Leptoquark resolustion of B meson anomalies

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Puzzles in B physics

Sign of LFU violation?

NP: effective Lagrangian approach for $R_{D(*)}$, R_K and new tests of NP

Model of NP: Leptoquarks

B physics anomalies: experimental results ≠ SM predictions!

charged current SM tree level

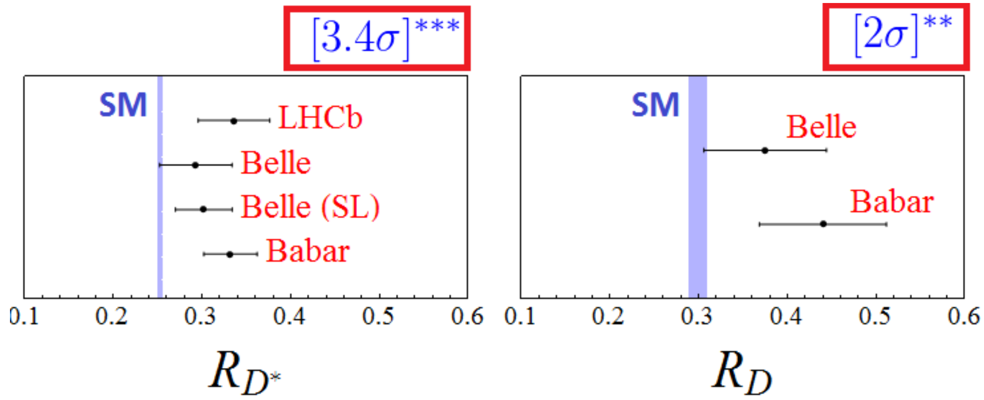
1) $R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$ 3.9σ

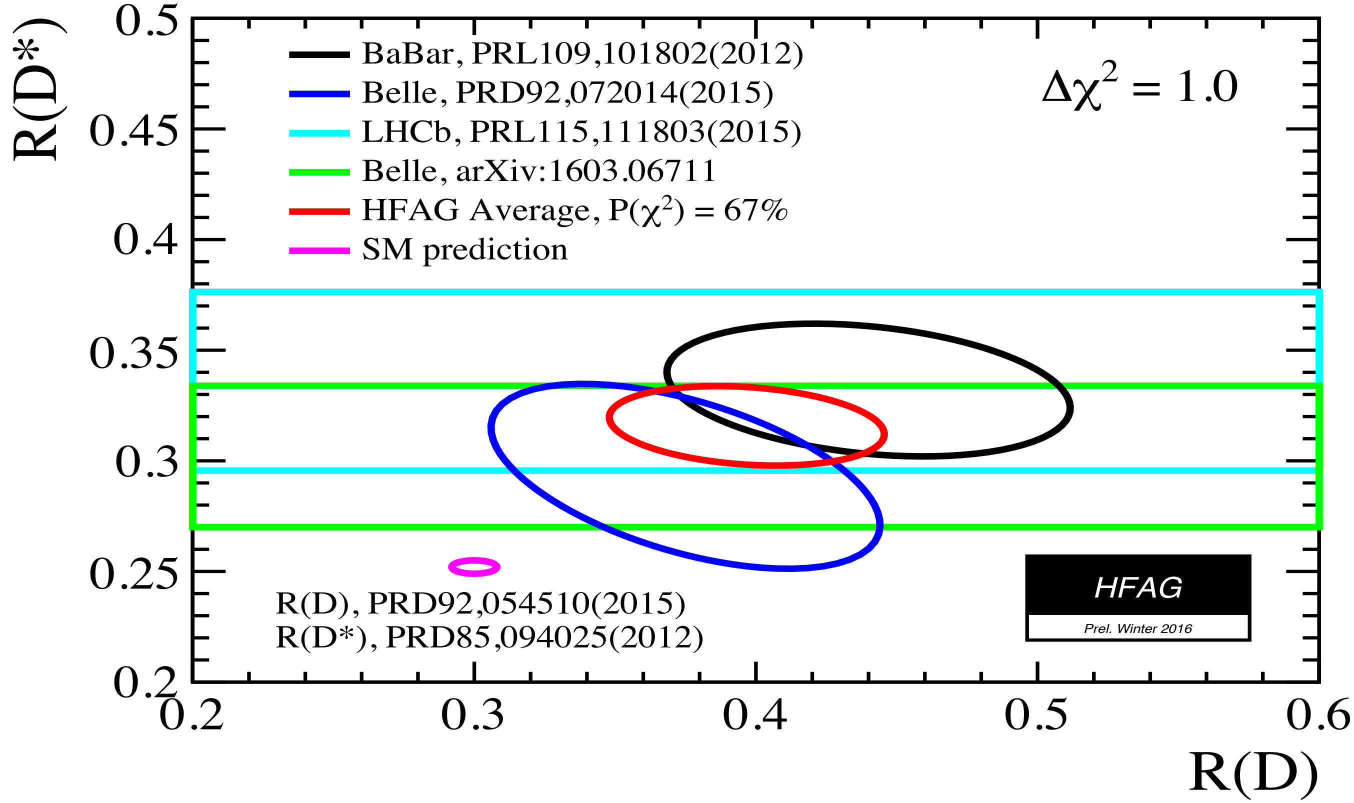
FCNC - SM loop process

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

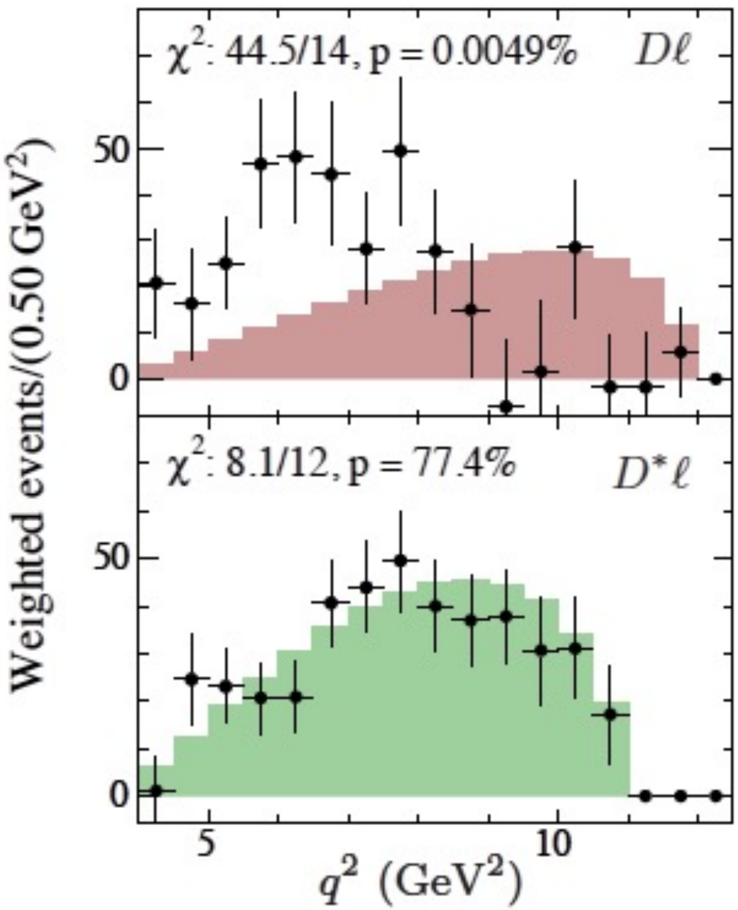
3) $R_K = \frac{\Gamma(B\to K\mu\mu)}{\Gamma(B\to Kee)}$ in the dilepton invariant mass bin $1\ \mathrm{GeV}^2 \leq q^2 \leq 6\ \mathrm{GeV}^2$ 2.6σ

Experimental results on R_D and R_{D*}





BaBar, 1303.0571



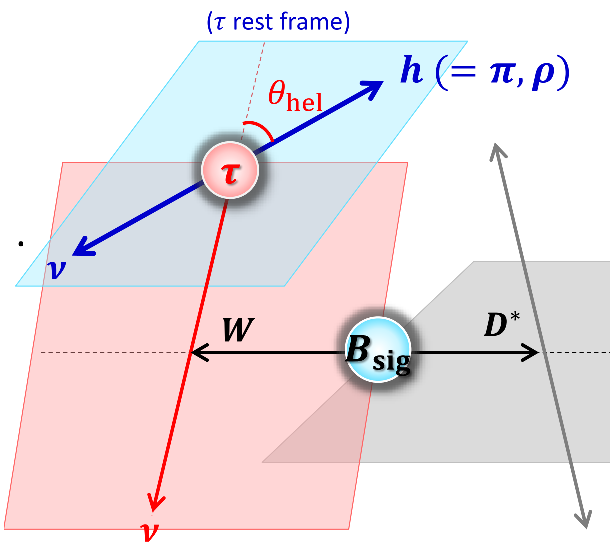
Momentum transfer distributions

1608.06931

Belle, Sato@ICHEP2016

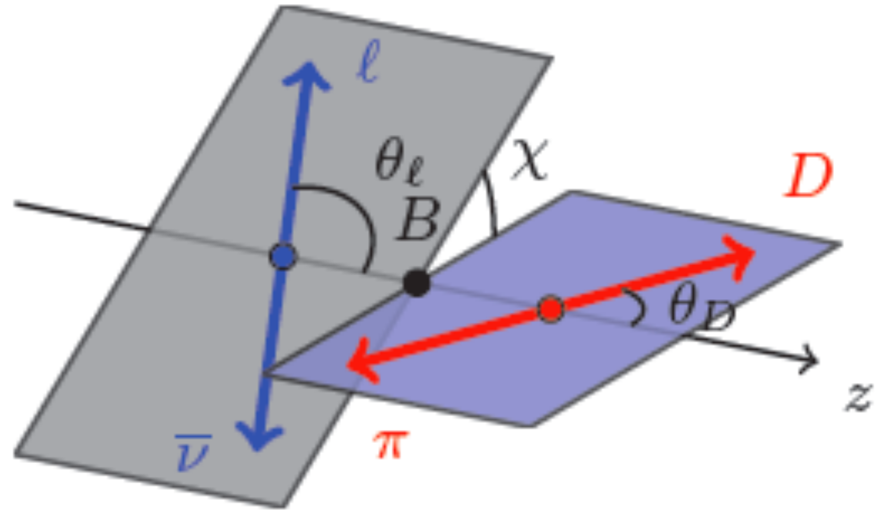
τ polarization $P_\tau = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$

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



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

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



There are 11 observables:

1. Differential decay distribution

2. Forward-backward asymmetry

3. Lepton polarization asymmetry

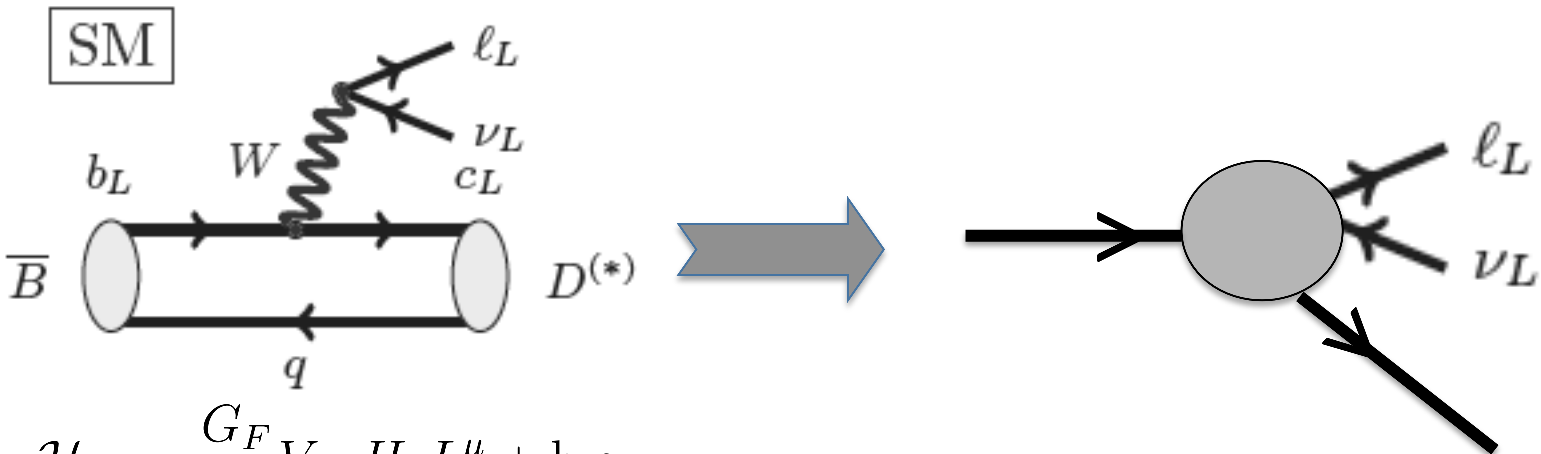
4. Partial decay rate according to the polarization of D*

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

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 Hamiltonian approach in $b \to c l \nu_l$ transition



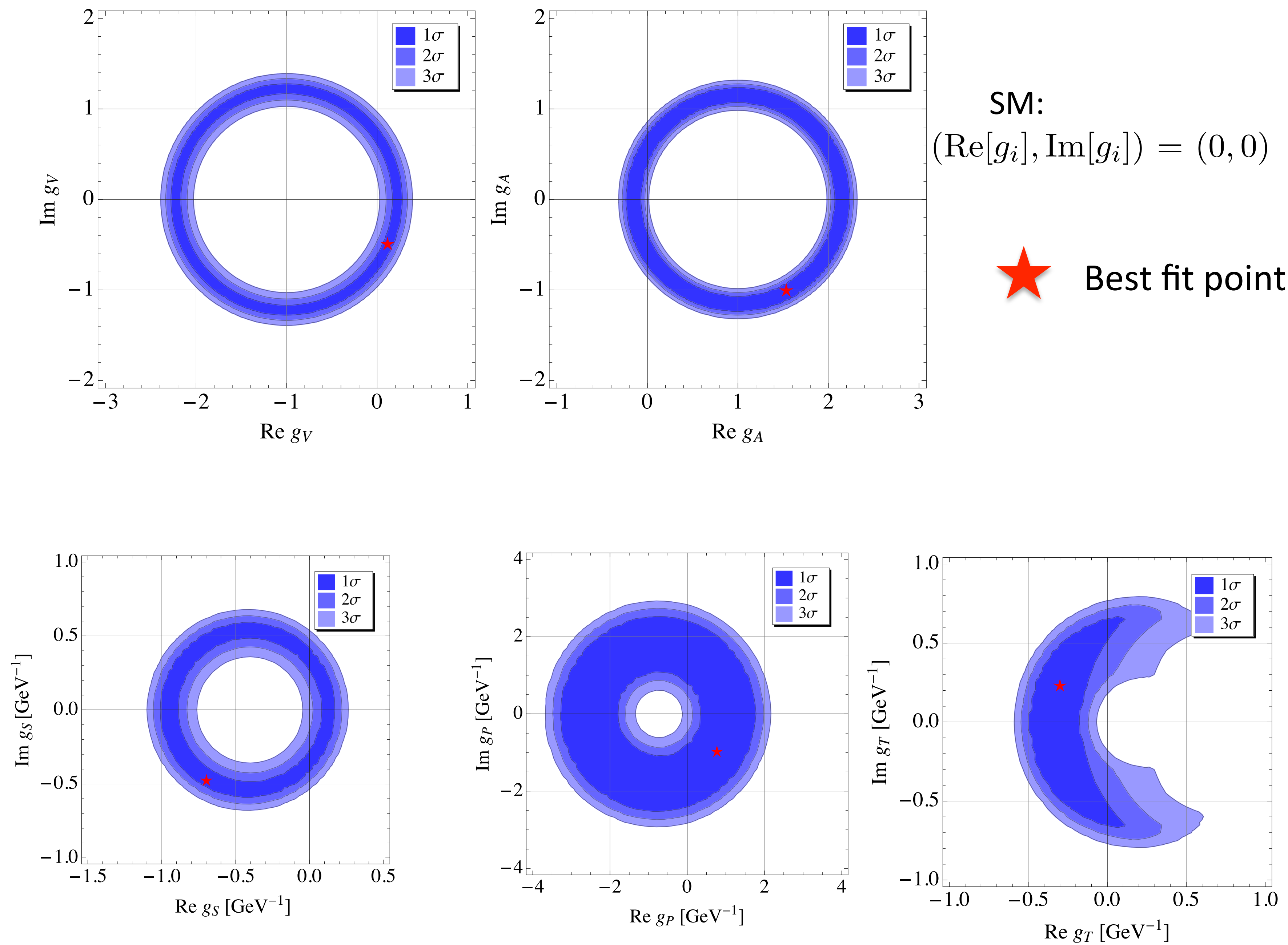
$$
\begin{aligned}
\mathcal{H}_{\text{eff}} &= \frac{G_F}{\sqrt{2}} V_{cb}\; H_\mu L^\mu + \text{h.c} \\
&= \frac{G_F}{\sqrt{2}} V_{cb} \Big[(1+g_V)\bar{c}\gamma_\mu b + (-1+g_A)\bar{c}\gamma_\mu\gamma_5 b + g_S\; i\partial_\mu(\bar{c}b) + g_P\; i\partial_\mu(\bar{c}\gamma_5 b) \\
&\qquad + g_T\; i\partial^\nu(\bar{c}i\sigma_{\mu\nu}b) + g_{T5}\; i\partial^\nu(\bar{c}i\sigma_{\mu\nu}\gamma_5 b)\Big]\; \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell + \text{h.c}\,,
\end{aligned}
$$

D. Becirevic, S.F. I. Nisandzic, A. Tayduganov, 1602.03030 (SM neutrino)

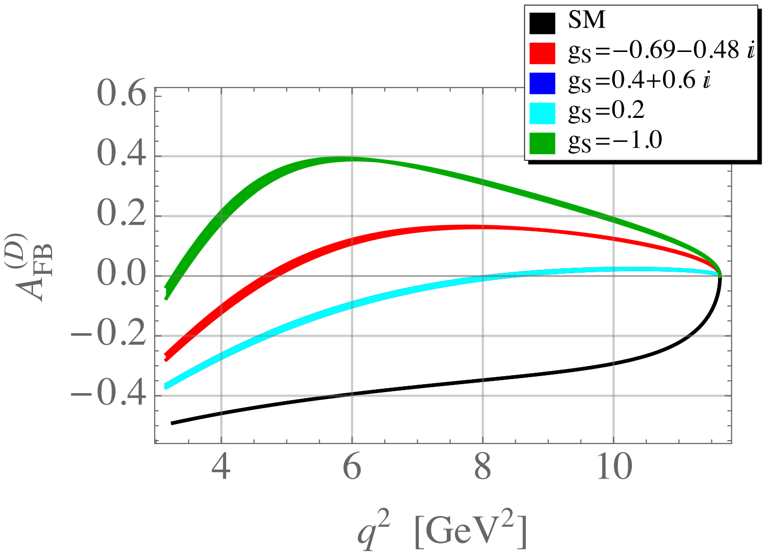
Best fit values

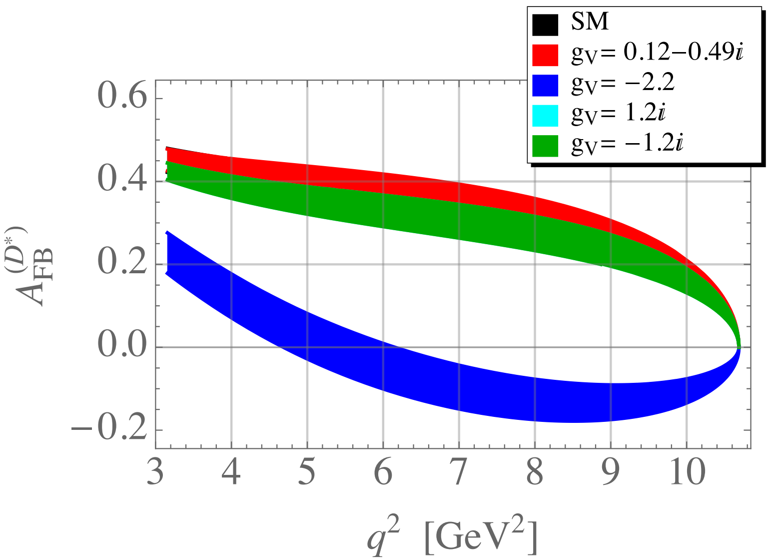
$g_V = 0.21 - i\;0.76,\qquad g_A = -0.18 - i\;0.05,$

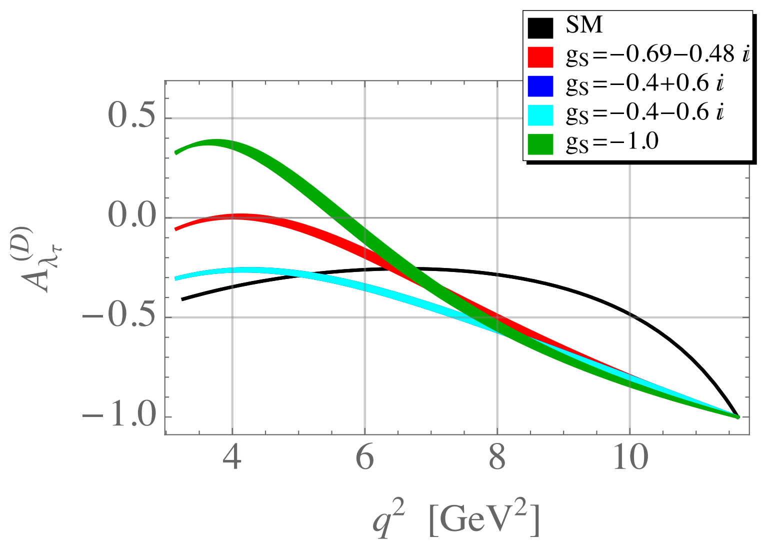
$g_S = -0.92 - i\;0.38,\qquad g_P = 0.91 + i\;0.38,\qquad g_T = -0.42 + i\;0.15,$

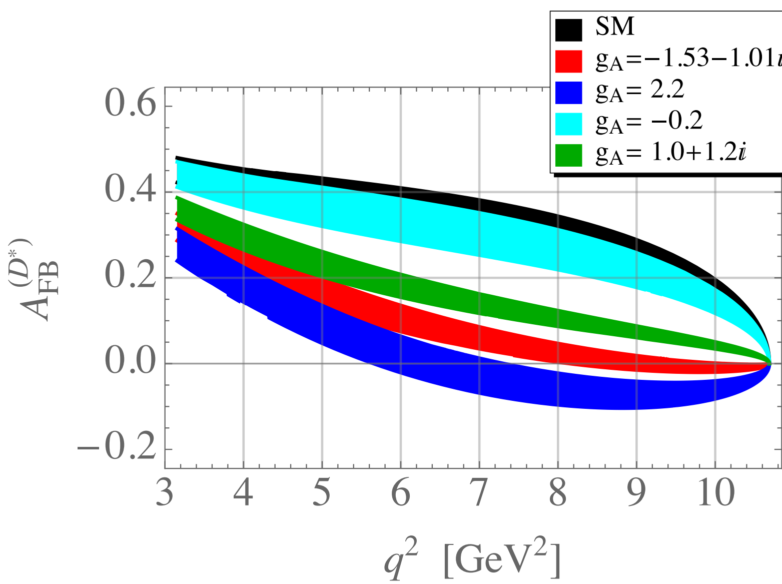


1σ
2σ
3σ
Re g_V
Im g_V
Re g_A
Im g_A
Re g_S [GeV^{-1}]
Im g_S [GeV^{-1}]
Re g_P [GeV^{-1}]
Im g_P [GeV^{-1}]
Re g_T [GeV^{-1}]
Im g_T [GeV^{-1}]
SM:
$(\mathrm{Re}[g_i], \mathrm{Im}[g_i]) = (0, 0)$
Best fit point


SM
gS=−0.69−0.48 i
gS=0.4+0.6 i
gS=0.2
gS=−1.0
$A_{FB}^{(D)}$
q^2 [GeV^2]


SM
gV= 0.12−0.49i
gV= −2.2
gV= 1.2i
gV= −1.2i
$A_{FB}^{(D^*)}$
q^2 [GeV^2]


SM
gS=−0.69−0.48 i
gS=−0.4+0.6 i
gS=−0.4−0.6 i
gS=−1.0
$A_{\lambda_\tau}^{(D)}$
q^2 [GeV^2]


SM
gA=−1.53−1.01i
gA= 2.2
gA= −0.2
gA= 1.0+1.2i
$A_{FB}^{(D^*)}$
q^2 [GeV^2]

$Quantity$	g_V	g_A	g_S	g_P	g_T
A_{FB}^{D}	$\times$	$-$	$\star\star\star$	$-$	$\star$
$A_{\lambda_\tau}^{D}$	$\times$	$-$	$\star\star\star$	$-$	$\star\star$
$A_{FB}^{D^*}$	$\star$	$\star\star\star$	$-$	$\star\star\star$	$\star$
$A_{\lambda_\tau}^{D^*}$	$\times$	$\times$	$-$	$\star\star$	$\star$
$R_{L,T}$	$\times$	$\times$	$-$	$\star\star$	$\star\star$
A_5	$\star\star$	$\star\star$	$-$	$\star$	$\star\star\star$
C_χ	$\star$	$\times$	$-$	$\star\star$	$\star\star$
S_χ	$\star\star\star$	$\star\star\star$	$-$	$\times$	$\star\star\star$
A_8	$\star\star$	$\star\star$	$-$	$\star\star$	$\star\star\star$
A_9	$\star$	$\star$	$-$	$\star\star$	$\star\star$
A_{10}	$\star\star$	$\star\star$	$-$	$\times$	$\star\star$
A_{11}	$\times$	$\times$	$-$	$\star\star$	$\star\star$

"Anatomy" of angular distributions observables

$\times$ stands for "not sensitive", and $\star\star\star$ for "maximally sensitive"

Lepton flavor non-universality in $b \to s\mu^+\mu^-$ decay

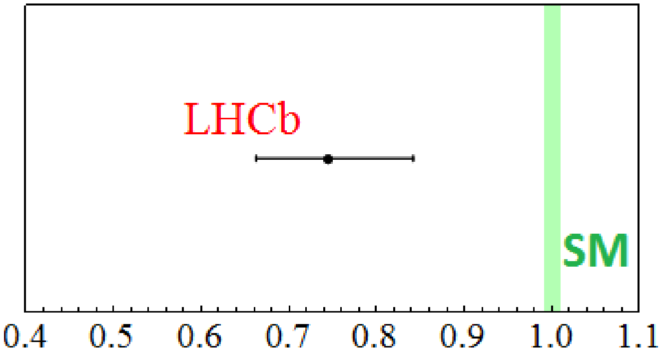
$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)_{q^2\in[1,6]\ \mathrm{GeV}^2}}{\mathcal{B}(B \to Ke^+e^-)_{q^2\in[1,6]\ \mathrm{GeV}^2}}$$

$$R_K^{\mathrm{LHCb}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$

$$R_K^{SM} = 1.0003 \pm 0.0001$$

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

$[2.4\sigma]^*$



R_K

LHCb, 1406.6482;
Altmannshofer and Straub,1411.3161S,
e.g.: Hiller&Schmaltz;1408.1627
Becirevic, SF, Kosnik arXiv:1503.09024

Crivellin et al, 1501.00993 ;
D. Becirevic et al, 1205.5811,
Descotes-Genonet al, 1307.5683,
1605.06059
and many more

Effective Hamiltonian for $b \to s\mu^+\mu^-$

$$\mathcal{L}_{\bar{q}^j q^i \ell\ell'} = -\frac{4G_F}{\sqrt{2}}\lambda_q \Bigg[C_7\mathcal{O}_7 + C_{7'}\mathcal{O}_{7'} + \sum_{i=9,10,S,P} \left(C_i^{\ell\ell'}\mathcal{O}_i^{\ell\ell'} + C_{i'}^{\ell\ell'}\mathcal{O}_{i'}^{\ell\ell'} \right) + C_T^{\ell\ell'}\mathcal{O}_T^{\ell\ell'} + C_{T5}^{\ell\ell'}\mathcal{O}_{T5}^{\ell\ell'} \Bigg] + \text{h.c.},$$

$$\mathcal{O}_7 = \frac{e m_q}{(4\pi)^2}\,(\bar{q}^j\sigma_{\mu\nu}P_R q^i)\,F^{\mu\nu}\,,$$

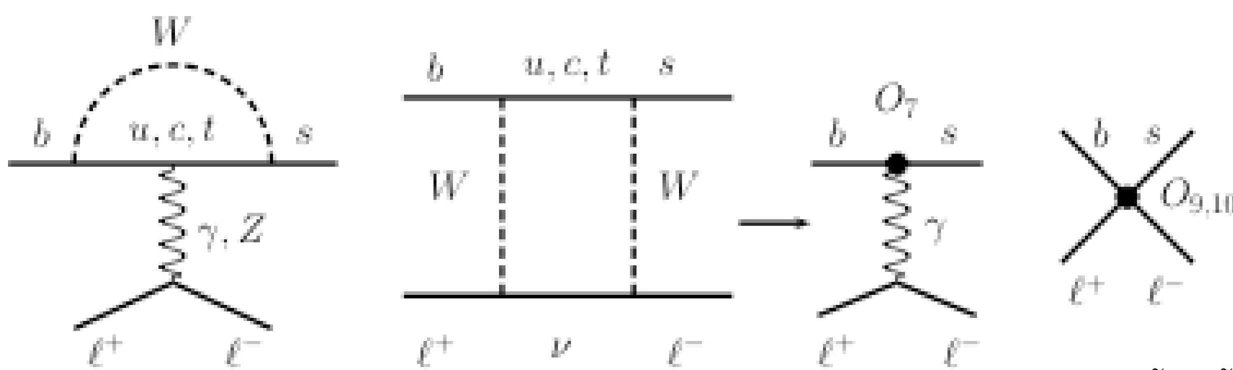
$$\mathcal{O}_9^{\ell\ell'} = \frac{e^2}{(4\pi)^2}\,(\bar{q}^j\gamma^\mu P_L q^i)(\bar{\ell}\gamma_\mu\ell')\,,$$

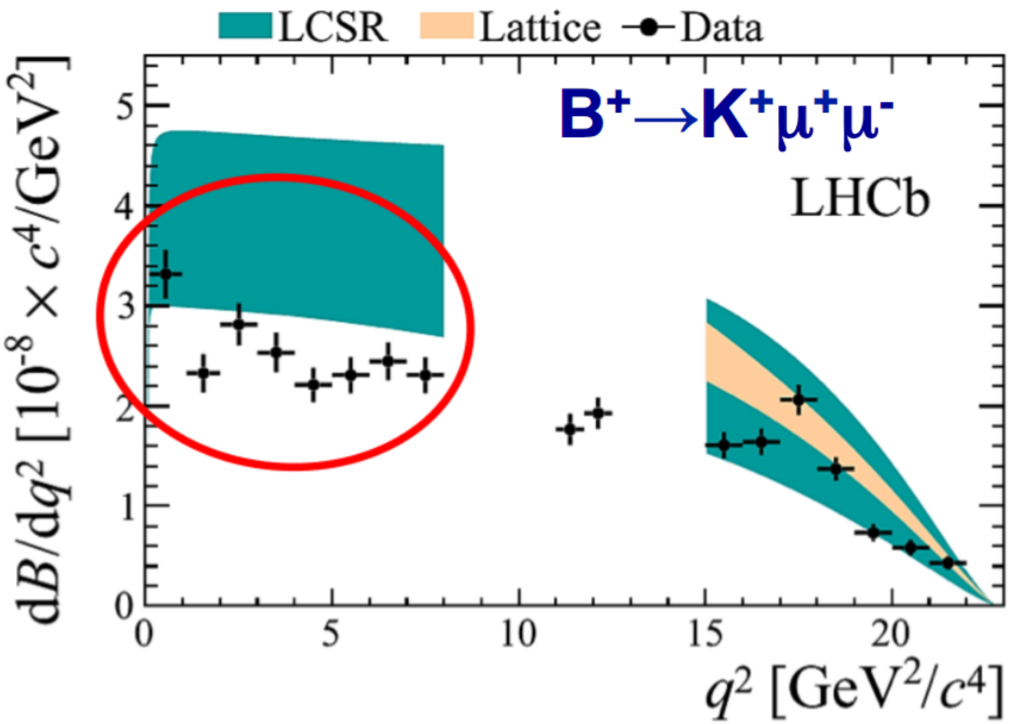
$$\mathcal{O}_{10}^{\ell\ell'} = \frac{e^2}{(4\pi)^2}\,(\bar{q}^j\gamma^\mu P_L q^i)(\bar{\ell}\gamma_\mu\gamma_5\ell').$$

$$\mathcal{O}_S^{\ell\ell'} = \frac{e^2}{(4\pi)^2}\,(\bar{q}^j P_R q^i)(\bar{\ell}\ell'),$$

$$\mathcal{O}_P^{\ell\ell'} = \frac{e^2}{(4\pi)^2}\,(\bar{q}^j P_R q^i)(\bar{\ell}\gamma_5\ell'),$$

"prime" indices stand for P_L replaced by P_R= ½(1+γ_5)





LHCb: 1403.8044

- Missing muons or too many electrons?
- $b \to s\mu\mu$ data are in favor decrease muonic decay rate for $B \to K\mu\mu$

- $C_S=-C_P$, $C_S'=C_P'$ is favored by muons are disfavored by $BR(B_s \to \mu\mu)$

$C_S=-C_P$, $C_S'=C_P'$ for electrons can decrease R_K, in conflict with $BR(B \to Kee)$

- Axial (vector) operators can affect μ or e (Hiller, Schmaltz 1408.1627,1411.4773)

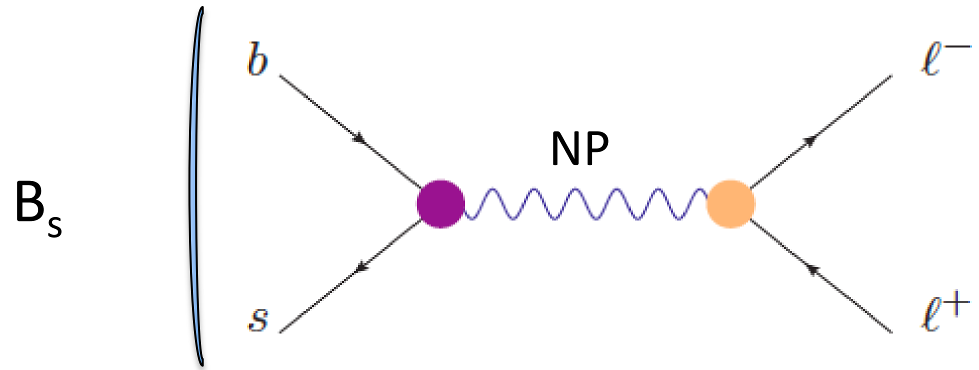
or

$$C_9 = -C_{10}$$
$$C_9' = -C_{10}'$$

$$C_9 \in [-0.81, -0.50]$$

R_K does not distinguished between chiralities in $\mathcal{O}_{9,10}$

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



$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\rm th} = \mathcal{B}_0 |P|^2 \,, \qquad \mathcal{B}_0 = \frac{f_{B_s}^2 m_{B_s}^3}{\Gamma_s} \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}|^2}{(4\pi)^3} \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}$$

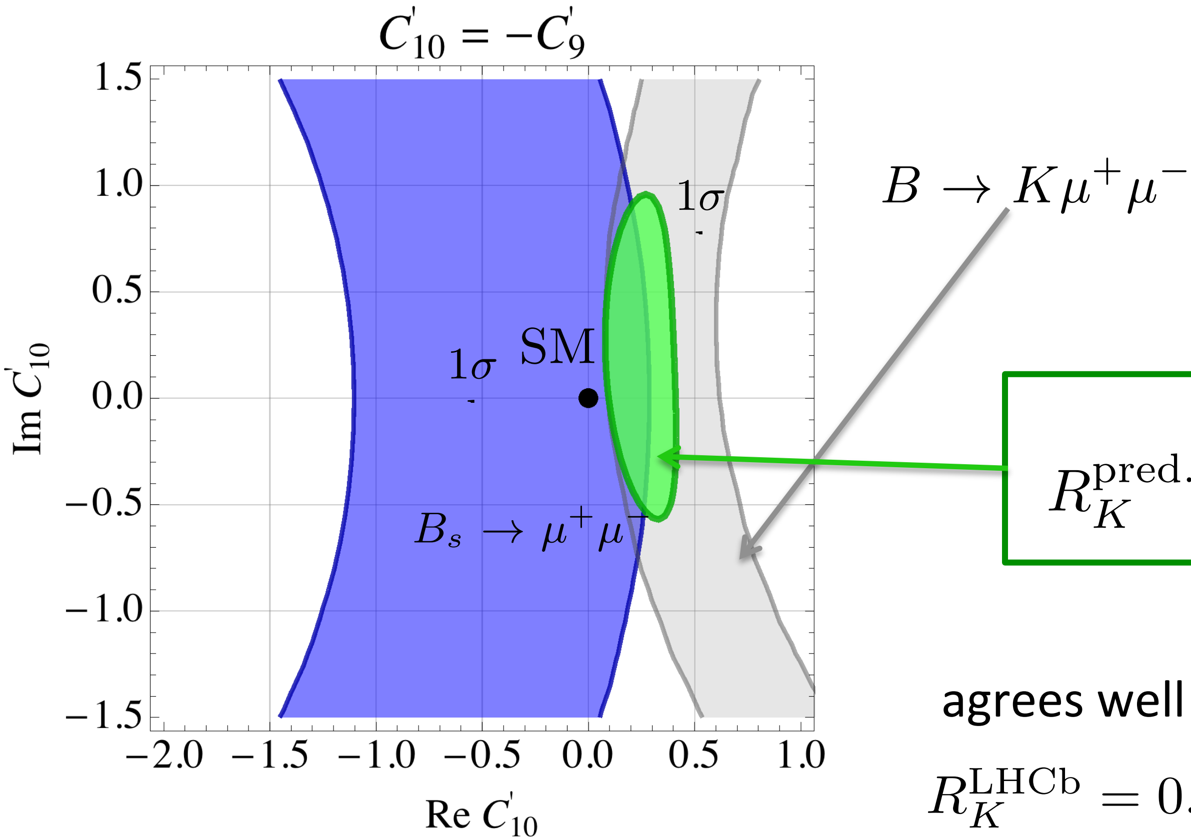
$$P = \frac{2m_\mu}{m_{B_s}}(C_{10} - C'_{10})$$

Rate is slightly smaller than the SM:

$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\rm LHCb+CMS} = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \quad \overline{\mathcal{B}}(B_s \to \mu\mu)^{\rm Atlas} = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$$

$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\rm SM} = (3.65 \pm 0.23) \times 10^{-9}$$

NP in $C_9' = -C_{10}'$ and prediction for R_K



Fit to the partial branching ratio (at high q^2)

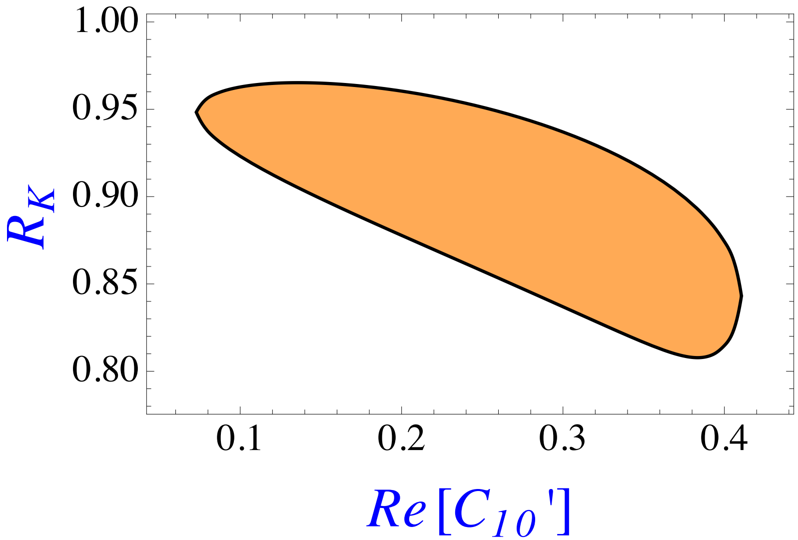
$$R_K^{\text{pred.}} = 0.88 \pm 0.08$$

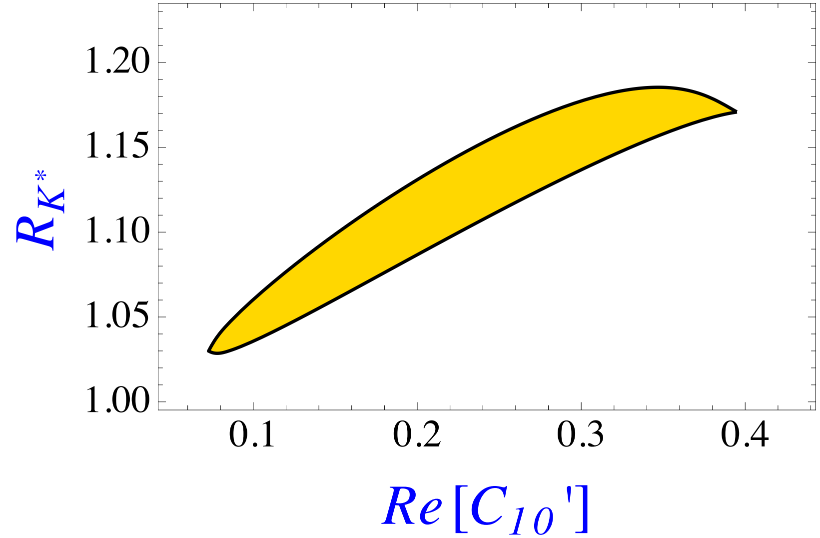
1 σ is defined as $\chi^2 < 2.30$

agrees well with

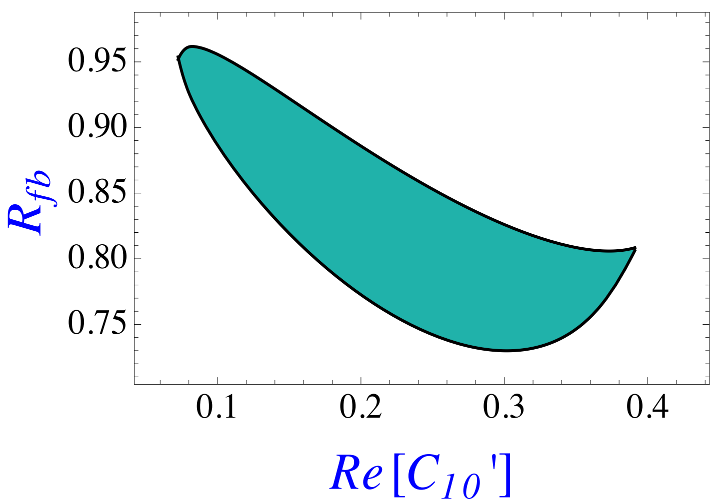
$$R_K^{\text{LHCb}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$

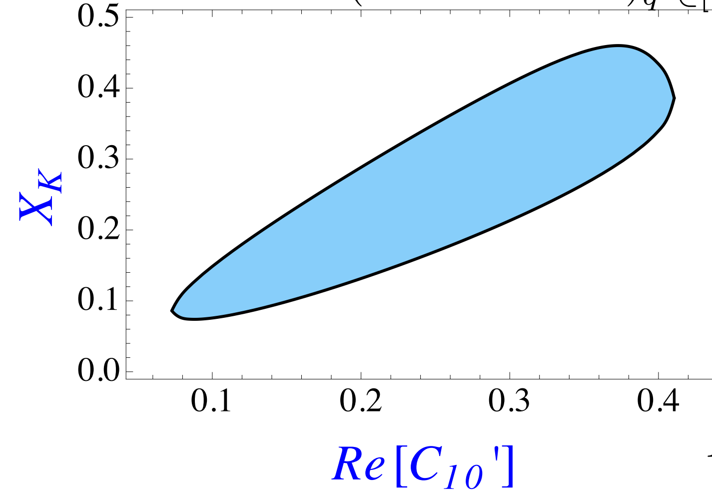
Becirevic, SF, Kosnik: arXiv:1503.09024





$$R_{K^*} = \frac{\Gamma(B \to K^* \mu^+ \mu^-)_{q^2 \in [1,6]\ \mathrm{GeV}^2}}{\Gamma(B \to K^* e^+ e^-)_{q^2 \in [1,6]\ \mathrm{GeV}^2}}$$





$$X_K = \frac{R_{K^*}}{R_K} - 1$$

$$R_{\mathrm{fb}} = \frac{A^{\mu}_{\mathrm{fb}[4-6]}}{A^{e}_{\mathrm{fb}[4-6]}}$$

$$R_K = 0.88 \pm 0.08\,, \qquad R_{K^*} = 1.11 \pm 0.08\,,$$
$$X_K = 0.27 \pm 0.19\,, \qquad R_{\mathrm{fb}} = 0.84 \pm 0.12\,,$$

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?

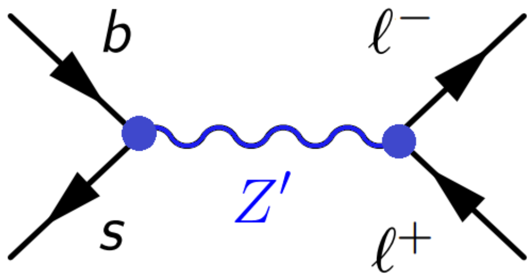
Are SM calculations of the existing observables precise enough?

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!

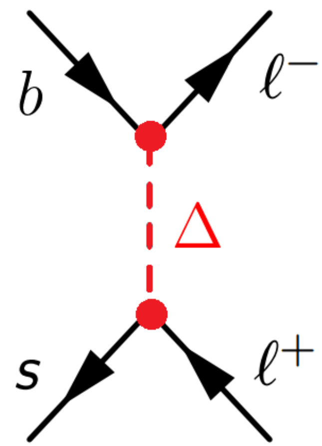
Representative modeks of NP

Z' models



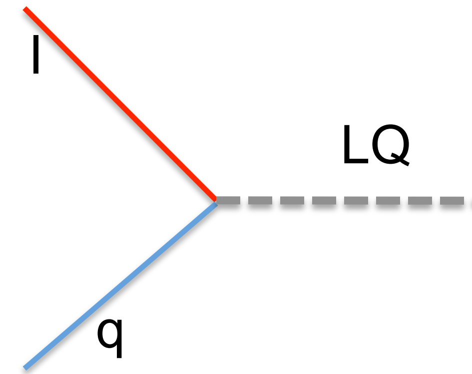
Altmannshofer and Straub,1411.3161S,
Crivellin et al, 1501.00993;
Buras and Girrbach, 1309.2466,....

Leptoquark models



Hiller&Schmaltz;1408.1627 ;
Kosnik, 1206,2970;
Becirevic, SF, Kosnik arXiv:1503.09024;
Barbieri et al,
1512.01560.Becirevic et al,1608.08501,
Sahoo et al, 1609.04367;.....

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
$(\mathbf{3},\mathbf{2},5/6)$	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

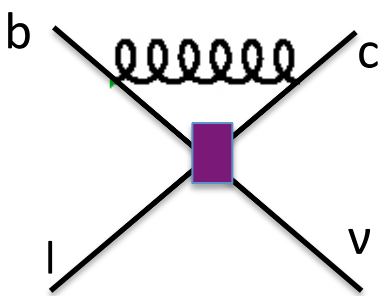
F=3B +L fermion number; F=0 no proton decay at tree level

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

LQ in charge 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.

$R_{D(*)}$ puzzles can be explained by modifications of the left-handed (right-handed, scalar/pseudoscular, tensor currents), if all other flavor constraints allow that!

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 $U(1)_{Y}$!

Examples of LQ

(3,2,7/6) two states with electric charge 5/3 and 2/3, has a coupling with SM neutrino

$$\mathcal{L}_{\rm Y} = -\, x_{ij}\bar{u}^i_R e^j_L R_2^{5/3} + (xV_{\rm PMNS})_{ij}\bar{u}^i_R \nu^j_L R_2^{2/3} + (yV^\dagger_{\rm CKM})_{ij}\bar{e}^i_R u^j_L R_2^{5/3\,*} + y_{ij}\bar{e}^i_R d^j_L R_2^{2/3\,*} + \text{h.c.},$$

The model is constrained by:

$Z \to b\bar{b}$ (τ in the loop)

$(g-2)_\mu$ (c –quark in the loop)

$\tau \to \mu\gamma$

$\mu \to e\gamma$

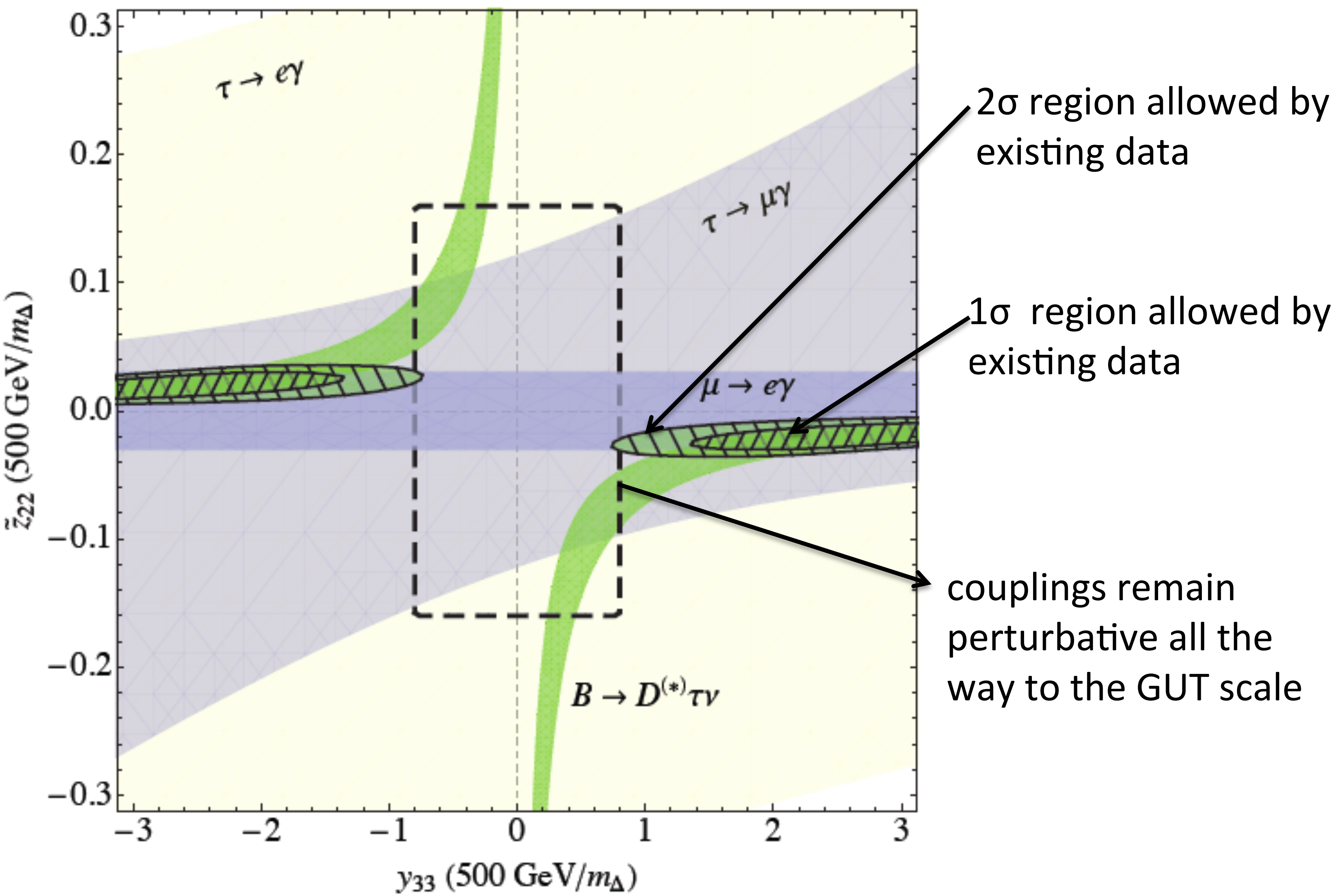
$\mathcal{B}(\mu \to e\gamma) < 5.7 \times 10^{-13}$

$\mathcal{B}(\tau \to e\gamma) < 3.3 \times 10^{-8}$

$\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-9}$

Not good candidate for R_K, $C_9 = C_{10}$!

I. Doršner, S.F., N. Košnik, arXiv: 1306.6493



$\tau \to e\gamma$
$\tau \to \mu\gamma$
$\mu \to e\gamma$
$B \to D^{(*)}\tau\nu$
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−3
−2
−1
0
1
2
3
y_{33} (500 GeV/m_Δ)
$\tilde{z}_{22}$ (500 GeV/m_Δ)
2σ region allowed by existing data
1σ region allowed by existing data
couplings remain perturbative all the way to the GUT scale

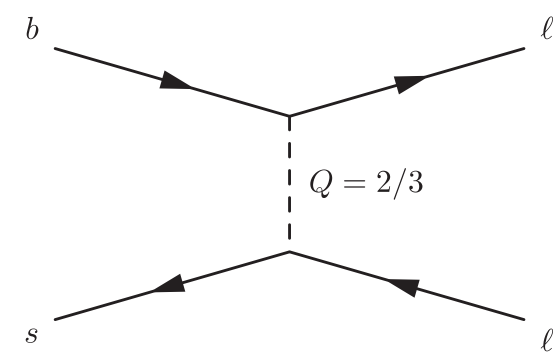
(3,2,1/6) can explain both R_K and $R_{D(*)}$ at tree level!

two states with electric charge 2/3 and -1/3

$$\mathcal{L}_{\rm Y} = - x_{ij} \bar{d}^i_R e^j_L \tilde{R}_2^{2/3} + (x V_{\rm PMNS})_{ij} \bar{d}^i_R \nu^j_L \tilde{R}_2^{-1/3} + (V_{\rm CKM} y)_{ij} \bar{u}^i_L \nu^j_R \tilde{R}_2^{2/3} + y_{ij} \bar{d}^i_L \nu^j_R \tilde{R}_2^{-1/3} + \text{h.c.}$$

1. Good candidate for R_K according to: Hiller&Schmaltz, 1408.1627; Hiller & de Medeiros Varzielas, 1503.01084 for R_K:

$C_9' = -C_{10}'$



D. Becirevic, SF, N. Kosnik (1503.09024)

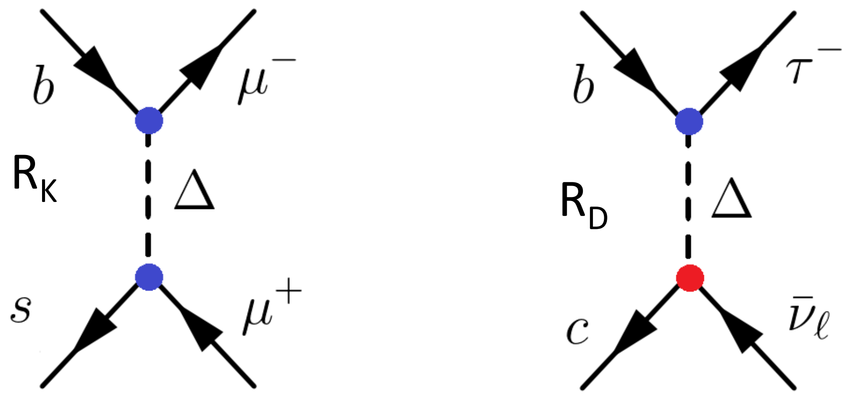
Prediction:

$$R_K = 0.88 \pm 0.08\,, \qquad R_{K^*} = 1.11 \pm 0.08\,,$$
$$X_K = 0.27 \pm 0.19\,, \qquad R_{\rm fb} = 0.84 \pm 0.12\,,$$

(3,2,1/6) does not modify $(g-2)_\mu$

RD(*) puzzle can be explained if neutrino is right-handed!

$$|\mathcal{M}(B \to D^{(*)}\ell\nu)|^2 = |\mathcal{M}_{\rm SM}|^2 + |\mathcal{M}_{\rm NP}|^2_{\rm h.c.}$$



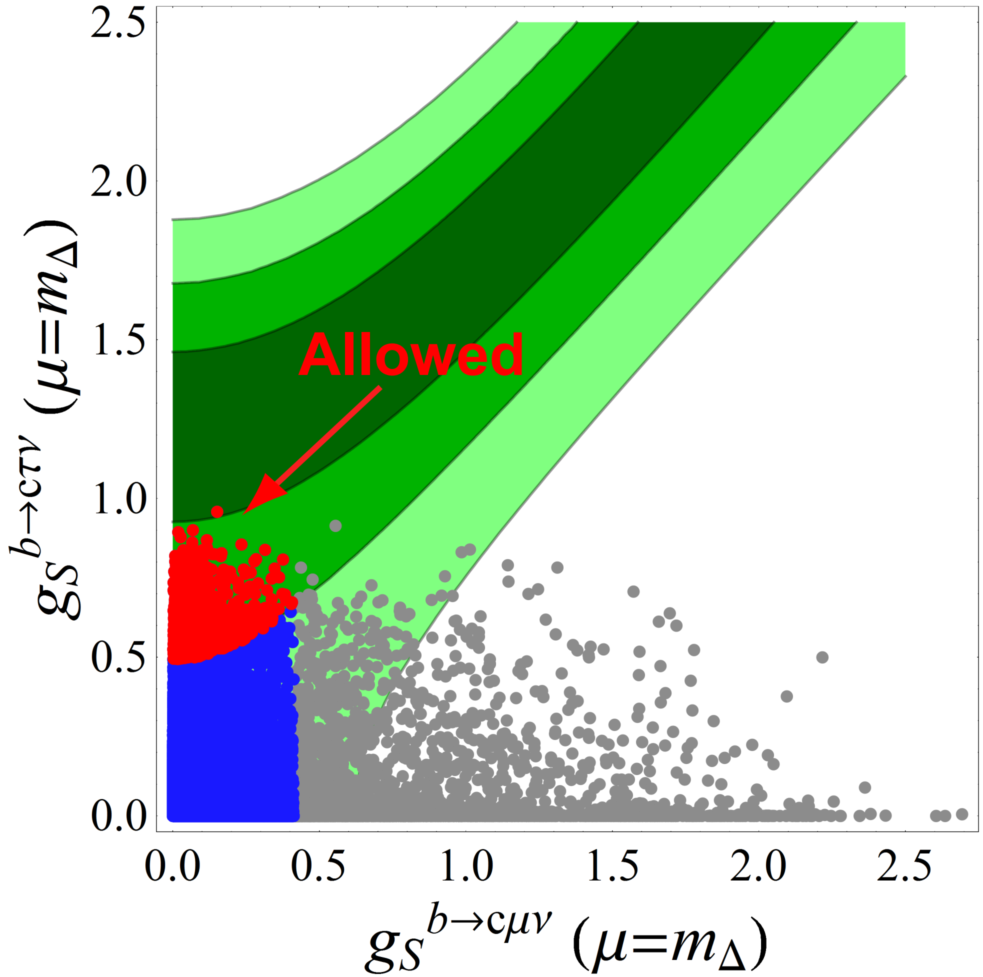
R_D: form factor from lattice QCD (Milc&Fermilab 2015)

Model passed all flavor tests: $B_s \to \mu^+\mu^-$, $\mathcal{B}(B \to K\mu\mu)_{\text{high } q^2}$, Δm_{B_s}

$\mathcal{B}(B \to \tau\bar{\nu})$, $\mathcal{B}(D_s \to \tau\bar{\nu})$, $\mathcal{B}(B \to K\nu\bar{\nu})$, $\mathcal{B}(B \to K\mu\tau)$ etc

D. Becirevic, SF, N. Kosnik and O. Sumensari (1608.08501)

$$\mathcal{H}_{\rm eff} \ni 2\sqrt{2}G_F\left[\boldsymbol{g_S(\mu)}(\bar{c}_L b_R)(\bar{\ell}_L\nu_R) + \boldsymbol{g_T(\mu)}(\bar{c}_L\sigma_{\mu\nu}b_R)(\bar{\ell}_L\sigma^{\mu\nu}\nu_R)\right] + \text{h.c.}$$



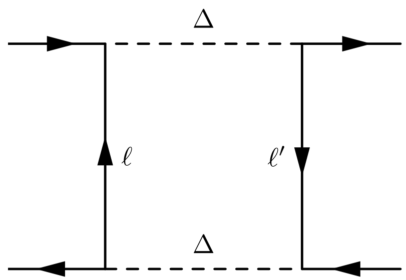
Substantially increases

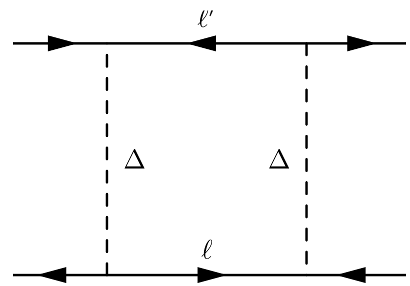
$$R_D^{\rm SM} = 0.286(12)$$

Both processes are corrected

- $B \to D\tau\nu_x$
- $B \to D\mu\nu_x$

Neutral meson anti-meson oscillations with LQ presence





$$\mathcal{O}_6 = \bar{q}\gamma_\mu P_R b\, \bar{q}\gamma^\mu P_R b$$

$$P_R = \frac{1}{2}(1+\gamma_5)$$

Combining Δ B =2 and Δ B =1

Δ B =2 $$C_6^{\rm LQ}(m_\Delta) = -\frac{G_F^2}{8\pi^4}(V_{tb}^* V_{ts})^2 \alpha^2 m_\Delta^2 (C_{10}'^*)^2$$ Δ B =1

an example $\mathrm{Re}[C_{10}'] \in [0.15, 0.35]$ leads to $m_\Delta \sim 100\ \mathrm{TeV}$

(3,2,1/6) does not modify $(g\text{-}2)_\mu$

Further experimental signatures

1. rare charm decays

in $c \to u\mu^+\mu^-$ decay $|\tilde{C}_9| \equiv |C_9^{(\bar{u}c)}/(\mathcal{V}_{ub}\mathcal{V}_{cb}^*)| \lesssim 0.05,$

Current experimental bound allows $|\tilde{C}_9| \leq 0.63$

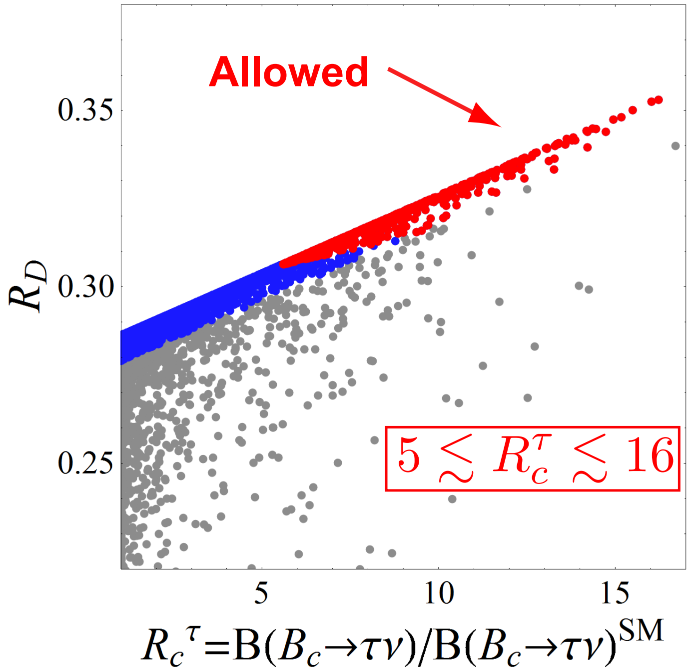
2. increase of the rate for $t \to b\tau^+\nu$ if $|g_{b\tau}| \sim 2,$

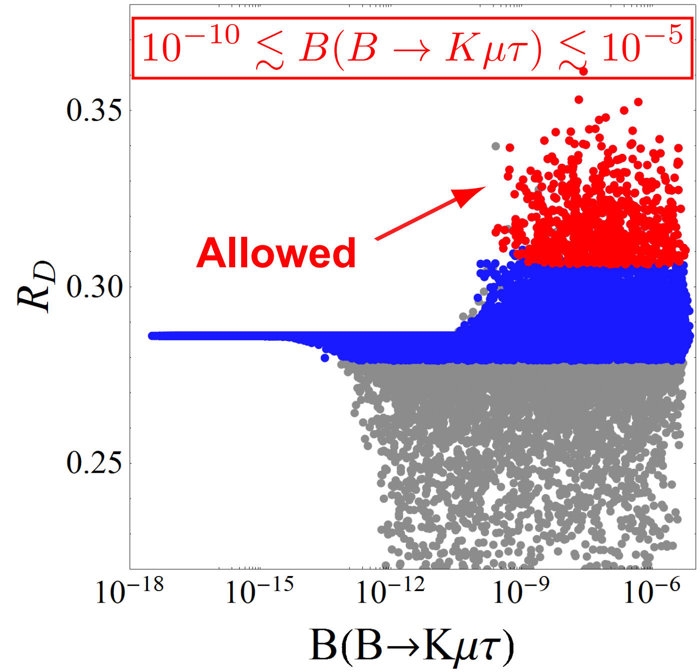
by 20%;

3. prediction

$$R_{K^*} = \Gamma(B \to K^*\mu^+\mu^-)/\Gamma(B \to K^*e^+e^-) \quad \sim 1$$

Predictions



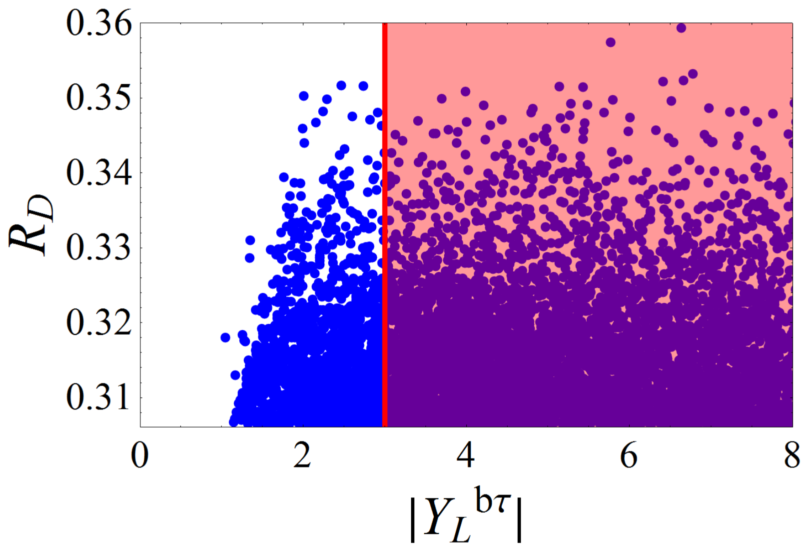


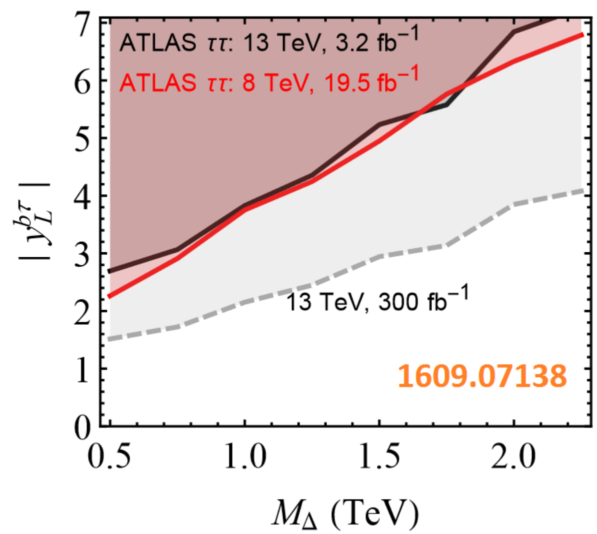
- Enhancement of B(Bc → τν̄) over B(Bc → τν̄)$_{SM}$= 2.21(12)%.
- Upper and lower bounds on the LFV rates.
- $R_{\eta_c} \equiv \mathcal{B}(B_c \to \eta_c \tau\nu)/\mathcal{B}(B_c \to \eta_c \ell\nu)$ increase for 20% over SM value!

Bounds from $b\bar{b} \to \tau^+\tau^-$ at LHC

A. Faroughy et al. 1609.07138

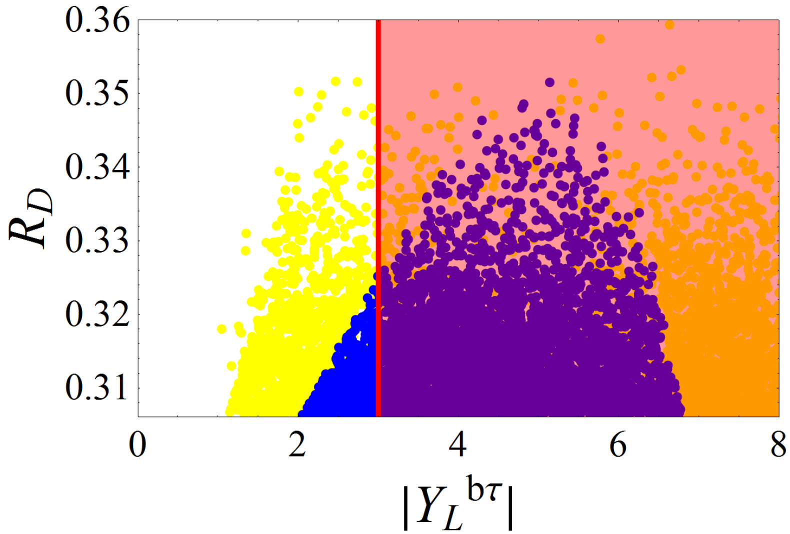
$$\mathcal{L}_\Delta \ni -\bar{d}_R \mathbf{Y_L} \ell_L \Delta^{2/3}$$





Perturbativity condition $|Y_i| \leq \sqrt{4\pi}$.

If one also imposes $\Gamma_\Delta/m_\Delta \leq 1$:



We can accommodate R^{exp}_D at the 1.5σ.

LQCD prediction $R^{SM}_D = 0.286(12) \Rightarrow$ 14% increase due to NP

Is this model a final solution? NO!

But it has some interesting features

- Accommodates $R_K^{NP} < R_K^{SM}$ and predicts $R_{K*}^{NP} > R_{K*}^{SM}$
- Naturally accommodates $R_{D(*)}^{NP} > R_{D(*)}^{SM}$, predicts $R_{\eta_c}^{NP} > R_{\eta_c}^{SM}$, $BR(B_c \to \tau\nu)^{NP}/BR(B_c \to \tau\nu)^{SM} \geq 5.5$
- LFUV in the charged sector depends on the existence of ν_R.

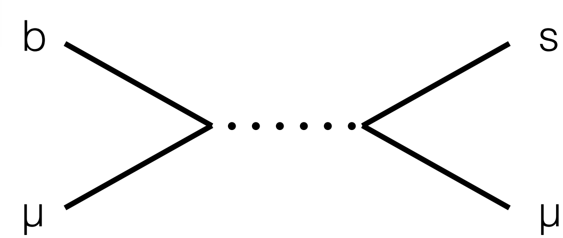
Vector leptoquark (3,3,2/3) and B anomalies

SF, Košnik (1511.06024) both anomalies at tree level!

Barbieri, Isidori, Pattori and Senia, 1512.01560,
Sahoo et al. 1609.04367 ,

$$\mathcal{L}_{U_3} = g_{ij}\bar{Q}_i\gamma^\mu\,\tau^A U^A_{3\mu}\,L_j + \mathrm{h.c.}$$ Q=I_3+Y $\Rightarrow$ $$U_{3\mu} = \begin{cases} U_{3\mu}^{(5/3)} \\ U_{3\mu}^{(2/3)} \\ U_{3\mu}^{(-1/3)} \end{cases}$$

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



Our assumption:

$$g = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_{s\mu} & 0 \\ 0 & g_{b\mu} & g_{b\tau} \end{pmatrix}, \qquad \mathcal{V}g = \begin{pmatrix} 0 & \mathcal{V}_{us}g_{s\mu} + \mathcal{V}_{ub}g_{b\mu} & \mathcal{V}_{ub}g_{b\tau} \\ 0 & \mathcal{V}_{cs}g_{s\mu} + \mathcal{V}_{cb}g_{b\mu} & \mathcal{V}_{cb}g_{b\tau} \\ 0 & \mathcal{V}_{ts}g_{s\mu} + \mathcal{V}_{tb}g_{b\mu} & \mathcal{V}_{tb}g_{b\tau} \end{pmatrix}$$

Important:

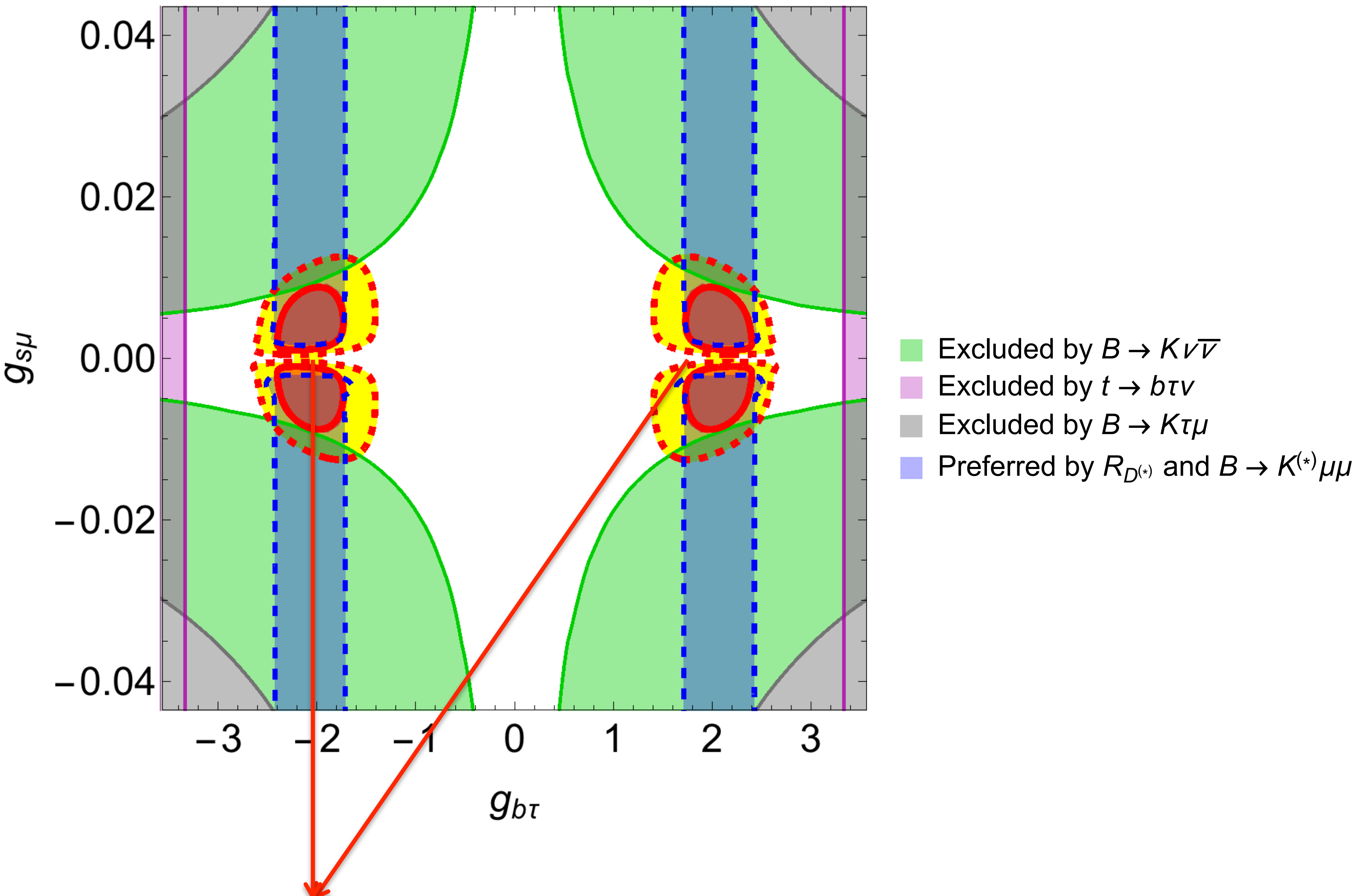
$$C_9 = -C_{10} = \frac{\pi}{\mathcal{V}_{tb}\mathcal{V}_{ts}^{*}\alpha}\, g_{b\mu}^{*} g_{s\mu}\, \frac{v^2}{M_U^2}$$

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

$$g_{b\tau}^2 - g_{b\mu}^2 \approx 4.4$$

$$|g_{b\tau}| \gtrsim 2$$

Additional constraints from	Predictions
LFU in K leptonic decays $b \to c\mu^{-}\bar{\nu}$ $t \to b\tau^{+}\nu$	$B \to K^{(*)}\nu\bar{\nu}$ the rates for K and K* can be increased by the same factor 1.17 $c \to u\mu^{+}\mu^{-}$ $t \to b\tau^{+}\nu$ v $R_{K*} \simeq R_K$



allowed parameter space -1σ (2σ)

Light vector leptoquarks: facing new problems

- UV completion is the main problem of this approach;

- Contrary to SM gauge bosons, if vector leptoquarks are not gauge bosons (e.g. SU(5) GUT with LQ being in some other representation of SU(5), not 24) we have to work with non-renormalizable model.

- Problem with loops within this approach (e.g. Barbieri et al. 1512.01560) discussed vector letpquarks (3,1,2/3), (3,3,2/3) and for loop processes they used cut-off.

Summary and outlook

- B physics anomalies offer unique tests of SM extensions at low energies;
- 3σ effects have to be further tested experimentally (e.g. R_{K*});
- Suggested new observables might clarify need for NP;
- Leptoquarks are one of suggested SM extension which might explain observed discrepancies;
- $(3,2,1/6)_0$ $(3,3,2/3)_1$ are our favorable candidates (do not destabilize proton);
- Light scalar leptoquarks are simpler to accommodate within GUT framework then vector leptoquarks;
- Is it possible to construct any GUT (or composite model) with only one light LQ?

Thanks!

More attempts to explain R_K and $R_{D(*)}$ at tree level

Greljo, Isidori , Marzoccaa, 1506.01705

- $SU(2)_L$ triplet of massive vector bosons, coupled predominantly to third generation fermions;
- based on $U(2)_q \times U(2)_l$ symmetry;
- effective interaction at only third generation SM fermions;
- connects low-energy deviations from the SM to direct searches for NP at high p_T.

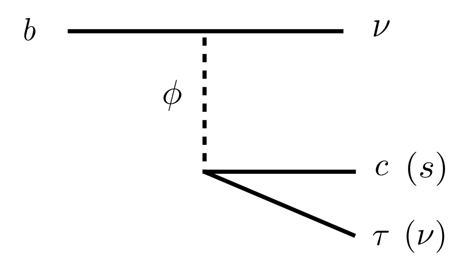
Model connects the breaking of LFU between charged and neutral currents, and between semi-leptonic and purely leptonic processes

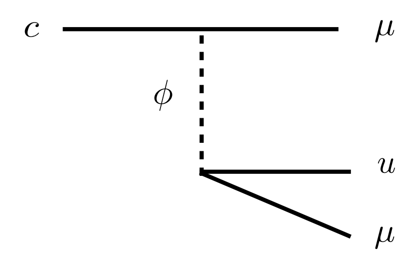
Problem no UV completion!

Another proposal of minimal explanation of both anomalies?

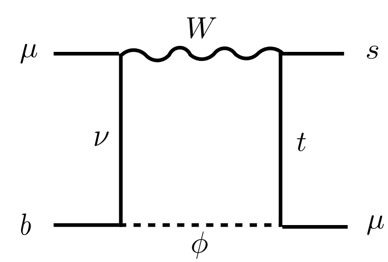
Bauer & Neubert, 1511.01900 proposal: scalar (3,1,-1/3) can accommodate $R_{D(*)}$, R_K and $(g-2)_{\mu}$!

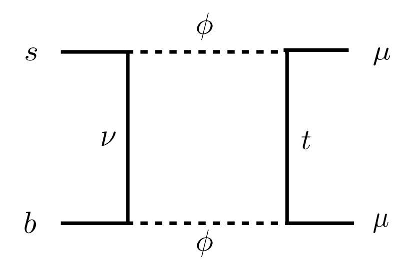
$R_{D(*)}$ tree level SM and LQ correction on tree level!





R_K and $(g-2)_{\mu}$: SM loop process LQ correction on loop level





Problem of (3,1,-1/3): it can mediate proton decay!
Produces extra contributions in SM observables as shown in 1608.07583, making this model impossible to explain R_K and $R_{D(*)}$.