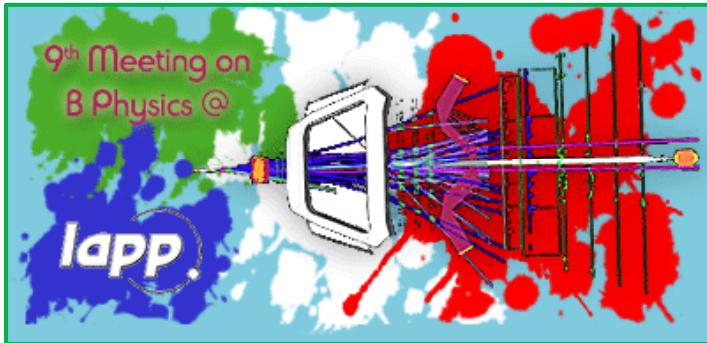




The anatomy of quark flavour observables in the flavour precision era

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Two topics

- What can be learnt about NP from flavour observables if the lightest NP messenger is a new Z' gauge boson?
- exclusive semileptonic $b \rightarrow c$ decays:
anomalous enhancement of modes with a τ in the final state

Based on works in collaboration with
A.J. Buras, J. Gирrbach (Munich)
&
P. Biancofiore, P. Colangelo (Bari)

Flavour Precision Era (FPE): working assumptions

- CKM parameters have been determined by means of tree-level decays
- Non-perturbative parameters are affected by very small uncertainties and fixed

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 $B(B \rightarrow \tau \nu_\tau)$

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

NP models on the market automatically select one or the other scenario

Let us consider the following case

- There exists a new neutral gauge boson Z' mediating tree-level FCNC processes
 $M_{Z'}=1$ TeV for definiteness
- Couplings to quarks are arbitrary while those to leptons are assumed already determined by purely leptonic modes

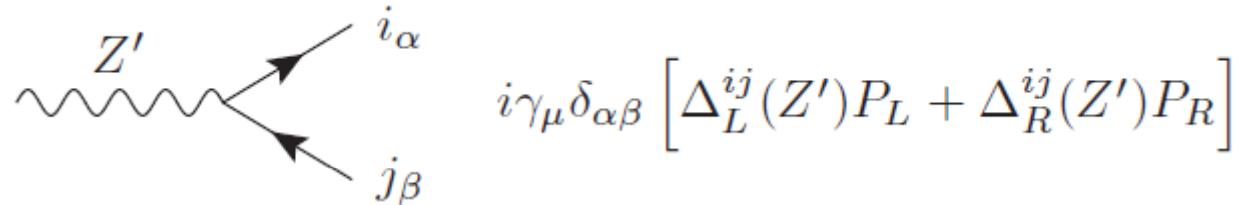


Existing data constrain Z' couplings to quarks

Four possible scenarios for such couplings can be considered

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

Anatomy of Z' with FCNC in the FPE



A Feynman diagram showing a wavy line labeled Z' branching into two arrows. The top arrow is labeled i_α and the bottom arrow is labeled j_β .

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

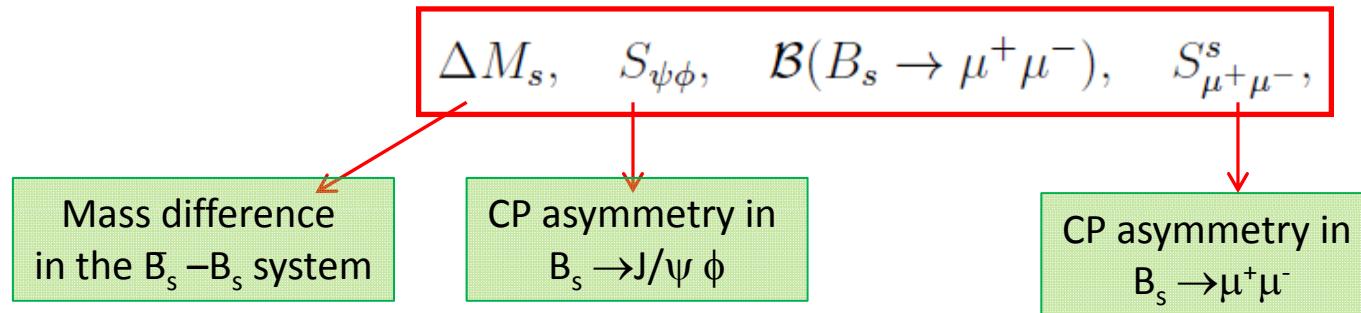
1. Left-handed Scenario (LHS) with complex $\Delta_L^{bq} \neq 0$ and $\Delta_R^{bq} = 0$,
2. Right-handed Scenario (RHS) with complex $\Delta_R^{bq} \neq 0$ and $\Delta_L^{bq} = 0$,
3. Left-Right symmetric Scenario (LRS) with complex $\Delta_L^{bq} = \Delta_R^{bq} \neq 0$,
4. Left-Right asymmetric Scenario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



Analogous scenarios can be considered for the quark pairs (bs) and (sd)

Anatomy of Z' with FCNC in the FPE: the B_s system

We consider the four observables:



They depend all on

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

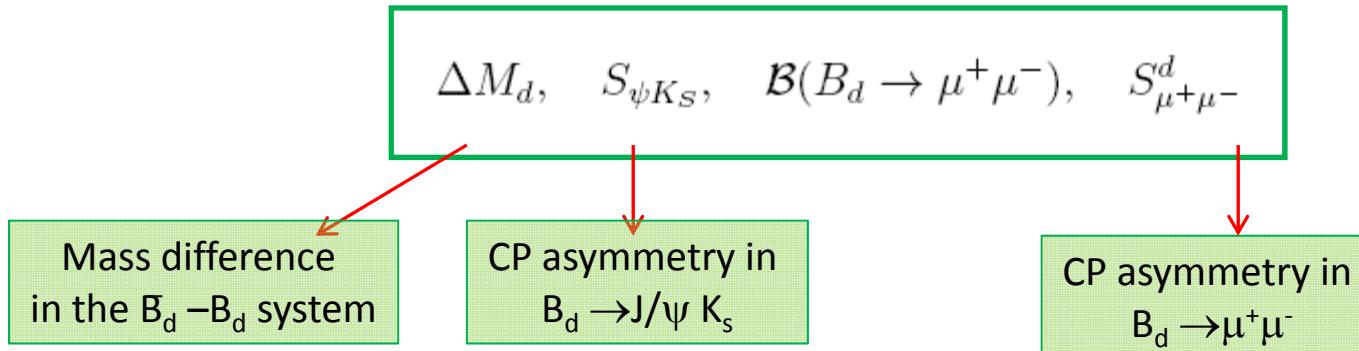
Imposing the experimental constraints:
we find allowed ranges for the parameters

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

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

Anatomy of Z' with FCNC in the FPE: the B_d system

We consider the four observables:



They depend all on

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

Imposing the experimental constraints:
we find allowed ranges for the parameters

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

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

Anatomy of Z' with FCNC in the FPE

Once the allowed ranges for the parameters have been fixed,
Predictions for other observables can be worked out :

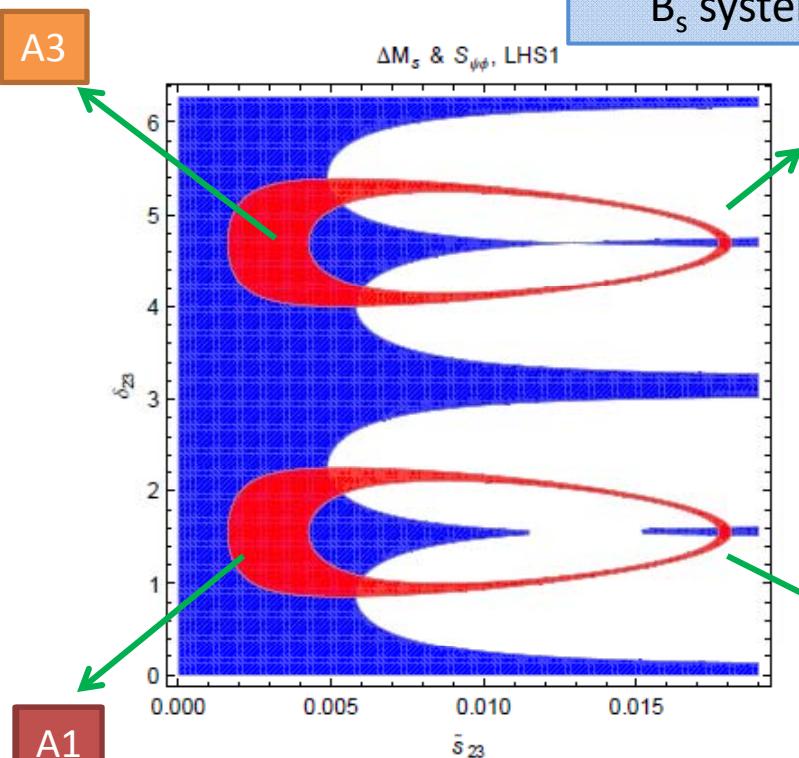
$$B \rightarrow X_s \ell^+ \ell^-, \quad B \rightarrow K \ell^+ \ell^-, \quad B \rightarrow K^* \ell^+ \ell^-$$

$$B \rightarrow K \nu \bar{\nu}, \quad B \rightarrow K^* \nu \bar{\nu}, \quad B \rightarrow X_s \nu \bar{\nu},$$



They provide additional constraints
on the parameters

B_s system in LHS1 scenario



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



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 $B_s \rightarrow \mu^+ \mu^-$

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:

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

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

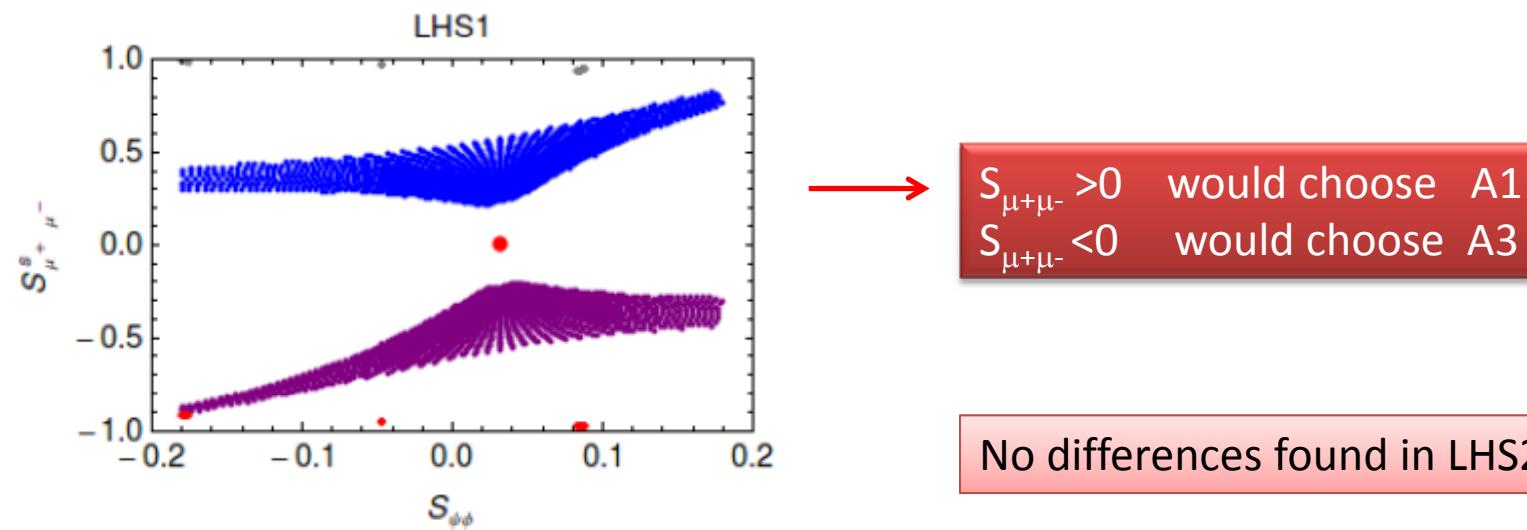
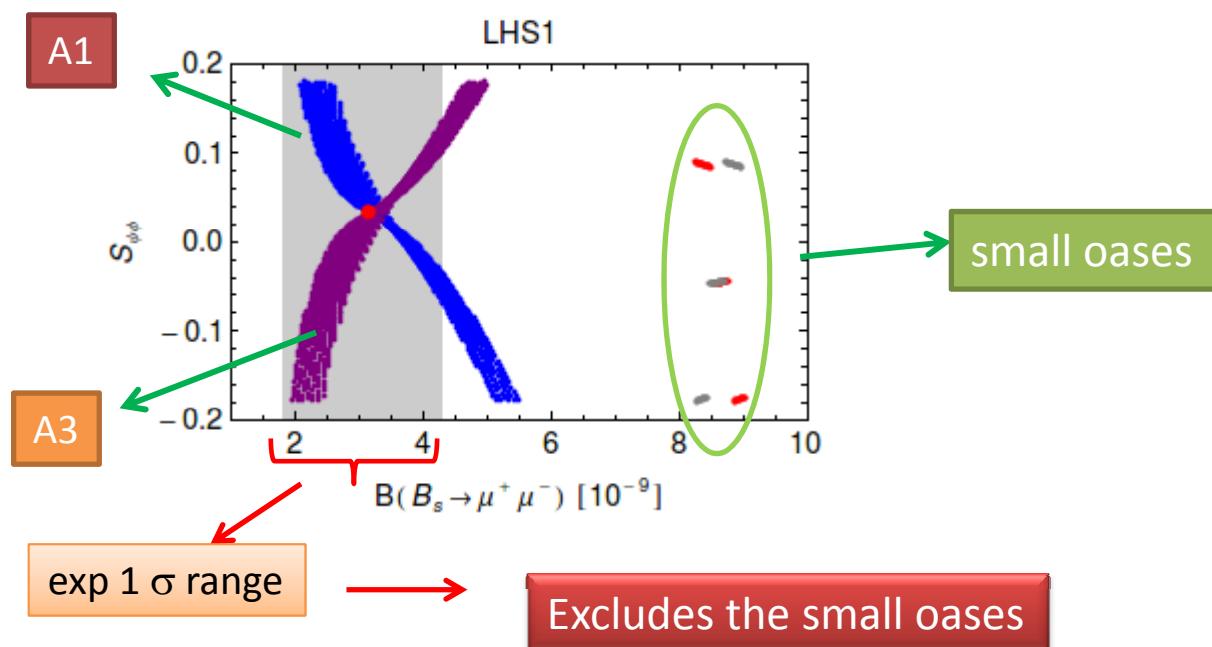
LHCb 1211.2674

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

SM

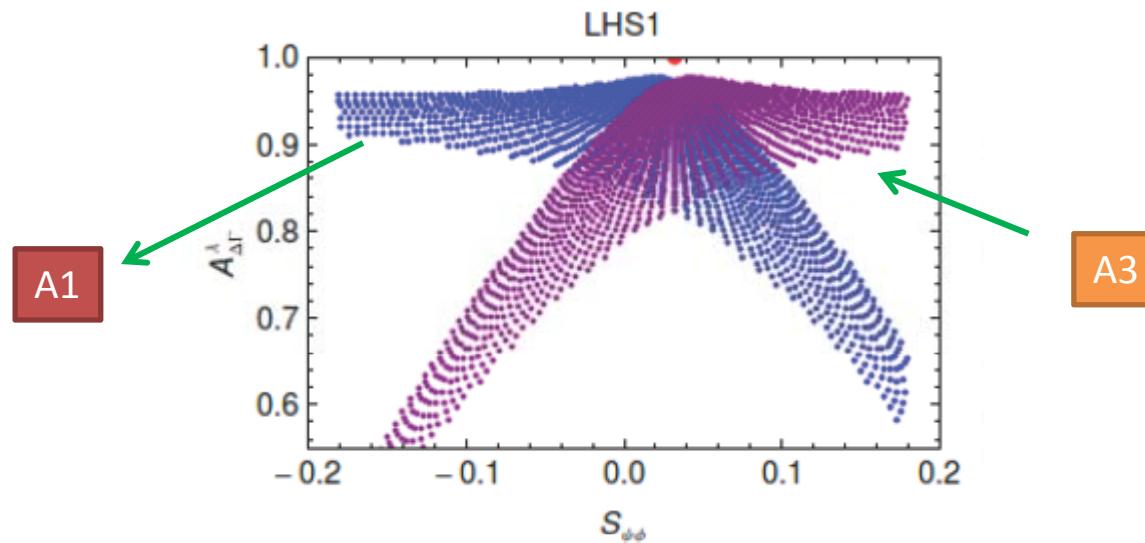
$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)^{\text{SM}} = (3.23 \pm 0.27) \times 10^{-9}$$

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

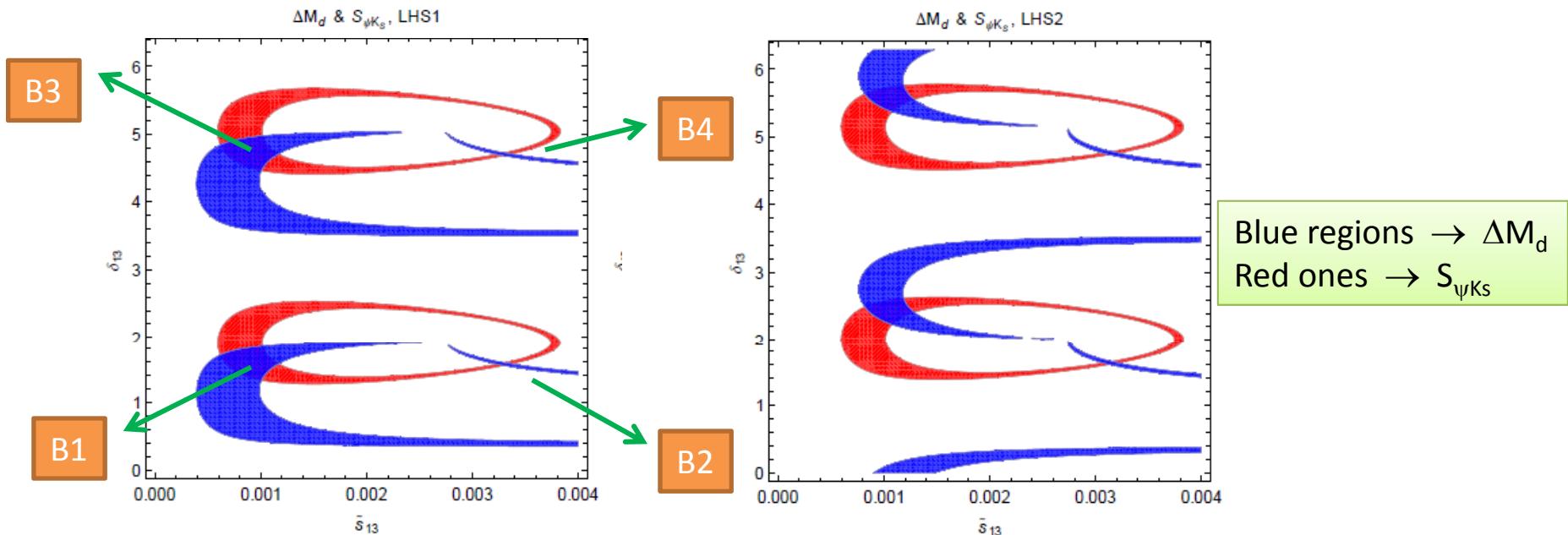


The decay $B_s \rightarrow \mu^+ \mu^-$

$$\mathcal{A}_{\Delta\Gamma}^\lambda = \cos(2\theta_Y^{B_s} - 2\varphi_{B_s}),$$

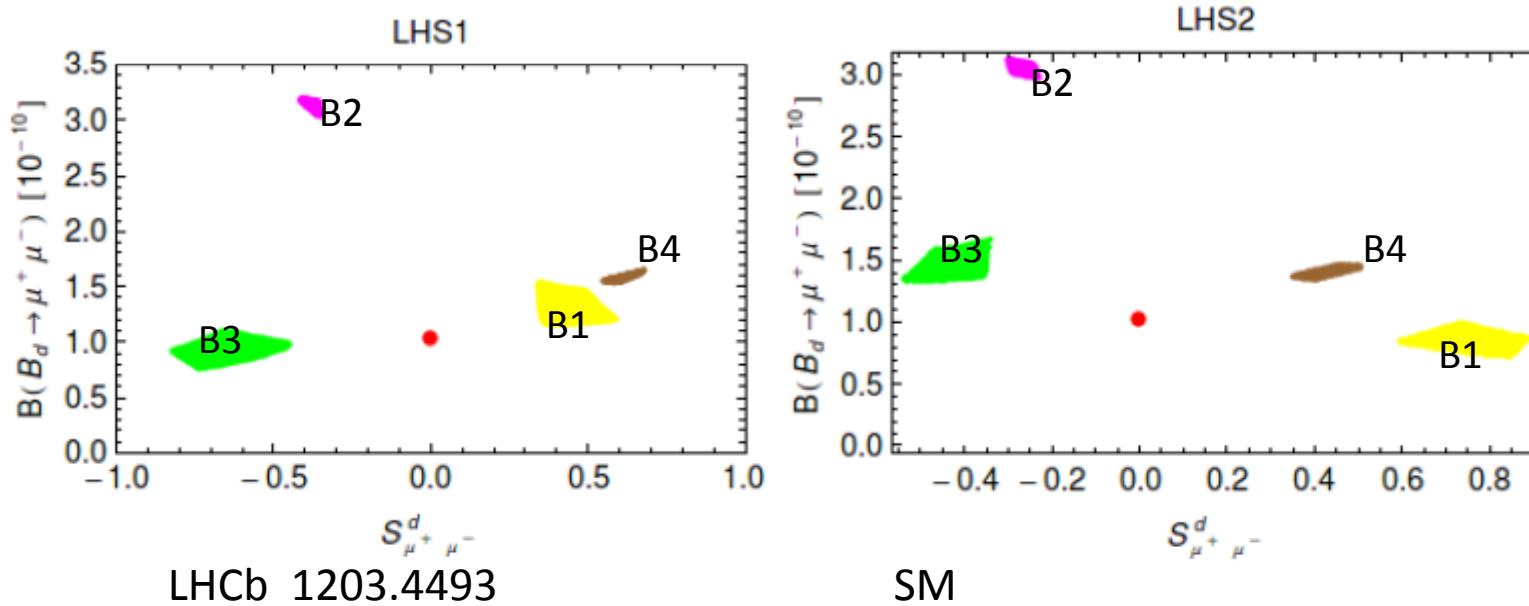


B_d system in LHS1 & LHS2 scenarios



	\tilde{s}_{13}	δ_{13}
$B_1(S1)$	0.00062 – 0.00117	$76^\circ – 105^\circ$
$B_2(S1)$	0.00322 – 0.00337	$89^\circ – 91^\circ$
$B_3(S1)$	0.00062 – 0.00117	$256^\circ – 285^\circ$
$B_4(S1)$	0.00322 – 0.00337	$269^\circ – 271^\circ$
$B_1(S2)$	0.00081 – 0.00128	$128^\circ – 150^\circ$
$B_2(S2)$	0.00306 – 0.00322	$92^\circ – 95^\circ$
$B_3(S2)$	0.00081 – 0.00128	$308^\circ – 330^\circ$
$B_4(S2)$	0.00306 – 0.00322	$272^\circ – 275^\circ$

B_d system in LHS1 & LHS2 scenarios



$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) \leq 9.4 \times 10^{-10}$$

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-)^{\text{SM}} = (1.07 \pm 0.10) \times 10^{-10}$$

- in the small oases $B(B_d \rightarrow \mu^+ \mu^-)$ is always larger than in SM
- the sign of $S_{\mu^+ \mu^-}$ distinguishes B1 from B3 and B2 from B4

Correlation between $S_{\mu^+ \mu^-}$ and $B(B_d \rightarrow \mu^+ \mu^-)$: LHS1 vs LHS2

LHS1 : in B1 $S_{\mu^+ \mu^-} > 0$ & $B(B_d \rightarrow \mu^+ \mu^-) > B(B_d \rightarrow \mu^+ \mu^-)_{\text{SM}}$
 in B3 $S_{\mu^+ \mu^-} < 0$ & $B(B_d \rightarrow \mu^+ \mu^-) < B(B_d \rightarrow \mu^+ \mu^-)_{\text{SM}}$

LHS2 : in B1 $S_{\mu^+ \mu^-} > 0$ & $B(B_d \rightarrow \mu^+ \mu^-) < B(B_d \rightarrow \mu^+ \mu^-)_{\text{SM}}$
 in B3 $S_{\mu^+ \mu^-} < 0$ & $B(B_d \rightarrow \mu^+ \mu^-) > B(B_d \rightarrow \mu^+ \mu^-)_{\text{SM}}$

RHS1 & RHS2 scenarios



Means Z' with exclusively RH couplings to quarks

QCD is parity conserving \Rightarrow hadronic matrix elements of operators with RH currents
& QCD corrections remain unchanged

$\Delta F=2$ constraints appear the same as in LHS scenarios \Rightarrow **the oases remain the same**

$\Delta F=1$ observables: decays to muons governed by the function Y

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



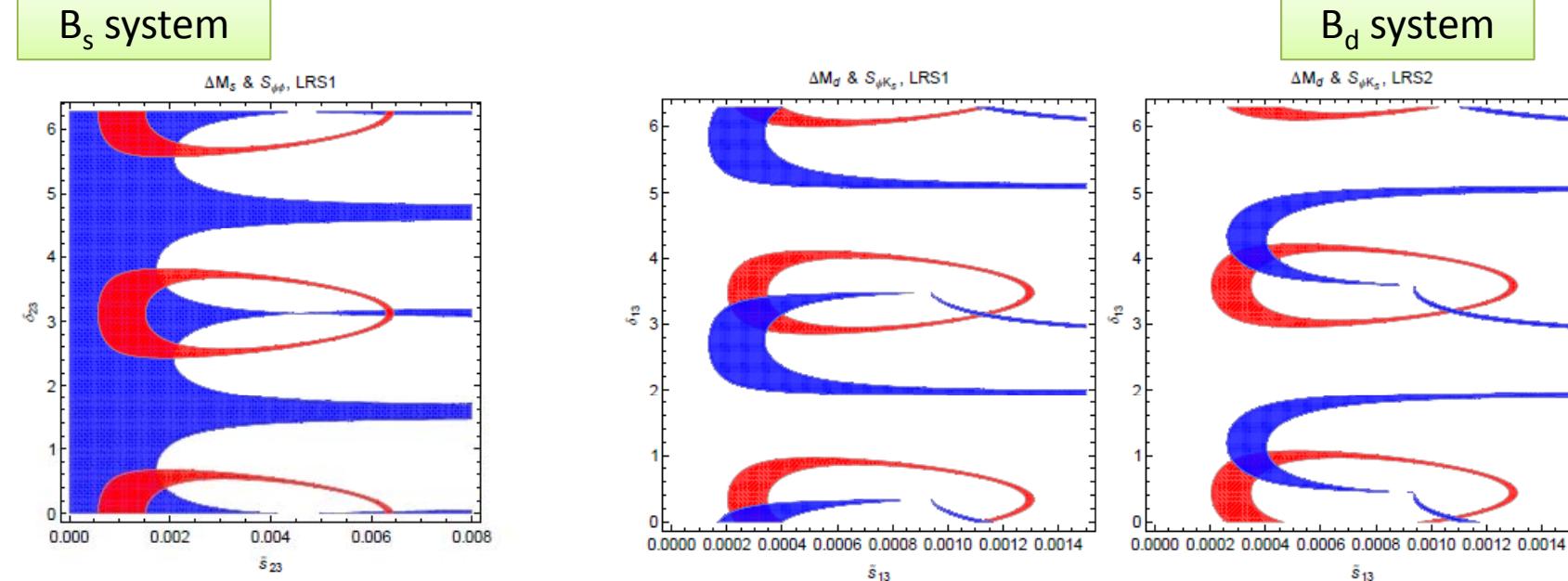
There is a change of sign of NP contributions in a given oasis

RHS1 & RHS2 scenarios



On the basis of these observables it would not be possible to know whether LHS in oases A1 (B1) is realized or RHS in oases A3 (B3)

LRS1 & LRS2 scenarios



Main difference with respect to the previous cases:

No NP contribution to $B_{d,s} \rightarrow \mu^+ \mu^-$

\Rightarrow We cannot rely on this observable to identify the right oases

ALRS1 & ALRS2 scenarios

Similar to LHS scenario, but NP effects much smaller

Can we exploit other observables?

$b \rightarrow s \ell^+ \ell^-$

$$\mathcal{H}_{\text{eff}}(b \rightarrow s\ell\bar{\ell}) = \mathcal{H}_{\text{eff}}(b \rightarrow s\gamma) - \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} V_{ts}^* V_{tb} \sum_{i=9,10} [C_i(\mu) Q_i(\mu) + C'_i(\mu) Q'_i(\mu)]$$



operators

$$Q_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \quad Q_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \\ Q'_9 = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell), \quad Q'_{10} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

coefficients

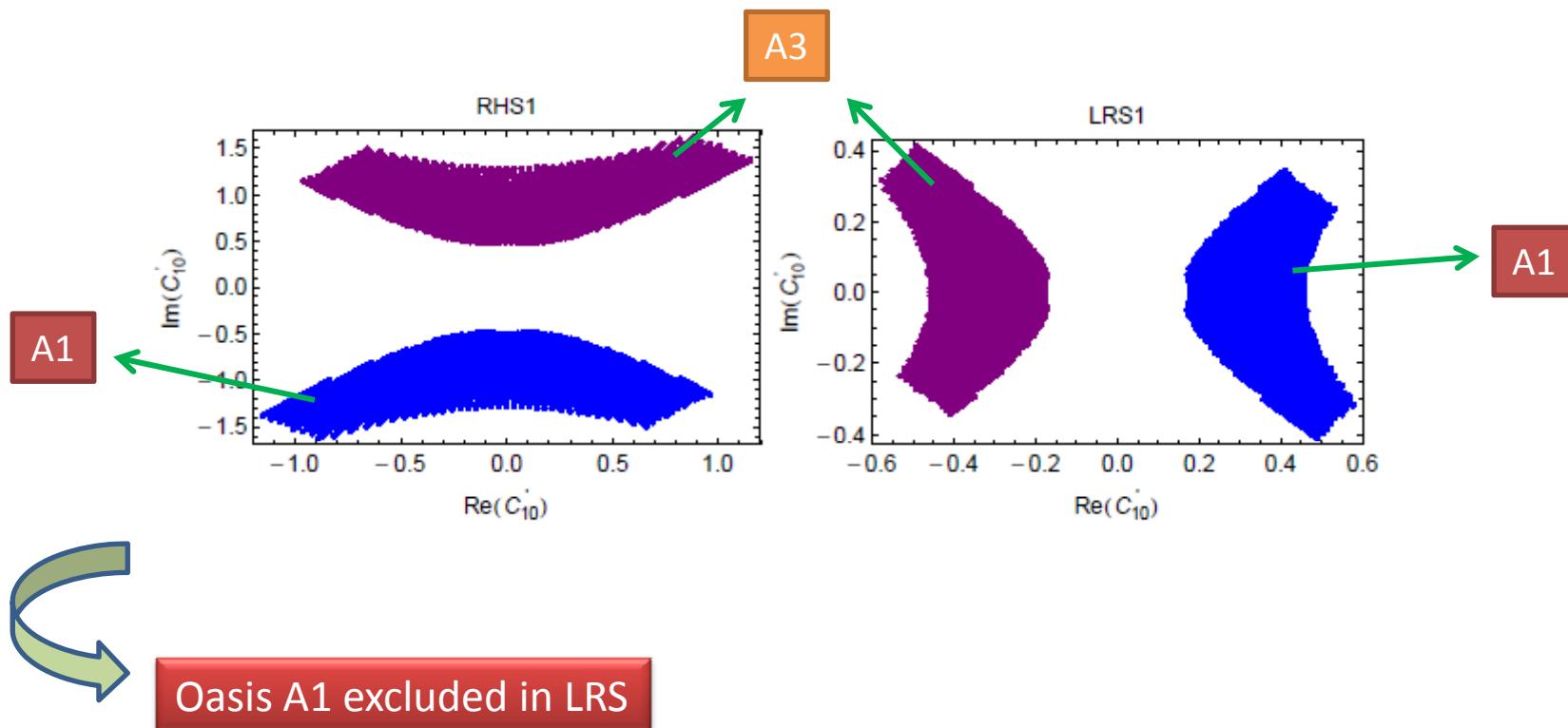
$$\sin^2 \theta_W C_9 = [\eta_Y Y_0(x_t) - 4 \sin^2 \theta_W Z_0(x_t)] - \frac{1}{g_{\text{SM}}^2} \frac{1}{M_{Z'}^2} \frac{\Delta_L^{sb}(Z') \Delta_V^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb}} \\ \sin^2 \theta_W C_{10} = -\eta_Y Y_0(x_t) - \frac{1}{g_{\text{SM}}^2} \frac{1}{M_{Z'}^2} \frac{\Delta_L^{sb}(Z') \Delta_A^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb}}, \\ \sin^2 \theta_W C'_9 = -\frac{1}{g_{\text{SM}}^2} \frac{1}{M_{Z'}^2} \frac{\Delta_R^{sb}(Z') \Delta_V^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb}}, \\ \sin^2 \theta_W C'_{10} = -\frac{1}{g_{\text{SM}}^2} \frac{1}{M_{Z'}^2} \frac{\Delta_R^{sb}(Z') \Delta_A^{\mu\bar{\mu}}(Z')}{V_{ts}^* V_{tb}},$$

$$b \rightarrow s \ell^+ \ell^-$$

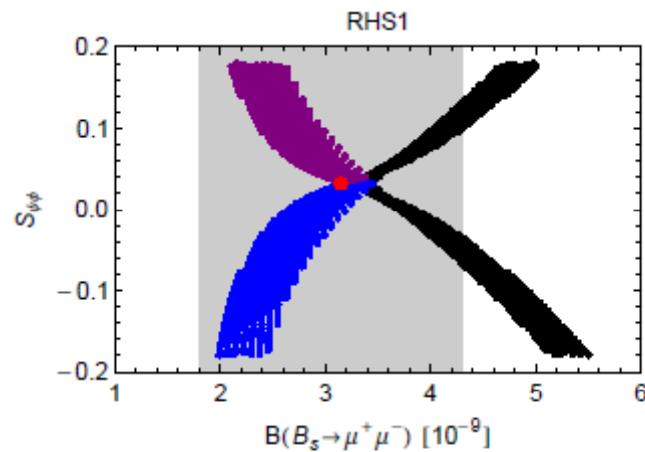
Exploiting present data constraints can be obtained:

W. Altmannshofer & D. Straub,
JHEP 1208 (2012) 121

$$-2 \leq \Re(C'_{10}) \leq 0, \quad -2.5 \leq \Im(C'_{10}) \leq 2.5.$$



$b \rightarrow s \ell^+ \ell^-$



Black regions are excluded
due to the constraint on C_{10}'



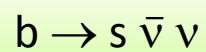
An enhancement of $B(B_s \rightarrow \mu^+ \mu^-)$ with respect to SM is excluded

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

ONLY in RHS!!



Possibility to differentiate between LHS and RHS scenarios,
but only if $B(B_s \rightarrow \mu^+ \mu^-) > B(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}}$



In presence of RH currents:

Altmannshofer, Buras, Straub, Wick
JHEP 04 (2009) 022

$$\begin{aligned}\mathcal{B}(B \rightarrow K \nu \bar{\nu}) &= \mathcal{B}(B \rightarrow K \nu \bar{\nu})_{\text{SM}} \times [1 - 2\eta] \epsilon^2, \\ \mathcal{B}(B \rightarrow K^* \nu \bar{\nu}) &= \mathcal{B}(B \rightarrow K^* \nu \bar{\nu})_{\text{SM}} \times [1 + 1.31\eta] \epsilon^2 \\ \mathcal{B}(B \rightarrow X_s \nu \bar{\nu}) &= \mathcal{B}(B \rightarrow X_s \nu \bar{\nu})_{\text{SM}} \times [1 + 0.09\eta] \epsilon^2.\end{aligned}$$

with

$$\epsilon^2 = \frac{|X_L(B_s)|^2 + |X_R(B_s)|^2}{|\eta_X X_0(x_t)|^2}, \quad \eta = \frac{-\text{Re}(X_L(B_s) X_R^*(B_s))}{|X_L(B_s)|^2 + |X_R(B_s)|^2}$$



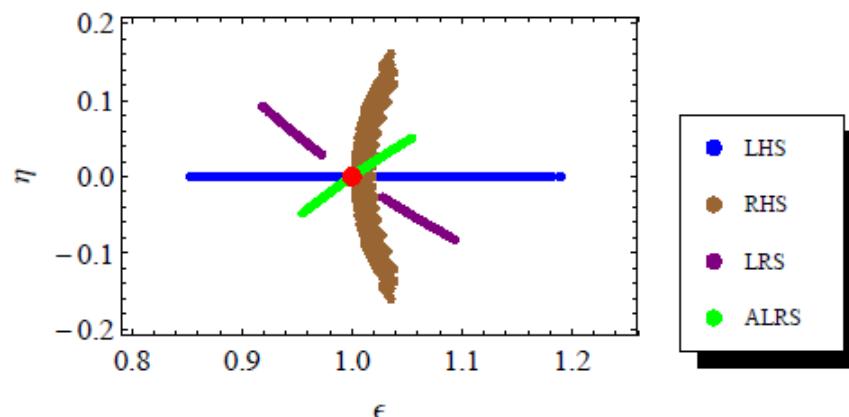
η vanishes in LHS

and

$$X_L(B_q) = \eta_X X_0(x_t) + \left[\frac{\Delta_L^{\nu\nu}(Z')}{M_{Z'}^2 g_{\text{SM}}^2} \right] \frac{\Delta_L^{qb}(Z')}{V_{tq}^* V_{tb}}$$

$$X_R(B_q) = \left[\frac{\Delta_L^{\nu\nu}(Z')}{M_{Z'}^2 g_{\text{SM}}^2} \right] \frac{\Delta_R^{qb}(Z')}{V_{tq}^* V_{tb}}$$

Sensitivity to the various scenarios



SM

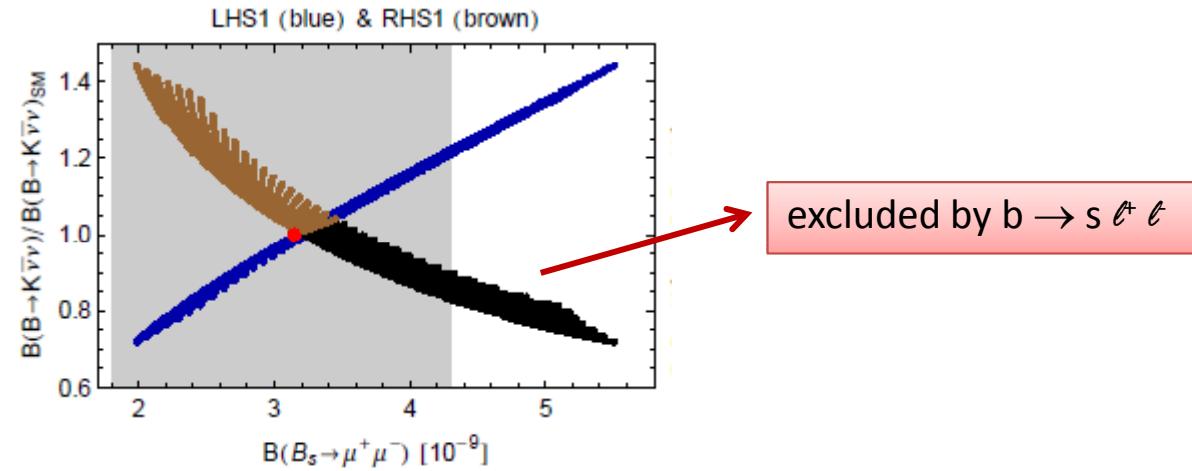
 $b \rightarrow s \bar{v} v$

EXP

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

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

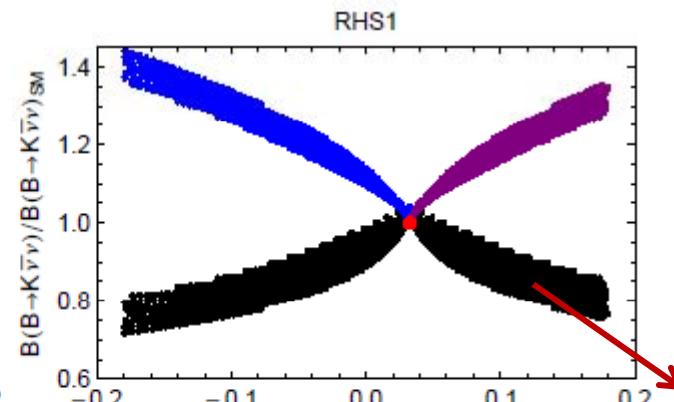
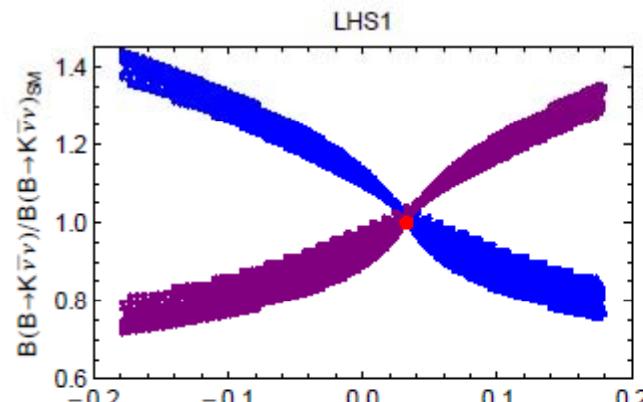
Sensitive observables



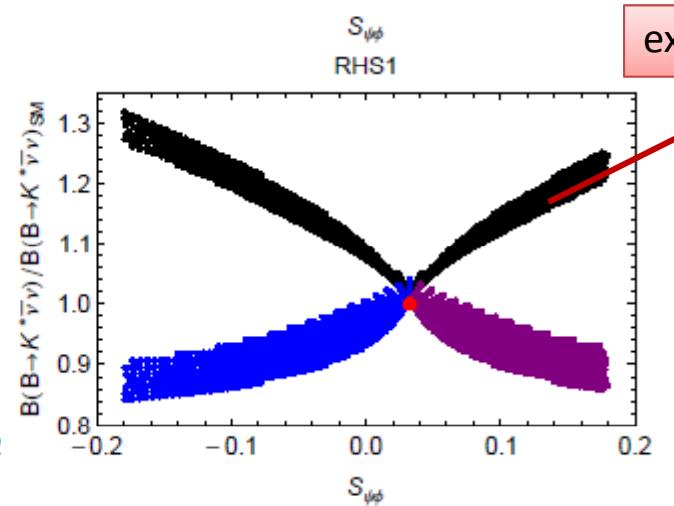
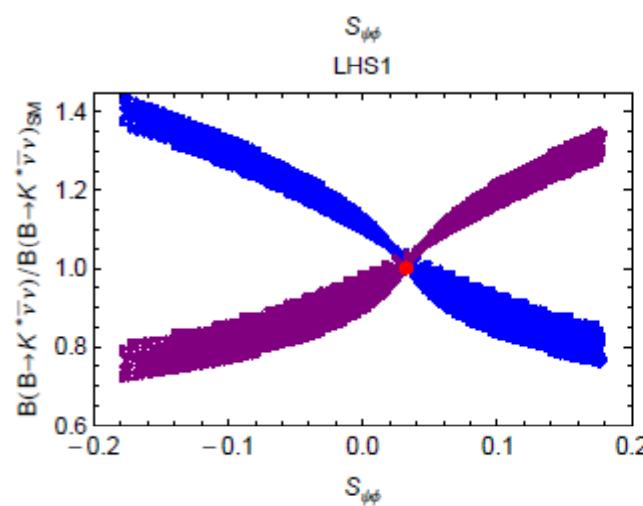
Clear distinction between LHS and RHS

Sensitive observables

$b \rightarrow s \bar{v} v$



Blue: A1
Purple: A3



excluded by $b \rightarrow s \ell^+ \ell^-$

Correlations in these cases identifies the oasis.

In RHS the value of $S_{\psi\phi}$ (if different from SM) discriminates A1 from A3

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

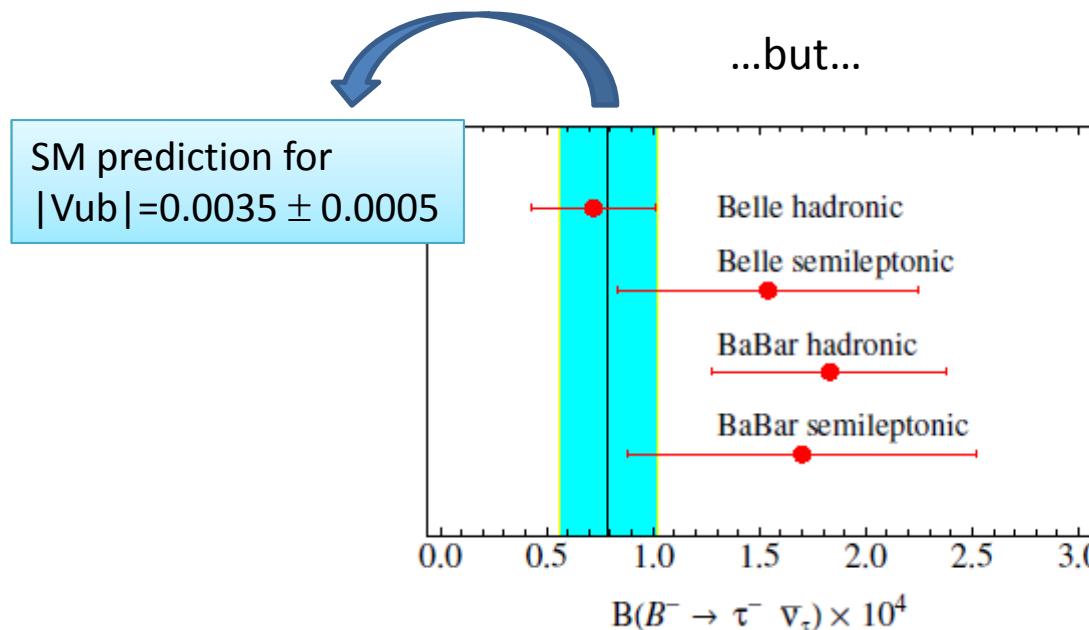
Recent BaBar measurements:

BaBar, PRL 109 (2012) 101802

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

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

- BaBar quotes a 3.4σ deviation from SM predictions
- main question arised : is this related to the enhancement of $B(B \rightarrow \tau^- \bar{\nu}_\tau)$?



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

Most natural explanation: new scalars with couplings to leptons proportional to their mass

- would explain the enhancement of τ modes
- would enhance both semileptonic and purely leptonic modes

The simplest of such models (2HDM) has been excluded by BaBar:
No possibility to simultaneously reproduce $R(D)$ and $R(D^*)$

Alternative explanations using several variants of effective hamiltonian

- S. Fajfer et al, PRD 85 (2012) 094025; PRL 109 (2012) 161801
- A. Crivellin et al., PRD 86 (2012) 054014
- A. Datta et al., PRD 86 (2012) 034027
- A. Celis et al., JHEP 1301 (2013) 054
- D. Choudhury et al, PRD 86 (2012) 114037

A different strategy:

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

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



SM

NP

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

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

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

$\propto |\epsilon_T|^2$

$\propto \text{Re}(\epsilon_T)$

A similar strategy in
M. Tanaka & R. Watanabe 1212.1878

$$B \rightarrow D \tau \bar{\nu}_\tau$$

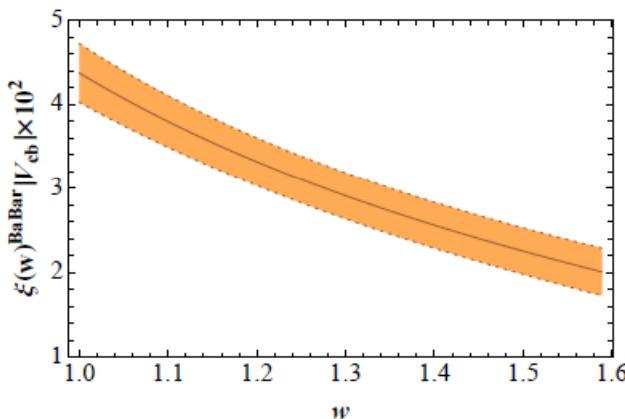
Several form factors required:

$$\begin{aligned} < D(p') | \bar{c} \gamma_\mu b | B(p) > &= F_1(q^2)(p + p')_\mu + \frac{m_B^2 - m_D^2}{q^2} [F_0(q^2) - F_1(q^2)] q_\mu , \\ < D(p') | \bar{c} \sigma_{\mu\nu} (1 - \gamma_5) b | B(p) > &= \frac{F_T(q^2)}{m_B + m_D} \epsilon_{\mu\nu\alpha\beta} p'^\alpha p^\beta + i \frac{G_T(q^2)}{m_B + m_D} (p_\mu p'_\nu - p_\nu p'_\mu) \end{aligned}$$



In the HQ limit all related to the Isgur-Wise function ξ

Model independence + theoretical improvement
 \Rightarrow Including corrections to the HQ limit in the theory expression
+ using the BaBar determination of ξ from $B \rightarrow D \mu \bar{\nu}_\mu$



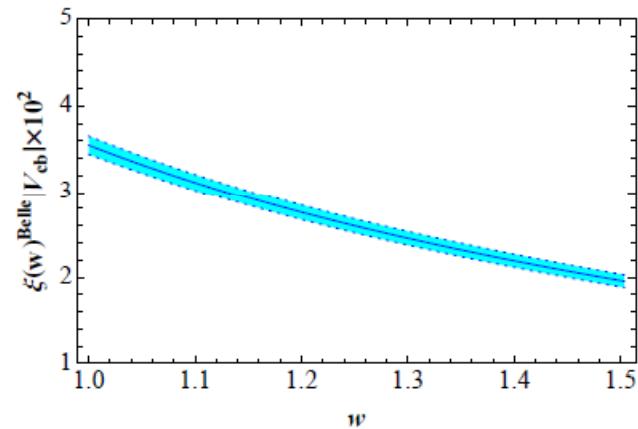
$\mathcal{R}^0(D)|_{SM} = \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^+ \ell^- \bar{\nu}_\ell)}|_{SM} = 0.324 \pm 0.022$



deviates 1.5σ from datum

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

Same procedure using the Belle determination of ξ from $B \rightarrow D^* \mu \bar{\nu}_\mu$



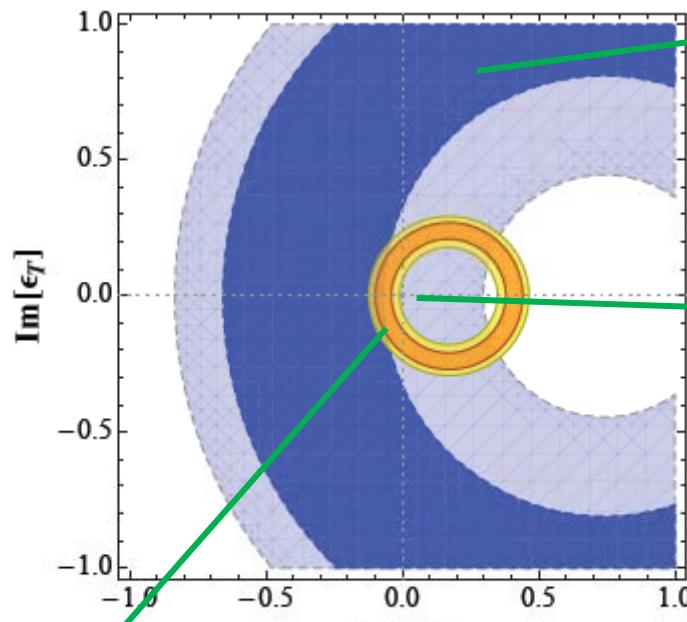
$$\mathcal{R}^0(D^*) \Big|_{SM} = \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell)} \Big|_{SM} = 0.250 \pm 0.003$$



deviates 2.3σ from datum

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

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:

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

$$\begin{aligned} Re[\epsilon_{T0}] &= 0.17, \quad Im[\epsilon_{T0}] = 0 \\ |a_T| &\in [0.24, 0.27] \\ \theta &\in [2.6, 3.7] \text{ rad} \end{aligned}$$

Small cicrle: $R(D^*)$ constraint

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

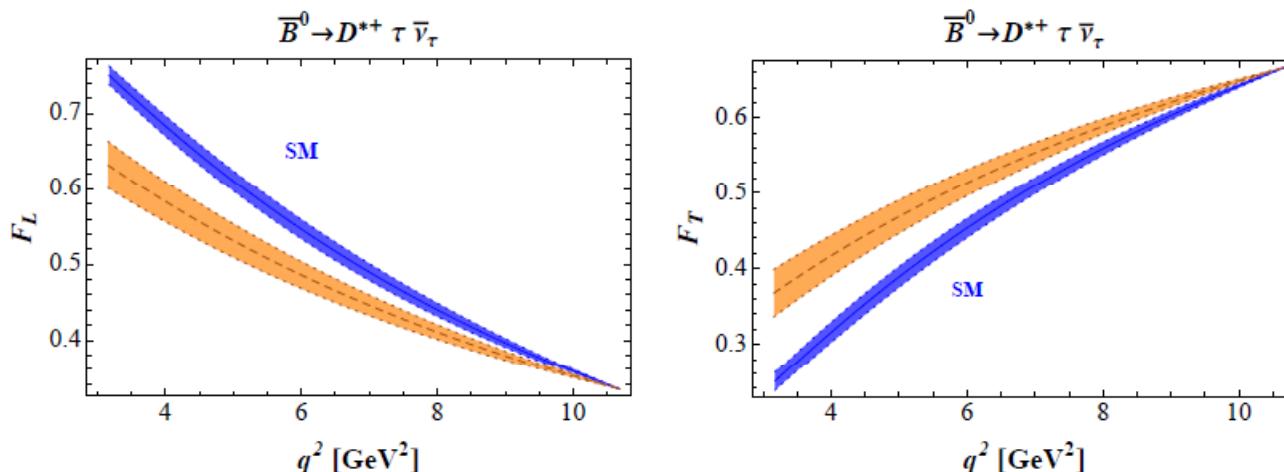
$$B \rightarrow D^* \tau \bar{\nu}_\tau$$

D^* polarization fractions

L=longitudinal

T=transverse

$$F_{L,T}(q^2) = \frac{d\Gamma_{L,T}(B \rightarrow D^* \tau \bar{\nu}_\tau)}{dq^2} \times \left(\frac{d\Gamma(B \rightarrow D^* \tau \bar{\nu}_\tau)}{dq^2} \right)^{-1}$$



- Uncertainty in the SM prediction is due to $1/m_Q$ corrections and to the parameters of the IW function fitted by Belle
- NP includes uncertainty on ε_T

For small values of q^2

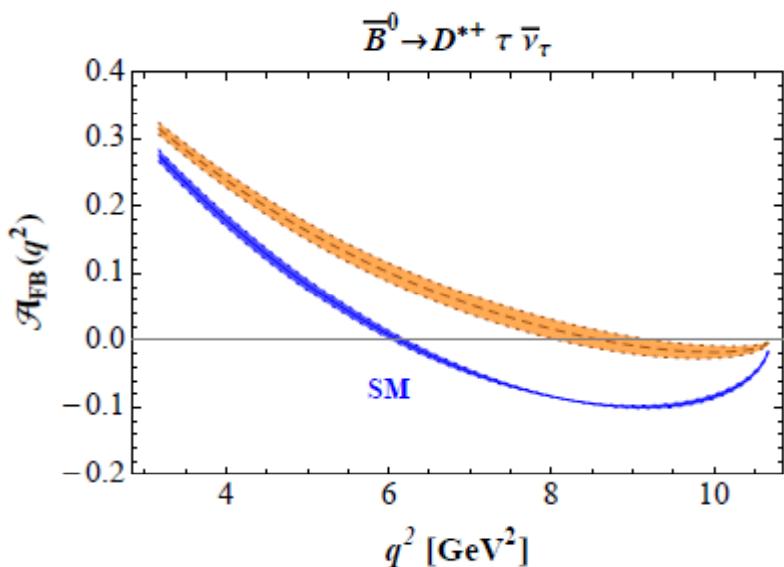
- SM predicts dominant F_L
- NP predicts F_L and F_T of similar size up to $q^2 \approx 6 \text{ GeV}^2$

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

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 $q^2 \approx 6.15 \text{ GeV}^2$
In NP the zero is shifted to $q^2 \in [8.1, 9.3] \text{ GeV}^2$

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

D^{**} =positive parity excited charmed mesons

Two doublets:

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

Form factors for semileptonic B decays to these states can be expressed in terms of universal functions analogous to the IW

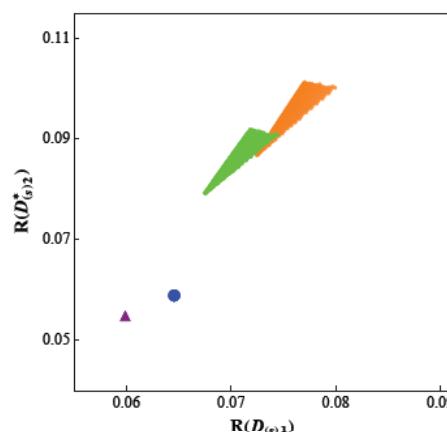
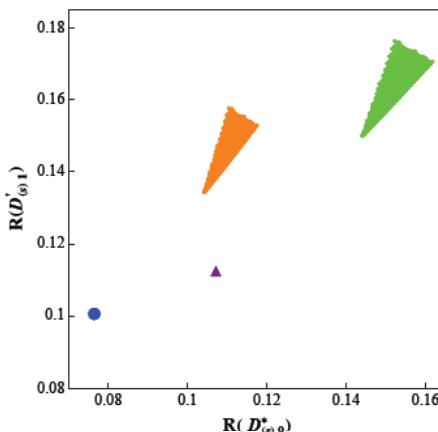
$$B \rightarrow (D_{(s)0}^*, D_{(s)1}') \longrightarrow \tau_{1/2}(w)$$

$$B \rightarrow (D_{(s)1}, D_{(s)2}^*) \longrightarrow \tau_{3/2}(w)$$

We consider again ratios in which the dependence on the model for the τ functions mostly drops out

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

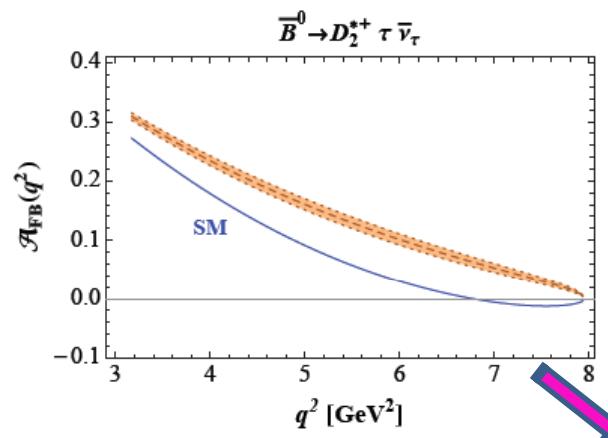
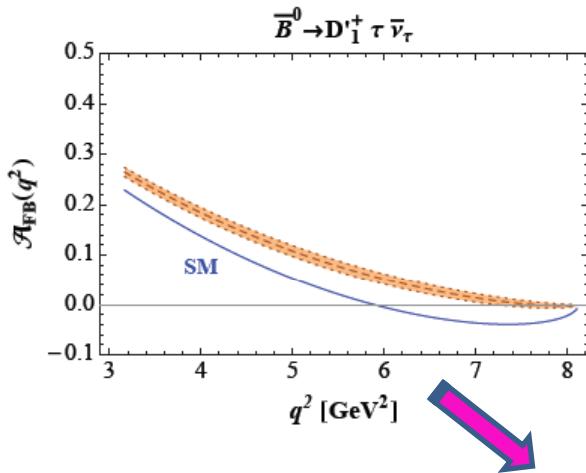
$B \rightarrow D^{**} \tau \bar{\nu}_\tau$



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

summary

Studying correlations between flavour observables may lead us to select the right scenario (if any) for Z' couplings to quarks for $M_{Z'}=1$ TeV
Larger masses (>5 TeV) have negligible impact on the observables considered

The most constrained system is that of B_s

- important role is played by $S_{\psi\phi}$ and $B(B_s \rightarrow \mu^+ \mu^-)$
- highest sensitivity to RHC is that of $b \rightarrow s \ell^+ \ell^-$ and $b \rightarrow s \bar{\nu} \nu$

Anomalous enhancement of $R(D^{(*)})$ could be explained introducing a new tensor operator in the effective hamiltonian.

Differential distributions help to discriminate this scenario from SM

Large effects foreseen in $B \rightarrow D^{**} \tau \bar{\nu}_\tau$