

A comprehensive study of vector LQ on the B-meson and Muon g-2 anomalies

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Based on arXiv:[2104.06656](https://arxiv.org/abs/2104.06656) [hep-ph]

Collaboration with
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조용수(CERN student fellow) ←



Dr. 첸포옌 (BK 연구교수) ←

반가영(NRF PhD fellow)





Experiment

Experiment

theory

theory

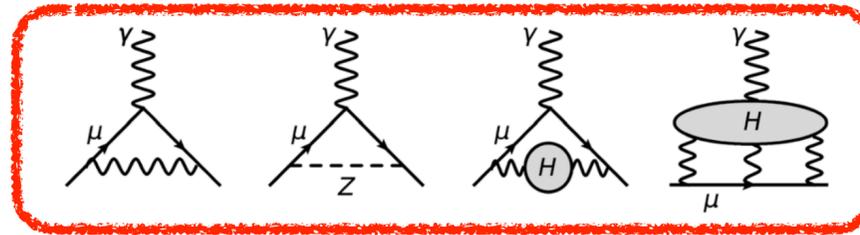
theory

Experiment

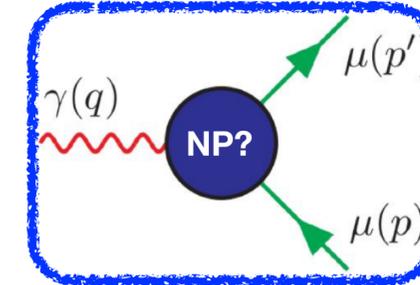
Experiment

Muon $g-2$ and New Physics

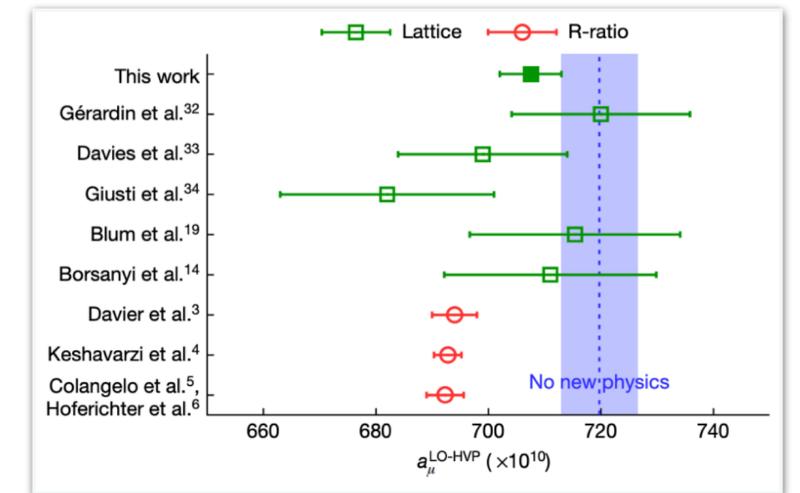
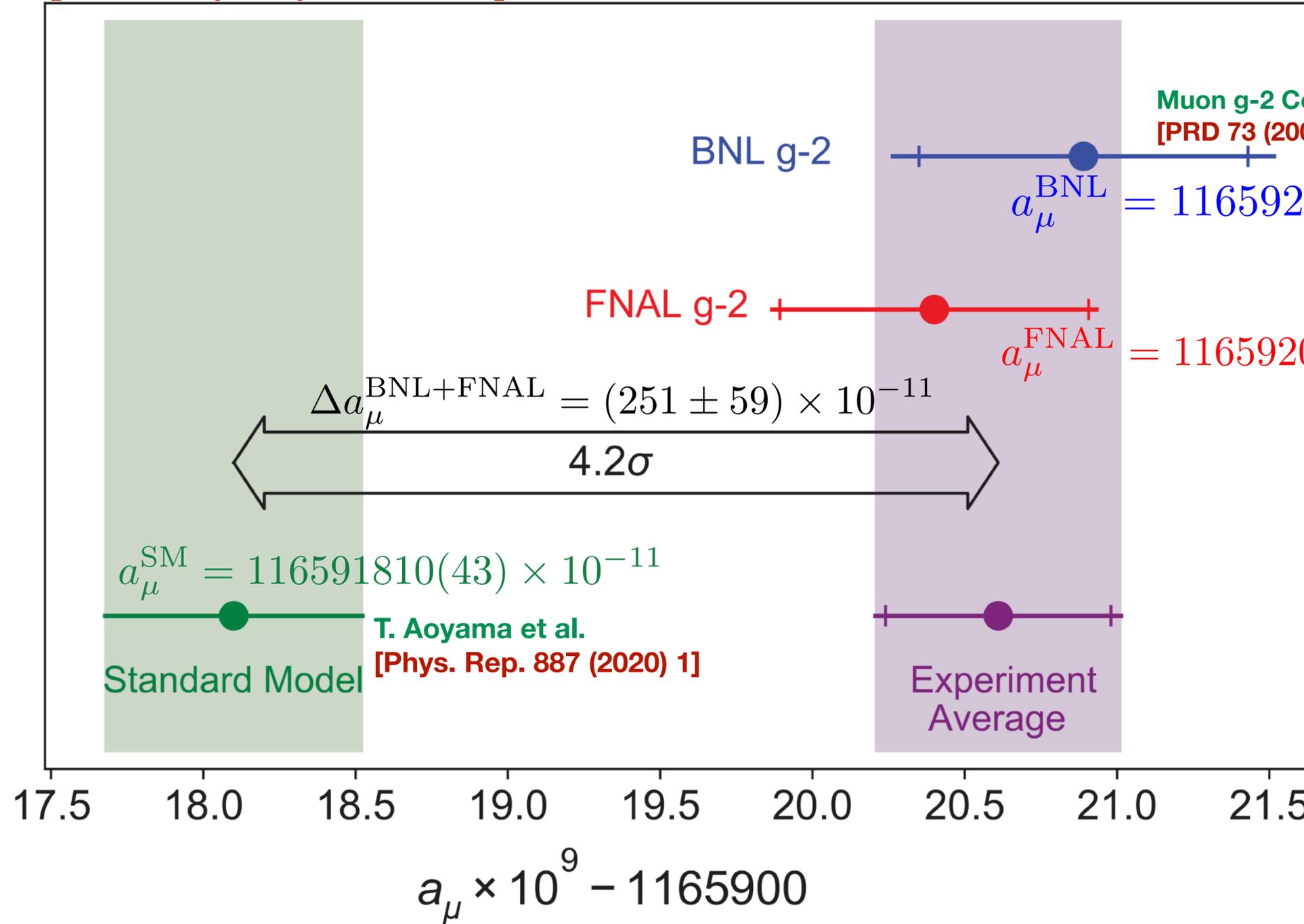
Muon $g-2$ Collaboration
 [PRL 126 (2021) 14, 141801]



SM

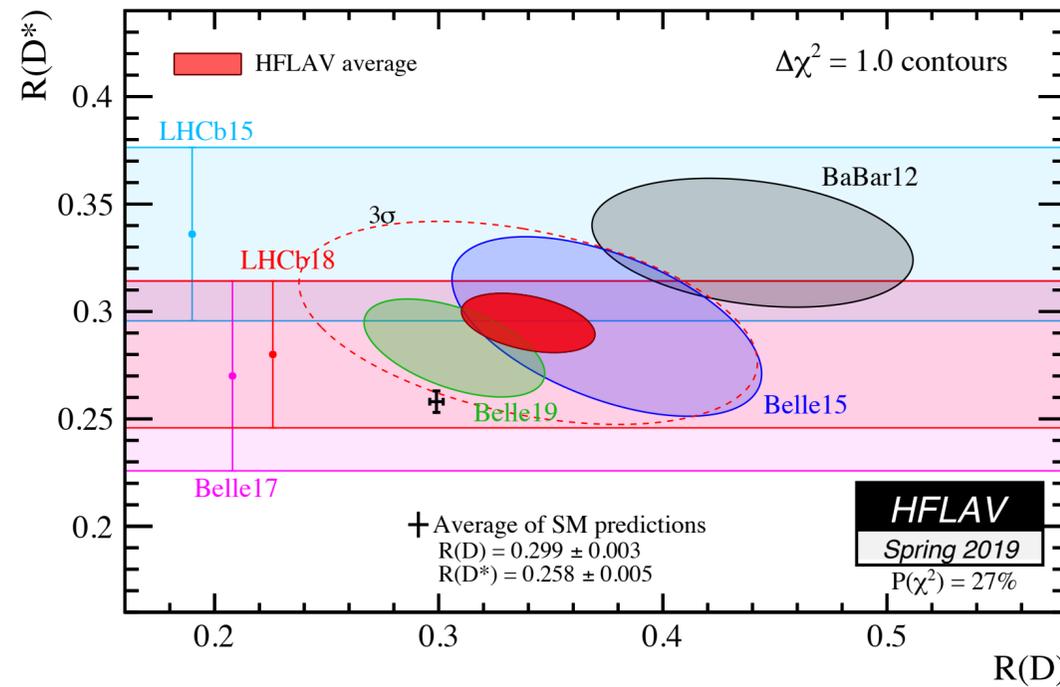


NP?



See however Sz. Borsanyi et al. *Nature* 593, 51–55 (2021)

Lepton universality tests in B-meson decays



$$R_{D^{(*)}} \equiv \frac{\text{Br}(B \rightarrow D^{(*)} \tau \bar{\nu}_\tau)}{\text{Br}(B \rightarrow D^{(*)} \ell \bar{\nu}_\ell)_{\ell=e,\mu}}$$

$$R_D = 0.340 \pm 0.027 \pm 0.013 \quad +1.4\sigma \text{ from SM}$$

$$R_{D^*} = 0.295 \pm 0.011 \pm 0.008 \quad +2.5\sigma \text{ from SM}$$

$$R_D/R_{D^*} \text{ combined} \quad +3.08\sigma \text{ from SM}$$

HFLAV Group
[EPJC 77 (2017) 895] [1612.07233 (hep-ph)]

BaBar Collaboration
[PRL 109 (2012) 101802]

Belle Collaboration
[PRD 92 (2015) 072014]

LHCb Collaboration
[PRL 115 (2015) 111803]

Belle Collaboration
[PRL 118 (2017) 211801]

LHCb Collaboration
[PRL 120 (2018) 171802]

Belle Collaboration
[PRL 124 (2020) 161803]

HFLAV average : <https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html>

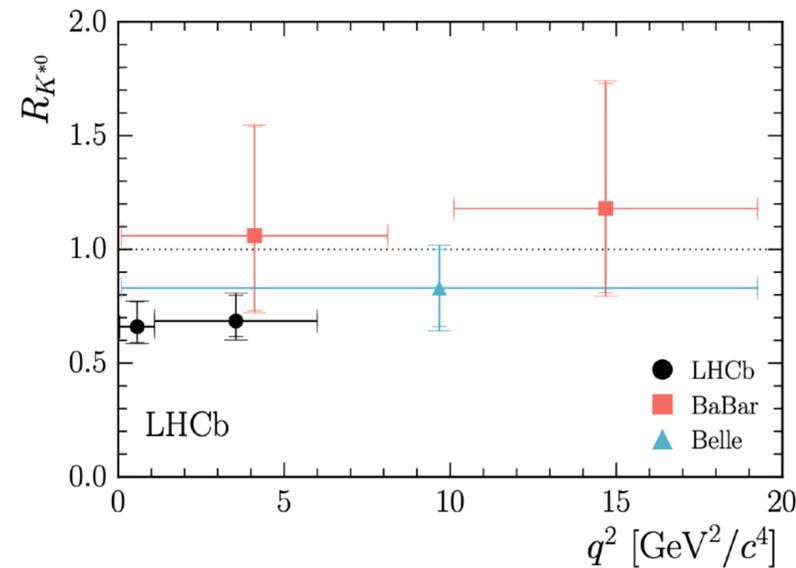
$$R_{K^{(*)}} \equiv \frac{\text{Br}(B \rightarrow K^{(*)} \mu^+ \mu^-)}{\text{Br}(B \rightarrow K^{(*)} e^+ e^-)}$$

R_{K^*}
LHCb Collaboration
[JHEP 08 (2017) 055]

R_K
BaBar Collaboration
[PRD 86 (2012) 032012]

Belle Collaboration
[JHEP 03 (2021) 105]

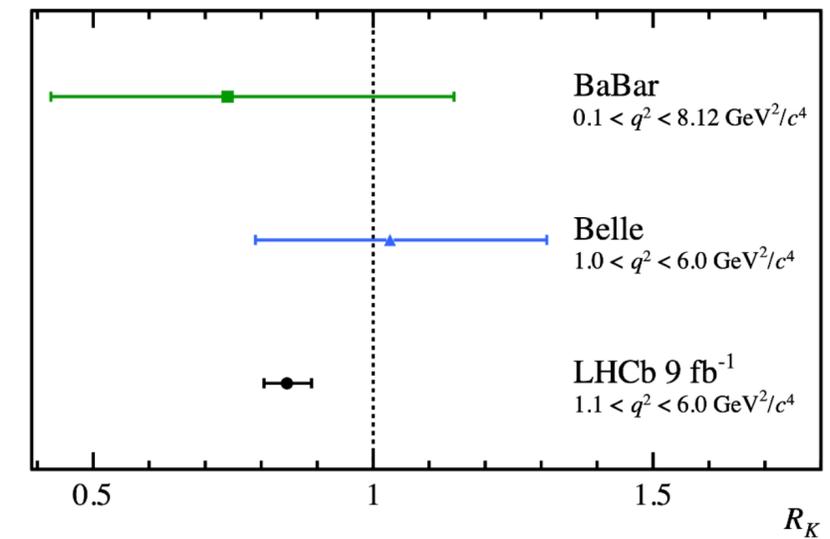
LHCb Collaboration
[2103.11769 (hep-ex)]



LHCb 2017, 7+8 TeV data set 3 fb⁻¹

$$R_{K^*}^{[0.045, 1.1]} = 0.66_{-0.07-0.03}^{+0.11+0.03} \quad (2.1-2.3)\sigma$$

$$R_{K^*}^{[1.1, 6.0]} = 0.69_{-0.07-0.05}^{+0.11+0.05} \quad (2.4-2.5)\sigma$$



LHCb 2021, Run 1+2 full data set 9 fb⁻¹

$$R_K^{[1.1, 6.0]} = 0.846_{-0.039-0.012}^{+0.042+0.013}$$

3.1σ from SM

LQ Scenarios

$$LQ \rightarrow q + \ell$$

1. Boson (s=0, 1) s=2: not impossible
2. Quantum numbers e.g.
 $Y = Y_q + Y_\ell = (\frac{1}{6}, \frac{2}{3}, -\frac{1}{3}) \oplus (-\frac{1}{2}, -1)$

All possible LQs couples to quark + lepton

W. Buchmüller, R. Rückl, and D. Wyler [PLB 191, 442 (1987)]

$$R_{D^{(*)}}^{\text{SM+LQ}} > R_{D^{(*)}}^{\text{SM}}$$

$$R_{K^{(*)}}^{\text{SM+LQ}} < R_{K^{(*)}}^{\text{SM}}$$

U_1 : isospin singlet
vector leptoquark

A. Angelescu et al.
[JHEP 10 (2018) 183]

Spin	$3B + L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Allowed coupling
0	-2	$\bar{3}$	1	1/3	$\bar{q}_L^c \ell_L$ or $\bar{u}_R^c e_R$
0	-2	$\bar{3}$	1	4/3	$\bar{d}_R^c e_R$
0	-2	$\bar{3}$	3	1/3	$\bar{q}_L^c \ell_L$
1	-2	$\bar{3}$	2	5/6	$\bar{q}_L^c \gamma^\mu e_R$ or $\bar{d}_R^c \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	-1/6	$\bar{u}_R^c \gamma^\mu \ell_L$
0	0	3	2	7/6	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	1/6	$\bar{d}_R \ell_L$
1	0	3	1	2/3	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	5/3	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	2/3	$\bar{q}_L \gamma^\mu \ell_L$

[From PDG LQ review]

$$\mathcal{L} \supset \underbrace{-\frac{1}{2} U_{1\mu\nu}^\dagger U_1^{\mu\nu}}_{\supset \text{QCD\&EM interactions}} + U_{1\mu} \underbrace{\sum_{i,j=1,2,3} \left[x_L^{ij} (\bar{d}_L^i \gamma^\mu e_L^j + (V_{\text{CKM}}^\dagger x_L U_{PMNS})_{ij} (\bar{u}_L^i \gamma^\mu \nu_L^j) + x_R^{ij} (\bar{d}_R^i \gamma^\mu e_R^j) \right]}_{\text{(effective) LQ interactions}} + \text{h.c.}$$

$$U_{1\mu\nu} = D_\mu U_{1\nu} - D_\nu U_{1\mu}$$

$$D_\mu \equiv \partial_\mu - ig_s G_\mu^a T^a - i\frac{2}{3} g_Y B_\mu$$

LQ Scenarios

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0	-2	$\bar{3}$	1	4/3	$\bar{d}_R^c e_R$
0	-2	$\bar{3}$	3	1/3	$\bar{q}_L^c \ell_L$
1	-2	$\bar{3}$	2	5/6	$\bar{q}_L^c \gamma^\mu e_R$ or $\bar{d}_R^c \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	-	large μ - t -LQ coupling
0	0	3	2	7/6	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	1/6	$\bar{d}_R \ell_L$
1	0	3	1	2/3	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	5/3	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	2/3	$\bar{q}_L \gamma^\mu \ell_L$

If one does focus on a simultaneous explanation of RK(*) / RD(*) anomalies only with a single LQ, other choices cannot make correct contributions for RK(*) & RD(*), or excluded by other rare decay processes, such as

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}} \& R_{D^{(*)}}$
S_1	\times^*	\checkmark	\times^*
R_2	\times^*	\checkmark	\times
\tilde{R}_2	\times	\times	\times
S_3	\checkmark	\times	\times
U_1	\checkmark	\checkmark	\checkmark
U_3	\checkmark	\times	\times

$\text{Br}(\tau \rightarrow \mu \gamma)$

$\text{Br}(B \rightarrow K \nu \bar{\nu})$ and so on.

A. Angelescu et al.
[JHEP 10 (2018) 183]

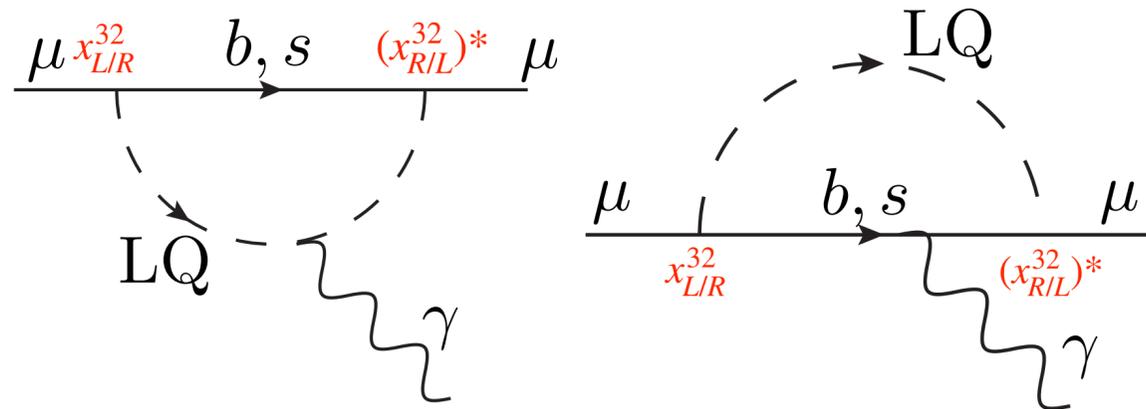
$$\mathcal{L} \supset \underbrace{-\frac{1}{2} U_{1\mu\nu}^\dagger U_1^{\mu\nu}}_{\supset \text{QCD\&EM interactions}} + U_{1\mu} \sum_{i,j=1,2,3} \underbrace{\left[x_L^{ij} (\bar{d}_L^i \gamma^\mu e_L^j + (V_{\text{CKM}}^\dagger x_L U_{PMNS})_{ij} (\bar{u}_L^i \gamma^\mu \nu_L^j) + x_R^{ij} (\bar{d}_R^i \gamma^\mu e_R^j) \right]}_{\text{(effective) LQ interactions}} + \text{h.c.}$$

$$U_{1\mu\nu} = D_\mu U_{1\nu} - D_\nu U_{1\mu}$$

$$D_\mu \equiv \partial_\mu - i g_s G_\mu^a T^a - i \frac{2}{3} g_Y B_\mu$$

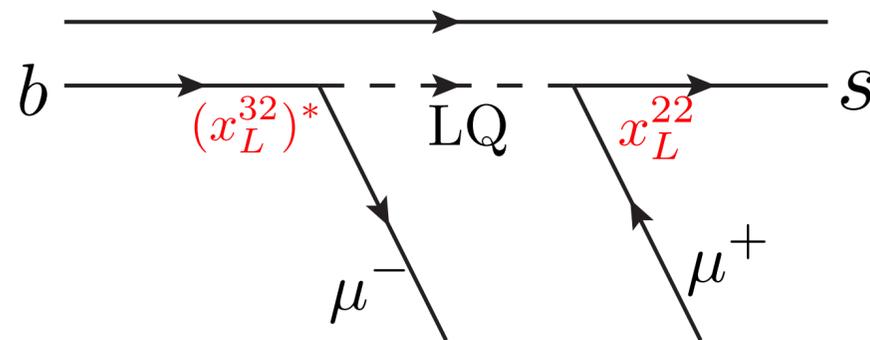
LQ Scenario

Possible contributions to Low-E anomalies from Leptoquark



$$\frac{1}{\Lambda_1} (\bar{\mu}_L \sigma^{\mu\nu} \mu_R) F_{\mu\nu} \quad (g-2)_\mu$$

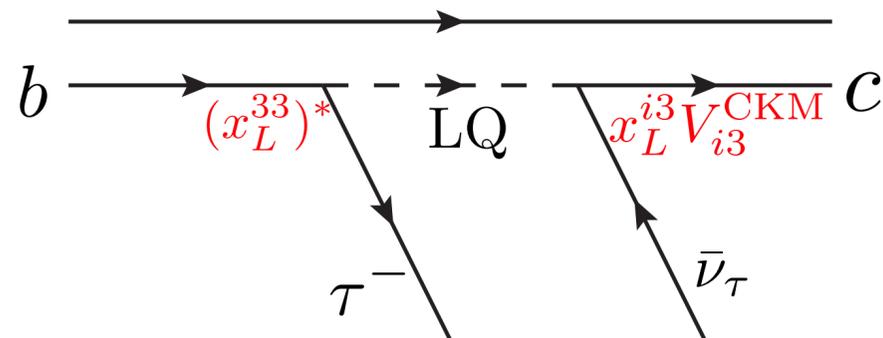
$$\Delta a_\mu \sim \frac{N_c}{16\pi^2} \cdot 4\text{Re}(x_L^{32} (x_R^{32})^*) \frac{m_b m_\mu}{m_{LQ}^2} (2Q_b - 2Q_{LQ})$$



$$\frac{1}{\Lambda_2^2} (\bar{s} \gamma_\mu P_L b) (\bar{\mu} \gamma^\mu \mu) \quad R_{K^{(*)}}$$

$$\text{Br}(B_s \rightarrow \mu\mu)$$

$$-\frac{x_L^{22} (x_L^{32})^*}{m_{LQ}^2} \subset [0.83, 1.41] \times 10^{-3} \text{ TeV}^{-2}$$

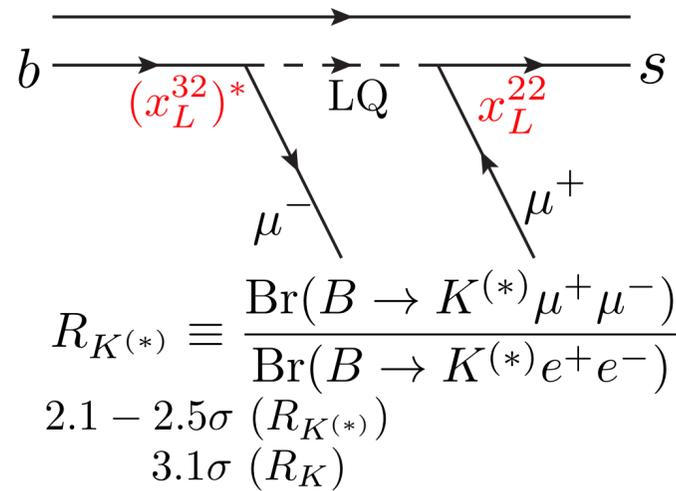


$$\frac{1}{\Lambda_3^2} (\bar{c} \gamma_\mu P_L b) (\bar{\tau} \gamma^\mu P_L \nu_\tau) \quad R_{D^{(*)}}$$

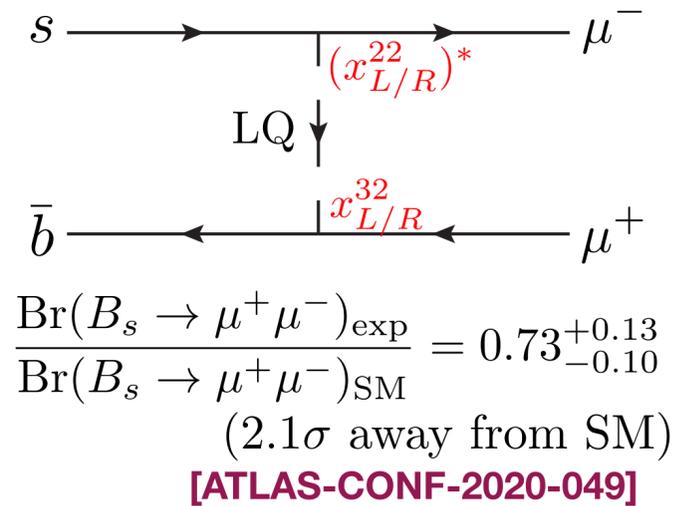
$$\frac{(V_{cs}^{\text{CKM}} x_L^{23} + V_{cb}^{\text{CKM}} x_L^{33}) (x_L^{33})^*}{m_{LQ}^2} \subset [0.12, 0.18] \text{ TeV}^{-2}$$

Ballpark & Constraints

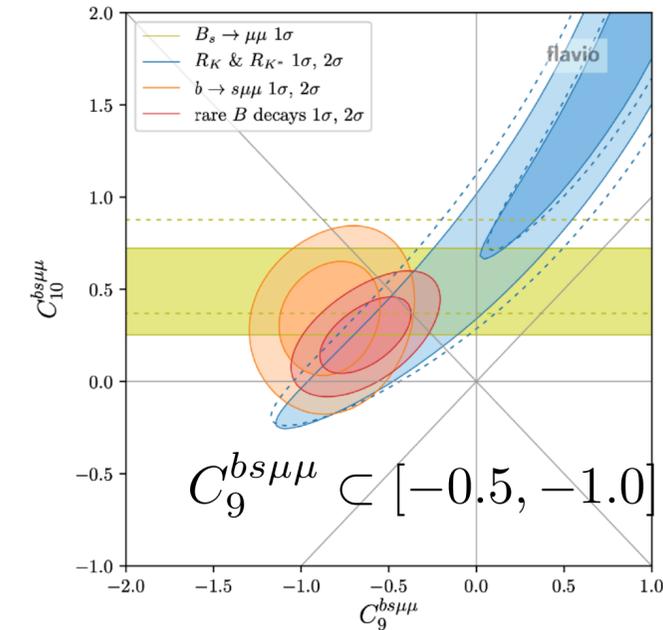
Ballpark for Anomalies(?)



+



W. Altmannshofer, P. Stangl [2103.13370]

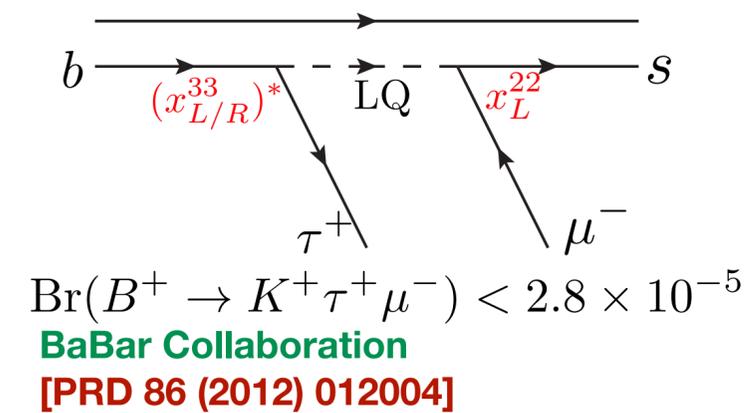
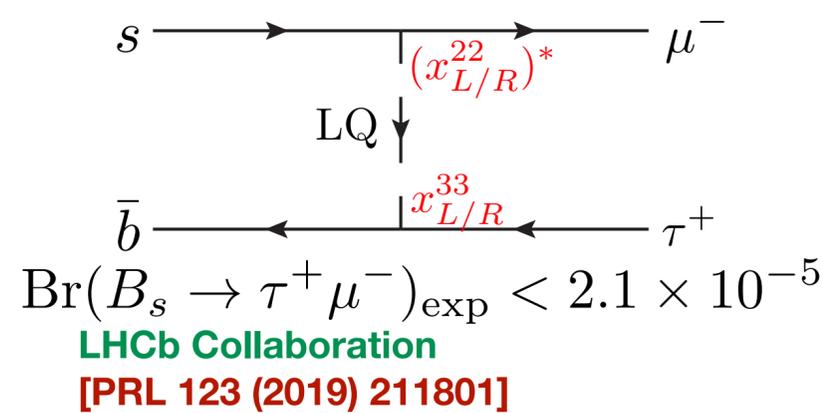
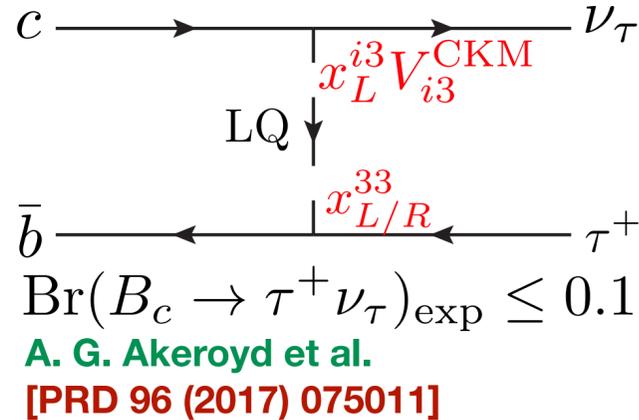


$$\mathcal{O}_9^{\ell_1 \ell_2} = \frac{e^2}{(4\pi)^2} (\bar{s} \gamma_\mu P_L b) (\bar{\ell}_1 \gamma^\mu \ell_2),$$

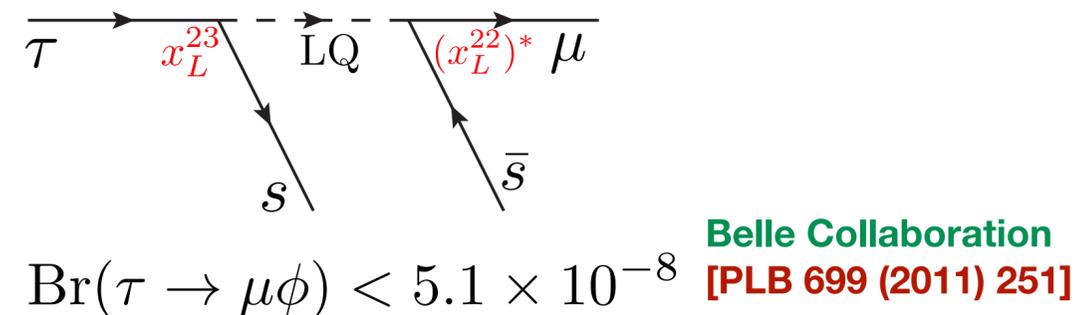
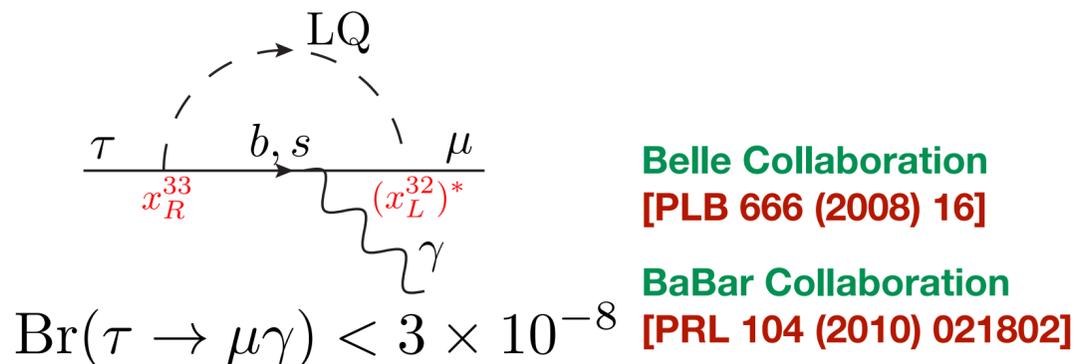
$$\mathcal{O}_{10}^{\ell_1 \ell_2} = \frac{e^2}{(4\pi)^2} (\bar{s} \gamma_\mu P_L b) (\bar{\ell}_1 \gamma^\mu \gamma^5 \ell_2),$$

(depends on scenarios / Wilson coefficients)

Upper limits from LFV in B-meson decays



Upper limits from LFV in tau decays

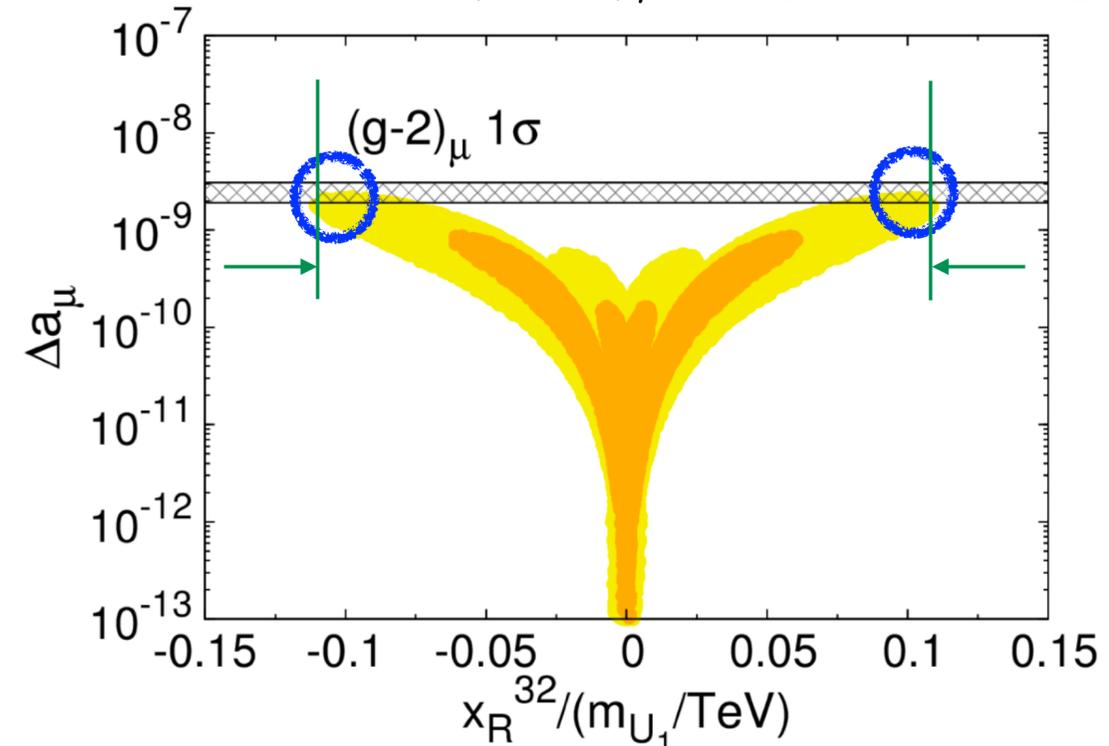
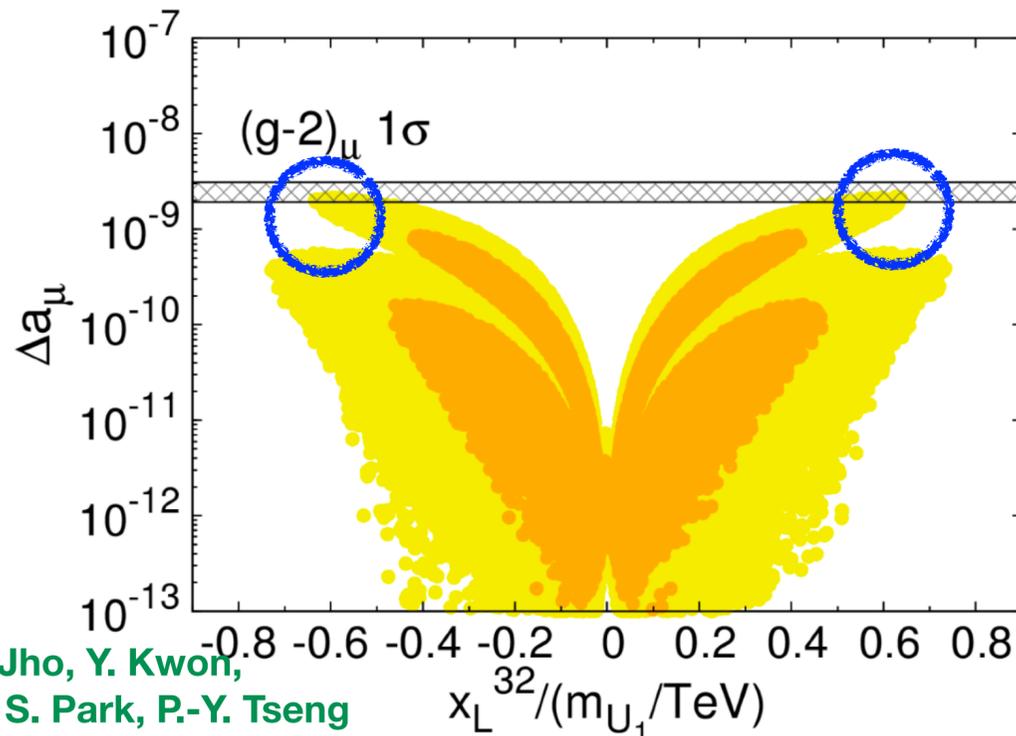


Result & best-fit parameters

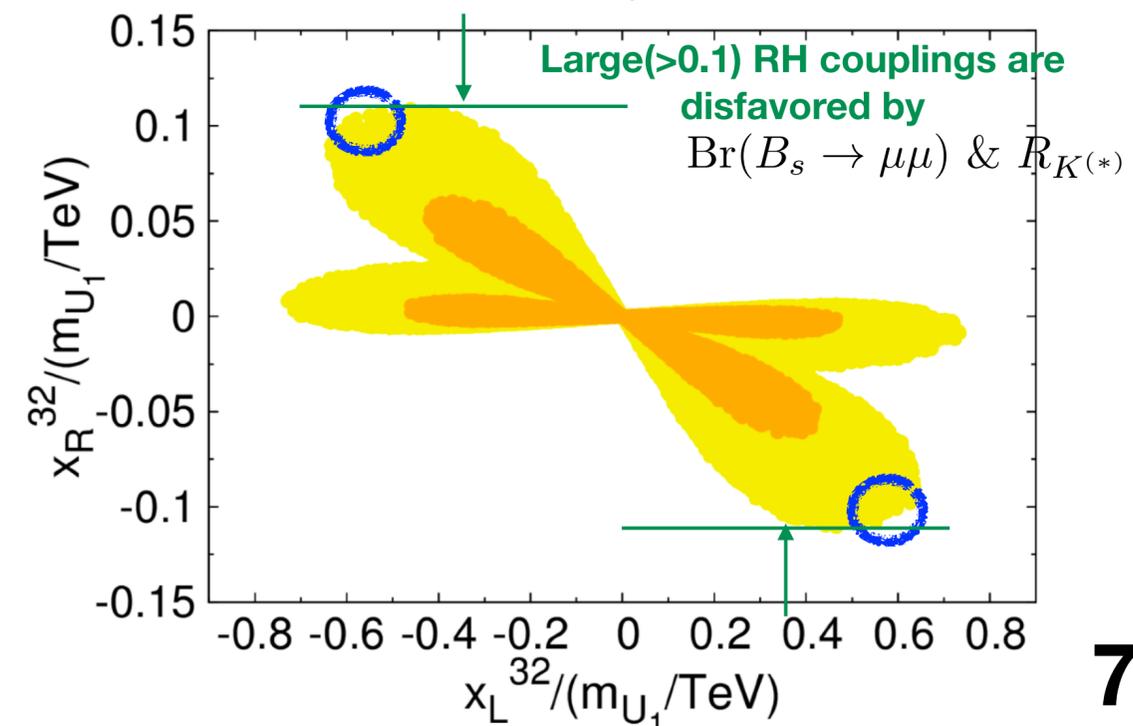
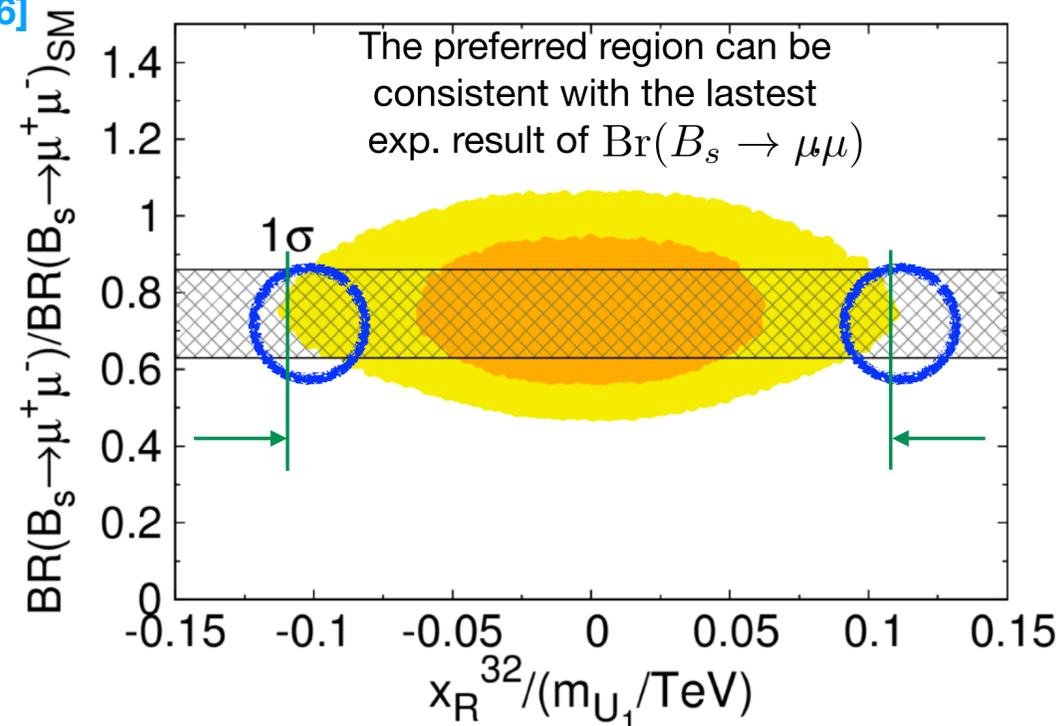
(For $m_{LQ} = 2$ TeV)

- $\Delta\chi \leq 5.99$
- $\Delta\chi \leq 2.30$

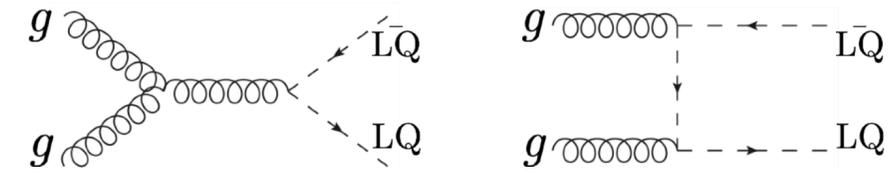
$x_L^{32} \simeq \pm 1.2$, $x_R^{32} \simeq \mp 0.18$ provides a simultaneous explanation for $(g-2)_\mu$, $R_{K^{(*)}}$, and $R_{D^{(*)}}$



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[2104.06656]

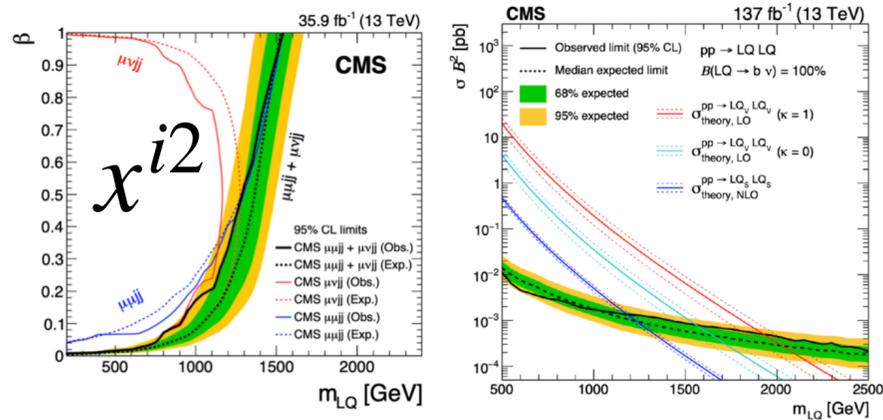


Searches for LQ at the LHC

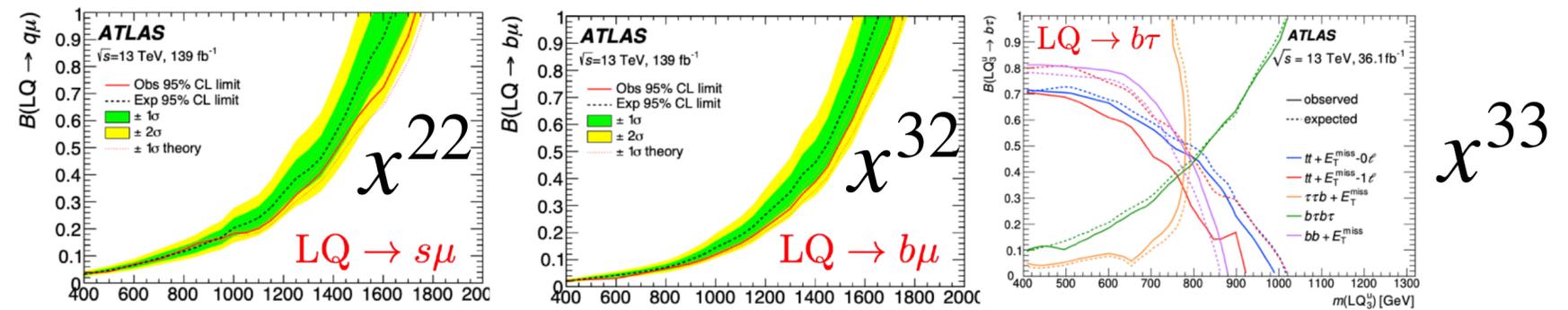


- LQ can be pair-produced with a large cross section. (QCD process)

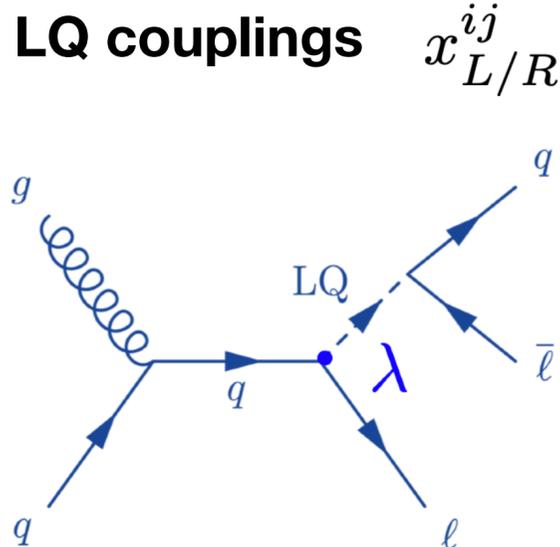
[PRD 99 (2019) 032014 (CMS Collab.)]



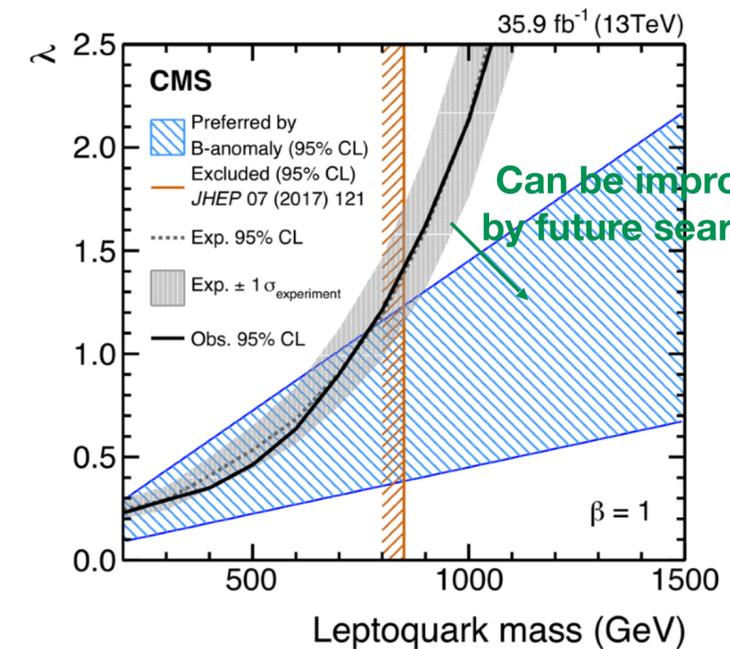
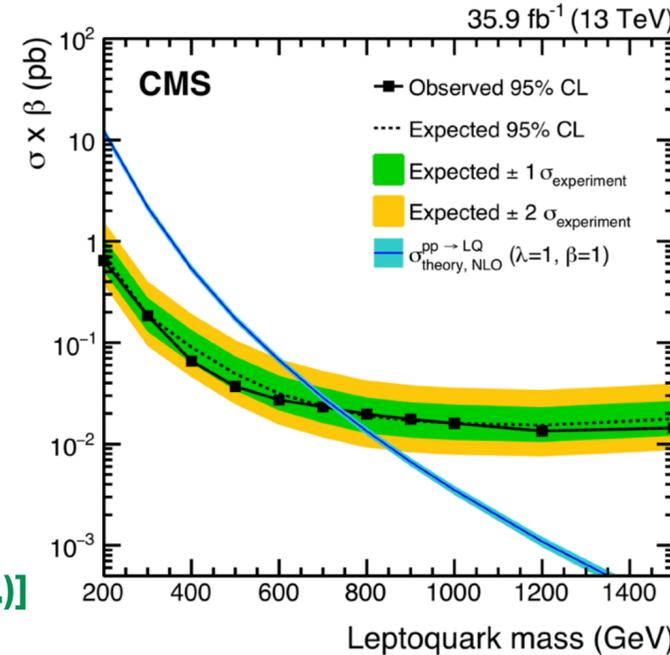
[JHEP 10 (2020) 112 (ATLAS Collab.)]



- For Single LQ production, current/future LHC searches can be sensitive to LQ couplings $x_{L/R}^{ij}$



[JHEP 07 (2018) 115 (CMS Collab.)]



Can be improved by future searches

Future prospects (B-factory)

- **With the target integrated luminosity, Belle II experiment will test Leptoquark scenario with $\sim\mathcal{O}(3-4)\%$ uncertainties in $R_{K^{(*)}}$ measurement.**

Observables	Belle 0.71 ab ⁻¹	Belle II 5 ab ⁻¹	Belle II 50 ab ⁻¹	Belle II Collaboration PTEP 2019 (2019) 12, 123C01
R_K ([1.0, 6.0] GeV ²)	28%	11%	3.6%	
R_K (> 14.4 GeV ²)	30%	12%	3.6%	
R_{K^*} ([1.0, 6.0] GeV ²)	26%	10%	3.2%	
R_{K^*} (> 14.4 GeV ²)	24%	9.2%	2.8%	
R_{X_s} ([1.0, 6.0] GeV ²)	32%	12%	4.0%	
R_{X_s} (> 14.4 GeV ²)	28%	11%	3.4%	

- **Observation of tau-involved rare processes**

$$B^+ \rightarrow K^+ \tau^+ \tau^-, B^0 \rightarrow K^0 \tau^+ \tau^-, B^+ \rightarrow K^{*+} \tau^+ \tau^-, B^0 \rightarrow K^{*0} \tau^+ \tau^-$$

- ▶ SM expectations: $\mathcal{O}(10^{-7})$
- ▶ Cannot be observed with 50 ab⁻¹
- ▶ UL prospects: $\mathcal{O}(10^{-6}-10^{-5})$

- **LFV process in B and tau decays at Belle II**

$$B^+ \rightarrow K^+ \ell^+ \ell'^- \quad \tau \rightarrow \mu \gamma$$

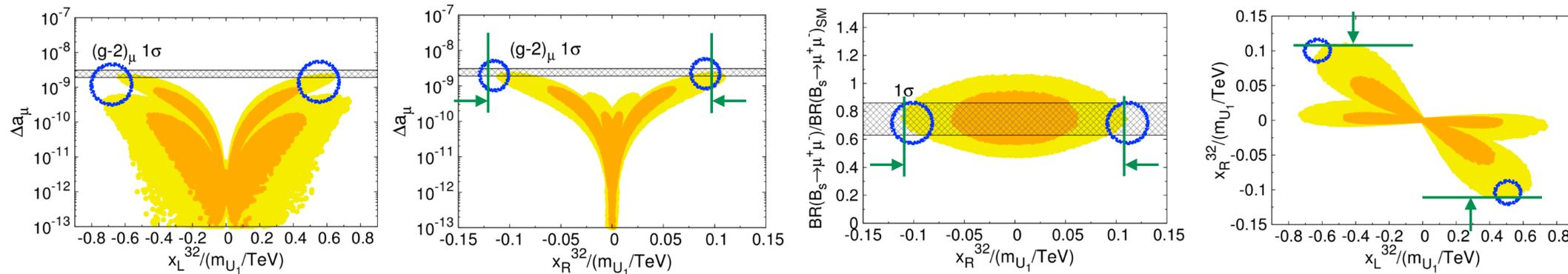
$$B_{(s)}^0 \rightarrow \mu^\pm \tau^\mp \quad \tau \rightarrow \mu \phi$$

Summary

- We focus on the single vector LQ scenario in this study, and found that, by enhancing RH coupling to LQ, it can have parameter space for a simultaneous explanation of

$$(g-2)_\mu \quad R_{K^{(*)}} \quad R_{D^{(*)}}$$

and all current constraints are consistent with preferred parameters. Future LHC/B-factory experiment can help to test this scenario in near future.



$x_L^{32} \simeq \pm 1.2$, $x_R^{32} \simeq \mp 0.18$ provides a simultaneous explanation for $(g-2)_\mu$, $R_{K^{(*)}}$, and $R_{D^{(*)}}$