B-physics Anomalies

Federico Mescia

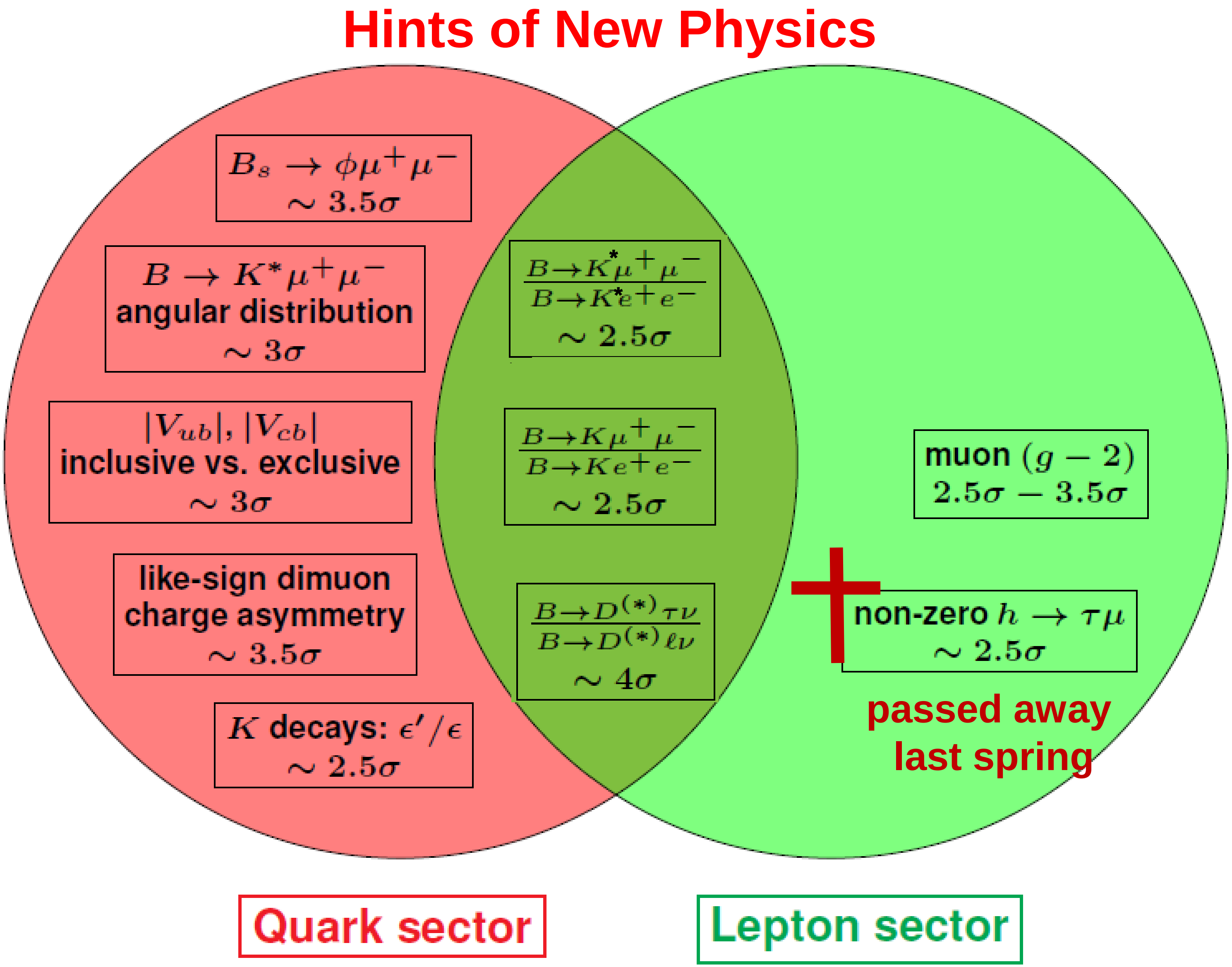
Universitat de Barcelona

Outline:

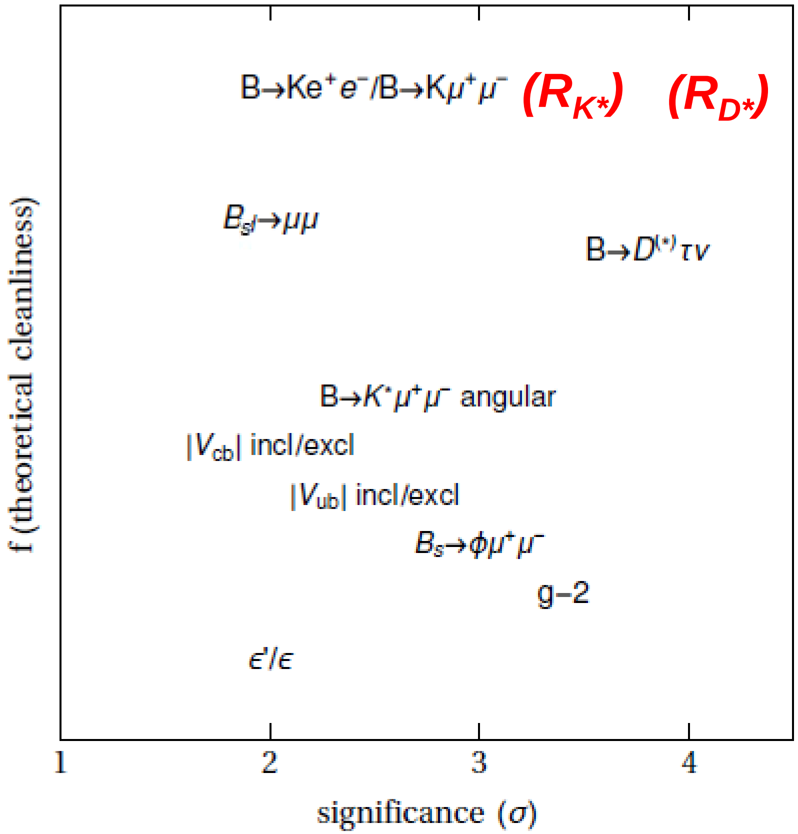
- Status of the recent tensions on *B*-physics:
  - Theoretical uncertainties
- Hints of a emergent New Physics scenario:
  - ***New left-handed couplings!***
- What Next and Conclusions

Frascati, September 21, 2017

Flavour Anomalies up to now



Flavour Anomalies: First cleanliness.



Z. Ligeti, Moriond QCD 2016

☺ Some channels are very clean, only limited by present exp. statistics

☹ Other channels require careful assessment of the theoretical error:

→ still useful in presence of NP correlations

- Very interesting pattern of anomalies:

→ pointing out to a consistent NP hints

B Anomalies: high cleanliness.

❖ *Breaking of Lepton Flavour Universality* (LFU)

➢ LFU from $b \rightarrow s$ neutral currents: μ vs e

$$R_{K^{(*)}} = \frac{Br\left(B \rightarrow K^{(*)}\mu\mu\right)}{Br\left(B \rightarrow K^{(*)}ee\right)} \qquad \sim 3.4\sigma$$

➢ LFU from $b \rightarrow c$ charged currents: τ vs μ /e

$$R_{D^{(*)}} = \frac{Br\left(B \rightarrow D^{(*)}\tau\nu\right)}{Br\left(B \rightarrow D^{(*)}\ell\,\nu\right)} \qquad \sim 4\sigma$$

❑ At LEP: LFU tests are only at the *Z* mass (SM gauge couplings)

❑ At *B*-factories: LFU tests only for 1st-2nd gen quarks & leptons

B Anomalies: direct searches?

❑ Hints of New Physics

- ❖ New Physics effects ~15% of the SM

$\frac{B\to K\mu^+\mu^-}{B\to K e^+e^-}$ $\sim 2.5\sigma$

$B \to K^*\mu^+\mu^-$ angular distribution $\sim 3\sigma$

$\frac{B\to D^{(*)}\tau\nu}{B\to D^{(*)}\ell\nu}$ $\sim 4\sigma$

- ➢ New Physics scales:

Di Luzio & Nardecchia. 1706.01868

1) *From* $b \to s\mu\mu$

$$\frac{g_{NP}^2}{\Lambda_{NP}^2} = G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{9,10}^{NP} \Rightarrow \frac{\Lambda_{NP}}{g_{NP}} = 31\ \mathrm{TeV}$$

2) *From* $b \to c\tau\nu$

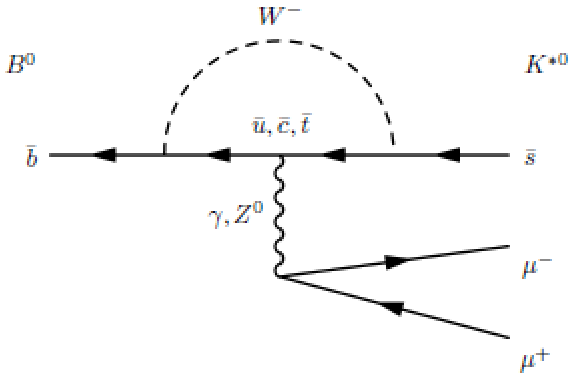
$$\frac{g_{NP}^2}{\Lambda_{NP}^2} = G_F V_{cb} C^{NP} \Rightarrow \frac{\Lambda_{NP}}{g_{NP}} = 3.4\ \mathrm{TeV}$$

- ❖ No tension with Atlas/CMS direct searches

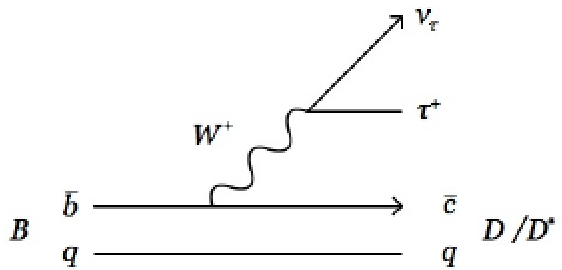
B Anomalies: $b \to s\ \mu\mu$ & $b \to c\ \tau\nu$

1) Flavour Changing Neutral Current: $b \to s\ \mu\mu$

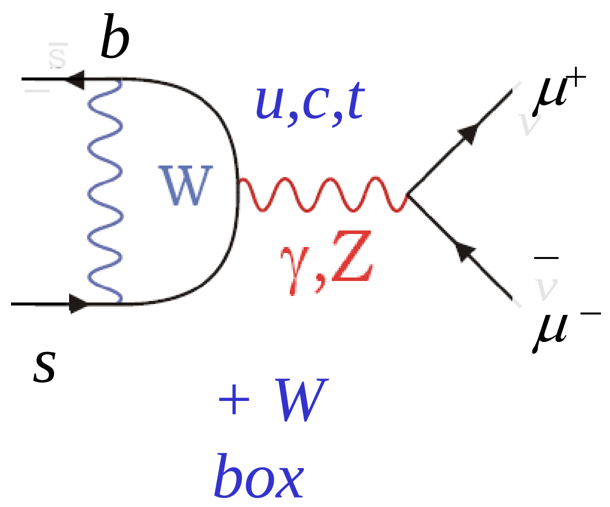
$$(B \to K^*\mu\mu, B \to \phi\mu\mu, R_K, \ldots)$$



2) Flavour Changing Charged Current: $b \to c\ \tau\nu$



B Anomalies: $b \to s\,\mu\mu$ (Theory)



At short-distance

$$Heff = \begin{cases} C_7 \times \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu} + \\ C_9 \times \bar{b}_L \gamma^{\mu} s_L \bar{l} \gamma^{\mu} l + \\ C_{10} \times \bar{b}_L \gamma^{\mu} s_L \bar{l} \gamma^{\mu} \gamma_5 l \end{cases}$$

Babar+Belle (7%)

$Br(B_d \to X_s \gamma) \propto |C_7|$

LHCb

$Br(B_s \to \mu^+\mu^-) \propto C_{10}$

$A(B_d \to K l^+ l^-) \propto C_{7,9,10}$

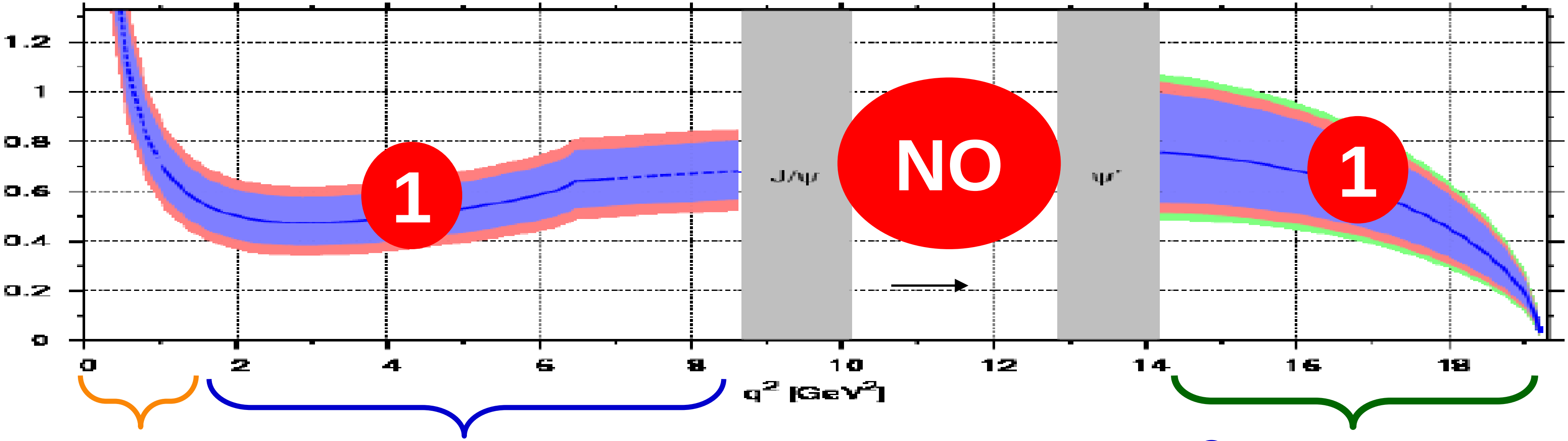
$A(B_d \to K^* l^+ l^-) \propto C_{7,9,10}$

$A(B_s \to \phi\, \mu^+\mu^-) \propto C_{7,9,10}$

sensitive to NP but plagued by potentially hadronic

$b\to s$ transitions: $B\to K^*\mu\mu$

$d\Gamma(B\to K^*ll)/dq^2$



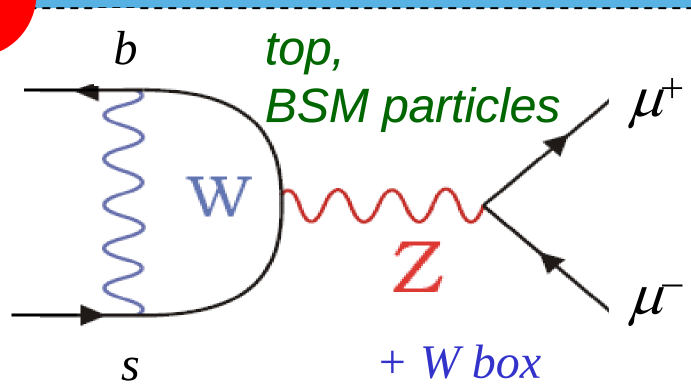
☺ γ pole C_7: chiral loops

😐 large recoil range
$C_{9,10}$(Z, t, NP)
$1\text{GeV}^2 < q^2 < 6\text{ GeV}^2$

☹ J/ψ Resonances:
(non-local) γ effects

☺ low recoil region
$C_{9,10}$ (Z, t, NP)
$q^2 > 14.2\text{ GeV}^2$

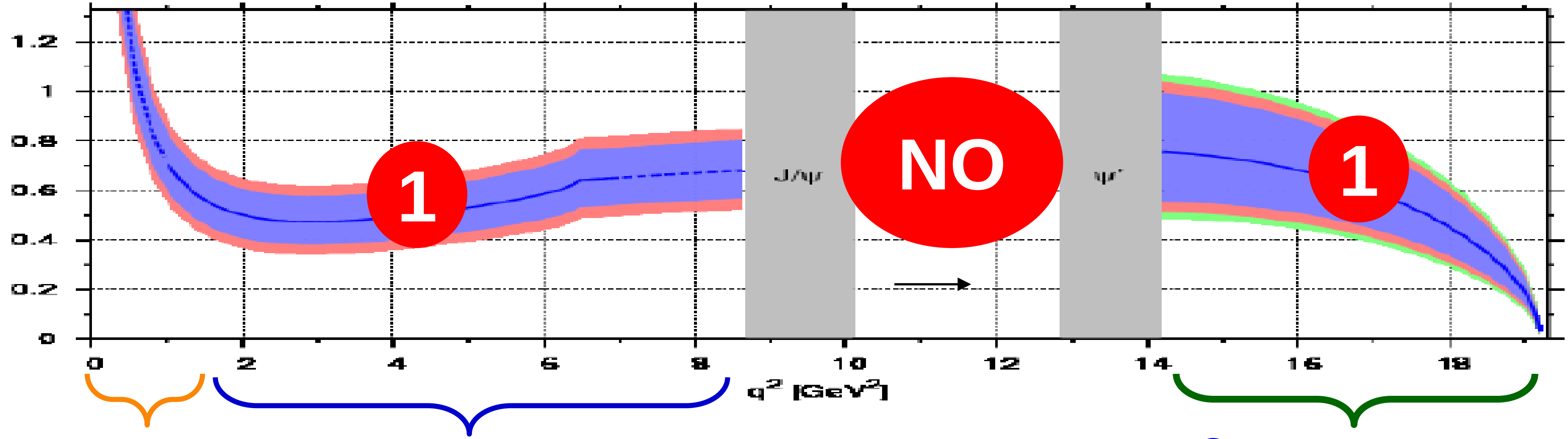
1



$$H_{SD}^{eff} = \begin{cases} C_7 \times \bar{b}\sigma^{\mu\nu} s F_{\mu\nu} \\ C_{10} \times \bar{b}\gamma_L^{\mu} s \bar{l}\gamma^{\mu}\gamma_5 l \\ C_9 \times \bar{b}\gamma_L^{\mu} s \bar{l}\gamma^{\mu} l \end{cases}$$

$b \to s$ transitions: $B \to K^* \mu\mu$

$d\Gamma(B \to K^* ll)/dq^2$



☺ **γ pole C_7:** chiral loops

😐 **large recoil range**
$C_{9,10}$(Z, t, NP)
$1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2$

☹ **J/ψ Resonances:**
(non-local) γ effects

☺ **low recoil region**
$C_{9,10}$ (Z, t, NP)
$q^2 > 14.2\,\text{GeV}^2$

1

Hadronic uncertainties:

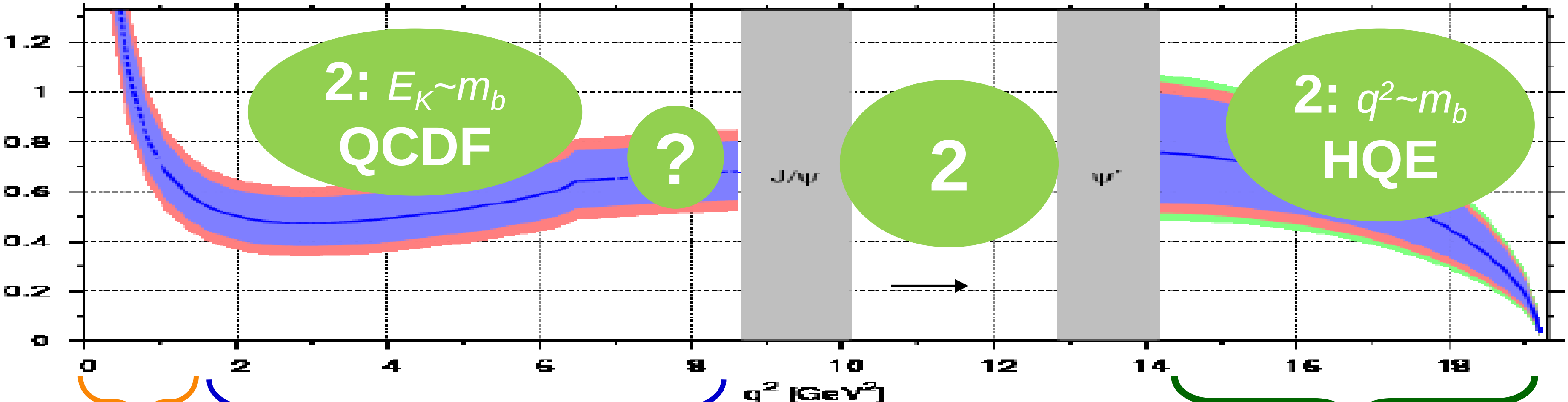
$$\langle K^* | Q_{7,9,10} | B \rangle ?$$

Form Factors.

$$H_{SD}^{eff} = \begin{cases} C_7 \times \bar{b}\sigma^{\mu\nu} s F_{\mu\nu} \\ C_{10} \times \bar{b}\gamma_L^{\mu} s \bar{l}\gamma^{\mu}\gamma_5 l \\ C_9 \times \bar{b}\gamma_L^{\mu} s \bar{l}\gamma^{\mu} l \end{cases}$$

$b \to s$ transitions: $B \to K^* \mu\mu$

$d\Gamma(B \to K^* ll)/dq^2$



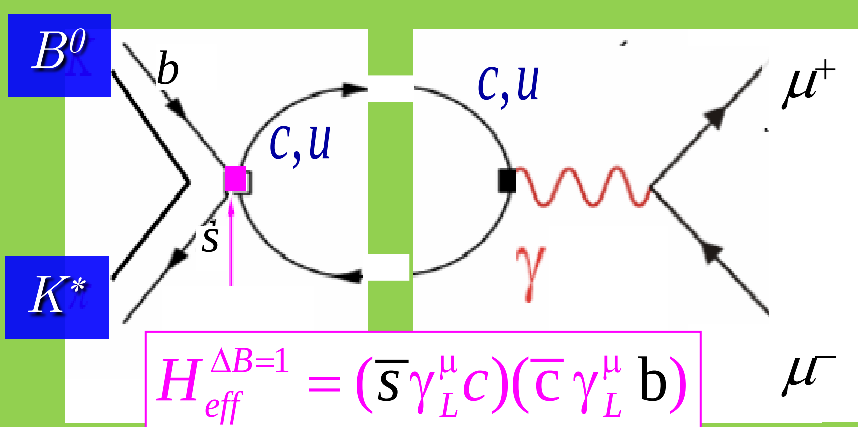
☺ **γ pole C_7:** chiral loops

😐 **large recoil range**
$C_{9,10}$(Z, t, NP) + LD γcc :
$1\text{GeV}^2 < q^2 < 6\ \text{GeV}^2$

☹ **J/ψ Resonances:**
(non-local) γ effects

☺ **low recoil region**
$C_{9,10}$ (Z, t, NP)
$q^2 > 14.2\ \text{GeV}^2$

2



$$H_{eff}^{\Delta B=1} = (\bar{s}\gamma_L^{\mu} c)(\bar{c}\gamma_L^{\mu} b)$$

- **Non-local Interaction (LD)**

$$H_{LD} = \frac{\alpha_{em}}{q^2}\langle K^*\gamma | T(H_{eff}^{\Delta B=1}(x) J_{\gamma}^{em}(0)) | B\rangle$$

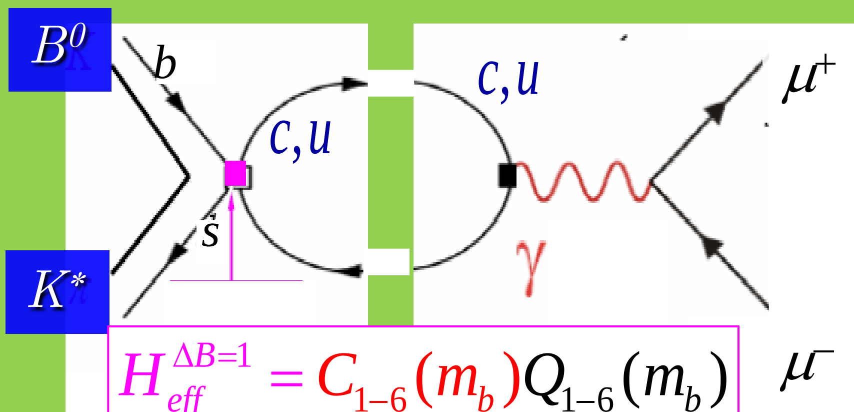
- "**Non-Factorizable Contributions**"

2

Non-Local operators: charm and chiral loops $[Q_{1-6}]$

$$Q_1^c = (\bar{s}_L\gamma_\mu T^a c_L)(\bar{c}_L\gamma^\mu T^a b_L) \qquad Q_2^c = (\bar{s}_L\gamma_\mu c_L)(\bar{c}_L\gamma^\mu b_L)$$

$$Q_3 = (\bar{s}_L\gamma_\mu b_L)\sum_q(\bar{q}\gamma^\mu q) \qquad Q_4 = (\bar{s}_L\gamma_\mu T^a b_L)\sum_q(\bar{q}\gamma^\mu T^a q)$$

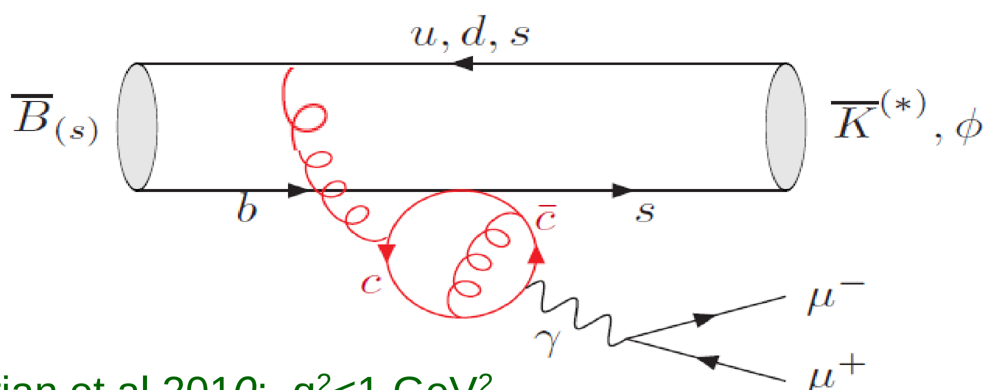


$$H_{eff}^{\Delta B=1} = C_{1-6}(m_b)Q_{1-6}(m_b)$$

$$\longrightarrow \frac{\alpha_{em}}{q^2}\langle K^*\gamma|T(H_{eff}^{\Delta B=1}(x)J_\gamma^{em}(0))|B\rangle$$

$$O_9 = (\bar{b}\gamma_L^\mu s)\bar{\ell}\gamma^\mu\ell$$

b) Tough contractions: Non-factorizable power corrections (spectator effects)

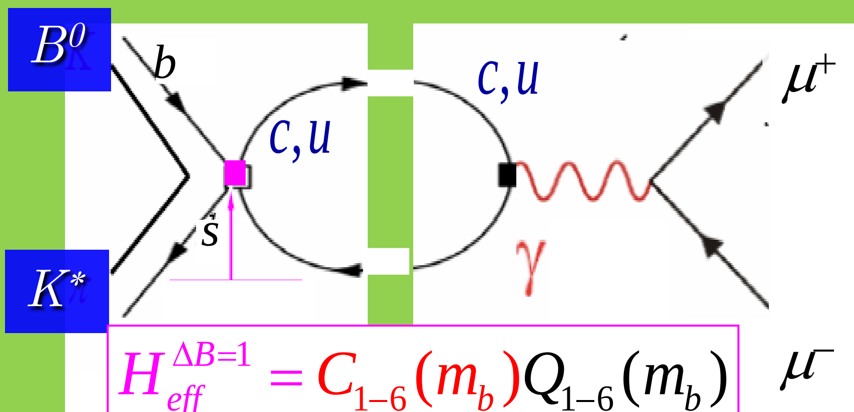


Khodjamirian et al,2010: $q^2<1$ GeV^2

Non-Local operators: charm and chiral loops $[Q_{1-6}]$

$$Q_1^c = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L) \qquad Q_2^c = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$

$$Q_3 = (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q} \gamma^\mu q) \qquad Q_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q} \gamma^\mu T^a q)$$



$$H_{eff}^{\Delta B=1} = C_{1-6}(m_b) Q_{1-6}(m_b)$$

$$\longrightarrow \frac{\alpha_{em}}{q^2} \langle K^* \gamma | T(H_{eff}^{\Delta B=1}(x) J_\gamma^{em}(0)) | B \rangle$$

$$O_9 = (\bar{b} \gamma_L^\mu s) \bar{\ell} \gamma^\mu \ell$$

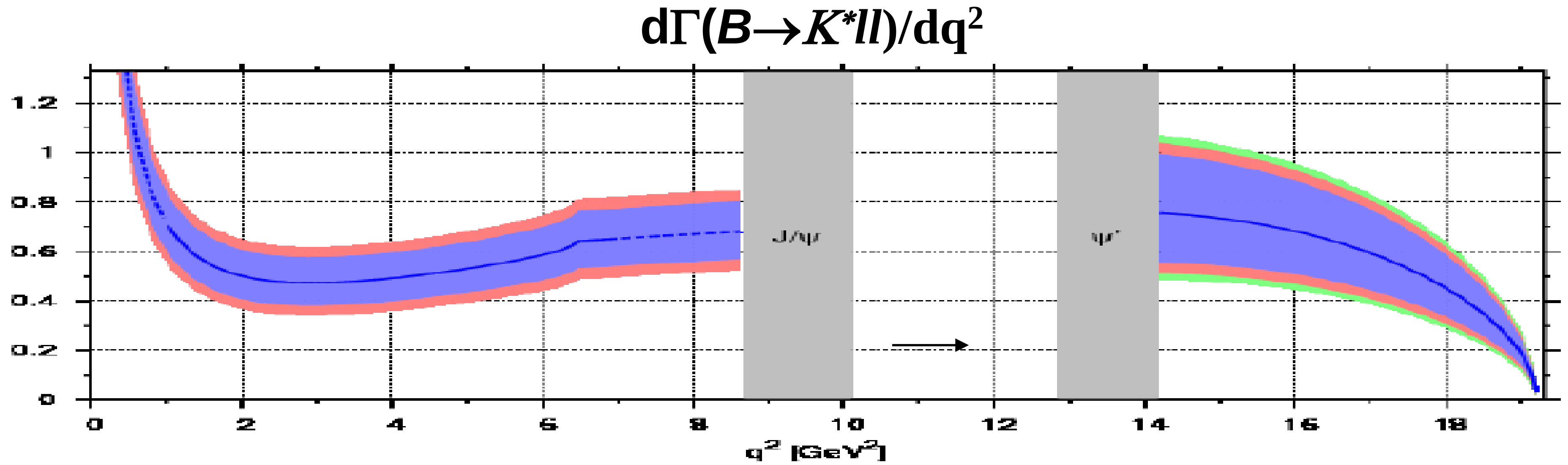
b) **Tough contractions**: Non-factorizable power corrections (spectator effects)

$$C_9^{tot} = C_9^{SD} + C_9^{cc-fac}(q^2) + C_9^{ccNoF}(q^2)$$

Ciuchini et al. 2015

SD: Z, t, NP	Charm-Fact c.:	Charm-No Fact c.:
q^2-independent	*OPE*	q^2-dependent
~4.0	~0.4	*TOUGH!!*

$b \to s$ transitions: $B \to K^* \mu\mu$



NO PANIC

To large extent, uncertainties cancel out in the ratio.

$$R_K = \frac{Br\left(B \to K\ \mu\mu\right)}{Br\left(B \to K\ ee\right)}$$

$$R_{K^*} = \frac{Br\left(B \to K^* \mu\mu\right)}{Br\left(B \to K^* ee\right)}$$

B Anomalies: LFU on $b \to s$

- **Clean observables**

Form Factors and Non-Factorizable effects are lepton universal

At q^2=[1,6] GeV2

$$R_K \equiv \frac{\mathrm{Br}\left(B^+ \to K^+ \mu^+ \mu^-\right)}{\mathrm{Br}\left(B^+ \to K^+ e^+ e^-\right)} = 1 + \mathcal{O}(10^{-4})$$

At q^2=[0.045,1.1] GeV2

$$R_{K^*} \equiv \frac{\Gamma\left(B^0 \to K^{*0} \mu^+ \mu^-\right)}{\Gamma\left(B^0 \to K^{0*} e^+ e^-\right)} = 0.91 +0.03$$

At q^2=[1.1,6.0]GeV2

$$R_{K^*} \equiv \frac{\Gamma\left(B^0 \to K^{*0} \mu^+ \mu^-\right)}{\Gamma\left(B^0 \to K^{0*} e^+ e^-\right)} = 1.00 +0.01$$

SM

* EM corrections are lepton-dependent but at ∼ % level Bordone *et al.* EPJC76(2016),8,440

B Anomalies: LFU on $b \to s$

- **Clean observables**

Form Factors and Non-Factorizable effects are lepton universal

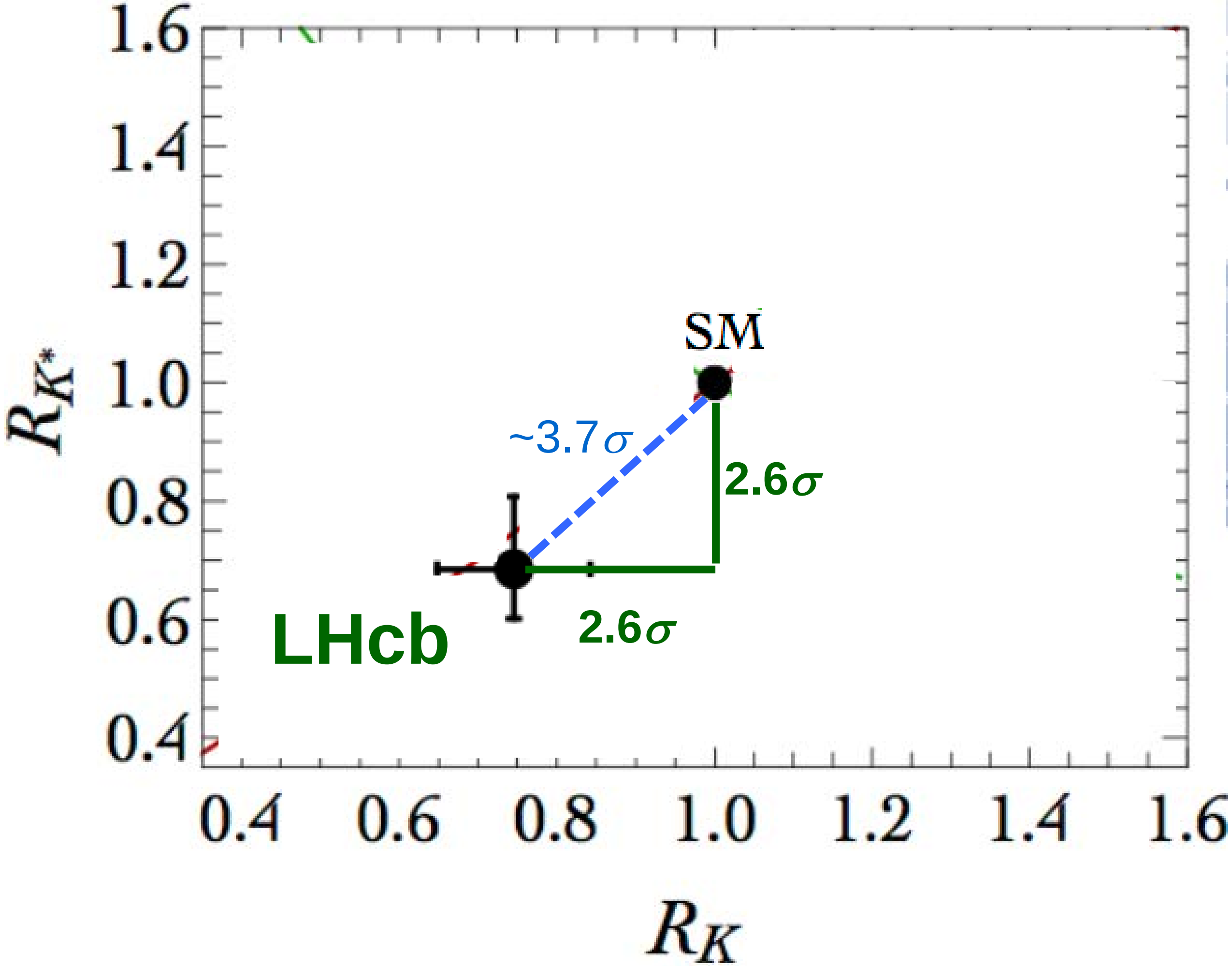
$0.745 \pm 0.09_{\rm stat} \pm 0.036_{\rm syst}$ $$R_K \equiv \frac{\text{Br}\left(B^+ \to K^+\mu^+\mu^-\right)}{\text{Br}\left(B^+ \to K^+e^+e^-\right)} = 1 + \mathcal{O}(10^{-4})$$

$0.685^{+0.113}_{-0.069} \pm 0.047$ $$R_{K^*} \equiv \frac{\Gamma\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{\Gamma\left(B^0 \to K^{0*}e^+e^-\right)}$$ = 0.91 +0.03

$0.660^{+0.110}_{-0.070} \pm 0.024$ $$R_{K^*} \equiv \frac{\Gamma\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{\Gamma\left(B^0 \to K^{0*}e^+e^-\right)}$$ = 1.00 +0.01

LHcb 2.6σ less than the SM

B Anomalies: LFU on $b \to s$



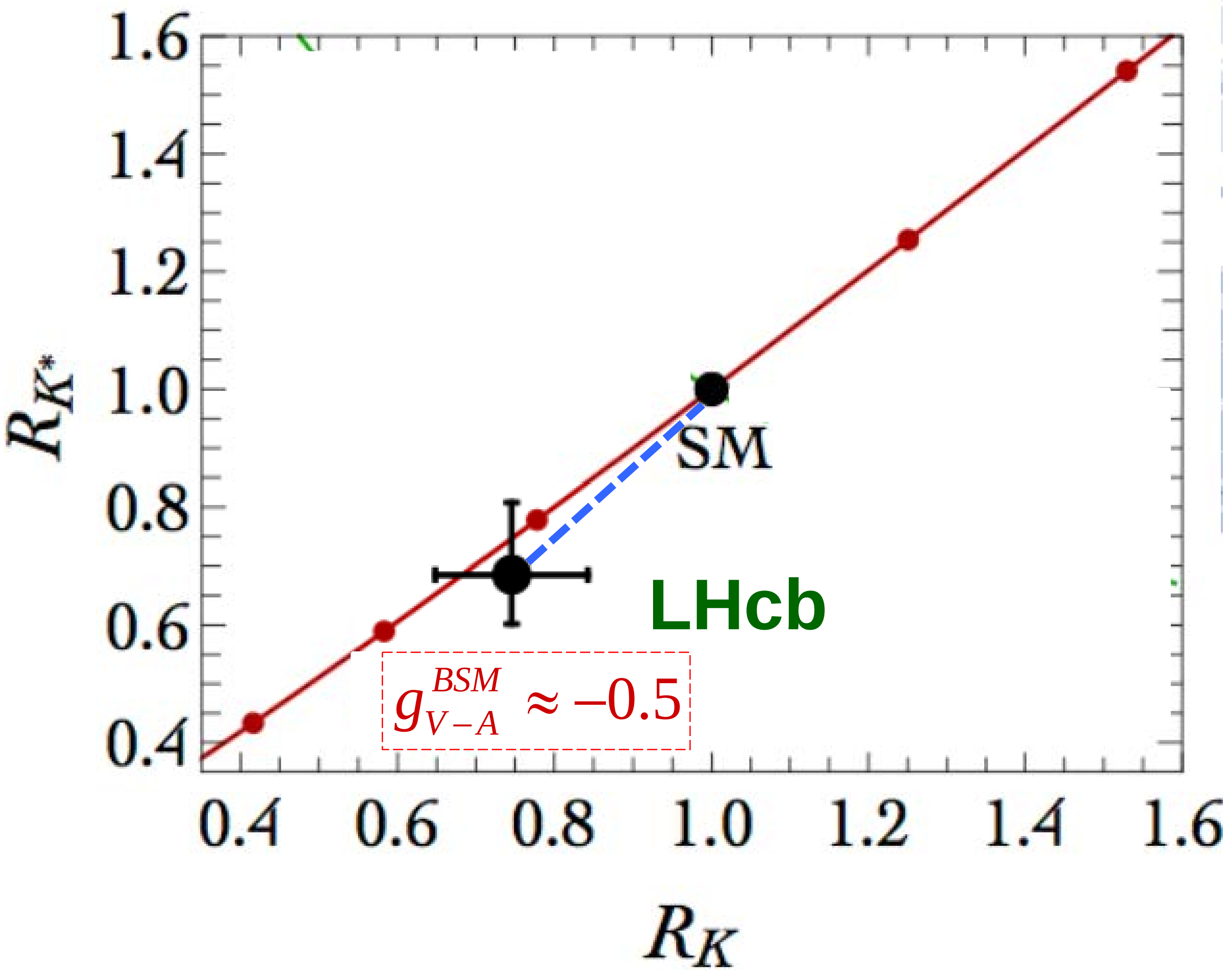
GOING STRAIGHT
~3.7σ
by Pitagora Theorem

Destructive interference with SM

At q^2=[1,6] GeV2

B Anomalies: LFU on $b \to s$

$$R_K = 1 + 0.23 g_{V-A}^{BSM} \longrightarrow R_{K^*} = R_K$$



Destructive interference with SM

→ new V-A operators

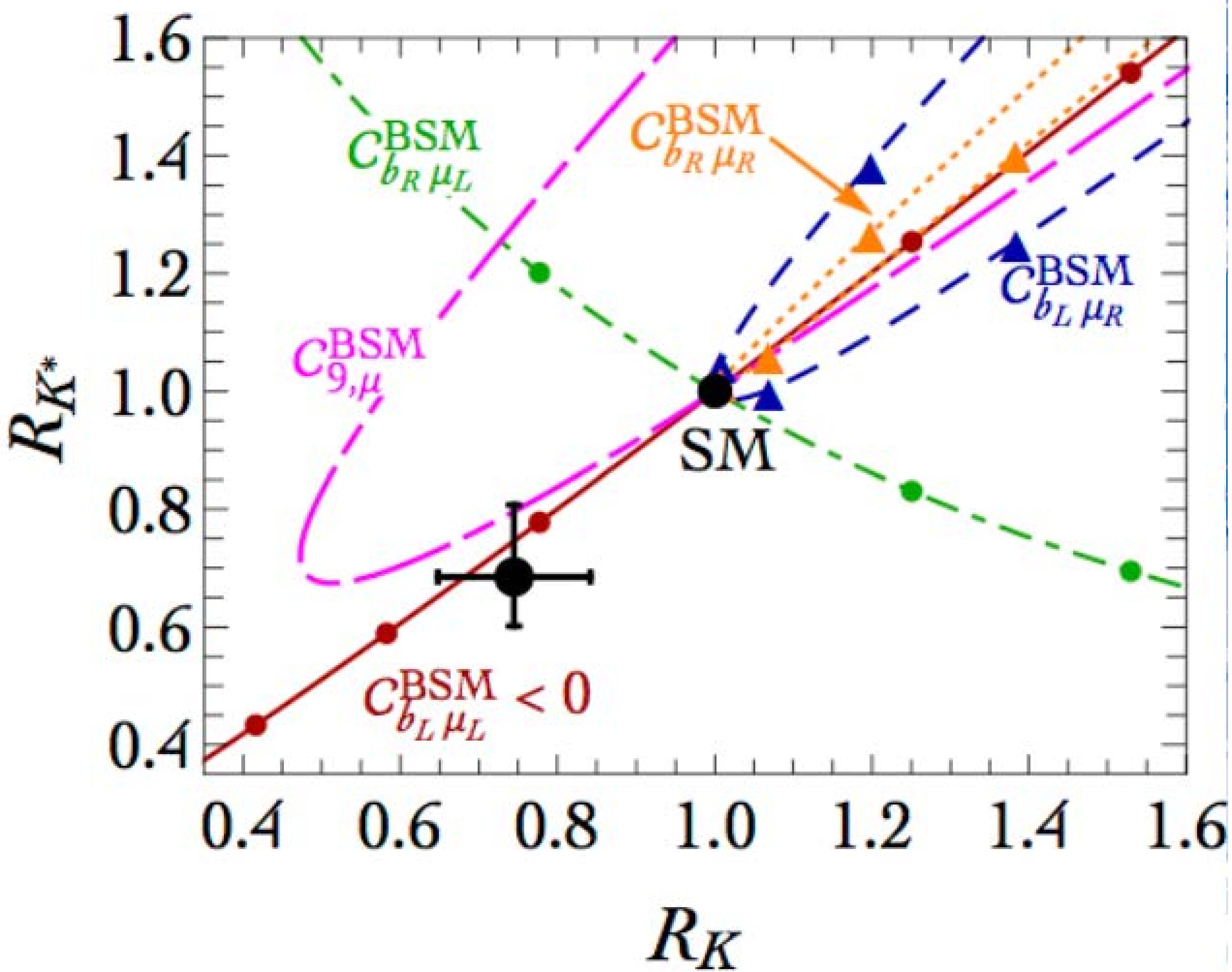
$$\left(\overline{s}_L \gamma^\mu b_L\right) \overline{\mu}_L \gamma^\mu \mu_L$$

$$g_{V-A}^{BSM} = \frac{C_9^\mu - C_{10}^\mu}{2}$$

At q^2=[1,6] GeV2

B Anomalies: LFU on $b \to s$

$$R_{K^*} \simeq R_K - 0.4\,\mathrm{Re}\left(C^{\mathrm{BSM}}_{b_R\mu_L} - C^{\mathrm{BSM}}_{b_R e_L}\right)$$



RR and scalar current disfavoured!

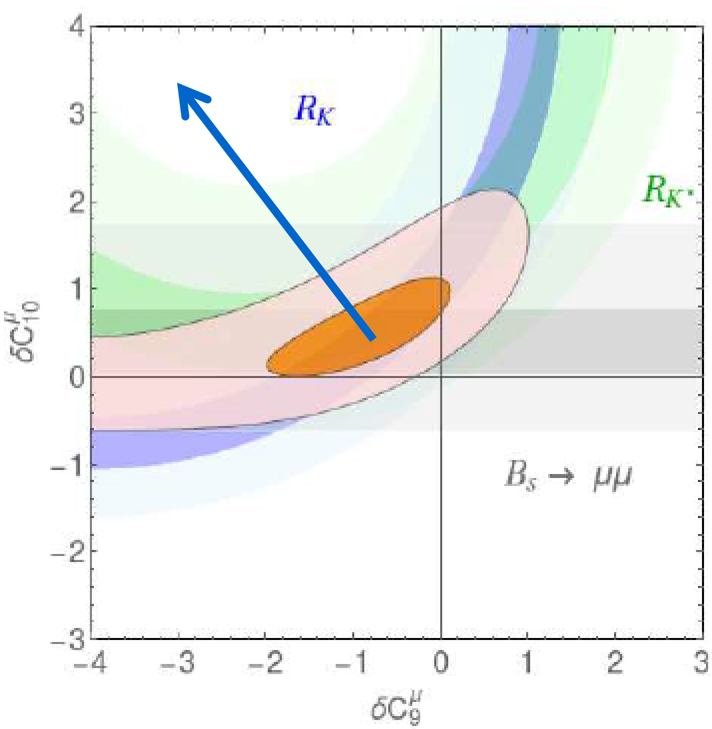
$$C_9^\mu = \frac{1}{2}\left(C_{b_L\mu_L} + C_{b_L\mu_R}\right)$$

$$C_{10}^\mu = \frac{1}{2}\left(C_{b_L\mu_R} - C_{b_L\mu_L}\right)$$

D'Amico et al.
B. Capdevila et al.
J. Camalich et al.
A. Celis, J. Fuentes-Martin.
D. Straub et. al
M. Ciuchini et. al

B Anomalies: LFU on $b \to s$

Obs.	Expt.	SM	$\delta C_L^\mu = -0.5$	$\delta C_9^\mu = -1$	$\delta C_{10}^\mu = 1$	$\delta C_9^{\prime\mu} = -1$
R_K [1, 6] GeV^2	0.745 ± 0.090	$1.0004^{+0.0008}_{-0.0007}$	$0.773^{+0.003}_{-0.003}$	$0.797^{+0.002}_{-0.002}$	$0.778^{+0.007}_{-0.007}$	$0.796^{+0.002}_{-0.002}$
R_{K^*} [0.045, 1.1] GeV^2	0.66 ± 0.12	$0.920^{+0.007}_{-0.006}$	$0.88^{+0.01}_{-0.02}$	$0.91^{+0.01}_{-0.02}$	$0.862^{+0.016}_{-0.011}$	$0.98^{+0.03}_{-0.03}$
R_{K^*} [1.1, 6] GeV^2	0.685 ± 0.120	$0.996^{+0.002}_{-0.002}$	$0.78^{+0.02}_{-0.01}$	$0.87^{+0.04}_{-0.03}$	$0.73^{+0.03}_{-0.04}$	$1.20^{+0.02}_{-0.03}$
R_{K^*} [15, 19] GeV^2	–	$0.998^{+0.001}_{-0.001}$	$0.776^{+0.002}_{-0.002}$	$0.793^{+0.001}_{-0.001}$	$0.787^{+0.004}_{-0.004}$	$1.204^{+0.007}_{-0.008}$



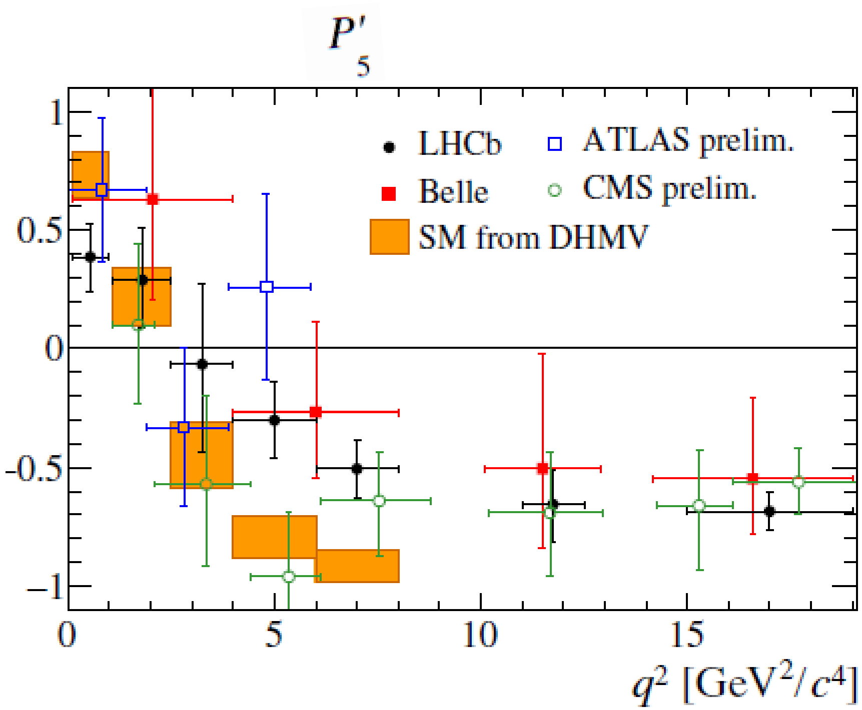
Hints:

Fit suggests nonzero $C_L = (C_9 - C_{10})/2$

Only from Clean observables:

J. Camalich et al.
D'Amico et al.
B. Capdevila et al.
A. Celis, J. Fuentes-Martin.
D. Straub et. Al
M. Ciuchini et.

B Anomalies: $B \to K^* (\to K\pi)\mu\mu$: P_5' ang. obs



$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} =$$

$$\frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

LHCb

2013: $1\,\mathrm{fb}^{-1}$ data
$3.7\,\sigma$ in $[4, 8.3]$

2015: $3\,\mathrm{fb}^{-1}$ data
$2.8\,\sigma$ in $[4, 6]$
$3.0\,\sigma$ in $[6, 8]$

Belle

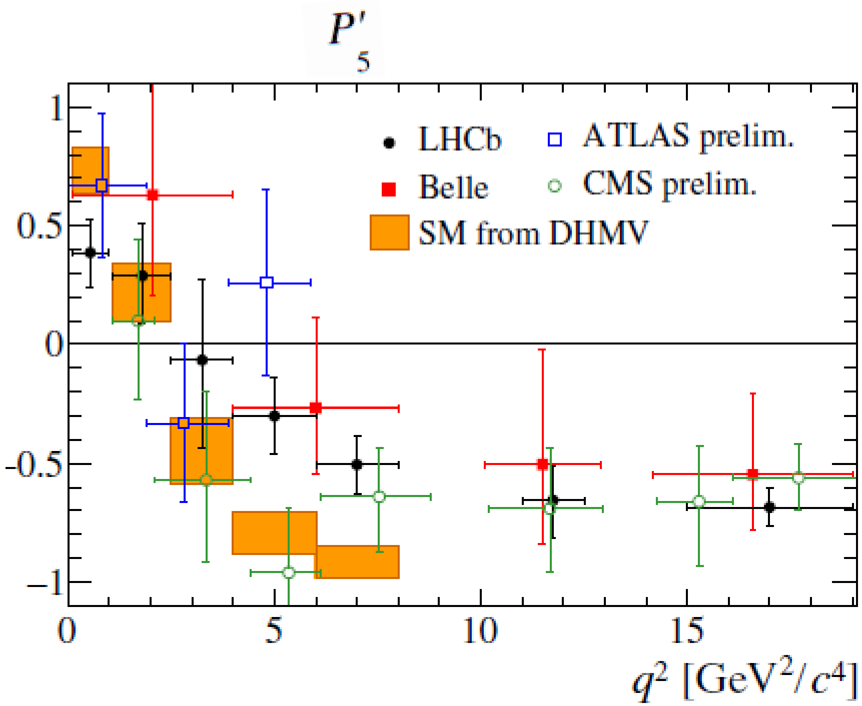
2016: $P_5'^{\ell}$ $(\ell = \mu, e)$
$2.5\,\sigma$ in $[4, 8]$

Moriond 2017

Atlas: tension consistent with LHCb and Belle

CMS: consistent with SM

B Anomalies: $B \to K^* (\to K\pi)\mu\mu$: P_5' ang. obs



$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} =$$

$$\frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

☺ Reduced sensitivity to Form factors uncertainties

☹ Still plagued by non-factorizable power corrections:

$$C_9^{tot} = C_9^{SD} + C_9^{cc-fac}(q^2) + C_9^{ccNoF}(q^2)$$

Ciuchini et al. 2015

B Anomalies: $B \to K^{(*)}$ Brs: going to dirty obs

Various measurements of branching ratios are low compared to the SM prediction

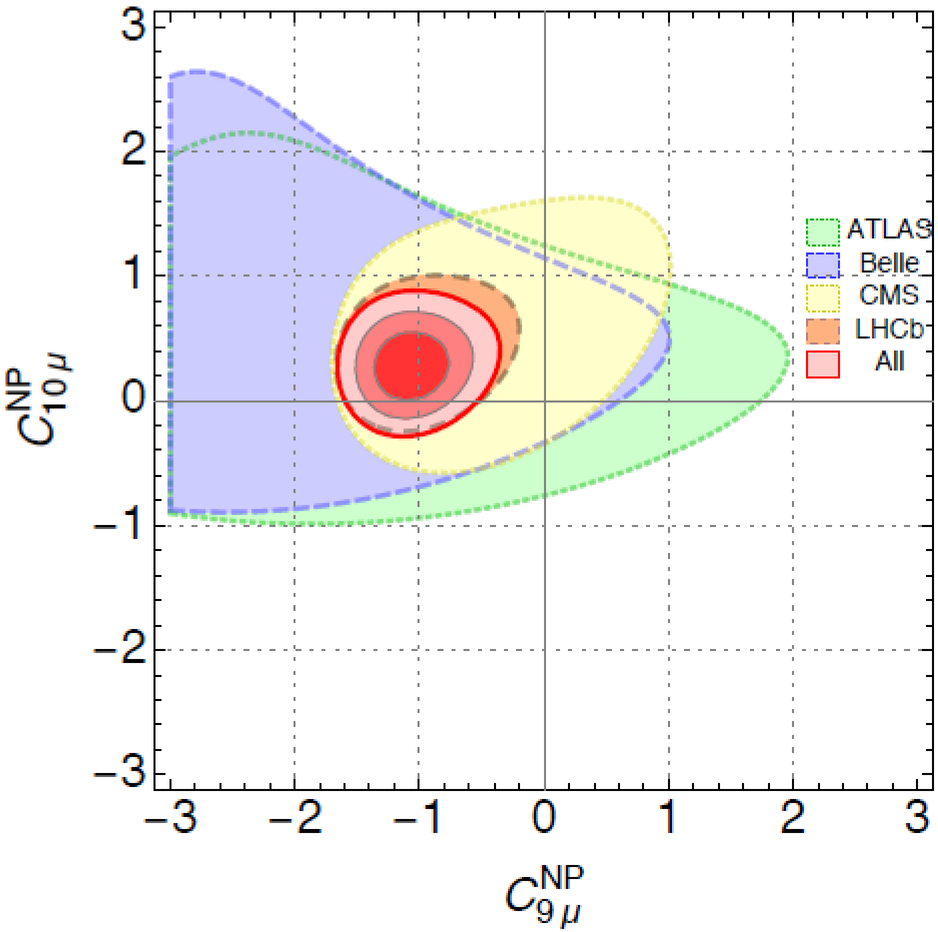
Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08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

[Altmannshofer, Straub 1503.06199]

[recently updated, LHCB 1506.08777] 0.26 ± 0.04 $+3.5$

☹ Potentially large hadronic uncertainties

B Anomalies: $b \to s$ observables together



Overall fit with

clean LFU observables
+ the less clean P_5
+ the dirty obs such as Br, …, F_L

still points out
a nonzero V-A coupling for μ:
$C_9 = -C_{10} = -0.61$

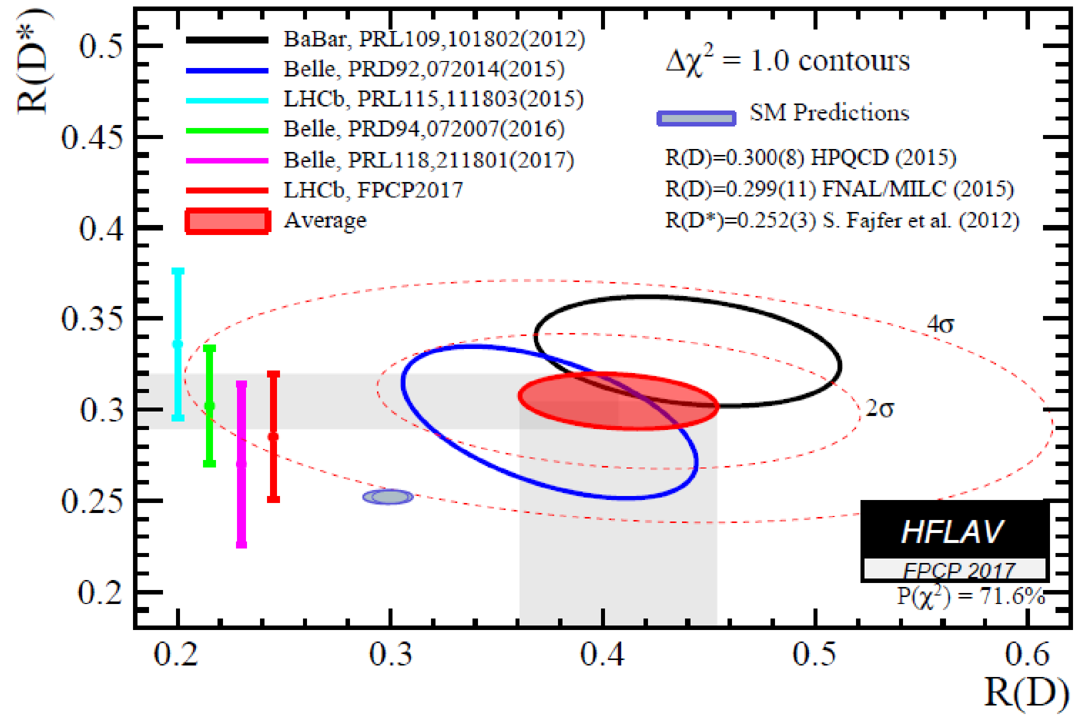
$$-\frac{\left(\bar{s}_L \gamma^\mu b_L\right) \bar{\mu}_L \gamma^\mu \mu_L}{\Lambda^2_{RK}}$$

$$\Lambda_{RK} = 31\ \text{TeV}$$

B Anomalies: LFU - $b \to c\tau\nu$

❑ HFAG 2017

$$R_{D^{(*)}} = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\ell\nu)}$$



- ❑ 3.3σ tension from BaBar (2012)
- ❑ next confirmed from Belle
- ❑ and recently from LHCb for R_{D^*}

R_D : SM < EXP at 2.2σ

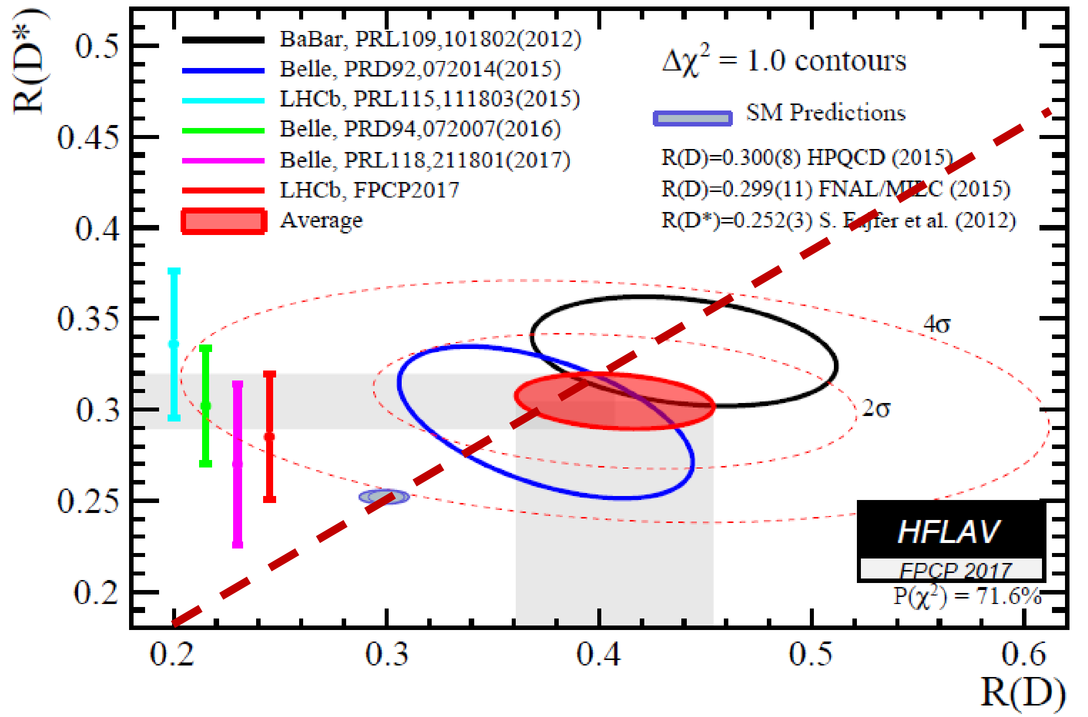
R_{D^*} : SM < EXP at 3.3σ

- ❑ Combining the two observables, excess of about 4σ

B Anomalies: LFU - $b \to c\tau\nu$

❑ HFAG 2017

$$R_{D^{(*)}} = \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\ell\nu)}$$



- ❑ 3.3σ tension from BaBar (2012)
- ❑ next confirmed from Belle
- ❑ and recently from LHCb for R_{D^*}

❑ Combining the two observables, excess of about 4σ

➢ **The two channels are well consistent with a new V-A coupling**

$$\frac{\left(\overline{c}_L \gamma^\mu b_L\right) \overline{\tau}_L \gamma^\mu \nu_L}{\Lambda_{RD}^2}$$

➢ *RH or scalar amplitudes disfavored.*

B Anomalies

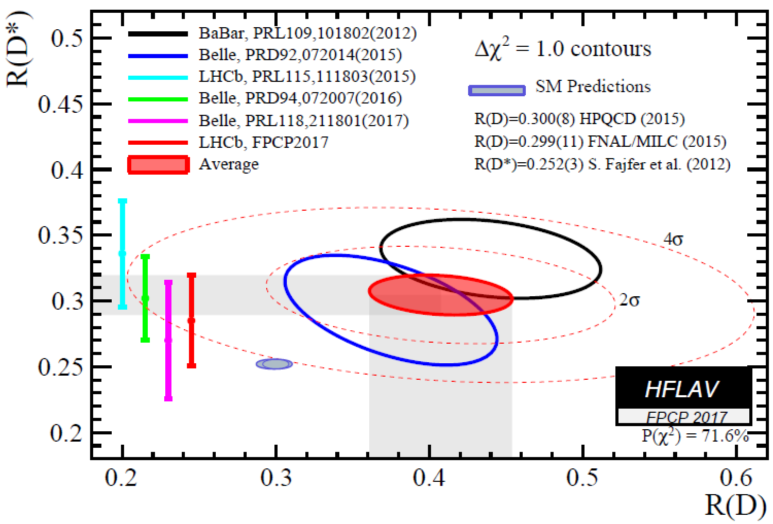
$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)} \tau \nu)}{\mathrm{Br}(B \to D^{(*)} \ell \nu)}$$

❖ Hadronic uncertainties?

- *Form Factors are lepton universal:*

$\rightarrow$ uncertainties largely cancel in R_D and R_{D*}

- *SM predictions of R_{D*} and R_{D*} are well under control*



- **Tension observed by three Experiments**

$$R_{D*} \equiv \frac{\mathcal{B}(B \to D^* \tau \bar{\nu}_\tau)_{\rm exp} / \mathcal{B}(B \to D^* \tau \bar{\nu}_\tau)_{\rm SM}}{\mathcal{B}(B \to D^* \ell \bar{\nu}_\ell)_{\rm exp} / \mathcal{B}(B \to D^* \ell \bar{\nu}_\ell)_{\rm SM}} = 1.23 \pm 0.07 \,,$$

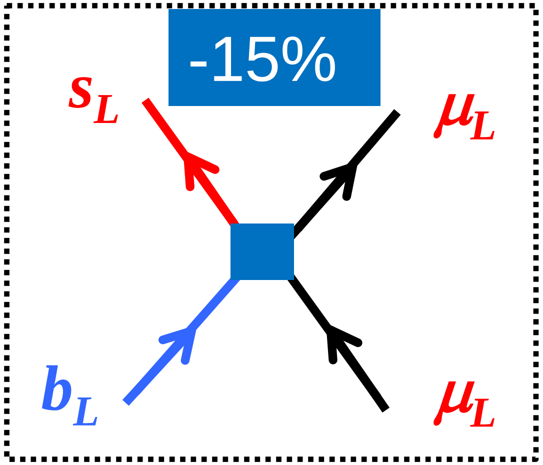
$$R_D \equiv \frac{\mathcal{B}(B \to D \tau \bar{\nu}_\tau)_{\rm exp} / \mathcal{B}(B \to D \tau \bar{\nu}_\tau)_{\rm SM}}{\mathcal{B}(B \to D \ell \bar{\nu}_\ell)_{\rm exp} / \mathcal{B}(B \to D \ell \bar{\nu}_\ell)_{\rm SM}} = 1.35 \pm 0.16 \,.$$

- Only from V-A coupling $R_{D^{(*)}} = 1.24 \pm 0.07.$

- **Excess observed at more than ~4σ**

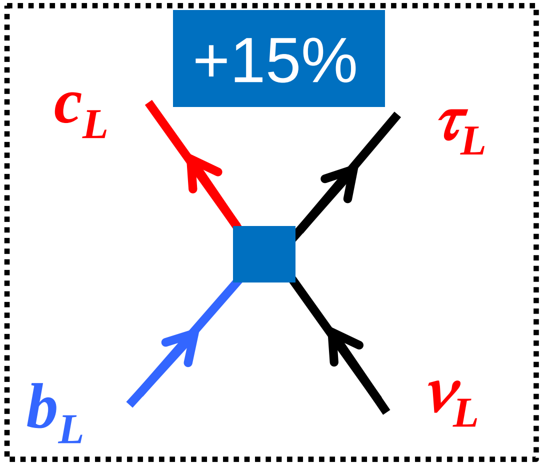
20% enhancement of the SM amplitude

How to explain the two effects simultaneously?



Below EW scale

new V-A interactions



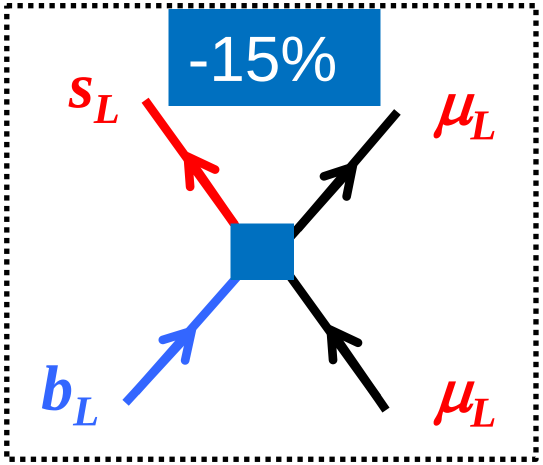
$$-\frac{\left(\bar{s}_L \gamma^\mu b_L\right)\bar{\mu}_L \gamma^\mu \mu_L}{\Lambda_{RK}^2}$$

$$\frac{\left(\bar{c}_L \gamma^\mu b_L\right)\bar{\tau}_L \gamma^\mu \nu_L}{\Lambda_{RD}^2}$$

$$\Lambda_{RK} = 31\ \text{TeV}$$

$$\Lambda_{RD} = 2.4\ \text{TeV}$$

How to explain the two effects simultaneously?



Below EW scale

$$\Lambda_{RK} = 31\ \mathrm{TeV}$$

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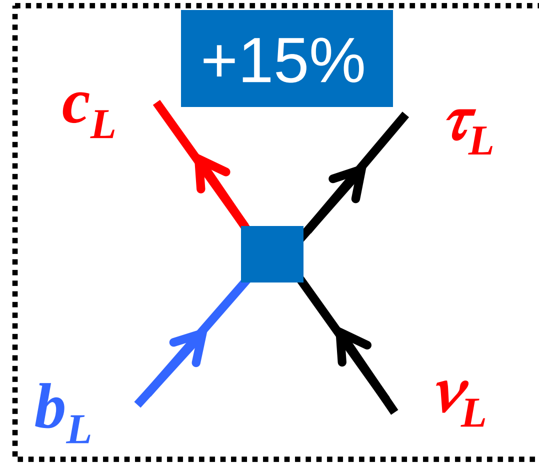


$$-\frac{\left(\bar{s}_L \gamma^\mu b_L\right)\bar{\mu}_L \gamma^\mu \mu_L}{\Lambda_{RK}^2}$$

$$\frac{\left(\bar{c}_L \gamma^\mu b_L\right)\bar{\tau}_L \gamma^\mu \nu_L}{\Lambda_{RD}^2}$$

Above EW scale

☺ $b \to s\ \mu\mu$, $b \to c\ \tau\nu$ by $SU(2)_L$ triplet

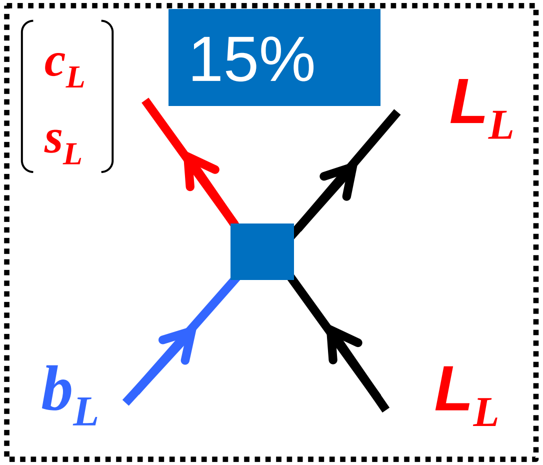
$$\Lambda_T = 3.4\ \mathrm{TeV}$$

$$\lambda_{22}^{\ell} = -0.01$$

$$\frac{\left(\bar{Q}_L^2 \gamma^\mu \tau^a Q_L^3\right) L_L^3 \gamma^\mu \tau^a L_L^3}{\Lambda_T^2} = 2\frac{\left(\bar{c}_L \gamma^\mu b_L\right)\bar{\tau}_L \gamma^\mu \nu_L}{\Lambda_T^2}$$

$$\lambda_{22}^{\ell}\frac{\left(\bar{Q}_L^2 \gamma^\mu \tau^3 Q_L^3\right) L_L^2 \gamma^\mu \tau^3 L_L^2}{\Lambda_T^2} = \lambda_{22}^{\ell}\frac{\left(\bar{s}_L \gamma^\mu b_L\right)\bar{\mu}_L \gamma^\mu \mu_L}{\Lambda_T^2}$$

EFT above EW



I. $SU(2)_L$ triplet elegant solution

$$\left(\bar{Q}_L^3 \gamma^\mu \tau^a Q_L^3\right)\bar{L}_L^\alpha \gamma^\mu \tau^a L_L^\beta \, / \, \Lambda_T^2$$

☺ $b \to c\, \tau\nu$ by V_{cb}=CKM$_{23}$ mixing

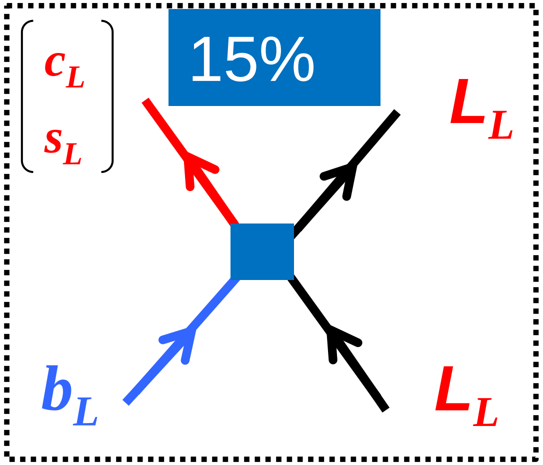
$$\bar{Q}_L^3 = \begin{pmatrix} V_{tb} t + V_{cb} c + V_{tb} u \\ b \end{pmatrix} \qquad L_L^3 = \begin{pmatrix} \nu_L^3 \\ \tau_L \end{pmatrix}$$

$$V_{cb}\,\frac{2\left(\bar{c}_L \gamma^\mu b_L\right)\bar{\tau}_L \gamma^\mu \nu_L}{\Lambda_T^2}$$

$$\Lambda_T = 0.7\ \text{TeV}$$

$$(\lambda_{bb}^q = \lambda_{\tau\tau}^q = 1)$$

EFT above EW



I. $SU(2)_L$ triplet elegant solution

$$\left(\bar{Q}_L^3 \gamma^\mu \tau^a Q_L^3\right) \bar{L}_L^\alpha \gamma^\mu \tau^a L_L^\beta / \Lambda_T^2$$

☺ $b \to c\ \tau\nu$ by V_{cb}=CKM$_{23}$ mixing

☺ $b \to s\ \mu\mu$ by $\lambda_{bs}^q = \lambda_{23}^{q,NP}$ & $\lambda_{22}^{\ell,NP}$ mixing

$$\bar{Q}_L^3 = \begin{pmatrix} (V_{CKM} u)^3 \\ b \end{pmatrix} + \lambda_{bs}^q \begin{pmatrix} (V_{CKM} u)^2 \\ s \end{pmatrix}$$

$$L_L^3 = \begin{pmatrix} \nu_L \\ \tau_L \end{pmatrix} + \sqrt{\lambda_{\mu\mu}^\ell} \begin{pmatrix} \nu_L \\ \mu_L \end{pmatrix}$$

$$\lambda_{bs}^q \lambda_{\mu\mu}^\ell \frac{\left(\bar{s}_L \gamma^\mu b_L\right) \bar{\mu}_L \gamma^\mu \mu_L}{\Lambda_T^2}$$

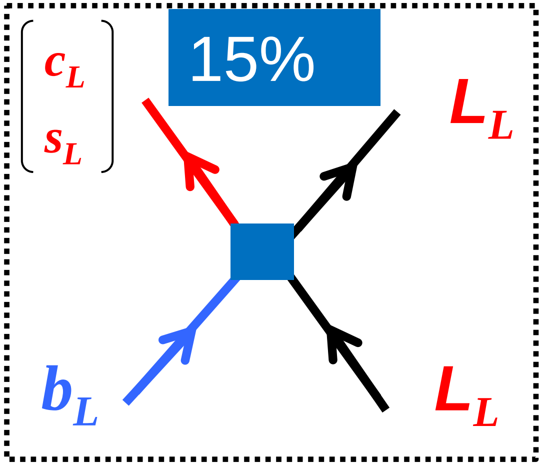
$$\Lambda_T = 0.7 \text{ TeV}$$

$$(\lambda_{bb}^q = \lambda_{\tau\tau}^q = 1)$$

$$\lambda_{bs}^q \lambda_{\mu\mu}^\ell \simeq -4 \times 10^{-4}$$

$$-3V_{cb} m_\mu^2 / m_\tau^2$$

EFT above EW



I. $SU(2)_L$ triplet elegant solution

$$\left(\overline{Q}_L^3 \gamma^\mu \tau^a Q_L^3\right) \overline{L}_L^\alpha \gamma^\mu \tau^a L_L^\beta \,/\, \Lambda_T^2$$

☺ $b \to c\ \tau\nu$ by V_{cb}=CKM$_{23}$ mixing

☺ $b \to s\ \mu\mu$ by $\lambda_{bs}^q = \lambda_{23}^{q,NP}$ & λ_{22} mixing

❑ **However,**

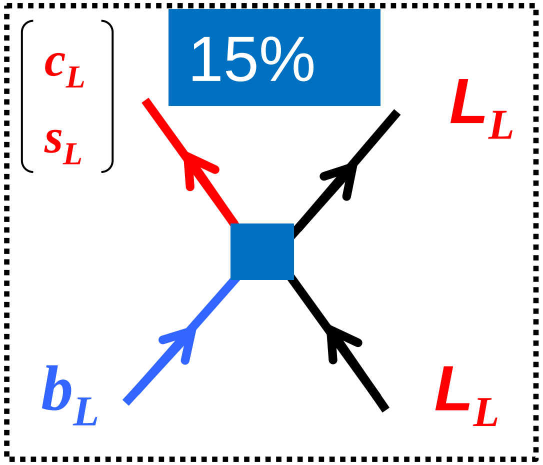
$\Lambda_T = 0.7$ TeV $pp \to \tau\tau$ $b \to s\nu\nu$

$$\left(\overline{Q}_L^3 \gamma^\mu \tau^a Q_L^3\right) \overline{L}_L^3 \gamma^\mu \tau^a L_L^3 = 2\left(V_{cb}\overline{c}_L \gamma^\mu b_L\right)\overline{\tau}_L \gamma^\mu \nu_L + \left(\overline{b}_L \gamma^\mu b_L\right)\overline{\tau}_L \gamma^\mu \tau_L - \left(\lambda_{bs}^q \overline{s}_L \gamma^\mu b_L\right)\nu_L \gamma^\mu \nu_L$$

$\Lambda_T \geq 0.6$ TeV $\lambda_{bs}^q \leq 0.01$

tensions with high p_T searches, $B \to K^* \nu\nu$, LEP constraints, LFV τ decays.

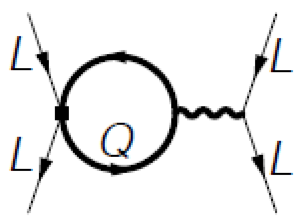
EFT above EW

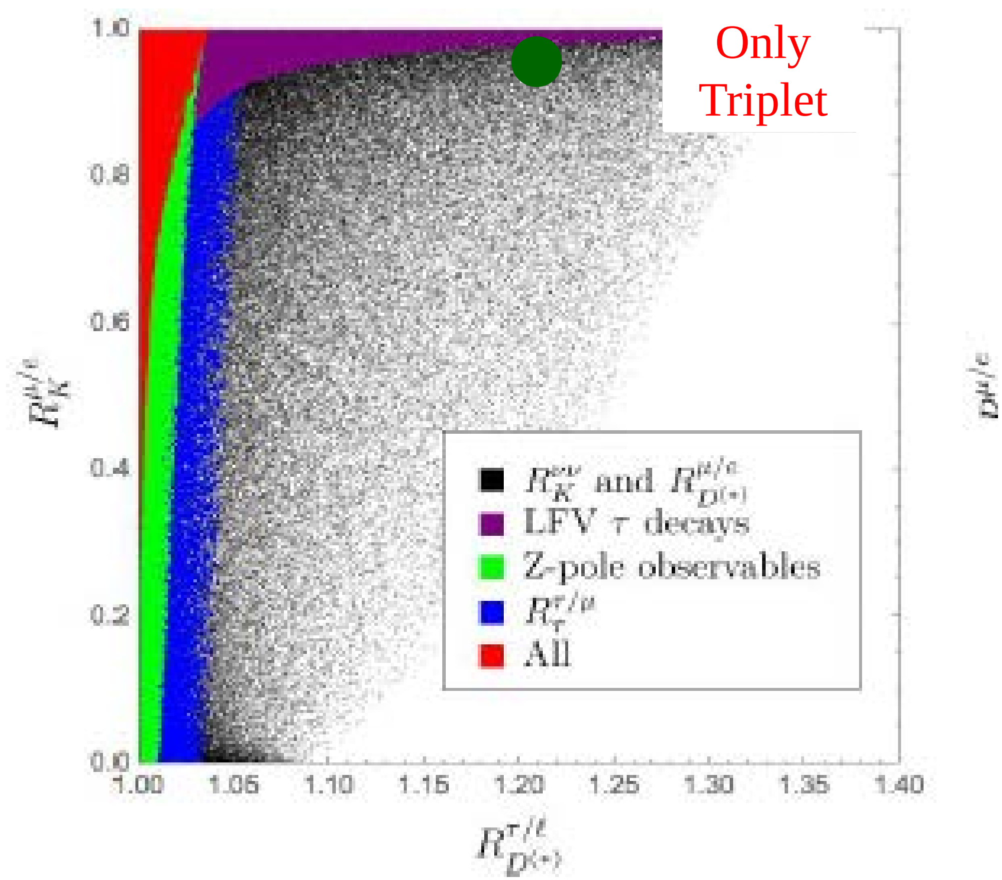


I. SU(2)$_L$ triplet elegant solution

$$\frac{\lambda^q_{ij}\lambda^\ell_{\alpha\beta}}{\Lambda_T^2}\left(\bar{Q}^i_L\gamma^\mu\tau^a Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu\tau^a L^\beta_L$$

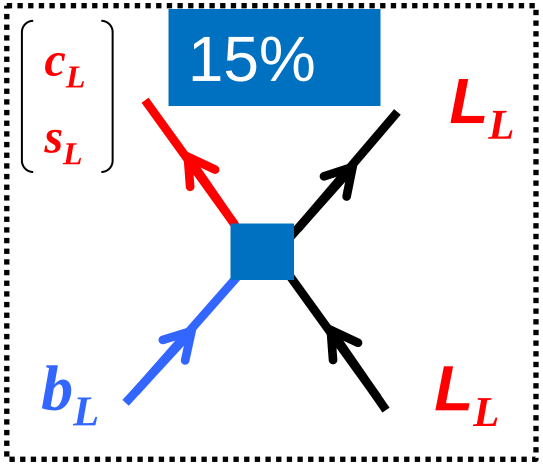
- *from LEP radiative constraints, LFV τ decays*





Feruglio, Paradisi and Pattori '17

EFT above EW



I. $SU(2)_L$ triplet elegant solution

$$\frac{\lambda^{q}_{ij}\lambda^{\ell}_{\alpha\beta}}{v^2} C_T \left(\bar{Q}^i_L \gamma^\mu \tau^a Q^j_L\right) \bar{L}^\alpha_L \gamma^\mu \tau^a L^\beta_L$$

☺ Triplet operator **mandatory** to explain $b \to c\ \tau\nu$

$$\left(\bar{Q}^2_L \gamma^\mu \tau^a Q^3_L\right) \bar{L}^3_L \gamma^\mu \tau^a L^3_L = 2\left(\bar{c}_L \gamma^\mu b_L\right) \bar{\tau}_L \gamma^\mu \nu_L$$

☺ However, $b \to s\ \mu\mu$ by SU(2) Triplet and Singlet

$$\left(\bar{Q}^2_L \gamma^\mu \tau^3 Q^3_L\right) \bar{L}^2_L \gamma^\mu \tau^3 L^2_L = \left(\bar{s}_L \gamma^\mu b_L\right) \bar{\mu}_L \gamma^\mu \mu_L$$

$$\left(\bar{Q}^2_L \gamma^\mu Q^3_L\right) \bar{L}^2_L \gamma^\mu L^2_L = \left(\bar{s}_L \gamma^\mu b_L\right) \bar{\mu}_L \gamma^\mu \mu_L$$

I. $SU(2)_L$ triplet

$$\frac{\lambda^q_{ij}\lambda^\ell_{\alpha\beta}}{v^2}\left(C_T\left(\bar{Q}^i_L\gamma^\mu\tau^a Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu\tau^a L^\beta_L\right)$$

$$C_T = v^2 / \Lambda_T^2$$

● (green)	$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})(1 - \lambda^\ell_{\mu\mu}/2)$
● (green)	$b \to s\mu\mu$	-0.61 ± 0.12	$-\frac{\pi}{\alpha_{em}V_{tb}V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}C_T$
● (red)	$B_{K^{(*)}\nu\bar{\nu}}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{em}V_{tb}V^*_{ts}C^{SM}_\nu}C_T\lambda^q_{sb}(1 + \lambda^\ell_{\mu\mu})$
● (red)	$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033C_T$
	$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033C_T$
	$\lvert g^W_\tau / g^W_\ell \rvert$	1.00097 ± 0.00098	$1 - 0.084C_T$
	$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})\lambda^\ell_{\mu\mu}$

Λ_T =0.7 TeV

⇒

$\lambda^q_{bs} \leq 0.01$

$C_T \leq 0.01$

$\Lambda_T \geq 2.5$ TeV

II. SU(2)$_L$ triplet + singlet

$$\frac{\lambda^q_{ij}\lambda^\ell_{\alpha\beta}}{v^2}\left(C_T\left(\bar{Q}^i_L\gamma^\mu\tau^a Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu\tau^a L^\beta_L + C_S\left(\bar{Q}^i_L\gamma^\mu Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu L^\beta_L\right)$$

$$C_T = v^2/\Lambda_T^2 \qquad C_S = v^2/\Lambda_S^2$$

● (green)	$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})(1 - \lambda^\ell_{\mu\mu}/2)$
● (green)	$b \to s\mu\mu$	-0.61 ± 0.12	$-\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}(C_T + C_S)$
● (red)	$B_{K^{(*)}\nu\bar{\nu}}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\rm em}V_{tb}V^*_{ts}C^{\rm SM}_\nu}(C_T - C_S)\lambda^q_{sb}(1 + \lambda^\ell_{\mu\mu})$
● (red)	$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033C_T - 0.043C_S$
	$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033C_T - 0.043C_S$
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	$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})\lambda^\ell_{\mu\mu}$

$\Rightarrow C_T \approx C_S$

II. $SU(2)_L$ triplet + singlet

$$\frac{\lambda^q_{ij}\lambda^\ell_{\alpha\beta}}{v^2}\left(C_T\left(\bar{Q}^i_L\gamma^\mu\tau^a Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu\tau^a L^\beta_L + C_S\left(\bar{Q}^i_L\gamma^\mu Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu L^\beta_L\right)$$

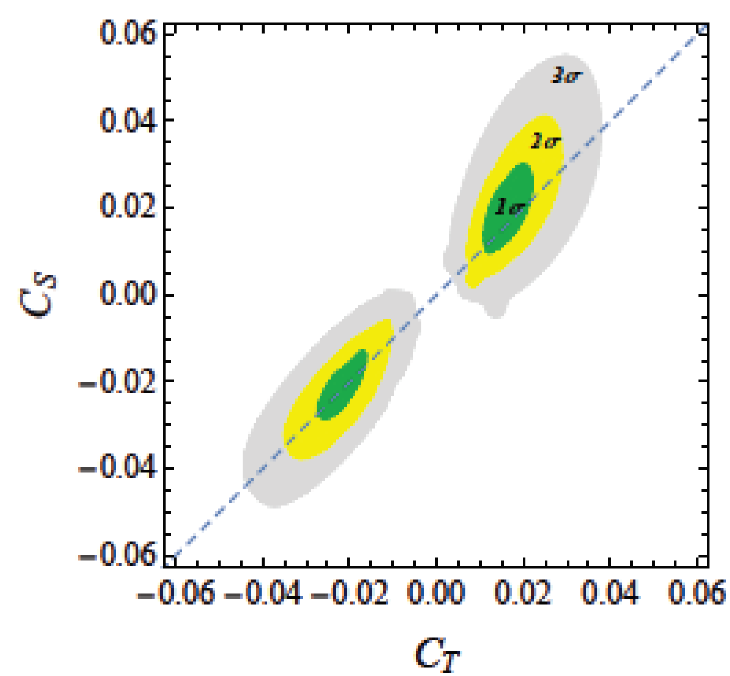
$$C_T = v^2/\Lambda_T^2 \qquad\qquad C_S = v^2/\Lambda_S^2$$

☺ Larger NP scale

$$\Lambda_T = 0.7\ \mathrm{TeV} \to \Lambda_T = 2\ \mathrm{TeV}$$

☺ from LEP constraints

$$\Lambda_T \approx \Lambda_S$$



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II. SU(2)$_L$ triplet + singlet

$$\frac{\lambda^q_{ij}\lambda^\ell_{\alpha\beta}}{v^2}\left(C_T\left(\bar{Q}^i_L\gamma^\mu\tau^a Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu\tau^a L^\beta_L + C_S\left(\bar{Q}^i_L\gamma^\mu Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu L^\beta_L\right)$$

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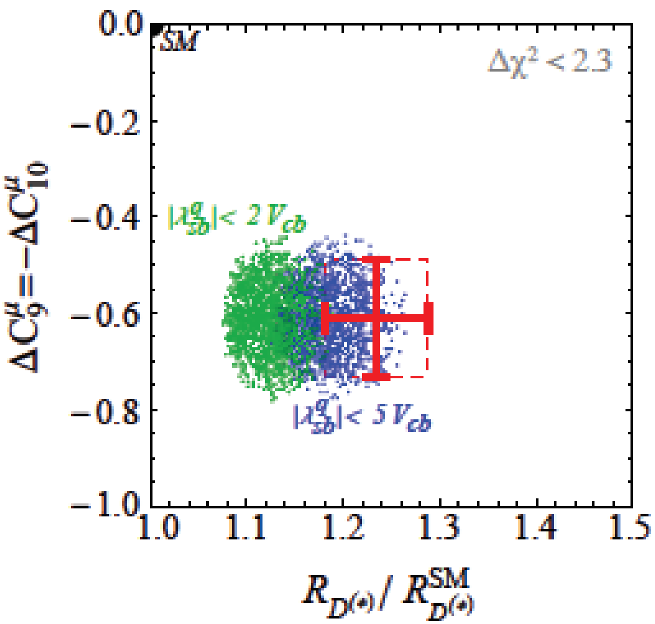
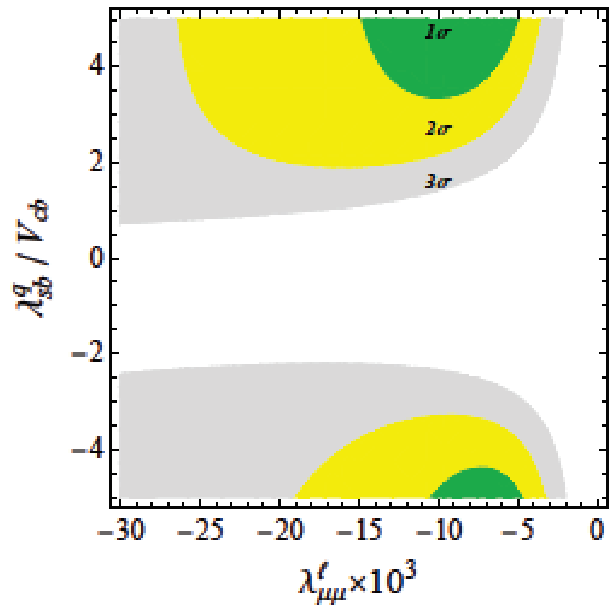
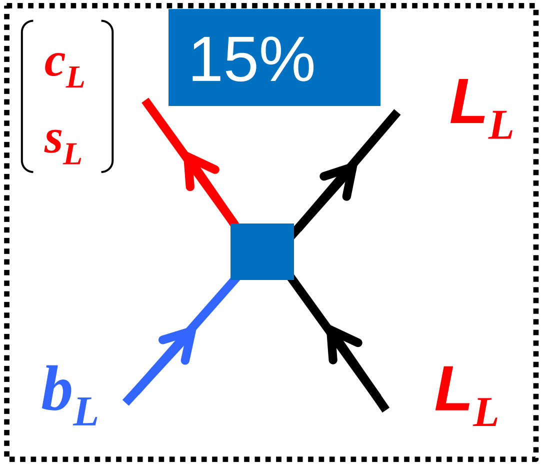




❖ *Small mixing between 3rd and 2nd families* of *Q, L*

EFT above EW



II. SU(2)$_L$ triplet + singlet

$$\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left(\frac{\left(\bar{Q}^i_L\gamma^\mu\tau^a Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu\tau^a L^\beta_L}{\Lambda_T^2}+\frac{\left(\bar{Q}^i_L\gamma^\mu Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu L^\beta_L}{\Lambda_S^2}\right)$$

$$\Lambda_T=\Lambda_S\approx 2\ \mathrm{TeV}$$

- *Large coupling to third Q, L families* to explain the tree-level enhancement of $b\to c\ \tau\nu$

$$\lambda^q_{bb}=\lambda^q_{\tau\tau}=1$$

- *Small mixing among 3rd and 2nd families* of Q, L to solve the loop-suppression of $b\to s\ \mu\mu$

$$\lambda^q_{bs}\simeq 4\times V_{cb}$$

$$\lambda^\ell_{\mu\mu}\simeq -m_\mu^2/m_\tau^2$$

$$(\lambda^q_{ds}\simeq V_{td})$$

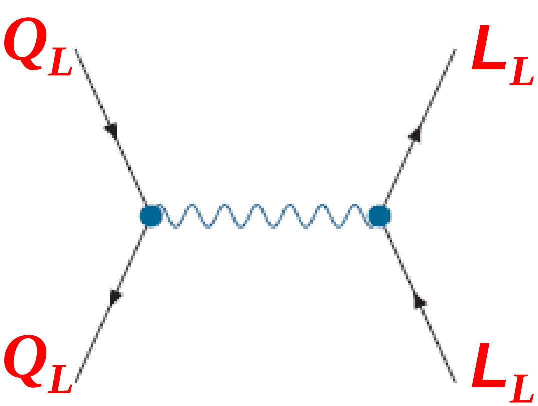
$$\lambda^q_{ij}\lambda^\ell_{\alpha\beta}=\delta_{ij}\delta_{\alpha\beta}+\text{small corrections for }2^{\text{nd}}\ (1^{\text{rt}})\text{ generations}$$

From EFT to UV models

II. $SU(2)_L$ triplet + singlet

$$\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left(\frac{\left(\bar{Q}^i_L\gamma^\mu\tau^a Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu\tau^a L^\beta_L}{\Lambda_T^2}+\frac{\left(\bar{Q}^i_L\gamma^\mu Q^j_L\right)\bar{L}^\alpha_L\gamma^\mu L^\beta_L}{\Lambda_S^2}\right)$$

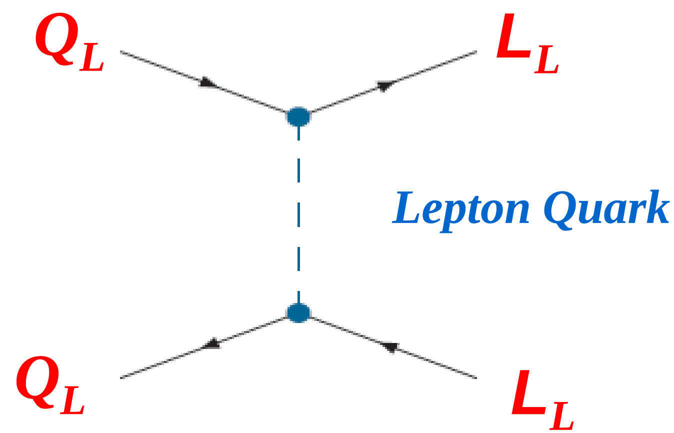
QQ current x *LL Current*



$W'_\mu \sim (1,3,0)$

$B'_\mu \sim (1,1,0)$

LQ current x *LQ Current*



$S_1 \sim (\bar{3},1,1/3)$

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

Scalar LQ

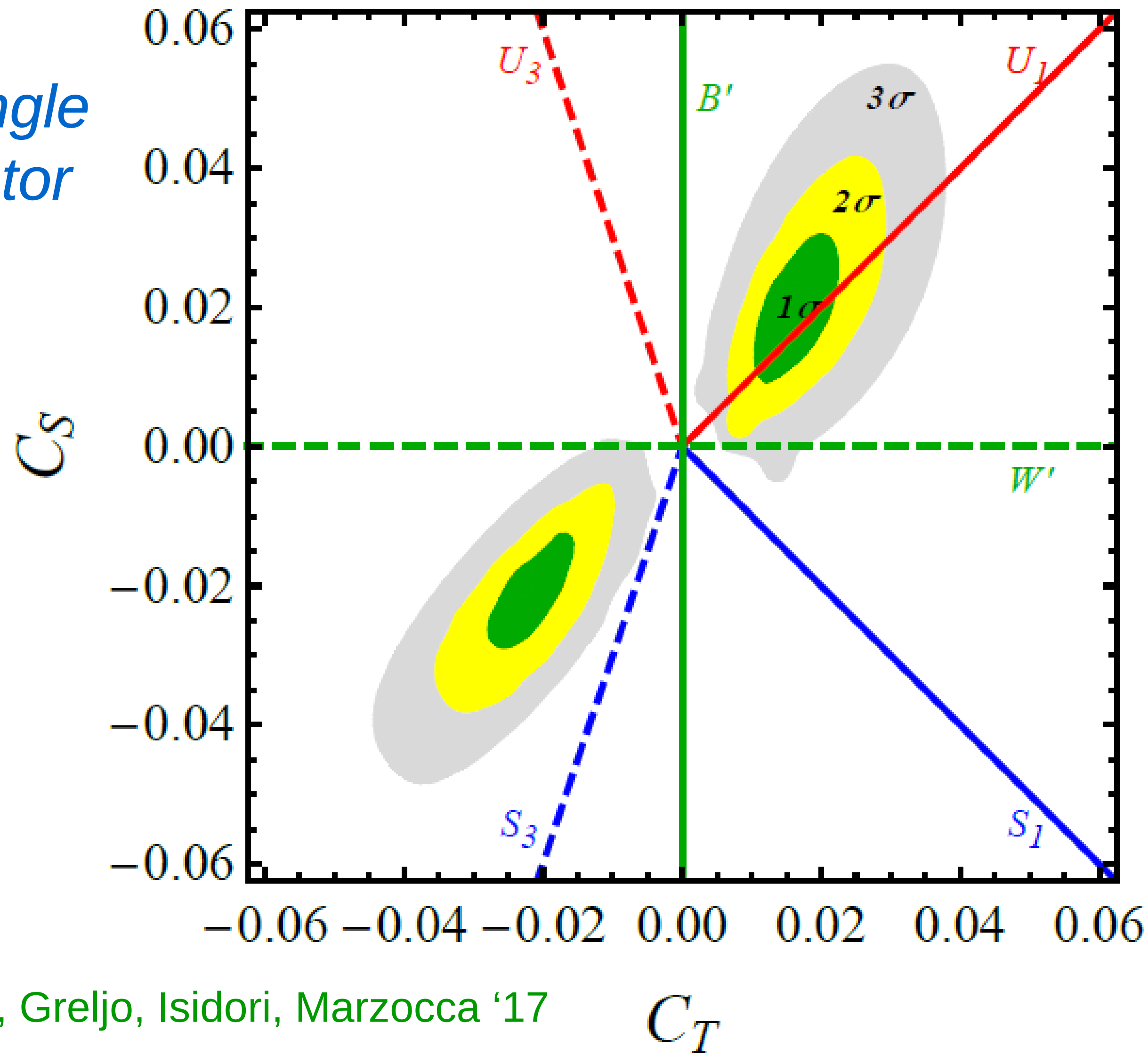
$U_1^\mu \sim (3,1,2/3)$

$U_3^\mu \sim (3,3,2/3)$

Vector LQ

From EFT to UV models

by a single mediator



$U_1^\mu \sim (3,1,2/3)$

Vector LQ

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From EFT to UV completion: $U_1^\mu \sim (3,1,2/3)$

Gauge leptoquark as the origin of B-physics anomalies

Luca Di Luzio,[1,*] Admir Greljo,[2,3,†] and Marco Nardecchia[4,‡]

The vector leptoquark representation, $U_\mu = (3,1,2/3)$, was recently identified as an exceptional single mediator model to address experimental hints on lepton flavour universality violation in semileptonic B-meson decays, both in neutral ($b \to s\mu\mu$) and charged ($b \to c\tau\nu$) current processes. Nonetheless, it is well-known that massive vectors crave an ultraviolet (UV) completion. We present the first full-fledged UV complete and calculable gauge model which incorporates this scenario while remaining in agreement with all other indirect flavour and electroweak precision measurements, as well as, direct searches at high-p_T. The model is based on a new non-abelian gauge group spontaneously broken at the TeV scale, and a specific flavour structure suppressing flavour violation in $\Delta F = 2$ processes while inducing sizeable semileptonic transitions.

$U_1^\mu \sim (3,1,2/3)$ from extended SU(4)xSU(3)xSU(2)xU(1) gauge group.

Flavour Anomalies: What Next?

❖ Many tensions at $< 3\,\sigma$: *Thanks GOD!*

❖ Intriguing correlation is emerging.

- LHCb: Electron / Muons efficiencies?

- Hadronic Uncertainties: no way!

Flavour Anomalies: What Next?

- Many tensions at $< 3\ \sigma$: *Thanks GOD!*

- Intriguing correlation is emerging.

  - LHCb: Electron / Muons efficiencies?

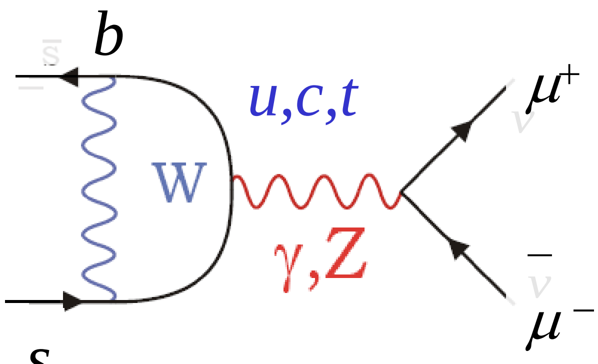
  - Hadronic Uncertainties: no way!

- New Physics?

- Large effects expected on many modes

$B_d \to K^{(*)}\tau^+\tau^-$	Belle II
$B_d \to K^{(*)}\bar{\nu}\nu$	
$K \to \pi\bar{\nu}\nu$	NA48
$B_s^0 \to \mu^+\mu^-$	**LHCb** ★ ⇨

b→s transitions: $B_s \to \mu\mu$



+ W box

$$CVC : q^{\mu}\bar{\ell}\gamma^{\mu}\ell = 0$$

1) No γ interactions: no $C_{9,7}$

2) Only *Z* interactions: C_{10}
m_c, m_u GIM suppressed

3) Only t,W,Z contributions

To large extent, pure local interaction:

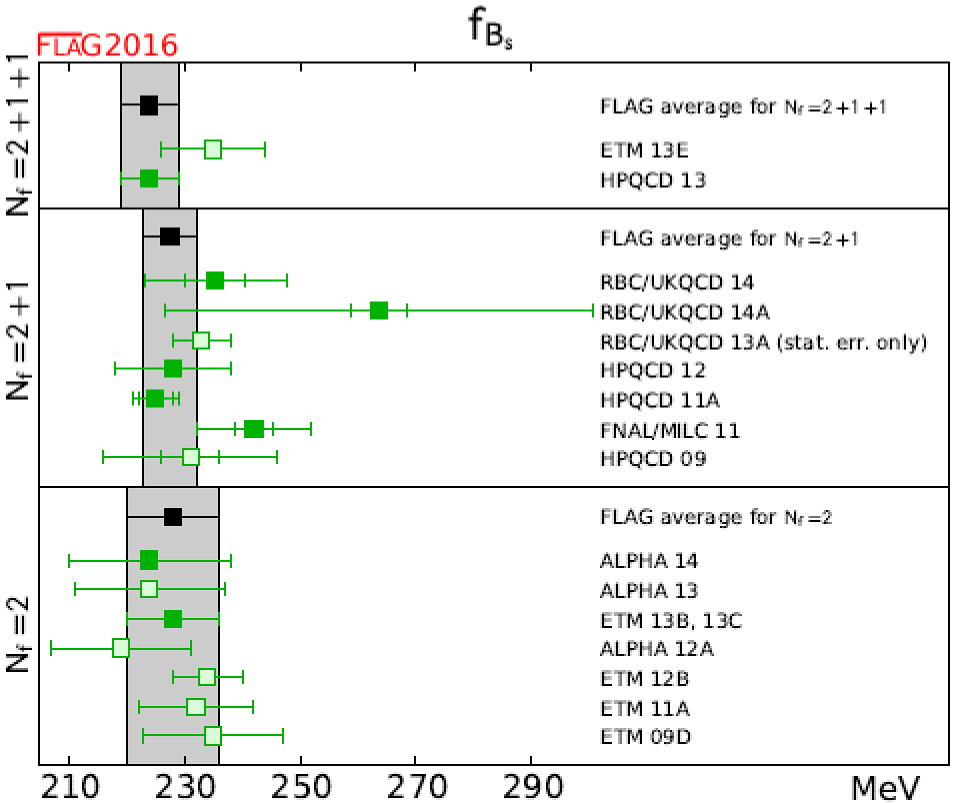
C_{10} *- short-distance couplings:*

$$\Gamma\left(B_s^0 \to \mu^+\mu^-\right) \sim \frac{G_F^2\alpha^2}{64\pi^3} m_{Bs}^2 f_{Bs}^2 \left|V_{tb}V_{ts}\right|^2 \left|2m_\mu C_{10}\right|^2$$

Only one hadronic parameter: *f_{Bs}*

$$\langle 0|\bar{b}\gamma^{\mu}\gamma_5 s|B_s^0\rangle = iq^{\mu} f_{Bs}$$

b→s transitions: $B_s \to \mu\mu$



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❖hadronic uncertainties under control

Lattice: ETMC, MILC, HPQCD

Practically a Miracle!

1) Continuum limit

2) different lattice approaches: NRQCD and Relativ. *b*

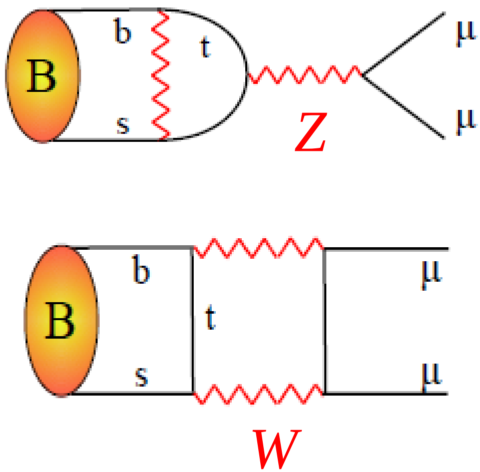
Only one hadronic parameter: f_{Bs}

$$\langle 0|\bar{b}\gamma^\mu\gamma_5 s|B_s^0\rangle = iq^\mu f_{Bs}$$

$$f_{Bs} = (228 \pm 4)\,\mathrm{MeV}$$

2% hadronic uncertainty

$b\to s$ transitions: $B_s\to\mu\mu$



$$\Gamma\left(B_s^0\to\mu^+\mu^-\right)\sim\frac{G_F^2\alpha^2}{64\pi^3}m_{Bs}^2 f_{Bs}^2\left|V_{tb}V_{ts}\right|^2\left|2m_\mu C_{10}\right|^2$$

$$O_{10}=\left(\bar{b}\gamma_L^\mu s\right)\bar{\ell}\gamma^\mu\gamma_5\ell$$

2% hadronic uncertainty

✓ $Br^{exp}(B_s\to\mu\mu)=(2.8\pm0.7)10^{-9}$ (25%)

➲ $Br^{SM}(B_s\to\mu\mu)=(3.65\pm0.23)10^{-9}$ (6%)

EXP 1.2 σ below SM

(small significance but ...)

C_{10} *: short-distance coupling – no charm loops.*

Flavour Anomalies: What Next?

- Many tensions at < 3 σ : *Thanks GOD!*
- Intriguing correlation is emerging.

- LHCb: Electron / Muons efficiencies?

- Hadronic Uncertainties: no way!

- New Physics?

- Still large NP potential from LHCb: improving

$$B_s^0 \to \mu^+ \mu^-$$

$$R_K, R_{K^*}$$

$$R_D \, ?$$

Flavour Anomalies: What Next?

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$B_s^0 \to \mu^+\mu^-$

R_K, R_{K^*}

R_D ?

P_i observables still important

	$\langle P_5' \rangle_{[4,6]}$
LHCb	-0.30 ± 0.16
SM	-0.82 ± 0.08

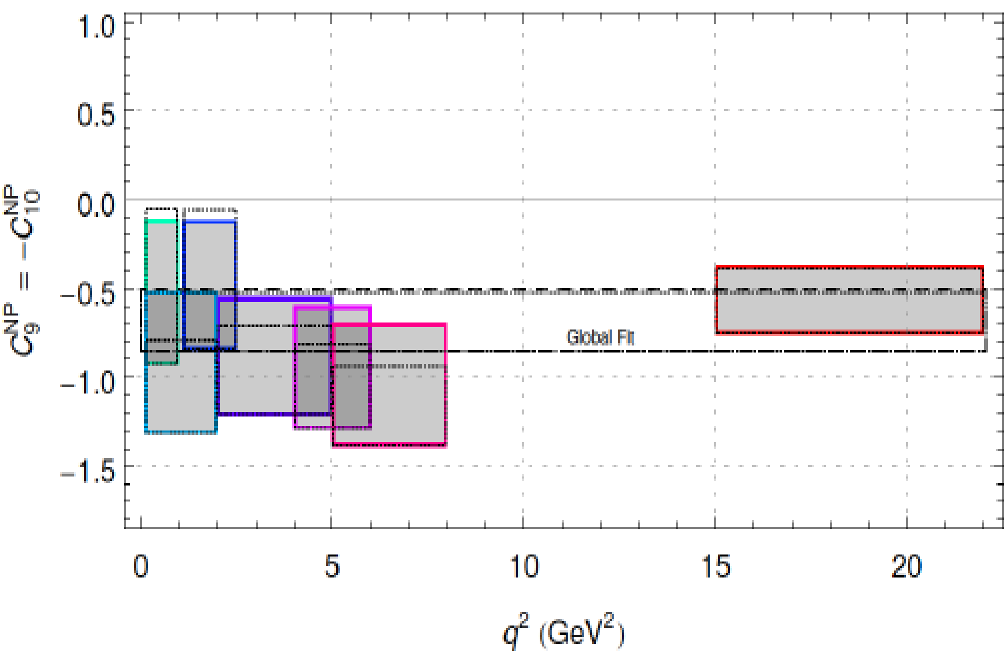
10%
Impossible to reduce
QCD uncertainties
from now on.

Flavour Anomalies: Conclusions

Thanks

B Anomalies: $B \to K^* (\to K\pi)\mu\mu$: P_5' *ang. obs*

☺ The P_5 *tension compatible to a fit by* a q^2-independent C_9 coefficient



No fact. effects induce q^2-dependence of C_9.

More precise data are needed to disentangle q^2-dependence of C_9

☹ Still plagued by non-factorizable power corrections:

$$C_9^{tot} = C_9^{SD} + C_9^{cc-fac}(q^2) + C_9^{ccNoF}(q^2)$$

Ciuchini et al. 2015