Leptoquarks in $R_{D(*)}$ and $R_{K(*)}$

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- Motivation

- Charged current $b \longrightarrow c\, \tau \upsilon_{\tau}$: $R_{D(*)}$ puzzle

- FCNC transition $b \longrightarrow s\, l^{+} l^{-}$: $R_{K(*)}$ puzzle

- Sign of LFU violation?

- Leptoquarks in $R_{D(*)}$, $R_{K(*)}$

B physics anomalies: experimental results ≠ SM predictions!

charged current SM tree level

1) $R_{D^{(*)}} = \dfrac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$ 3.9σ

FCNC - SM loop process

2) P_5' in $B \to K^*\mu^+\mu^-$ (angular distribution functions) 3σ

3) $R_{K^{(*)}} = \dfrac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)}$ in the dilepton invariant mass bin $1\ \mathrm{GeV}^2 \leq q^2 \leq 6\ \mathrm{GeV}^2$ 2.4σ

Standard Model or New Physics?

Can flavor physics resolves puzzles relying on the existing SM tools?

QCD impact: knowledge of form-factors!

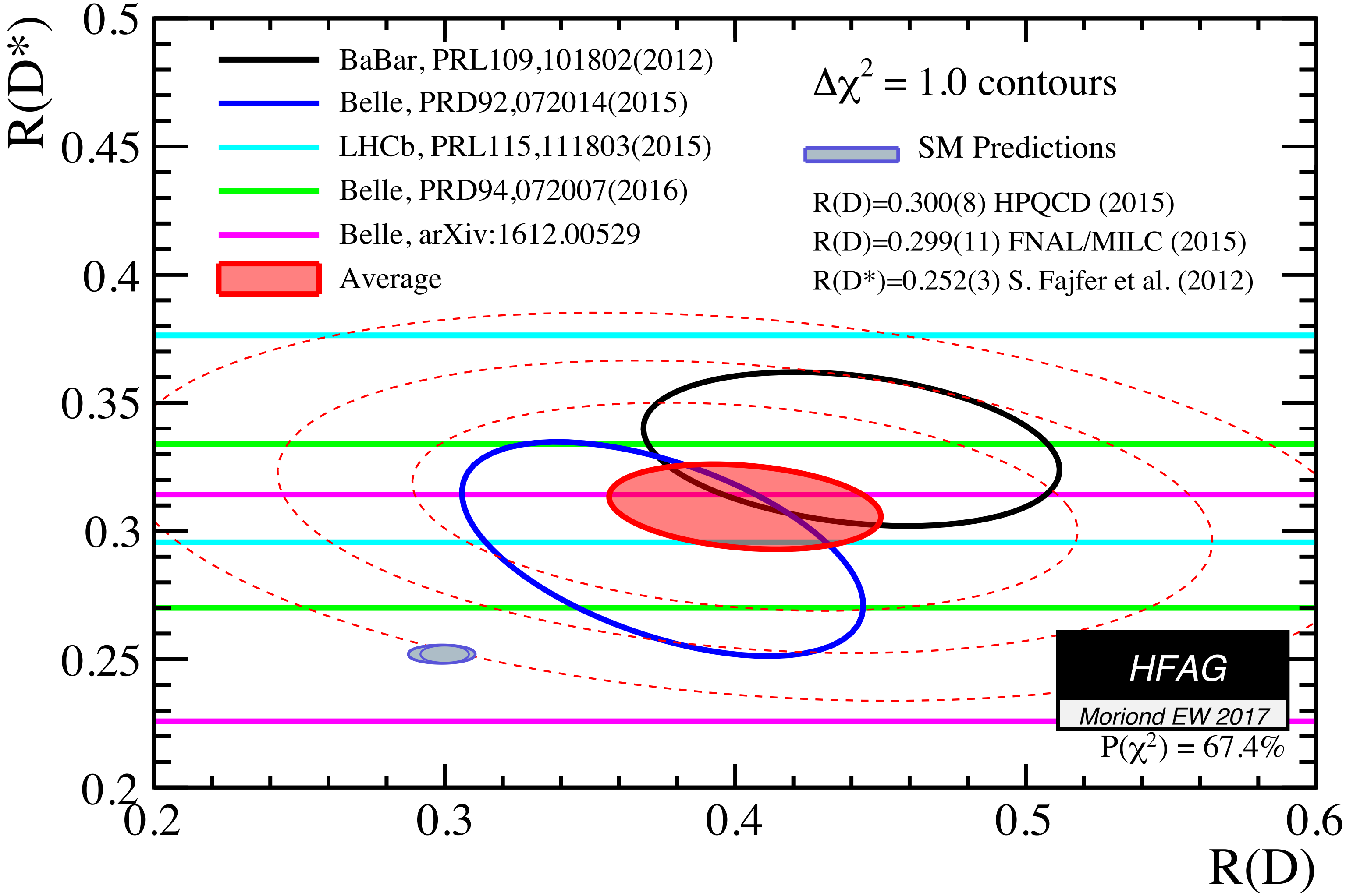
How well do we know all new/old form-factors? Lattice improvements?

Are SM calculations of the existing observables precise enough?

B physics puzzles indicate **lepton flavor universality violation** in semileptonic decays (?)!

π and K physics: tests of LFU conservation holds up to 1 percent level for all three lepton generations.   Experiment and SM expectations – excellent agreement!

Charged current in $b \to c\, \tau \nu_\tau$ " $R_{D(*)}$ puzzle"

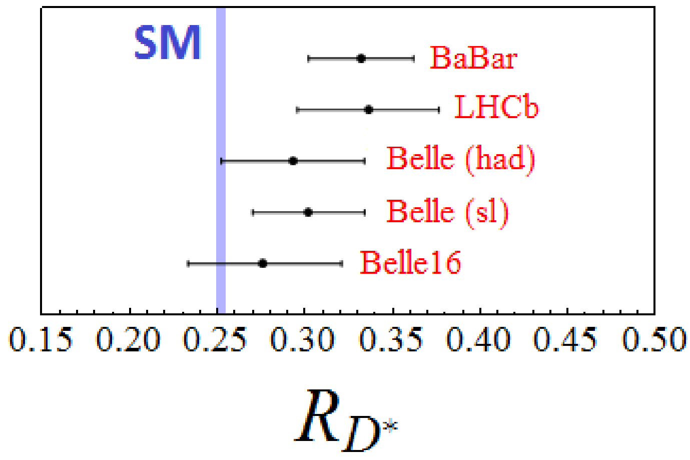


B physics anomalies: experimental results ≠ SM predictions!

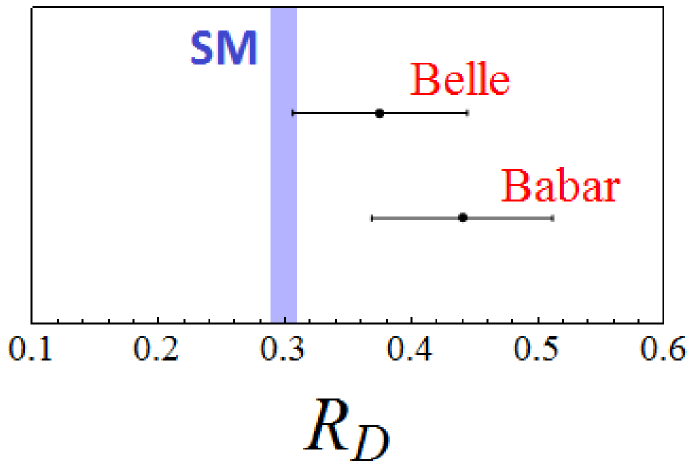
charged current (SM tree level)

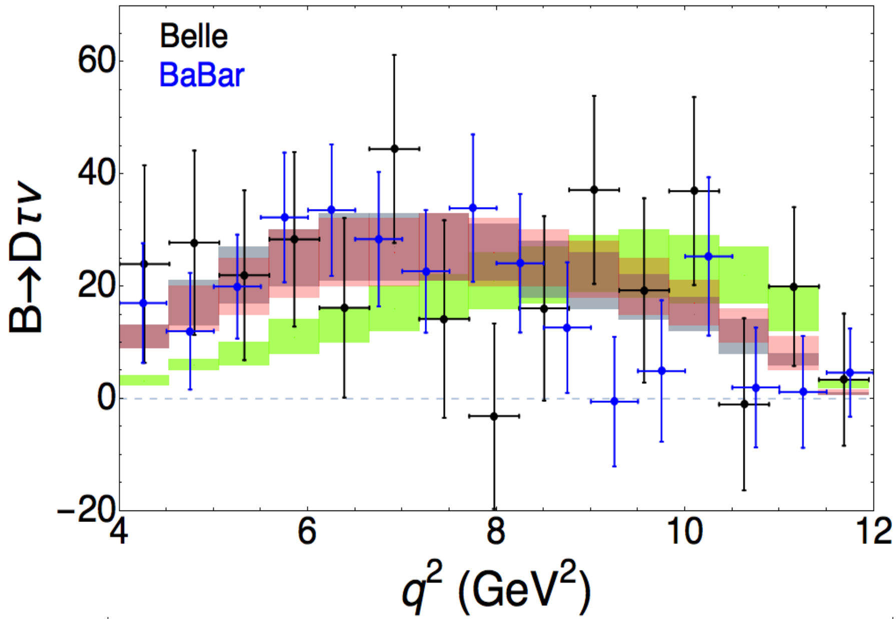
1) $R_{D^{(*)}} = \dfrac{BR(B \to D^{(*)} \tau \nu_\tau)}{BR(B \to D^{(*)} \mu \nu_\mu)}$ 3.9σ

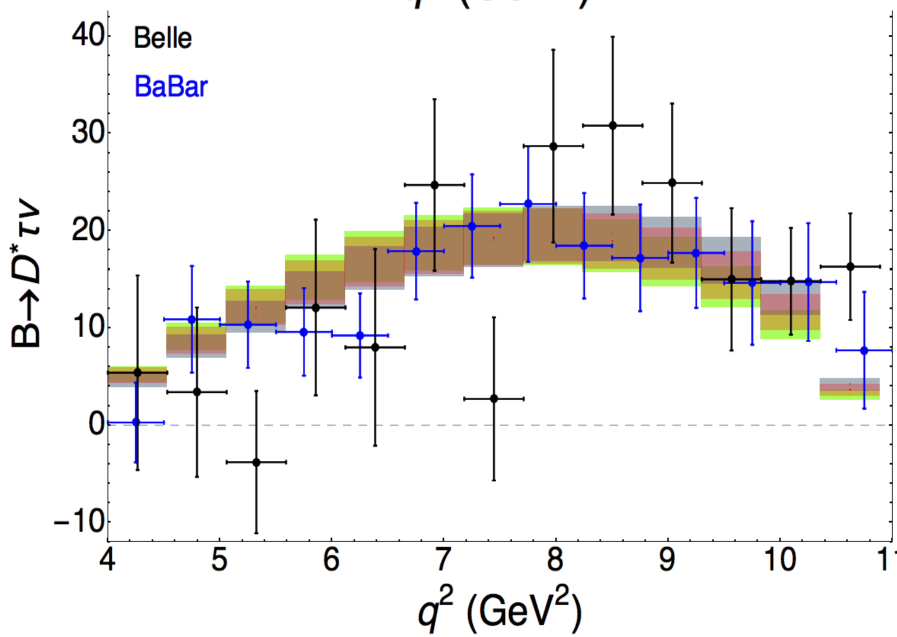
$[3.4\sigma]^{***}$



$[2\sigma]^{**}$







Momentum transfer distributions, A. Cellis et al,1612.07757

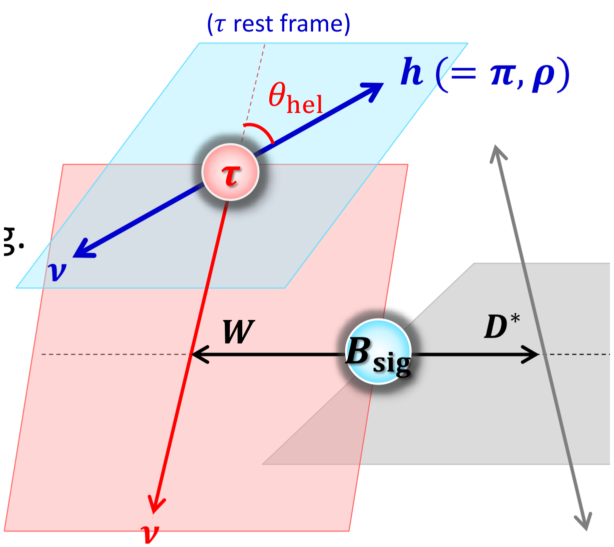
1608.06931

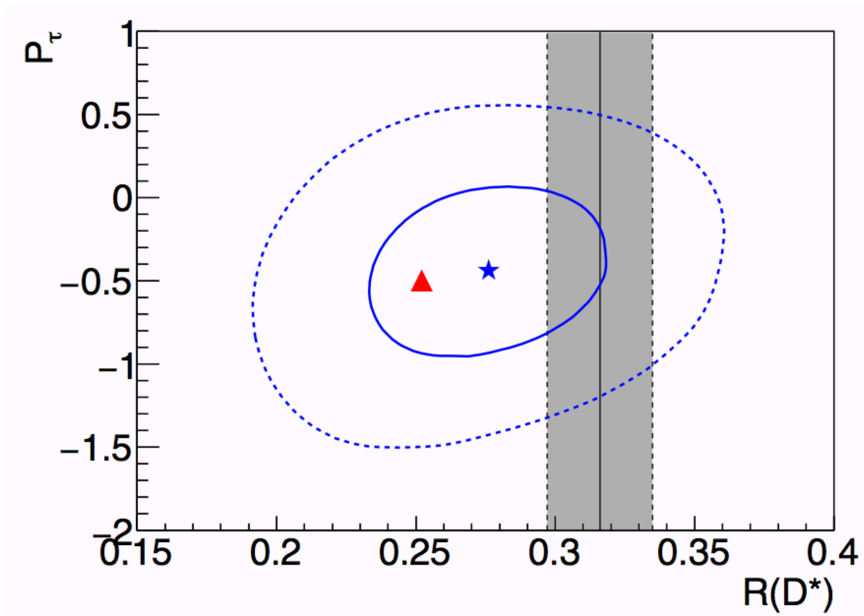
Belle, Sato@ICHEP2016

τ polarization

$$P_\tau = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

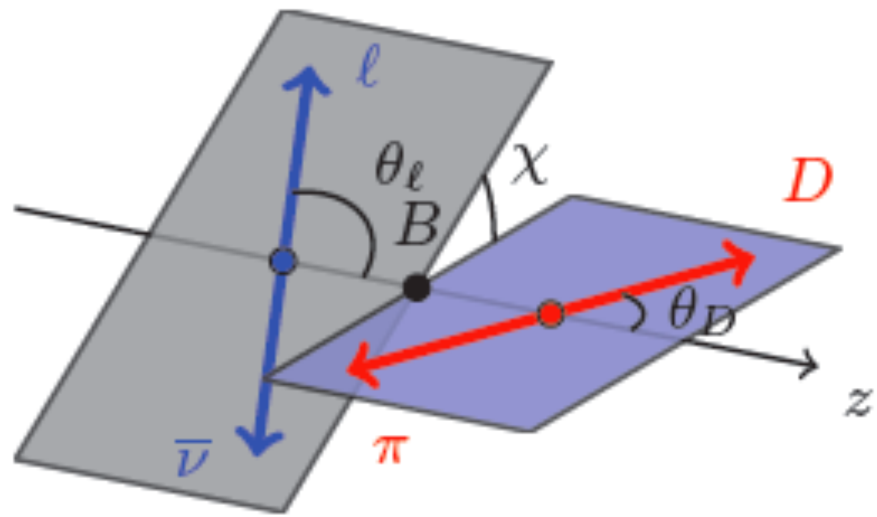
$$\boxed{\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\mathrm{hel}}} = \frac{1}{2}\left(1 + \alpha \cdot \mathcal{P}_\tau \cos\theta_{\mathrm{hel}}\right)}$$





$$P_\tau = -0.44 \pm 0.47(\mathrm{stat.})^{+0.20}_{-0.17}(\mathrm{syst.})$$

$$B \to D^* \tau \nu_\tau$$



There are 11 observables:

1. Differential decay distribution

2. Forward-backward asymmetry

3. Lepton polarization asymmetry

4. Partial decay rate according to the polarization of D*

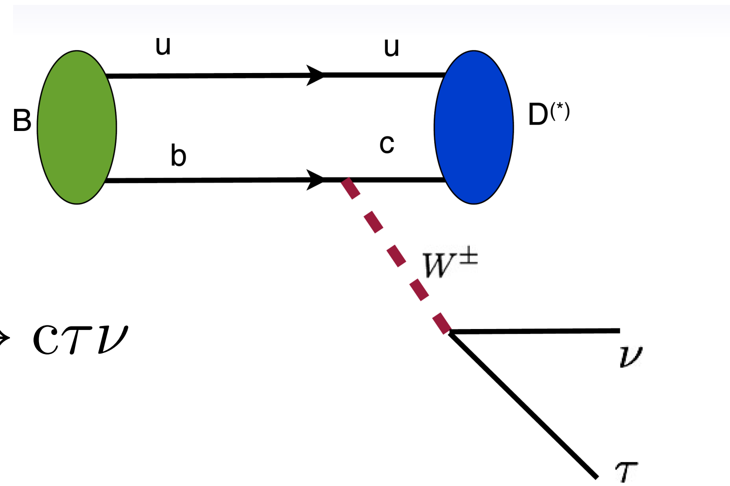
$$R_{L,T} = \frac{d\Gamma_L/dq^2}{d\Gamma_T/dq^2}$$

S.F. , J.F.Kamenik, Nišandžić, 1203.2654
S.F. J.F. Kamenik, I. Nišandžić, J. Zupan, 1206.1872
Körner& Schuller, ZPC 38 (1988) 511,
Kosnik, Becirevic, Tayduganov, 1206.4977
D. Becirevic, S.F. I. Nisandzic, A. Tayduganov, 1602.03030, Fretsis et al, 1506.08896, ….

S. Faller et al., 1105.3679,
Sakai&Tanaka, 1205.4908.
Biancofiore , Collangelo, DeFazio 1302.1042,
R.Alonso et al, 1602.0767,Bardhan et al., 1610.03038

Effective Lagrangian approach for $b \to c\tau\nu_\tau$ decay

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb}\bar{c}\,\gamma_\mu P_L\, b\,,\bar{\nu}\,\gamma^\mu P_L\,\tau + \frac{1}{\Lambda}\Sigma_i c_i O_i$$



$\mathrm{b} \to c\tau\nu$

$$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$$
$$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$$
$$(\bar{c}P_R b)\,(\bar{\tau}P_L \nu)$$
$$(\bar{c}P_L b)\,(\bar{\tau}P_L \nu)$$
$$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$$

If NP scale is above electroweak scale, NP effective operators have to respect $SU(3) \times SU(2)_L \times U(1)_Y$

no ν_R

Freytsis, Ligeti, Ruderman1506.08896

FCNC - SM loop process

2) P_5' in $B \to K^* \mu^+ \mu^-$ (angular distribution functions) 3σ

3)

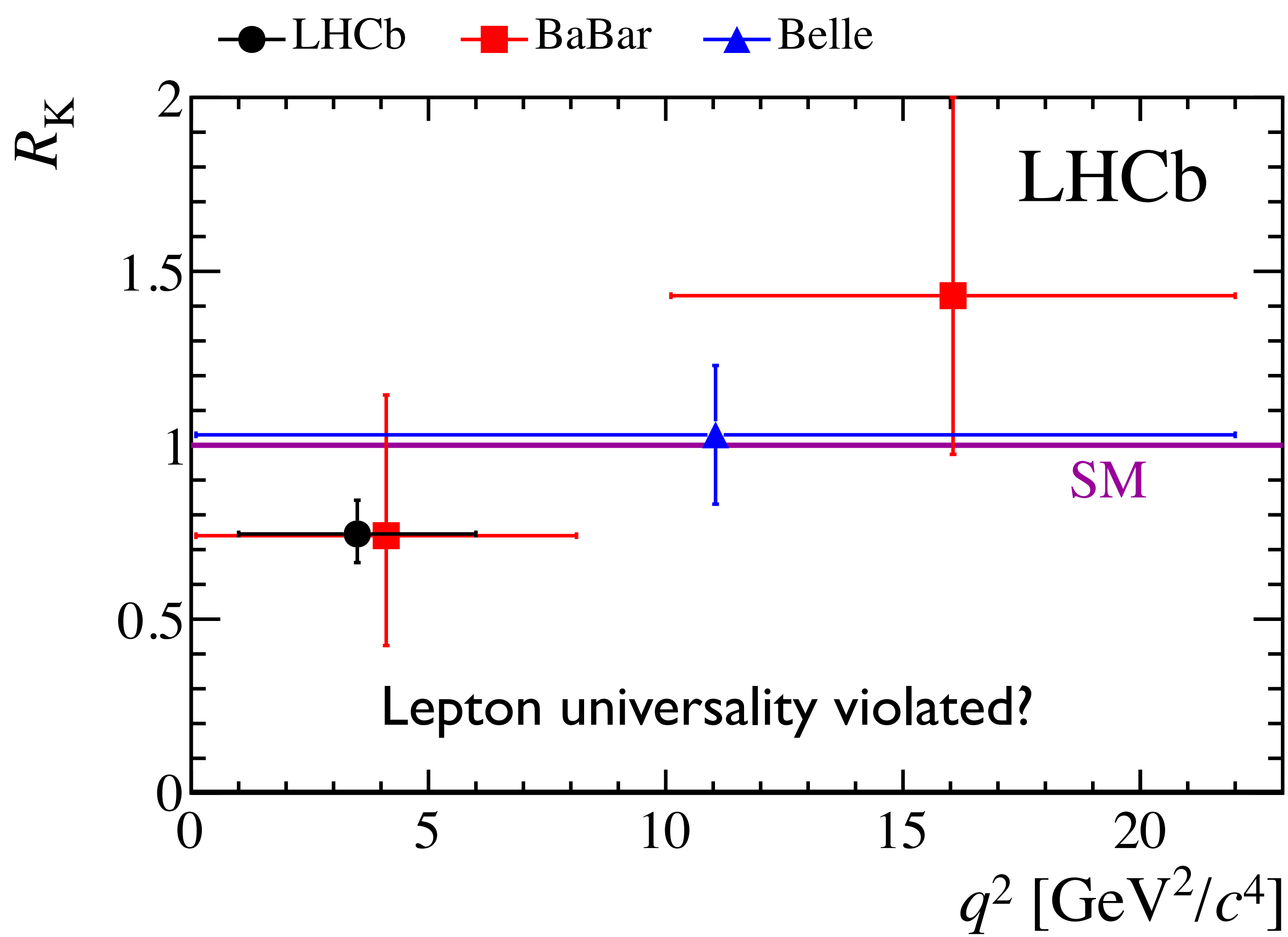
$$R_K = \frac{\mathcal{B}(B \to K\mu\mu)_{q^2\in[1,6]\mathrm{GeV}^2}}{\mathcal{B}(B \to Kee)_{q^2\in[1,6]\mathrm{GeV}^2}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$

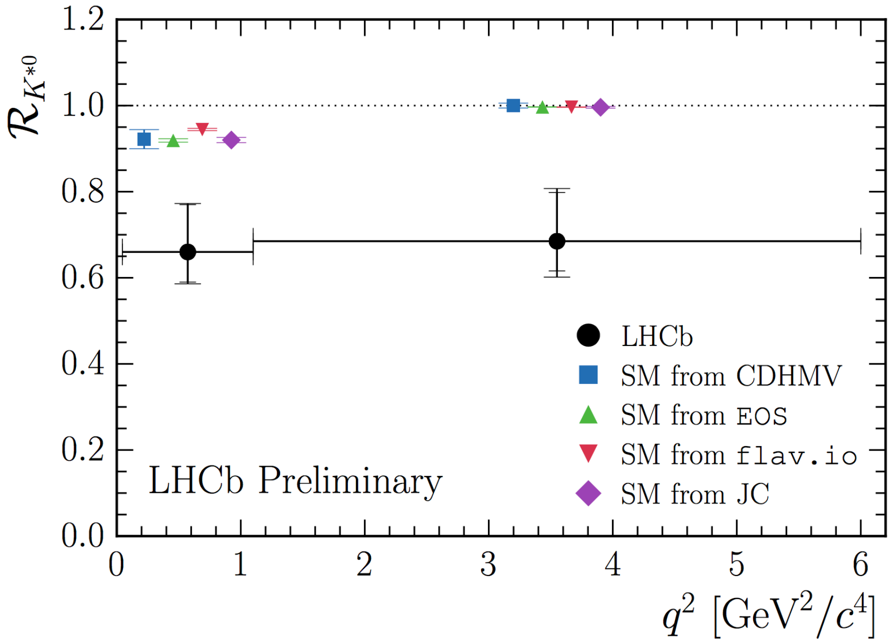
2.4σ

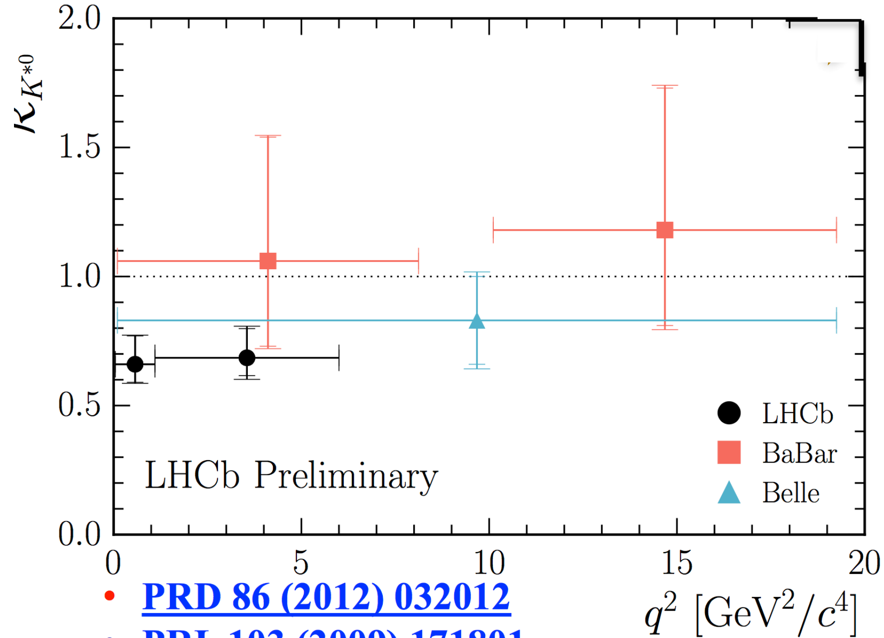
$$R_{K^*}^{\mathrm{low}} = \frac{\mathcal{B}(B \to K\mu\mu)_{q^2\in[0.045,1.1]\mathrm{GeV}^2}}{\mathcal{B}(B \to Kee)_{q^2\in[0.045,1.1]\mathrm{GeV}^2}} = 0.660 \pm^{0.110}_{0.070} \pm 0.024$$

$$R_{K^*}^{\mathrm{central}} = \frac{\mathcal{B}(B \to K\mu\mu)_{q^2\in[1.1,6]\mathrm{GeV}^2}}{\mathcal{B}(B \to Kee)_{q^2\in[1.1,6]\mathrm{GeV}^2}} = 0.685 \pm^{0.113}_{0.069} \pm 0.047\,,$$

2.2 σ - 2.4σ


LHCb
BaBar
Belle
R_K
LHCb
SM
Lepton universality violated?
0
0.5
1
1.5
2
0
5
10
15
20
q^2 [GeV^2/c^4]



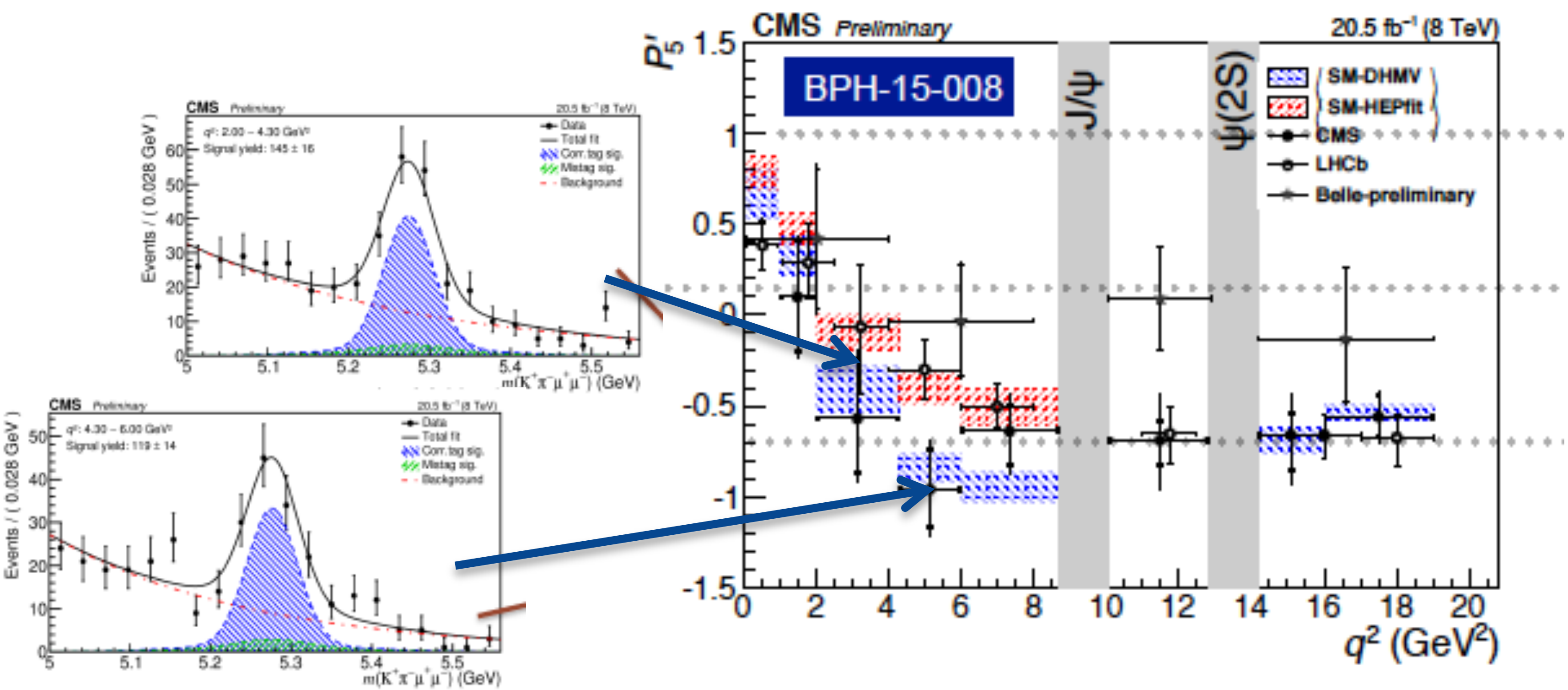


- **PRD 86 (2012) 032012**
- **PRL 103 (2009) 171801**

	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$
95% CL	0.517–0.891	0.530–0.935
99.7% CL	0.454–1.042	0.462–1.100

Altmannshofer et al., 1703.09189

- the $B \to K^* \mu^+ \mu^-$ angular analysis by LHCb alone leads to a pull of 3.3σ,
- the new $B \to K^* \mu^+ \mu^-$ angular analysis by CMS reduces the pull, but the new ATLAS measurement increases it.



From Joel Butler, LHCP 2017 Shanghai, China May 15, 2017

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W. Wang and S. Zhao, arXiv:1704.08168 [hep- ph].

A. Greljo and D. Marzocca, arXiv:1704.09015 [hep-ph].

C. Bonilla, T. Modak, R. Srivastava, and J. W. F. Valle, arXiv:1705.00915 [hep-ph].

F. Feruglio, P. Paradisi, and A. Pattori, arXiv:1705.00929 [hep-ph].

Effective Lagrangian approach in $R_{K(*)}$

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,\ldots,10} \left(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu) \right) \right]$$

$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} \,, \qquad \mathcal{O}_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} G^{\mu\nu} P_R b) \,,$$

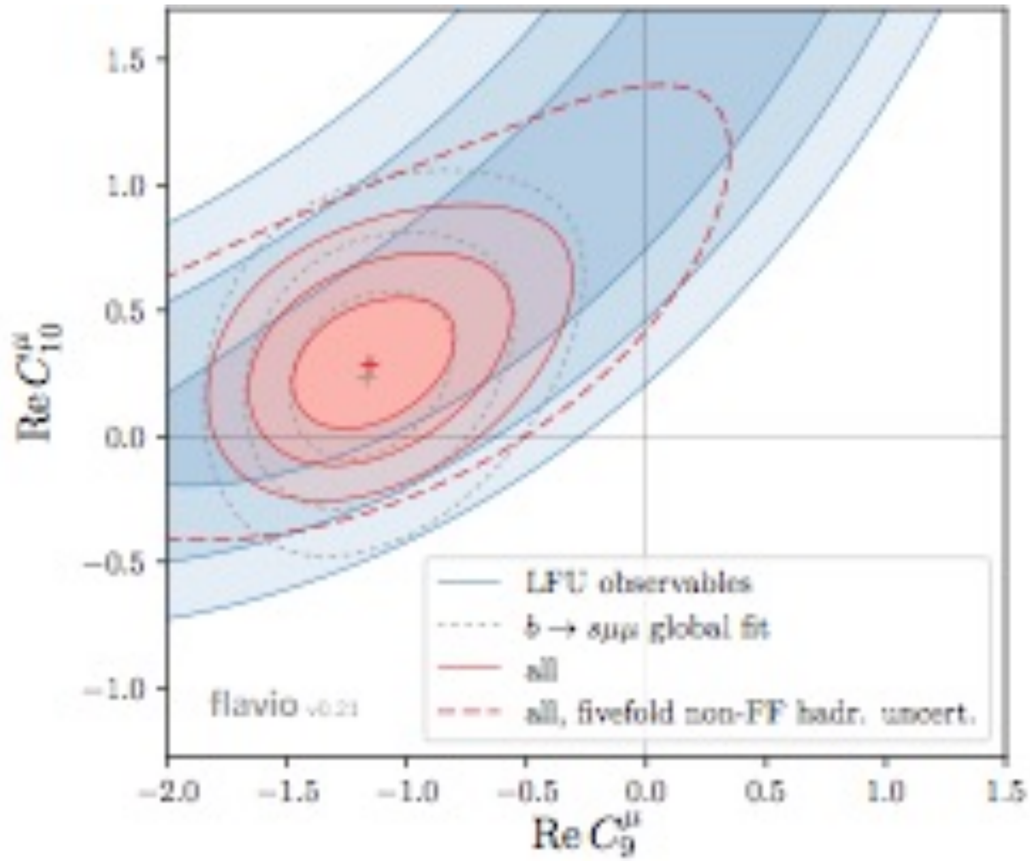
$$\mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \,, \qquad \mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

SM: $C_7 = -0.304$, $C_9 = 4.211$, and $C_{10} = -4.103$

Buras et al,hep-ph/9311345;
Altmannshofer et al, 0811.1214
Bobeth et al, hep-ph/9910220

R_K and R_{K*} and New Physics

Altmannshofer, Stangl, Straub
1704.05435



$$C_9^{\mu} = -C_{10}^{\mu} = -0.64$$

$$[-0.81, -0.48]$$

Similar values obtained by Capdevila et al., 1704.05340

In agreement with fit from R_K Hiller, Schmaltz, 1408.1627, 1411.4773

$$\boxed{C_9^{\mu} = -C_{10}^{\mu} \sim -[0.5, 1]}$$

Do these deviations suggest Lepton Flavour Universality violation?

There are many attempts to understand each of them separately.

- Glashow, Guadagnoli and Lane, 1411.0565: lepton flavor non-universality is necessarily associated with lepton flavor violation. NP couples preferentially to third generation:

$$G(b'_L \gamma_\mu b'_L)(\bar{\tau}'_L \gamma^\mu \tau'_L)$$

$$d'_{L3} \equiv b'_L = \sum_{i=1}^{3} U^d_{L3i} d_i \quad , \qquad \ell'_{L3} \equiv \tau'_L = \sum_{i=1}^{3} U^\ell_{L3i} \ell_i$$

$$\boxed{G\left[U^d_{L33} U^{d*}_{L32} |U^\ell_{L32}|^2 (\bar{b}_L \gamma_\mu s_L)(\bar{\mu}_L \gamma^\mu \mu_L) + h.c.\right]}$$

- Feruglio et al, 1606.00524; Battacharaya et al., 1412.7164:

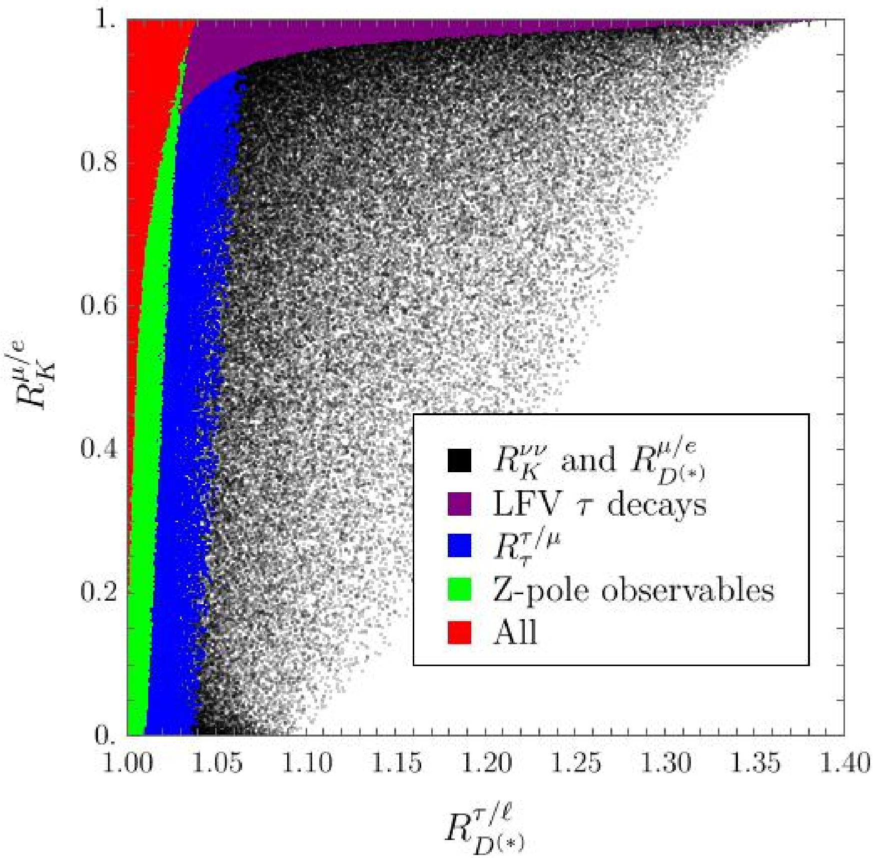
If NP scale is above electroweak scale, NP effective operators have to respect SU(3) x SU$(2)_L$ x U$(1)_{Y.}$ assuming NP in the third generation

$$\boxed{\begin{aligned}\mathcal{L}_{\rm NP} = \; & \frac{C_1}{\Lambda^2}\,(\bar{q}_{3L}\gamma^\mu q_{3L})\left(\bar{\ell}_{3L}\gamma_\mu \ell_{3L}\right) + \\ & \frac{C_3}{\Lambda^2}\,(\bar{q}_{3L}\gamma^\mu \tau^a q_{3L})\left(\bar{\ell}_{3L}\gamma_\mu \tau^a \ell_{3L}\right)\end{aligned}}$$

$$\begin{array}{lll} u_L \to V_u u_L & d_L \to V_d d_L & V_u^\dagger V_d = V\,, \\ \nu_L \to U_e \nu_L & e_L \to U_e e_L\,, & \end{array}$$

$$\begin{aligned}\mathcal{L}_{\rm NP} = \frac{1}{\Lambda^2}\big[& (C_1+C_3)\,\lambda^u_{ij}\lambda^e_{kl}\,(\bar{u}_{Li}\gamma^\mu u_{Lj})(\bar{\nu}_{Lk}\gamma_\mu \nu_{Ll}) \; + \\ & (C_1-C_3)\,\lambda^u_{ij}\lambda^e_{kl}\,(\bar{u}_{Li}\gamma^\mu u_{Lj})(\bar{e}_{Lk}\gamma_\mu e_{Ll}) \; + \\ & (C_1-C_3)\,\lambda^d_{ij}\lambda^e_{kl}\,(\bar{d}_{Li}\gamma^\mu d_{Lj})(\bar{\nu}_{Lk}\gamma_\mu \nu_{Ll}) \; + \\ & (C_1+C_3)\,\lambda^d_{ij}\lambda^e_{kl}\,(\bar{d}_{Li}\gamma^\mu d_{Lj})(\bar{e}_{Lk}\gamma_\mu e_{Ll}) \; + \\ & 2C_3\left(\lambda^{ud}_{ij}\lambda^e_{kl}\,(\bar{u}_{Li}\gamma^\mu d_{Lj})(\bar{e}_{Lk}\gamma_\mu \nu_{Ll}) + h.c.\right)\big]\end{aligned}$$

$$\lambda^q_{ij} = V^*_{q3i}V_{q3j} \qquad \lambda^e_{ij} = U^*_{e3i}U_{e3j} \qquad \lambda^{ud}_{ij} = V^*_{u3i}V_{d3j}$$



from Feruglio et al, 1606.00524
color regions are allowed

the experimental bounds on Z and τ decays significantly constrain LFU breaking effects in B-decays,

Models of NP for $R_{D(*)}$ and $R_{K(*)}$ separately

Spin	Color singlet	Color tripet
0	2HDM	Scalar LQ
1 LQ	W' ,Z'	Vector

$R_{D(*)}$

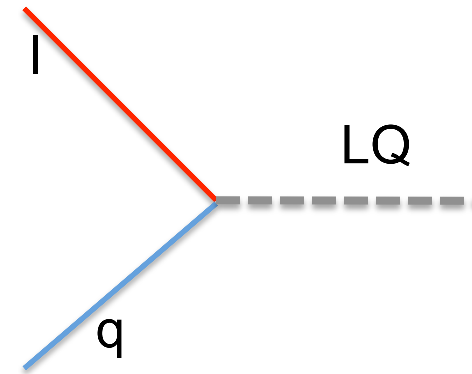
2 HDM: Celis, Jung, Li, Pich 1612.07757, 1210.8443;
W': Greljo, Isidori, Marzocca,1506.01705

LQ: Doršner, SF, Greljo, Kamenik., Košnik, (1603.04993)…
S.F. J.F. Kamenik, I. Nišandžić, J. Zupan, 1206.187

$R_{K(*)}$

Z': Altmannshofer and Straub,1411.3161S,
Crivellin et al, 1501.00993;
Buras and Girrbach, 1309.2466,...
Hiller&Schmaltz;1408.1627 ;
Kosnik, 1206,2970;
LQ: Becirevic, SF, Kosnik arXiv:1503.09024;
Barbieri et al,1512.01560.
Becirevic et al,1608.08501....

Leptoquarks as a resolution of B anomalies:



Brief "history"

1) 1974 Salam & Pati: partial unification of quark and leptons –four color charges, left-right symmetry;

2) GUT models contain them as gauge bosons (e.g. Georgi-Glashow 1974);

3) Within GUT they can be scalars too;

4) 1997 false signal et DESY (~200 GeV);

5) In recent years LQ might offer explanations of B physics anomalies;

6) LHC has bounds on the masses of LQ_1,LQ_2, LQ_3 of the order ~ 1 TeV.

Leptoquarks in R_K and $R_{D(*)}$

Suggested by many authors: naturally acoomodate LUV and LFV

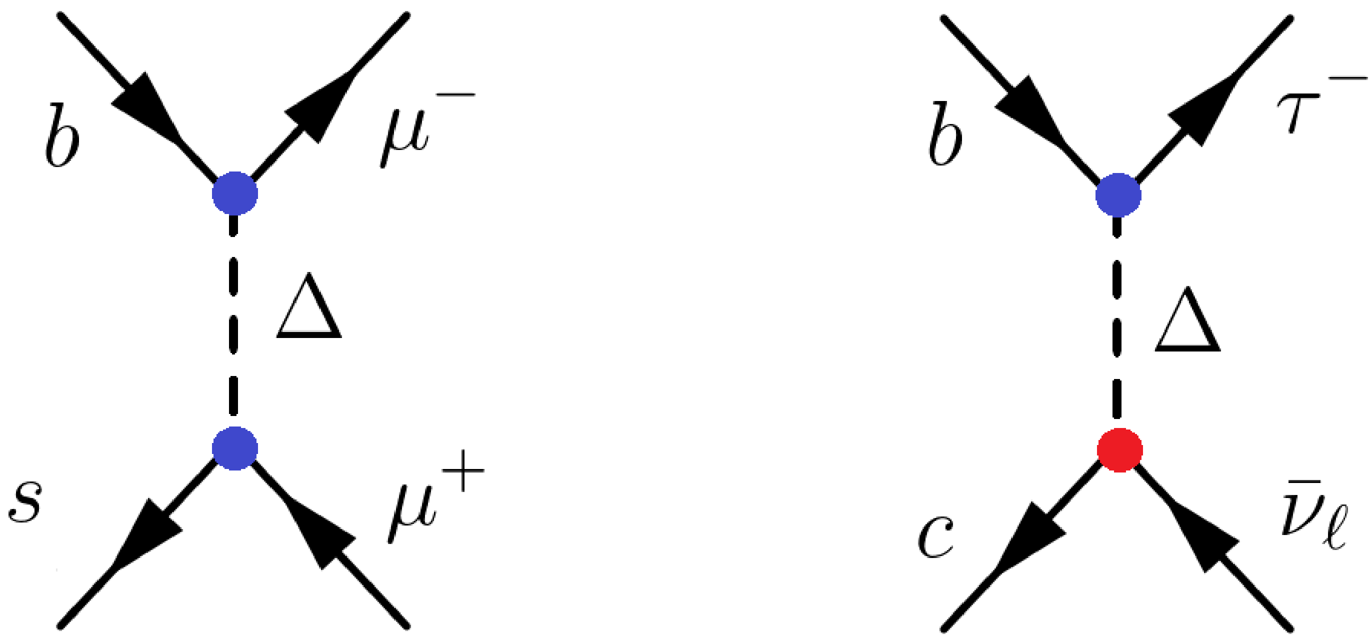
color SU(3), weak isospin SU(2) , weak hypercharge U(1) $Q=I_3 + Y$

$SU(3)\times SU(2)\times U(1)$	Spin	Symbol	Type	$3B+L$
$(\overline{\mathbf{3}},\mathbf{3},1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3},\mathbf{2},7/6)$	0	R_2	$RL\,(S_{1/2}^L),\ LR\,(S_{1/2}^R)$	0
$(\mathbf{3},\mathbf{2},1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L),\ \overline{LR}$	0
$(\overline{\mathbf{3}},\mathbf{1},4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
$(\overline{\mathbf{3}},\mathbf{1},1/3)$	0	S_1	$LL\,(S_0^L),\ RR\,(S_0^R),\ \overline{RR}$	-2
$(\overline{\mathbf{3}},\mathbf{1},-2/3)$	0	$\bar{S}_1$	$\overline{RR}$	-2
$(\mathbf{3},\mathbf{3},2/3)$	1	U_3	$LL\,(V_1^L)$	0
$(\overline{\mathbf{3}},\mathbf{2},5/6)$	1	V_2	$RL\,(V_{1/2}^L),\ LR\,(V_{1/2}^R)$	-2
$(\overline{\mathbf{3}},\mathbf{2},-1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}_{1/2}^L),\ \overline{LR}$	-2
$(\mathbf{3},\mathbf{1},5/3)$	1	$\tilde{U}_1$	$RR\,(\tilde{V}_0^R)$	0
$(\mathbf{3},\mathbf{1},2/3)$	1	U_1	$LL\,(V_0^L),\ RR\,(V_0^R),\ \overline{RR}$	0
$(\mathbf{3},\mathbf{1},-1/3)$	1	$\bar{U}_1$	$\overline{RR}$	0

F=3B +L fermion number; F=0 no proton decay at tree level

Doršner, SF, Greljo, Kamenik Košnik, (1603.04993)

Explaining B anomalies by LQ at tree level

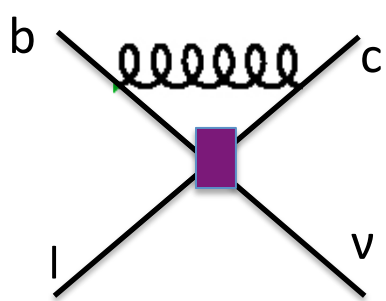


If one wants to explain both anomalies at tree level by leptoquarks

LQ in $R_{D(*)}$ and charged current processes at low energies

Effective Lagrangian for charged current process:

$$\mathcal{L}_{\rm eff}^{\rm SL} = -\frac{4G_F}{\sqrt{2}} V_{ij} \Big\{ (U_{\ell k} + g^L_{ij;\ell k})(\bar{u}^i_L \gamma^\mu d^j_L)(\bar{\ell}_L \gamma_\mu \nu^k_L)$$
$$+ g^R_{ij;\ell k}(\bar{u}^i_R \gamma^\mu d^j_R)(\bar{\ell}_R \gamma_\mu \nu^k_R)$$
$$+ g^{RR}_{ij;\ell k}(\bar{u}^i_R d^j_L)(\bar{\ell}_R \nu^k_L) + h^{RR}_{ij;\ell k}(\bar{u}^i_R \sigma^{\mu\nu} d^j_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu^k_L)$$
$$+ g^{LL}_{ij;\ell k}(\bar{u}^i_L d^j_R)(\bar{\ell}_L \nu^k_R) + h^{LL}_{ij;\ell k}(\bar{u}^i_L \sigma^{\mu\nu} d^j_R)(\bar{\ell}_L \sigma_{\mu\nu} \nu^k_R)$$
$$+ g^{LR}_{ij;\ell k}(\bar{u}^i_L d^j_R)(\bar{\ell}_R \nu^k_L)$$
$$+ g^{RL}_{ij;\ell k}(\bar{u}^i_R d^j_L)(\bar{\ell}_L \nu^k_R) \Big\} + \text{h.c.}.$$



running from LQ mass scale to m_q should be considered for scalar, pseudoscalar and tensor Wilson coefficents.

$S=0$	$\frac{m_{\rm LQ}^2}{v^2}\, g^L_{ij;\ell k}$	$\frac{m_{\rm LQ}^2}{v^2}\, g^R_{ij;\ell k}$	$\frac{m_{\rm LQ}^2}{v^2}\begin{pmatrix} g^{RR}_{ij;\ell k} \\ h^{RR}_{ij;\ell k}\end{pmatrix}$	$\frac{m_{\rm LQ}^2}{v^2}\begin{pmatrix} g^{LL}_{ij;\ell k} \\ h^{LL}_{ij;\ell k}\end{pmatrix}$
S_3	$-\frac{(y_3^{LL\dagger}V^*)_{\ell i}(y_3^{LL}U)_{jk}}{4}$			
R_2			$\frac{(y_2^{RL}U)_{ik}\, y^{LR}_{2\,\ell j}}{16}\begin{pmatrix}4\\1\end{pmatrix}$	
$\tilde{R}_2$				$\frac{(V\tilde{y}_2^{\overline{LR}})_{ik}\,\tilde{y}^{RL*}_{2\,j\ell}}{16}\begin{pmatrix}4\\1\end{pmatrix}$
S_1	$\frac{(y_1^{LL}U)_{jk}(V^T y_1^{LL})^*_{i\ell}}{4}$	$-\frac{y^{\overline{RR}}_{1\,jk}\, y^{RR*}_{1\,i\ell}}{4}$	$\frac{(y_1^{LL}U)_{jk}\, y^{RR*}_{1\,i\ell}}{16}\begin{pmatrix}4\\-1\end{pmatrix}$	$\frac{y^{\overline{RR}}_{1\,jk}(V^T y_1^{LL})^*_{i\ell}}{16}\begin{pmatrix}4\\-1\end{pmatrix}$

Important constraints from

$$P = \pi, K, D, B$$

$$\left\{ \begin{array}{l} P \to l\nu_l \\ \tau \to P\nu_\tau \\ P \to P'(V)\, l\nu_l \end{array} \right.$$

FCNC processes

LQ	$d_i \to d_j \ell^- \ell'^+$ decays, $\lambda_q = V_{qi} V^*_{qj}$	$u_i \to u_j \ell^- \ell'^+$ decays, $\lambda_q = V^*_{iq} V_{jq}$
S_3	$C_9 = -C_{10} = -\frac{v^2}{M^2}\frac{\pi}{\alpha\lambda_q} x_{i\ell'} x^*_{j\ell}$	$C_9 = -C_{10} = -\frac{v^2}{M^2}\frac{\pi}{\alpha\lambda_q}(V^T x)_{i\ell'}(V^T x)^*_{j\ell}$
R_2	$C_9 = C_{10} = \frac{v^2}{M^2}\frac{\pi}{2\alpha\lambda_q} y_{\ell i} y^*_{\ell' j}$	$C_9 = C_{10} = \frac{v^2}{M^2}\frac{\pi}{2\alpha\lambda_q}(yV^\dagger)_{\ell i}(yV^\dagger)^*_{\ell' j}$ $C_{9'} = -C_{10'} = \frac{v^2}{M^2}\frac{\pi}{2\alpha\lambda_q} x_{j\ell'} x^*_{i\ell}$ $C_S = C_P = -\frac{v^2}{M^2}\frac{\pi}{2\alpha\lambda_q} x^*_{i\ell}(yV^\dagger)^*_{\ell' j}$ $C_{S'} = -C_{P'} = -\frac{v^2}{M^2}\frac{\pi}{2\alpha\lambda_q} x_{j\ell'}(yV^\dagger)_{\ell i}$ $C_T = (C_S + C_{S'})/4$ $C_{T5} = (C_S - C_{S'})/4$
$\tilde{R}_2$	$C_{9'} = -C_{10'} = \frac{v^2}{M^2}\frac{\pi}{2\lambda_q\alpha} x_{j\ell'} x^*_{i\ell}$	
$\tilde{S}_1$	$C_{9'} = C_{10'} = -\frac{v^2}{M^2}\frac{\pi}{2\lambda_q\alpha} x_{i\ell'} x^*_{j\ell}$	
S_1		$C_9 = -C_{10} = -\frac{v^2}{M^2}\frac{\pi}{2\alpha\lambda_q}(V^T v)_{i\ell'}(V^T v)^*_{j\ell}$ $C_{9'} = C_{10'} = -\frac{v^2}{M^2}\frac{\pi}{2\alpha\lambda_q} x_{i\ell'} x^*_{j\ell}$ $C_S = C_P = \frac{v^2}{M^2}\frac{\pi}{2\alpha\lambda_q} x_{i\ell'}(V^T v)^*_{j\ell}$ $C_{S'} = -C_{P'} = \frac{v^2}{M^2}\frac{\pi}{2\alpha\lambda_q}(V^T v)_{i\ell'} x^*_{j\ell}$ $C_T = (C_S + C_{S'})/4$ $C_{T5} = (C_S - C_{S'})/4$

Down quark sector has only these modifications due to $U(1)_{Y}$!

Constraints from flavor observables

$B_c \to \tau\nu$

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

$B_s^0 - \bar{B}_s^0$

$B \to D\mu\nu_\mu$

$K \to \mu\nu_\mu$

$D_{d,s} \to \tau, \mu\nu$

$K \to \pi\mu\nu_\mu$

Becirevic et al, 1608.07583, 1608.08501
Alonso et al, 1611.06676,…

Oblique corrections

Constraints from LFV

$(g-2)_\mu$

$\tau \to \mu\gamma$

$\mu \to e\gamma$

$\tau \to K(\pi)\mu(e)$

$K \to \mu e$

$B \to K\mu e$

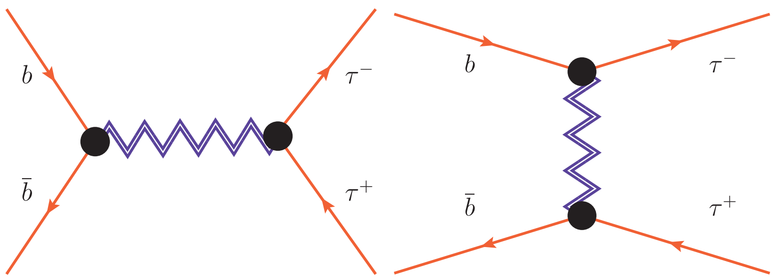
$\tau \to \mu\mu\mu$

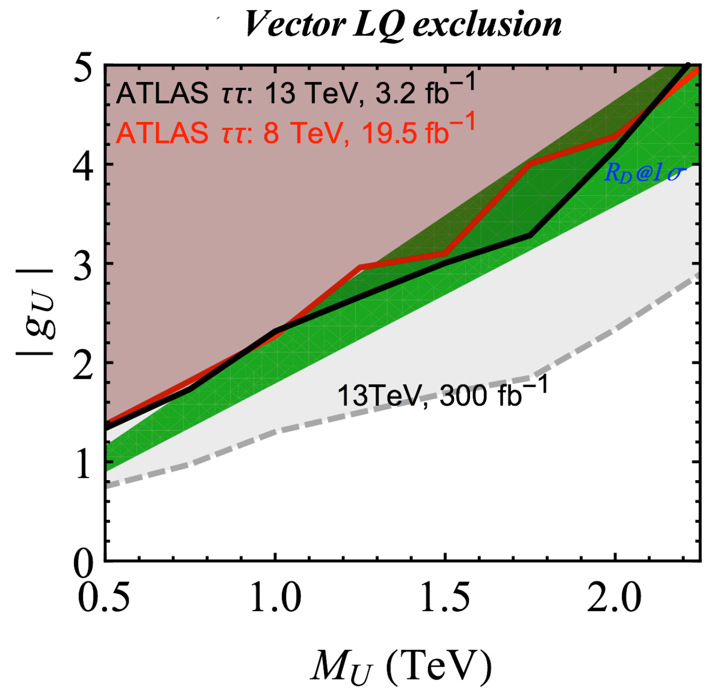
$t \to c\ell^+\ell'^-$

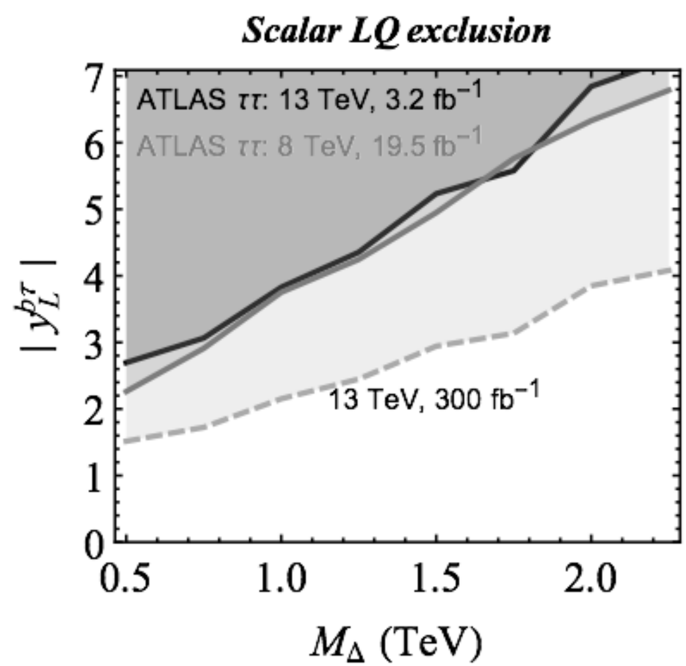
$Z \to b\bar{b}$

Constraints from high p_T searches at LHC

Faroughy et al., 1609.07138



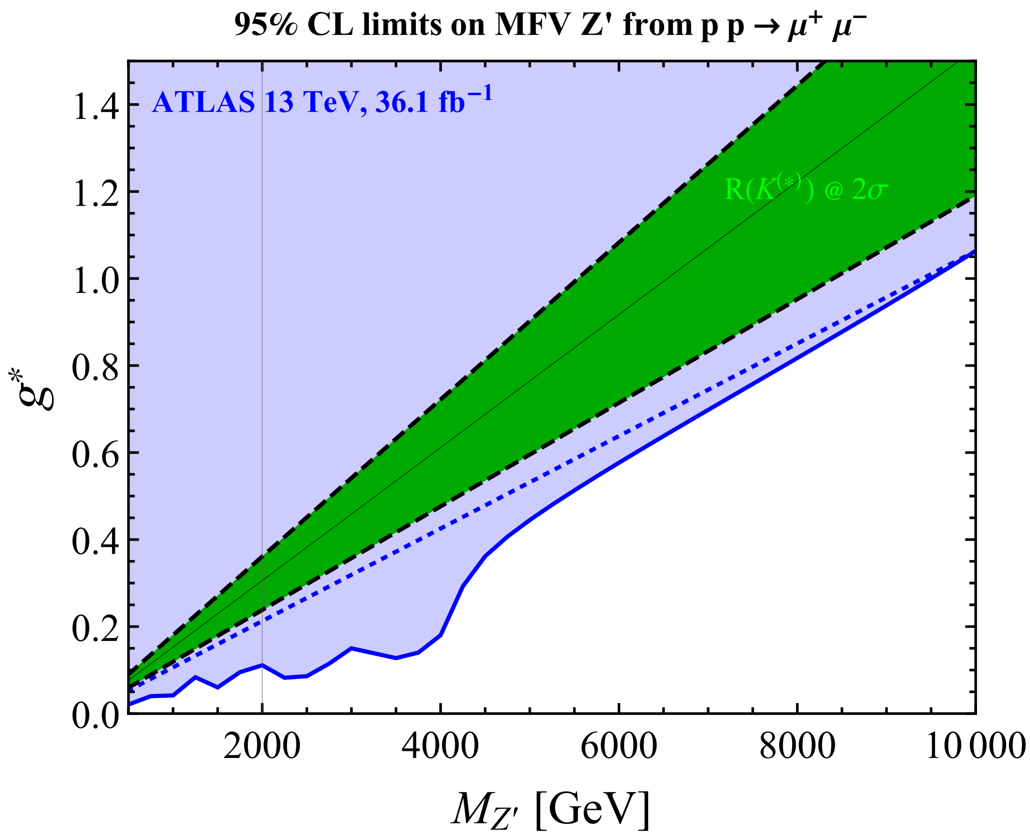




2HDM cannot reconcile ττ searches at LHC for

$$m_{A,H^0} \gtrsim 200\ \text{GeV}$$

$R_{K(*)}$ Greljo and Marzocca, 1704.09015
Z' model with MFV



effective Lagrangian
full theory

LHC dimuon searches already exclude such a scenario independently of the Z' mass.

Two LQs solution of $R_{D(*)}$ and $R_{K(*)}$

- One scalar LQ cannot explain both anomalies;

- GUT possible with light scalar LQs within SU(5) if there are 2 LQs (Doršner, SF, Greljo, Kamenik, Košnik 1603.04993) ;

- Neutrino masses might be explained with 2 light LQs within a loop (Doršner, SF, Košnik, 1701.08322);

Scanario with 2 light LQs used in Crivellin, Müller, Ota, 1703.09226
LQs: $(\bar{3},1,-1/3)$ and $(\bar{3},3,1/3)$,

Doršner, SF, Faroughy, Košnik, 1705.xxxxx

Doršner, SF, Košnik, (1701.08322) LQ S_3 , if accommodated within SU(5) does not cause proton decay.

Our proposal S_3 and $\tilde{R}_2$

$$\mathcal{L}_{S_3} = -\, y_{ij} \bar{d}_L^{C\,i} \nu_L^j S_3^{1/3} - \sqrt{2} y_{ij} \bar{d}_L^{C\,i} e_L^j S_3^{4/3} + \\ + \sqrt{2} (V^* y)_{ij} \bar{u}_L^{C\,i} \nu_L^j S_3^{-2/3} - (V^* y)_{ij} \bar{u}_L^{C\,i} e_L^j S_3^{1/3} + \text{h.c.}$$

$$\mathcal{L}_{\tilde{R}_2} = -\, \tilde{y}_{ij} \bar{d}_R^i e_L^j \tilde{R}_2^{2/3} + \tilde{y}_{ij} \bar{d}_R^i \nu_L^j \tilde{R}_2^{-1/3} + \text{h.c.}$$

Textures:

$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}, \qquad V^* y = \begin{pmatrix} 0 & V^*_{us} y_{s\mu} + V^*_{ub} y_{b\mu} & V^*_{us} y_{s\tau} + V^*_{ub} y_{b\tau} \\ 0 & V^*_{cs} y_{s\mu} + V^*_{cb} y_{b\mu} & V^*_{cs} y_{s\tau} + V^*_{cb} y_{b\tau} \\ 0 & V^*_{ts} y_{s\mu} + V^*_{tb} y_{b\mu} & V^*_{ts} y_{s\tau} + V^*_{tb} y_{b\tau} \end{pmatrix}$$

$$\tilde{y} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \tilde{y}_{s\tau} \\ 0 & 0 & \tilde{y}_{b\tau} \end{pmatrix}$$

$$S_3(\bar{3}, 3 - 1/3)$$

three states $S_3^{2/3}, S_3^{-1/3}, S_3^{-4/3}$

$R_{D(*)}$ can be explained by rescaling the SM value, (tree level contribution of $S_3^{-2/3}$)

$\boxed{R_{D(*)}(\text{exp}) > R_{D(*)}(\text{SM})}$

$$\mathcal{L}_{\bar{c}b\bar{\ell}\nu_k} = -\frac{4G_F}{\sqrt{2}}\left[(V_{cb}\delta_{\ell k} + g^L_{cb;\ell k})(\bar{c}_L\gamma^\mu b_L)(\bar{\ell}_L\gamma_\mu\nu^k_L)\right]$$

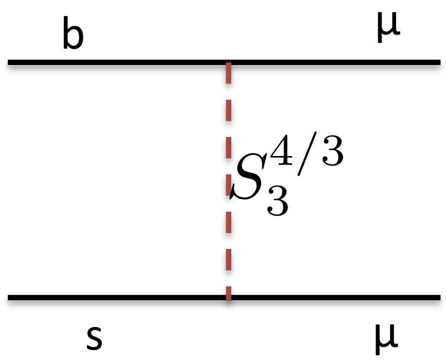
$$g^L_{cb;\ell\ell} = -\frac{v^2}{4m^2_{S_3}}(Vy^*)_{c\ell}y_{b\ell}.$$

following Freytsis et al, (1506.08896) fit at 1 σ

$$\boxed{y_{b\tau}y^*_{s\tau} \approx -0.4(m_{S_3}/\text{TeV})^2}$$

$R_{K(*)}(\text{exp}) < R_{K(*)}(\text{SM})$

$R_{K(*)}$ can be explained by S_3



$$C_9 = -C_{10} = \frac{\pi}{V_{tb}V_{ts}^*\alpha}\, y_{b\mu}y_{s\mu}^*\, \frac{v^2}{m_{S_3}^2}$$

$$\boxed{y_{b\mu}y_{s\mu}^* \in [0.7, 1.3] \times 10^{-3}\ (m_{S_3}/\mathrm{TeV})^2}$$

$\tilde{R}_2$ has right-handed couplings which have negligible effects

Constraints from flavour physics

LFU in charged currents

$$R^K_{e/\mu} = \frac{\Gamma(K^- \to e^- \bar{\nu})}{\Gamma(K^- \to \mu^- \bar{\nu})}, \qquad R^K_{\tau/\mu} = \frac{\Gamma(\tau^- \to K^- \nu)}{\Gamma(K^- \to \mu^- \bar{\nu})}.$$

$$B \to D^{(*)} \mu\nu$$

$$c \to s \ell \nu_\ell$$

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

Constraints from LFV processes $B \to K\mu\tau$, $\tau \to \mu\gamma$

Rare charm decays

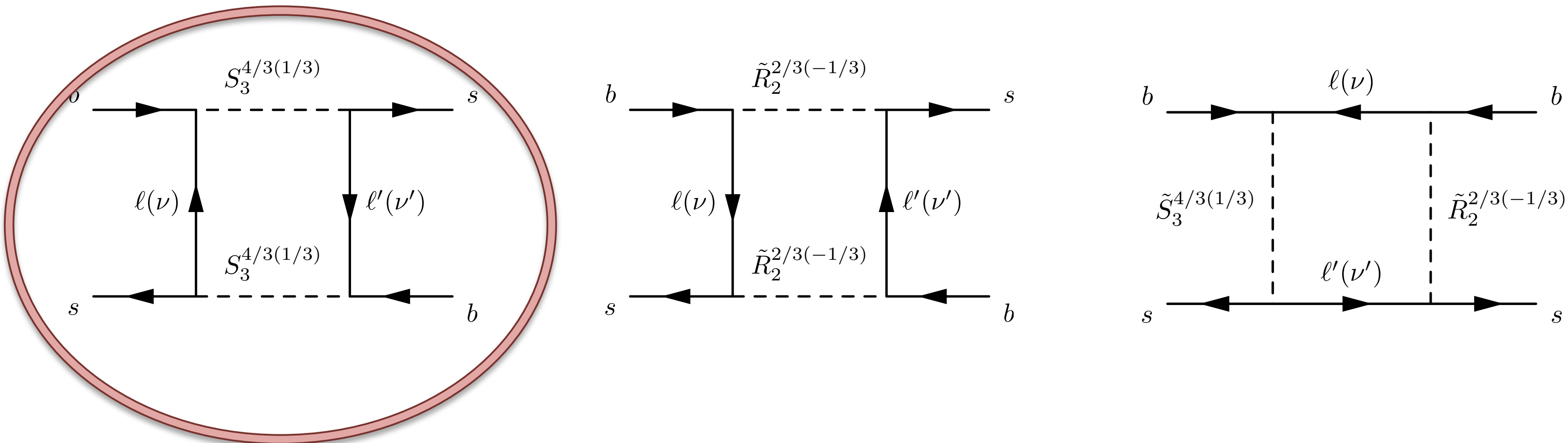
Best fit points

$$y_{s\mu} = 0.026;\ y_{b\mu} = 1.03;\ y_{s\tau} = 0.88;\ y_{b\tau} = -0.77;$$

$$\tilde{y}_{s\tau} = 0.726;\ \tilde{y}_{b\tau} = -1.037;$$

$m_{LQ} \approx 1500$ GeV

$B_s - \bar{B}_s$ oscillation



$$\Delta m_s^{\rm exp} = (17.757 \pm 0.021)\ {\rm ps}^{-1}$$

S_3 alone gives rather large contribution due to rather large $y_{s\tau} y_{b\tau}$

$$\mathcal{H}_{\Delta m_s} = (C_1^{\rm SM} + C_1^{S_3})\,(\bar{s}_L \gamma^\nu b_L)^2 + \tilde{C}_1^{\tilde{R}_2}\,(\bar{s}_R \gamma^\nu b_R)^2 + C_4^{S_3 \tilde{R}_2}\,(\bar{s}_R b_L)(\bar{s}_L b_R) + C_5^{S_3 \tilde{R}_2}\,(\bar{s}_R^\alpha b_L^\beta)(\bar{s}_L^\beta b_R^\alpha)$$

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

most constraining bound by Belle $\mathcal{B}(B \to K^*\nu\bar{\nu}) < 2.7 \times 10^{-5}$

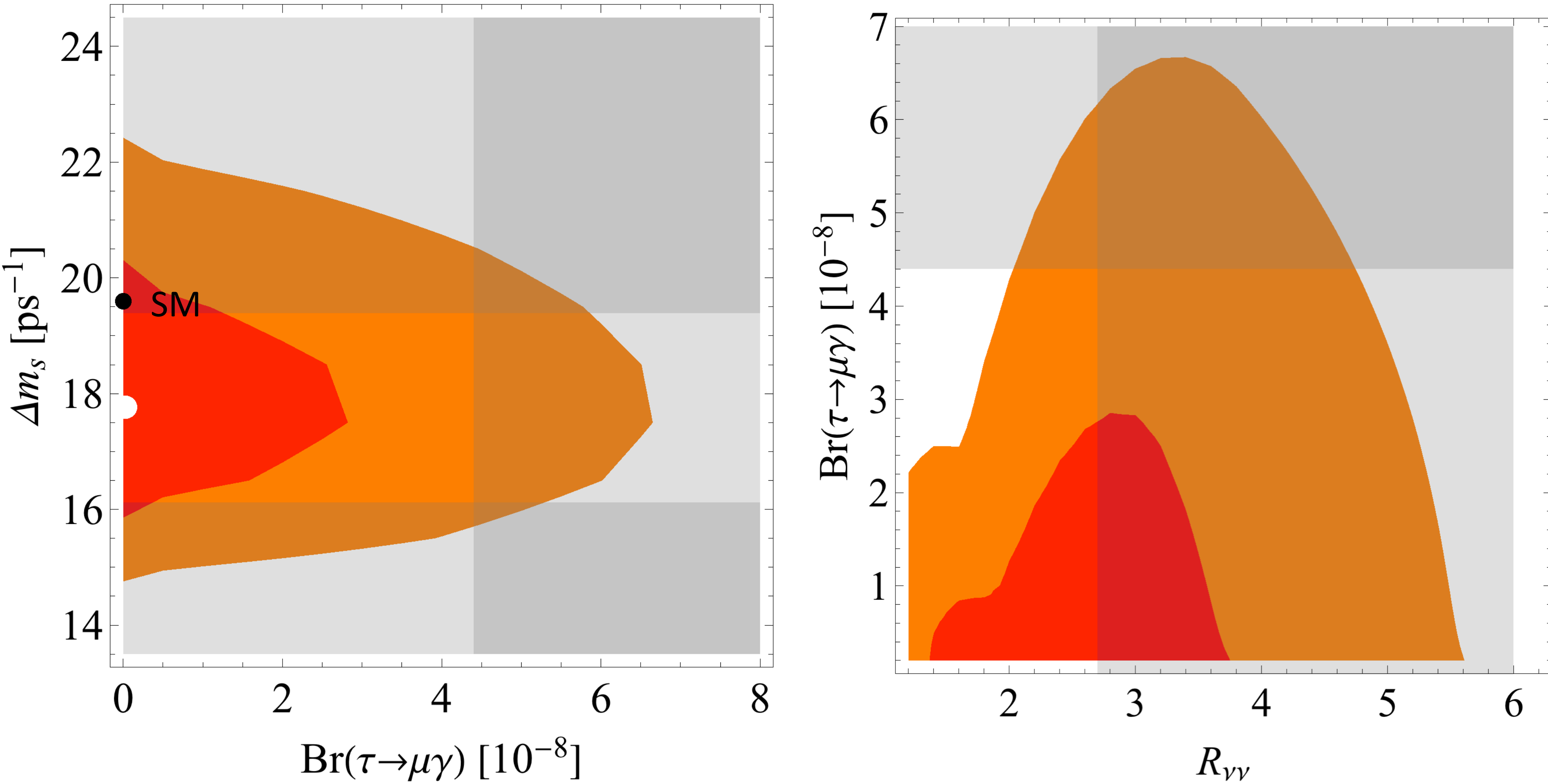
Both S_3 and $\tilde{R}_2$ contribute

$$\mathcal{L}_{\rm eff}^{b\to s\bar{\nu}\nu} = \frac{G_F\alpha}{\pi\sqrt{2}} V_{tb}V_{ts}^* \left(\bar{s}\gamma_\mu[C_L^{ij}P_L + C_R^{ij}P_R]b\right)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j).$$

$$C_L^{S_3,ij} = \frac{\pi v^2}{2\alpha V_{tb}V_{ts}^* m_{S_3}^2} y_{bj}y_{si}^*, \qquad C_R^{\tilde{R}_2,ij} = -\frac{\pi v^2}{2\alpha V_{tb}V_{ts}^* m_{\tilde{R}_2}^2}\tilde{y}_{sj}\tilde{y}_{bi}^*$$

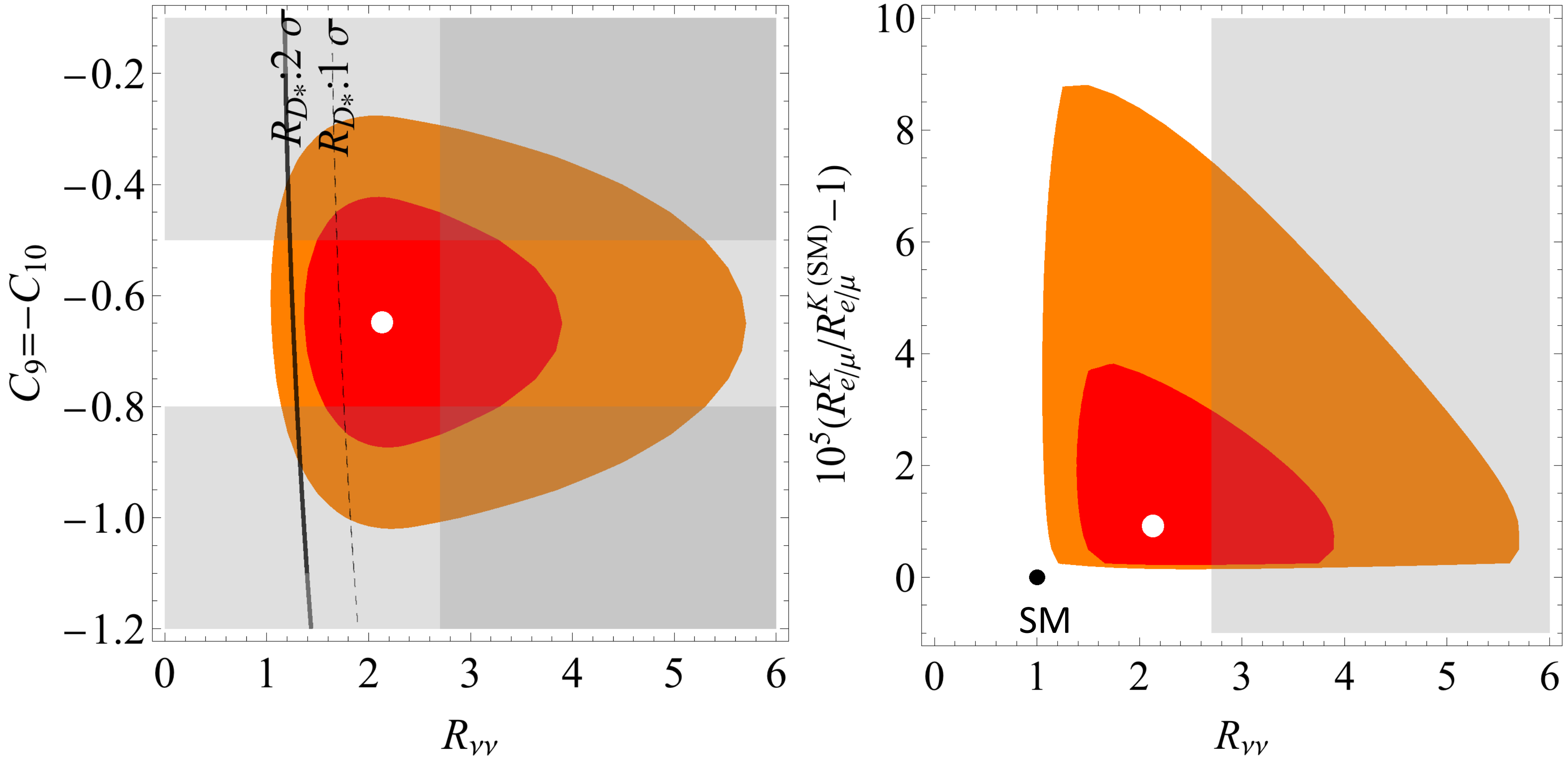
The same factor modifies both processes: $B \to K\nu\bar{\nu}$

$B \to K^*\nu\bar{\nu}$



experimental bounds grey

white point best fit

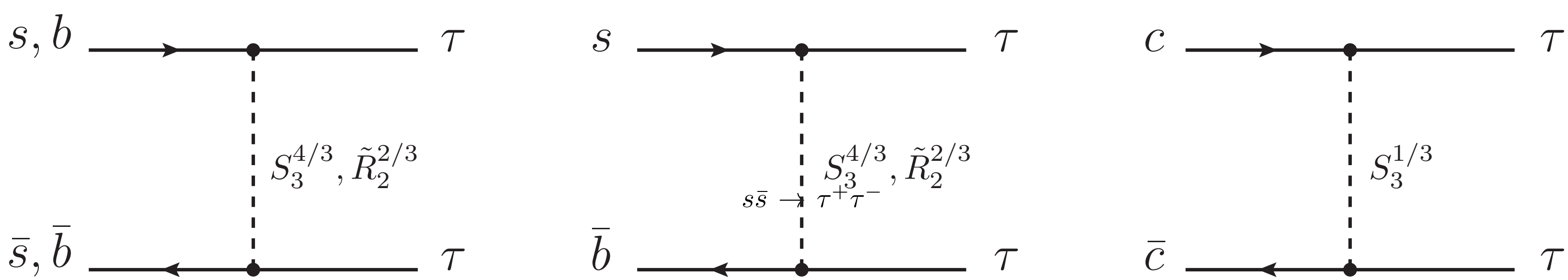


experimental bounds grey

white point best fit

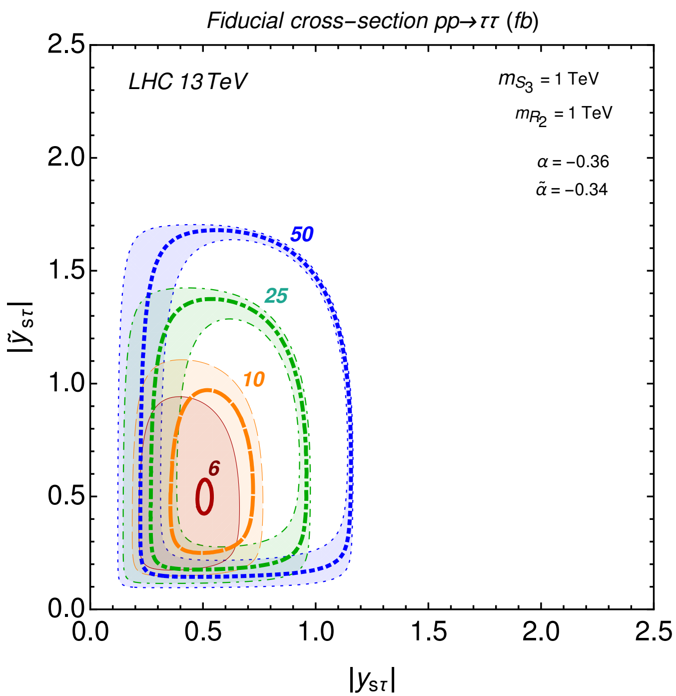
LHC constraints on S_3 and $\tilde{R}_2$

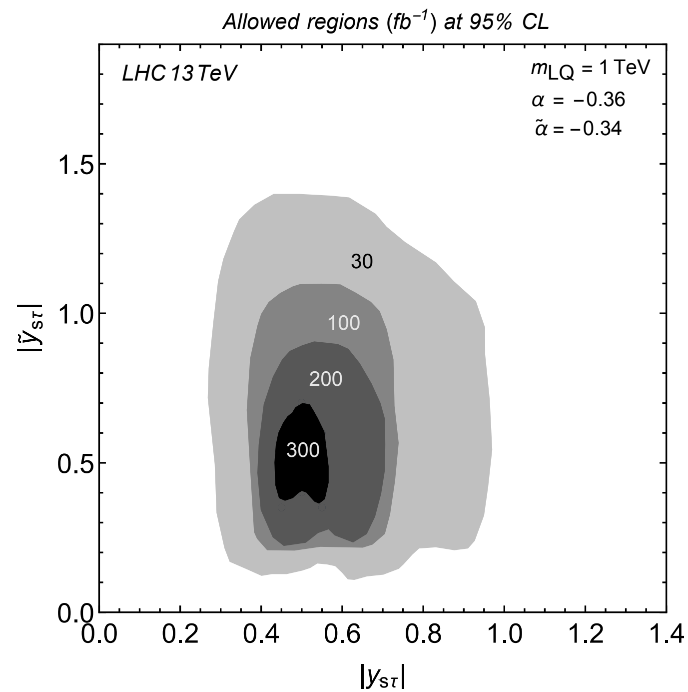
Processes in t-channel $pp \to \tau^+\tau^-$



Flavour anomalies generate s τ , bτ and cτ relatively large couplings.
s quark pdf function for protons are ~ 3 times lagrer contribution then for b quark.

Allowed 95% CL regions of parameter space for LHC luminosites of 30, 100, 200 and 300 fb^{-1} projected from the high-mass ττ resonance search by ATLAS.





$$m_{\tau\tau} > 300 \text{ GeV}$$

$$\alpha \equiv y_{s\tau} y_{b\tau}$$
$$\tilde{\alpha} \equiv \tilde{y}_{s\tau} \tilde{y}_{b\tau}$$

Fixing these couplings one can get full total cross-section. The MC samples generated in MadGraph were subsequently hadronized and showered in Pythia6

GUT possible: SU(5)

LEPTOQUARK	$(SU(3), SU(2), U(1))$	$SU(5)$	$SO(10)$
S_3	$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	$\overline{\mathbf{45}}$	$\mathbf{120}$, $\overline{\mathbf{126}}$
R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$	$\overline{\mathbf{45}}$, $\overline{\mathbf{50}}$	$\mathbf{120}$, $\overline{\mathbf{126}}$
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	$\mathbf{10}$, $\mathbf{15}$	$\mathbf{120}$, $\overline{\mathbf{126}}$
$\tilde{S}_1$	$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	$\mathbf{45}$	$\mathbf{120}$
S_1	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	$\overline{\mathbf{5}}$, $\overline{\mathbf{45}}$, $\overline{\mathbf{50}}$	$\mathbf{10}$, $\mathbf{120}$, $\overline{\mathbf{126}}$

$SU(5)$		S_3
		$\mathbf{45}$
$\tilde{R}_2$	$\mathbf{10}$	$\mathbf{5}^i\overline{\mathbf{10}}_{jk}\mathbf{45}_i^{jk}$
		$\mathbf{5}^i\overline{\mathbf{10}}_{lj}\mathbf{45}_i^{jk}\mathbf{24}_k^l$
		$\mathbf{5}^i\overline{\mathbf{10}}_{lm}\mathbf{45}_j^{lm}\mathbf{24}_i^j$
	$\mathbf{15}$	$\mathbf{45}_k^{ij}\overline{\mathbf{15}}_{jl}\mathbf{45}_i^{lk}$
		$\mathbf{5}^i\overline{\mathbf{15}}_{lj}\mathbf{45}_i^{jk}\mathbf{24}_k^l$
		$\mathbf{45}_k^{ij}\overline{\mathbf{15}}_{jl}\mathbf{45}_m^{lk}\mathbf{24}_i^m$

$$y_3^{LL} \to y_{45}/\sqrt{2}$$

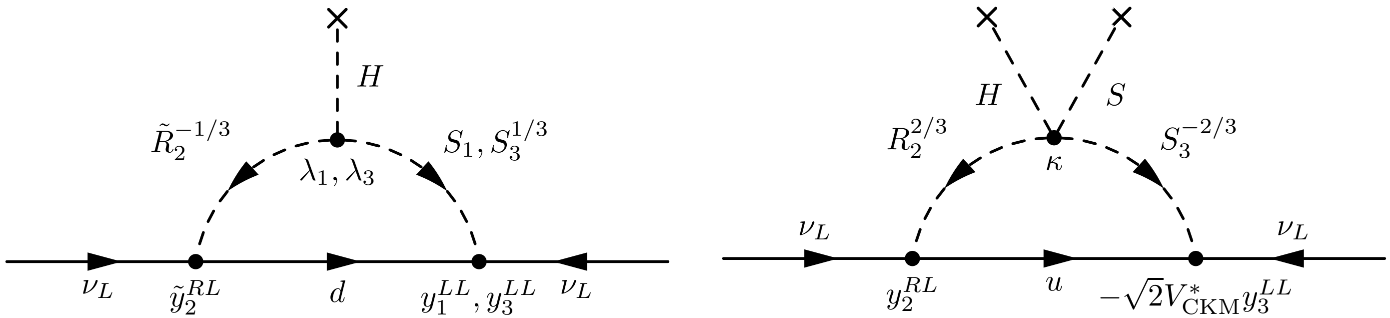
$$m_D = -y^{45}v_{45} - y^5 v_5/2,$$

$$m_E^T = 3y^{45}v_{45} - y^5 v_5/2,$$

$$m_U = \sqrt{2}(\bar{y} + \bar{y}^T)v_5,$$

$$m_{\mathrm{GUT}} \geq 5 \times 10^{15}\ \mathrm{GeV}$$

Neutrino masses (Doršner, SF, Košnik, 1701.08322);



one-loop neutrino mass mechanism within the framework of GUT

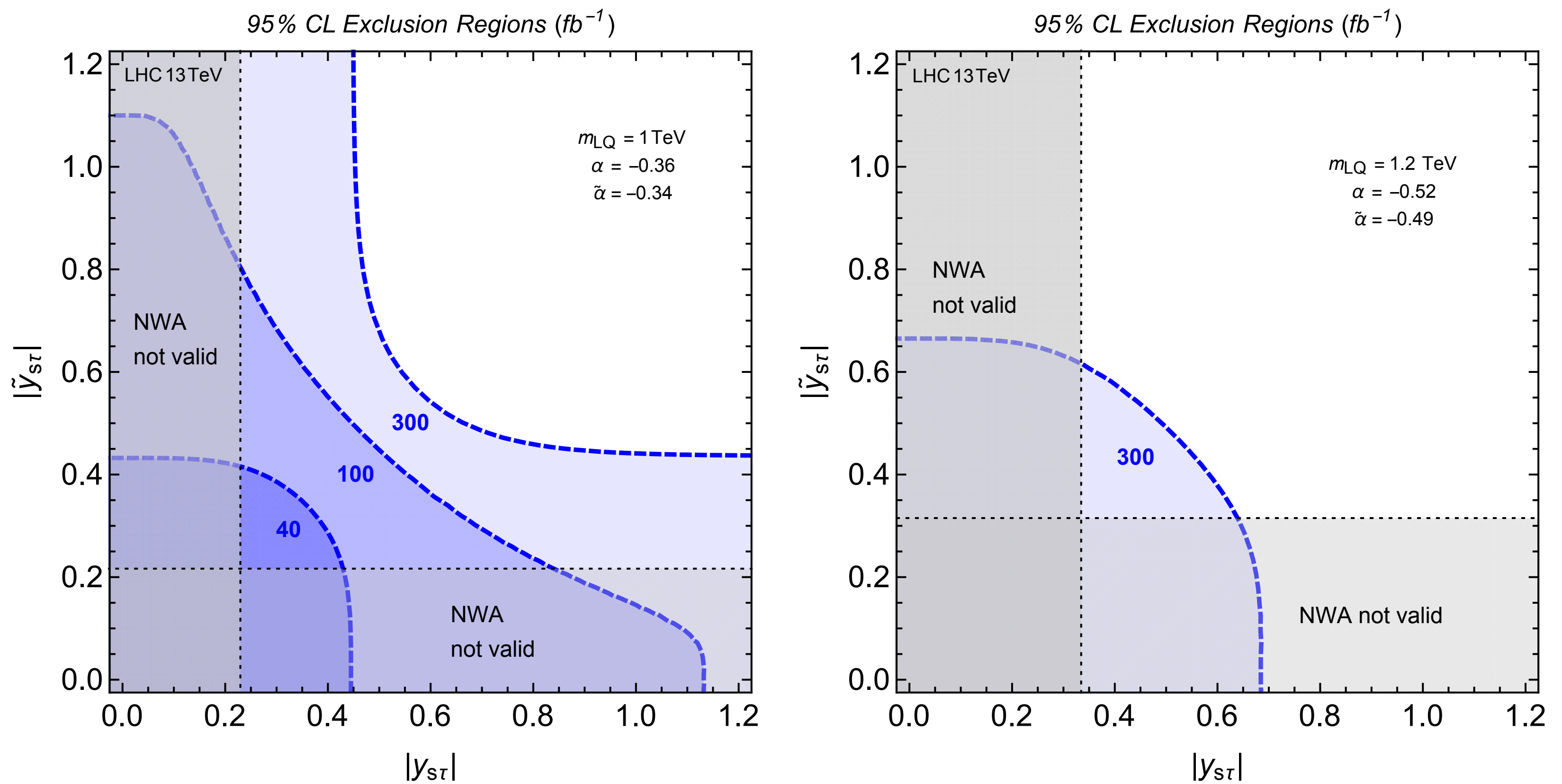
$$\begin{bmatrix} \tilde{R}_2^{-1/3\,*} \\ S_3^{1/3} \end{bmatrix} \rightarrow \begin{bmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{bmatrix} \begin{bmatrix} \tilde{R}_2^{-1/3\,*} \\ S_3^{1/3} \end{bmatrix} \qquad \begin{bmatrix} m_1^2 & \lambda\langle H\rangle \\ \lambda\langle H\rangle & m_2^2 \end{bmatrix} \rightarrow \begin{bmatrix} m^2_{\mathrm{LQ}\,1} & 0 \\ 0 & m^2_{\mathrm{LQ}\,2} \end{bmatrix}$$

$$m_N \sim sin(2\theta)\, y_3 \tilde{y}_2 \, ln(m_{LQ1}/m_{LQ2})^2$$

Summary

- Light scalar LQs offer an explanation of B anomalies;
- Many other scenarios of NP are already ruled out by the LHC high p_T searches;
- GUT model with 2 light LQs might explain anomalies not being in conflict with either flavour or LHC searches.

THANK YOU!



95% CL Exclusion Regions (fb^{-1})
LHC 13TeV
m_{LQ} = 1 TeV
α = −0.36
$\tilde{\alpha}$ = −0.34
NWA
not valid
300
100
40
NWA
not valid
$|\tilde{y}_{s\tau}|$
$|y_{s\tau}|$
95% CL Exclusion Regions (fb^{-1})
LHC 13TeV
m_{LQ} = 1.2 TeV
α = −0.52
$\tilde{\alpha}$ = −0.49
NWA
not valid
300
NWA not valid
$|\tilde{y}_{s\tau}|$
$|y_{s\tau}|$

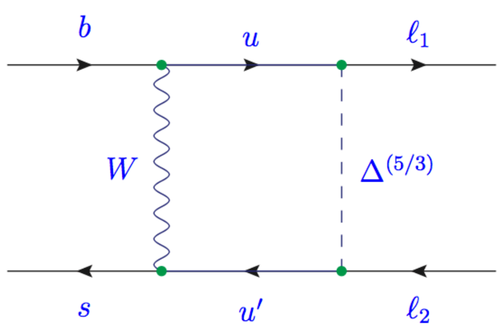
Minimal set-up $R_2(3,2,7/6)$ R_{K^*} at loop level

$$\mathcal{L}_{\Delta^{(7/6)}} = (g_R)_{ij}\bar{Q}_i\boldsymbol{\Delta}^{(7/6)}\ell_{Rj} + (g_L)_{ij}\bar{u}_{Ri}\widetilde{\boldsymbol{\Delta}}^{(7/6)\dagger}L_j + \text{h.c.},$$

$$= (Vg_R)_{ij}\bar{u}_i P_R \ell_j\, \Delta^{(5/3)} + (g_R)_{ij}\bar{d}_i P_R \ell_j\, \Delta^{(2/3)}$$

$$+ (Ug_L)_{ij}\bar{u}_i P_L \nu_j\, \Delta^{(2/3)} - (g_L)_{ij}\bar{u}_i P_L \ell_j\, \Delta^{(5/3)} + \text{h.c.}$$

$$g_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_L^{c\mu} & g_L^{c\tau} \\ 0 & g_L^{t\mu} & g_L^{t\tau} \end{pmatrix}, \qquad g_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & g_R^{b\tau} \end{pmatrix}, \qquad Vg_R = \begin{pmatrix} 0 & 0 & V_{ub}g_R^{b\tau} \\ 0 & 0 & V_{cb}g_R^{b\tau} \\ 0 & 0 & V_{tb}g_R^{b\tau} \end{pmatrix}$$



(Becirevic and Sumensary, 1704.05835)