テラスケール研究会

2 April 2018

Does complete set of data still prefer the B anomalies?

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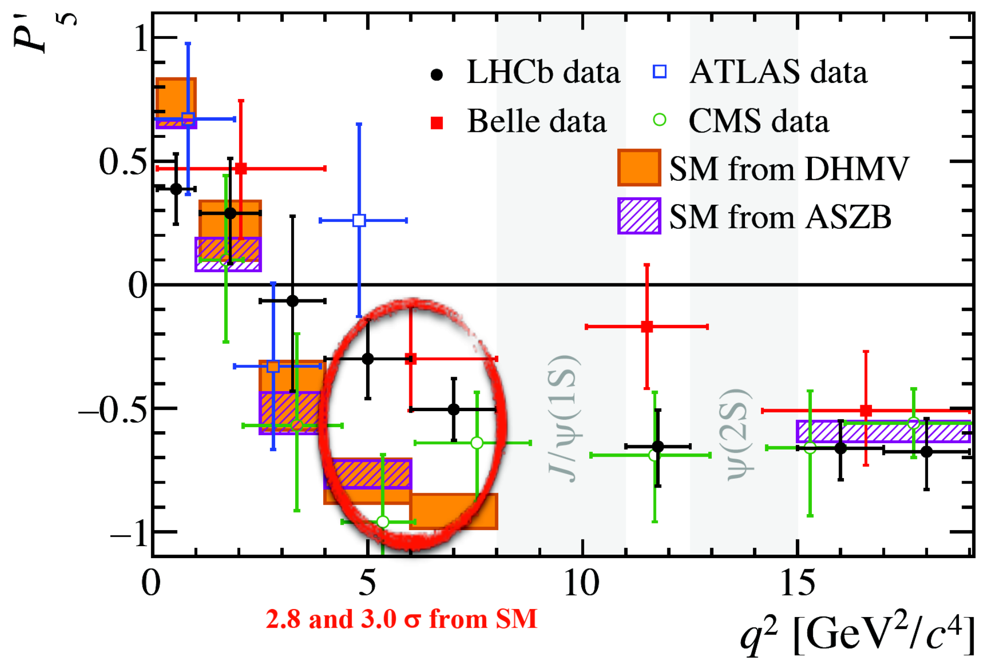
Based on arXiv:1609.09078 [JHEP01(2017)015], arXiv:1804.xxxxx

With David London and Jacky Kumar

B anomaly of $b \to s\mu^+\mu^-$

Measurements

[1] Angular distribution of $\Gamma(B \to [K^* \to K\pi]\mu^+\mu^-)$



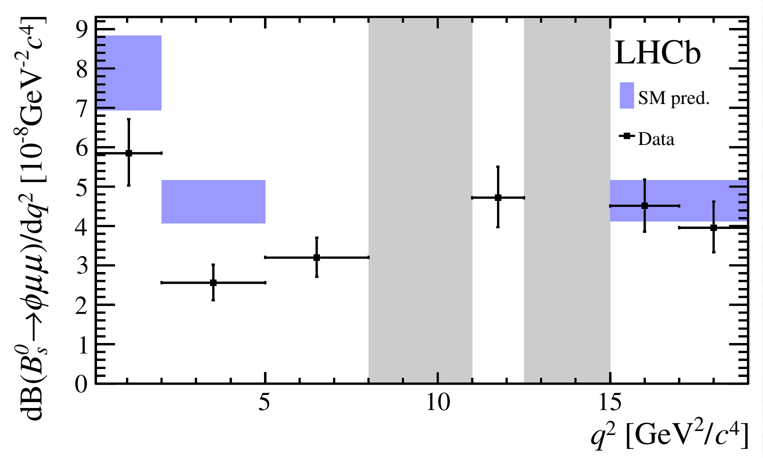
2.8 and 3.0 σ from SM

- **"Optimized observable"**
- **Long-standing anomaly since 2013**

LHCb : PRL 111, 191801 (2013)
LHCb : LHCb-CONF-2015-002
LHCb : JHEP 1602, 104 (2016)

$\sim 3\,\sigma$

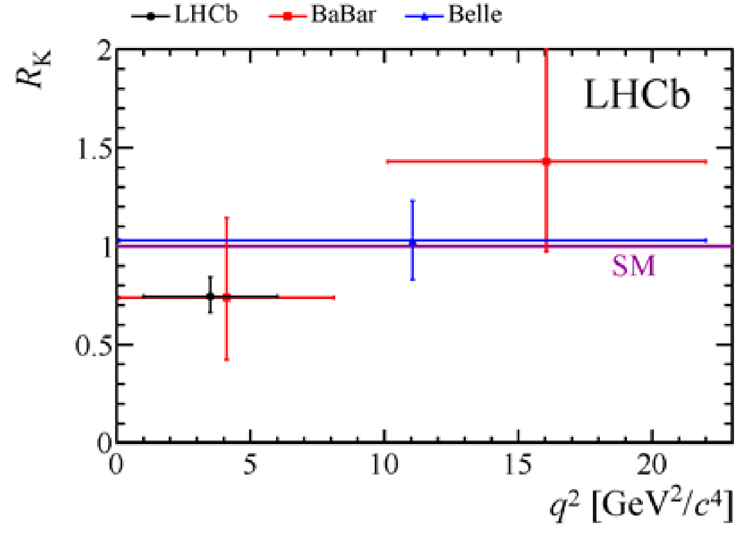
[2] Branching ratio of $\Gamma(B_s \to \phi\mu^+\mu^-)$



LHCb : JHEP 1509, 179 (2015)

$\sim 3.2\,\sigma$

[3] $R_K = \Gamma(B \to K\mu^+\mu^-) \big/ \Gamma(B \to K e^+ e^-)$

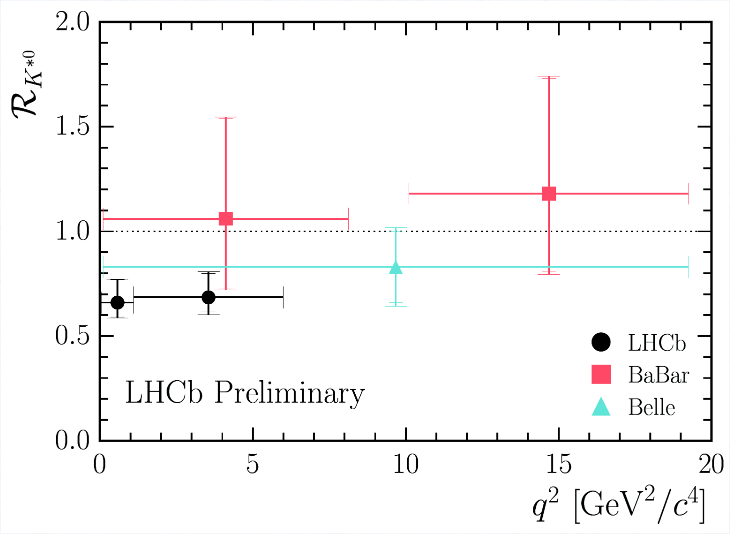


- **Lepton Flavour Universality test**
- **SM prediction is very accurate ~ 1**
- **LHCb measurement in [1 - 6] GeV^2 bin**

$\sim$ 2.6 σ

LHCb : PRL 113, 151601 (2014)
BaBar : PRD 86, 032012 (2012)
Belle : PRL 103, 171801 (2009)

[4] $R_{K^*} = \Gamma(B \to K^*\mu^+\mu^-) \big/ \Gamma(B \to K^* e^+ e^-)$



- **Very recent measurement**

LHCb : JHEP 08, 055 (2017)
BaBar : PRD 86, 032012 (2012)
Belle : PRL 103, 171801 (2009)

$\sim$ 2.2 - 2.5 σ

B anomaly of $b \to s\mu^+\mu^-$

NP solutions

Global fit to all available data for

$$H_{\text{eff}}^{\text{NP}} = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^{*} \sum_i C_i^{\text{NP}} \mathcal{O}_i$$ **(NP contributions)**

suggests three solutions within a single NP source

$$(\text{a}) : \mathcal{O} = [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu \mu] \quad \Longrightarrow C_9^{\text{NP}} < 0$$

$$(\text{b}) : \mathcal{O} = [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu P_L \mu] \quad \Longrightarrow C_9^{\text{NP}} = -C_{10}^{\text{NP}} < 0$$

$$(\text{c}) : \mathcal{O} = [\bar{s}\gamma_\mu \gamma^5 b][\bar{\mu}\gamma^\mu \mu] \quad \cdots$$

B. Capdevila et al.	**[1704.05340]**
D. Straub et al.	**[1704.05435]**
G. D'Amico et al.	**[1704.05438]**
G. Hiller et al.	**[1704.05444]**
L. S. Geng et al.	**[1704.05446]**
M. Ciuchini et al.	**[1704.05447]**
A. Celis et al.	**[1704.05672]**

General consensus:

4-6σ disagreement with SM, even taking theoretical hadronic uncertainties into account

Three solutions

Ashutosh et al., arXiv: 1704.07397

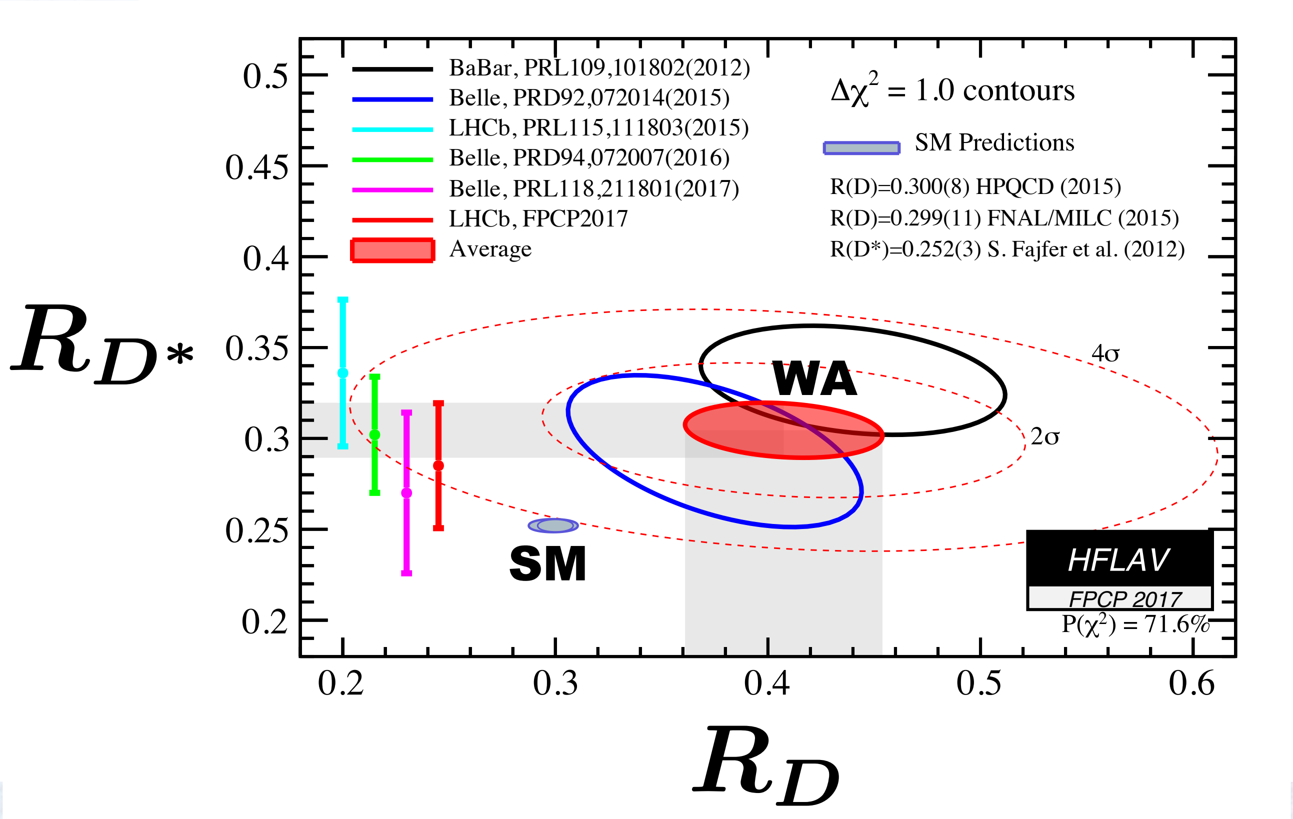
Scenario	Fit result	"Pull"
(a) $C_9^{\rm NP}$	-1.25 ± 0.19	5.9
(b) $C_9^{\rm NP} = -C_{10}^{\rm NP}$	-0.68 ± 0.12	5.9
(c) $C_9^{\rm NP} = -C_9'^{\rm NP}$	-1.11 ± 0.17	5.6

Implication : $\text{Pull} = \sqrt{\chi^2_{\rm SM} - \chi^2_{\rm NP:min}}$

NP can improve fit at $\sim 6\sigma$

B anomaly of $b \to c\,\tau^- \nu$

Measurements



$\sim 4.1\,\sigma$

BaBar : PRL 109, 101802 (2012), PRD 88, 072012 (2013)
Belle : PRD 92, 072014 (2015), PRD 94, 072007 (2016), arXiv 1608.06391
LHCb : PRL 115, 111803 (2015), arXiv 1708.08856

B anomaly of $b \to c\,\tau^-\nu$

NP solutions

Possible explanation

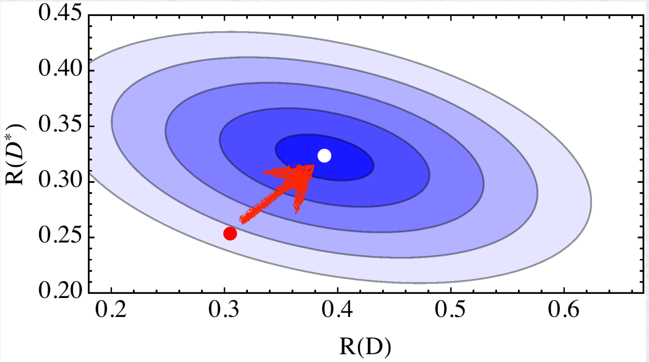
$$\mathcal{L}_{\rm eff}^{\rm NP} \equiv -2\sqrt{2} G_F V_{cb}\, C_{\rm NP}\, \mathcal{O}_{\rm NP}$$

NP contributions that reproduce the central value

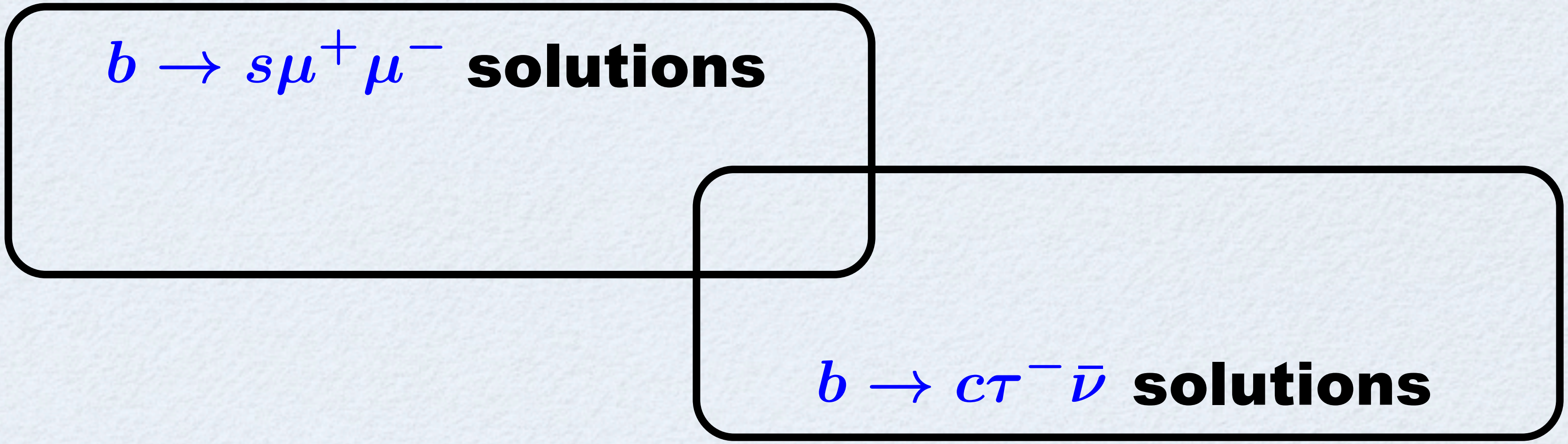
$$\mathcal{O}_{V_1} = (\bar{c}\gamma^{\mu} P_L b)(\bar{\tau}\gamma_{\mu} P_L \nu) \qquad \mathcal{C}_{V_1} \simeq 0.13$$

$$\mathcal{O}_{V_2} = (\bar{c}\gamma^{\mu} P_R b)(\bar{\tau}\gamma_{\mu} P_L \nu) \qquad \mathcal{C}_{V_2} \simeq 0.53i$$

$$\mathcal{O}_{S_2} = (\bar{c} P_L b)(\bar{\tau} P_L \nu) \qquad \mathcal{C}_{S_2} \simeq -1.6$$



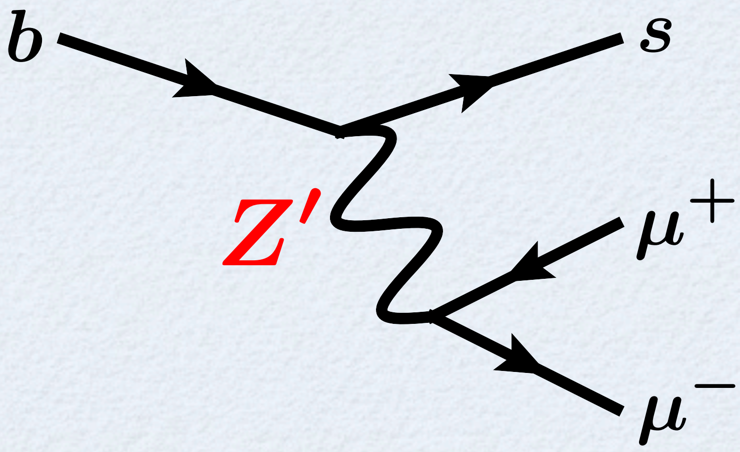
Combined Explanations



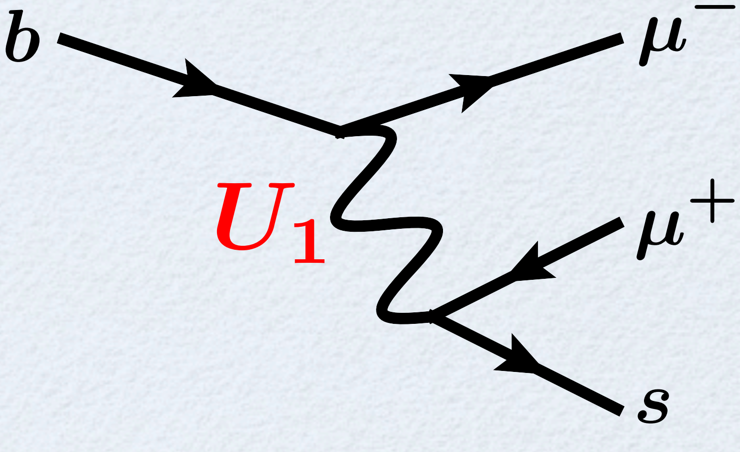
$b \to s\mu^+\mu^-$ **solutions**

$b \to c\tau^-\bar{\nu}$ **solutions**

NP models :



Vector Boson type



LeptoQuark type

General setup

Start with mass basis :

	spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
U_1^μ	1	3	1	4/3

$$\mathcal{L}_{U_1} = h_{U_1}^{ij} (\bar{q}_L^i \gamma_\mu \ell_L^j) U_1^\mu \Big|_{\mathrm{mass}} + \mathrm{h.c.}$$

$$q_L^i = \begin{pmatrix} (V^\dagger u)^i \\ d^i \end{pmatrix}_L \qquad \ell_L^i = \begin{pmatrix} \nu^i \\ e^i \end{pmatrix}_L$$

LQ couplings :

$$h_{U_1} \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & h_{22} & h_{23} \\ 0 & h_{32} & h_{33} \end{pmatrix}$$

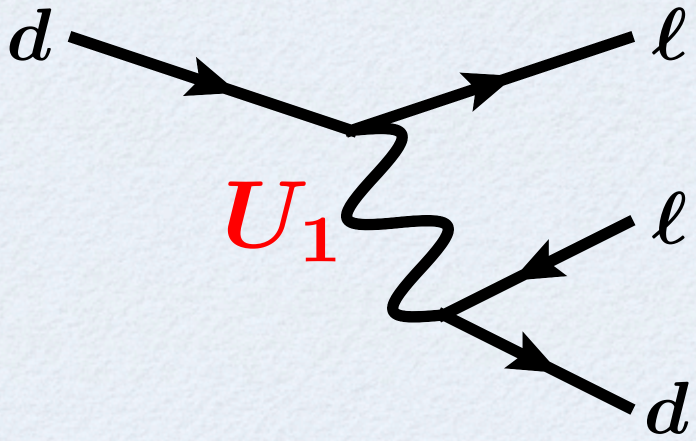
quark

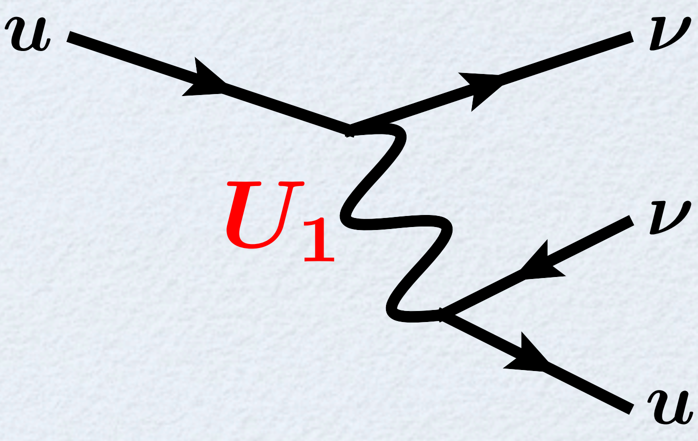
lepton

$h_{U_1}^{ij}$

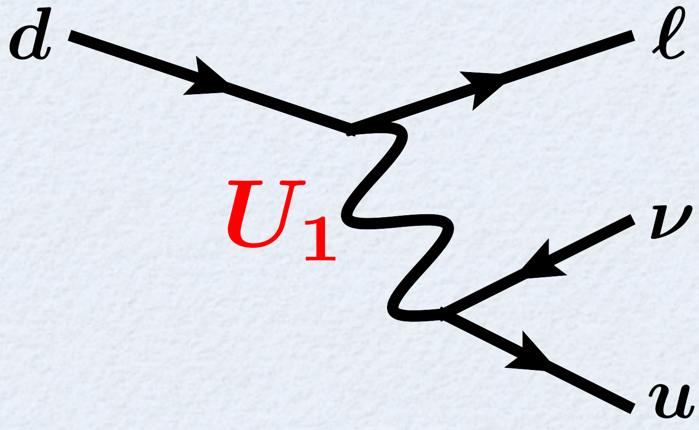
All $2q2\ell$ processes for 2&3 generations are affected

Neutral process :





Charged process :



Related to B anomalies :

$$\Gamma(B \to K\mu^+\mu^-) \propto \left| h_{32}h_{22} + \mathrm{SM} \right|^2$$

$$\Gamma(\bar{B} \to D\tau\bar{\nu}_\tau) \propto \left| h_{33}h_{23}V_{cs} + h_{33}h_{33}V_{cb} + \mathrm{SM} \right|^2$$

$$\Gamma(\bar{B} \to D\tau\bar{\nu}_\mu) \propto \left| h_{33}h_{22}V_{cs} + h_{33}h_{32}V_{cb} \right|^2$$

$$\Gamma(\bar{B} \to D\mu\bar{\nu}_\mu) \propto \left| h_{32}h_{22}V_{cs} + h_{32}h_{32}V_{cb} + \mathrm{SM} \right|^2$$

$$\Gamma(\bar{B} \to D\mu\bar{\nu}_\tau) \propto \left| h_{32}h_{23}V_{cs} + h_{32}h_{33}V_{cb} \right|^2$$

Addition :

$$R_{\mu/e}^{B\to D^*} \equiv \frac{\Gamma(B \to D^*\mu\bar{\nu})}{\Gamma(B \to D^*e\bar{\nu})} = 1.00 \pm 0.05$$

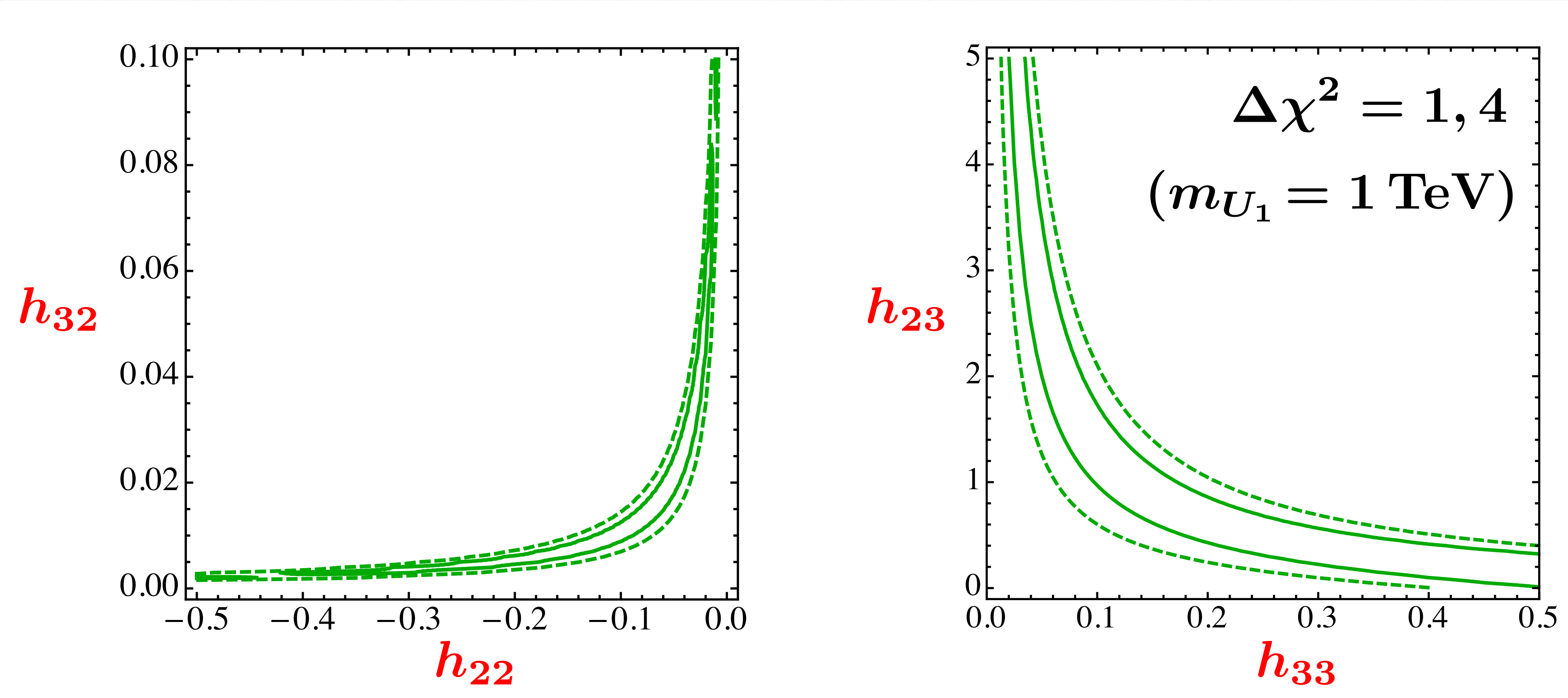
PDG

Trivial thing :

$$\Gamma(B \to K\mu^+\mu^-) \propto \left| h_{32}h_{22} + \mathrm{SM} \right|^2$$

$$\Gamma(\bar{B} \to D\tau\bar{\nu}_\tau) \propto \left| h_{33}h_{23}V_{cs} + h_{33}h_{33}V_{cb} + \mathrm{SM} \right|^2$$

two independent products of the LQ couplings



Single couplings :

$$\Gamma(\Upsilon \to \tau^+\tau^-) = \left| F^{\Upsilon}_{U_1}(|h_{33}|^2/m^2_{U_1}) + F^{\Upsilon}_{\rm SM}(\alpha/m^2_{\Upsilon}) \right|^2$$

$$\Gamma(\Upsilon \to \mu^+\mu^-) = \left| F^{\Upsilon}_{U_1}(|h_{32}|^2/m^2_{U_1}) + F^{\Upsilon}_{\rm SM}(\alpha/m^2_{\Upsilon}) \right|^2$$

$$\Gamma(\phi \to \mu^+\mu^-) = \left| F^{\phi}_{U_1}(|h_{22}|^2/m^2_{U_1}) + F^{\phi}_{\rm SM}(\alpha/m^2_{\Upsilon}) \right|^2$$

- h_{23} **cannot be singled out**
- **Large EM effect, hence loose constraints**

$$h_{33}, h_{32}, h_{22} \lesssim 40 \qquad (m_{U_1} = 1\,\mathrm{TeV})$$

not useful to make sure the B anomalies...

LFV :

6 independent products

$$\underline{h_{32}h_{22},\ h_{33}h_{23},}\ \ \underline{h_{33}h_{22},\ h_{32}h_{23},\ h_{33}h_{32},\ h_{23}h_{22}}$$

B anomalies **Lepton Flavor Violation**

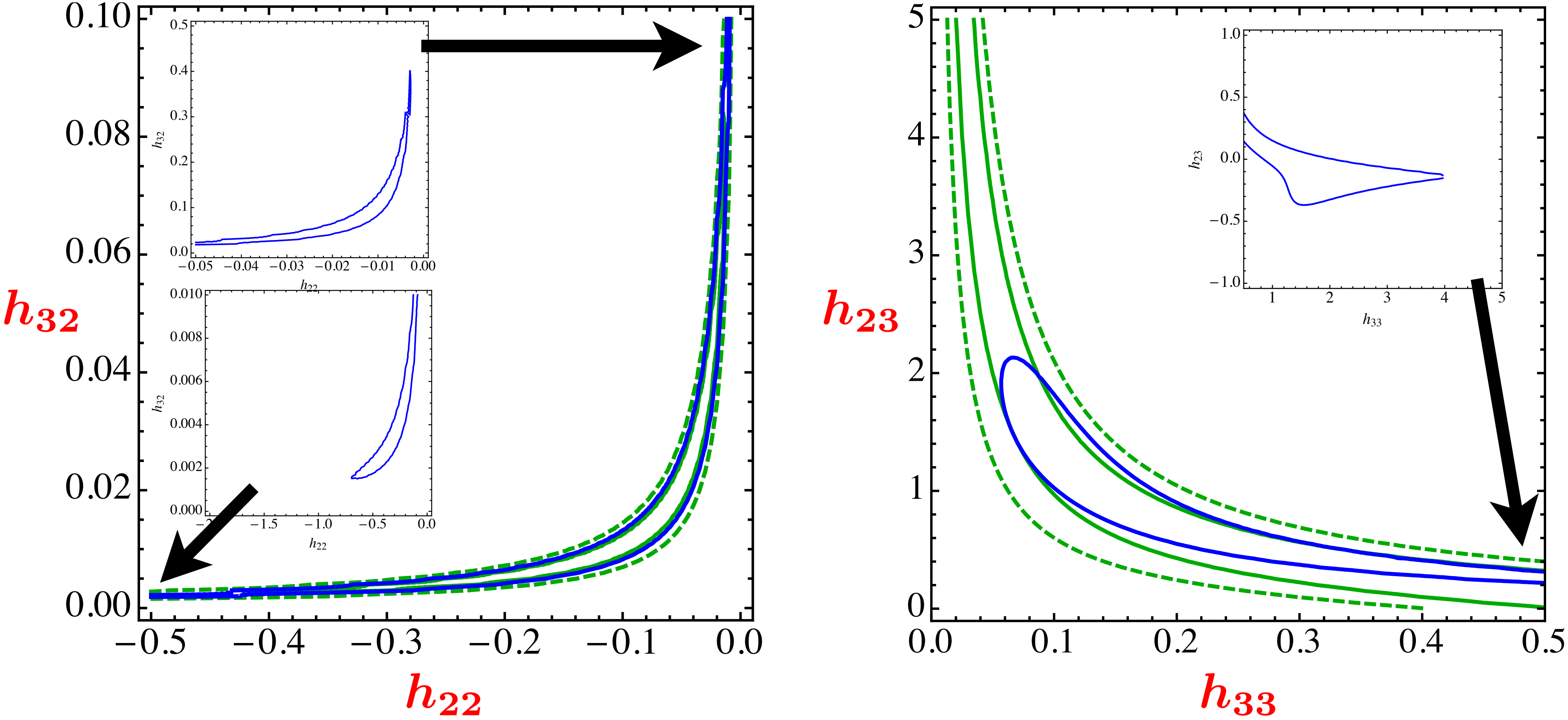
$$\mathcal{B}(\Upsilon \to \tau^{\pm}\mu^{\mp}) \propto \left|h_{33}h_{32}\right|^2 \qquad \text{limit : } \lesssim 6 \times 10^{-6}$$

$$\mathcal{B}(B \to K\tau^{-}\mu^{+}) \propto \left|h_{33}h_{22}\right|^2 \qquad \text{limit : } < 4.5 \times 10^{-5}$$

$$\mathcal{B}(B \to K\tau^{+}\mu^{-}) \propto \left|h_{32}h_{23}\right|^2 \qquad \text{limit : } < 2.8 \times 10^{-5}$$

$$\mathcal{B}(\tau^{\pm} \to \phi\mu^{\pm}) \propto \left|h_{23}h_{22}\right|^2 \qquad \text{limit : } < 8.4 \times 10^{-8}$$

$$\Delta\chi^2 = 1 \text{ (solid)},\ 4 \text{ (dashed)}$$



Constrained, to some extent

$$h_{33} \lesssim 4\,, \quad h_{23} \lesssim 2\,, \quad -h_{22} \lesssim 0.8\,, \quad h_{32} \lesssim 0.4$$

$$(m_{U_1} = 1\,\text{TeV})$$

Future LFV

Present data :

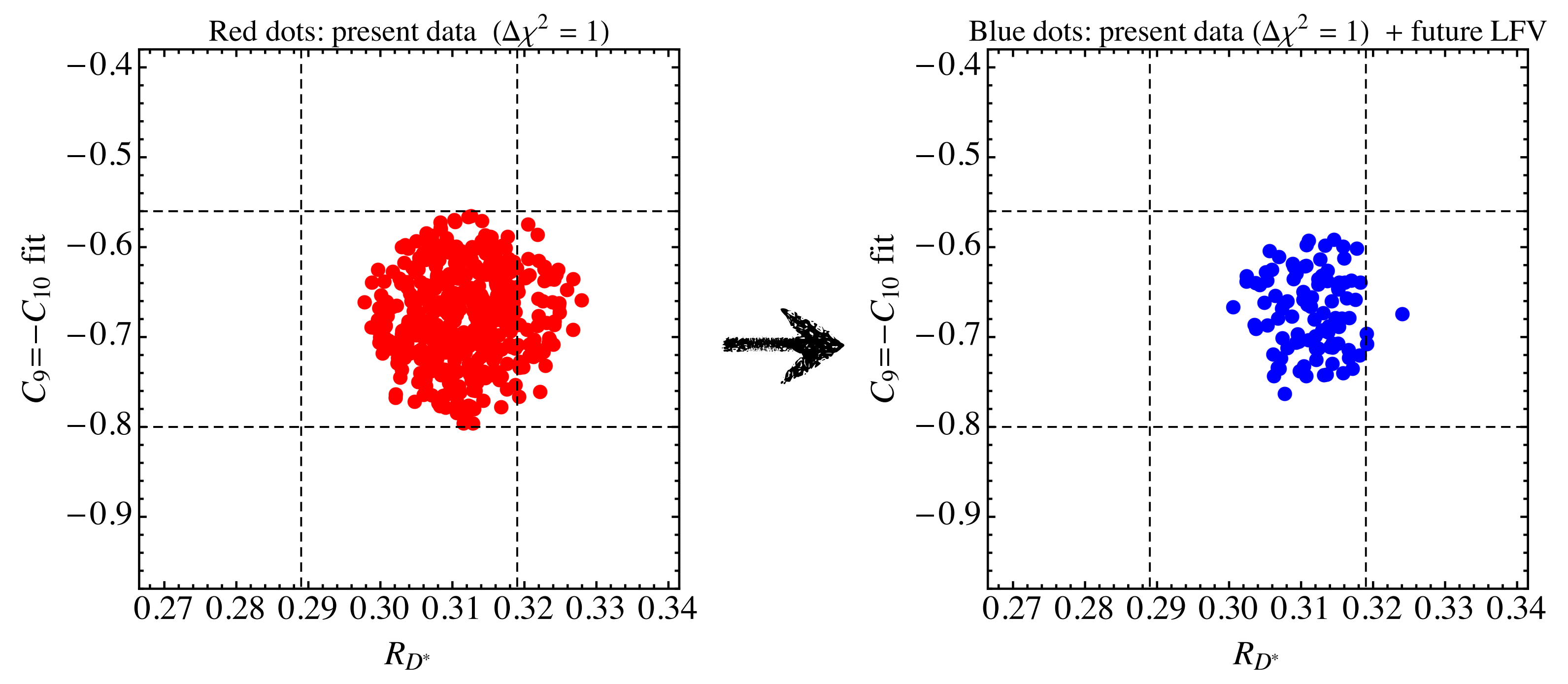
$$h_{33} \lesssim 4\,, \quad h_{23} \lesssim 2\,, \quad -h_{22} \lesssim 0.8\,, \quad h_{32} \lesssim 0.4$$

↓

With future LFV bound :

$$h_{33} \lesssim 2\,, \quad h_{23} \lesssim 0.2\,, \quad -h_{22} \lesssim 0.02\,, \quad h_{32} \lesssim 0.4$$

Consistency with the B anomalies :



Future LFV

Present data :

$$h_{33} \lesssim 4\,, \quad h_{23} \lesssim 2\,, \quad -h_{22} \lesssim 0.8\,, \quad h_{32} \lesssim 0.4$$

With future LFV bound :

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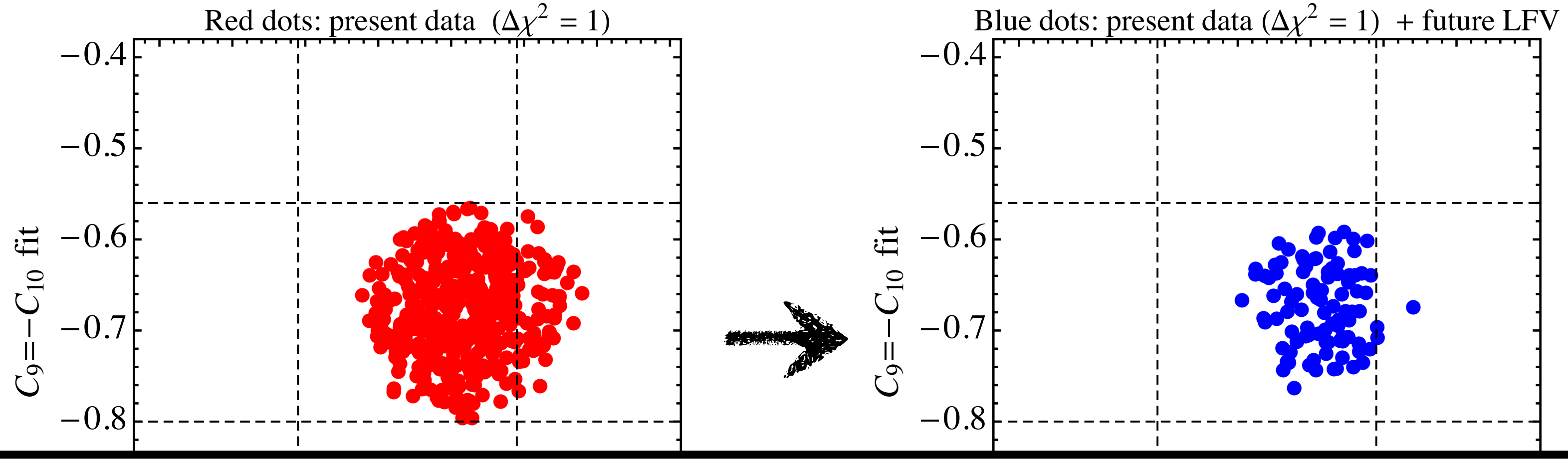
Consistency with the B anomalies :



Even if LFVs are not observed, the B anomaly explanation does work

[Summary so far]

U1 Leptoquark model

$$\mathcal{L}_{U_1} = h_{U_1}^{ij} (\bar{q}_L^i \gamma_\mu \ell_L^j) U_1^\mu \Big|_{\text{mass}} + \text{h.c.} \qquad q_L^i = \begin{pmatrix} (V^\dagger u)^i \\ d^i \end{pmatrix}_L , \quad \ell_L^i = \begin{pmatrix} \nu^i \\ e^i \end{pmatrix}_L$$

$$h_{U_1} \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & h_{22} & h_{23} \\ 0 & h_{32} & h_{33} \end{pmatrix}$$

B anomalies : (mostly) **independent couplings**

$$\Gamma(B \to K \mu^+ \mu^-) \propto \left| h_{32} h_{22} + \text{SM} \right|^2$$

$$\Gamma(\bar{B} \to D \tau \bar{\nu}_\tau) \propto \left| h_{33} h_{23} V_{cs} + h_{33} h_{33} V_{cb} + \text{SM} \right|^2$$

Taking all available present data :

$$h_{33} \lesssim 4 , \quad h_{23} \lesssim 2 , \quad -h_{22} \lesssim 0.8 , \quad h_{32} \lesssim 0.4$$

[Summary so far]

What can we do?

This conclusion could be negative since we have nothing to make predictions to probe B anomalies.

- **Direct LQ searches**
- **Discovery of LFV**
- **…?**

Thank you!

Example : U1 LQ with minimum setup

$$\mathcal{L}_{U_1} = h_{U_1}^{33} (\bar{q}_L^3 \gamma_\mu \ell_L^3) U_1^\mu + \text{h.c.}$$

$$q_L^3 = \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \ell_L^3 = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

	spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
U_1^μ	1	3	1	4/3

Flavour mixing

$$\begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix}_{\text{gauge}} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_L & \sin\theta_L \\ 0 & -\sin\theta_L & \cos\theta_L \end{pmatrix} \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix}_{\text{mass}}$$

$$\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\text{gauge}} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_D & \sin\theta_D \\ 0 & -\sin\theta_D & \cos\theta_D \end{pmatrix} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}_{\text{mass}}$$

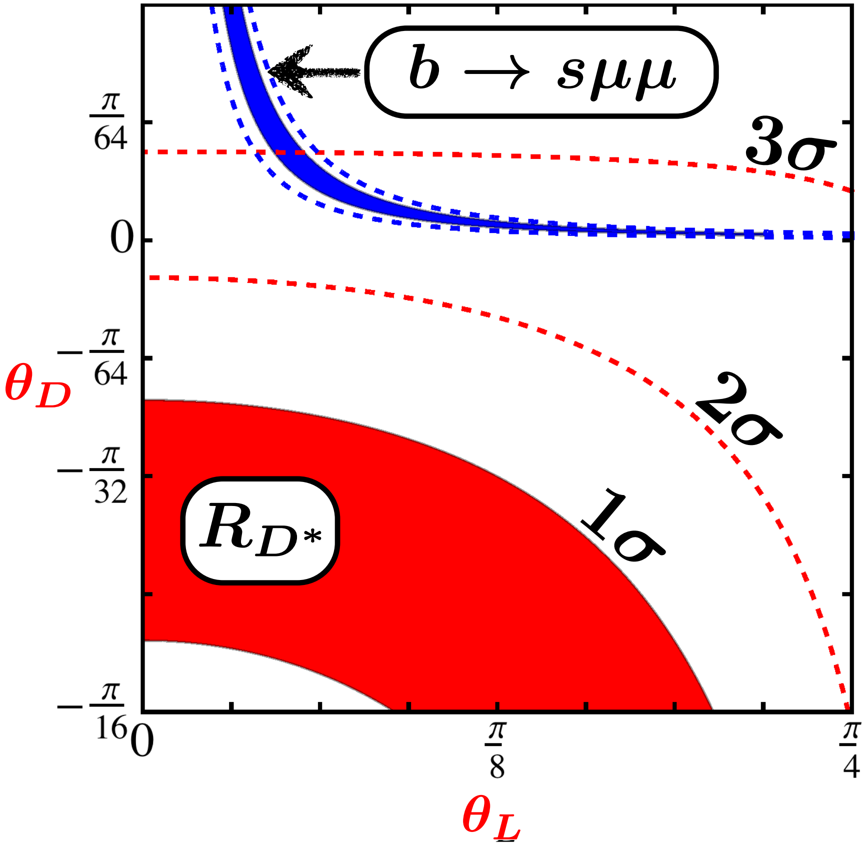
Mixing structure correlates different processes

$$\mathcal{L}^{\rm eff} \supset -\frac{(h_{U_1}^{33})^2}{m_{U_1}^2} \sin\theta_D \cos\theta_D \sin^2\theta_L\, (\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma^\mu\mu_L)$$

$$+2V_{cs}\frac{(h_{U_1}^{33})^2}{m_{U_1}^2} \sin\theta_D \cos\theta_D \cos^2\theta_L\, (\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L)$$

$$+\cdots$$

$h_{U_1}^{33}/M_{U_1} = 1/(1\mathrm{TeV})$



Anomalous B observables :

- **Central values cannot be reproduced**
- **h/M does not help to improve the fit**

→ Minimal setup does not work well

- **Implication**

→ $R_{D^{(*)}}$ should be very close to the SM value

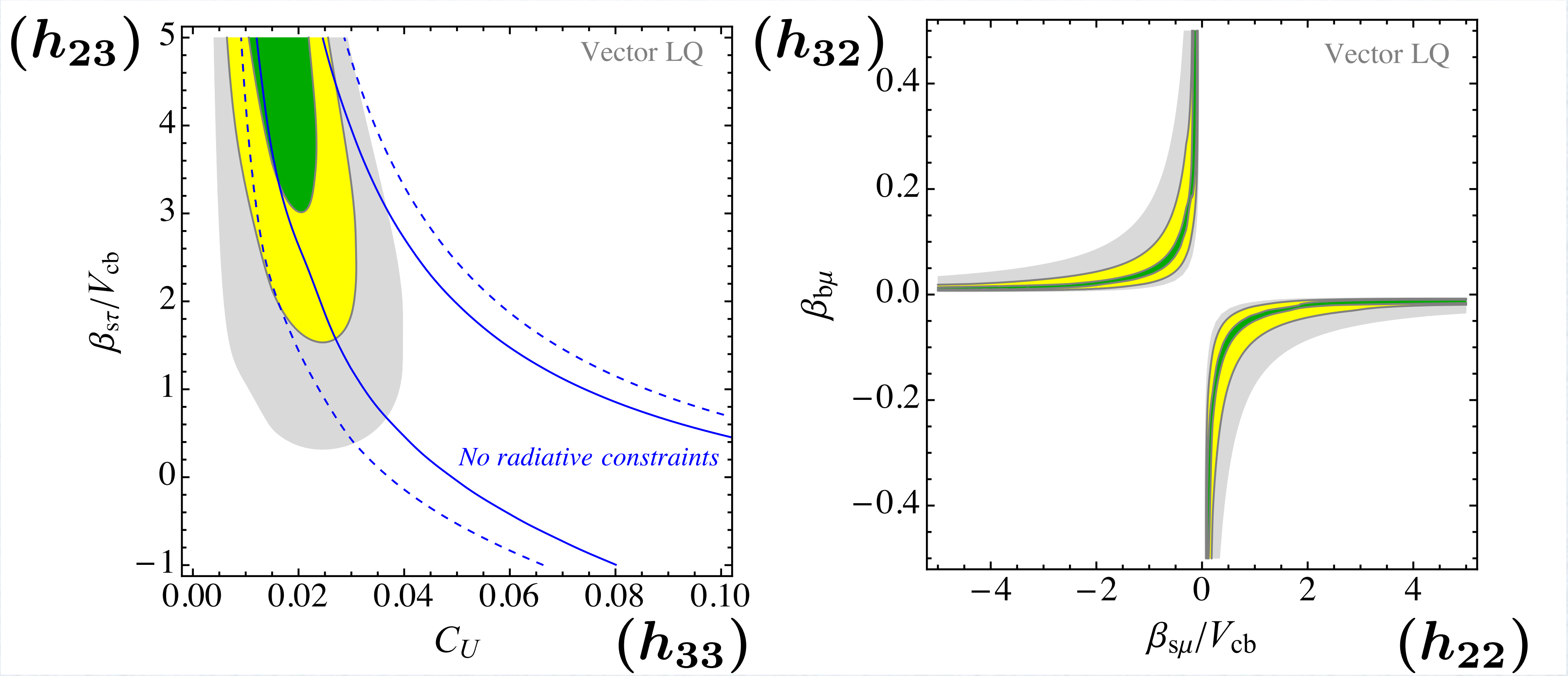
Loop process

- **Highly depends on UV setup**
- **With hard cut-off, some constraints could be evaluated**

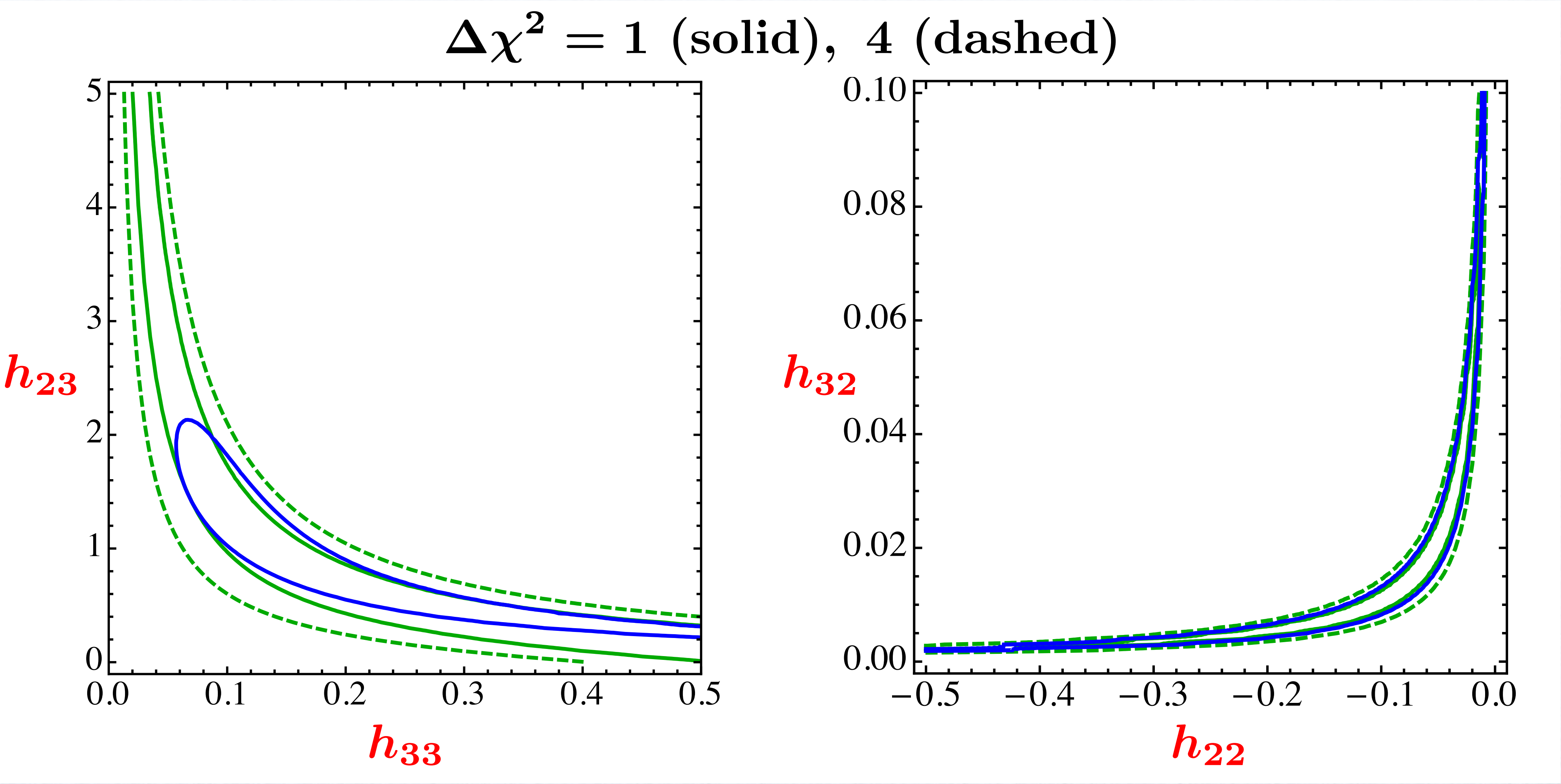
Isidori et al., arXiv:1706.07808

$$\text{significant}\ :\ \tau \to 3\mu, \quad \delta g_Z, \quad \delta g_W$$

$$h_{ij} \equiv g_U \beta_{ij} \quad (g_U = h_{33}), \qquad \Lambda = 2\,\text{TeV} \quad (\text{cut-off})$$



(For comparison)



All relevant observables

Meson	LFUV	LFV	Invisible
$\Upsilon(1S)$	$R_{\tau/\ell} = 1.005 \pm 0.026,\ R_{\mu/e} = 1.04 \pm 0.05$	$B_{\tau\mu} < 6.0 \times 10^{-6}$	$\left[B_{\nu\nu} < 3.0 \times 10^{-4}\right]$
$\Upsilon(2S)$	$R_{\tau/\ell} = 1.04 \pm 0.06,\ R_{\mu/e} = 1.01 \pm 0.12$	$B_{\tau\mu} = (0.2 \pm 1.8) \times 10^{-6}$	[no data]
$\Upsilon(3S)$	$R_{\tau/\ell} = 1.05 \pm 0.09,\ R_{\mu/e} = 1.00 \pm 0.13$	$B_{\tau\mu} = (-0.8 \pm 2.0) \times 10^{-6}$	[no data]
$\psi(1S)$	$\left[R_{\mu/e} = 0.998 \pm 0.008\right]$	$\left[B_{\tau\mu} < 2.0 \times 10^{-6}\right]$	$B_{\nu\nu} = (0.2 \pm 1.9) \times 10^{-3}$
$\psi(2S)$	$\left[R_{\tau/\ell} = 0.39 \pm 0.05,\ R_{\mu/e} = 1.00 \pm 0.12\right]$	[no data]	$B_{\nu\nu} = (5.6 \pm 6.2) \times 10^{-3}$
ϕ	$R_{\mu/e} = 0.971 \pm 0.065$	$B_{\tau\mu} < 8.4 \times 10^{-8}$ (*)	[no data]
$B_c \to J/\psi$	$R_{\tau/\mu} = 0.71 \pm 0.25$	–	–
B_s	$B_{\tau\tau} = (0.94 \pm 2.87) \times 10^{-3}$	no data	–
$B_s \to \phi$	no data	no data	$\left[B_{\nu\nu} < 5.4 \times 10^{-3}\right]$
$B \to D$	$R_{\tau/\ell} = 0.407 \pm 0.046,\ R_{\mu/e} = 0.995 \pm 0.045$	–	–
$B \to D^*$	$R_{\tau/\ell} = 0.304 \pm 0.015,\ R_{\mu/e} = 1.00 \pm 0.05$	–	–
$B \to K$	$B_{\tau\tau} = (1.31 \pm 0.70) \times 10^{-3}$	$B_{\tau^-\mu^+} = (0.8 \pm 1.7) \times 10^{-5},\ B_{\tau^+\mu^-} = (-0.4 \pm 1.2) \times 10^{-5}$	$\left[B_{\nu\nu} < 1.7 \times 10^{-5}\right]$
$B \to K^*$	no data	no data	$\left[B_{\nu\nu} < 4.0 \times 10^{-5}\right]$
D_s	$R_{\tau/\mu} = 11.0 \pm 1.3$	–	–
$D \to K$	$R_{\mu/e} = 0.969 \pm 0.024$	–	–
$b \to s\mu\mu$	$C_9^{bs\mu\mu} = -0.64 \pm 0.16$ with $\chi^2_{\min} = 6.8$		

Leptoquark models

$$\mathcal{L}_{U_1} = h_{U_1} (\bar{q}_L^3 \gamma_\mu \ell_L^3) U_1^\mu + \text{h.c.}$$ **Singlet Vector LQ**

$$\mathcal{L}_{U_3} = h_{U_3} (\bar{q}_L^3 \gamma_\mu \sigma^I \ell_L^3) U_3^{I\,\mu} + \text{h.c.}$$ **Triplet Vector LQ**

$$\mathcal{L}_{S_3} = h_{S_3} (\bar{q}_L^3 \sigma^I i\sigma^2 \ell_L^{c3}) S_3^I + \text{h.c.}$$ **Triplet Scalar LQ**

Direct search

$bb \to \tau^+\tau^-$

Isidori et al., arXiv:1706.07808

h_{33}