INFN Istituto Nazionale di Fisica Nucleare

Quark flavour observables in the flavor precision era

WHAT NEXT FLAVOUR WG EXTREME FLAVOUR

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A.J. Buras, J. Girrbach (Munich)

What can be learnt about NP from flavour observables in the Flavour Precision Era (FPE)?

Ingredients of this contribution

- overview of existing problems
- sketch of forseen directions
- theory qb

Recent results for flavour observables deviating from SM predictions

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

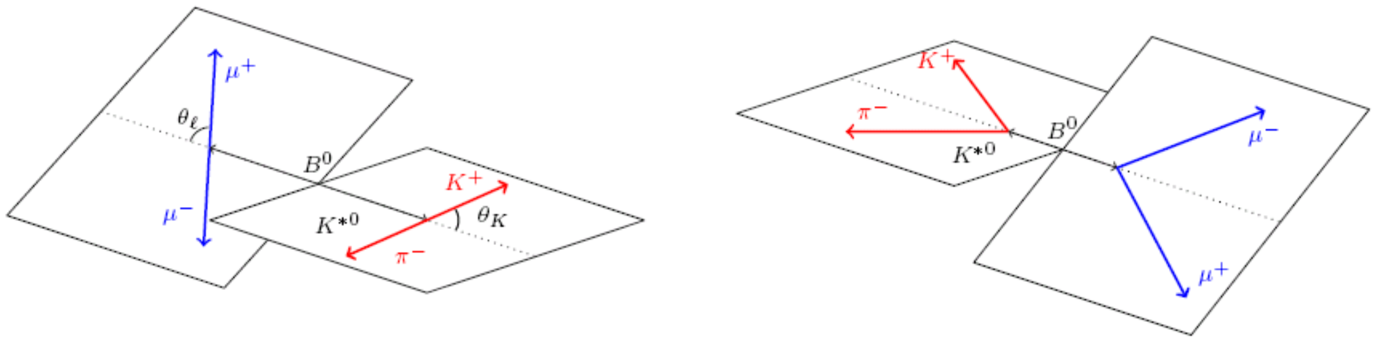
$$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$
$$\mathcal{B}(B_d \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

LHCb+ CMS

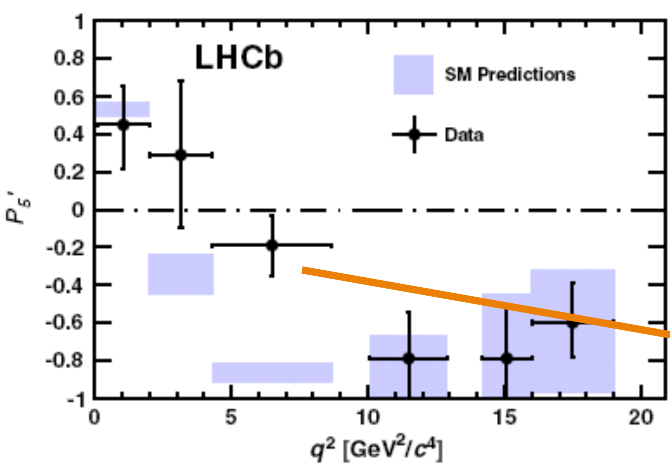
$$\bar{\mathcal{B}}(B_s \to \mu^+\mu^-)_{SM} = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B_d \to \mu^+\mu^-)_{SM} = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al, 1311.0903

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



$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_K\sin2\theta_\ell\cos\phi$$
$$+ S_5\sin2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin2\theta_K\sin2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big],$$



Form factor (almost) independent observables:

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

One measurement turns out to be discrepant

LHCB Collab.
PRL 111 (2013) 191801

$B \to D^{(*)} \tau \bar{\nu}_\tau$

Recent BaBar measurements:

BaBar, PRL 109 (2012) 101802

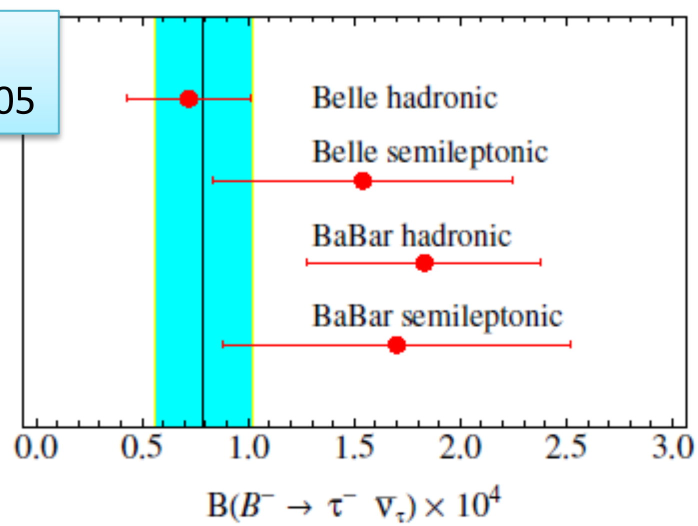
$$\mathcal{R}^-(D) = \frac{\mathcal{B}(B^- \to D^0 \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^- \to D^0 \ell^- \bar{\nu}_\ell)} = 0.429 \pm 0.082 \pm 0.052 \ , \ \mathcal{R}^-(D^*) = \frac{\mathcal{B}(B^- \to D^{*0} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^- \to D^{*0} \ell^- \bar{\nu}_\ell)} = 0.322 \pm 0.032 \pm 0.022 \ ,$$

$$\mathcal{R}^0(D) = \frac{\mathcal{B}(\bar{B}^0 \to D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell)} = 0.469 \pm 0.084 \pm 0.053 \ , \ \mathcal{R}^0(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell)} = 0.355 \pm 0.039 \pm 0.021$$

- BaBar quotes a 3.4 σ deviation from SM predictions
- main question arised : is this related to the enhancement of $B(B \to \tau \nu_\tau)$?

...but...

SM prediction for |Vub|=0.0035 ± 0.0005



Which direction should we follow in the Flavour Precision Era (FPE)?

Three points for discussion:

- what can be learnt about NP from flavour observables
  if the lightest NP messanger is a new Z' gauge boson?

- are there other observvbles to be considered
  in an improved experimental environment to understand the deviation in P_5' ?

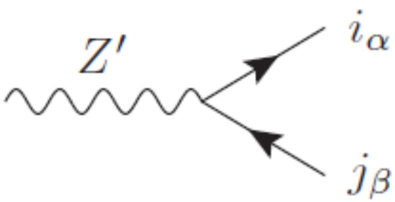
- are there other modes that can show an anomalous enhancement as R(D) and R(D*)?

Anatomy of Z' with FCNC in the FPE

A.J. Buras, J. Girrbach, FDF
JHEP 1302 (2013) 116

- There exists a new neutral gauge boson Z' mediating tree-level FCNC processes $M_{Z'}$=1 TeV - 3 TeV

- Existing data constrain Z' couplings to quarks



$$i\gamma_\mu\delta_{\alpha\beta}\left[\Delta_L^{ij}(Z')P_L+\Delta_R^{ij}(Z')P_R\right]$$

Four possible scenarios for such couplings can be considered

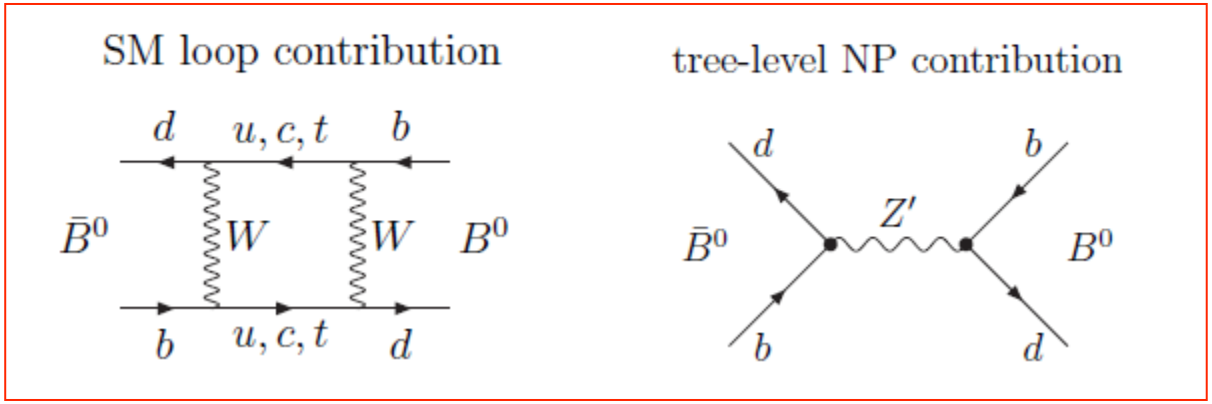
1. Left-handed Scenario (LHS) with complex $\Delta_L^{bq}\neq 0$ and $\Delta_R^{bq}=0$,
2. Right-handed Scenario (RHS) with complex $\Delta_R^{bq}\neq 0$ and $\Delta_L^{bq}=0$,
3. Left-Right symmetric Scenario (LRS) with complex $\Delta_L^{bq}=\Delta_R^{bq}\neq 0$,
4. Left-Right asymmetric Scenario (ALRS) with complex $\Delta_L^{bq}=-\Delta_R^{bq}\neq 0$

Predictions on correlations among flavour observables provide the path to identify which, in any, of them is realized in nature

Oases in the parameter space from ΔF=2 observables

ΔM_d	$S_{\psi K_s}$	ΔM_s	$S_{\psi\phi}$
Mass difference in the $\bar{B}_d - B_d$ system	CP asymmetry in $B_d \to J/\psi\, K_s$	Mass difference in the $\bar{B}_s - B_s$ system	CP asymmetry in $B_s \to J/\psi\, \phi$

Example of NP contribution:
The case of B_d mixing



$$\frac{\Delta_L^{bs}(Z')}{M_{Z'}} = -\frac{\tilde{s}_{23}}{M_{Z'}} e^{-i\delta_{23}}$$

$$\frac{\Delta_L^{bd}(Z')}{M_{Z'}} = \frac{\tilde{s}_{13}}{M_{Z'}} e^{-i\delta_{13}}$$

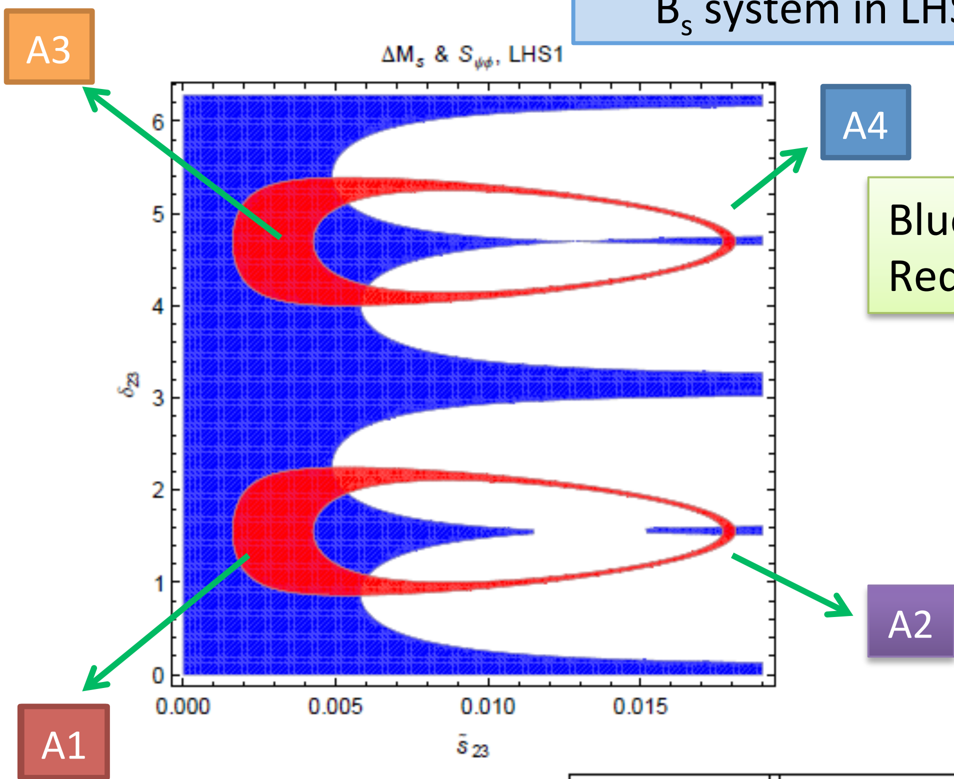
Imposing the experimental constraints one finds the allowed oases for the parameters

$$0.48/\mathrm{ps} \le \Delta M_d \le 0.53/\mathrm{ps}, \quad 0.64 \le S_{\psi K_S} \le 0.72$$

$$16.9/\mathrm{ps} \le \Delta M_s \le 18.7/\mathrm{ps}, \quad -0.18 \le S_{\psi\phi} \le 0.18$$

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

B_s system in LHS1 scenario



Blue regions come from the constraint on $S_{\psi\phi}$
Red ones from the constraint on ΔM_s

Four allowed oases:
two *big* ones & two *small* ones

	$\tilde{s}_{23}$	δ_{23}	
$A_1(S1)$	$0.0016 - 0.0061$	$49^\circ - 129^\circ$	Big
$A_2(S1)$	$0.0176 - 0.0181$	$87^\circ - 92^\circ$	Small
$A_3(S1)$	$0.0016 - 0.0061$	$229^\circ - 309^\circ$	Big
$A_4(S1)$	$0.0176 - 0.0181$	$267^\circ - 272^\circ$	Small

How to find the optimal oasis?

The decay $B_s \to \mu^+ \mu^-$

SM effective hamiltonian → 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:

$$Y_A(B_q) = \eta_Y Y_0(x_t) + \frac{[\Delta_A^{\mu\bar{\mu}}(Z')]}{M_{Z'}^2 g_{SM}^2}\left[\frac{\Delta_L^{qb}(Z') - \Delta_R^{qb}(Z')}{V_{tq}^* V_{tb}}\right] \equiv |Y_A(B_q)| e^{i\theta_Y^{B_q}}$$

The various scenarios predict different results

a new phase

Theoretically clean observable:

$$S_{\mu^+\mu^-}^s = \sin(2\theta_Y^{B_s} - 2\varphi_{B_s})$$

phase of the function S entering in the box diagram vanishes in SM

the new phase involved

LHCb 1211.2674

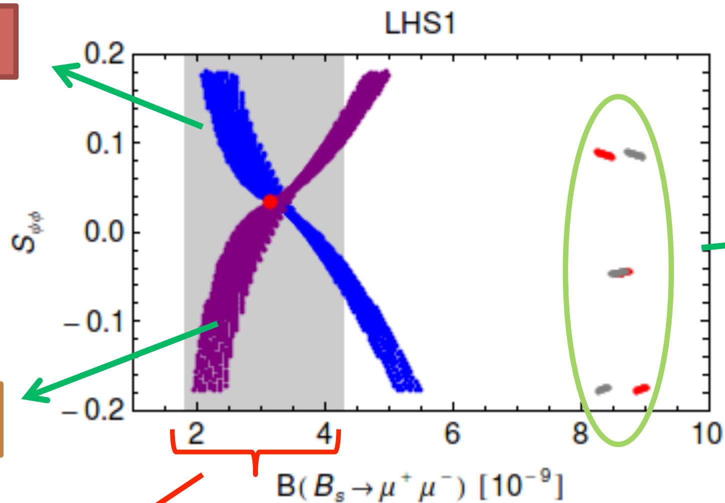
$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

SM

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{SM} = (3.23 \pm 0.27) \times 10^{-9}$$

The decay $B_s \to \mu^+ \mu^-$

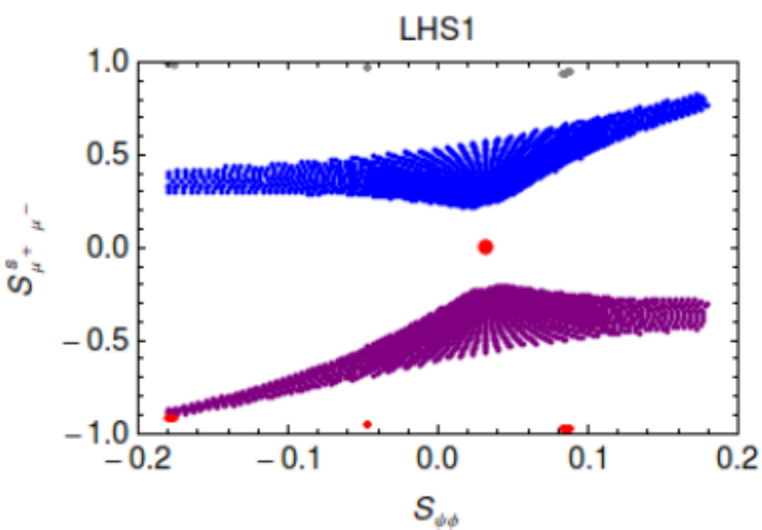
A1



A3

small oases

exp 1 σ range → Excludes the small oases



$S_{\mu+\mu-} > 0$ would choose A1
$S_{\mu+\mu-} < 0$ would choose A3

$b \to s \bar{\nu} \nu$

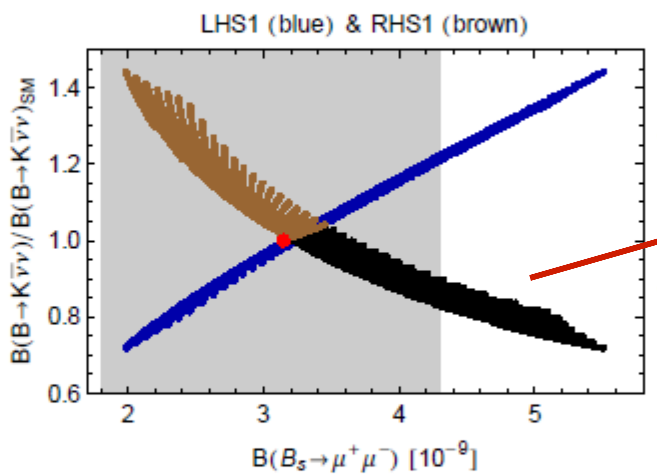
SM

$$\mathcal{B}(B \to K \nu \bar{\nu})_{SM} = (3.64 \pm 0.47) \times 10^{-6} ,$$
$$\mathcal{B}(B \to K^* \nu \bar{\nu})_{SM} = (7.2 \pm 1.1) \times 10^{-6} ,$$
$$\mathcal{B}(B \to X_s \nu \bar{\nu})_{SM} = (2.7 \pm 0.2) \times 10^{-5} ,$$

EXP

$$\mathcal{B}(B \to K \nu \bar{\nu}) < 1.4 \times 10^{-5} ,$$
$$\mathcal{B}(B \to K^* \nu \bar{\nu}) < 8.0 \times 10^{-5} ,$$
$$\mathcal{B}(B \to X_s \nu \bar{\nu}) < 6.4 \times 10^{-4} .$$

Sensitive observables



excluded by $b \to s\, l^+ l^-$

Clear distinction between LHS and RHS

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

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

Most relevant operators

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

→ Magnetic penguin operators

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

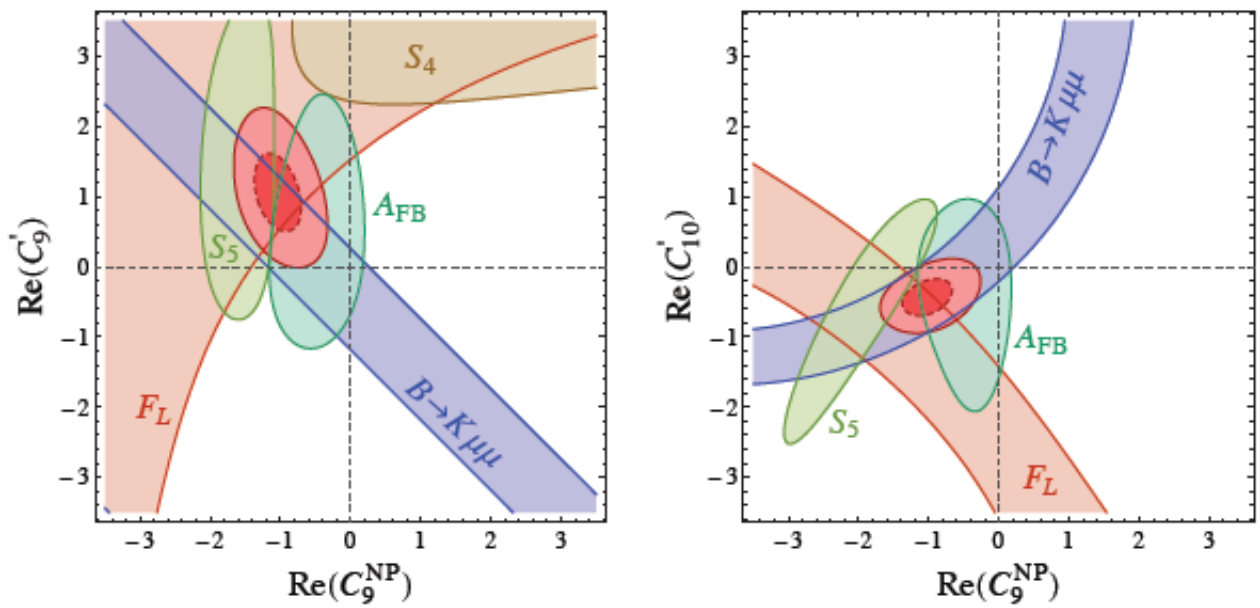
→ Semileptonic electroweak penguin operators

The decay B → $K^* \mu^+ \mu^-$

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

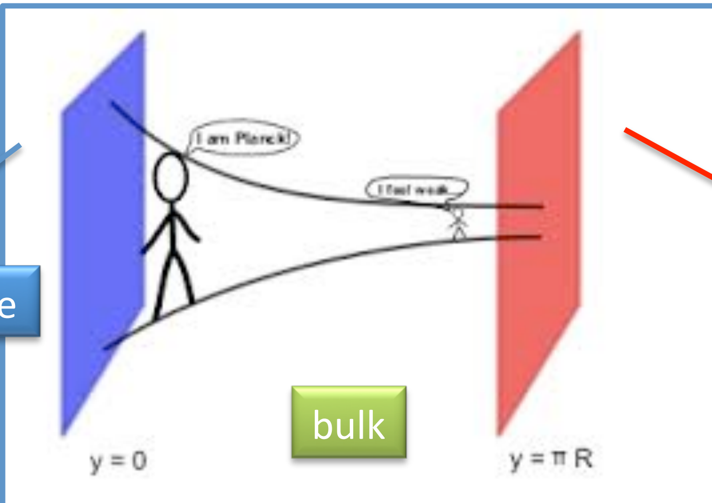
W. Altmanshofer, D. Straub
EPJC73 (2013) 2646



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

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

Planck (UV) brane



bulk

SM (IR) brane

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

$$k \simeq \mathcal{O}(M_{Planck})$$

All fields propagate in the bulk, Higgs localized close to or on the IR brane

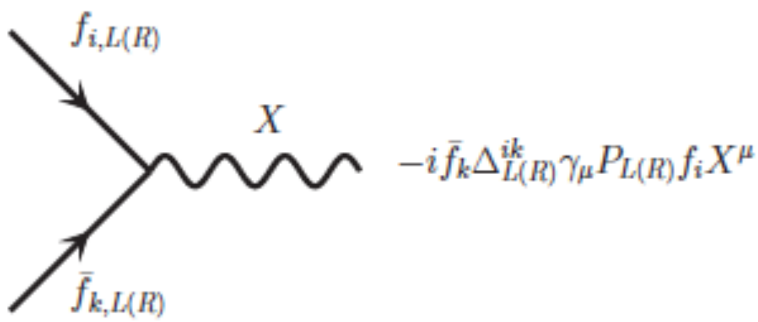
Gauge group enlarged to $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{L,R}$

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

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

Particle content:
SM particles+ their KK excitations
New particles
Zero modes identified with SM fields

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)

New contributions to the Wilson coefficients

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: $(u\ d)_L$ $(c\ s)_L$ $(t\ b)_L$ $(e\ \nu_e)_L$ $(\mu\ \nu_\mu)_L$ $(\tau\ \nu_\tau)_L$

4D Yukawa coulings:

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

5D Yukawa matrices

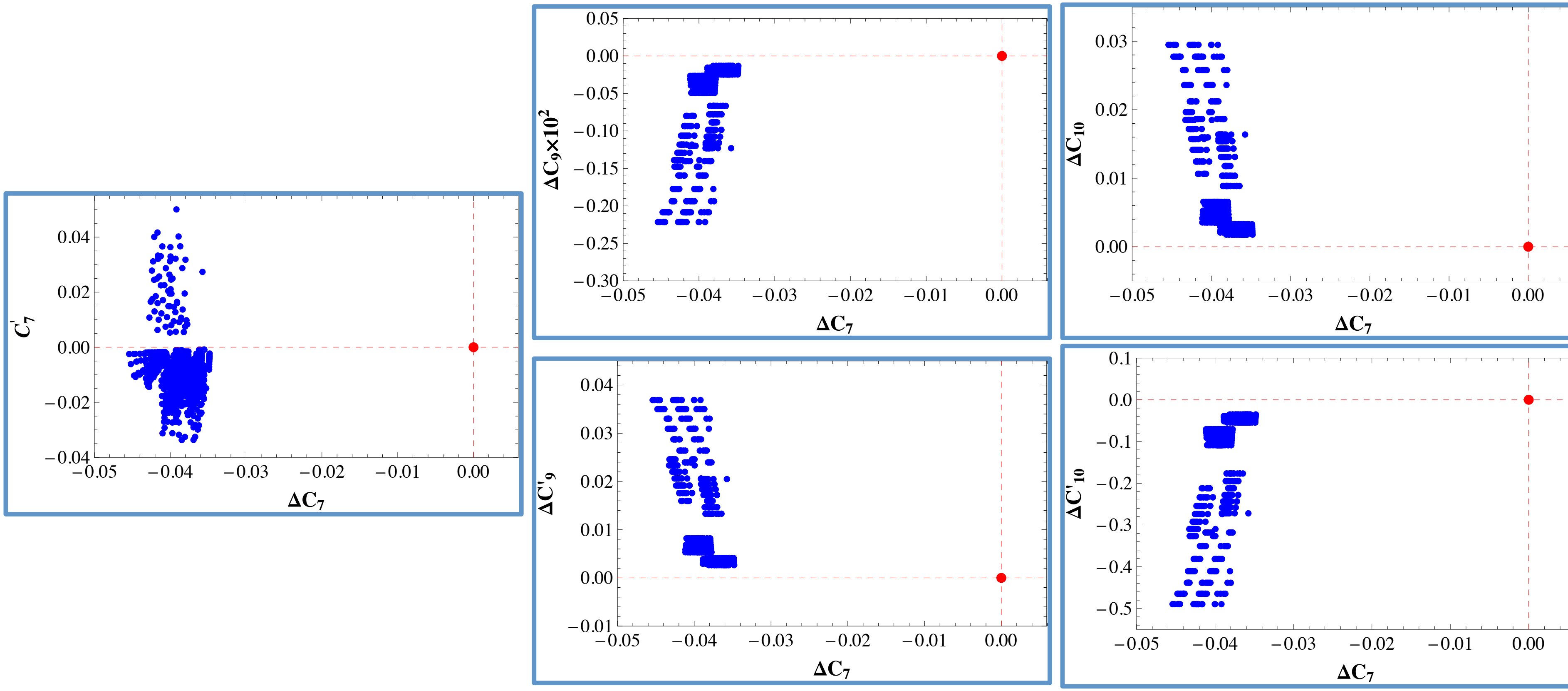
Constraints: $\lambda^{u,d}$ should reproduce

- quark masses
- CKM elements

remaining independent parameters

$$\lambda^u_{12}, \quad \lambda^u_{13}, \quad \lambda^u_{23}$$
$$\lambda^d_{12}, \quad \lambda^d_{13}, \quad \lambda^d_{23}$$

Results

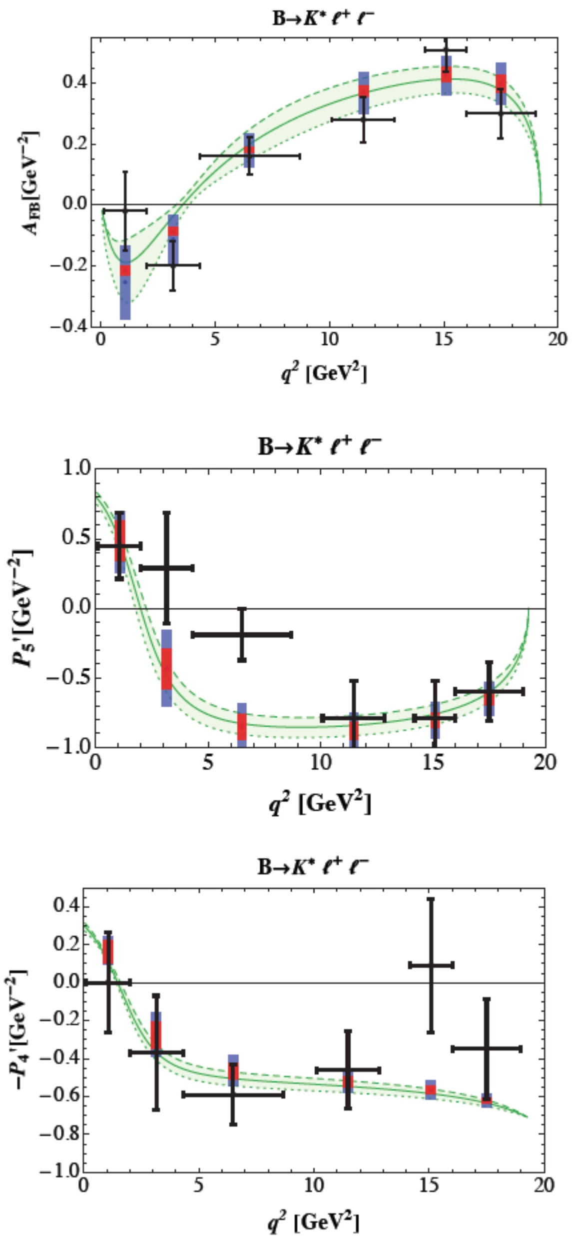


Largest deviations from SM results:

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

P. Biancofiore, P. Colangelo, FDF
PRD 89 (2014) 095018

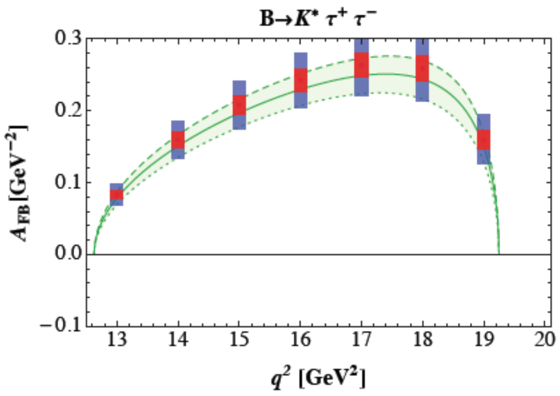
Results

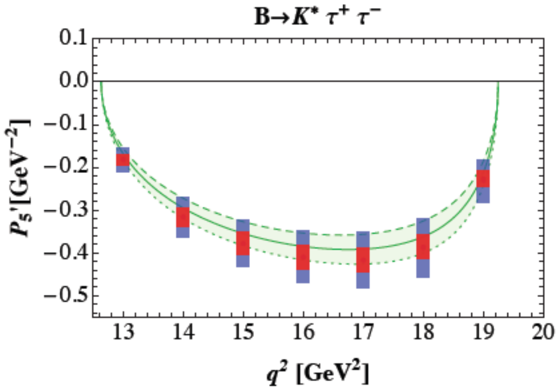


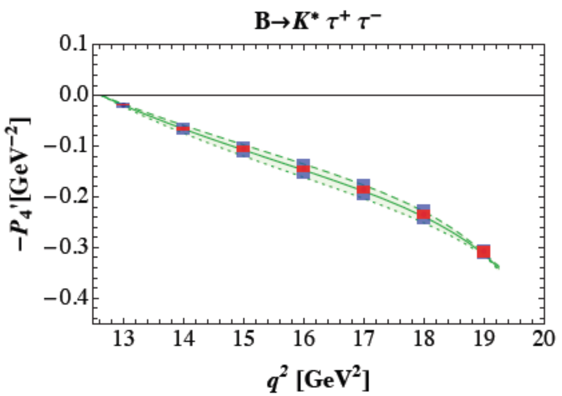
- **SM** (green): Uncertainty on FF taken into account
- **RS_c** (red): Uncertainty reflects only the variation of input parameters
- **RS_c** (blue): Uncertainty reflects the variation of input parameters & FF errors
- **LHCb Data** (black)

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

τ in the final state







No measurements available yet to test SM

Deviations in $B \to K^* \mu^+ \mu^-$ distributions and correlations with other flavour observables in 331 models

331 Models: general features

P. Frampton, PRL 69 (92) 2889
F. Pisano & V. Pleitez, PRD 46 (92) 410

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 $SU(3)_C \times U(1)_Q$

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

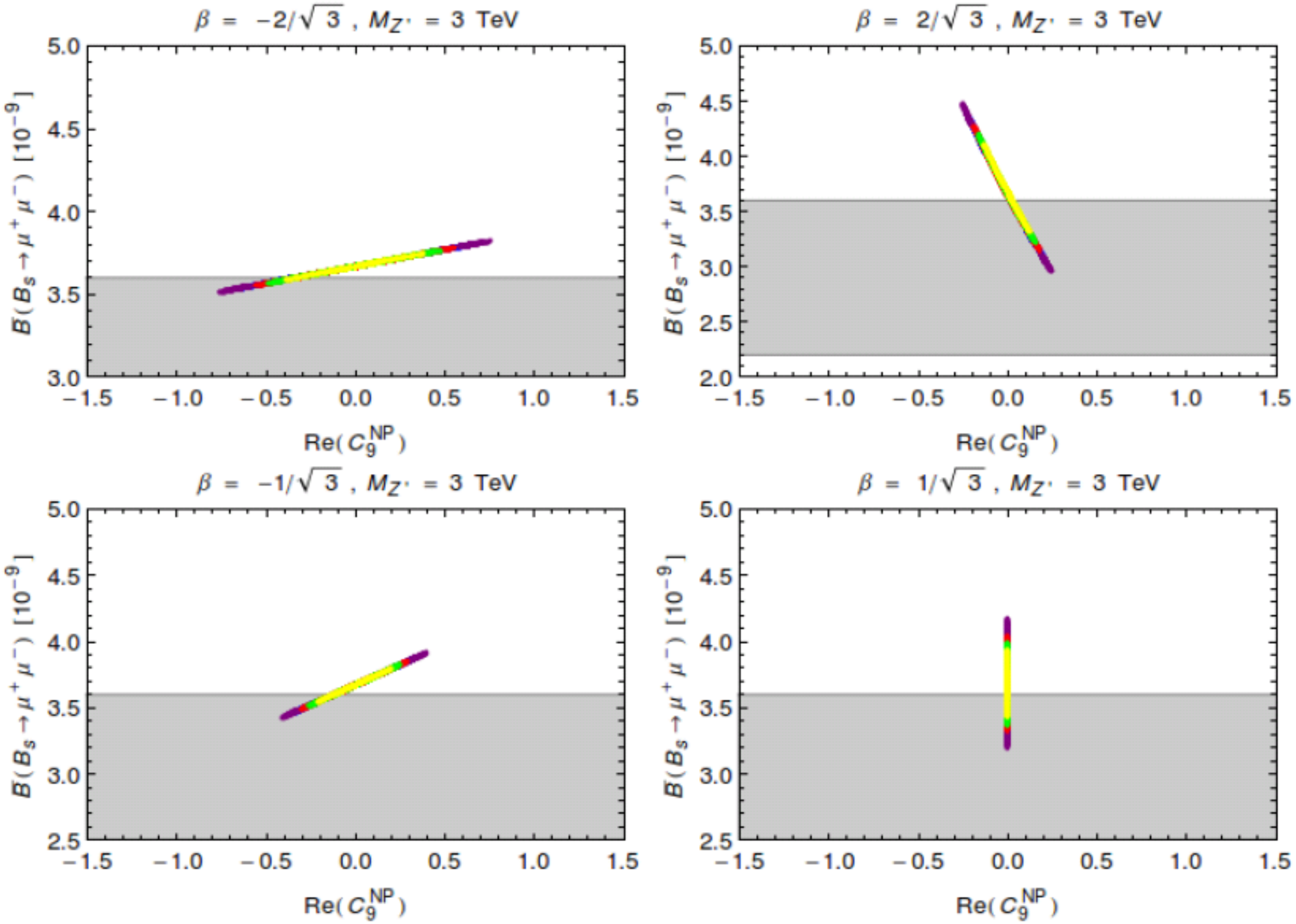
New Gauge Bosons, with charges depending on the chosen value of β

However: always present a new neutral **Z'**

Mediates tree level FCNC in the quark sector

Correlation between C_9 and BR($B_s \to \mu^+\mu^-$)

A.J. Buras, J. Girrbach, FDF
JHEP 1402 (2014) 112



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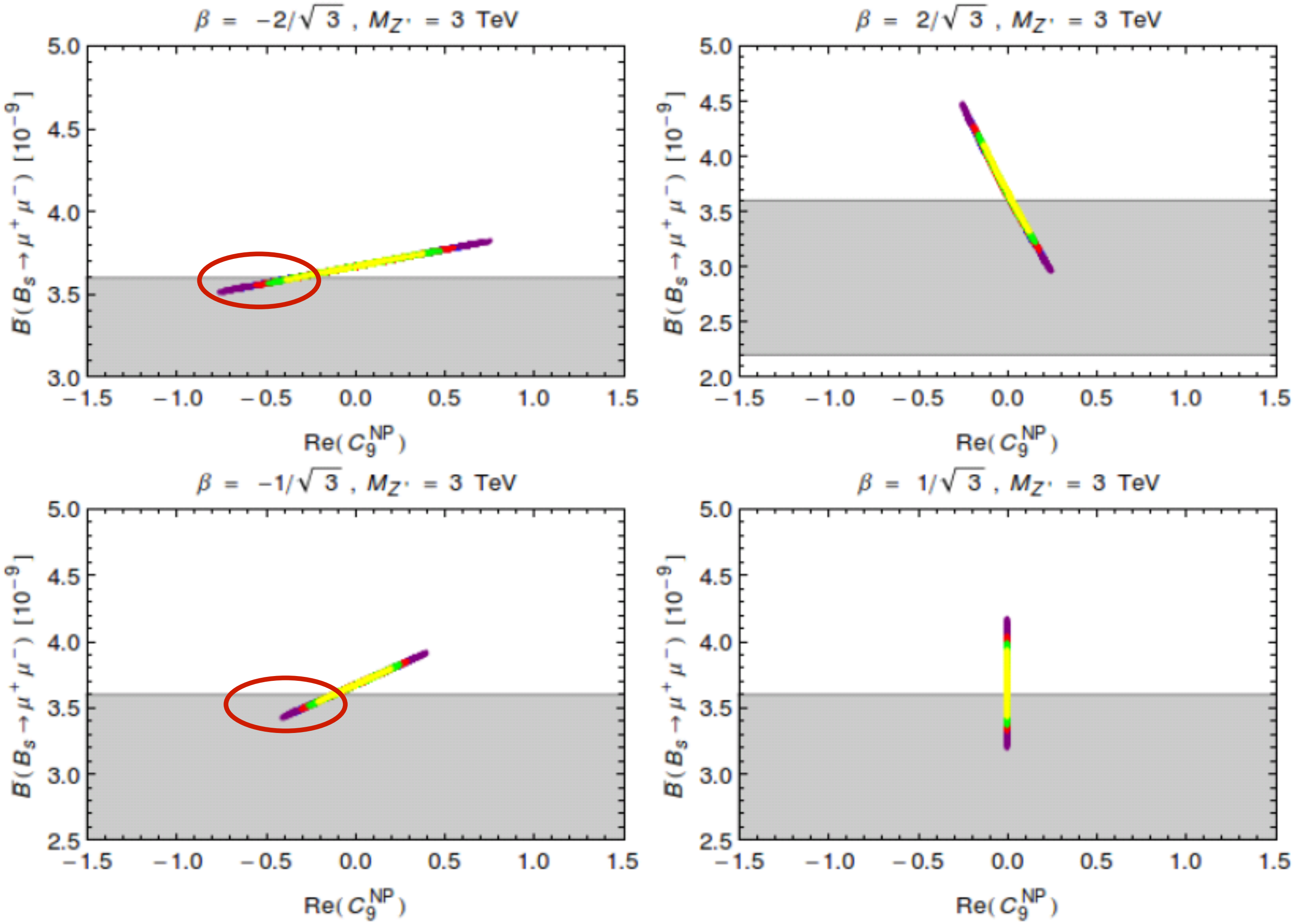
JHEP 1402 (2014) 112



$B \to D^{(*)} \tau \bar{\nu}_\tau$

strategy:

- consider a NP scenario that enhances semileptonic modes but not leptonic ones
- predict similar effects in other analogous modes

$$H_{eff} = H_{eff}^{SM} + H_{eff}^{NP} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\bar{c}\gamma_\mu(1-\gamma_5)b\,\bar{\ell}\gamma^\mu(1-\gamma_5)\bar{\nu}_\ell + \epsilon_T^\ell\,\bar{c}\sigma_{\mu\nu}(1-\gamma_5)b\,\bar{\ell}\sigma^{\mu\nu}(1-\gamma_5)\bar{\nu}_\ell \right]$$

SM NP

new complex coupling: $\varepsilon_T^{\mu,e}=0$, $\varepsilon_T^\tau \neq 0$

Charmed meson

$$\frac{d\Gamma}{dq^2}(B \to M_c \ell \bar{\nu}_\ell) = C(q^2) \left[\frac{d\tilde{\Gamma}}{dq^2}(B \to M_c \ell \bar{\nu}_\ell)\Big|_{SM} + \frac{d\tilde{\Gamma}}{dq^2}(B \to M_c \ell \bar{\nu}_\ell)\Big|_{NP} + \frac{d\tilde{\Gamma}}{dq^2}(B \to M_c \ell \bar{\nu}_\ell)\Big|_{INT} \right]$$

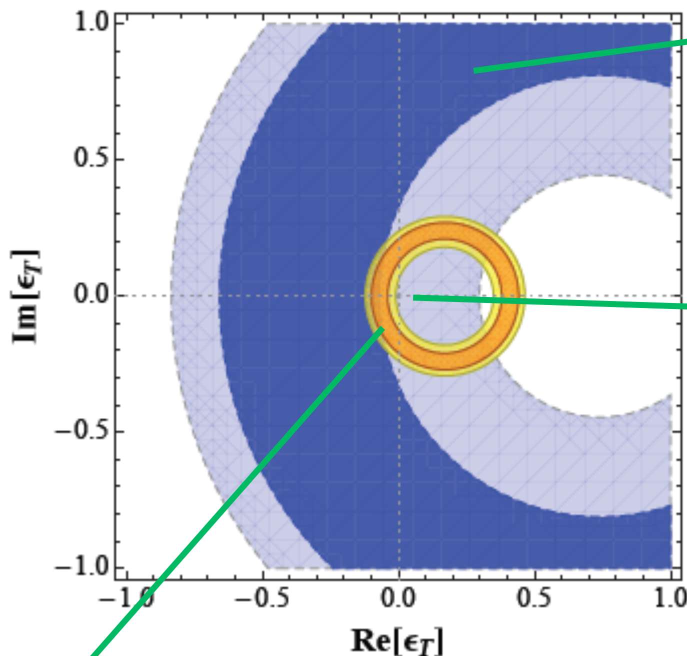
$$C(q^2) = \frac{G_F^2 |V_{cb}|^2 \lambda^{1/2}(m_B^2, m_{M_c}^2, q^2)}{192\pi^3 m_B^3} \left(1 - \frac{m_\ell^2}{q^2}\right)^2$$

$\propto |\varepsilon_T|^2$ $\propto \mathrm{Re}(\varepsilon_T)$

P. Biancofiore, P. Colangelo, FDF
PRD 87 (2013) 074010

$B \to D^{(*)} \tau \bar{\nu}_\tau$

Including a new tensor operator in H_{eff} :
is it possible to reproduce both R(D) and R(D*)?



Big circle: R(D) constraint

overlap region: $\epsilon_T = |a_T| e^{i\theta} + \epsilon_{T0}$

$Re[\epsilon_{T0}] = 0.17 \quad , \quad Im[\epsilon_{T0}] = 0$

$|a_T| \in [0.24,\ 0.27]$

$\theta \in [2.6,\ 3.7]$ rad

Small cicrcle: R(D*) constraint

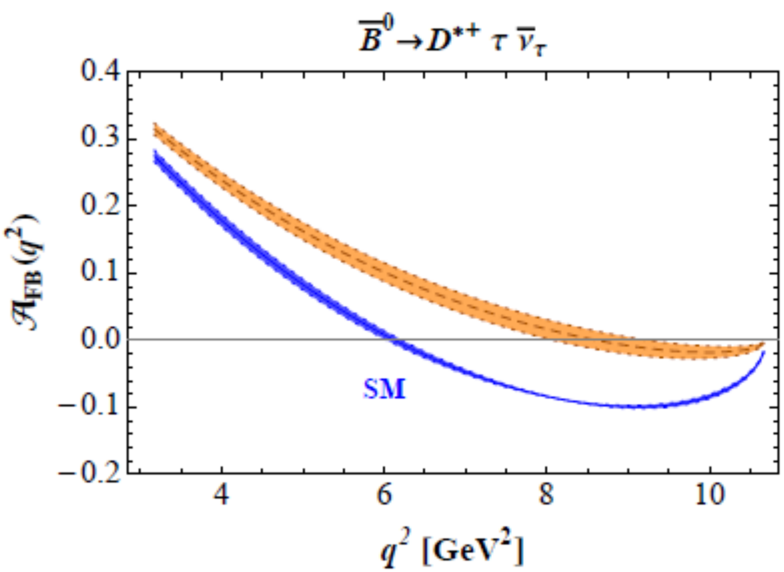
varying ε_T in this range predictions for several observables can be gained

$B \to D^* \tau \bar{\nu}_\tau$

Forward-Backward asymmetry

$$\mathcal{A}_{FB}(q^2) = \frac{\int_0^1 d\cos\theta_\ell \frac{d\Gamma}{dq^2 d\cos\theta_\ell} - \int_{-1}^0 d\cos\theta_\ell \frac{d\Gamma}{dq^2 d\cos\theta_\ell}}{\frac{d\Gamma}{dq^2}}$$

angle between the charged lepton and the D^* in the lepton pair rest-frame



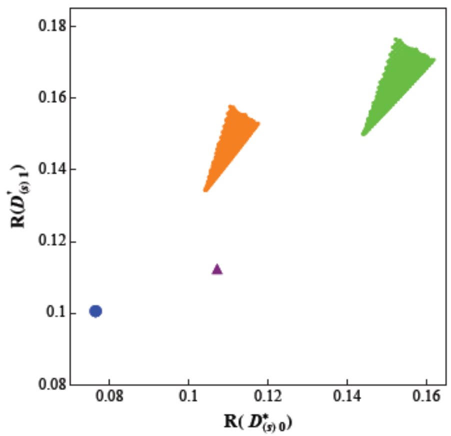
The SM predicts a zero at $q^2 \approx 6.15$ GeV^2
In NP the zero is shifted to $q^2 \in [8.1, 9.3]$ GeV^2

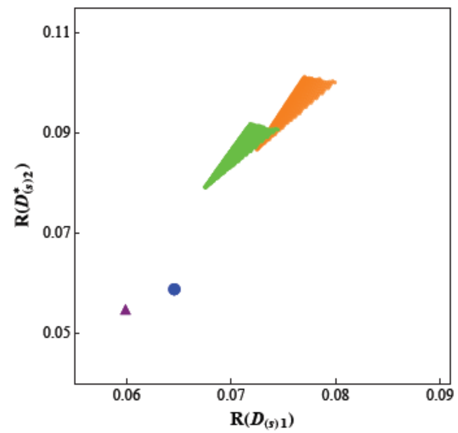
$B \to D^{**} \tau \bar{\nu}_\tau$

$$\mathcal{R}(D^{**}) = \frac{\mathcal{B}(B \to D^{**}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{**}\mu\bar{\nu}_\mu)}$$

Two doublets of positive parity excited charmed mesons :

$(D_{(s)0}^*, D_{(s)1}')$ with $J^P=(0^+,1^+)$ and **$(D_{(s)1}, D_{(s)2}^*)$** with $JP=(1^+,2^+)$

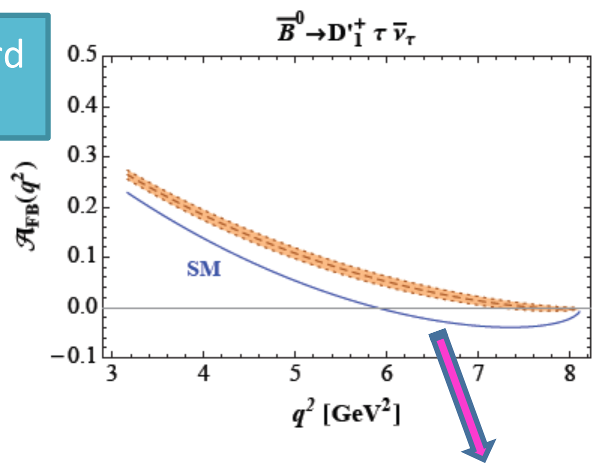


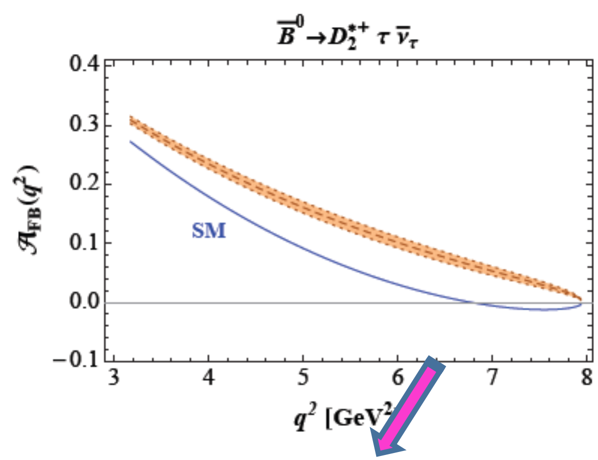


Orange= non strange
Blue circle= SM
Green= strange
Triangle= SM

The inclusion of the tensor operator produces a sizable increase in the ratios

Forward-backward asymmetries





shift in the position of the zero

the zero disappears

Wish list…

Difficult but promising observables:

- CP asymmetry in $B_s \to \mu^+ \mu^-$ (+ correlations)
- $B \to K^{(*)} \nu \bar{\nu}$

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

- FB asymmetry in $B \to D^* \tau \bar{\nu}_\tau$
- $B \to D^{**} \tau \bar{\nu}_\tau$ + FB asymmetries