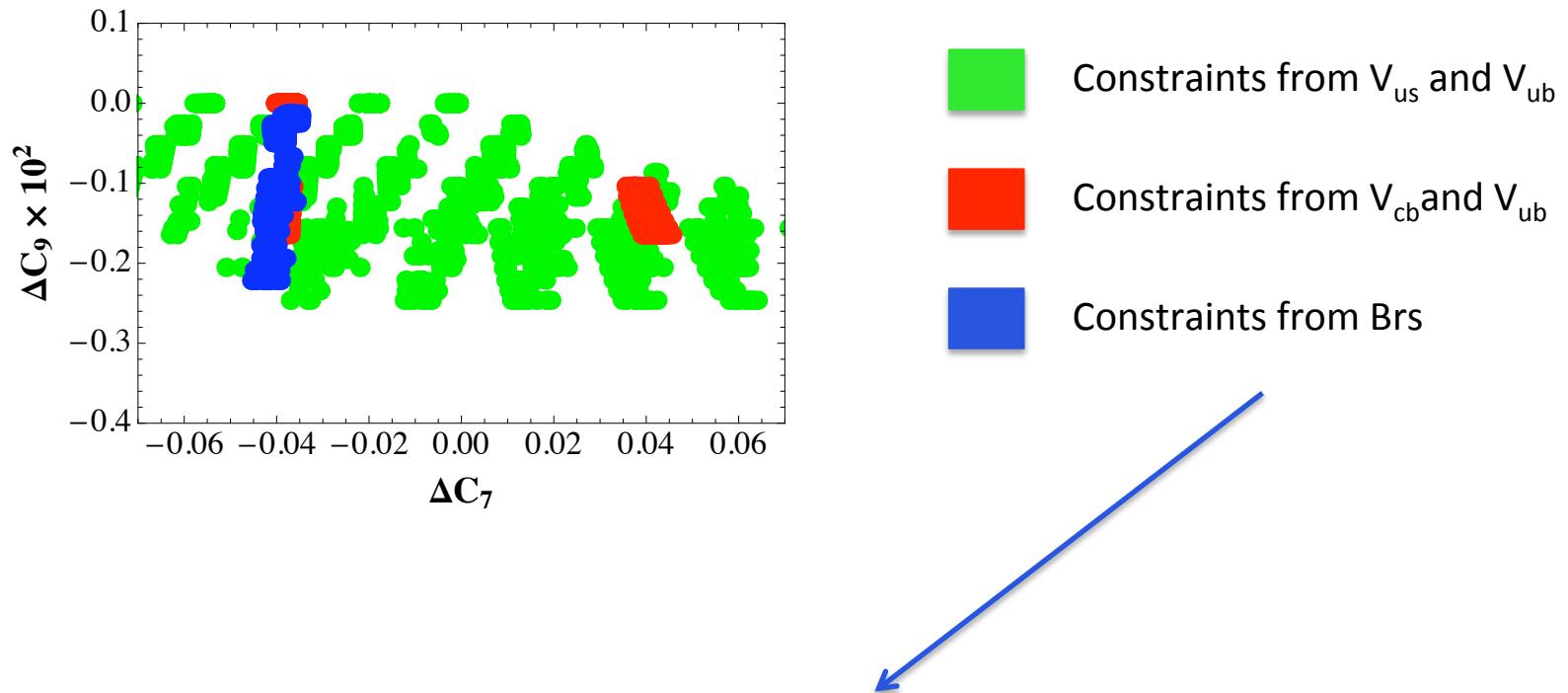
quark rotation matrices
 depend on the $\lambda^{u,d}$ elements

$$\begin{aligned} m_u &= \frac{v}{\sqrt{2}} \frac{\det(\lambda^u)}{\lambda_{33}^u \lambda_{22}^u - \lambda_{23}^u \lambda_{32}^u} \frac{e^{kL}}{L} f_{u_L} f_{u_R} \\ m_c &= \frac{v}{\sqrt{2}} \frac{\lambda_{33}^u \lambda_{22}^u - \lambda_{23}^u \lambda_{32}^u}{\lambda_{33}^u} \frac{e^{kL}}{L} f_{c_L} f_{c_R} \\ m_t &= \frac{v}{\sqrt{2}} \lambda_{33}^u \frac{e^{kL}}{L} f_{t_L} f_{t_R} , \end{aligned}$$

remaining independent parameters

$$\begin{array}{ccc} \lambda_{12}^u & , & \lambda_{13}^u & , & \lambda_{23}^u \\ \lambda_{12}^d & , & \lambda_{13}^d & , & \lambda_{23}^d \end{array}$$

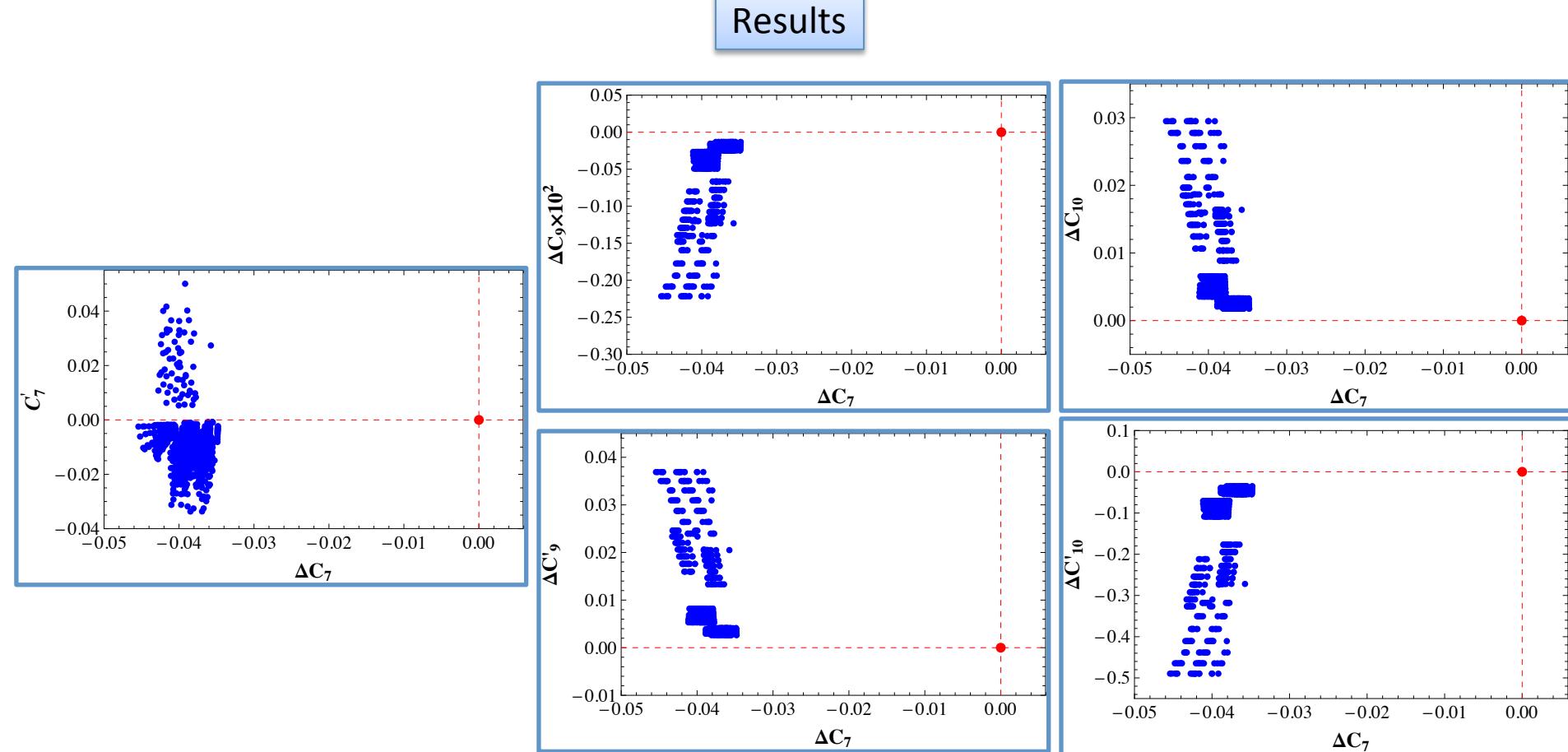
Results



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

$$\mathcal{B}(B \rightarrow X_s \gamma)_{exp} = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$$

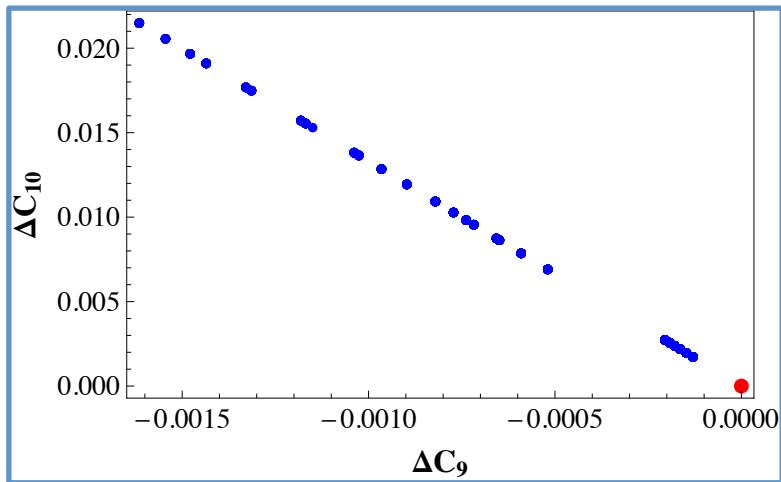
Results



Largest deviations from SM results:

$$\begin{aligned}
 |\Delta C_7|_{max} &\simeq 0.046 \\
 |\Delta C'_7|_{max} &\simeq 0.05 \\
 |\Delta C_9|_{max} &\simeq 0.0023 \\
 |\Delta C'_9|_{max} &\simeq 0.038 \\
 |\Delta C_{10}|_{max} &\simeq 0.030 \\
 |\Delta C'_{10}|_{max} &\simeq 0.50
 \end{aligned}$$

Results



Linear relation

$C_9^{(')}$ and $C_{10}^{(')}$ essentially depend on $\lambda_{23}^d k$

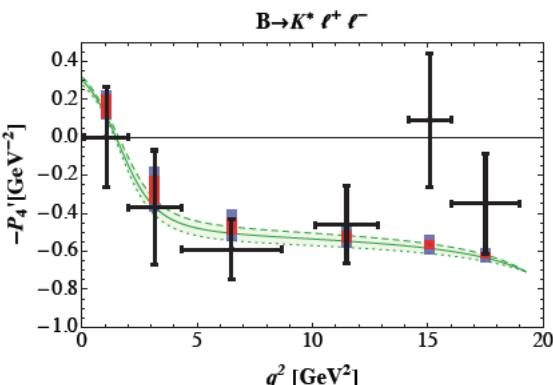
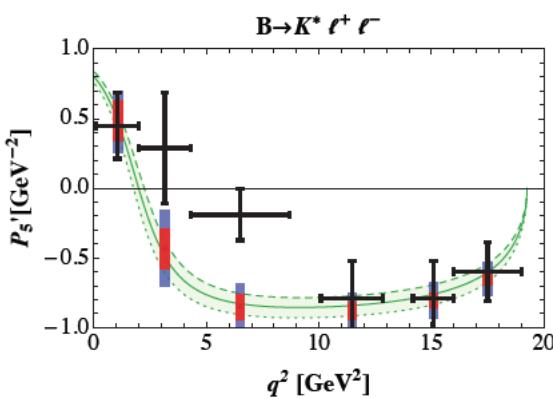
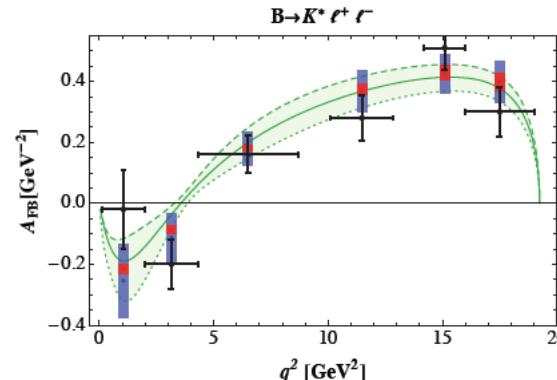
$$\Delta C_9 \simeq -7.18 10^{-4} \lambda_{23}^d k$$

$$\Delta C'_9 \simeq 1.22 10^{-2} \lambda_{23}^d k$$

$$\Delta C_{10} \simeq 9.55 10^{-3} \lambda_{23}^d k$$

$$\Delta C'_{10} \simeq -1.62 10^{-1} \lambda_{23}^d k$$

Results



SM result.

Uncertainty on FF taken into account

RS_c result.

Uncertainty reflects only
the variation of input parameters

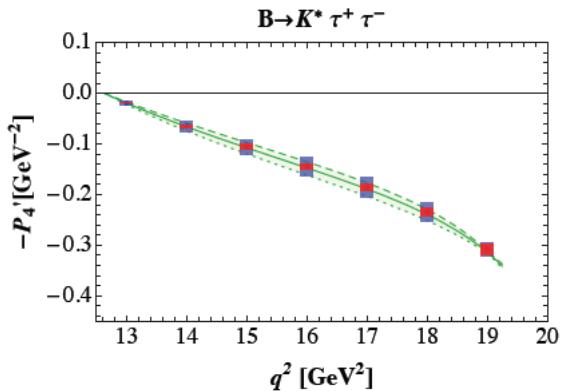
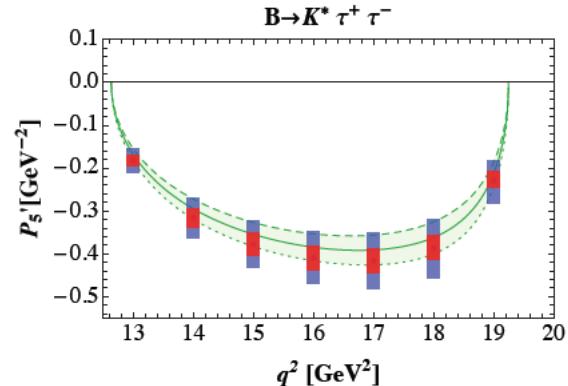
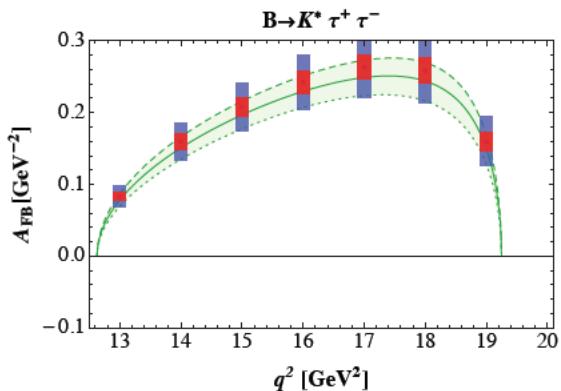
RS_c result.

Uncertainty reflects
the variation of input parameters & FF errors

LHCb Data

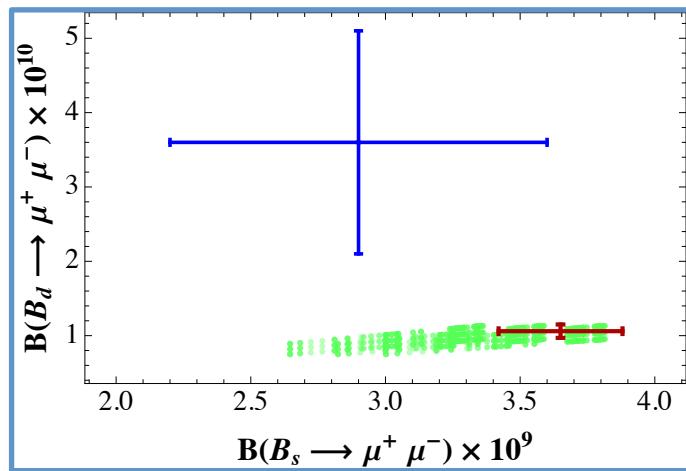
- Deviations from SM results are possible
- Presently hidden by hadronic uncertainties
- Anomalies in data cannot be explained

Results: τ in the final state



No measurements available yet
to test SM

More results



Modification wrt the SM: $C_{10} \rightarrow C_{10} - C_{10}'$

- RS_c result
- SM result
- data

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

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

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

- BR in the B_d case still lower than data



Conclusions

- 331 models might be in accordance with data but
 - $\text{Re}[C_9]$ cannot be smaller than -1
 - for $\beta < 0$ the 1 bin -deviation in P_5' in $B \rightarrow K^* \mu^+ \mu^-$ can be softened and $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ can be shifted closer to data
 - by no means the experimental datum for $\text{BR}(B_d \rightarrow \mu^+ \mu^-)$ can be reproduced
- RS_c predicts Wilson coefficients that may deviate from SM ones
Deviations are not enough to explain present puzzles
 τ modes represent interesting cross check of SM predictions vs NP scenarios

QCD@Work

International Workshop on Quantum Chromodynamics Theory and Experiment

VII edition

Giovinazzo (Bari – Italy), June 16 - 19, 2014



Low energy and nonperturbative QCD - Advances in perturbative QCD
Heavy quarks - Hot and dense QCD - Holographic methods for QCD

International Advisory Committee

G. Altarelli (Roma 3 U. and CERN) M. Mangano (CERN)
R. Casalbuoni (Firenze U.) N. Paver (Trieste U.)
F. Ferroni (Roma Sapienza U. and INFN) M. Shifman (Minnesota U.)
R. Gatto (Geneva U. - chairman) G. Sterman (SUNY Stony Brook)
U. Heinz (Ohio State U.) S. Stone (Syracuse U.)

Local Organizing Committee

L. Angelini, G.E. Bruno (Bari U.)
G. Chiodini (INFN Lecce)
P. Colangelo (INFN Bari)
C. Corianò (UniSalento)
D. Creanza (Bari Polytech.)
F. De Fazio, E. Nappi (INFN Bari)
S. Spagnolo (UniSalento)

Scientific secretariat

F. Giannuzzi, S. Nicotri (INFN and Bari U.)

www.ba.infn.it/~wqcd/2014/

workshop.qcd@ba.infn.it



Supporting Institutions

Istituto Nazionale di Fisica Nucleare
Università degli Studi "Aldo Moro" - Bari
Università del Salento - Lecce
Dipartimento Interateneo di Fisica - Bari
Dipartimento di Matematica e Fisica - Lecce

QCD@Work

International Workshop on Quantum Chromodynamics Theory and Experiment

VII edition

Giovinazzo (Bari – Italy), June 16 - 19, 2014



Low energy and nonperturbative QCD - Advances in perturbative QCD
Heavy quarks - Hot and dense QCD - Holographic methods for QCD

International Advisory Committee

G. Altarelli (Roma 3 U. and CERN) M. Mangano (CERN)
R. Casalbuoni (Firenze U.) N. Paver (Trieste U.)
F. Ferroni (Roma Sapienza U. and INFN) M. Shifman (Minnesota U.)
R. Gatto (Geneva U. - chairman) G. Sterman (SUNY Stony Brook)
U. Heinz (Ohio State U.) S. Stone (Syracuse U.)

Local Organizing Committee

L. Angelini, G.E. Bruno (Bari U.)
G. Chiodini (INFN Lecce)
P. Colangelo (INFN Bari)
C. Corianò (UniSalento)
D. Creanza (Bari Polytech.)
F. De Fazio, E. Nappi (INFN Bari)
S. Spagnolo (UniSalento)

Scientific secretariat

F. Giannuzzi, S. Nicotri (INFN and Bari U.)

www.ba.infn.it/~wqcd/2014/

workshop.qcd@ba.infn.it



Supporting Institutions

Istituto Nazionale di Fisica Nucleare
Università degli Studi "Aldo Moro" - Bari
Università del Salento - Lecce
Dipartimento Interateneo di Fisica - Bari
Dipartimento di Matematica e Fisica - Lecce