Scalar Leptoquarks and B anomalies

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Outline

Experimental status: of - B anomalies $R_{D(*)}$ and $R_{K(*)}$

Effective Lagrangian approach: $R_{D(*)}$ and $R_{K(*)}$

Flavour constraints on LQs

Scalar Leptoquarks solution of $R_{D(*)}$ and $R_{K(*)}$

Interpretation: sign of LFU violation?

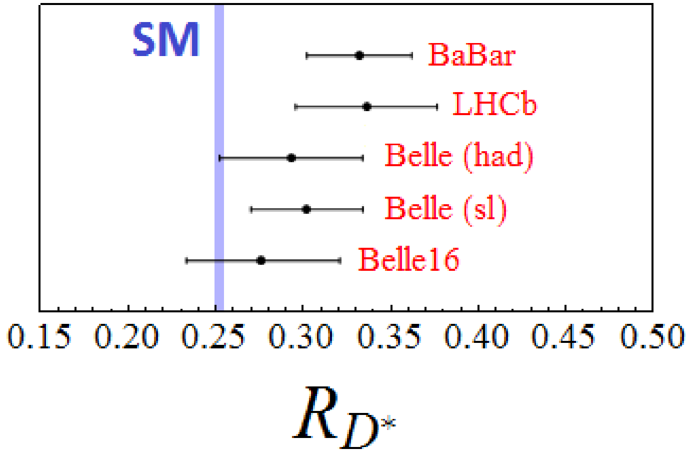
Signature at LHC

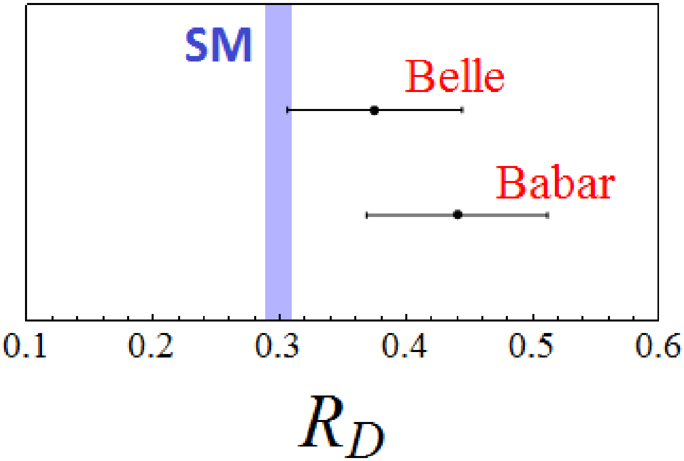
B physics anomalies: experimental results ≠ SM predictions!

charged current (SM tree level)

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$

3.9σ

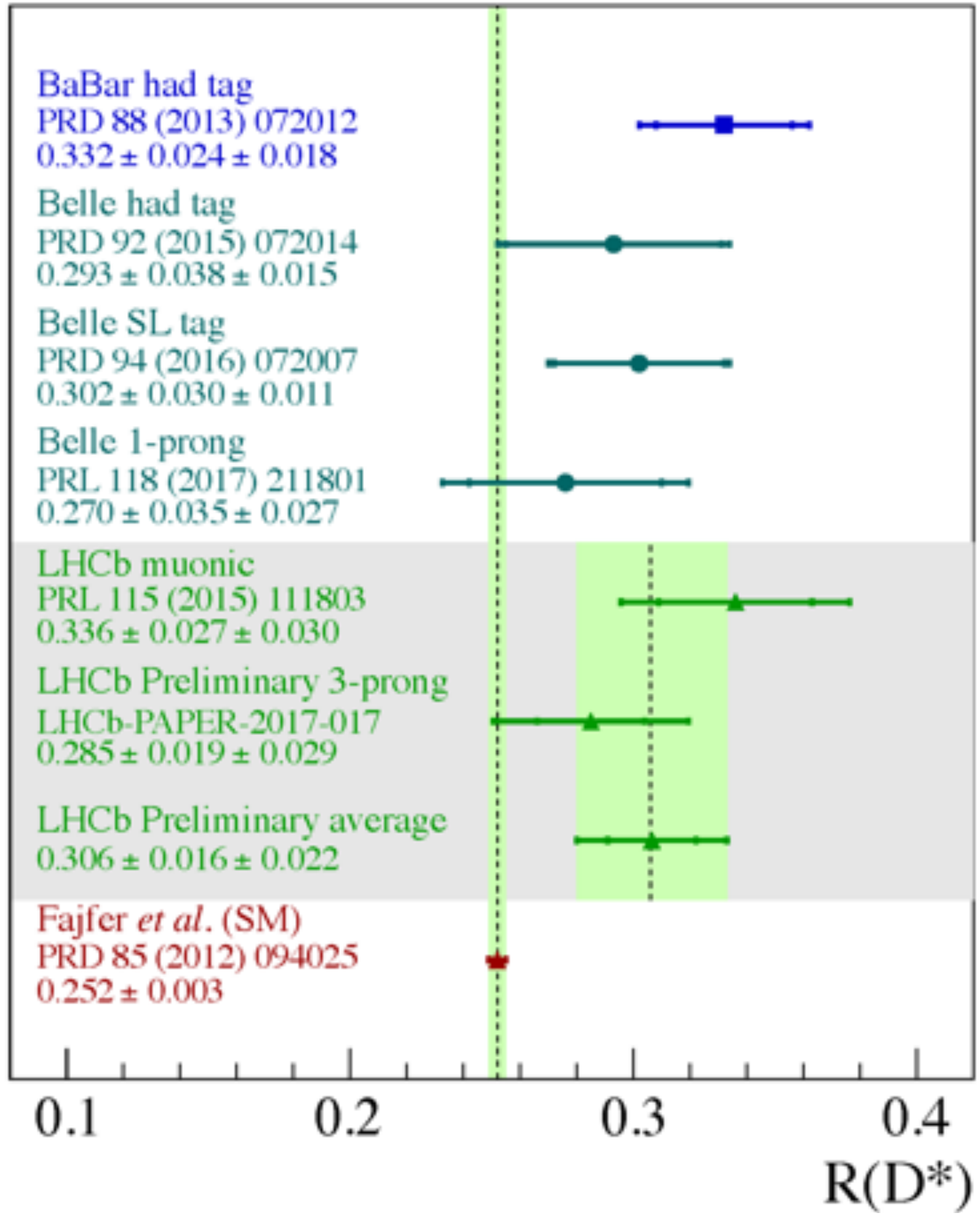




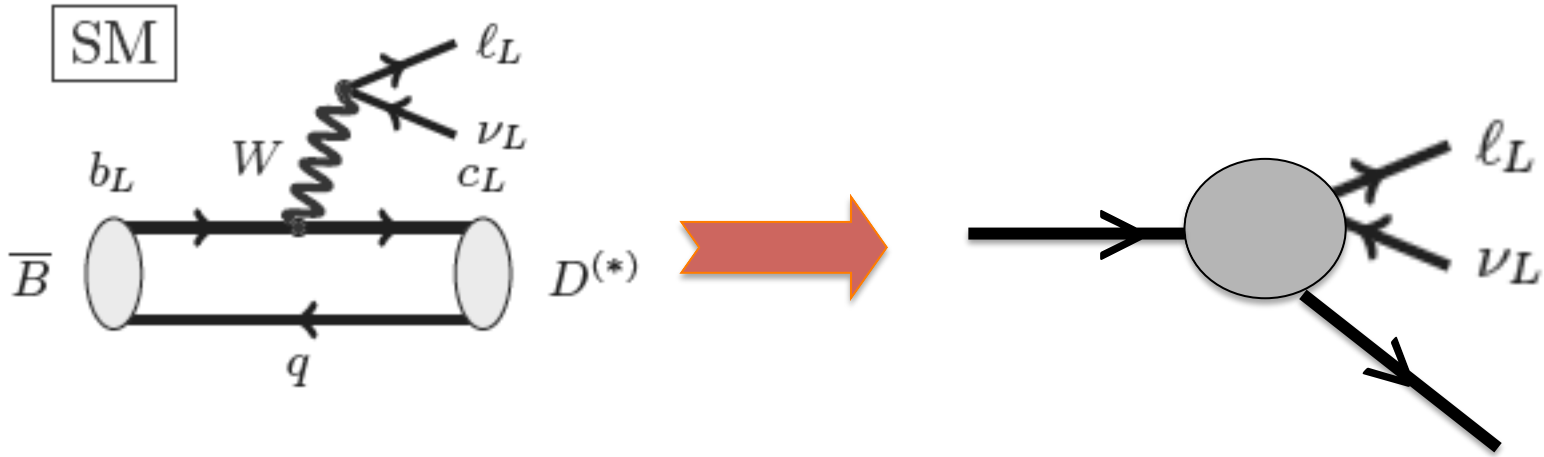
$$\frac{BR(B_c \to J/\Psi\tau\nu_\tau)}{BR(B_c \to J/\Psi\mu\nu_\mu)} = 0.71 \pm 0.17 \pm 0.18$$

2017
LHCb result

~2 σ


BaBar had tag
PRD 88 (2013) 072012
0.332 ± 0.024 ± 0.018
Belle had tag
PRD 92 (2015) 072014
0.293 ± 0.038 ± 0.015
Belle SL tag
PRD 94 (2016) 072007
0.302 ± 0.030 ± 0.011
Belle 1-prong
PRL 118 (2017) 211801
0.270 ± 0.035 ± 0.027
LHCb muonic
PRL 115 (2015) 111803
0.336 ± 0.027 ± 0.030
LHCb Preliminary 3-prong
LHCb-PAPER-2017-017
0.285 ± 0.019 ± 0.029
LHCb Preliminary average
0.306 ± 0.016 ± 0.022
Fajfer et al. (SM)
PRD 85 (2012) 094025
0.252 ± 0.003
0.1
0.2
0.3
0.4
R(D*)

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



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

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

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

Freytsis, Ligeti, Ruderman 1506.08896
S.F. J.F. Kamenik, I. Nišandžić, J. Zupan, 1206.1872

no ν_R

FCNC - SM loop process

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

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

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

R_K and R_{K*} and New Physics

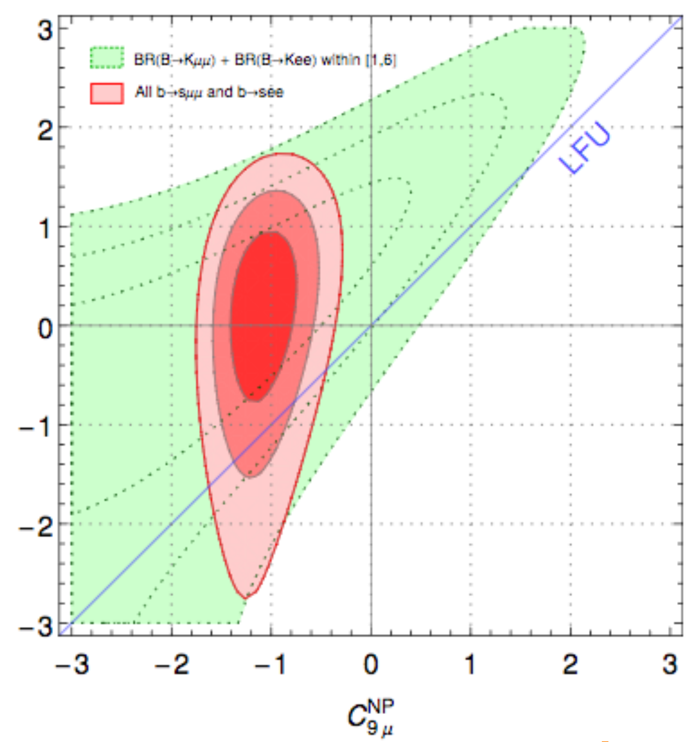
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu) \mathcal{O}_i(\mu) + \sum_{i=7,\ldots,10} \left(C_i(\mu) \mathcal{O}_i(\mu) + C_i'(\mu) \mathcal{O}_i'(\mu) \right) \right]$$

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

Global analysis suggests no NP in

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

$$C_9^\mu = -C_{10}^\mu \in (-0.85, -0.50)$$



Capdevila et al., 1704.05340
Similar result obtained by Altmannshofer et al, 1704.05435

How to approach to anomalies?

- Is the anomaly SM or NP?

- First step at low energies: to construct effective Lagrangian which might explain experimental data;

- Find new particle which can mimic effective Lagrangian;

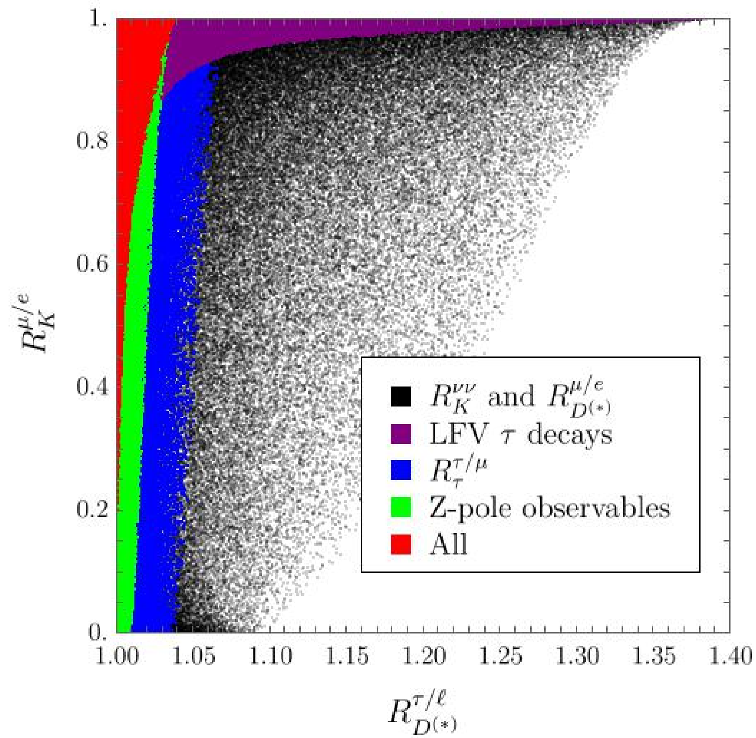
Check all other low energy flavour constraints, check electroweak observables, include LHC direct searches for NP;

- Make consistent model of NP!

Effective Lagrangian approach: NP in third generation

Feruglio, Paradisi, Pattori, 1606.00524; Battacharaya et al., 1412.7164;
Glashow, Guadagnoli and Lane, 1411.0565 NP couples preferentially to third generation.

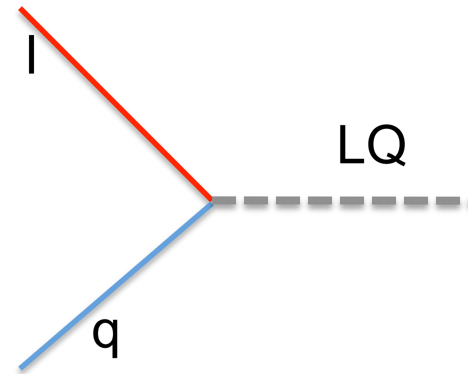
$$\mathcal{L}_{\rm NP} = \frac{C_1}{\Lambda^2}\left(\bar{q}_{3L}\gamma^\mu q_{3L}\right)\left(\bar{\ell}_{3L}\gamma_\mu \ell_{3L}\right) + \frac{C_3}{\Lambda^2}\left(\bar{q}_{3L}\gamma^\mu \tau^a q_{3L}\right)\left(\bar{\ell}_{3L}\gamma_\mu \tau^a \ell_{3L}\right)$$



Paradigm: only one new mediator leading to such effective Lagrangian!

Spin	Color singlet	Color tripet
0	2HDM	Scalar LQ R̸ parity - sbottom
1	W' ,Z'	Vector LQ

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 accomodate LUV and LFV

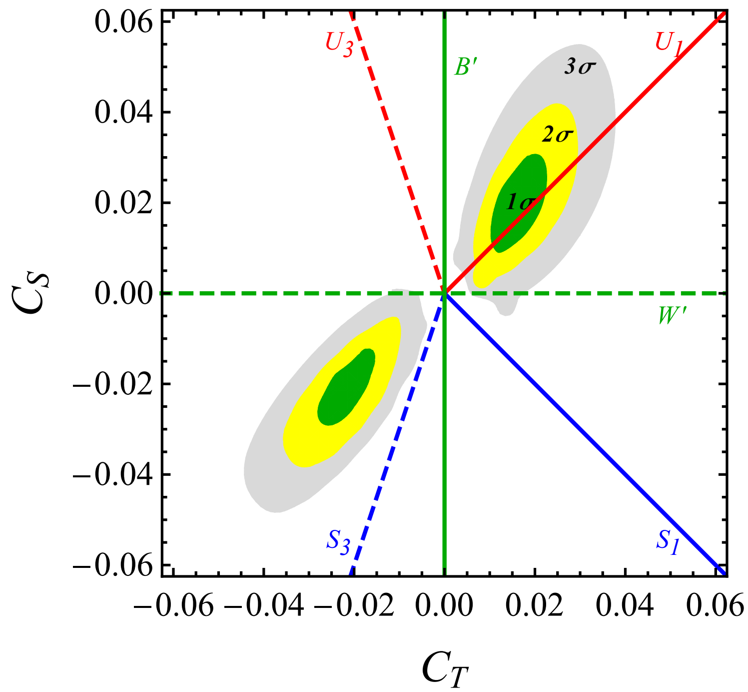
color SU(3), weak isospin SU(2) , weak hypercharge U(1) $Q=I_3 +Y$

$SU(3)\times SU(2)\times U(1)$	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	U_1	$RR\,(V_0^R)$	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 (see Assad et al, 1708.06350)

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

Buttazzo, Greljo, Isidoria, Marzocca
1706.07808



All test passes $SU(2)_L$-singlet vector leptoquark (3,1,2/3)

Helps to know: according to Asad, Fornal Grinstein 1708.06350;
proton decay at tree cannot be mediated by U(3,1,2/3).

Admir's talk!

If vector LQ is not a gauge boson − difficult to handle!

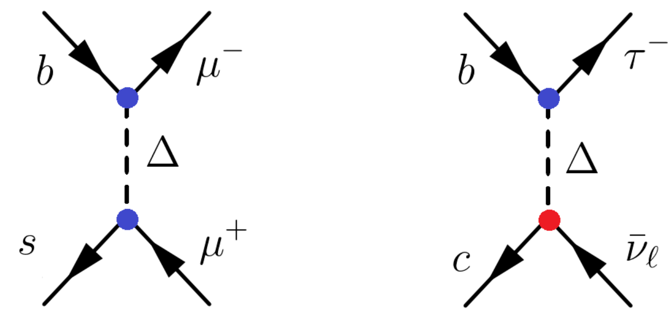
Possible to make Pati-Salam-like unified model vector LQ- gauge boson!:
Di Luzio, Greljo, Nardecchia, 1708.08450;
Bordone et al, 1712.01368;
Callibi, Crivellin, Li, 1709.00692, Marzocca, 1803.10972.

One scalar Leptoqaurk resolving both B anomalies:

(3,2,1/6)

Tree level solutions for $R_{D(*)}$ and $R_{K(*)}$

Right-handed neutrino introduced LQ (3,2,1/6)

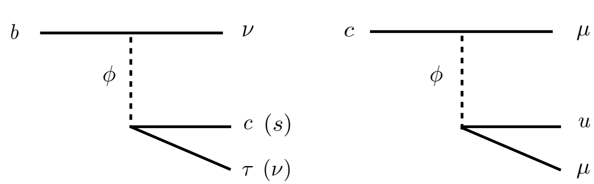


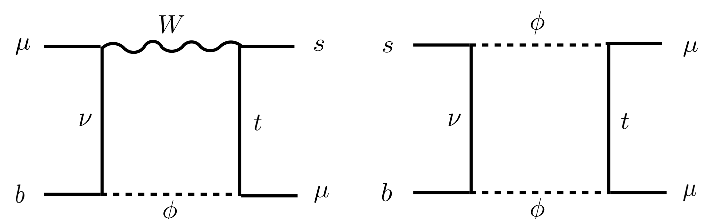
$$|M_{SM}|^2 + |M_{LQ}|^2$$

Becirevic et al, 1608.08501

passes all flavor constraints, but leads to R_{K*}>1!

(3,1,-1/3) destabilizes proton!





Bauer&Neubert, 1511.01900

$R_{D(*)}$ at tree level

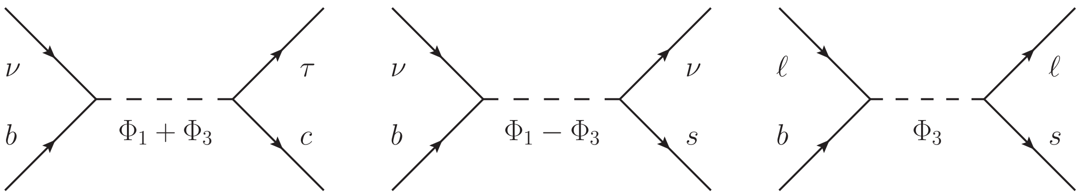
$R_{K(*)}$) at loop level

+ muon anomalous magnetic moment

Bečirević et al, 1608.07583 – troubles with charm, K, leptonic decays and $B \to D^{(*)} e(\mu)\nu$

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

(3,3,1/3) + (3,1,-1/3)
Crivellin et al, 1703.09226,
Marzocca, 1803.10972.

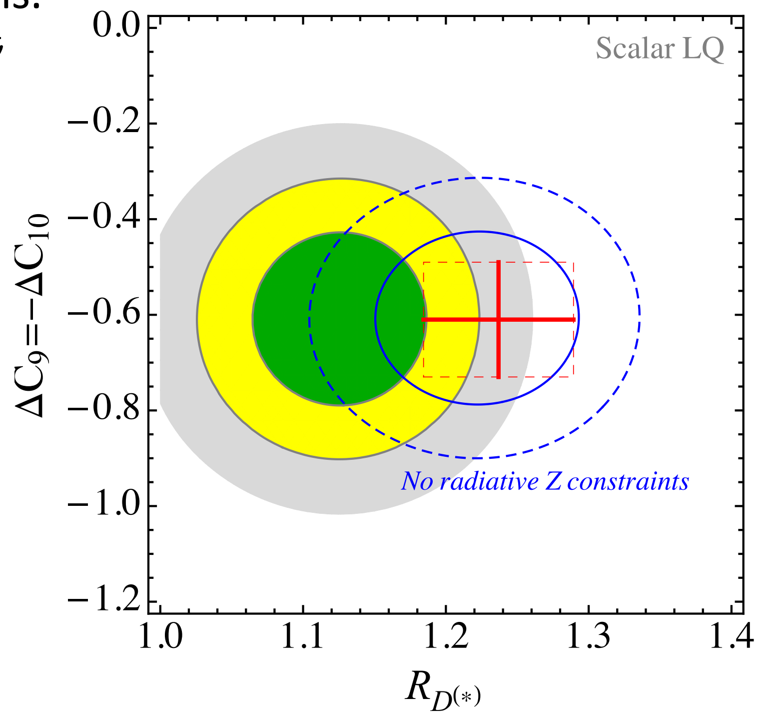


- (3,3,1/3) alone has a proper structure according to effective Lagrangian – it couples to only left-handed quarks and leptons.
- it leads to to large contribution in $B \to K^{(*)}\nu\bar{\nu}$

Buttazzo, Greljo, Isidori, Marzocca
1706.07808 :

$$C_S = -C_1 - 3C_3 \ , \qquad C_T = C_1 - C_3$$

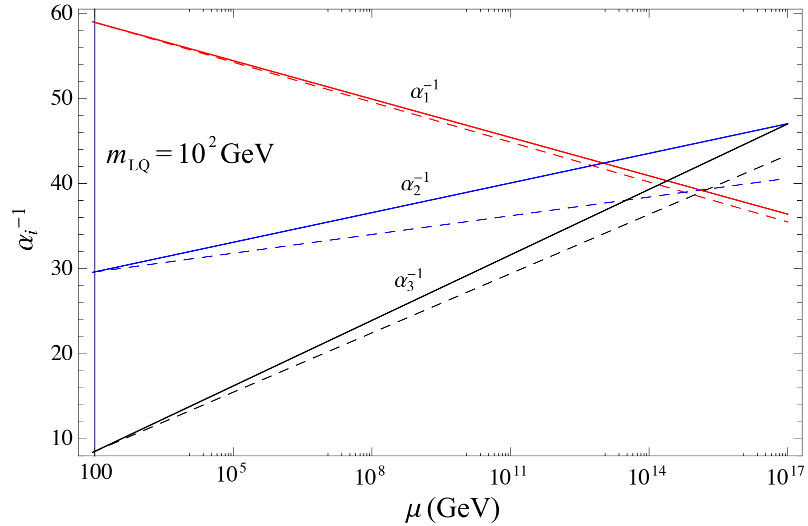
- radiative corrections to $Z \to \tau\bar{\tau}, \nu\bar{\nu}$ observables are enhanced by the factor of 3, implying a ~ 1.5σ tension in $R_{D(*)}$;



Potentially large sμ coupling disfavored by Ds/K ⟶ μν

Why two leptoquarks?

Leptoquarks are natural within GUT theories!



- GUT possible with light scalar LQs within SU(5) if there are 2 LQs (Doršner, SF, Greljo, Kamenik, Košnik 1603.04993) ;
- LQ S_3 , if accommodated within SU(5) does not cause proton decay, Doršner, SF, Faroughy, Košnik 1706.07779;
- Neutrino masses might be explained with 2 light LQs within a loop (Doršner, SF, Košnik, 1701.08322);

New Proposal: Two Leptoquarks

D. Becirevic,I. Dorsner, , S. F, D. Faroughy, N. Kosnik and O. Sumensari 1804.xxxxx

Not complete V-A picture of NP!

Scalar LQ better than Vector LQ − simpler UV completion;

R_2 =(3,2,7/6) contains two states with electric charges 5/3 and 2/3.

$$\mathcal{L}_{R_2} = (V y_R)^{ij}\, \bar{u}_{Li} \ell_{Rj} R_2^{(5/3)} + y_R^{ij}\, \bar{d}_{Ri} \ell_{Rj} R_2^{(2/3)} + (y_L U)^{ij}\, \bar{u}_{Ri} \nu_{Lj} R_2^{(2/3)} - y_L^{ij}\, \bar{u}_{Ri} \ell_{Lj} R_2^{(5/3)} + \text{h.c.}$$

Flavour basis!

S_3 =($\bar{3}$,3,1/3) contains three states with electric charges $S_3^{2/3}, S_3^{-1/3}, S_3^{-4/3}$

$$\mathcal{L}_{S_3} = y^{ij}\, \bar{Q}_i^C i\tau_2 (\vec{\tau} \cdot \vec{S}_3) L_j + \text{h.c.}$$

Mass eigenstate basis:

$$\mathcal{L}_{R_2\&S_3} = + (V_{\rm CKM}\, y_R\, E_R^\dagger)^{ij}\, \bar{u}'_{Li}\ell'_{Rj}R_2^{(5/3)} + (y_R\, E_R^\dagger)^{ij}\, \bar{d}'_{Li}\ell'_{Rj}R_2^{(2/3)}$$
$$+ (U_R\, y_L\, U_{\rm PMNS})^{ij}\, \bar{u}'_{Ri}\nu'_{Lj}R_2^{(2/3)} - (U_R\, y_L)^{ij}\, \bar{u}'_{Ri}\ell'_{Lj}R_2^{(5/3)}$$
$$- (y\, U_{\rm PMNS})^{ij}\, \bar{d}'^{C}_{Li}\nu'_{Lj}S_3^{(1/3)} - \sqrt{2}\, y^{ij}\, \bar{d}'^{C}_{Li}\ell'_{Lj}S_3^{(4/3)}$$
$$+ \sqrt{2}(V^*_{\rm CKM}\, y\, U_{\rm PMNS})_{ij}\, \bar{u}'^{C}_{Li}\nu'_{Lj}S_3^{(-2/3)} - (V^*_{\rm CKM}\, y)_{ij}\, \bar{u}'^{C}_{Li}\ell'_{Lj}S_3^{(1/3)} + \text{h.c.}$$

$$u'_{L,R} = U_{L,R}\, u_{L,R},\; d'_{L,R} = D_{L,R}\, d_{L,R},\; \ell'_{L,R} = E_{L,R}\, \ell_{L,R},\; \nu'_L = N_L\, \nu_L$$

$$V_{\rm CKM} = U_L\, D_L^\dagger \qquad U_{\rm PMNS} \equiv E_L\, N_L^\dagger$$

We assume following: $y_R = y_R^T$ $\quad y = -y_L$ from SU(5) GUT

Appealing feature: the same coupling for S_3 and R_2

$$y_R\, E_R^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix},\; U_R\, y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix},\; U_R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

Parameters: $m_{R_2},\ m_{S_3},\ y_R^{b\tau},\ y_L^{c\mu},\ y_L^{c\tau}$ and θ

Phenomenology suggest $\theta \approx \pi/2$ and y_R complex!

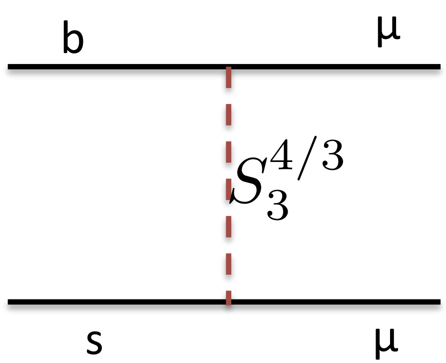
Explaining $R_{K(*)}$

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

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

$$C_9^\mu = -C_{10}^\mu \in (-0.85, -0.50)$$

S$_3$ explains it! V-A explanation:



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

Explaining $R_{D(*)}$

Not V-A explanation: T and S from R_2 very small contribution from S_3

$$\mathcal{L}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\,V_{cb}\Big[(1+g_V)(\bar{u}_L\gamma_\mu d_L)(\bar{\ell}_L\gamma^\mu\nu_L) + g_S(\mu)\,(\bar{u}_R d_L)(\bar{\ell}_R\nu_L) + g_T(\mu)\,(\bar{u}_R\sigma_{\mu\nu}d_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{h.c.}$$

$$g_S = 4\,g_T = \left.\frac{y_L^{u\ell'}\,\left(y_R^{d\ell}\right)^*}{4\sqrt{2}\,m_{R_2}^2\,G_F\,V_{ud}}\right|_{\mu=m_{R_2}} \qquad g_V = -\frac{y_{d\ell'}\,(Vy^*)_{u\ell}}{4\sqrt{2}\,m_{S_3}^2\,G_F\,V_{ud}}$$

S_3 creates g_V $S_3^{-2/3}$

Important constraints

Tree level constraints

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

$$R^{K\ \mathrm{exp}}_{e/\mu} = 2.488(10) \times 10^{-5}$$

$$R^{K\ \mathrm{SM}}_{e/\mu} = 2.477(1) \times 10^{-5}$$

$$R^{D^{(*)}}_{\mu/e} = \frac{\Gamma(B \to D^{(*)}\mu\bar{\nu})}{\Gamma(B \to D^{(*)}e\bar{\nu})}$$

PDG

$$R^{D\ \mathrm{exp}}_{\mu/e} = 0.995(45)$$

(Belle)

$$\mathcal{B}(\tau \to \mu\phi) < 8.4 \times 10^{-8}$$

$$R^{D^*\ \mathrm{exp}}_{\mu/e} = 1.04(5)$$

Loop constraints

$$\Delta m^{\mathrm{exp}}_{B_s} = 17.7(2)\ \mathrm{ps}^{-1} \qquad (19.0 \pm 2.4)\ \mathrm{ps}^{-1}$$

SM- FLAG

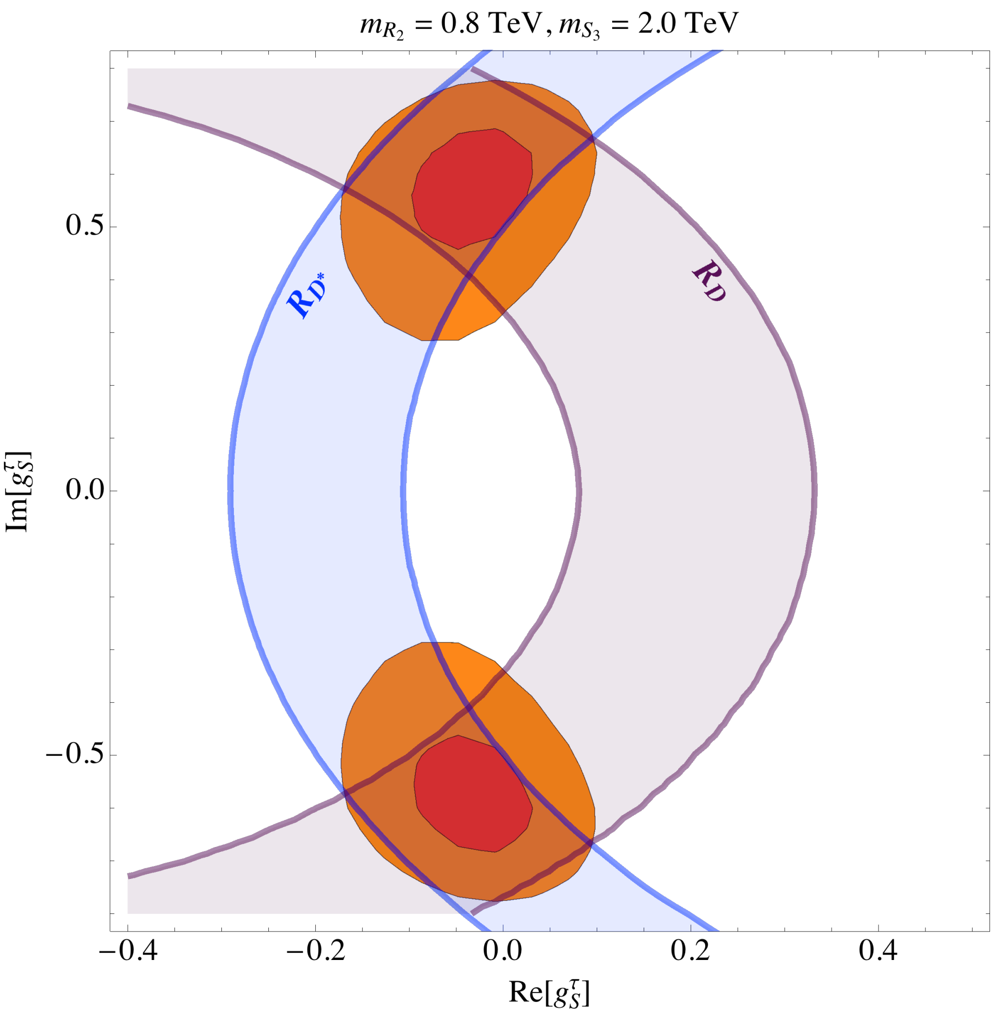
$$Z \to \mu\mu,\ Z \to \tau\tau,\ Z \to \nu\nu$$

$$\frac{g^\tau_V}{g^e_V} = 0.959(29)\,, \frac{g^\tau_A}{g^e_A} = 1.0019(15) \qquad \frac{g^\mu_V}{g^e_V} = 0.961(61)\,, \frac{g^\mu_A}{g^e_A} = 1.0001(13)$$

$$N^{\mathrm{exp}}_\nu = 2.9840(82)$$

Results and Predictions

$$\mathcal{L}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{cb}\big[(1+g_V)(\bar{u}_L\gamma_\mu d_L)(\bar{\ell}_L\gamma^\mu\nu_L) + g_S(\mu)\,(\bar{u}_R d_L)(\bar{\ell}_R\nu_L) + g_T(\mu)\,(\bar{u}_R\sigma_{\mu\nu}d_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\big]$$

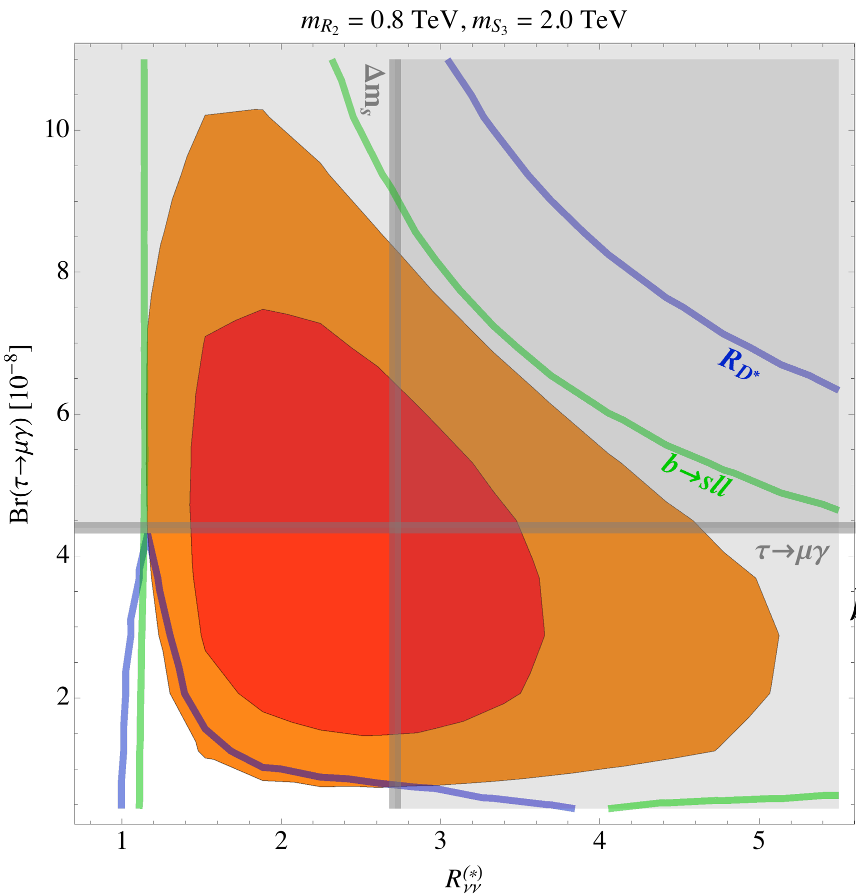


$$g_S(\mu = m_\Delta) = 4\,g_T(\mu = m_\Delta) = \frac{y_L^{u\ell'}\,\left(y_R^{d\ell}\right)^*}{4\sqrt{2}\,m_{R_2}^2\,G_F V_{ud}}\,,$$

$$g_V = -\frac{y_{d\ell'}\,(V y^*)_{u\ell}}{4\sqrt{2}\,m_{S_3}^2 G_F V_{ud}}\,;$$

For $\mathrm{Re}[g_S^\tau] = 0$ we get $\mathrm{Im}[g_S^\tau]| = 0.59^{+0.13(+0.20)}_{-0.14(-0.29)}$

Constraints



$R_{\nu\nu} = B(B\to K\nu\nu)/B(B\to K\nu\nu)^{SM}$

$$\mathcal{L}_{\rm eff}^{b\to s\nu\nu} = \frac{G_F\alpha_{\rm em}}{\pi\sqrt{2}} V_{tb}V_{ts}^* \, C_L^{ij} \, \left(\bar{s}\gamma_\mu P_L b\right)\left(\nu_i\gamma^\mu(1-\gamma_5)\nu_j\right)$$

$$C_L^{ij} = \delta_{ij}C_L^{\rm SM} + \delta C_L^{ij} \qquad C_L^{\rm SM} = -6.38(6)$$

$$\delta C_L^{ij} = \frac{\pi v^2}{2\alpha_{\rm em}V_{tb}V_{ts}^*}\frac{y_{bj}y_{si}^*}{m_{S_3}^2}$$

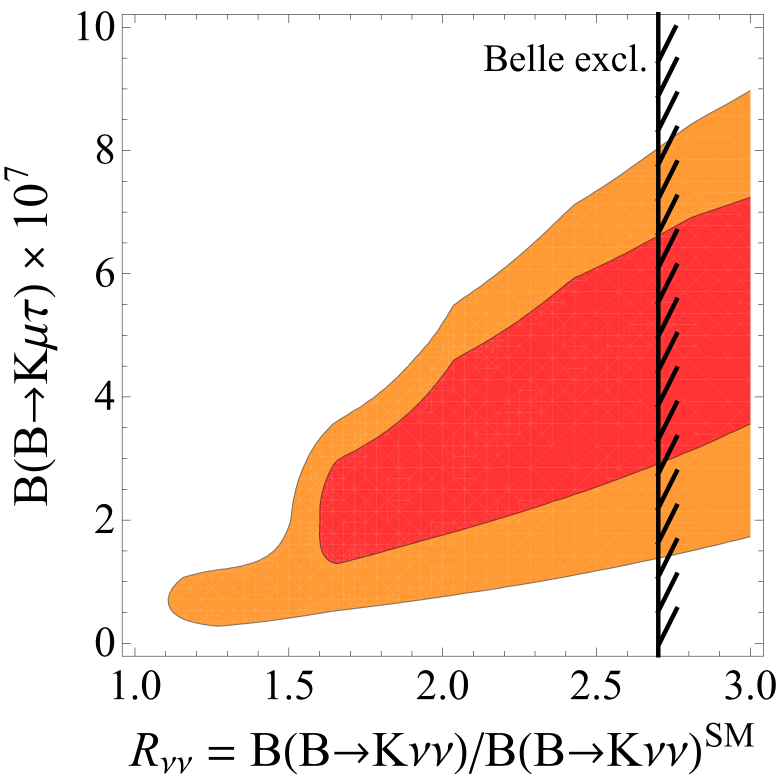
$$R_{\nu\nu}^{(*)} = \frac{\sum_{ij}|\delta_{ij}C_L^{SM} + \delta C_L^{ij}|^2}{3|C_L^{\rm SM}|^2}$$

$$\mathcal{B}(\tau\to\mu\gamma) = \tau_\tau \frac{\alpha_{\rm em}(m_\tau^2 - m_\mu^2)^3}{4m_\tau^3}\left(|\sigma_L|^2 + |\sigma_R|^2\right)$$

c quark in the loop

s and b quarks in the loop

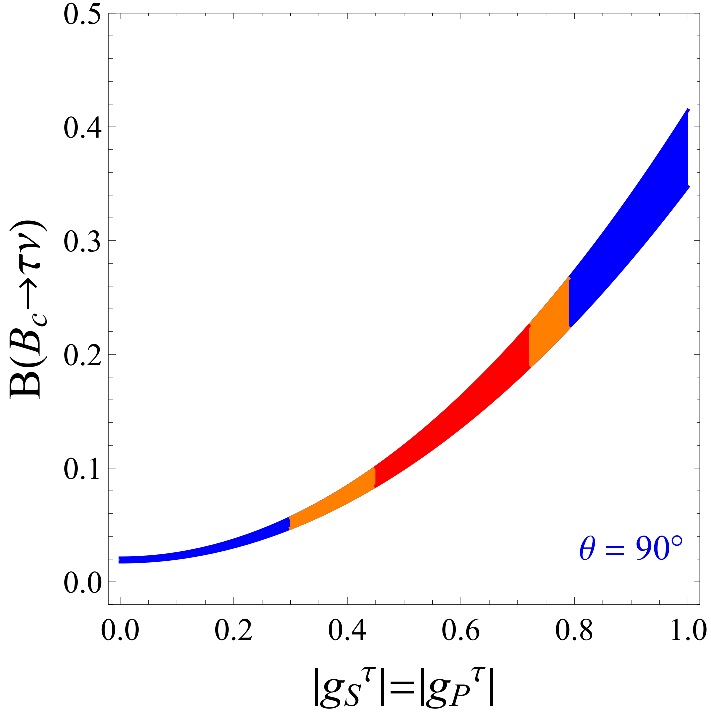
Predictions

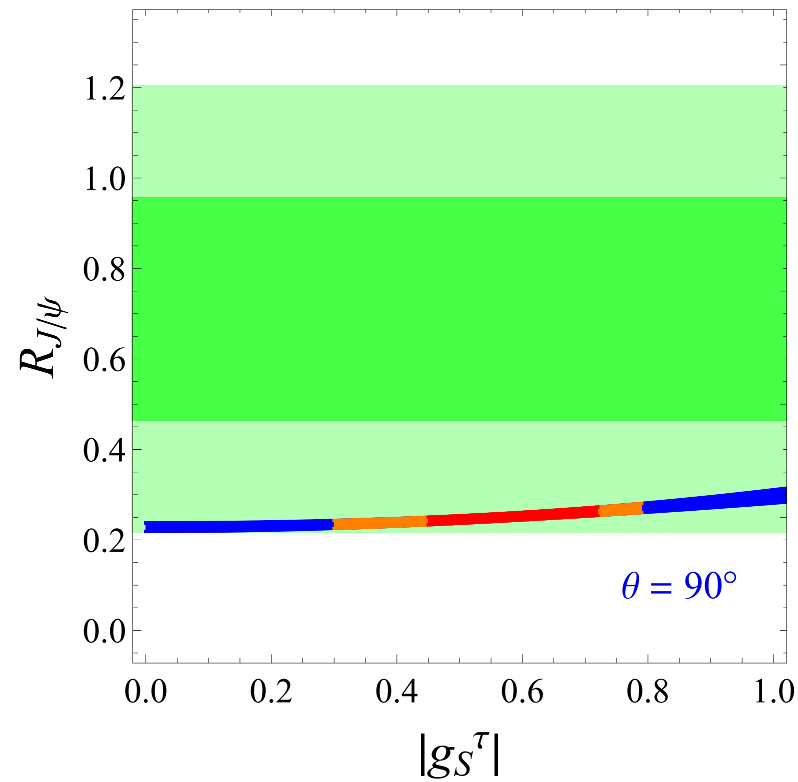


Increase of $\mathcal{B}(B \to K\nu\bar{\nu})$ by $\gtrsim 50\%$ in comparison with SM value

Upper and lower bounds on the LFV rates: $B(B \to K\mu\tau) \geq 2 \times 10^{-7}$

Becirevic et al, 1608.07583





$$\mathcal{B}(B_c \to \tau\nu) < 30\%$$

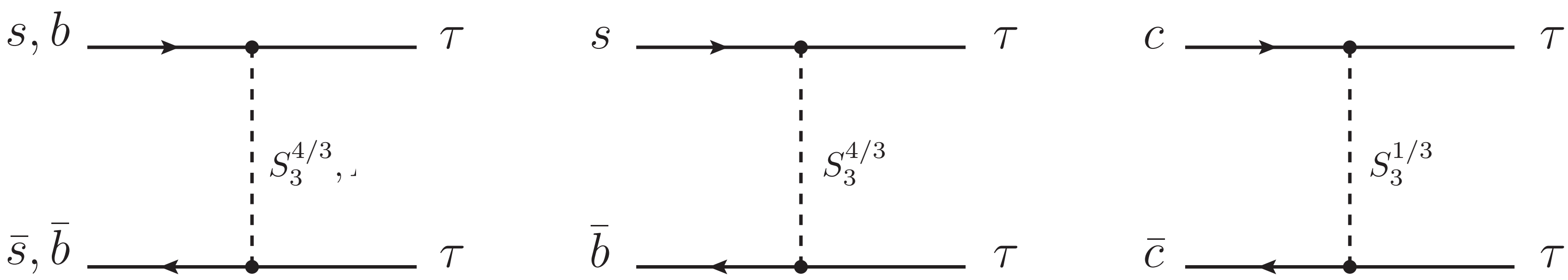
Alonso, Grinstein, Camalich, 1611.06676

$$R_{J/\psi} > R_{J/\psi}^{SM}$$

new FF estimate QCDSR + latt
(Becirevic et al., 2018)

LHC constraints on LQ couplings

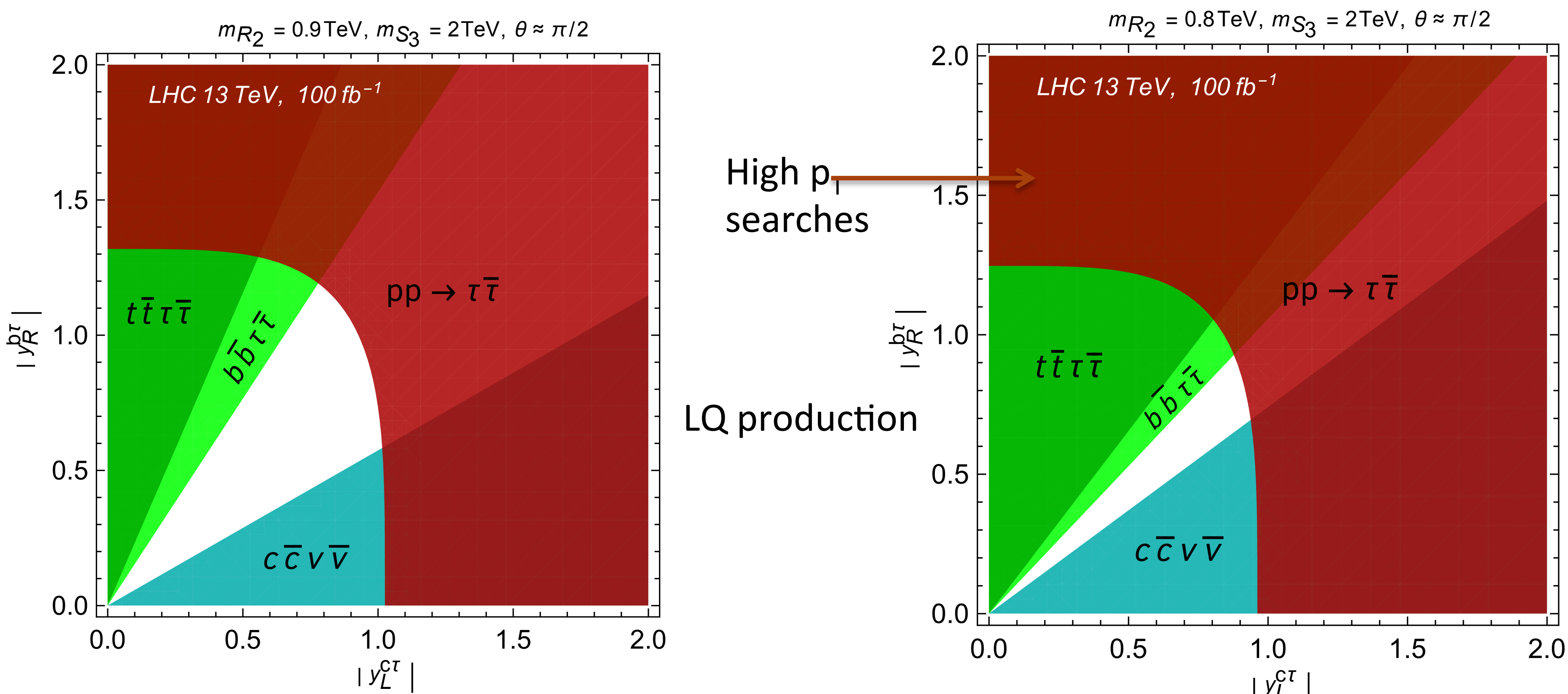
Processes in t-channel $pp \to \tau^+\tau^-$



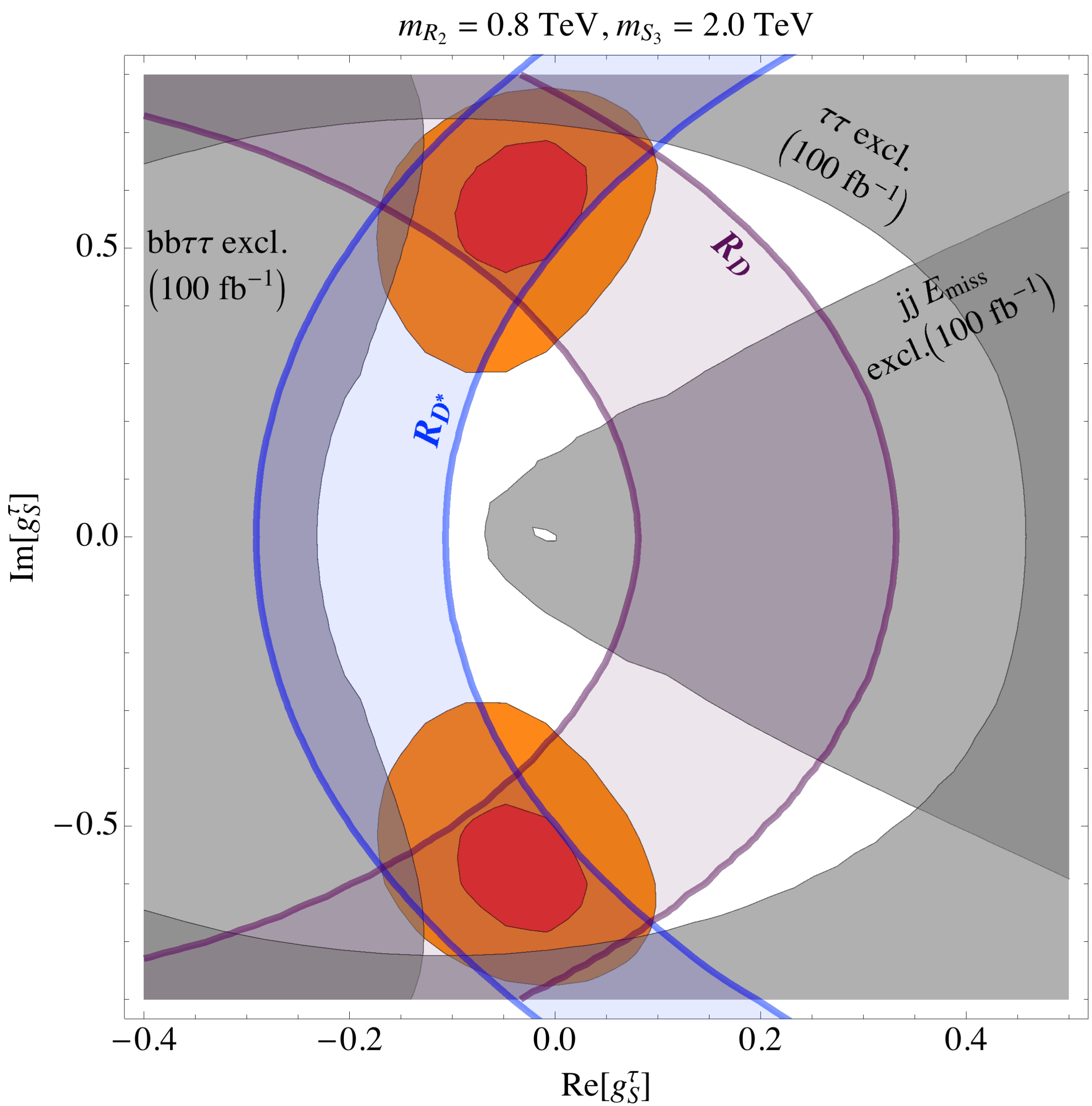
Flavour anomalies generate s τ , bτ and cτ relatively large couplings.
s quark pdf function for protons are ~ 3 times lagrer contribution then for b quark.

Light LQ → impact on the shape of pp → ll distributions (Faroughy, Greljo and Kamenik, 1609.07138, Greljo and Marzocca, 1704.09015)

- Recast Atlas searches for pp → (Z′ →)ττ leads to bounds on R_2 and (weak) ones on S_3 for our θ≈π/2
- pp → μμ not very useful to us, but LQ pair-production data are
- Experimental bounds with 3.2 fb^{-1} result in constraints not competitive with those obtained from flavor data. Projecting to 100 fb^{-1}:



Direct searches (projections to 100 fb^{-1})



Light Leptoquarks in SU(5) GUT

- Scalars: $R_2 \in 45, 50$, $S_3 \in 45$. SM matter fields in 5_i and 10_i ;

- R_2 does not have diquark couplings − no proton decay. Operators $10_i\, 10_j\, 45$ Might lead to proton decay (Dorsner, SF, Kosnik, 1701.08322).

Available operators

$$\mathbf{10}_i \mathbf{5}_j \underline{\mathbf{45}}: \quad y_{2\,ij}^{RL}\, \overline{u}_R^i R_2^a \varepsilon^{ab} L_L^{j,b}, \quad y_{3ij}^{LL} \overline{Q^c}_L^{i,a} \varepsilon^{ab} (\tau^k S_3^k)^{bc} L_L^{j,c}$$

$$\mathbf{10}_i \mathbf{10}_j \underline{\mathbf{50}}: \quad y_{2\,ij}^{LR}\, \overline{e}_R^i R_2^{a\,*} Q_L^{j,a}$$

- by breaking SU(5) to SM the two R_2's mix – one can be light and the other (very) heavy.
- the Yukawa couplings determined from flavor physics remain perturbative ($< \sqrt{4\pi}$) up to the GUT scale;

Summary

- Building a viable model which accommodates B-physics anomalies and remains consistent with all other measured flavor observables is difficult;

- We propose a minimalistic model with two light (O(1 TeV)) scalar leptoquarks. Model passes all constraints and satisfactorily accommodates B-physics anomalies. (g_S complex, i.e. one Yukawa must be complex - e.g. $y^{b\tau}{}_R$);

- Model is of “V − A”structure in describing $b \to sll$, but it is NOT for $b \to cl\bar{\nu}$. At $\mu = m_{R2}$, effective $b \to c$ couplings satisfy $g_S = -g_P = 4g_T$;

- Our model is GUT inspired and allows for unification with only two LQ’s. Yukawa couplings remain perturbative after 1-loop running to Λ_{GUT} ;

- Results of the direct LHC searches might soon become relevant constraints too. Opportunities for direct searches at LHC!

Thanks!

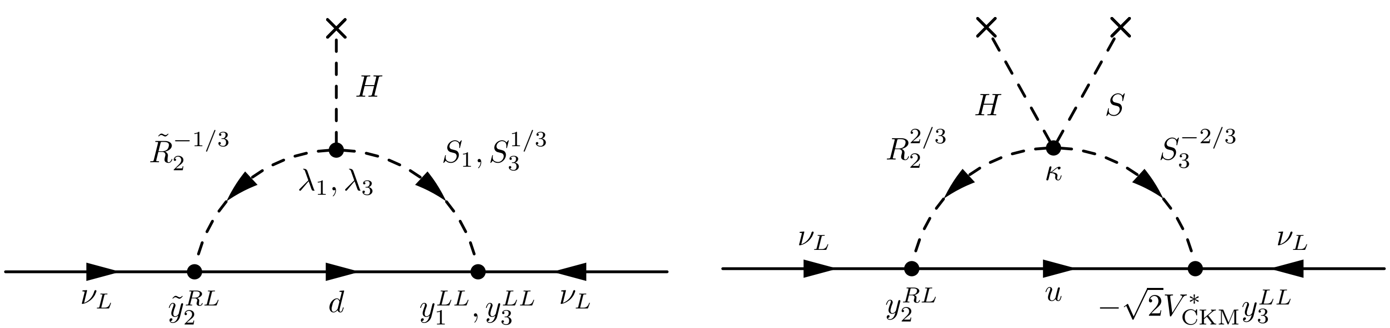
“It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong. “

Richard P. Feynman

SU(5) GUT with (3,3,1/3) + (3,2,1/6)
Doršner, SF, Faroughy, Košnik

- GUT possible with light scalar LQs within SU(5) if there are 2 LQs (Doršner, SF, Greljo, Kamenik, Košnik 1603.04993) ;
- LQ S_3 , if accommodated within SU(5) does not cause proton decay;
- Neutrino masses might be explained with 2 light LQs within a loop (Doršner, SF, Košnik, 1701.08322);
-

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



one-loop neutrino mass mechanism within the framework of GUT

Constraints from flavor observables

$(g-2)_\mu$

$B_c \to \tau\nu$

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

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

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

$K \to \mu\nu_\mu$

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

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

$W \to \tau\bar{\nu},\ \tau \to \ell\bar{\nu}\nu$

$Z \to b\bar{b} \qquad Z \to l^+l^-$

Constraints from LFV

$\tau \to \mu\gamma$

$\mu \to e\gamma$

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

$K \to \mu e$

$B \to K\mu e$

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

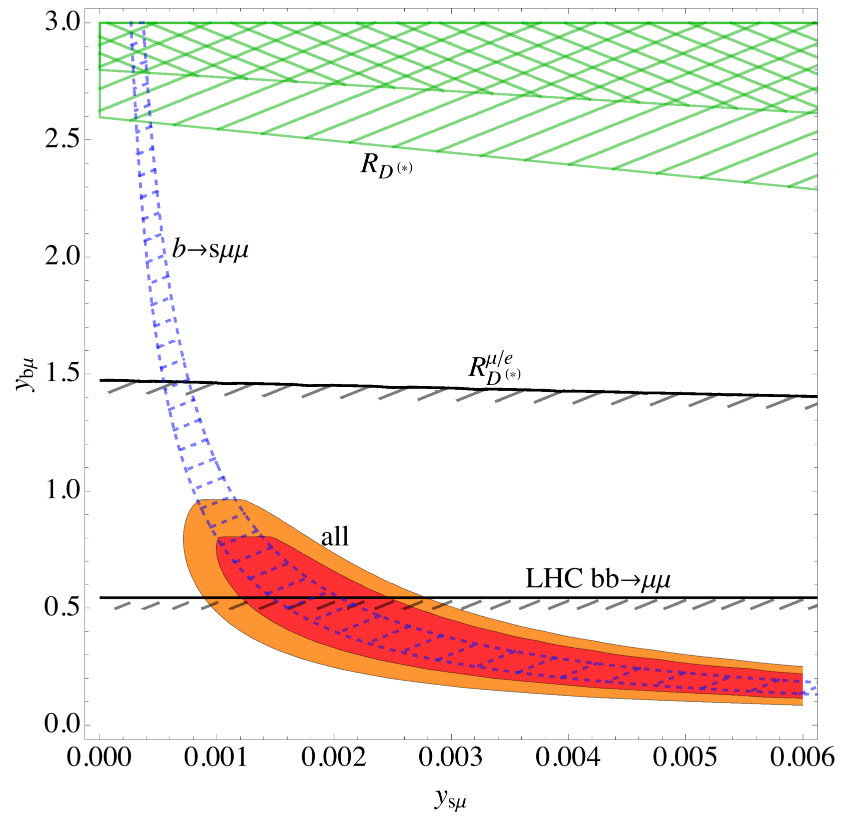
$\tau \to \phi\mu$

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

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

S$_3$ coupled to the muons only

$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{s\mu} & 0 \\ 0 & y_{b\mu} & 0 \end{pmatrix}$$



$R_{D(*)}$ is resolved in hatched (2 σ) and doubly hatched (1 σ) regions,
the b → sμμ puzzle is resolved in dashed-hatched region at 1 σ.
Region below the black line with a hatching is in 1 σ agreement with Rμ/e .

Recent update on SM value of $R_{D(*)}$

Bigi, Gambino, Schacht 1707.09509

"Luke's theorem does not protect the form factors from $1/m^2$ corrections, it is therefore natural to expect $1/m^2$ corrections of order 10-20%, and one cannot exclude that occasionally they can be even larger".

$$A_1(1) = 0.857(41)$$

$$A_1(1) = 0.906(13)$$

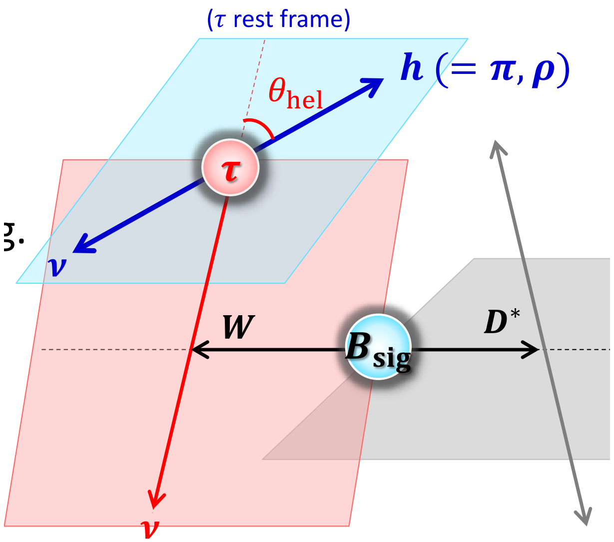
approach now includes HQET constraints with realistic uncertainties and improves on the CLN parametrization in several ways.

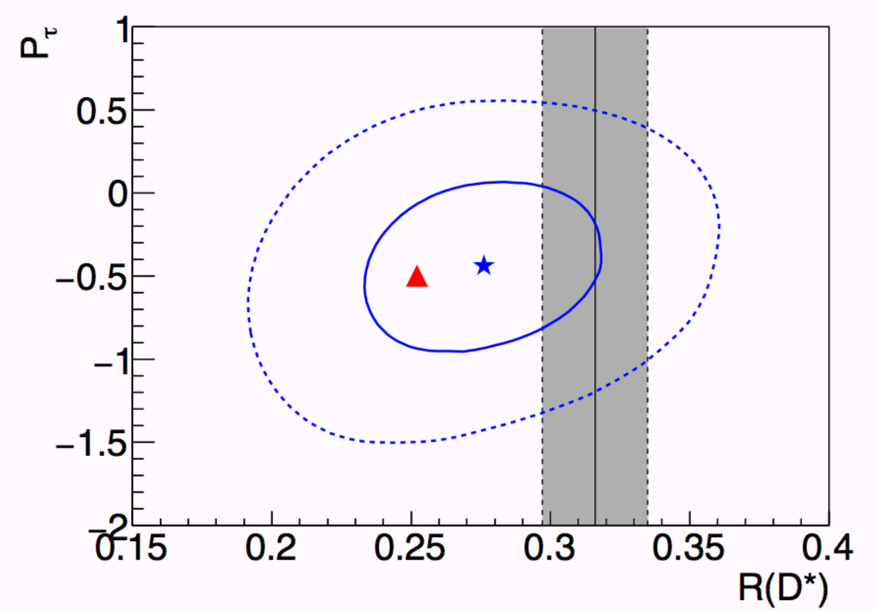
Belle: 1608.06931

τ polarization

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

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





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

	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\text{int}}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L) W'_\mu$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$			
$\mathcal{O}_{S_R}$	$(\bar{c} P_R b)\,(\bar{\tau} P_L \nu)$			
$\mathcal{O}_{S_L}$	$(\bar{c} P_L b)\,(\bar{\tau} P_L \nu)$		$\rangle(\mathbf{1},\mathbf{2})_{1/2}$	$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$			
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow\ \mathcal{O}_{V_L} \langle$	$(\mathbf{3},\mathbf{3})_{2/3}$	$\lambda\, \bar{q}_L \boldsymbol{\tau}\gamma_\mu \ell_L \boldsymbol{U}^\mu$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow\ -2\mathcal{O}_{S_R}$	$\rangle(\mathbf{3},\mathbf{1})_{2/3}$	$(\lambda\, \bar{q}_L \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{d}_R \gamma_\mu e_R) U^\mu$
$\mathcal{O}'_{S_R}$	$(\bar{\tau} P_R b)\,(\bar{c} P_L \nu)$	$\longleftrightarrow\ -\frac{1}{2}\mathcal{O}_{V_R}$		
$\mathcal{O}'_{S_L}$	$(\bar{\tau} P_L b)\,(\bar{c} P_L \nu)$	$\longleftrightarrow\ -\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$	$(\mathbf{3},\mathbf{2})_{7/6}$	$(\lambda\, \bar{u}_R \ell_L + \tilde{\lambda}\, \bar{q}_L i\tau_2 e_R) R$
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L b)\,(\bar{c}\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow\ -6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$		
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow\ -\mathcal{O}_{V_R}$		
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow\ -2\mathcal{O}_{S_R}$	$(\bar{\mathbf{3}},\mathbf{2})_{5/3}$	$(\lambda\, \bar{d}^c_R \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{q}^c_L \gamma_\mu e_R) V^\mu$
$\mathcal{O}''_{S_R}$	$(\bar{\tau} P_R c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow\ \frac{1}{2}\mathcal{O}_{V_L} \langle$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$	$\lambda\, \bar{q}^c_L i\tau_2 \boldsymbol{\tau} \ell_L \boldsymbol{S}$
$\mathcal{O}''_{S_L}$	$(\bar{\tau} P_L c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow\ -\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$	$\rangle(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$(\lambda\, \bar{q}^c_L i\tau_2 \ell_L + \tilde{\lambda}\, \bar{u}^c_R e_R) S$
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow\ -6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$		

From Freytsis, Ligeti,and Ruderman, arXiv:1506.08896
Comment: neutrino SM-like!