New Physics in $R_{D(*)}$

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Lattice Meets Continuum: QCD Calculations in Flavour Physics - 2nd Workshop
18 - 20 Sep. 2017

- Experimental status of $R_{D(*)}$

- Effective Lagrangian approach in $R_{D(*)}$

- Models of NP in $R_{D(*)}$

- Interpretation: Sign of LFU violation?

- Any signature at higher energies at LHC?

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

$$\frac{BR(B_c \to J/\Psi \tau \nu_\tau)}{BR(B_c \to J/\Psi \mu \nu_\mu)} = 0.71 \pm 0.17 \pm 0.18$$ ~2 σ

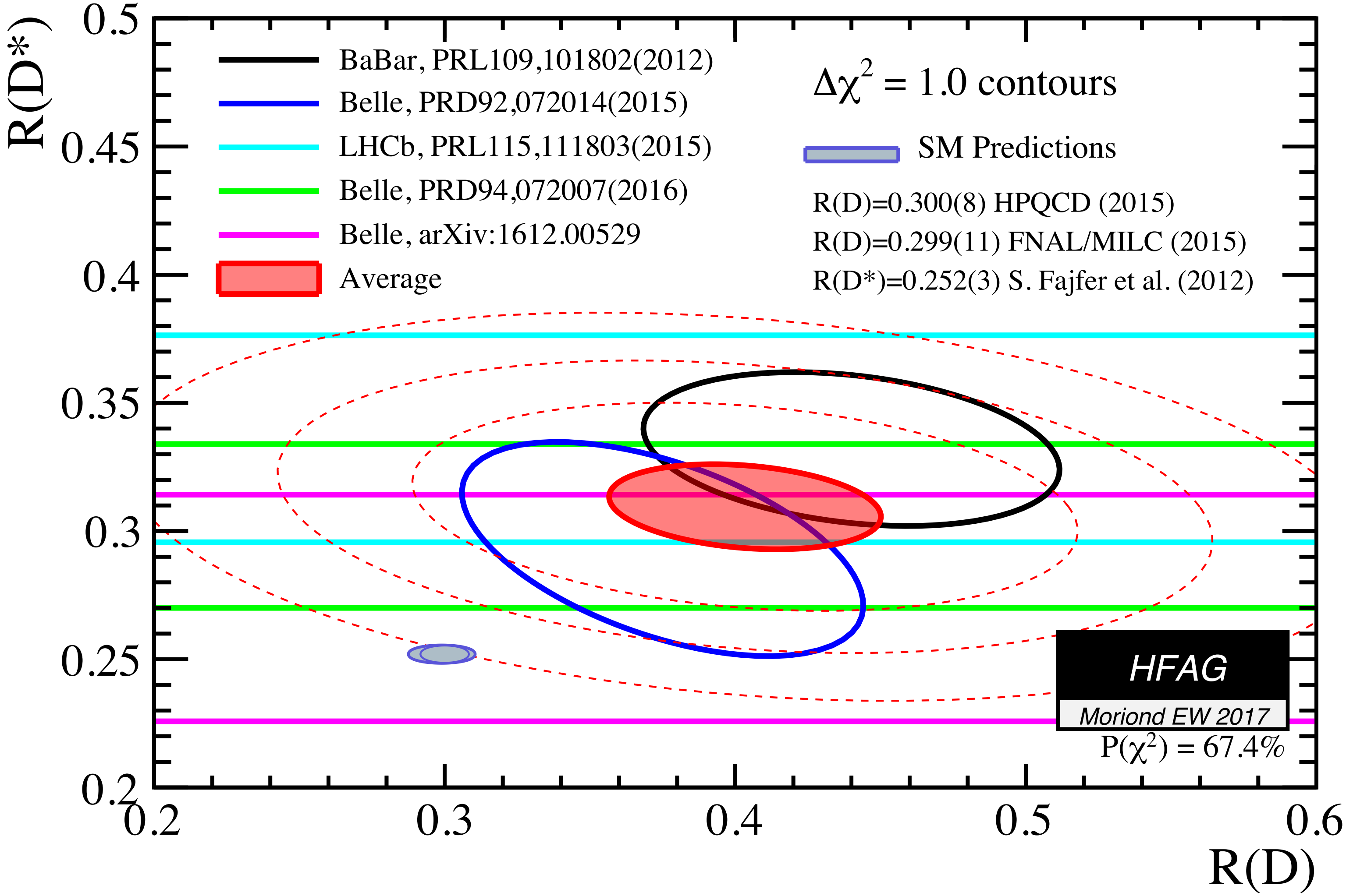
13 Sept. 2017
LHCb result

FCNC - SM loop process

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

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

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

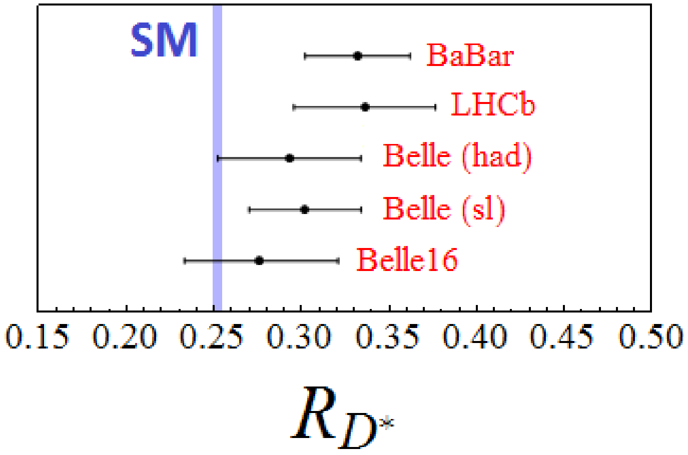


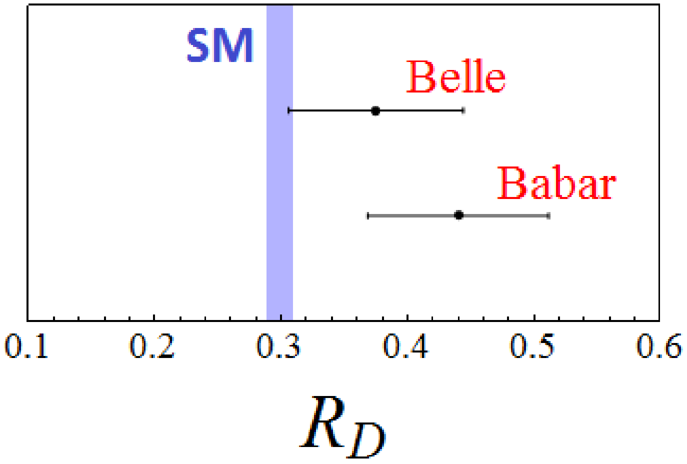
B physics anomalies: experimental results ≠ SM predictions!

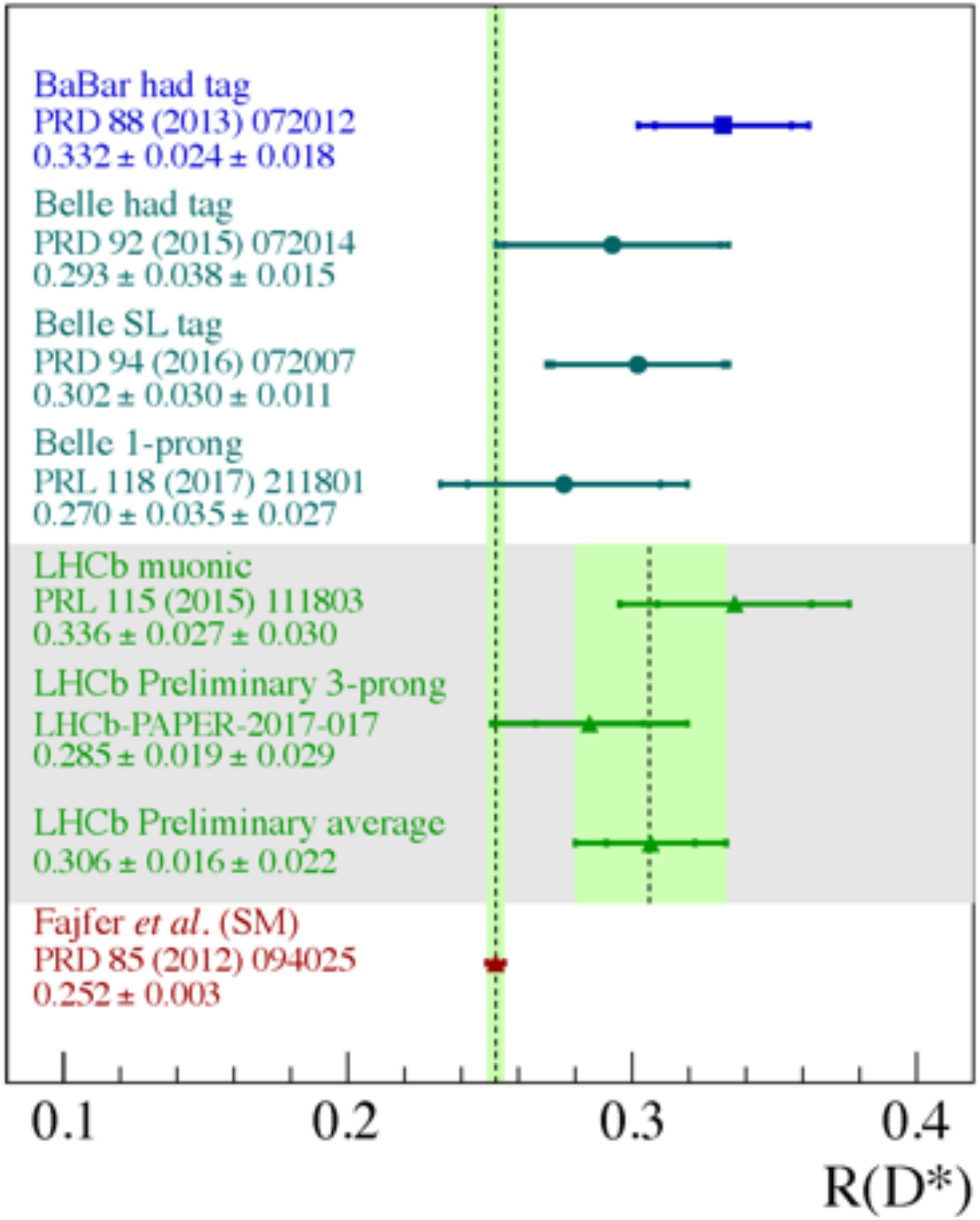
charged current (SM tree level)

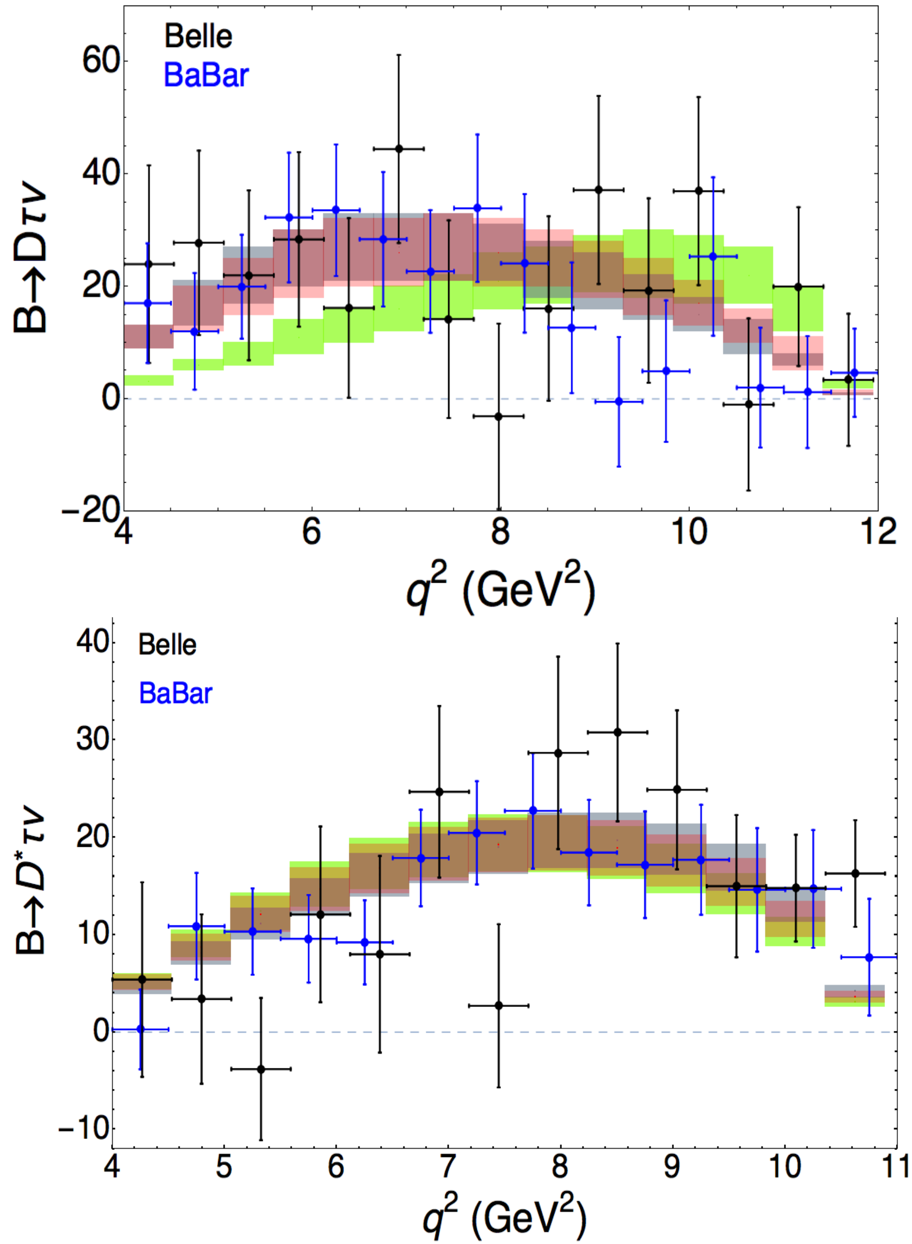
$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$

3.9σ






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*)



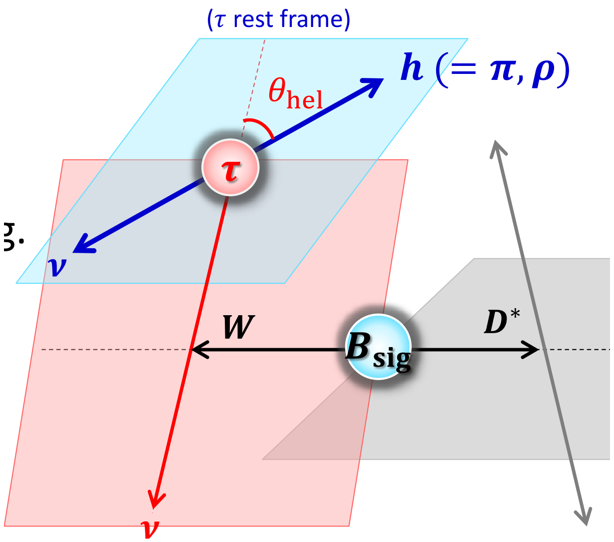
Momentum transfer distributions, A. Cellis et al,1612.07757

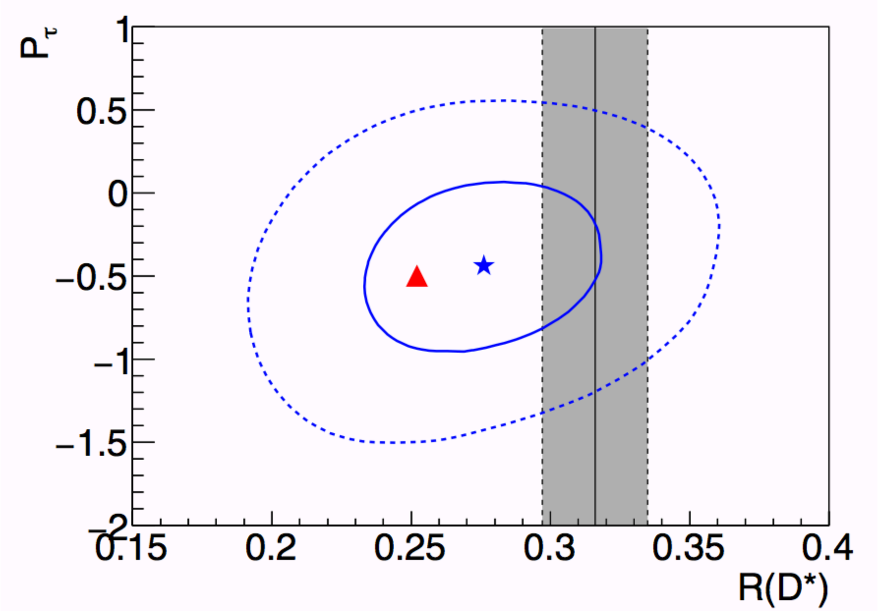
Belle: 1608.06931

τ polarization

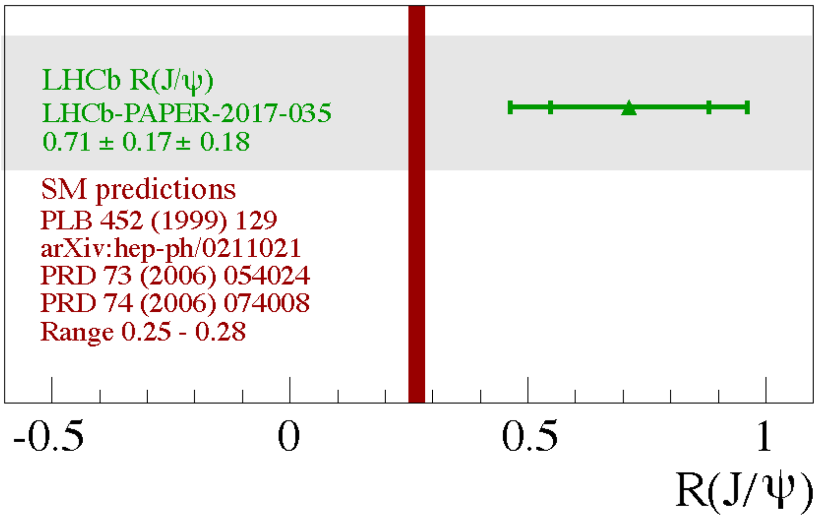
$$P_\tau = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

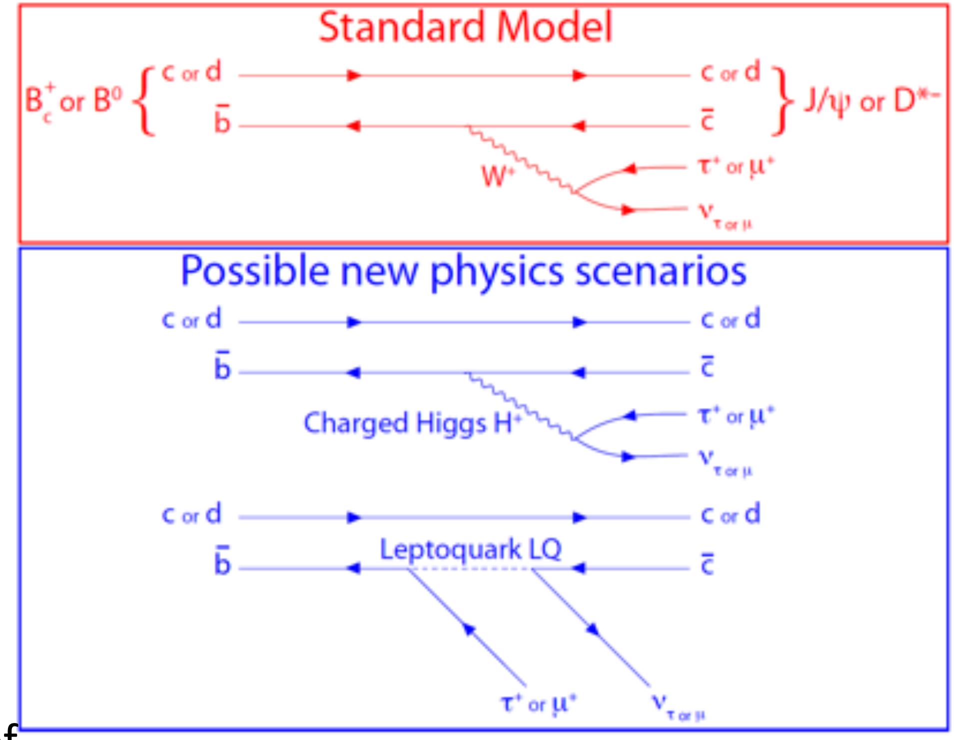
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{1}{2}\left(1 + \alpha \cdot \mathcal{P}_\tau \cos\theta_{\rm hel}\right)$$





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





LHCb on 13 September 2017: First test of lepton universality using charmed-beauty meson decays.

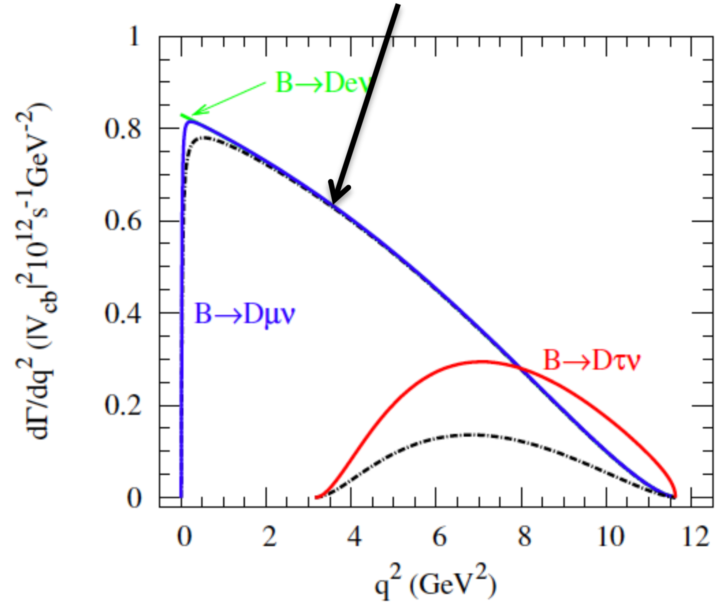
$$\frac{BR(B_c \to J/\Psi \tau \nu_\tau)}{BR(B_c \to J/\Psi \mu \nu_\mu)} = 0.71 \pm 0.17 \pm 0.18$$

Exclusive semileptonic B⟶D lν_l decays

$$\langle D(p')|\bar{c}\gamma_\mu b|\bar{B}(p)\rangle = \left(p_\mu + p'_\mu - \frac{m_B^2 - m_D^2}{q^2} q_\mu\right) F_+(q^2) + \frac{m_B^2 - m_D^2}{q^2} q_\mu F_0(q^2)$$

- B⟶ D $\tau\nu_\tau$: scalar form factor contributes!
- massless lepton: only vector form factor contributes.
- mostly HQ approach useful;
- perturbative corrections + HQE (Nierste et al, 0801.4938, Tanaka & Watanabe, 1006.4306);

necessary to know $F_0(q^2)$!

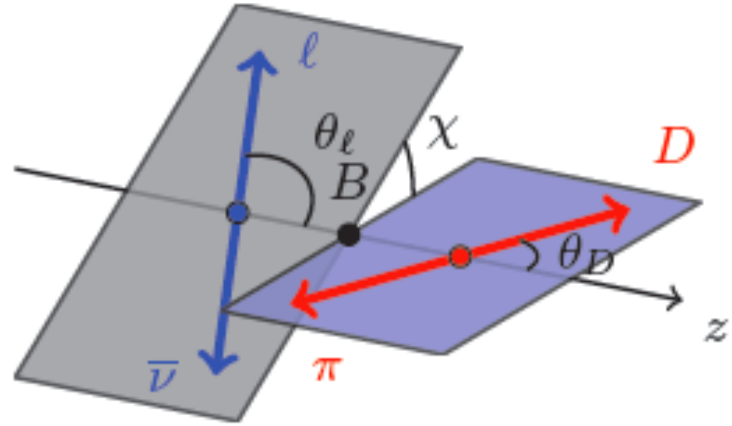


- complete information comes from – lattice QCD;
- in ratio uncertainties
- cancel:

$$R \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$

Mescia& Kamenik, 0802.3790
Tanaka & Watanabe,1006.430
Faller, Mannel &Tyrczyk 1105.36796
Nierste, Trine & Westhoff, 0801.4938

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



$$\frac{d^2\Gamma_\tau}{dq^2 d\cos\theta} = \frac{G_F^2 |V_{cb}|^2 |\mathbf{p}| q^2}{256\pi^3 m_B^2}\left(1 - \frac{m_\tau^2}{q^2}\right)^2 \times$$

$$\Big[(1-\cos\theta)^2 |H_{++}|^2 + (1+\cos\theta)^2 |H_{--}|^2 + 2\sin^2\theta |H_{00}|^2 +$$

$$\frac{m_\tau^2}{q^2}\left((\sin^2\theta(|H_{++}|^2 + |H_{--}|^2) + 2|H_{0t} - H_{00}\cos\theta|^2\right)\Big],$$

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….

$$H_{\pm\pm}^{\rm SM}(q^2) = (m_B + m_{D^*})A_1(q^2) \mp \frac{2m_B}{m_B + m_{D^*}}|\mathbf{p}|V(q^2)\,,$$

$$H_{00}^{\rm SM}(q^2) = \frac{1}{2m_{D^*}\sqrt{q^2}}\left[(m_B^2 - m_{D^*}^2 - q^2)(m_B + m_{D^*})A_1(q^2) - \frac{4m_B^2|\mathbf{p}|^2}{m_B + m_{D^*}}A_2(q^2)\right]$$

$$H_{0t}^{\rm SM}(q^2) = \frac{2m_B|\mathbf{p}|}{\sqrt{q^2}}A_0(q^2)\,.$$

Recent progres: talks of Gambino and Wingate, LmC 2017!

$$A_0(q^2) = \frac{R_0(w)}{R_{D^*}}h_{A_1}(w)$$

$$A_2(q^2) = \frac{R_2(w)}{R_{D^*}}h_{A_1}(w)$$

$$V(q^2) = \frac{R_1(w)}{R_{D^*}}h_{A_1}(w)$$

$$h_{A_1}(w) = A_1(q^2)\frac{1}{R_{D^*}}\frac{2}{w+1}$$

$$w \equiv v_B \cdot v_{D^*} = \frac{m_B^2 + m_{D*}^2 - q^2}{2m_B m_{D*}}$$

Caprini et al., hep-ph/9712417

Gambino et a.l, 1206.2296

Bigi, Gambino, Schacht 1707.09509

R_{D*}=0.260(8)

How to approach to anomalies?

- Is the anomaly SM or NP?

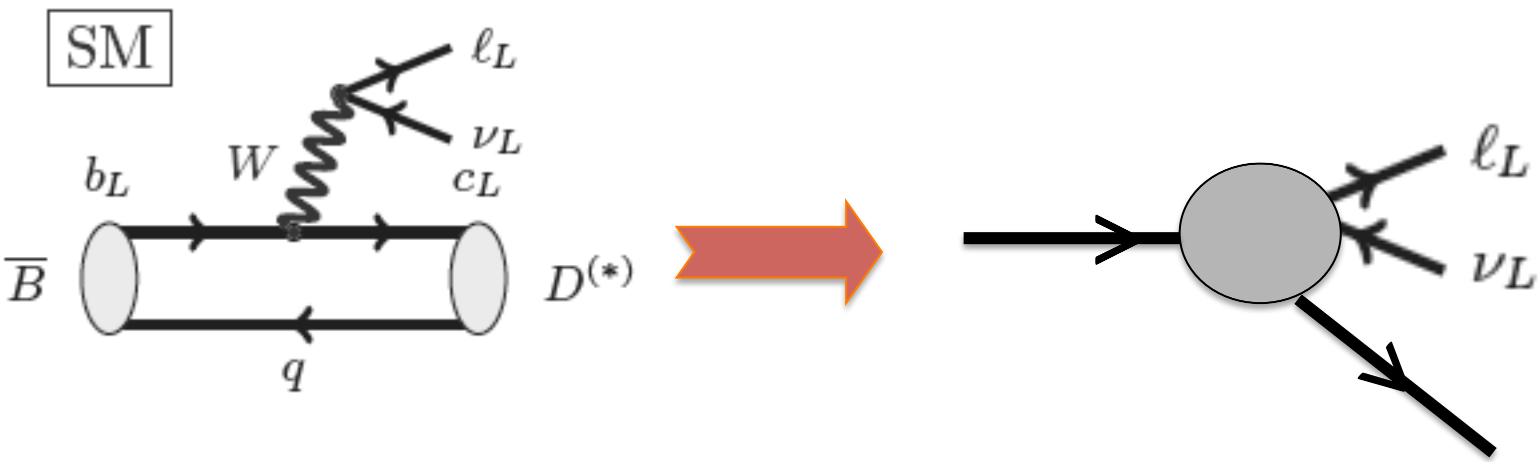
- First step at low energies: to construct effective Lagrangian which might explain experimental data;

- 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 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

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

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

Do not forget: 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

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

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

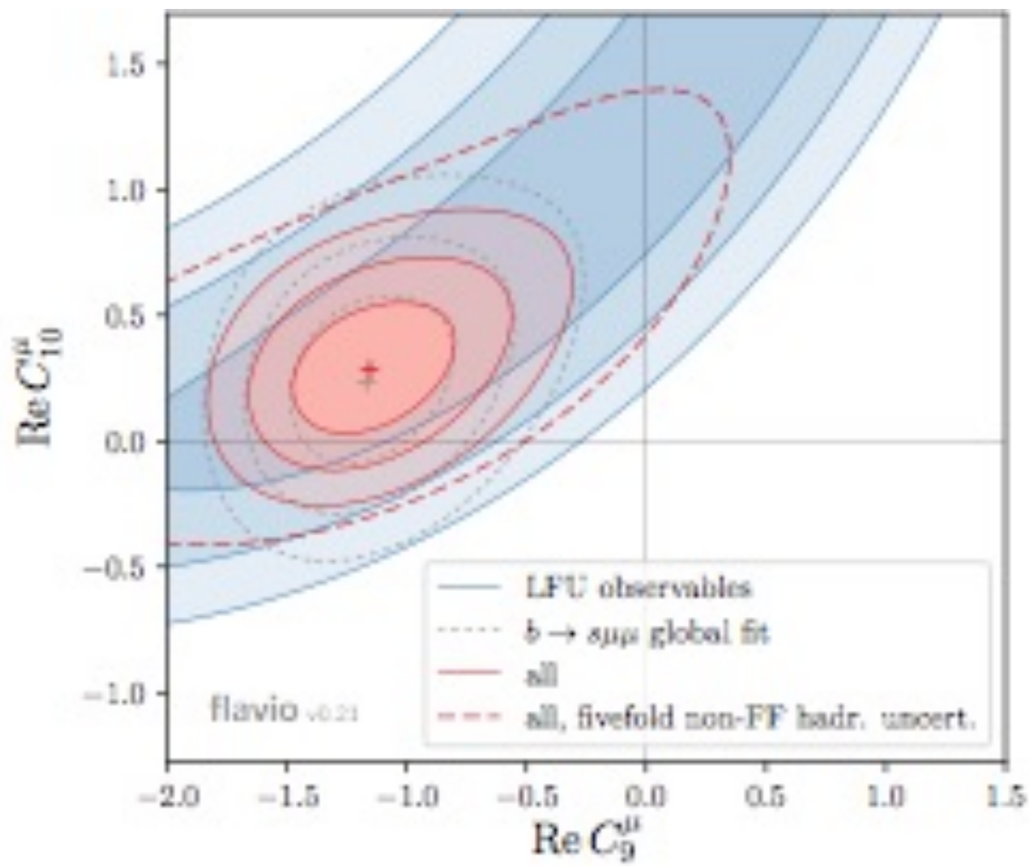
2.2 σ - 2.4σ

R$_K$ and R$_{K*}$ and New Physics

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 Hiller, Schmaltz, 1408.1627, 1411.4773
fit from R$_K$

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

Do these deviations suggest Lepton Flavour Universality violation?

- 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: τ/μ and μ/e(?)!

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!

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.

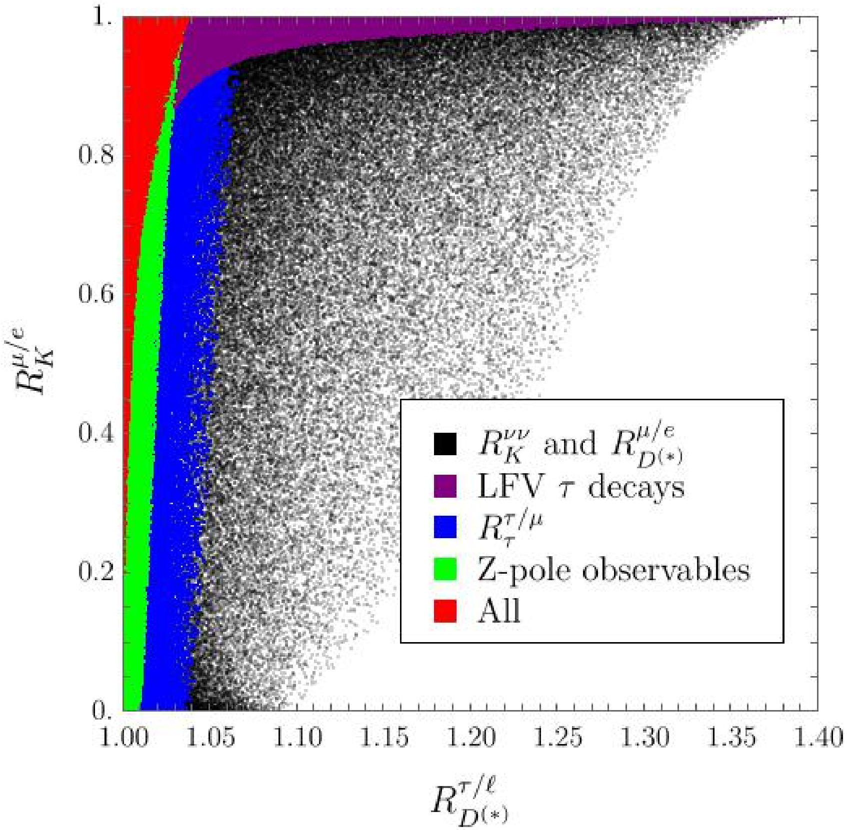
For NP scale above electroweak scale, SU(3) x $SU(2)_L$ x $U(1)_Y$ at low energies should be respected!

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

$$u_L \to V_u u_L \qquad d_L \to V_d d_L \qquad V_u^\dagger V_d = V\,,$$
$$\nu_L \to U_e \nu_L \qquad e_L \to U_e e_L\,,$$

Different proposal with h τ_R by Choudhury, Kundu,Mandal, Sinha, arXiv:1706.08437

$$\mathcal{H}^{\rm NP} = A_1\left(\overline{Q}_{2L}\gamma_\mu L_{3L}\right)\left(\overline{L}_{3L}\gamma^\mu Q_{3L}\right) + A_2\left(\overline{Q}_{2L}\gamma_\mu Q_{3L}\right)\left(\overline{\tau}_R\gamma^\mu \tau_R\right)$$



from Feruglio et al, 1606.00524
color regions are allowed

Effective Lagrangian receives one-loop induced RGE contributions of order $y_t^2/16\pi^2$ and $e^2/16\pi^2$.

- leptonic couplings to W and Z vector bosons are modified.
- quantum effects generate also a purely leptonic effective Lagrangian and corrections to the semileptonic interactions

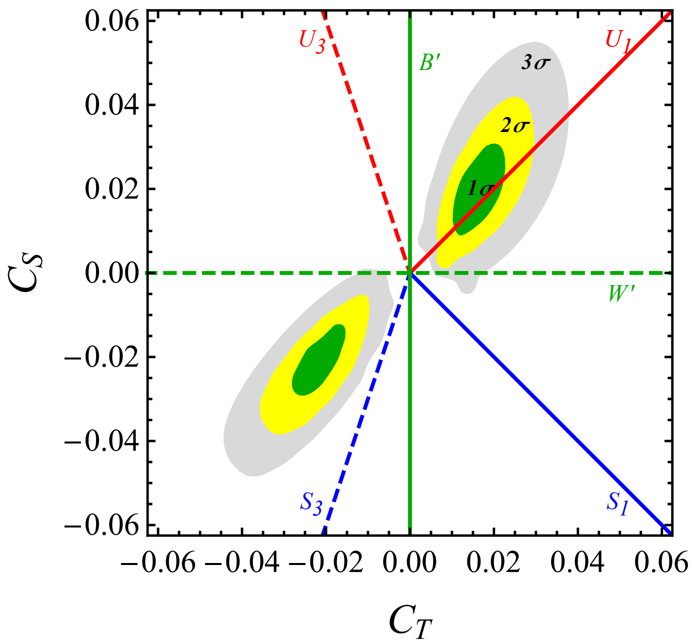
the experimental bounds on Z and τ decays significantly constrain LFU breaking effects in B-decays, Search for a model with mediators in the TeV range;

Buttazzo, Greljo, Isidoria, Marzocca 1706.07808

- exemplify the general EFT results − search for a model with mediators in the TeV range;
- coloured scalar or vector leptoquarks and colour-less vectors.

$SU(2)_L$-singlet vector leptoquark emerges as a particularly simple and successful framework!

Observable	Experimental bound	Linearised expression
$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1 - \lambda^q_{sb} V^*_{tb}/V^*_{ts})(1 - \lambda^\ell_{\mu\mu}/2)$
$\Delta C^\mu_9 = -\Delta C^\mu_{10}$	-0.61 ± 0.12 [36]	$-\frac{\pi}{\alpha_{\rm em} V_{tb} V^*_{ts}} \lambda^\ell_{\mu\mu} \lambda^q_{sb}(C_T + C_S)$
$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1 - \lambda^q_{sb} V^*_{tb}/V^*_{ts})\lambda^\ell_{\mu\mu}$
$B_{K^{(*)}\nu\bar\nu}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\rm em} V_{tb} V^*_{ts} C^{\rm SM}_\nu}(C_T - C_S)\lambda^q_{sb}(1 + \lambda^\ell_{\mu\mu})$
$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033 C_T - 0.043 C_S$
$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033 C_T - 0.043 C_S$
$\lvert g^W_\tau / g^W_\ell \rvert$	1.00097 ± 0.00098	$1 - 0.084 C_T$
$\mathcal{B}(\tau \to 3\mu)$	$(0.0 \pm 0.6) \times 10^{-8}$	$2.5 \times 10^{-4}(C_S - C_T)^2(\lambda^\ell_{\tau\mu})^2$



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

$$\mathcal{L}_U = -\frac{1}{2}U^{\dagger}_{1,\mu\nu}U^{1,\mu\nu} + M_U^2 U^{\dagger}_{1,\mu}U_1^{\mu} + g_U(J_U^{\mu}U_{1,\mu} + \text{h.c.})$$

$$J_U^{\mu} \equiv \beta_{i\alpha}\, \bar{Q}_i \gamma^{\mu} L_{\alpha} \quad .$$

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

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

Spin	Color singlet	Color tripet
0	2HDM	Scalar LQ $\not{R}$ parity - sbottom
1	W' ,Z'	Vector LQ

S.F. J.F. Kamenik, I. Nišandžić, J. Zupan, 1206.187;

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

Scalar LQ:
e.g. LQ: Doršner, SF, Greljo, Kamenik., Košnik, (1603.04993),
Crivellin et al, 1703.09226

Scalar or Vector LQ
Buttazzo et al, 1706.07808,

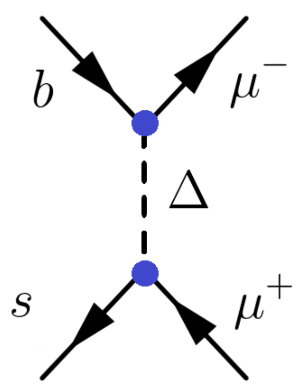
Vector LQ: Greljo et al, 1708.08450
Calibbi et al, 1708.00692

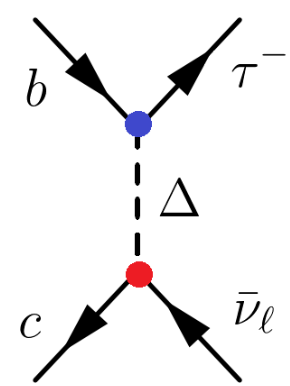
SUSY with R-parity violation
Altmannshofer et al, arXiv: 1704.06659

- 2HDMII cannot explain $R_{D(*)}$
- New gauge bosons, W', Z'- difficult to construct UV complete theory

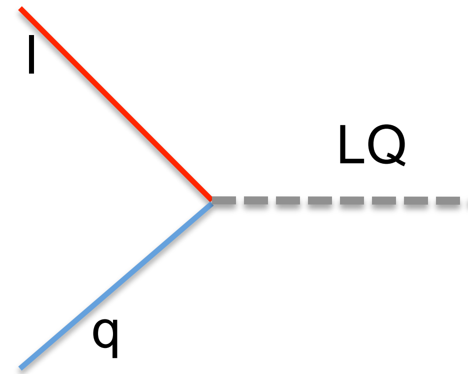
Leptoquarks?

Nature of anomaly requires NP in quark and lepton sector!
It seems that LQs are ideal candidates to explain all B anomalies at tree leve!





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 (see Assad et al, 1708.06350)

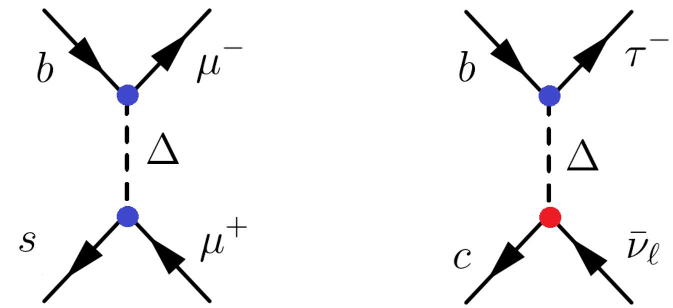
Doršner, SF, Greljo, Kamenik Košnik, (1603.04993)

One 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

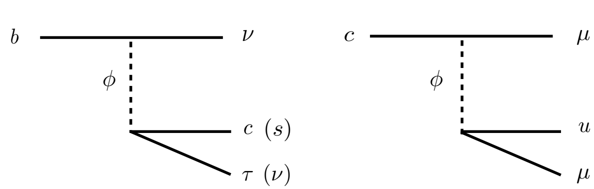


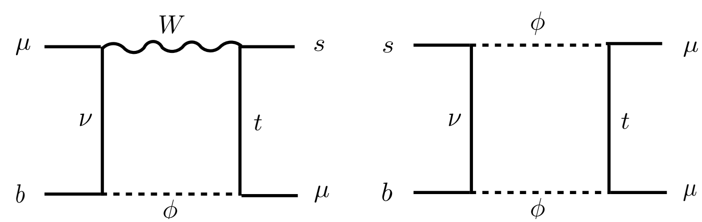
$$|M_{SM}|^2 + |M_{LQ}|^2$$

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

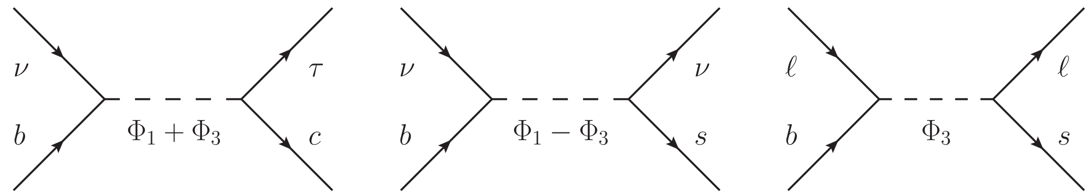
$R_{K(*)}$ at loop level

+ 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



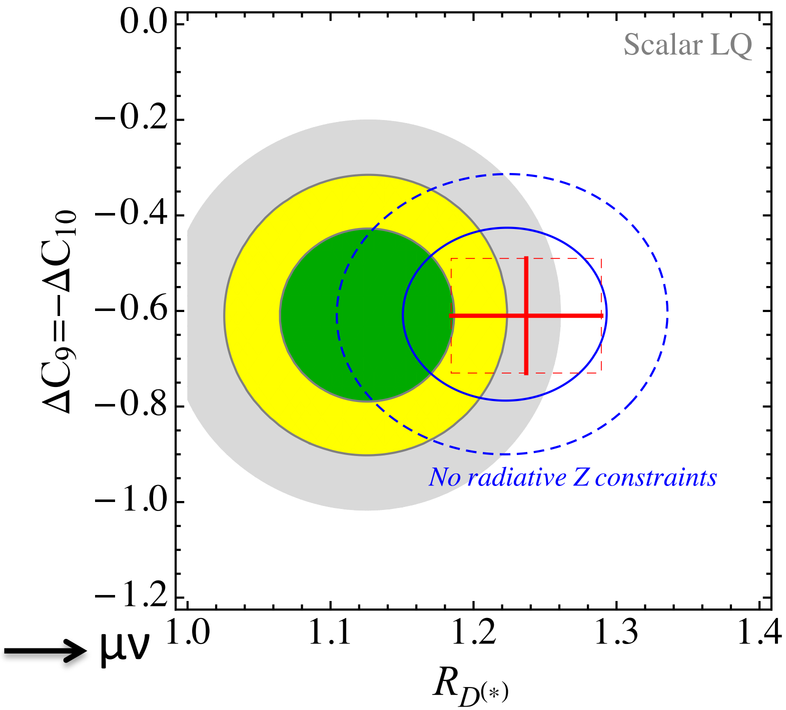
- (3,3,1/3) alone has a proper structure according to effective Lagrangian –
it couples to only left-handed quarks and leptons.
- it leads to to large contribution in $B \to K^{(*)}\nu\bar{\nu}$

Buttazzo, Greljo, Isidori, Marzocca
1706.07808 :

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

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

Potentially large sμ coupling disfavored by Ds/K⟶ μν



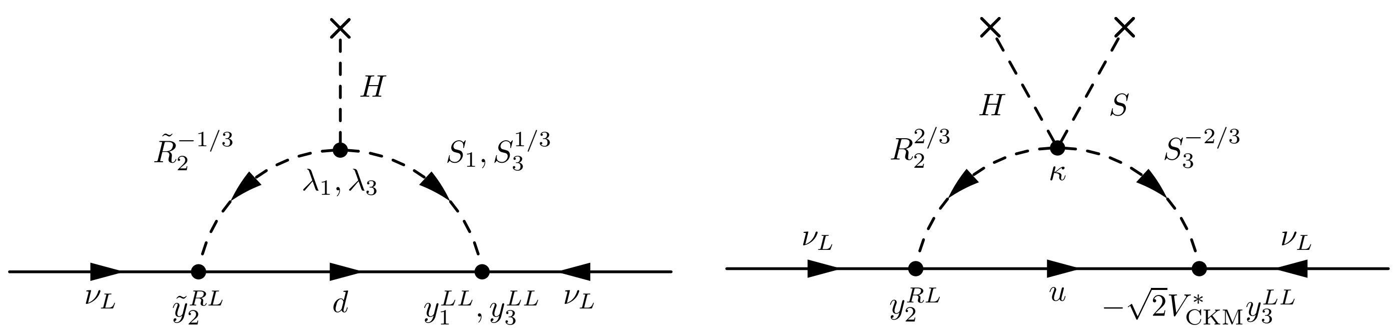
SU(5) GUT with (3,3,1/3) + (3,2,1/6)
Doršner, SF, Faroughy, Košnik

- 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

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 $S_3^{-2/3}$)

$R_{D^{(*)}}$(exp) > $R_{D^{(*)}}$ (SM)

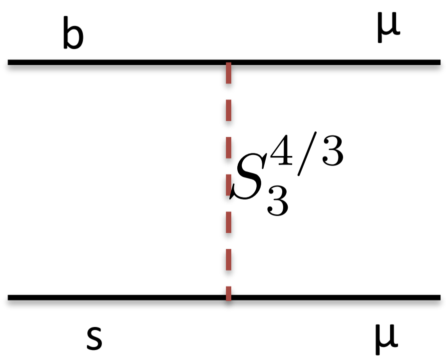
$$\mathcal{L}_{\bar{c}b\bar{\ell}\nu_k} = -\frac{4G_F}{\sqrt{2}}\left[(V_{cb}\delta_{\ell k} + g^L_{cb;\ell k})(\bar{c}_L\gamma^\mu b_L)(\bar{\ell}_L\gamma_\mu\nu^k_L)\right]$$

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

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

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

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



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

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

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

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

Constraints from flavor observables

$B_c \to \tau\nu$

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

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

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

$K \to \mu\nu_\mu$

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

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

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

$Z \to b\bar{b}$

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

$R_{K(*)}$

Constraints from LFV

$(g-2)_\mu$

$\tau \to \mu\gamma$

$\mu \to e\gamma$

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

$K \to \mu e$

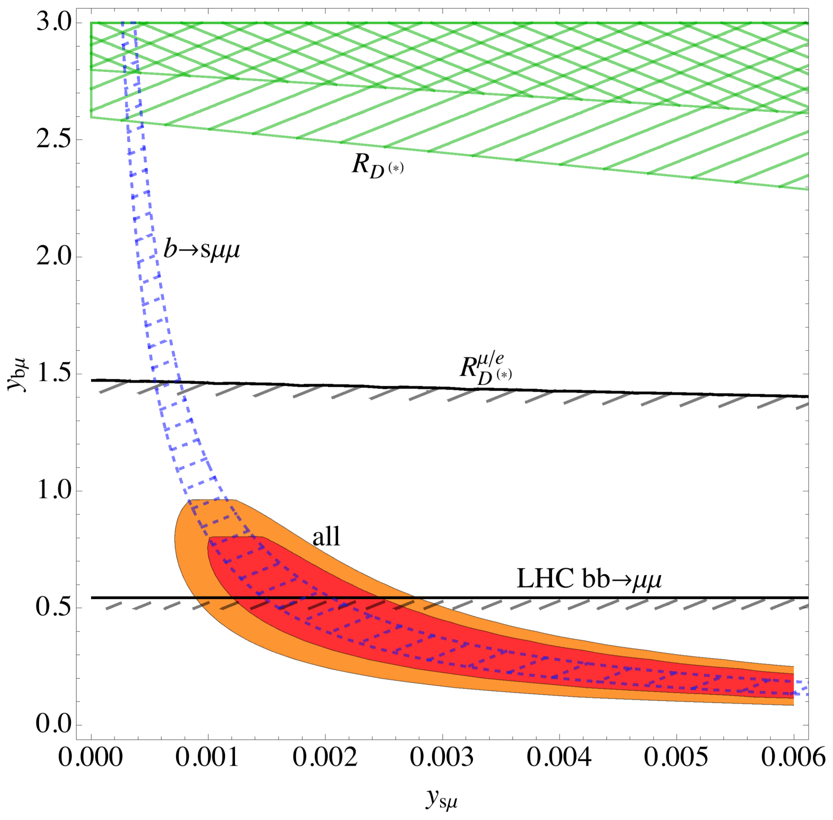
$B \to K\mu e$

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

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

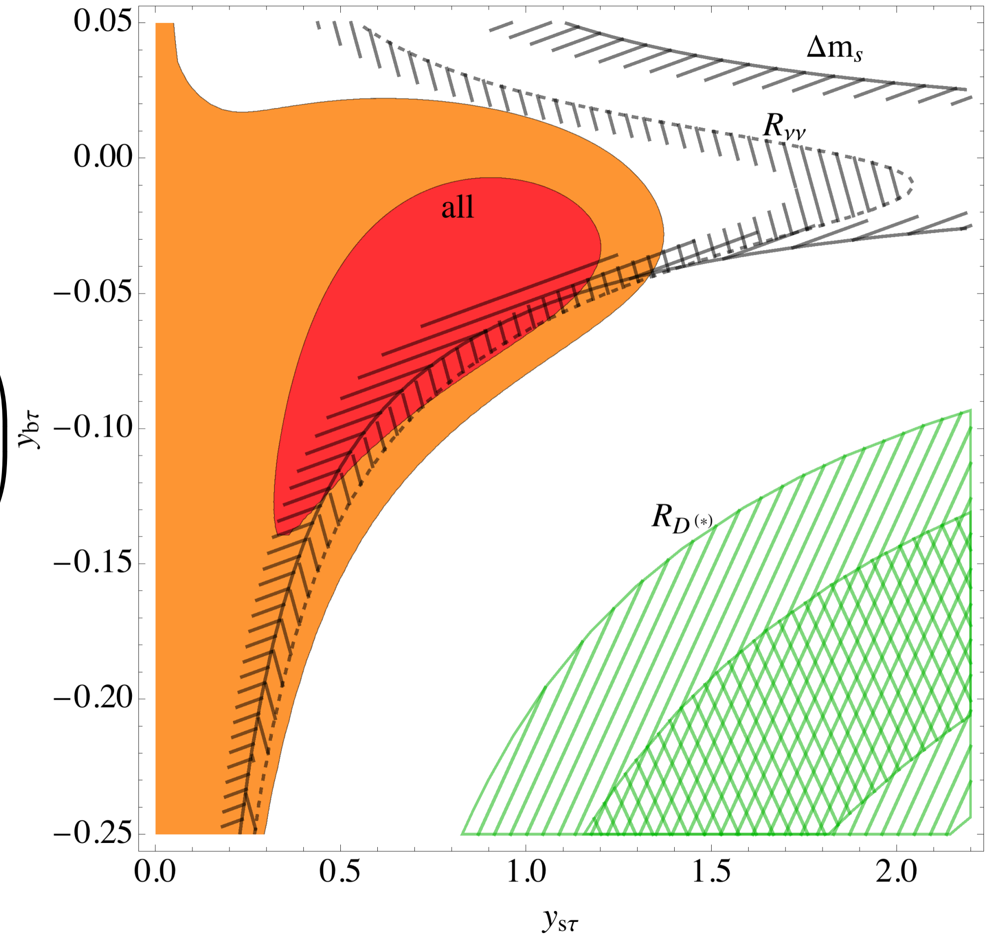
S$_3$ coupled to the muons only

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



$R_{D(*)}$ 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 .

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

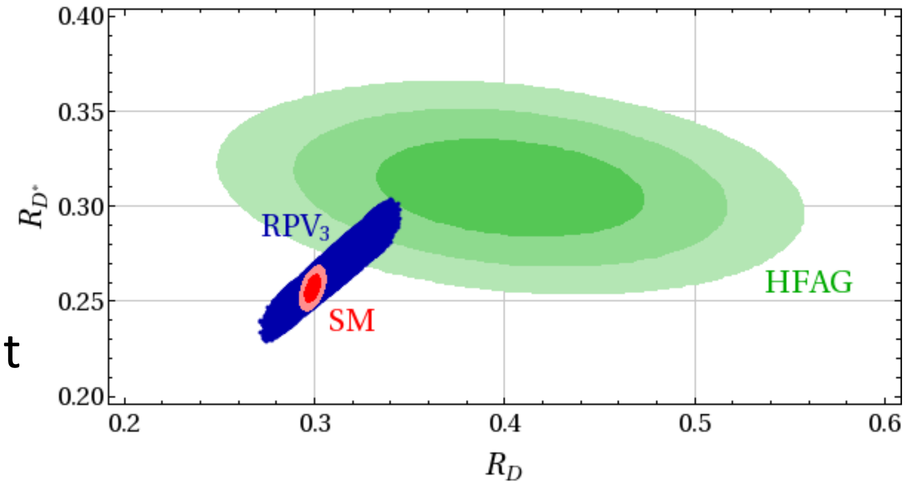


Fit to the m_{S3} = 1TeV scenario with four free couplings. $R_{D(*)}$ is resolved within hatched (2σ) and doubly hatched (1σ) regions. Region to the left of the dashed line (hatched) is in 1σ agreement with $R_{\nu\nu}$ and $R^*_{\nu\nu}$. Δm_s prefers (at 2σ) a region on the hatched side of full line. Red and orange regions are 1 σ and 2 σ results of the fit.

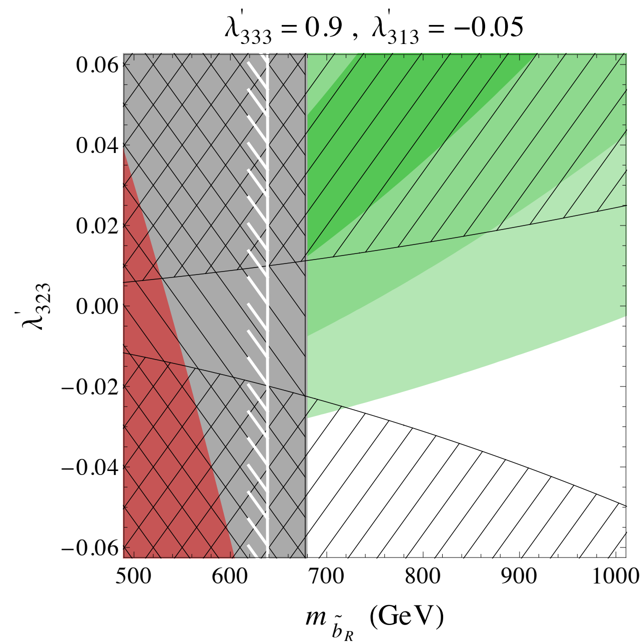
SUSY with R-parity violation

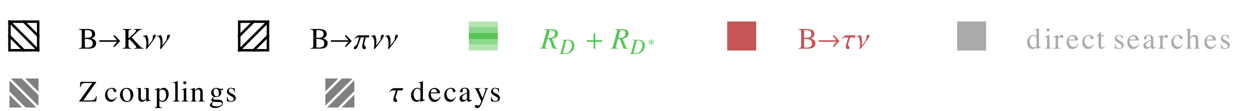
Altmannshofer, Dev, Soni 1704.06659

the 3rd generation of sfermions to be light



$$\mathcal{L}_{\text{eff}} \supset \frac{\lambda'_{ijk}\lambda'^{*}_{mnk}}{2m^2_{\tilde{d}_{kR}}}\Big[\bar{\nu}_{mL}\gamma^\mu\nu_{iL}\bar{d}_{nL}\gamma_\mu d_{jL} + \bar{e}_{mL}\gamma^\mu e_{iL}\left(\bar{u}_L V_{\text{CKM}}\right)_n\gamma_\mu\left(V^\dagger_{\text{CKM}}u_L\right)_j - \nu_{mL}\gamma^\mu e_{iL}\bar{d}_{nL}\gamma_\mu\left(V^\dagger_{\text{CKM}}u_L\right)_j + \text{h.c.}\Big] - \frac{\lambda'_{ijk}\lambda'^{*}_{mjn}}{2m^2_{\tilde{u}_{jL}}}\bar{e}_{mL}\gamma^\mu e_{iL}\bar{d}_{kR}\gamma_\mu d_{nR}\ ,$$





GUT Pati-Salam Model for $U_1(3,1,2/3)$: explain $R_{D(*)}$, $R_{K(*)}$, $(g-2)_\mu$

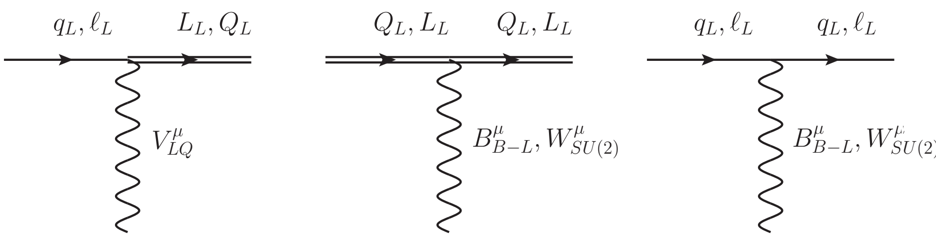
- Di Luzio, Greljo, Nardecchia 1708.08450, gauge group $SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$
- a new colored octet, a triplet and three SM singlets; Their masses ~ TeV region

$M_{Z'}$ = 1.3 TeV, M_U = 1.5 TeV, and $M_{g'}$ = 1.9 TeV. → $R_{D(*)}$

- in the minimal setup two generations of quark and lepton $SU(2)_L$ doublets, mixing with second and third generation SM fermions; a c/s partner with $m_C/_S$ = 740 GeV, a b/t partner with $m_B/_T$ = 1.7 TeV, a μ/νμ partner with $m_{L\mu}$ = 740 GeV and a τ /ντ partner with $m_{L\tau}$ = 1.3 TeV.

- Calibbi, Crivellin and Li, 1709.00692; gauge group SU(4) x $SU(2)_L$ x $SU(2)_R$, new vectorlike fermions (3 generations), one more Higgs;

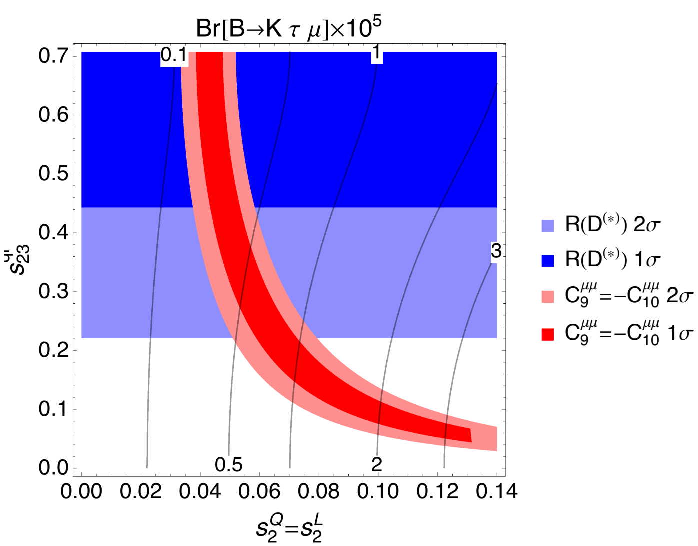
$K_L \to \mu e$ and $K \to \pi\mu e$ in PS model: strong constraints on the scale PeV; they make scale teV possible!



Mixing among SM-like and vector-like fermions, the leptoquark couplings to flavour are non-universal.
Couplings to the other gauge bosons (specially B – L) remain flavour diagonal.

$$\mathcal{L} \supset \kappa_{ij}\, \bar{q}_i^L \gamma^\mu P_L \ell_j^L V_\mu + h.c.$$

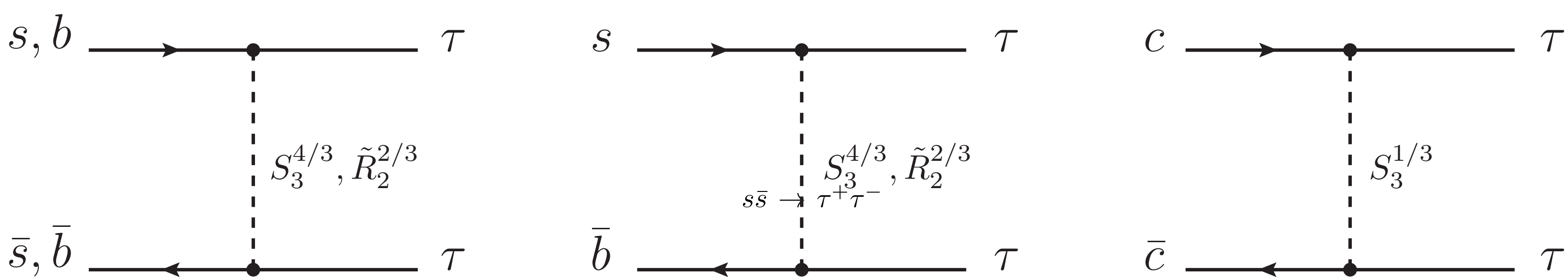
$$\kappa_{ij} = \frac{-g_s}{\sqrt{2}} \begin{pmatrix} c_1^Q s_1^L + c_1^L s_1^Q & 0 & 0 \\ 0 & \left(c_2^Q s_2^L + c_2^L s_2^Q\right) c_{23}^{q\ell} & -s_{23}^{q\ell}\left(c_2^Q s_2^L + c_2^L s_2^Q\right) \\ 0 & \left(c_2^Q s_2^L + c_2^L s_2^Q\right) s_{12}^{q\ell} & c_{23}^{q\ell}\left(c_3^Q s_3^L + c_3^L s_3^Q\right) \end{pmatrix}$$



Rate for $B_s \to \tau^+\tau^-$ significantly enhanced.

LHC constraints on LQ couplings

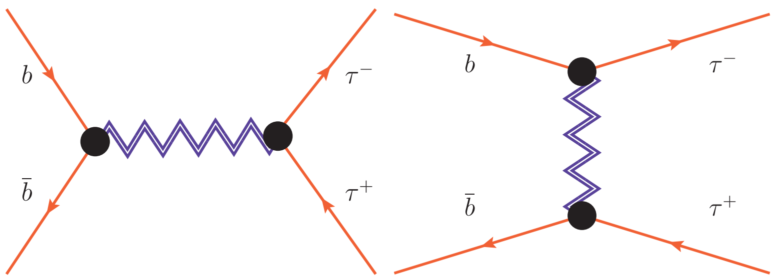
Processes in t-channel $pp \to \tau^+\tau^-$

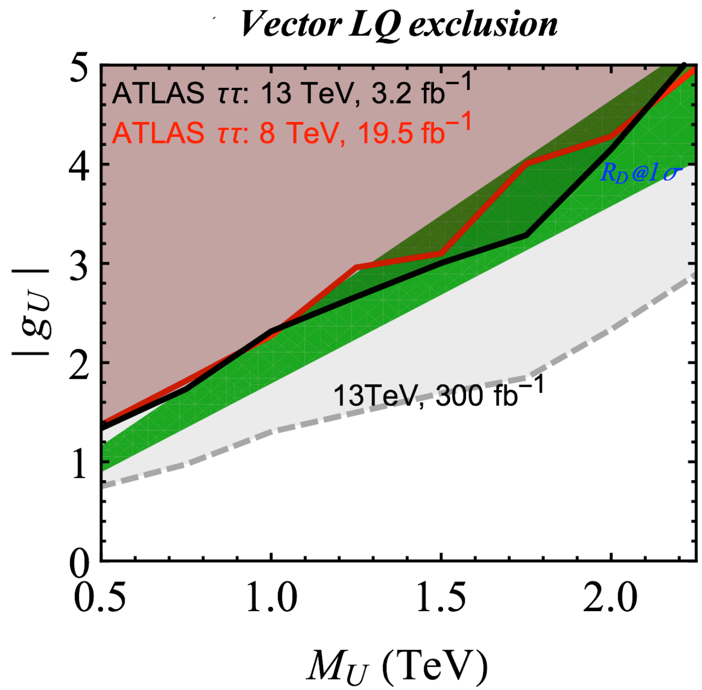


Flavour anomalies generate s τ , bτ and cτ relatively large couplings.
s quark pdf function for protons are ~ 3 times lagrer contribution then for b quark.

Constraints from high p_T searches at LHC

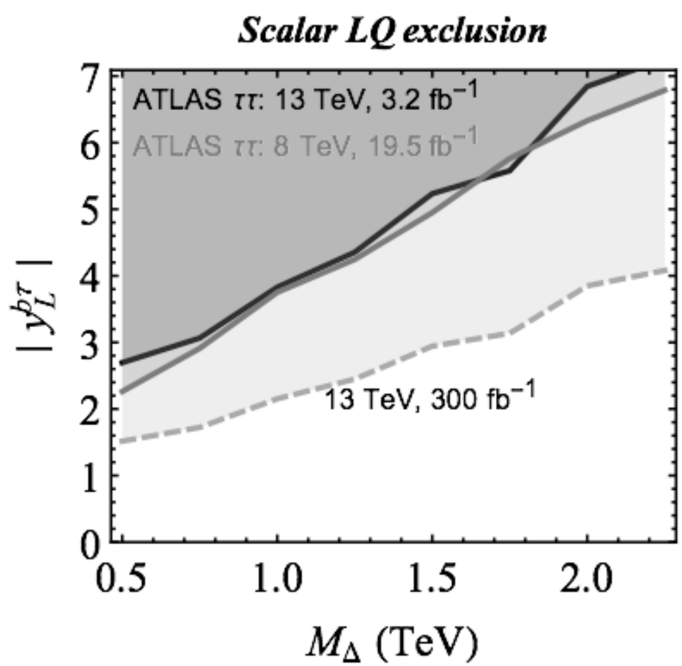
Faroughy et al., 1609.07138

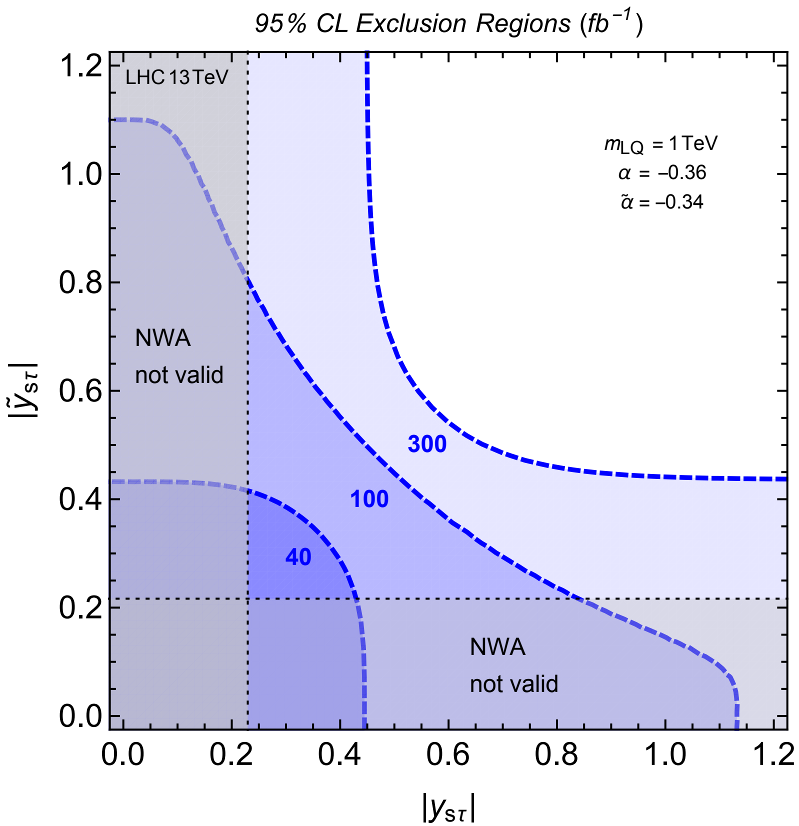




2HDM cannot reconcile ττ searches at LHC for

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





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.

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

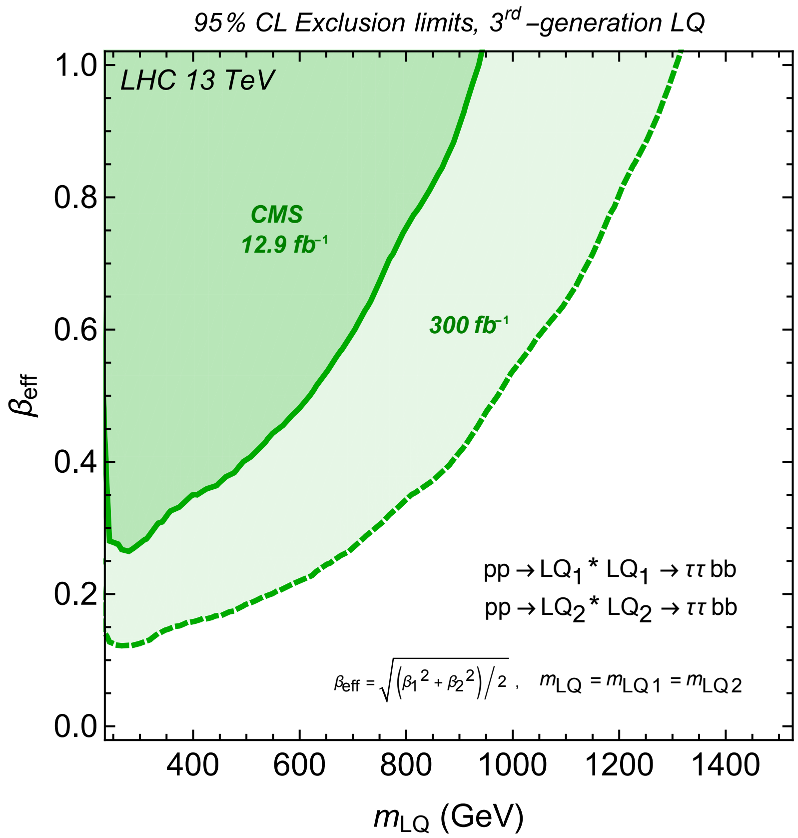
$$\alpha \equiv y_{s\tau} y_{b\tau}$$
$$\tilde{\alpha} \equiv \tilde{y}_{s\tau} \tilde{y}_{b\tau}$$

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

Summary

- Effective Lagrangian for NP for B anomalies well established;
- $R_{D(*)}$ explanation by NP very intriguing, due to strong flavour constraints;
- Constraints from LHC high p_T searches important;
- Simple models of one NP particle present in all B anomalies prefer weak singlet vector LQ;
- More sophisticated GUT models are already constructed!

Thanks!



The reinterpretation of the CMS Collaboration exclusion limits for two degenerate third-generation LQs decaying into ττbb final state in the βeff–mLQ plane

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.

There are 11 observables. Most promising to trace NP

1. Differential decay distribution

2. Forward-backward asymmetry

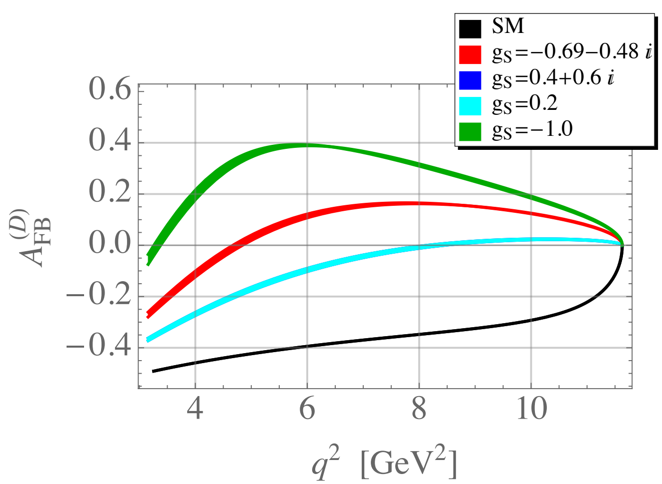
3. Lepton polarization asymmetry

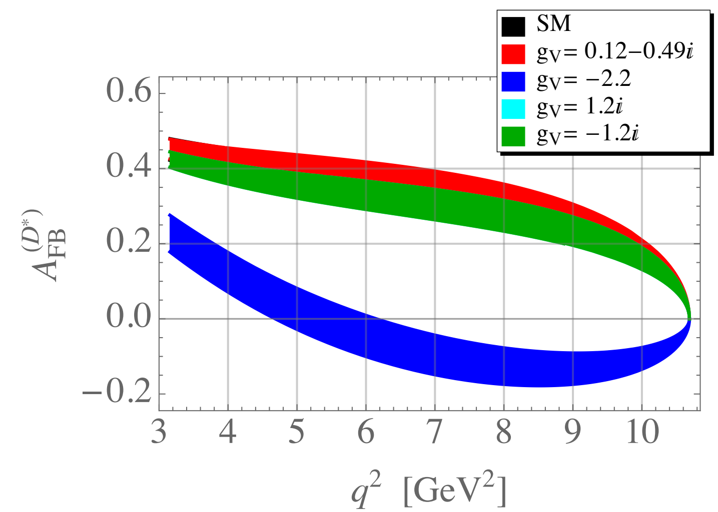
$$R_{L,T} = \frac{d\Gamma_L/dq^2}{d\Gamma_T/dq^2}$$

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

$g_V = 0.21 - i\ 0.76,\qquad g_A = -0.18 - i\ 0.05,$ best fit values

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





$Quantity$	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"