One Leptoquark To Rule Them All

Martin Bauer, Matthias Neubert, PRL **116** (2016) 141802

Martin Bauer, Clara Hörner, Matthias Neubert, 16??.?????

Effective Field Theories for Collider Physics, Flavor Phenomena and Electroweak Symmetry Breaking

Eltville 2016

erc

PRiSMA

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

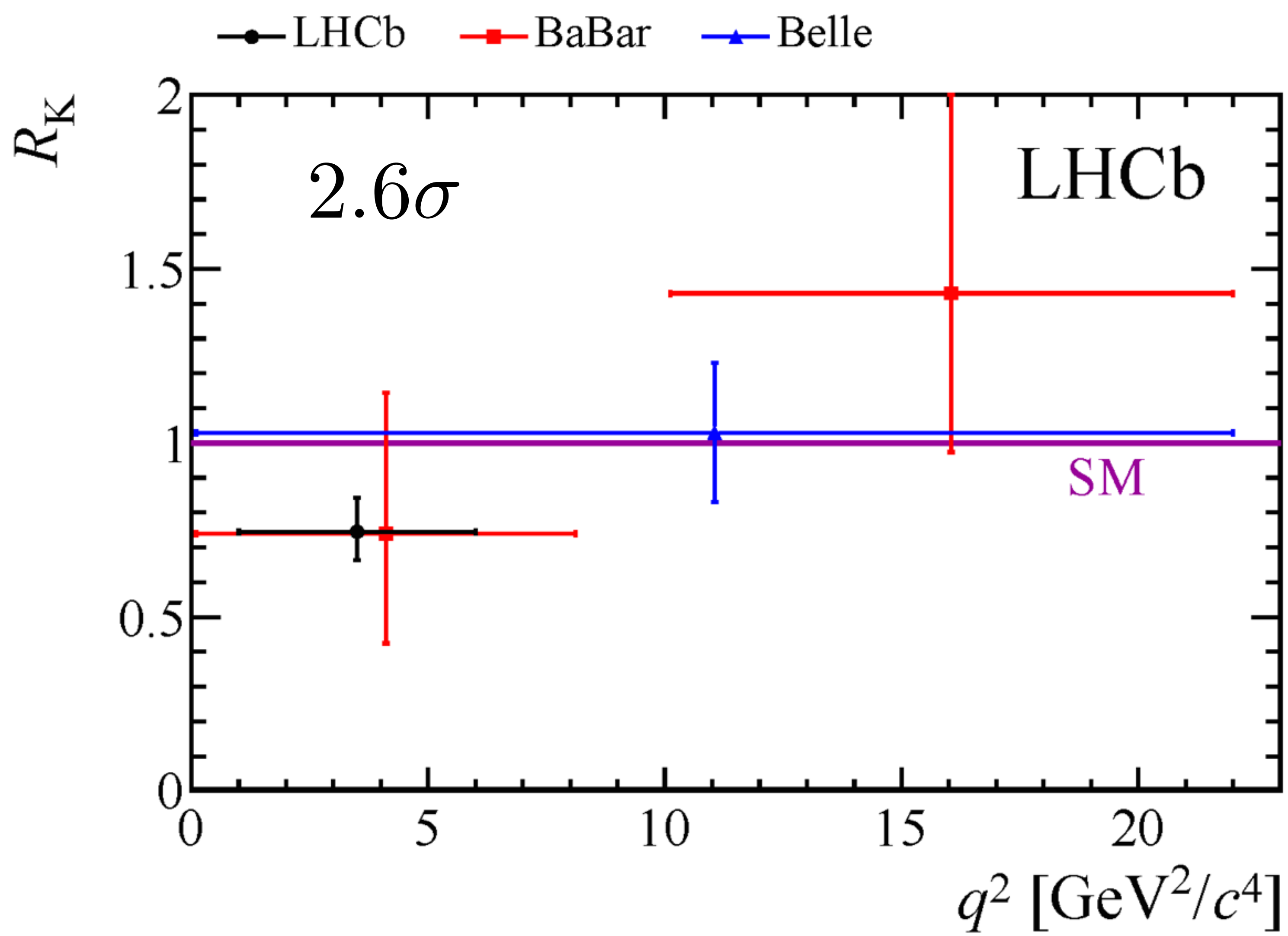
Anomalies in the B sector: R_K

- $$R_K = \frac{\Gamma(\bar{B} \to \bar{K}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}e^+e^-)} = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

  LHCb, arXiv:1406.6482 hep-ex

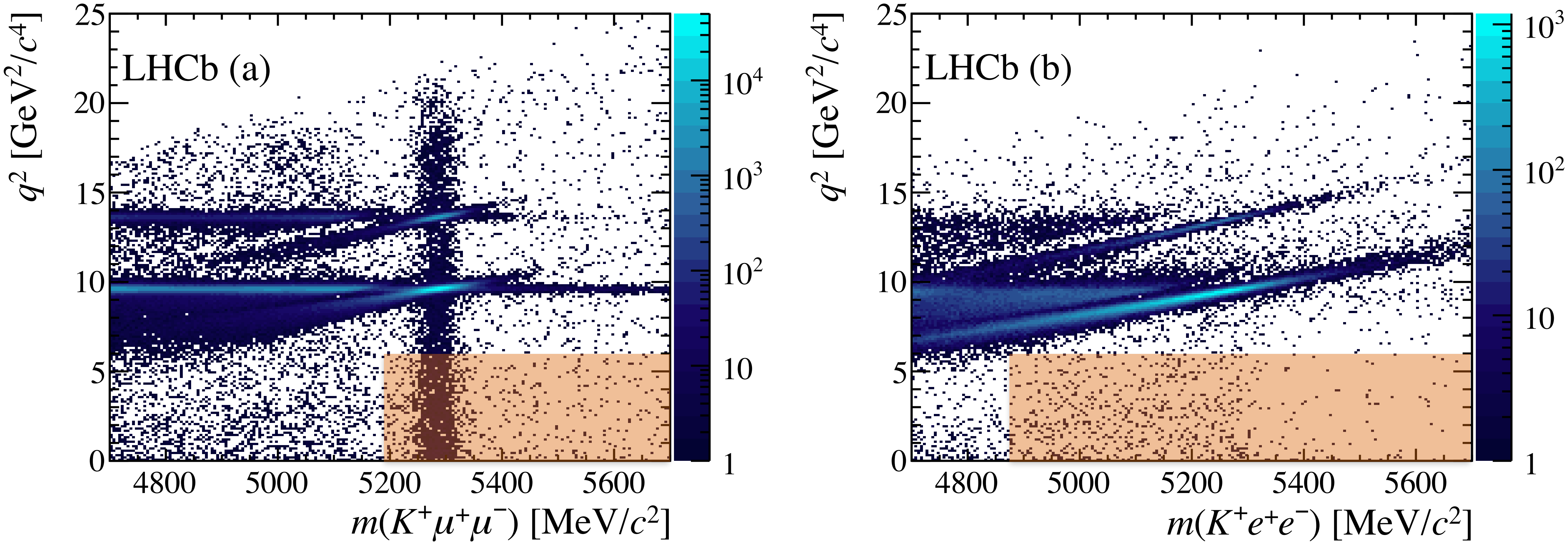
- Theoretically very clean

- Cannot be explained by Form Factors or Charm Contributions!



ANOMALIES IN THE B SECTOR: R_K

LHCb, arXiv:1406.6482 hep-ex



Number of muon pairs

$$1226 \pm 41$$

Number of electron pairs

$$172^{+20}_{-19} + 20^{+16}_{-14} + (62 \pm 13)$$

Experimentalists:

Anomalies in the B sector: Semileptonic decays

- $b \to s$ transitions

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{d\text{BR}}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{d\text{BR}}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

Altmannshofer, Straub 1503.06199

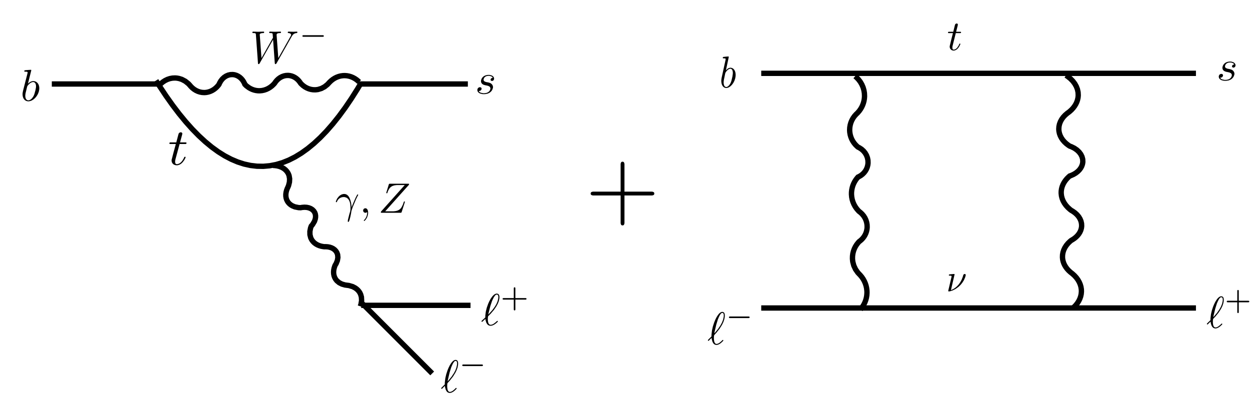
Anomalies in the B sector

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \,\frac{\alpha_e}{4\pi}\, \sum_i C_i(\mu) \mathcal{O}_i(\mu)\,,$$

$$\mathcal{O}_9 = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}_{10} = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]\,,$$

$$\mathcal{O}_S = [\bar{s} P_R b]\,[\bar{\ell}\ell]\,, \quad \mathcal{O}_P = [\bar{s} P_R b]\,[\bar{\ell}\gamma_5 \ell]\,,$$

Standard Model:

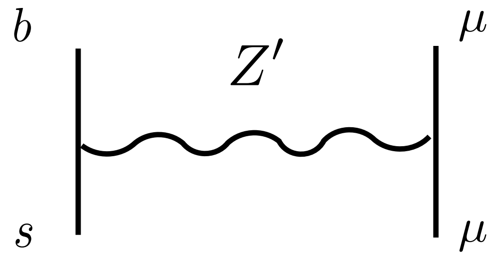


$$\Rightarrow \quad C_9^{\rm SM} = -C_{10}^{\rm SM} = 4.2$$

Anomalies in the B sector

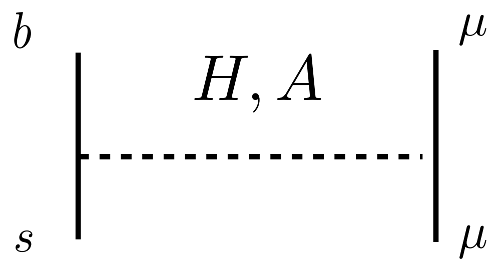
Vector currents

$$R_K: \quad 0.7 \lesssim \mathrm{Re}\left[\left(C_9^e + C_9'^e - C_{10}^e - C_{10}'^e\right) - (e \to \mu)\right] \lesssim 1.5$$



Scalar currents

$$R_K: \quad 15 \lesssim |C_S^e + C_S'^e|^2 + |C_P^e + C_P'^e|^2 - (e \to \mu) \lesssim 34$$



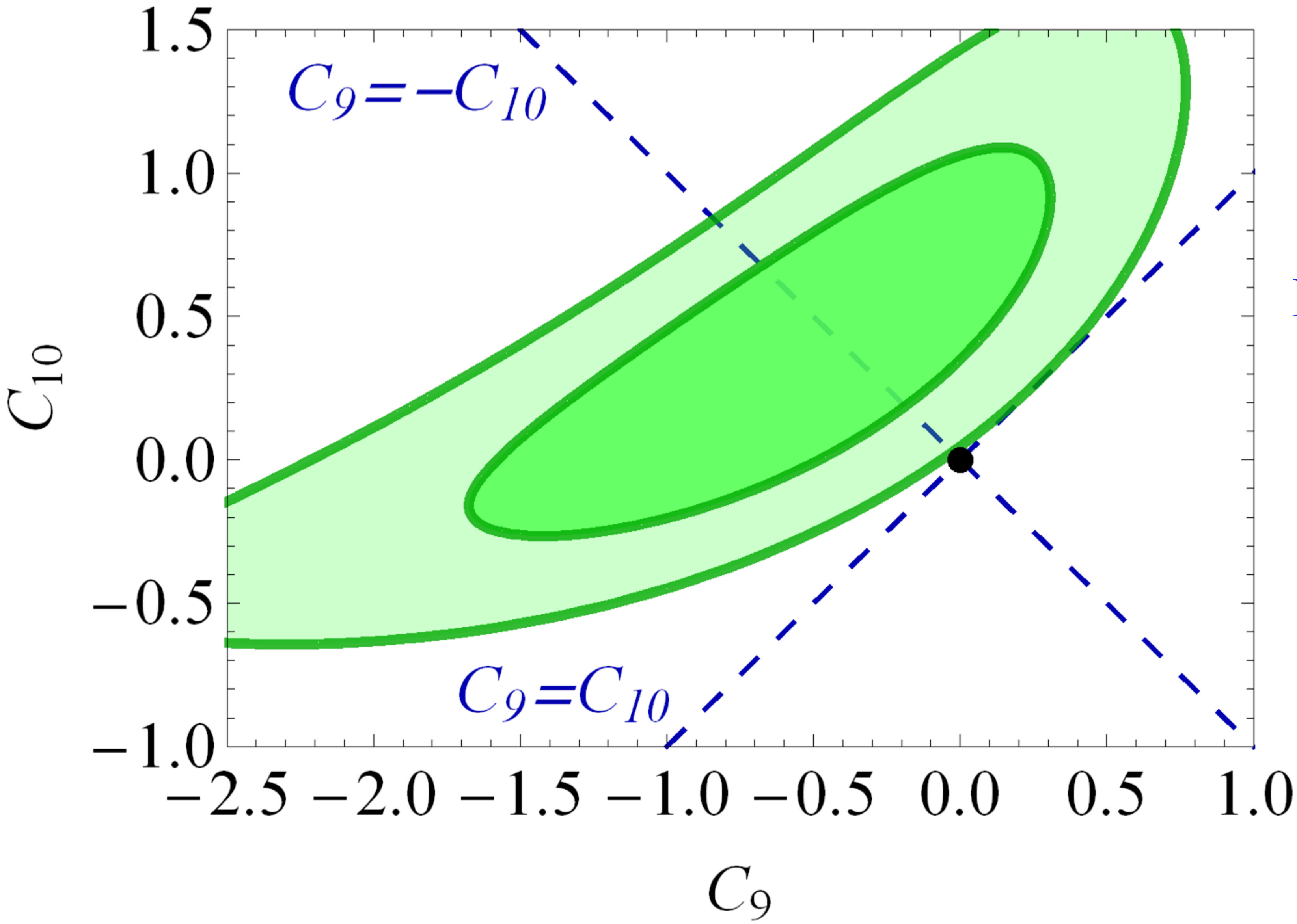
Constraints from

$$\frac{\mathcal{B}(\bar{B}_s \to \ell^+\ell^-)}{\mathcal{B}(\bar{B}_s \to \ell^+\ell^-)^{\mathrm{SM}}} = \left|1 - 0.24(C_{10} - C_{10}') - y_\ell(C_P - C_P')\right|^2 + \left|y_\ell(C_S - C_S')\right|^2 \qquad y_\mu = 7.7, \qquad y_e = 1600$$

$$\frac{\mathcal{B}(\bar{B}_s \to ee)^{\mathrm{exp}}}{\mathcal{B}(\bar{B}_s \to ee)^{\mathrm{SM}}} < 3.3 \cdot 10^6 \,, \qquad |C_S^e - C_S'^e|^2 + |C_P^e - C_P'^e|^2 \lesssim 1.3$$

$$\frac{\mathcal{B}(\bar{B}_s \to \mu\mu)^{\mathrm{exp}}}{\mathcal{B}(\bar{B}_s \to \mu\mu)^{\mathrm{SM}}} = 0.79 \pm 0.20 \,. \qquad 0 \lesssim \mathrm{Re}[C_{10}^\mu - C_{10}'^\mu] \lesssim 1.9$$

Anomalies in the B sector



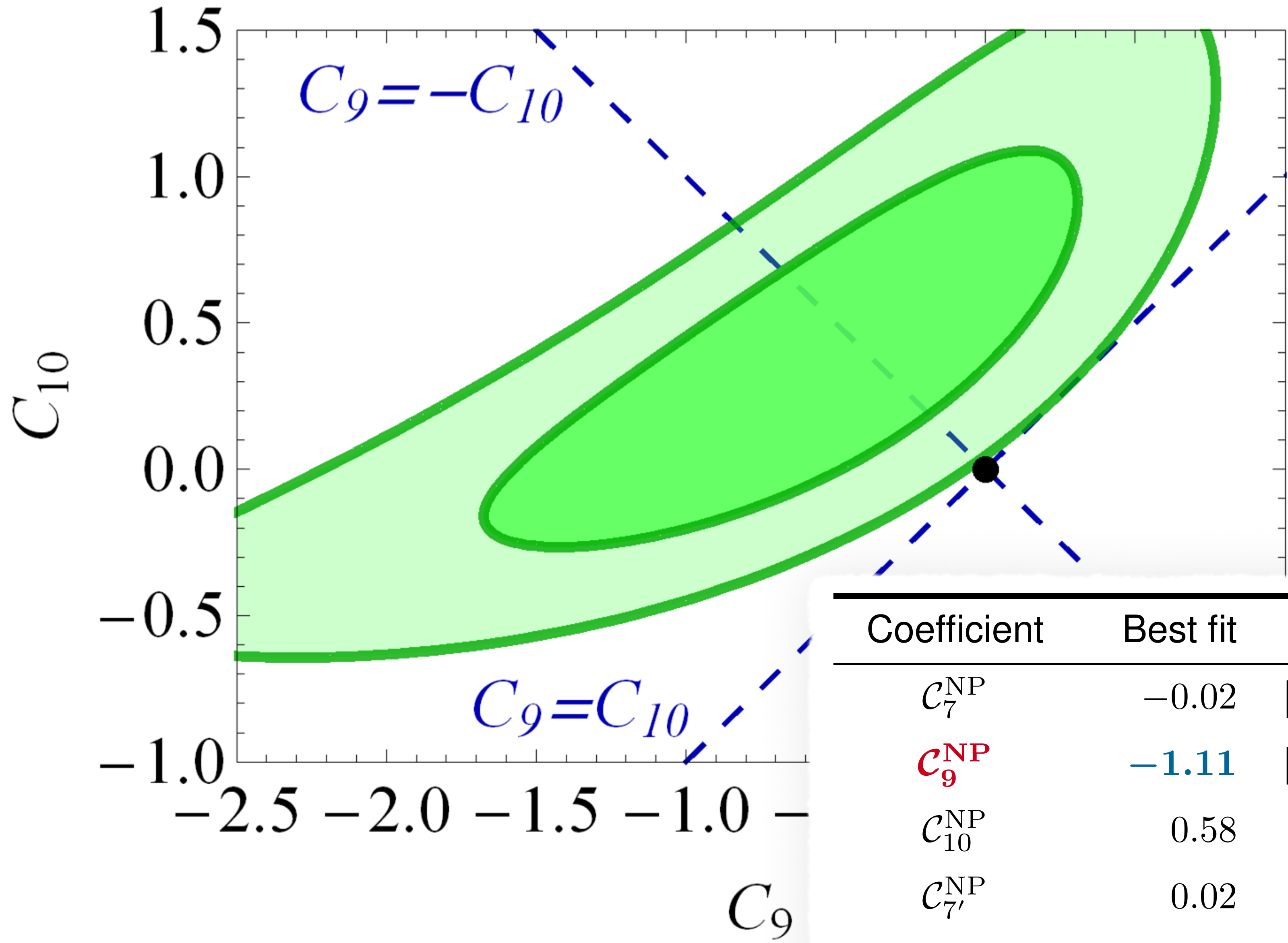
$B^+ \to K^+ \mu^+ \mu^-$

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

Becirevic et al. 1608.07583

More details: Tobias and Fulvias talks

ANOMALIES IN THE B SECTOR



$B^+ \to K^+ \mu^+ \mu^-$

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

Becirevic et al. 1608.07583

DHMV, 1510.04239

Coefficient	Best fit	1σ	3σ	$\mathrm{Pull}_{\mathrm{SM}}$
$\mathcal{C}_7^{\mathrm{NP}}$	-0.02	$[-0.04, -0.00]$	$[-0.07, 0.04]$	1.1
$\mathcal{C}_9^{\mathrm{NP}}$	-1.11	$[-1.32, -0.89]$	$[-1.71, -0.40]$	4.5
$\mathcal{C}_{10}^{\mathrm{NP}}$	0.58	$[0.34, 0.84]$	$[-0.11, 1.41]$	2.5
$\mathcal{C}_{7'}^{\mathrm{NP}}$	0.02	$[-0.01, 0.04]$	$[-0.05, 0.09]$	0.7
$\mathcal{C}_{9'}^{\mathrm{NP}}$	0.49	$[0.21, 0.77]$	$[-0.33, 1.35]$	1.8
$\mathcal{C}_{10'}^{\mathrm{NP}}$	-0.27	$[-0.46, -0.08]$	$[-0.84, 0.28]$	1.4
$\mathcal{C}_9^{\mathrm{NP}} = \mathcal{C}_{10}^{\mathrm{NP}}$	-0.21	$[-0.40, 0.00]$	$[-0.74, 0.55]$	1.0
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}}$	-0.69	$[-0.88, -0.51]$	$[-1.27, -0.18]$	4.1
$\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}}$	-1.09	$[-1.28, -0.88]$	$[-1.62, -0.42]$	4.8

Cancels in RK →

Anomalies in the B sector

Need

$$C_{9/10}^{\rm NP} \approx C_{10}^{\rm SM}/4 \quad \Rightarrow \quad \frac{1}{M^2}\left(\frac{2V_{tb}V_{ts}^*}{v^2}\frac{\alpha_e}{4\pi}\right)^{-1} = \frac{1}{4}$$

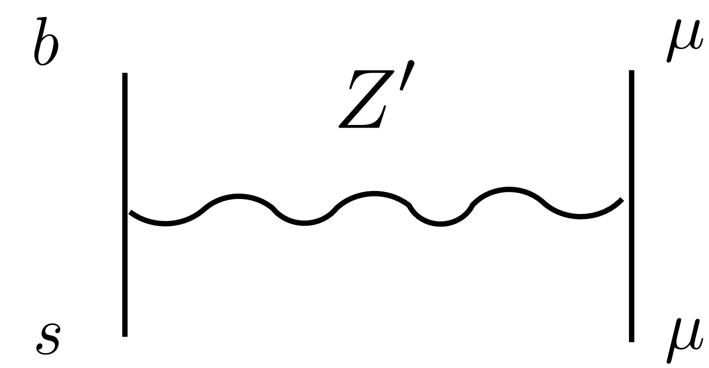
$$\Rightarrow \quad M \approx 35\,\text{TeV}$$

DHMV, 1510.04239

Coefficient	Best fit	1σ	3σ	Pull$_{\rm SM}$
$\mathcal{C}_7^{\rm NP}$	-0.02	$[-0.04, -0.00]$	$[-0.07, 0.04]$	1.1
$\mathcal{C}_9^{\rm NP}$	-1.11	$[-1.32, -0.89]$	$[-1.71, -0.40]$	**4.5**
$\mathcal{C}_{10}^{\rm NP}$	0.58	$[0.34, 0.84]$	$[-0.11, 1.41]$	2.5
$\mathcal{C}_{7'}^{\rm NP}$	0.02	$[-0.01, 0.04]$	$[-0.05, 0.09]$	0.7
$\mathcal{C}_{9'}^{\rm NP}$	0.49	$[0.21, 0.77]$	$[-0.33, 1.35]$	1.8
$\mathcal{C}_{10'}^{\rm NP}$	-0.27	$[-0.46, -0.08]$	$[-0.84, 0.28]$	1.4
$\mathcal{C}_9^{\rm NP} = \mathcal{C}_{10}^{\rm NP}$	-0.21	$[-0.40, 0.00]$	$[-0.74, 0.55]$	1.0
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$	-0.69	$[-0.88, -0.51]$	$[-1.27, -0.18]$	**4.1**
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}$	-1.09	$[-1.28, -0.88]$	$[-1.62, -0.42]$	**4.8**

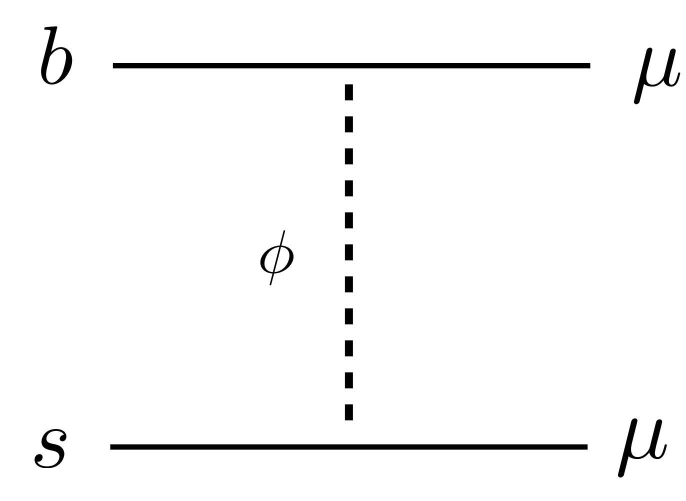
Two Main Candidates

$C_9:$ Vector Currents



Gauld, Goetz, Haisch, 1310.1082
Altmannshofer, Gori, Pospelov, Yavin, 1403.1269
Crivellin, D'Ambrosio, Heeck 1501.00993
many more!

$C_9 = -C_{10}:$ Leptoquarks



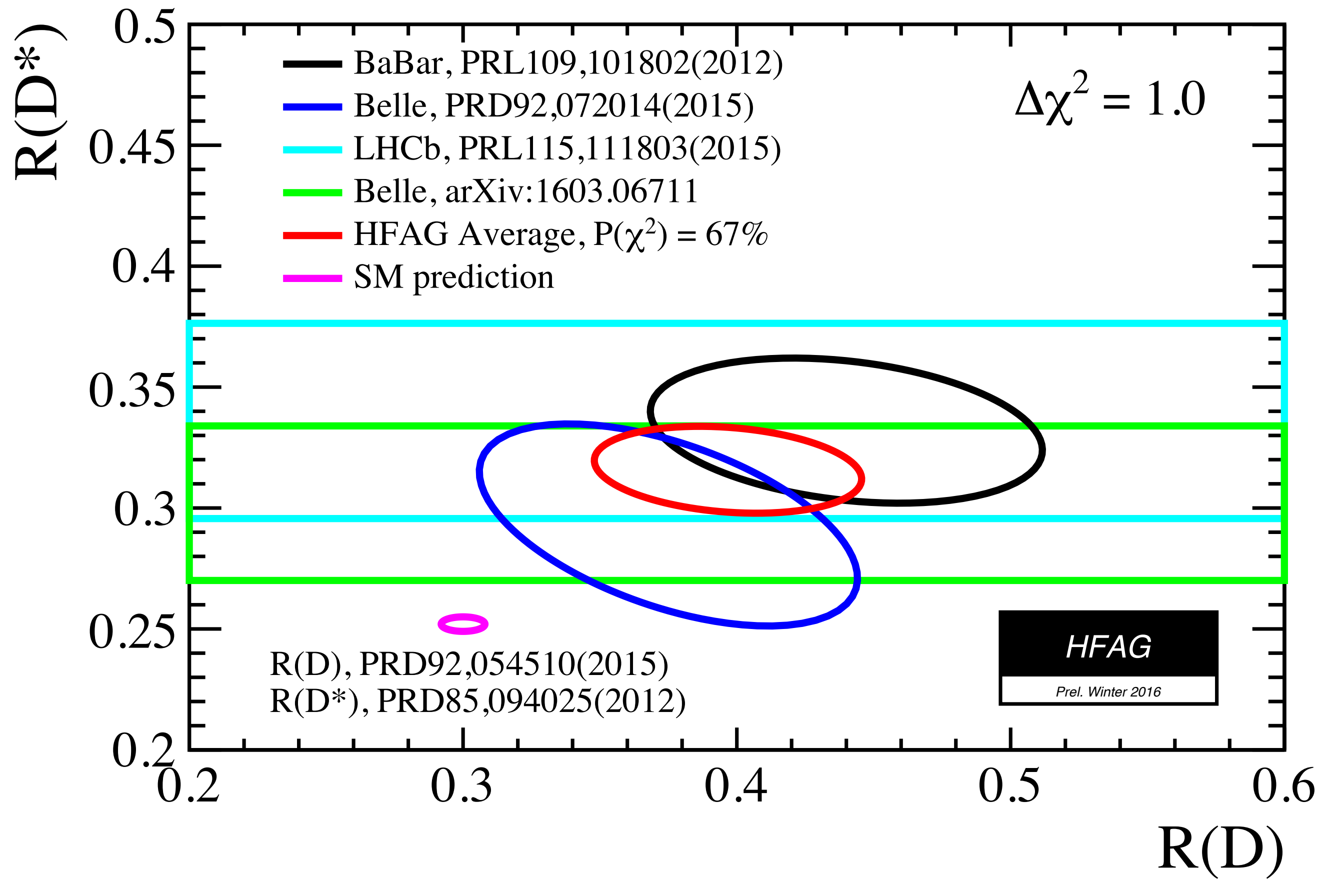
$(3,3)_{-1/3}$ $(3,2)_{1/6}$ Hiller, Schmaltz 1408.1627
Becirevic et al. 1608.08501

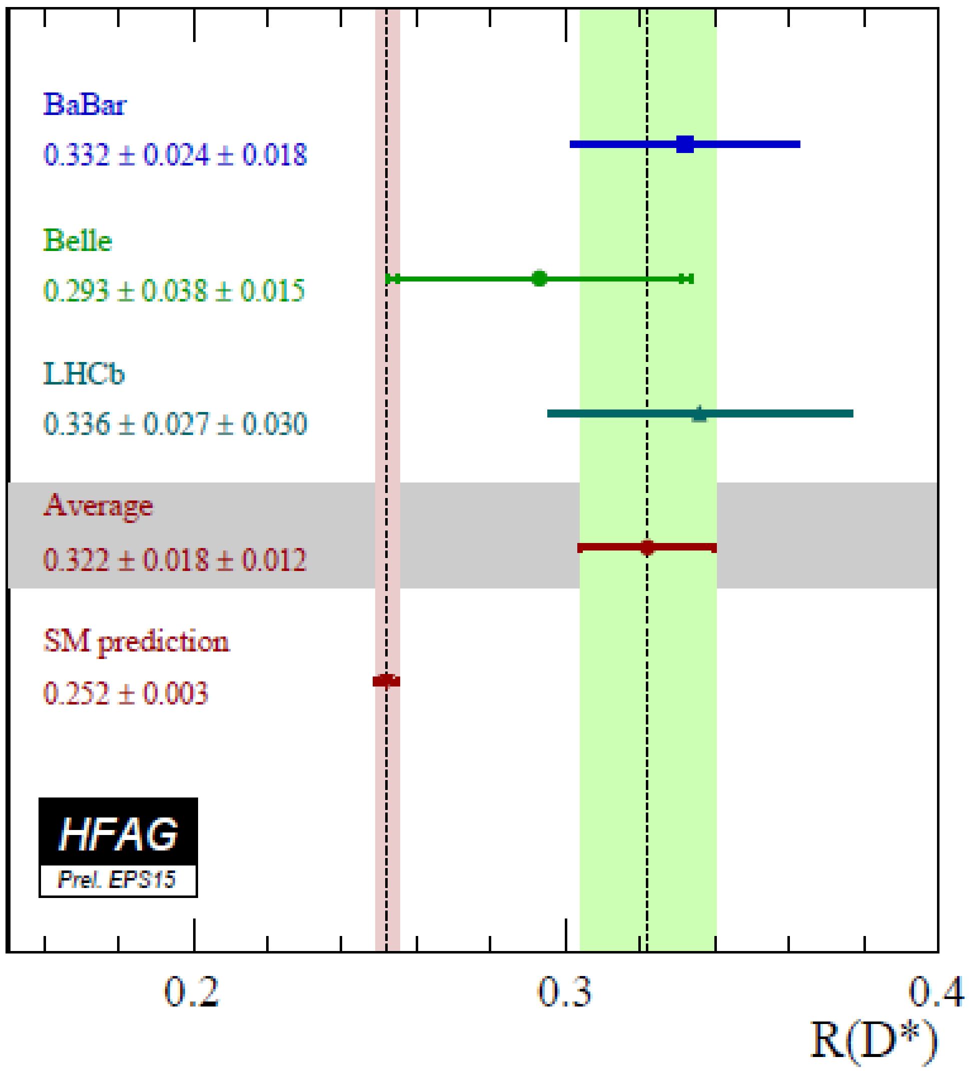
$(3,3)_{2/3}$ Fajfer, Kosnik 1511.06024

Anomalies in the B sector: $R(D^{(*)})$

- $R(D^{(*)}) = \dfrac{\bar{B} \to D^{(*)}\tau\bar{\nu}}{\bar{B} \to D^{(*)}\ell\bar{\nu}}$
- Combined Significance: 4σ
- Belle II is expected to improve exp. error by factor ~5 !

HFAG EPS 2015



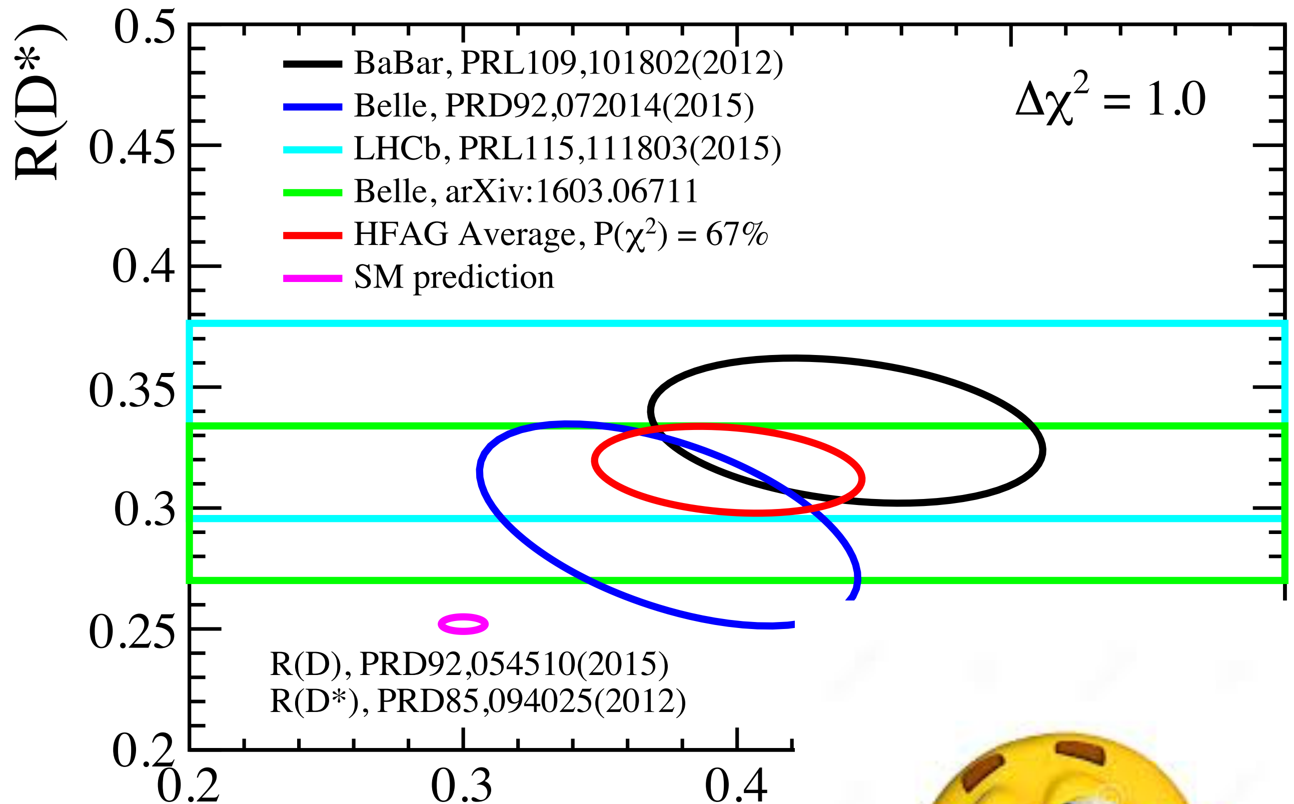


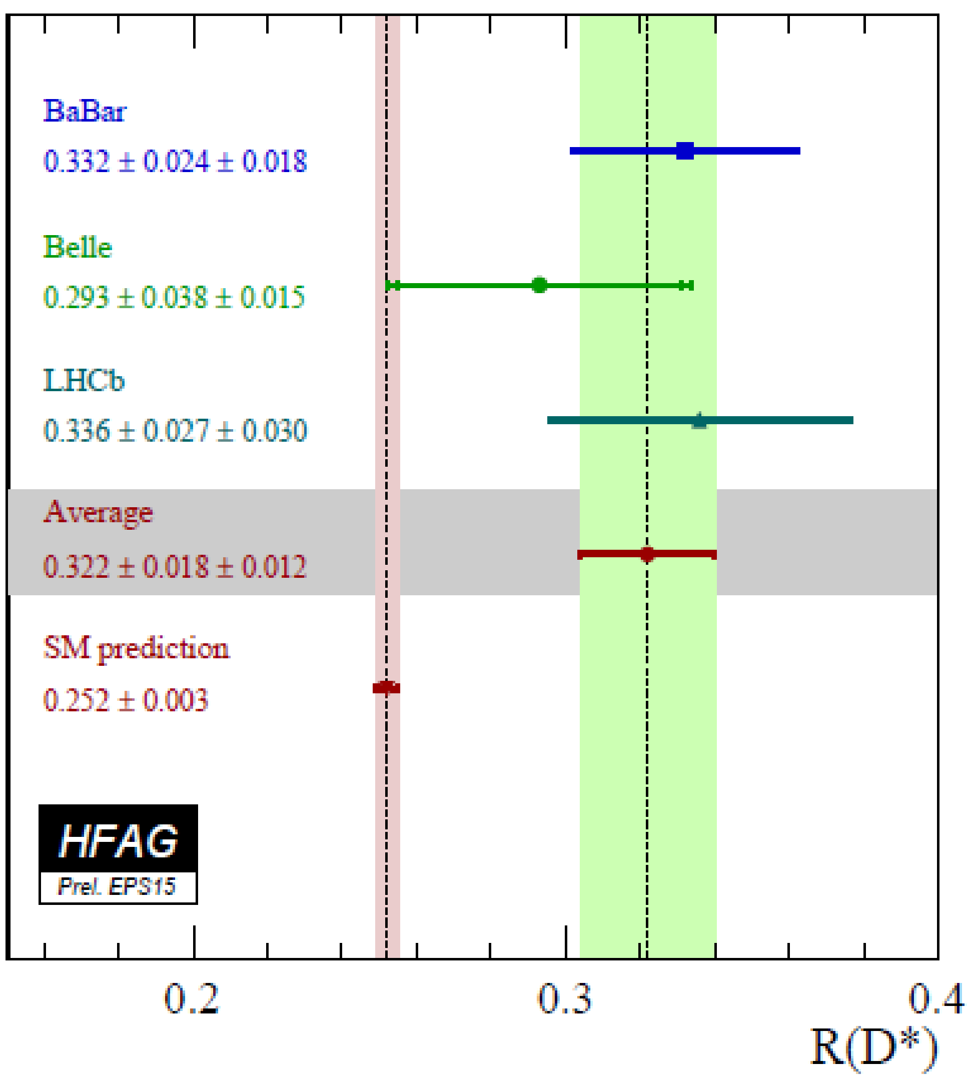
Experimentalists:

Anomalies in the B sector: $R(D^{(*)})$

- $R(D^{(*)}) = \frac{\bar{B} \to D^{(*)}\tau\bar{\nu}}{\bar{B} \to D^{(*)}\ell\bar{\nu}}$
- Combined Significance: 4σ
- Belle II is expected to improve exp. error by factor ~5 !

HFAG EPS 2015



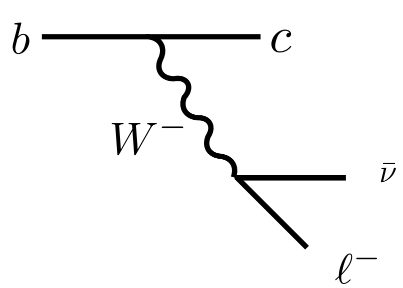


Experimentalists:

Anomalies in the B sector: $R(D^{(*)})$

	Measurement	SM Prediction
$R(D^{(*)}) = \frac{\bar{B} \to D^{(*)}\tau\bar{\nu}}{\bar{B} \to D^{(*)}\ell\bar{\nu}}$	$0.388 \pm 0.047\,, \quad D$	$0.300 \pm 0.010\,, \quad D$
	$0.321 \pm 0.021\,, \quad D^*$	$0.252 \pm 0.005\,, \quad D^*$

SM contribution is tree-level…



$$\propto \frac{V_{cb} g^2}{M_W^2}$$

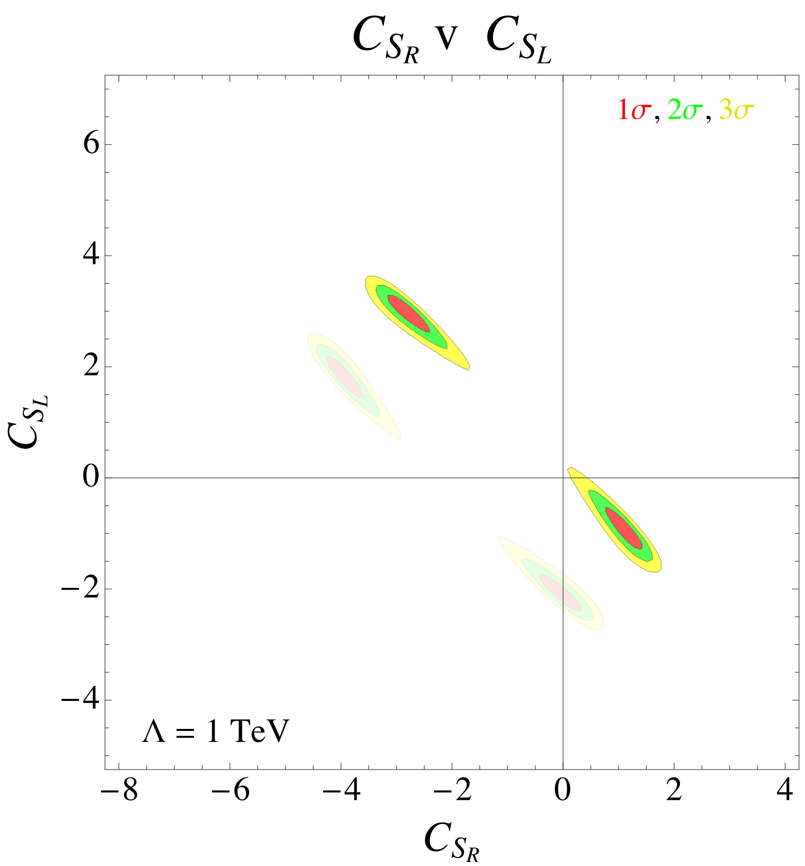
…and we want a 10-20% shift

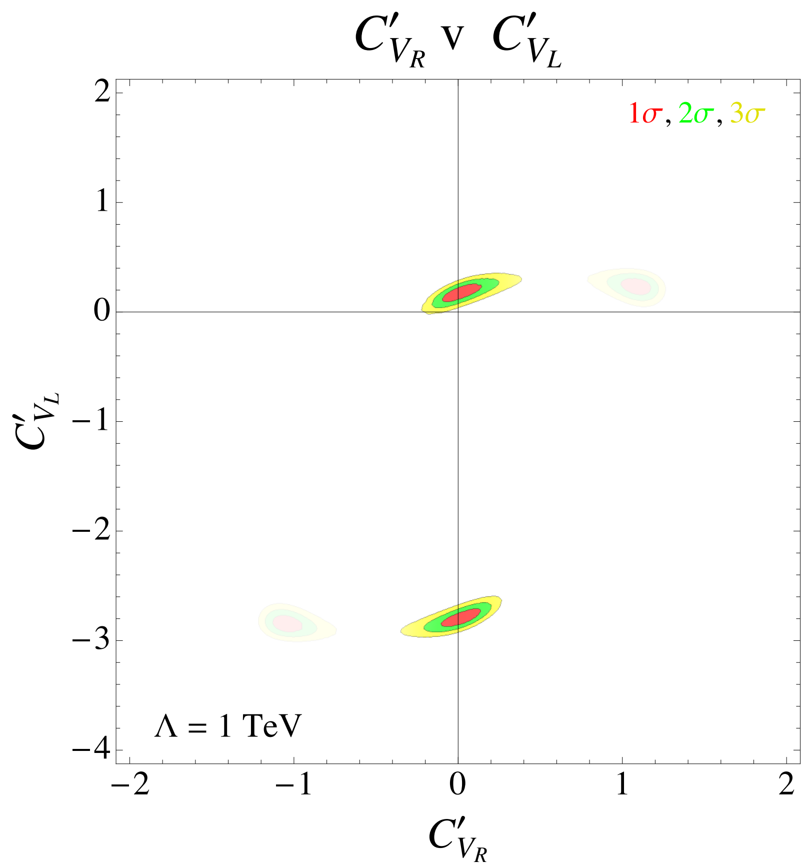
Needs a large new physics contribution:

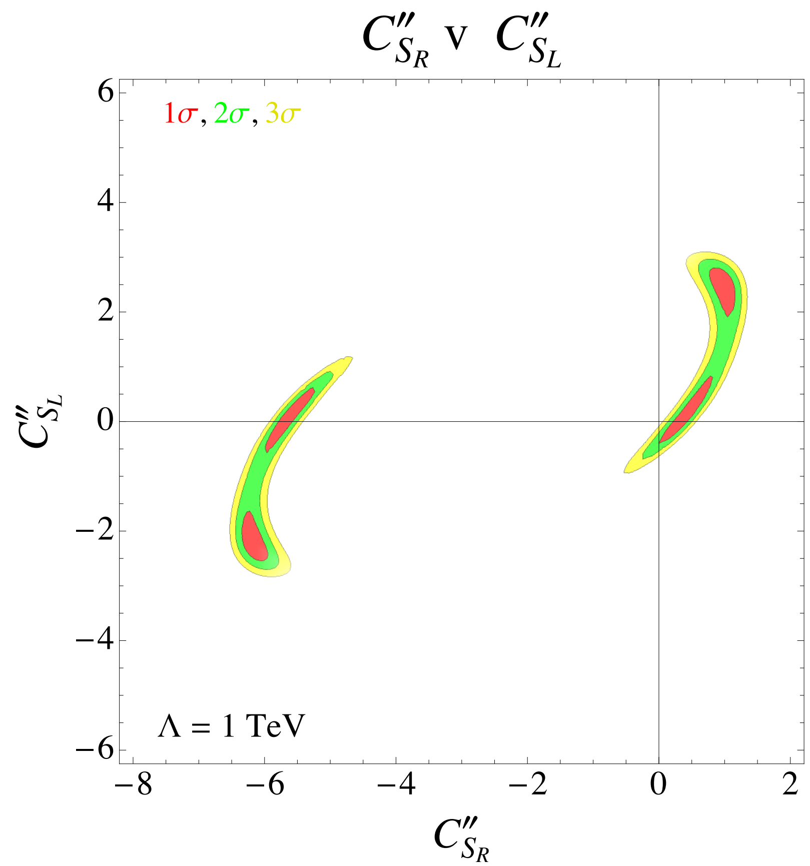
$$C_{NP} \approx C_{SM}/10 \quad \Rightarrow \quad \frac{1}{V_{cb}}\left(\frac{v}{M}\right)^2 = \frac{1}{10} \qquad \Rightarrow \; M = 1 - 2\,\mathrm{TeV}$$

Anomalies in the B sector: $R(D^{(*)})$

- Using $\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb}\, \mathcal{O}_{V_L} + \frac{1}{\Lambda^2} \sum_i C_i^{(\prime,\prime\prime)}\, \mathcal{O}_i^{(\prime,\prime\prime)}$ Freytsis *et al.*, 1506.08896







$$\mathcal{O}_{S_L} = (\bar{c} P_L b)(\bar{\tau} P_L \nu)$$
$$\mathcal{O}_{S_R} = (\bar{c} P_R b)(\bar{\tau} P_L \nu)$$

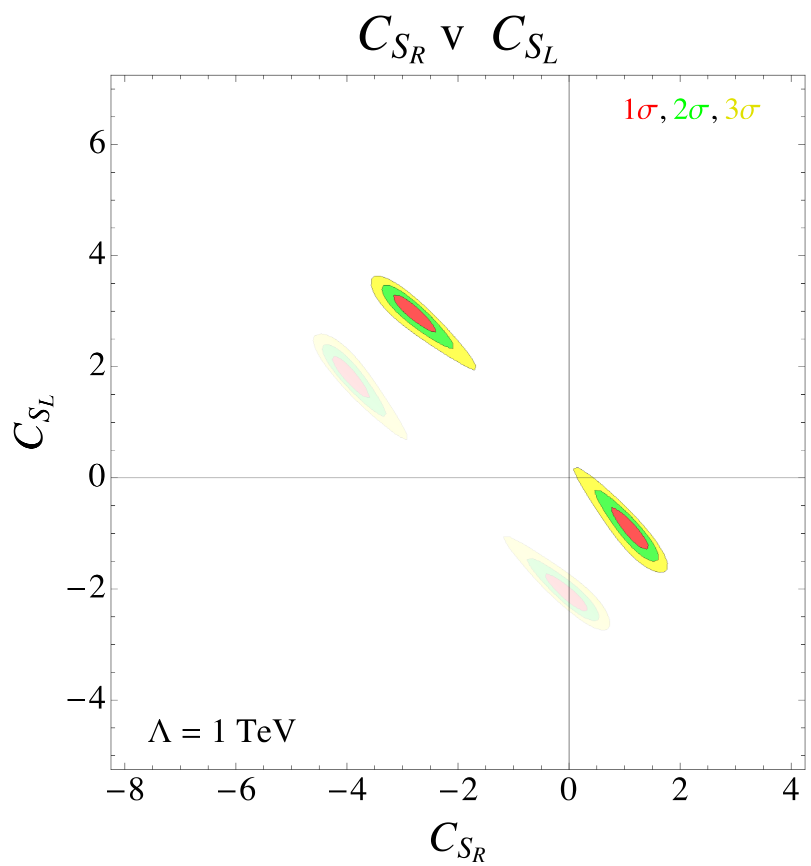
$$\mathcal{O}'_{V_L} = (\bar{\tau}\gamma_\mu P_L b)(\bar{c}\gamma^\mu P_L \nu)$$
$$\mathcal{O}'_{V_R} = (\bar{\tau}\gamma_\mu P_R b)(\bar{c}\gamma^\mu P_L \nu)$$

$$\mathcal{O}''_{S_L} = (\bar{\tau} P_L c^c)(\bar{b}^c P_L \nu)$$
$$\mathcal{O}''_{S_R} = (\bar{\tau} P_R c^c)(\bar{b}^c P_L \nu)$$

New H^+ New W' New Leptoquark

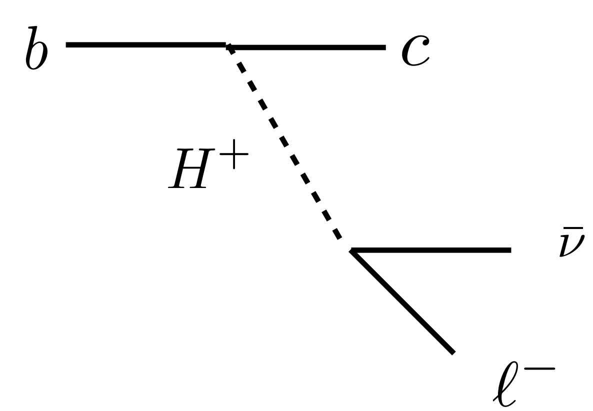
Anomalies in the B sector: $R(D^{(*)})$

- Using $\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb}\, \mathcal{O}_{V_L} + \frac{1}{\Lambda^2} \sum_i C_i^{(\prime,\prime\prime)}\, \mathcal{O}_i^{(\prime,\prime\prime)}$ Freytsis *et al.*, 1506.08896



$$\mathcal{O}_{S_L} = (\bar{c} P_L b)(\bar{\tau} P_L \nu)$$
$$\mathcal{O}_{S_R} = (\bar{c} P_R b)(\bar{\tau} P_L \nu)$$

New H^+

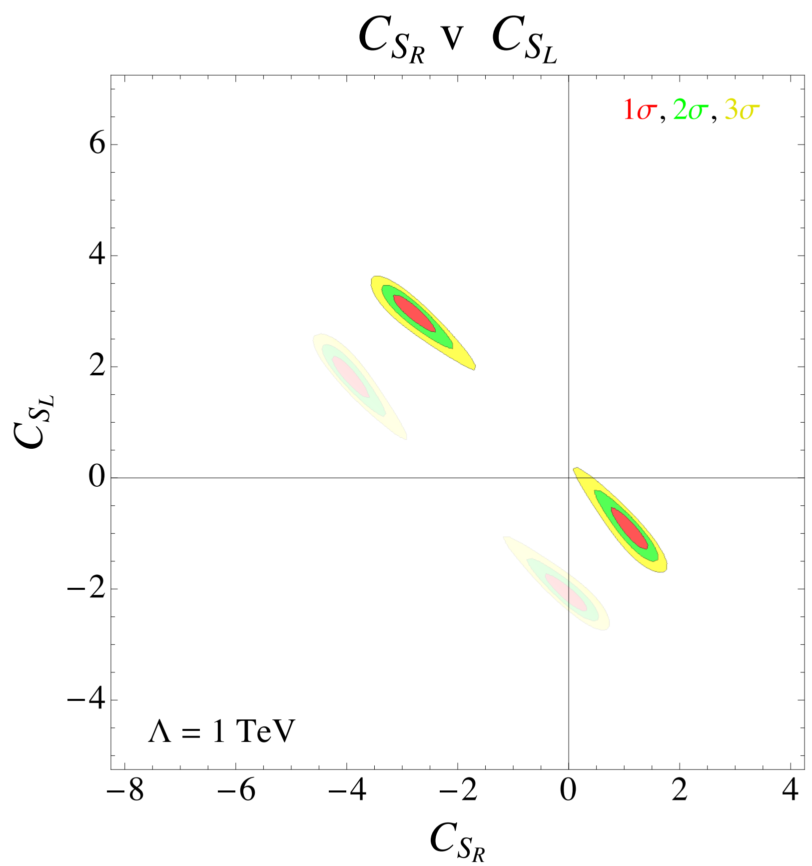


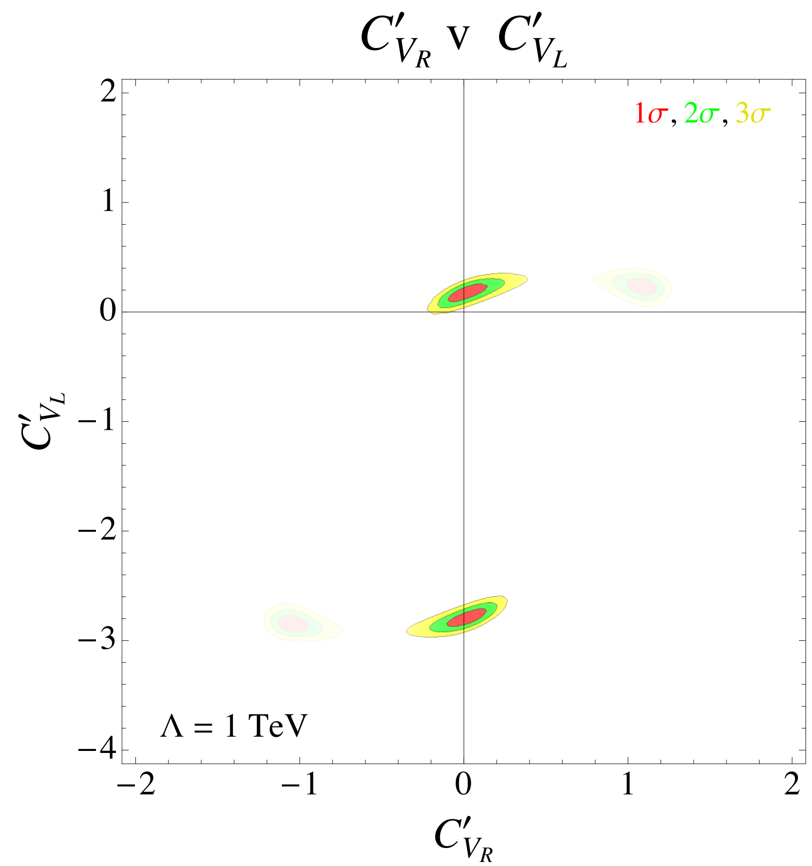
$$C_{S_R} = \frac{-2\sqrt{2}G_F}{M_{H^+}^2} V_{cb} m_b m_\tau \ \tan\beta^2$$
$$C_{S_L} = \frac{-2\sqrt{2}G_F}{M_{H^+}^2} V_{cb} m_c m_\tau \frac{1}{\tan\beta^2}$$

Hard to get two sizable coefficients

Anomalies in the B sector: $R(D^{(*)})$

- Using $\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb}\, \mathcal{O}_{V_L} + \frac{1}{\Lambda^2} \sum_i C_i^{(\prime,\prime\prime)}\, \mathcal{O}_i^{(\prime,\prime\prime)}$ Freytsis *et al.*, 1506.08896





$$\mathcal{O}_{S_L} = (\bar{c} P_L b)(\bar{\tau} P_L \nu)$$
$$\mathcal{O}_{S_R} = (\bar{c} P_R b)(\bar{\tau} P_L \nu)$$

~~New H^+~~

$$\mathcal{O}'_{V_L} = (\bar{\tau} \gamma_\mu P_L b)(\bar{c} \gamma^\mu P_L \nu)$$
$$\mathcal{O}'_{V_R} = (\bar{\tau} \gamma_\mu P_R b)(\bar{c} \gamma^\mu P_L \nu)$$

New W'

Enhanced SM operator gives a good fit

$$0.2 \approx g^2 |V_{cb}|^2 \left(\frac{\text{TeV}}{M_{W'}} \right)^2$$

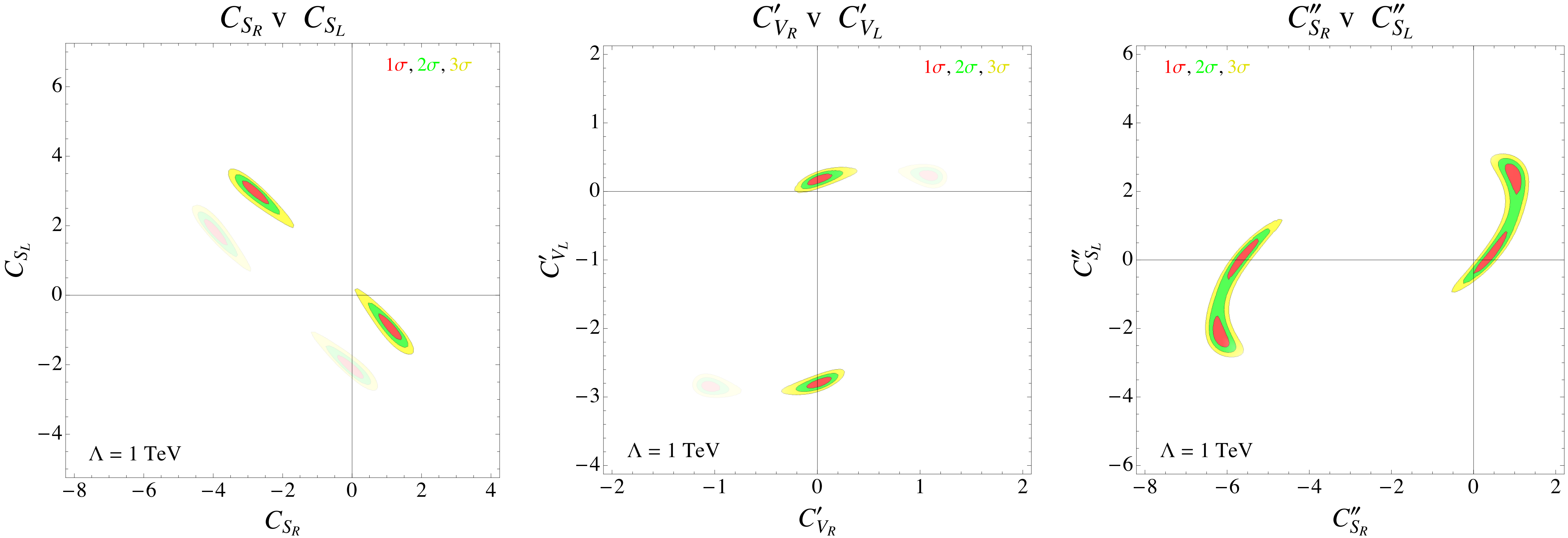
but

$$M_{W'} > 1.8\,\text{TeV}$$

from LHC searches

Anomalies in the B sector: $R(D^{(*)})$

- Using $\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb}\,\mathcal{O}_{V_L} + \frac{1}{\Lambda^2}\sum_i C_i^{(\prime,\prime\prime)}\,\mathcal{O}_i^{(\prime,\prime\prime)}$ Freytsis *et al.*, 1506.08896



$$\mathcal{O}_{S_L} = (\bar{c}P_L b)(\bar{\tau}P_L\nu)$$
$$\mathcal{O}_{S_R} = (\bar{c}P_R b)(\bar{\tau}P_L\nu)$$

$$\mathcal{O}'_{V_L} = (\bar{\tau}\gamma_\mu P_L b)(\bar{c}\gamma^\mu P_L\nu)$$
$$\mathcal{O}'_{V_R} = (\bar{\tau}\gamma_\mu P_R b)(\bar{c}\gamma^\mu P_L\nu)$$

$$\mathcal{O}''_{S_L} = (\bar{\tau}P_L c^c)(\bar{b}^c P_L\nu)$$
$$\mathcal{O}''_{S_R} = (\bar{\tau}P_R c^c)(\bar{b}^c P_L\nu)$$

~~New H^+~~

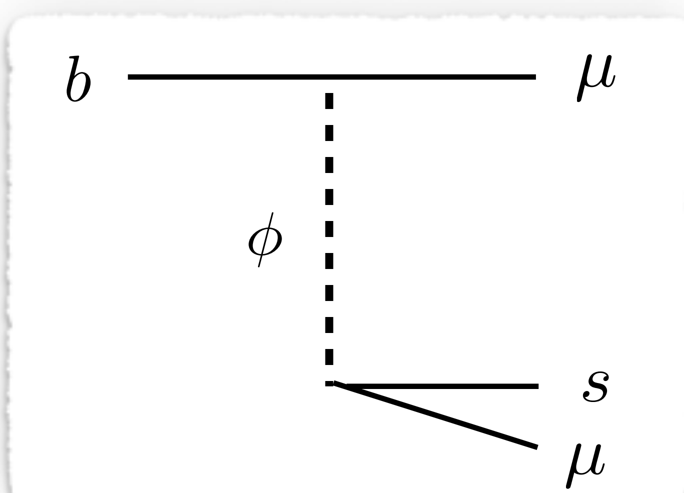
~~New W'~~

New Leptoquark!

The situation

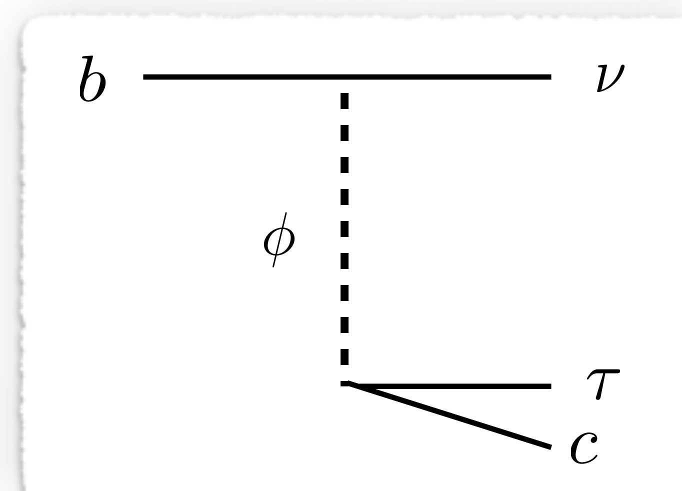
- Both anomalies in neutral and charged b -> 2nd generation transition can be described by leptoquark currents
- However, one needs leptoquarks with different properties

$b \to s$



$$M_\phi = 35\,\mathrm{TeV} \times \sqrt{g_{s\mu} g_{b\mu}}$$

$b \to c$



$$M_\phi = 1\,\mathrm{TeV} \times \sqrt{g_{b\nu} g_{c\tau}}$$

One Leptoquark

Add a single leptoquark $\phi \sim (\mathbf{3},\mathbf{1})_{-1/3}$

$$\mathcal{L}_\phi = (D_\mu\phi)^\dagger D_\mu\phi - M_\phi^2\,|\phi|^2 - g_{h\phi}\,|\Phi|^2|\phi|^2$$
$$+\bar{Q}^c\boldsymbol{\lambda}^L i\tau_2 L\,\phi^* + \bar{u}_R^c\,\boldsymbol{\lambda}^R e_R\,\phi^* + \text{h.c.}$$

Rotation to mass eigenstates

$$\mathcal{L}_\phi \ni \bar{u}_L^c\,\boldsymbol{\lambda}_{ue}^L e_L\,\phi^* - \bar{d}_L^c\,\boldsymbol{\lambda}_{d\nu}^L \nu_L\phi^* + \bar{u}_R^c\,\boldsymbol{\lambda}_{ue}^R e_R\,\phi^* + \text{h.c.}$$

with $\boldsymbol{V}_{\text{CKM}}^T\,\boldsymbol{\lambda}_{ue}^L = \boldsymbol{\lambda}_{d\nu}^L\boldsymbol{V}_{\text{PMNS}}$

One Leptoquark

Add a single leptoquark $\phi \sim (\mathbf{3}, \mathbf{1})_{-1/3}$

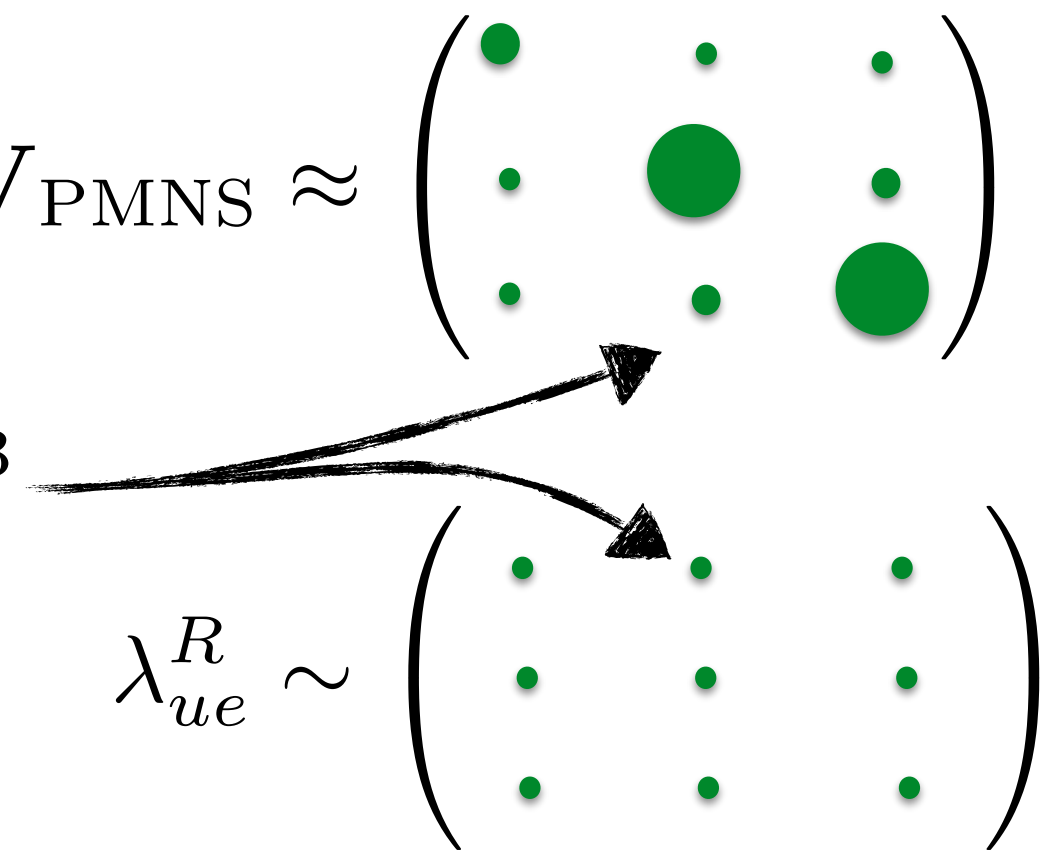
$$\mathcal{L}_\phi \ni \bar{u}^c_L \, \boldsymbol{\lambda}^L_{ue} e_L \, \phi^* - \bar{d}^c_L \, \boldsymbol{\lambda}^L_{d\nu} \nu_L \phi^* + \bar{u}^c_R \, \boldsymbol{\lambda}^R_{ue} e_R \, \phi^* + \text{h.c.}$$

with

$$\lambda_{ue} = \mathbf{V}^*_{\text{CKM}} \lambda^L_{d\nu} \mathbf{V}_{\text{PMNS}} \approx$$

$$10^{-1} - 10^{-3}$$

$$\lambda^R_{ue} \sim$$



UV Motivation:

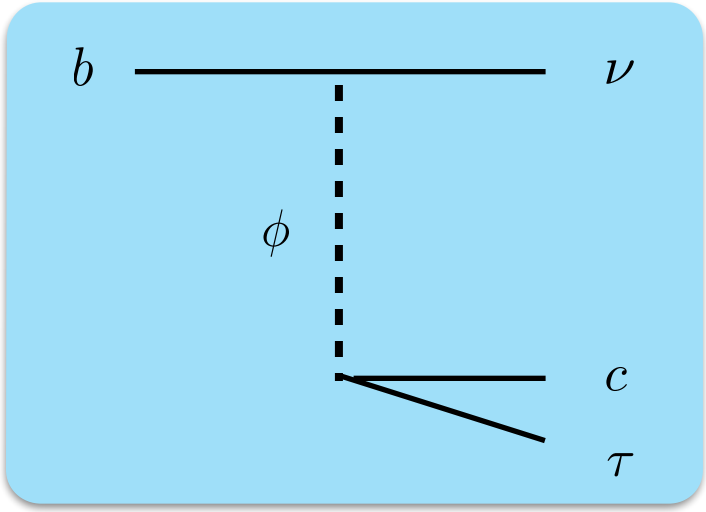
$$W = \lambda_L \, LQD$$

One Leptoquark

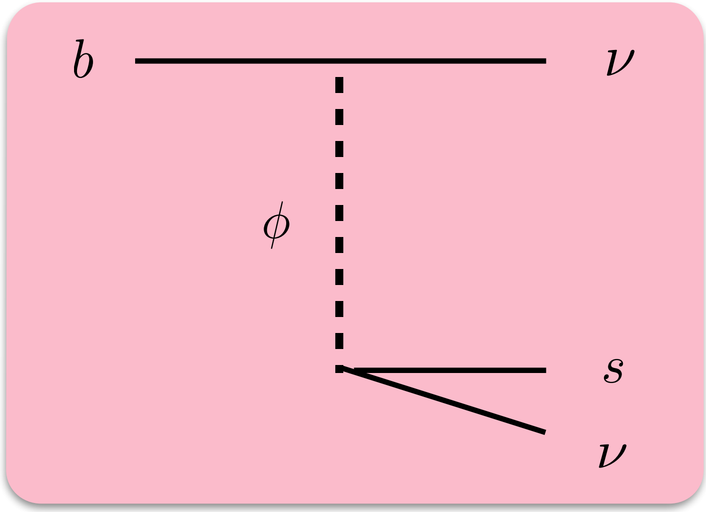
$$\mathcal{L}_\phi \ni \bar{u}^c_L\, \boldsymbol{\lambda}^L_{ue} e_L\, \phi^* - \bar{d}^c_L\, \boldsymbol{\lambda}^L_{d\nu} \nu_L \phi^* + \bar{u}^c_R\, \boldsymbol{\lambda}^R_{ue} e_R\, \phi^* + \text{h.c.}$$

at tree level gives rise to

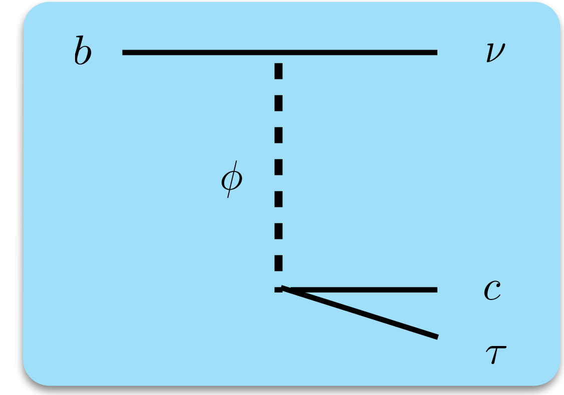
up-quark - charged lepton couplings



down-quark - neutrino couplings

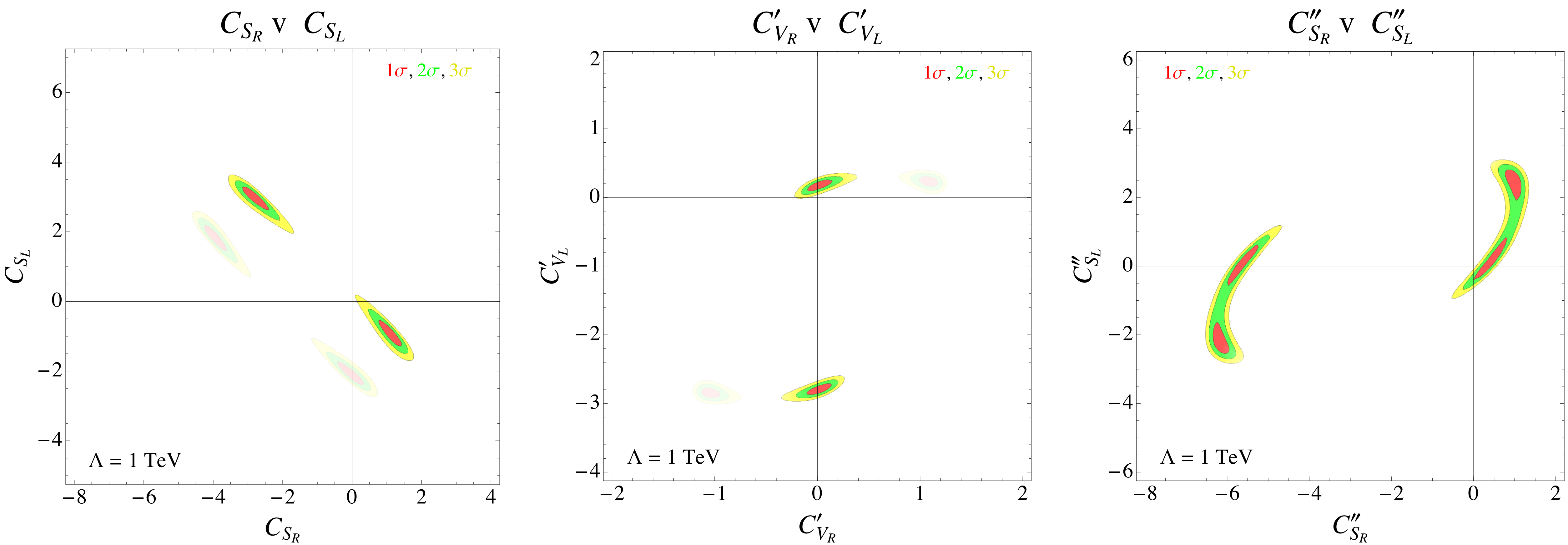


ONE LEPTOQUARK: $R(D^{(*)})$



- Using $\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb}\, \mathcal{O}_{V_L} + \frac{1}{\Lambda^2} \sum_i C_i^{(\prime,\prime\prime)}\, \mathcal{O}_i^{(\prime,\prime\prime)}$

Freytsis *et al.*, 1506.08896

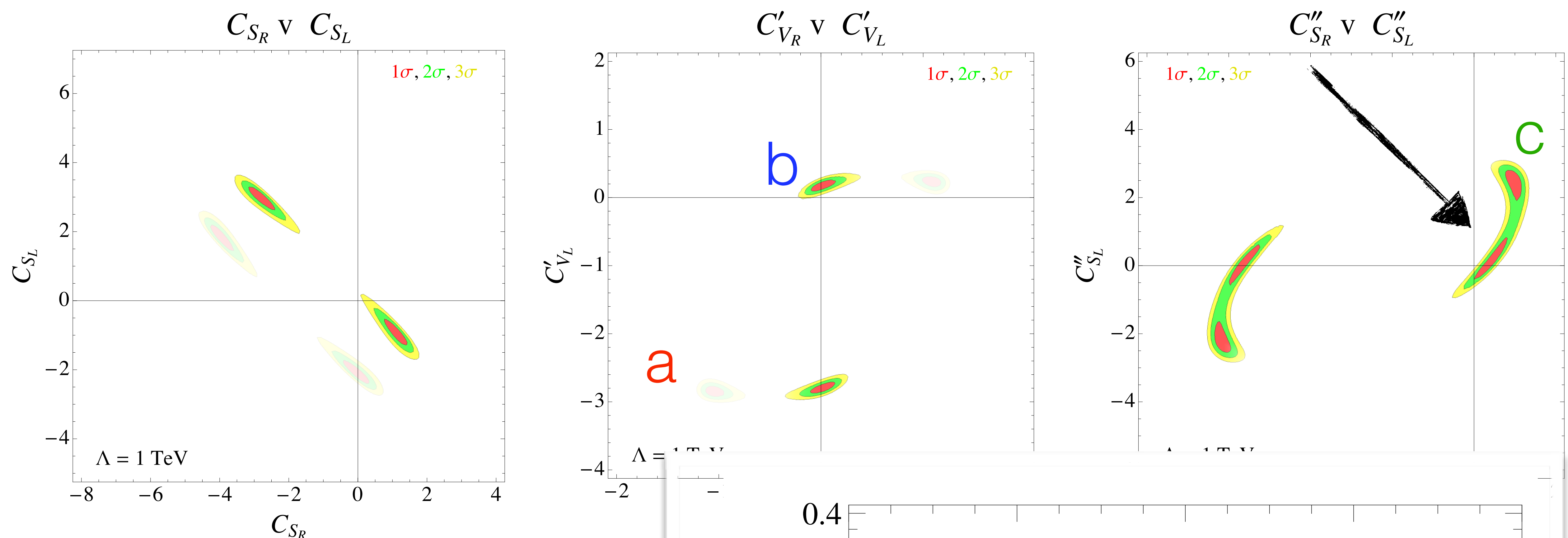


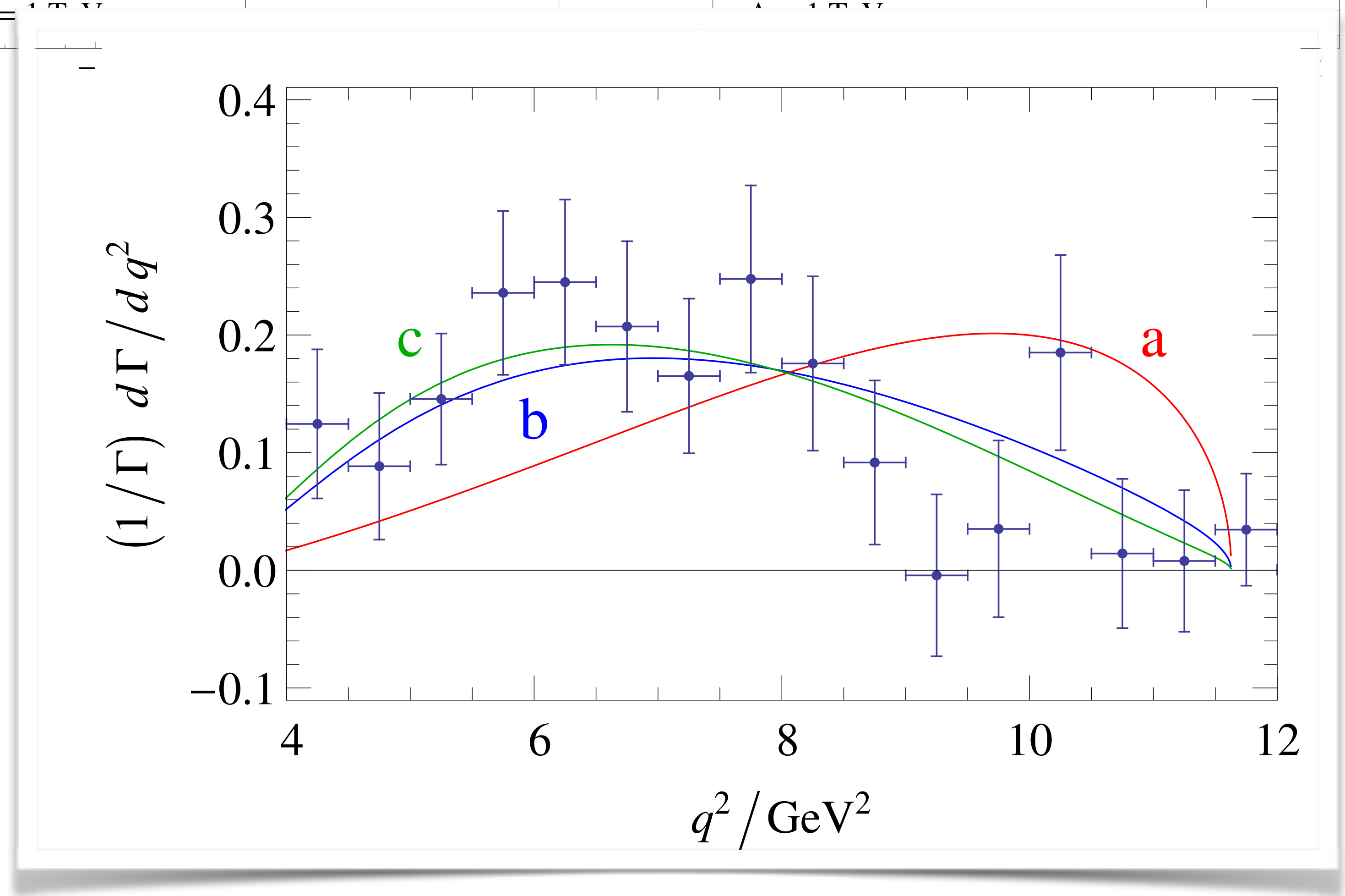
$$\mathcal{O}_{S_L} = (\bar{c} P_L b)(\bar{\tau} P_L \nu)$$
$$\mathcal{O}_{S_R} = (\bar{c} P_R b)(\bar{\tau} P_L \nu)$$

$$\mathcal{O}'_{V_L} = (\bar{\tau}\gamma_\mu P_L b)(\bar{c}\gamma^\mu P_L \nu)$$
$$\mathcal{O}'_{V_R} = (\bar{\tau}\gamma_\mu P_R b)(\bar{c}\gamma^\mu P_L \nu)$$

$$\mathcal{O}''_{S_L} = (\bar{\tau} P_L c^c)(\bar{b}^c P_L \nu)$$
$$\mathcal{O}''_{S_R} = (\bar{\tau} P_R c^c)(\bar{b}^c P_L \nu)$$

One Leptoquark: $R(D^{(*)})$





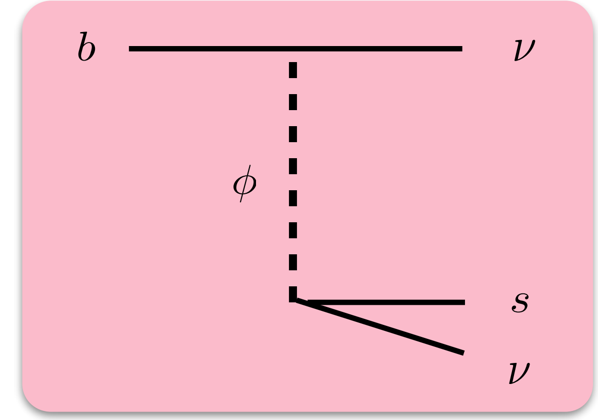
Needs

$$\frac{\lambda^{L*}_{c\tau}\,\lambda^{L}_{b\nu_\tau}}{M_\phi^2} \approx \frac{0.35}{\mathrm{TeV}^2},$$

$$\frac{\lambda^{R*}_{c\tau}\,\lambda^{L}_{b\nu_\tau}}{M_\phi^2} \approx -\frac{0.03}{\mathrm{TeV}^2}$$

Freytsis *et al.*, 1506.08896

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



- BaBar $R_{\nu\bar{\nu}} = \dfrac{\Gamma}{\Gamma_{\rm SM}} < 4.3 \quad \text{at } 90\,\%\text{CL}$
- We have

$$R^{(\phi)}_{\nu\bar{\nu}} = 1 - \frac{2r}{3}\,\mathrm{Re}\,\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V^*_{ts}} + \frac{r^2}{3}\,\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bb}\left(\lambda^L\lambda^{L\dagger}\right)_{ss}}{\left|V_{tb}V^*_{ts}\right|^2}$$

with $\left(\lambda^L\lambda^{L\dagger}\right)_{bs} = \sum_i \lambda^L_{b\nu_i}\,\lambda^{L*}_{s\nu_i}$, $\quad r = \dfrac{s_W^4}{2\alpha^2}\,\dfrac{1}{X_0(x_t)}\,\dfrac{m_W^2}{M_\phi^2} \approx 1.91\,\dfrac{\mathrm{TeV}^2}{M_\phi^2}$

Using the Schwarz Inequality $(x\,y)^2 \leq x^2 y^2$ yields

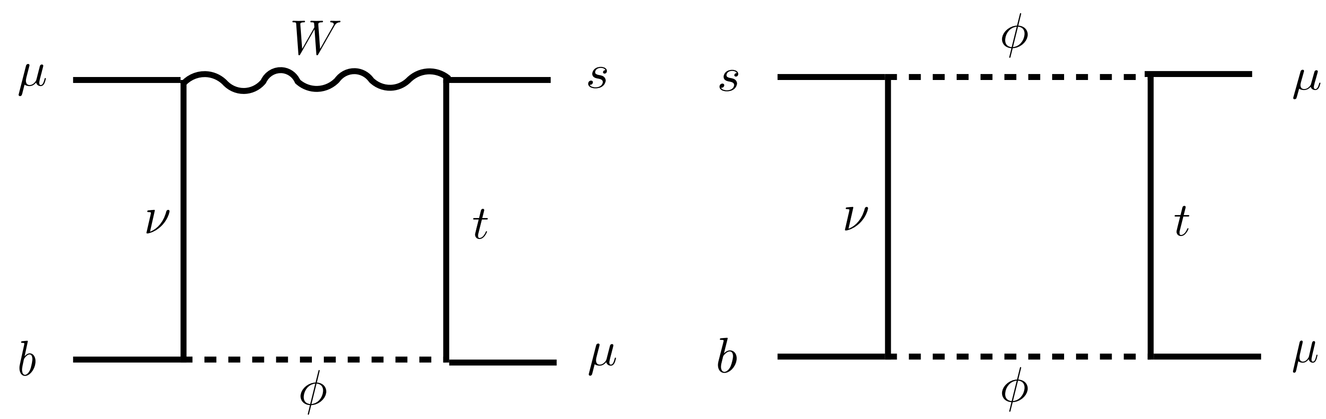
$$-\frac{1.2}{\mathrm{TeV}^2} < \frac{1}{M_\phi^2}\,\mathrm{Re}\,\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V^*_{ts}} < \frac{2.3}{\mathrm{TeV}^2}\,.$$

One Leptoquark

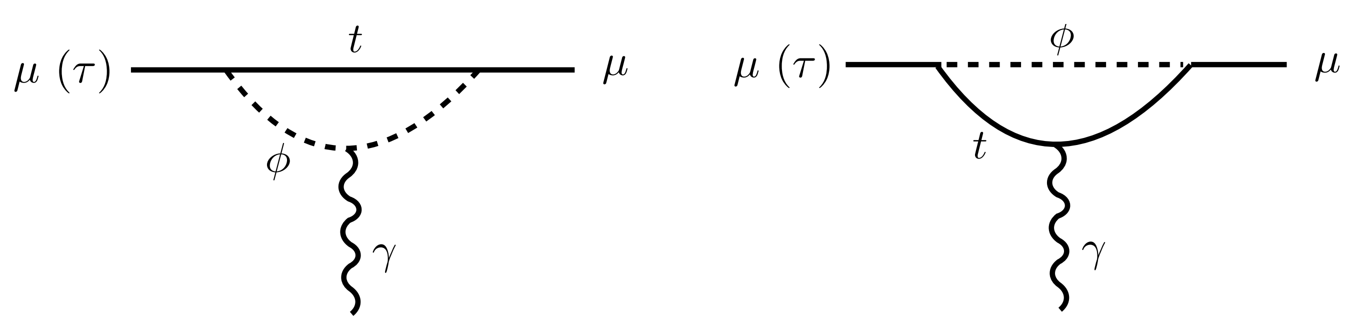
$$\mathcal{L}_\phi \ni \bar{u}_L^c\,\boldsymbol{\lambda}_{ue}^L e_L\,\phi^* - \bar{d}_L^c\,\boldsymbol{\lambda}_{d\nu}^L \nu_L \phi^* + \bar{u}_R^c\,\boldsymbol{\lambda}_{ue}^R e_R\,\phi^* + \text{h.c.}$$

at 1-loop gives rise to

- $R_K, B_s - \bar{B}_s \quad \text{mixing}\,, B_s \to \mu^- \mu^+$



- $g-2,\ \tau \to \mu\gamma,\ \delta g_{Z\mu\mu}$



One Leptoquark: R_K

- Using $$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu)$$

$$\mathcal{O}_9 = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}_{10} = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]$$

and $$\mathcal{O}^\ell_{LL} \equiv (\mathcal{O}^\ell_9 - \mathcal{O}^\ell_{10})/2\,, \quad \mathcal{O}^\ell_{LR} \equiv (\mathcal{O}^\ell_9 + \mathcal{O}^\ell_{10})/2\,,$$
$$\mathcal{O}^\ell_{RL} \equiv (\mathcal{O}'^\ell_9 - \mathcal{O}'^\ell_{10})/2\,, \quad \mathcal{O}^\ell_{RR} \equiv (\mathcal{O}'^\ell_9 + \mathcal{O}'^\ell_{10})/2\,,$$

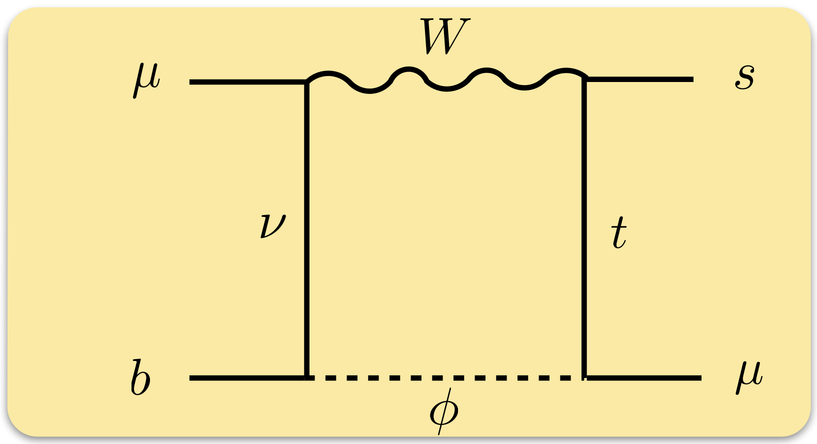
a good fit is found for

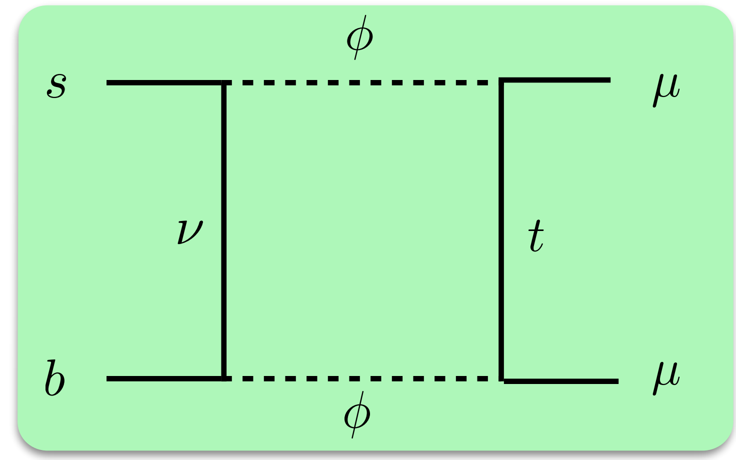
$$0.0 \lesssim \mathrm{Re}[C^\mu_{LR} + C^\mu_{RL} - C^\mu_{LL} - C^\mu_{RR}] \lesssim 1.9\,,$$
$$0.7 \lesssim -\mathrm{Re}[C^\mu_{LL} + C^\mu_{RL}] \lesssim 1.5\,.$$

Benchmark: $C^\mu_{LL} \simeq -1\,, \quad C^\mu_{ij} = 0$ otherwise

ONE LEPTOQUARK: R_K

We have





$$C_{LL}^{\mu(\phi)} = \frac{m_t^2}{8\pi\alpha M_\phi^2}\left|\lambda_{t\mu}^L\right|^2 - \frac{1}{64\pi\alpha}\frac{\sqrt{2}}{G_F M_\phi^2}\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V_{ts}^*}\left(\lambda^{L\dagger}\lambda^L\right)_{\mu\mu},$$

$$C_{LR}^{\mu(\phi)} = \frac{m_t^2}{16\pi\alpha M_\phi^2}\left|\lambda_{t\mu}^R\right|^2\left[\ln\frac{M_\phi^2}{m_t^2} - f(x_t)\right] - \frac{1}{64\pi\alpha}\frac{\sqrt{2}}{G_F M_\phi^2}\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V_{ts}^*}\left(\lambda^{R\dagger}\lambda^R\right)_{\mu\mu},$$

The $W-\phi$ box contributions have the wrong sign, but they are chirally suppressed and inherit a partial GIM-suppression. Penguins cancel!

One Leptoquark: R_K

$$C_{LL}^{\mu(\phi)} = \frac{m_t^2}{8\pi\alpha M_\phi^2}\left|\lambda_{t\mu}^L\right|^2 - \frac{1}{64\pi\alpha}\frac{\sqrt{2}}{G_F M_\phi^2}\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V_{ts}^*}\left(\lambda^{L\dagger}\lambda^L\right)_{\mu\mu},$$

$$C_{LR}^{\mu(\phi)} = \frac{m_t^2}{16\pi\alpha M_\phi^2}\left|\lambda_{t\mu}^R\right|^2\left[\ln\frac{M_\phi^2}{m_t^2} - f(x_t)\right] - \frac{1}{64\pi\alpha}\frac{\sqrt{2}}{G_F M_\phi^2}\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V_{ts}^*}\left(\lambda^{R\dagger}\lambda^R\right)_{\mu\mu},$$

For the Benchmark $C_{LL}^\mu \simeq -1\,,\quad C_{ij}^\mu = 0$ otherwise, we need

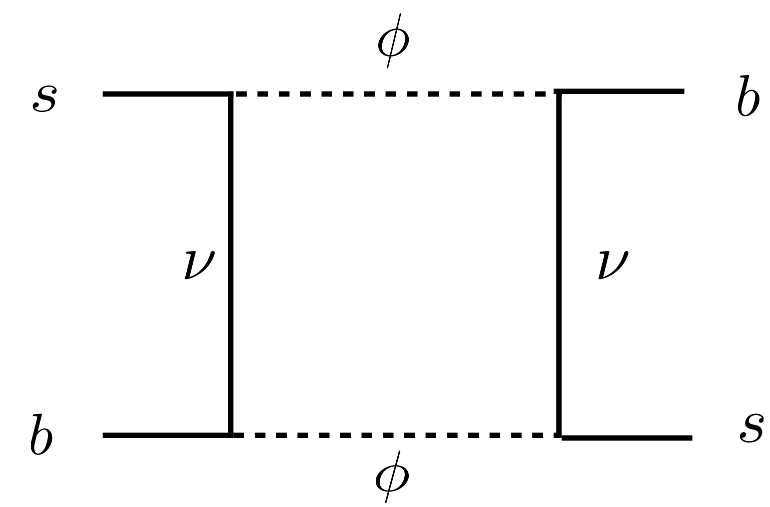
$$\sum_i \left|\lambda_{u_i\mu}^L\right|^2 \mathrm{Re}\,\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V_{ts}^*} - 1.74\left|\lambda_{t\mu}^L\right|^2 \approx 12.5\,\frac{M_\phi^2}{\mathrm{TeV}^2}$$

Constrained to be < 2.3 by $R_{\nu\nu}$

$$\Rightarrow \quad \sqrt{\left|\lambda_{u\mu}^L\right|^2 + \left|\lambda_{c\mu}^L\right|^2 + \left(1 - \frac{0.77}{\hat{M}_\phi^2}\right)\left|\lambda_{t\mu}^L\right|^2} > 2.36$$

One Leptoquark: $\bar{B}_s - B_s$

$\bar{B}_s - B_s$ gives a weaker bound than $R_{\nu\nu}$



$$C_{B_s}^{(\phi)}\, e^{2i\phi_{B_s}^{(\phi)}} = 1 + \frac{1}{g^4 S_0(x_t)}\, \frac{m_W^2}{M_\phi^2} \left[\frac{\left(\lambda^L \lambda^{L\dagger}\right)_{bs}}{V_{tb} V_{ts}^*} \right]^2$$

with $\quad C_{B_s}\, e^{2i\phi_{B_s}} \equiv \dfrac{\langle B_s |\, H_{\rm eff}^{\rm full}\, | \bar{B}_s \rangle}{\langle B_s |\, H_{\rm eff}^{\rm SM}\, | \bar{B}_s \rangle}$

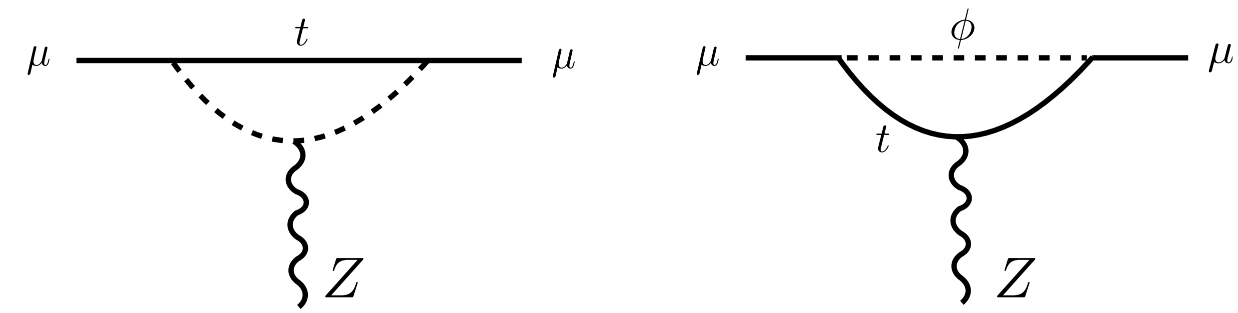
$$C_{B_s} = 1.052 \pm 0.084 \quad \text{and} \quad \phi_{B_s} = (0.72 \pm 2.06)^\circ$$

$$\frac{\left(\lambda^L \lambda^{L\dagger}\right)_{bs}}{V_{tb} V_{ts}^*} \approx (1.87 + 0.45 i)\, \frac{M_\phi}{\rm TeV}$$

$$\left| \frac{\left(\lambda^L \lambda^{L\dagger}\right)}{V_{tb} V_{ts}^*} \right| < 3.6\, \frac{M_\phi}{\rm TeV} \quad \text{at } 90\,\%\ \text{CL}$$

One Leptoquark: $\delta g_{Z\mu\mu}$

- One-loop Corrections to Z couplings



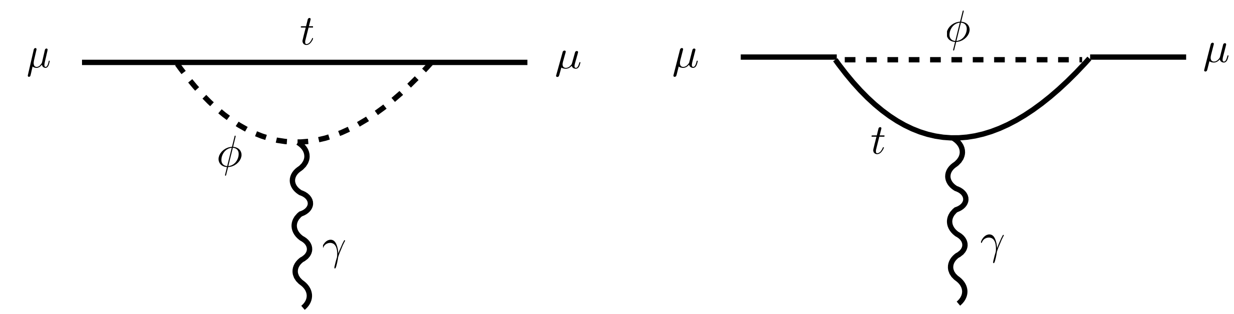
$$g_A^\mu = g_A^{\mu,\mathrm{SM}} \pm \frac{3}{32\pi^2}\frac{m_t^2}{M_\phi^2}\left(\ln\frac{M_\phi^2}{m_t^2} - 1\right)\left|\lambda_{t\mu}^A\right|^2$$
$$- \frac{1}{32\pi^2}\frac{m_Z^2}{M_\phi^2}\left(\left|\lambda_{u\mu}^A\right|^2 + \left|\lambda_{c\mu}^A\right|^2\right)$$
$$\times\left[\left(\delta_{AL} - \frac{4s_W^2}{3}\right)\left(\ln\frac{M_\phi^2}{m_Z^2} + i\pi + \frac{1}{3}\right) - \frac{s_W^2}{9}\right],$$

$$\Rightarrow \quad \sqrt{\left|\lambda_{c\mu}^L\right|^2 + \left|\lambda_{u\mu}^L\right|^2} < \frac{3.24}{b_{cu}^{1/2}}\frac{M_\phi}{\mathrm{TeV}}, \quad \left|\lambda_{t\mu}^L\right| < \frac{1.22}{b_t^{1/2}}\frac{M_\phi}{\mathrm{TeV}},$$

$$b_{cu} = 1 + 0.39\,\ln M_\phi/\mathrm{TeV} \quad \text{and} \quad b_t = 1 + 0.76\,\ln M_\phi/\mathrm{TeV}$$

ONE LEPTOQUARK: $(g-2)_\mu$

- One-loop Contribution to g-2



$$a_\mu^{(\phi)} = \sum_{q=t,c} \frac{m_\mu m_q}{4\pi^2 M_\phi^2}\left(\ln\frac{M_\phi^2}{m_q^2} - \frac{7}{4}\right)\mathrm{Re}(\lambda^R_{q\mu}\lambda^{L*}_{q\mu}) - \frac{m_\mu^2}{32\pi^2 M_\phi^2}\left[\left(\lambda^{L\dagger}\lambda^L\right)_{\mu\mu} + \left(\lambda^{R\dagger}\lambda^R\right)_{\mu\mu}\right]$$

$$\Delta a_\mu = (287 \pm 80)\times 10^{-11}$$

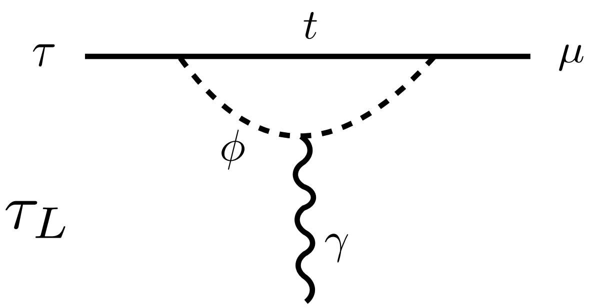
-37×10^{-11}

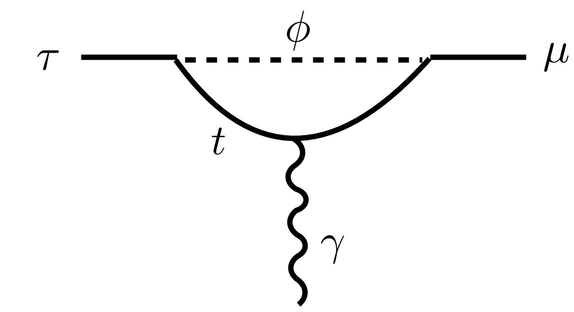
…wrong sign, but small

$$\left(1 + 0.17\ln\frac{M_\phi}{\mathrm{TeV}}\right)\mathrm{Re}(\lambda^R_{c\mu}\lambda^{L*}_{c\mu}) + 20.7\left(1 + 1.06\ln\frac{M_\phi}{\mathrm{TeV}}\right)\mathrm{Re}(\lambda^R_{t\mu}\lambda^{L*}_{t\mu}) \approx 0.08\,\frac{M_\phi^2}{\mathrm{TeV}^2}$$

For $|\lambda^L_{c\mu}| \sim 2.4$, we need $|\lambda^R_{c\mu}| \sim 0.03$.

ONE LEPTOQUARK: $\tau \to \mu\gamma$





$$\mathcal{L}_{\rm eff} = C_{LR}\,\bar{\mu}_L\,\sigma_{\mu\nu}F^{\mu\nu}\,\tau_R + C_{RL}\,\bar{\mu}_R\,\sigma_{\mu\nu}F^{\mu\nu}\,\tau_L$$

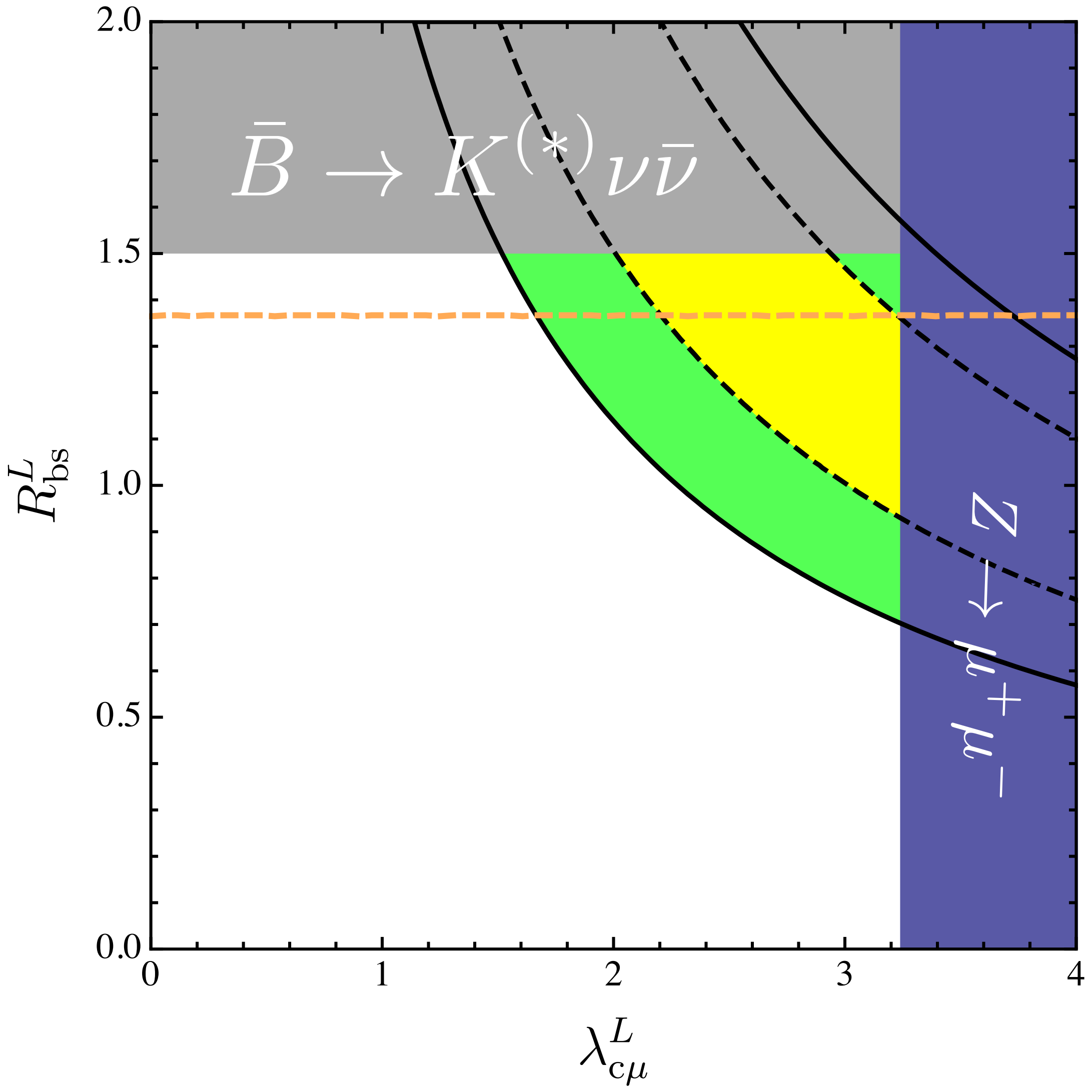
$$\text{BR}(\tau \to \mu\gamma) < 4.4\cdot 10^{-8} \quad \text{at } 90\% \ \ \text{CL}$$

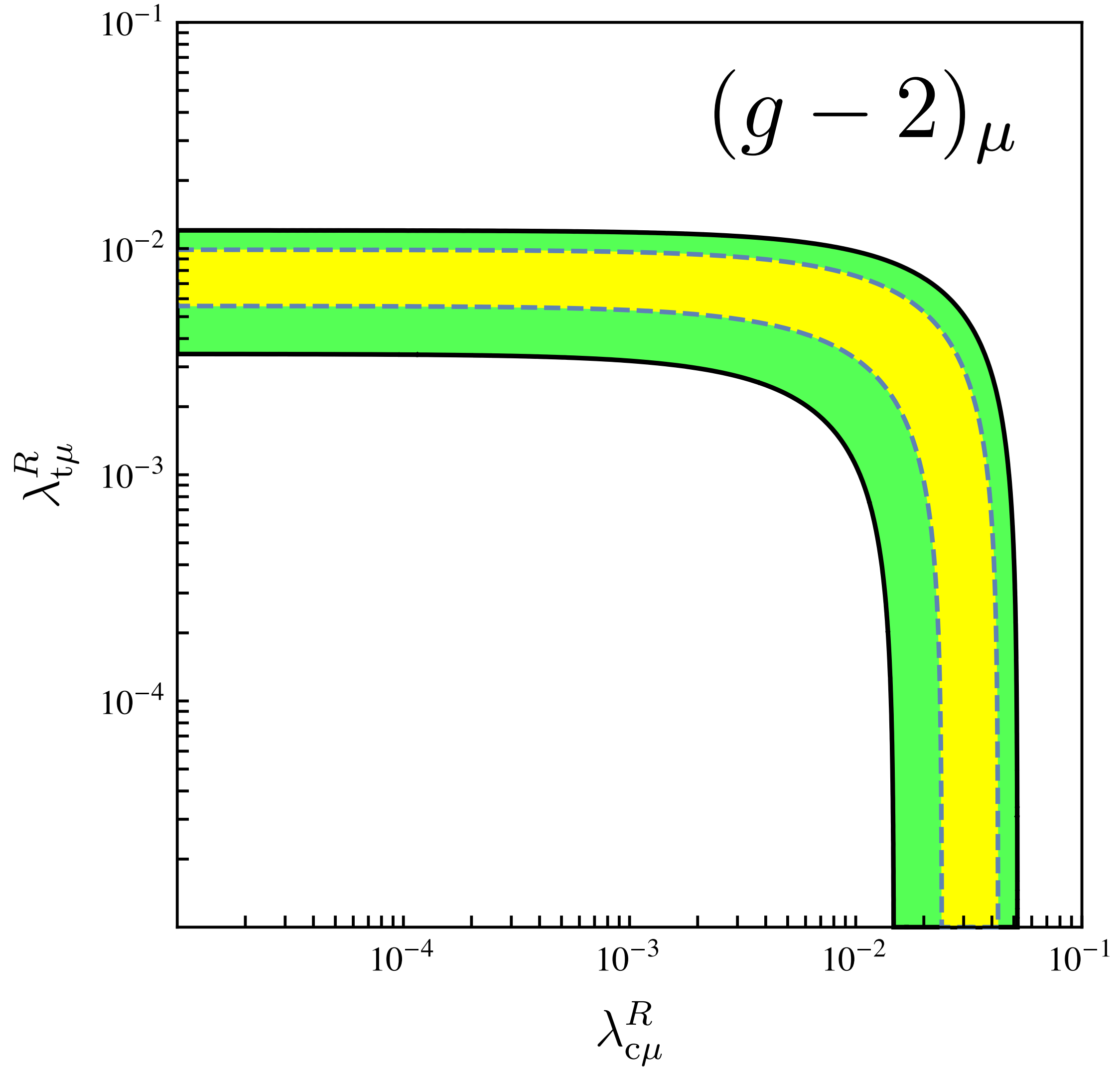
$$\left[\left|a_c\,\lambda^R_{c\tau}\lambda^{L*}_{c\mu} + 20.7a_t\,\lambda^R_{t\tau}\lambda^{L*}_{t\mu} - 0.015(\lambda^{L\dagger}\lambda^L)_{\mu\tau}\right|^2 + (L\leftrightarrow R)\right]^{1/2} < 0.017\,\frac{M_\phi^2}{\text{TeV}^2}\,.$$

$$\Rightarrow \quad |\lambda^R_{t\tau}\lambda^{L*}_{t\mu}|^2 + |\lambda^L_{t\tau}\lambda^{R*}_{t\mu}|^2 < 6\times 10^{-7}$$

With these values, $\text{BR}(h \to \mu\tau) \approx 10^{-9}$.
The central value of the CMS measurement is 0.84%.

One Leptoquark



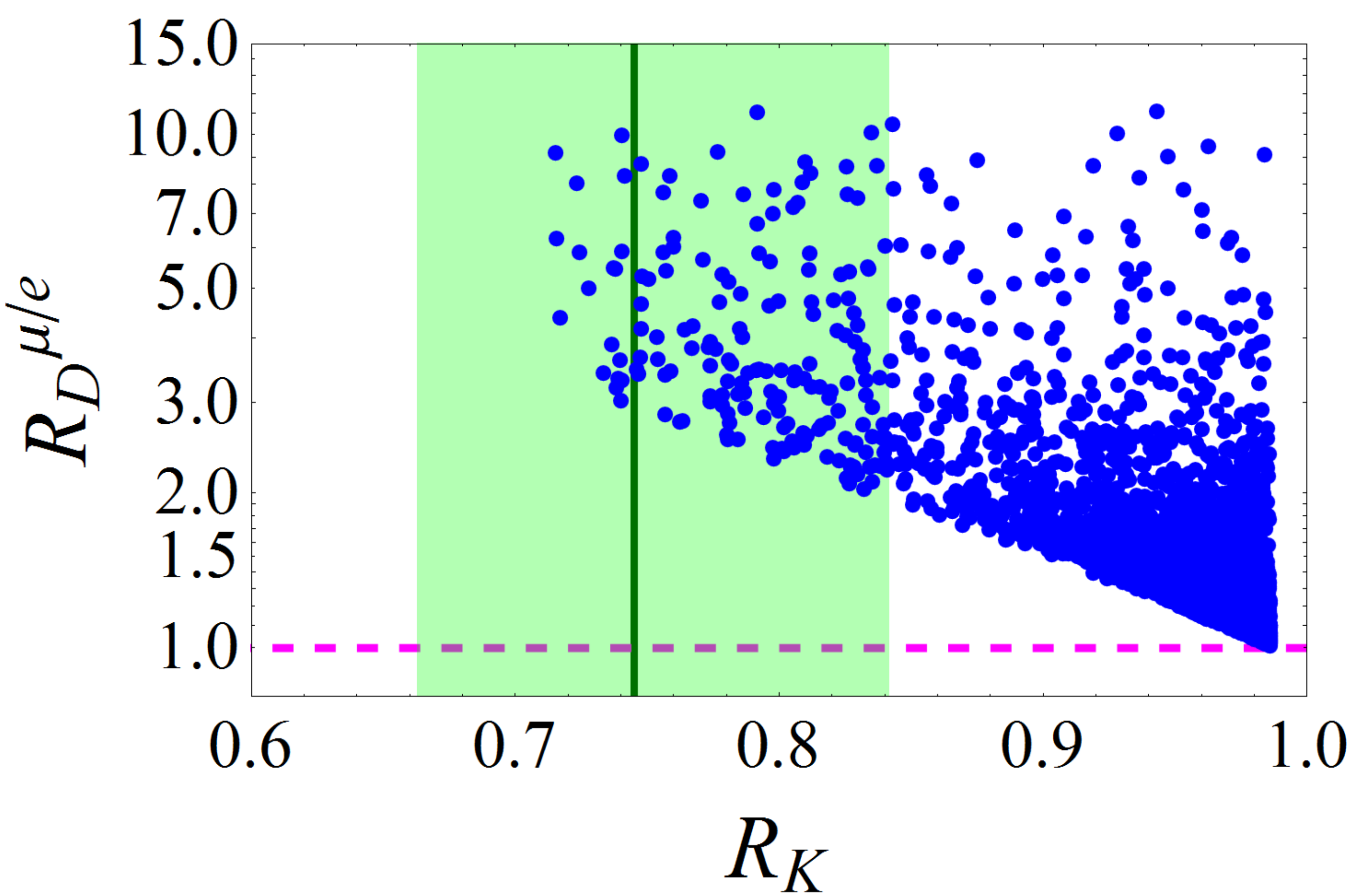


$$R^L_{bs} \equiv \mathrm{Re}\left[\frac{(\lambda^L \lambda^{L\dagger})_{bs}}{V_{tb}V^\dagger_{ts}}\right]$$

One Leptoquark: Full Disclosure

Potentially problematic: the ratio $R_D^{\mu/e} = \frac{\bar{B} \to D\mu\bar{\nu}}{\bar{B} \to De\bar{\nu}}$

Not measured, but unlikely to be large from PDG combination of B data to extract Vcb



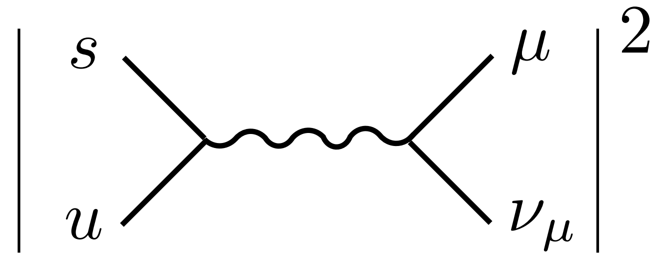
Becirevic et al. 1608.07583

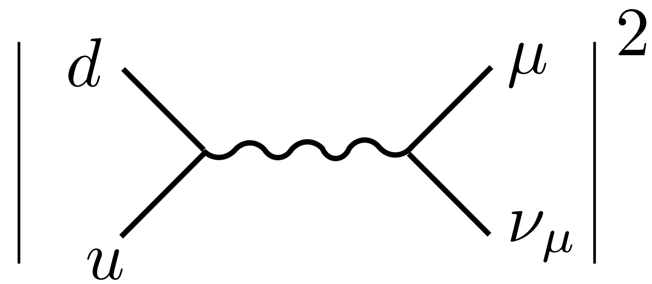
One Leptoquark to Rule Them All: Conclusions

- An extension of the SM with a single leptoquark $\phi \sim (\mathbf{3}, \mathbf{1})_{-1/3}$ can explain $R_K, R(D^{(*)})$ and $(g-2)_\mu$ assuming order one generation- diagonal and suppressed off-diagonal couplings
- Correlated effects in $R_{\nu\nu}, B_s - \bar{B}_s$ mixing unavoidable
- Z boson coupling modifications can be probed at TLEP
- UV motivation: R-parity violating SUSY with a split spectrum and TeV scale right-handed sbottoms

Ancient Times

$$\frac{\Gamma(K^- \to \mu^- \nu_\mu)}{\Gamma(\pi^- \to \mu^- \nu_\mu)} =$$



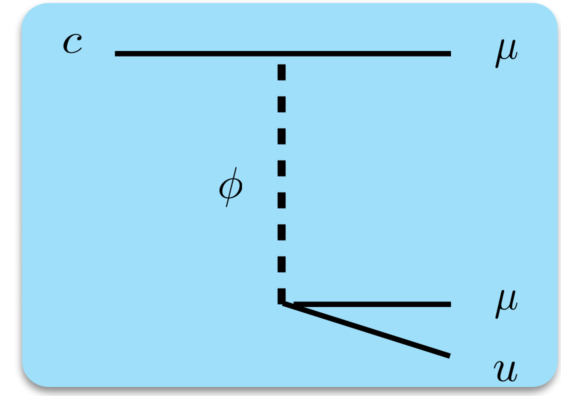


$$\approx \frac{1}{20} = \frac{\sin^2\theta}{\cos^2\theta}$$

Cabibbo

$$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta + s\,\sin\theta \end{pmatrix}$$

ONE LEPTOQUARK: $D^0 \to \mu^+\mu^-$



$$\Gamma = \frac{f_D^2\, m_D^3}{256\pi M_\phi^4}\left(\frac{m_D}{m_c}\right)^2 \beta_\mu \Bigg[\beta_\mu^2 \left|\lambda^L_{c\mu}\lambda^{R*}_{u\mu} - \lambda^R_{c\mu}\lambda^{L*}_{u\mu}\right|^2 + \left|\lambda^L_{c\mu}\lambda^{R*}_{u\mu} + \lambda^R_{c\mu}\lambda^{L*}_{u\mu} + \frac{2m_\mu m_c}{m_D^2}\left(\lambda^L_{c\mu}\lambda^{L*}_{u\mu} + \lambda^R_{c\mu}\lambda^{R*}_{u\mu}\right)\right|^2\Bigg]$$

The experimental limit $\mathrm{Br}(D^0 \to \mu^+\mu^-) < 7.6\cdot 10^{-9}$ at 95% CL

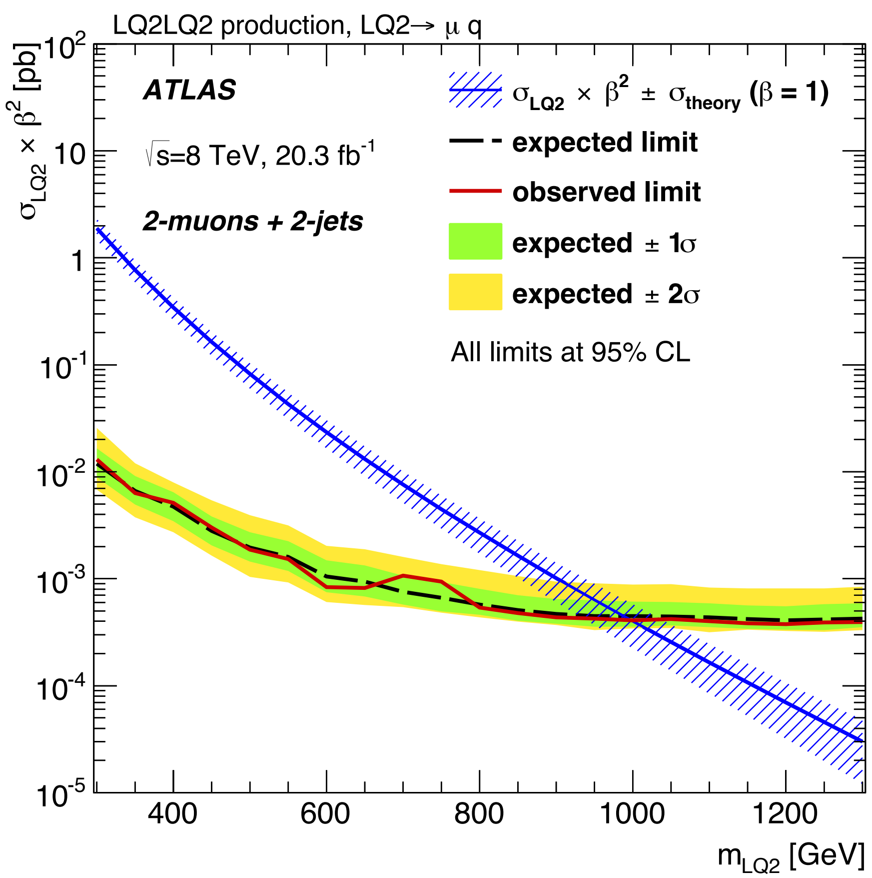
Leads to the bounds:

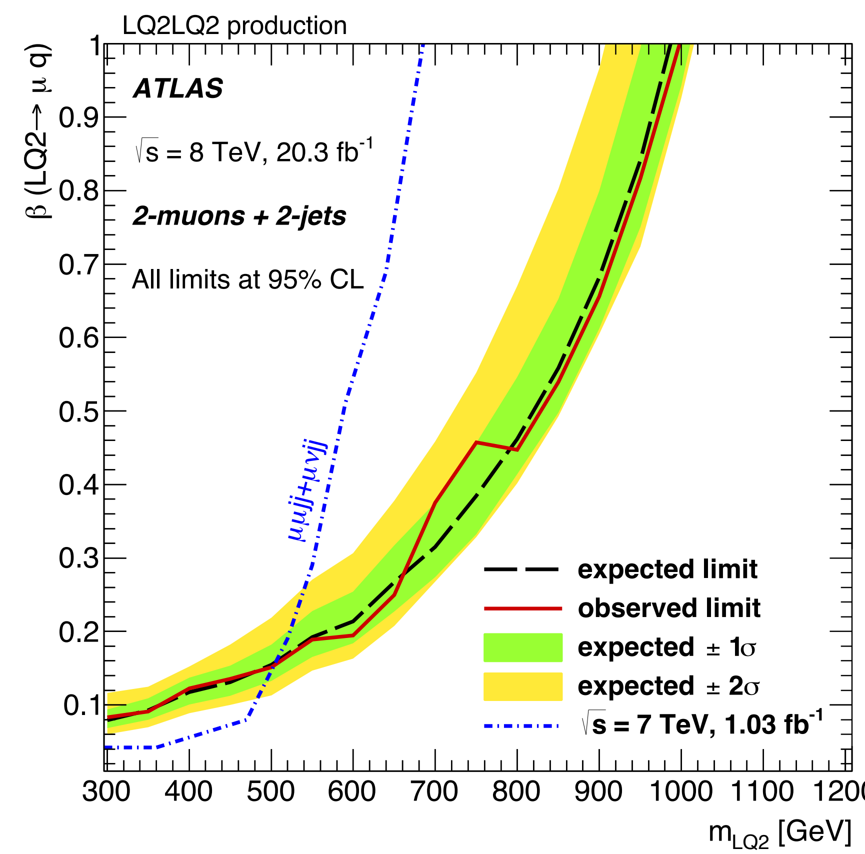
$$\left|\lambda^L_{c\mu}\lambda^{L*}_{u\mu} + \lambda^R_{c\mu}\lambda^{R*}_{u\mu}\right| < 0.052\,\frac{M_\phi^2}{\mathrm{TeV}^2}$$

$$\sqrt{\left|\lambda^L_{c\mu}\right|^2\left|\lambda^R_{u\mu}\right|^2 + \left|\lambda^R_{c\mu}\right|^2\left|\lambda^L_{u\mu}\right|^2} < 1.2\cdot 10^{-3}\,\frac{M_\phi^2}{\mathrm{TeV}^2}$$

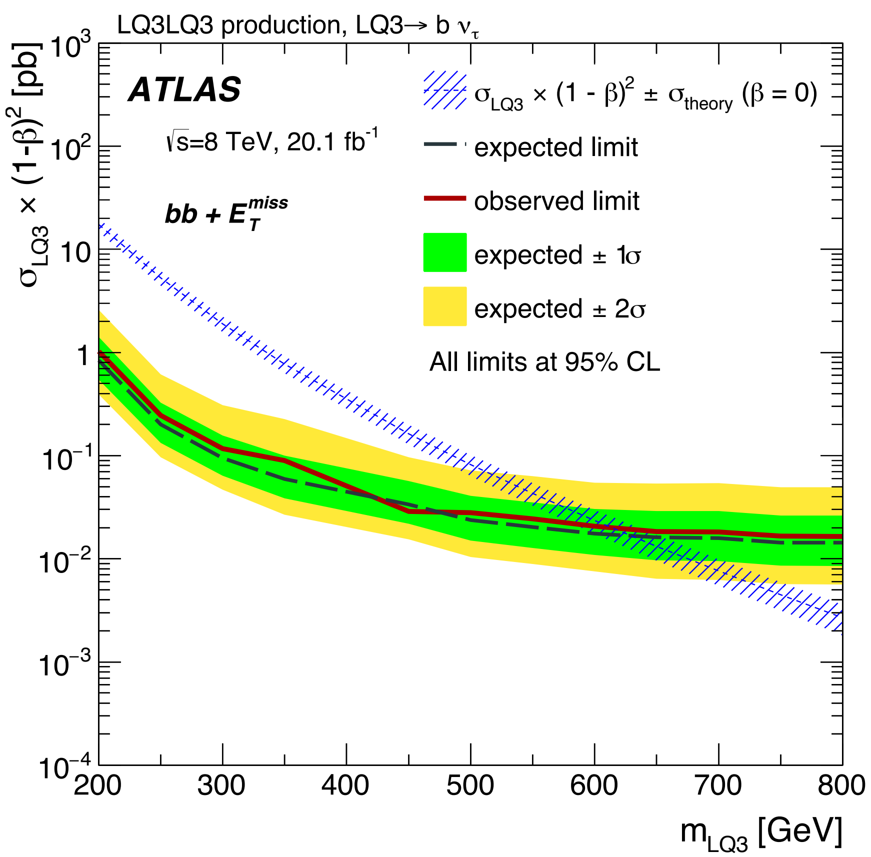
Collider Bounds

$\phi \to \mu c$





$\phi \to \nu_\tau b$



ATLAS 1508.04735

Neutrino Couplings

$$\mathcal{L}_\phi = (D_\mu \phi)^\dagger D_\mu \phi - M_\phi^2\,|\phi|^2 - g_{h\phi}\,|\Phi|^2|\phi|^2$$

$$+\,\bar{Q}^c \boldsymbol{\lambda}^L i\tau_2 L\,\phi^* + \bar{u}_R^c\,\boldsymbol{\lambda}^R e_R\,\phi^* + \text{h.c.}$$

$$\lambda^L_{ue} = U_u^T \lambda^L U_e\,, \quad \lambda^L_{d\nu} = U_d^T \lambda^L U_\nu\,, \quad \lambda^R_{ue} = V_u^T \lambda_R V_e\,,$$

$$\lambda^L_{ue} = V^*_{\text{CKM}} \quad U_d^T\,\lambda_L \quad U_e$$

Diagonal!