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

S.C.Park

Based on arXiv:2104.06656 [hep-ph]

Collaboration with
Kayoung Ban (Yonsei U.), **Yongsoo Jho** (Yonsei U.),
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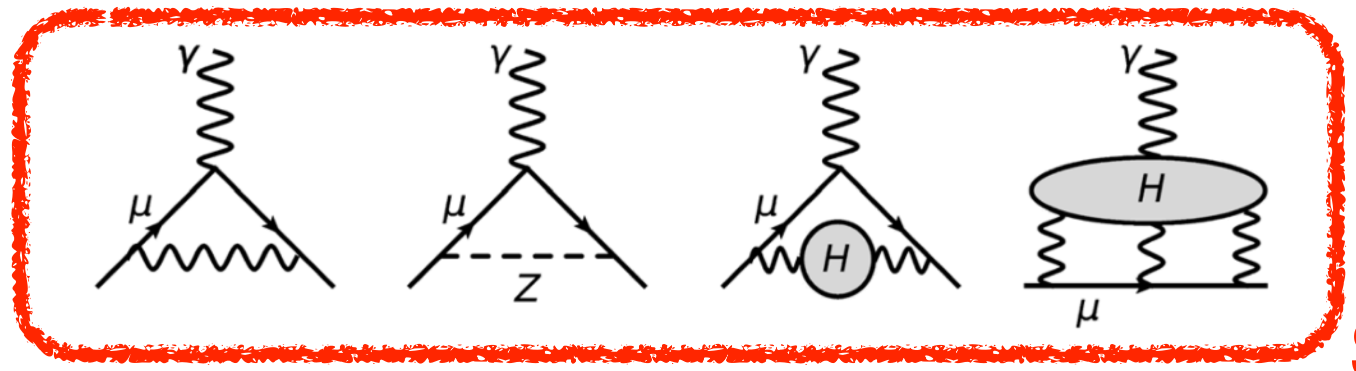
Seokhee Park (KEK) and **Po-Yan Tseng** (Yonsei U.)

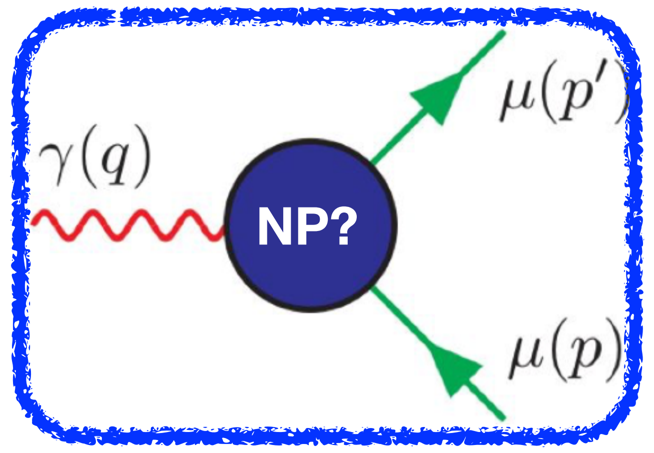
★= me

IDT-WG3-Phys Kickoff Meeting & Mini-Symposium on Muon g-2
Thursday 27 May 2021, 15:00 → 17:15 Europe/Zurich

Muon g-2 and New Physics

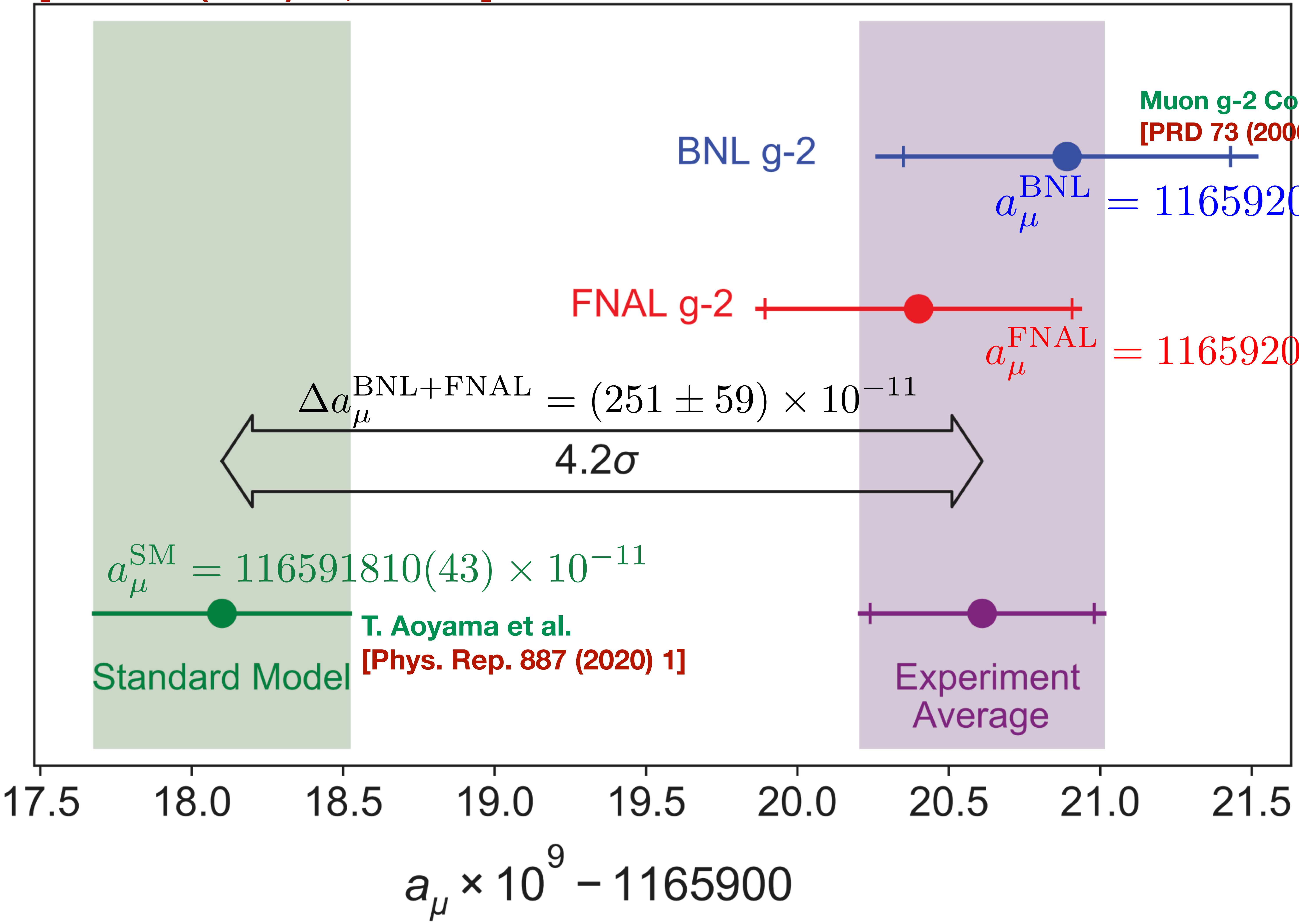


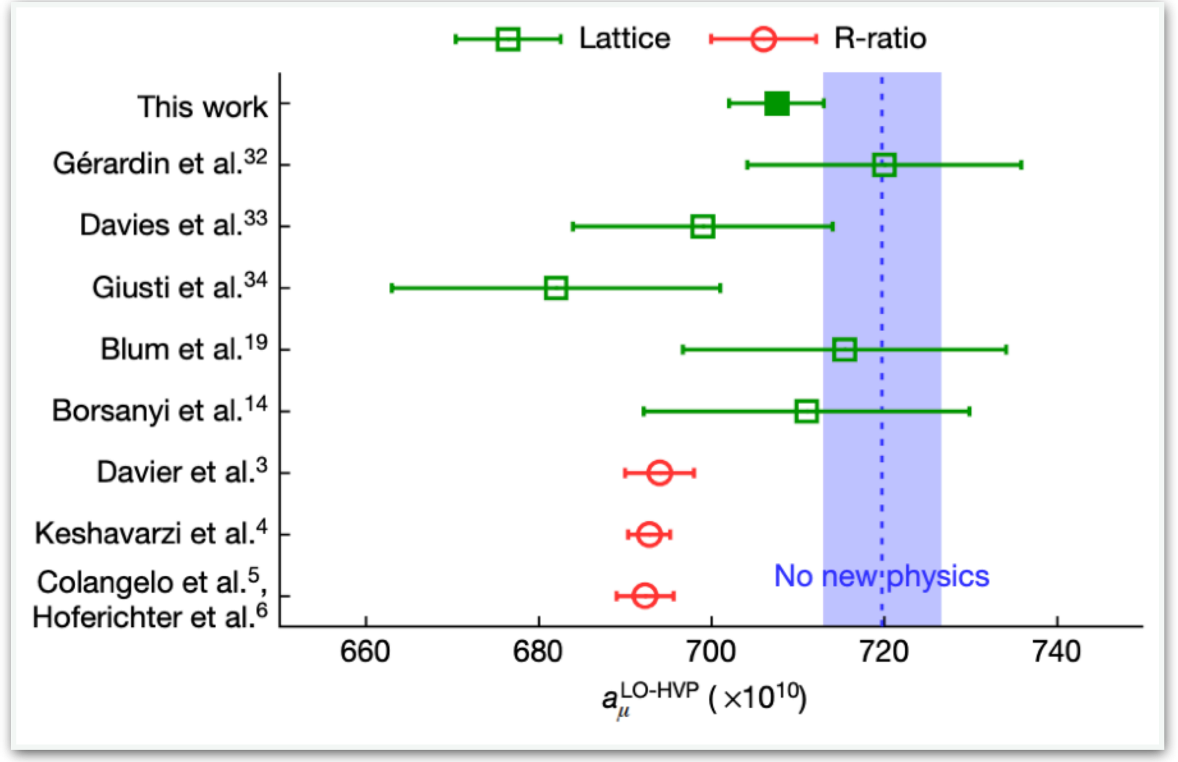
SM



NP?

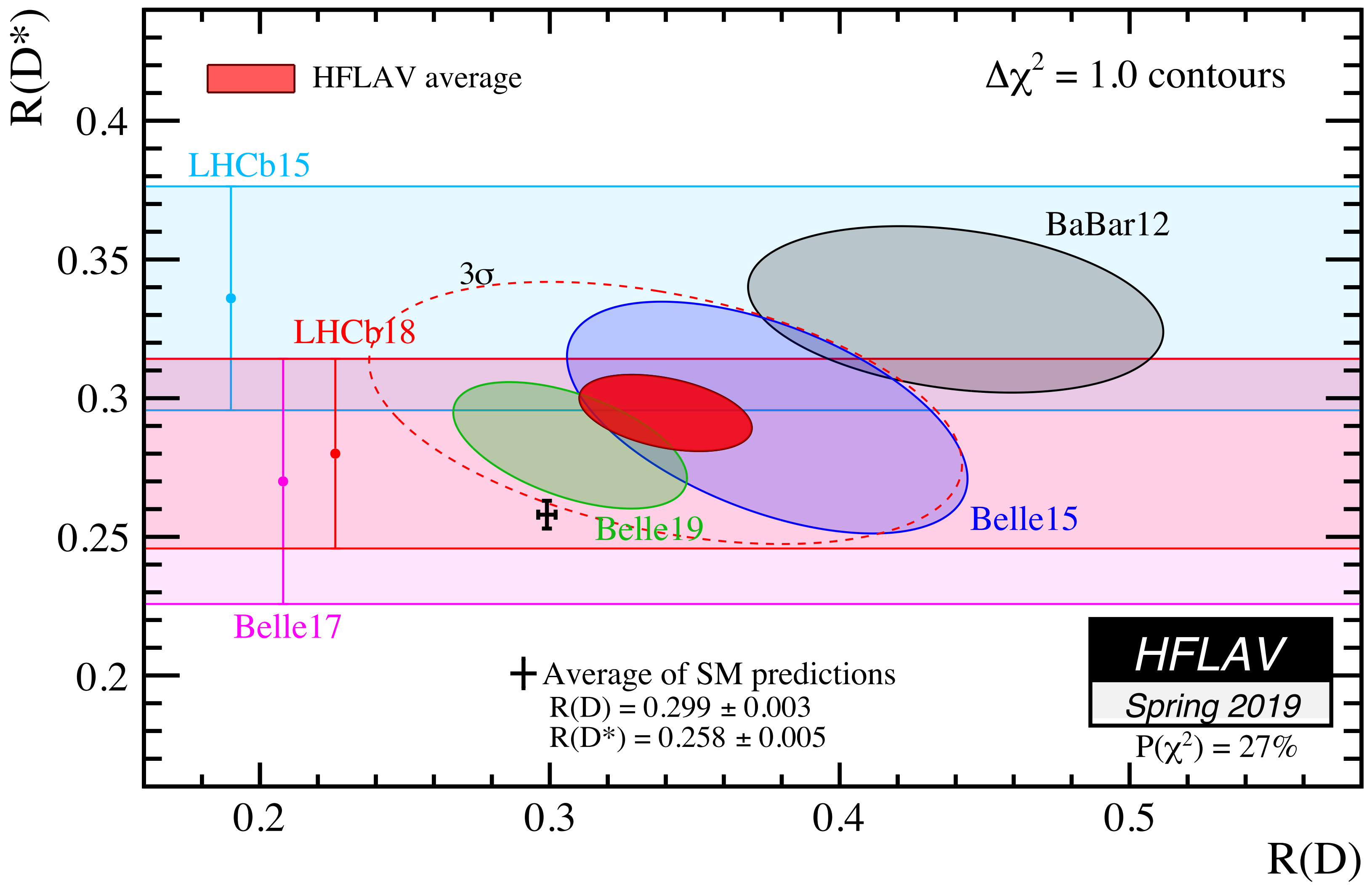
Muon g-2 Collaboration
[PRL 126 (2021) 14, 141801]





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

Lepton universality tests in B-meson decays



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

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

$R_D = 0.340 \pm 0.027 \pm 0.013$ $+1.4\sigma$ from SM

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

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

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

BaBar Collaboration
[PRL 109 (2012) 101802]

Belle Collaboration
[PRD 92 (2015) 072014]

Belle Collaboration
[PRL 118 (2017) 211801]

Belle Collaboration
[PRL 124 (2020) 161803]

LHCb Collaboration
[PRL 115 (2015) 111803]

LHCb Collaboration
[PRL 120 (2018) 171802]

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

R_{K^*}

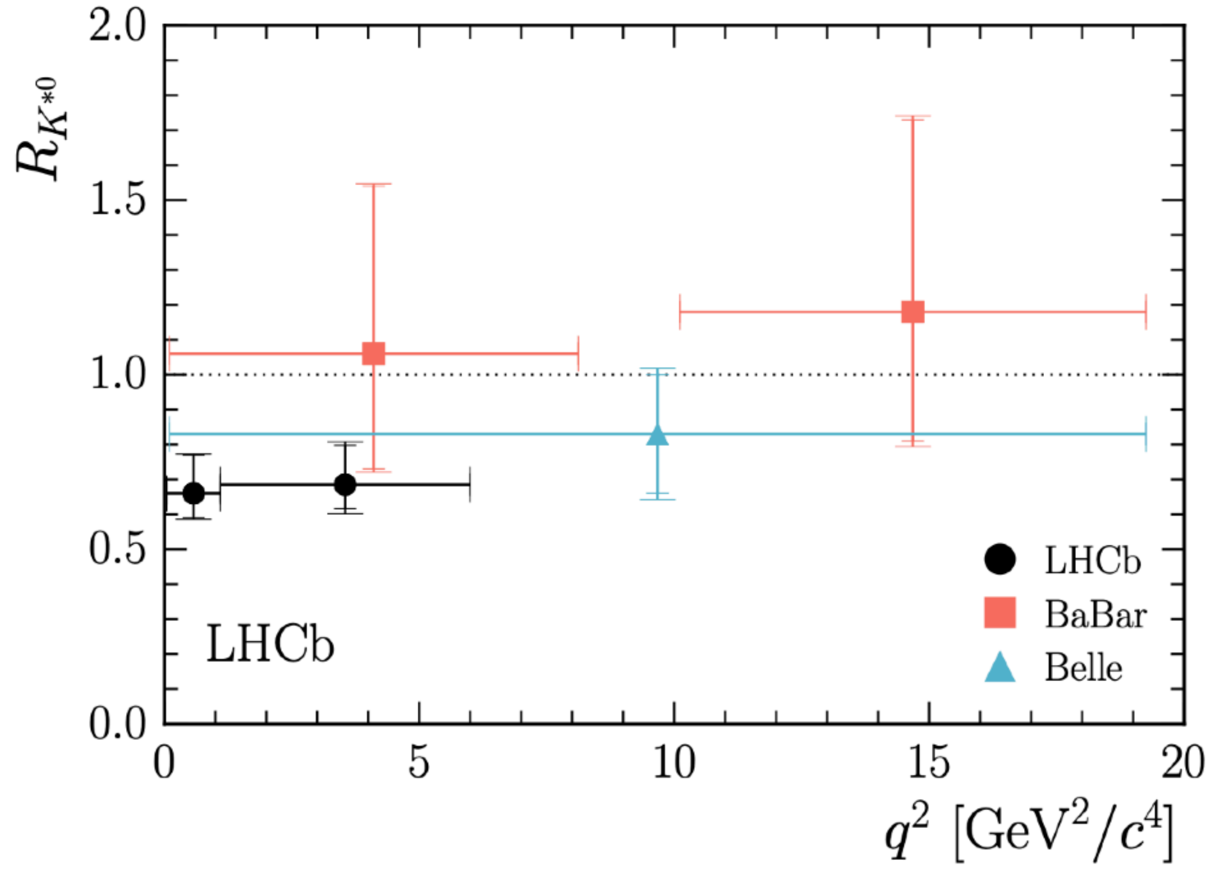
LHCb Collaboration
[JHEP 08 (2017) 055]

R_K

BaBar Collaboration
[PRD 86 (2012) 032012]

Belle Collaboration
[JHEP 03 (2021) 105]

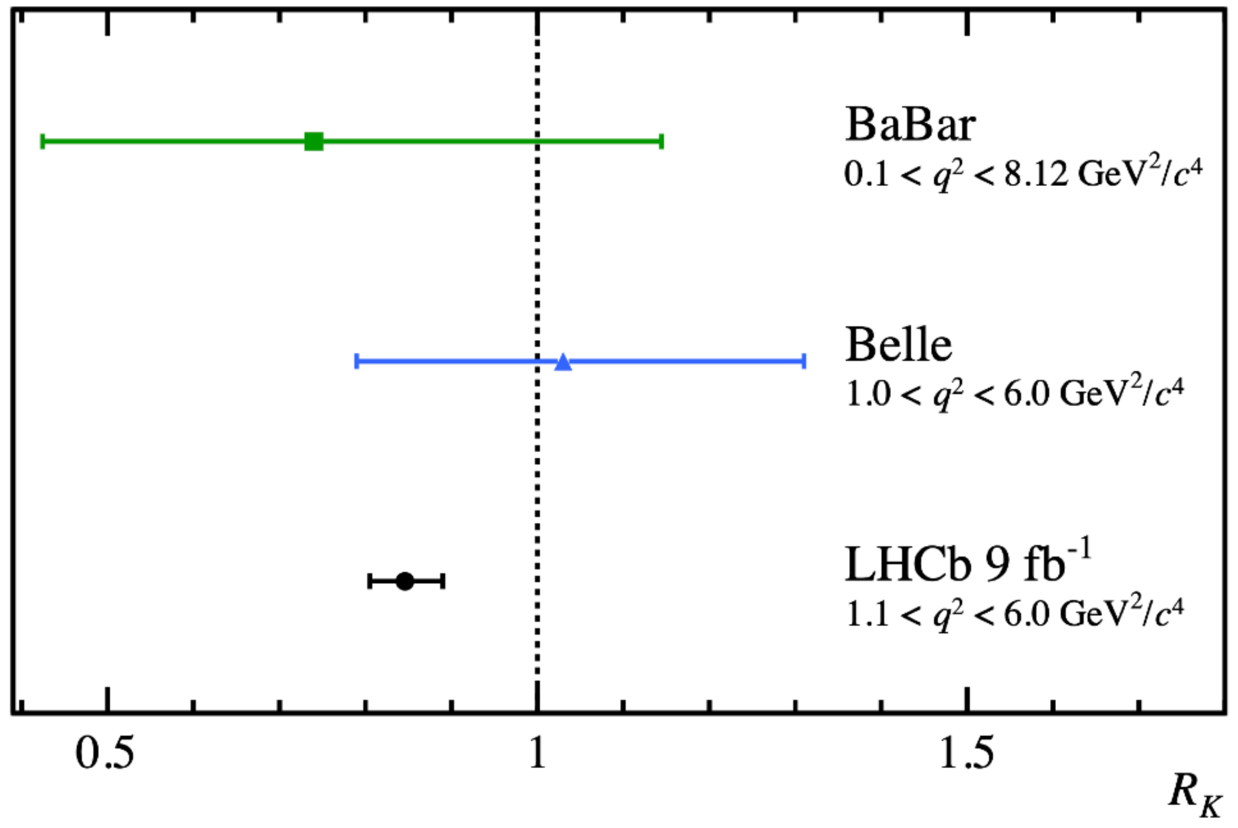
LHCb Collaboration
[2103.11769 (hep-ex)]



LHCb 2017, 7+8 TeV data set $3\ \mathrm{fb}^{-1}$

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

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



LHCb 2021, Run 1+2 full data set $9\ \mathrm{fb}^{-1}$

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

3.1σ from SM

LQ Scenarios

$LQ \to q + \ell$
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)]

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]

$R_{D^{(*)}}^{\rm SM+LQ} > R_{D^{(*)}}^{\rm SM}$
$R_{K^{(*)}}^{\rm SM+LQ} < R_{K^{(*)}}^{\rm SM}$

U_1: isospin singlet vector leptoquark

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

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

$\supset$ QCD&EM interactions

(effective) LQ interactions

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

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

LQ Scenarios

All possible LQs couples to quark + lepton

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

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

large μ-t-LQ coupling

large ν-b-LQ coupling

$$R^{\rm SM+LQ}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$
$$R^{\rm SM+LQ}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$$

U_1: isospin singlet vector leptoquark

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

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

$\mathrm{Br}(\tau \to \mu\gamma)$

$\mathrm{Br}(B \to K\nu\bar{\nu})$ and so on.

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

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

$$\mathcal{L} \supset -\frac{1}{2} U^\dagger_{1\mu\nu} U^{\mu\nu}_1 + U_{1\mu} \sum_{i,j=1,2,3} \left[x^{ij}_L (\bar{d}^i_L \gamma^\mu e^j_L + \left(V^\dagger_{\rm CKM} x_L U_{PMNS}\right)_{ij} (\bar{u}^i_L \gamma^\mu \nu^j_L) + x^{ij}_R (\bar{d}^i_R \gamma^\mu e^j_R) \right] + \text{h.c.}$$

⊃ QCD&EM interactions

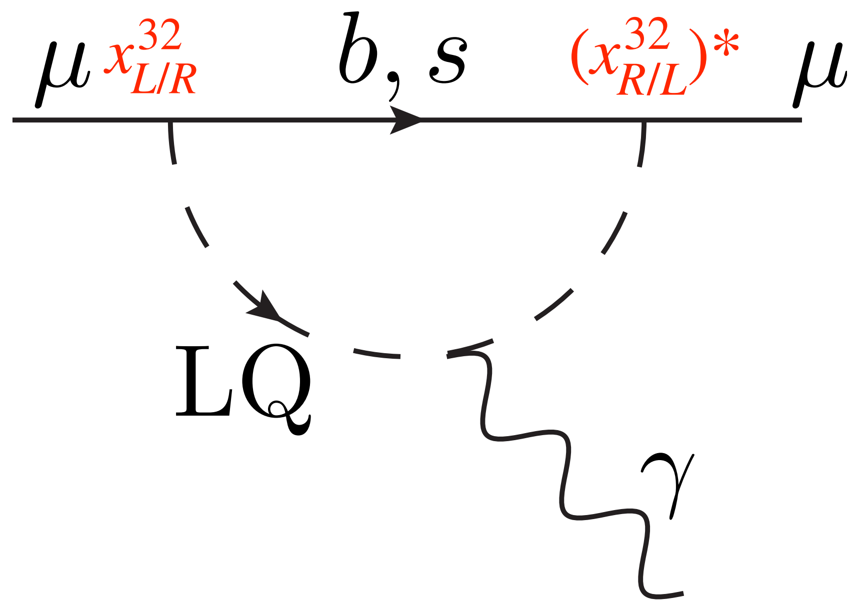
(effective) LQ interactions

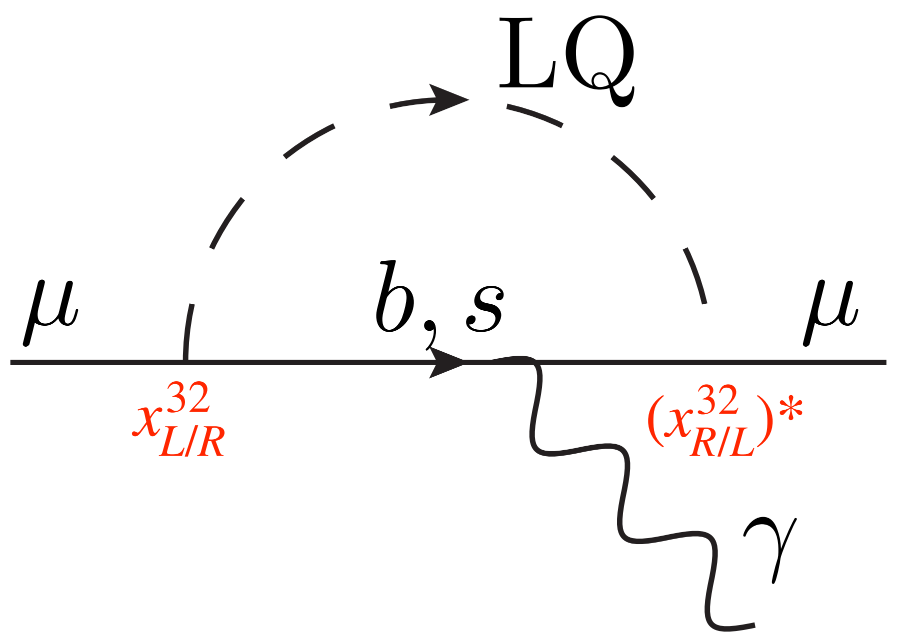
$$U_{1\mu\nu} = D_\mu U_{1\nu} - D_\nu U_{1\mu}$$

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

LQ Scenario

Possible contributions to Low-E anomalies from Leptoquark

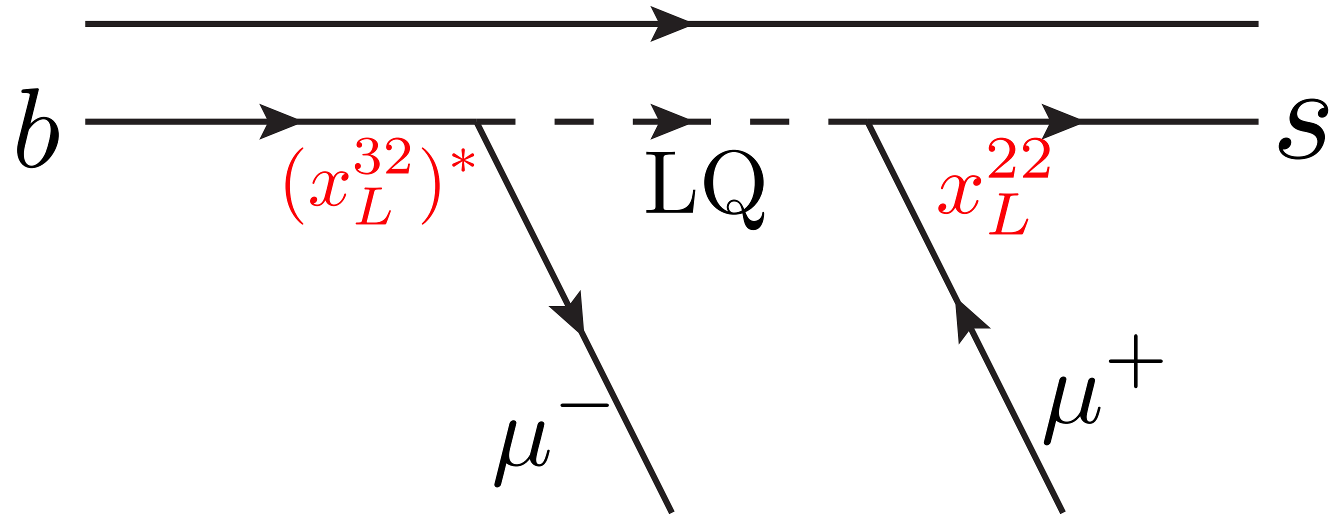




$$\frac{1}{\Lambda_1}(\bar{\mu}_L \sigma^{\mu\nu} \mu_R) F_{\mu\nu}$$

$(g-2)_\mu$

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

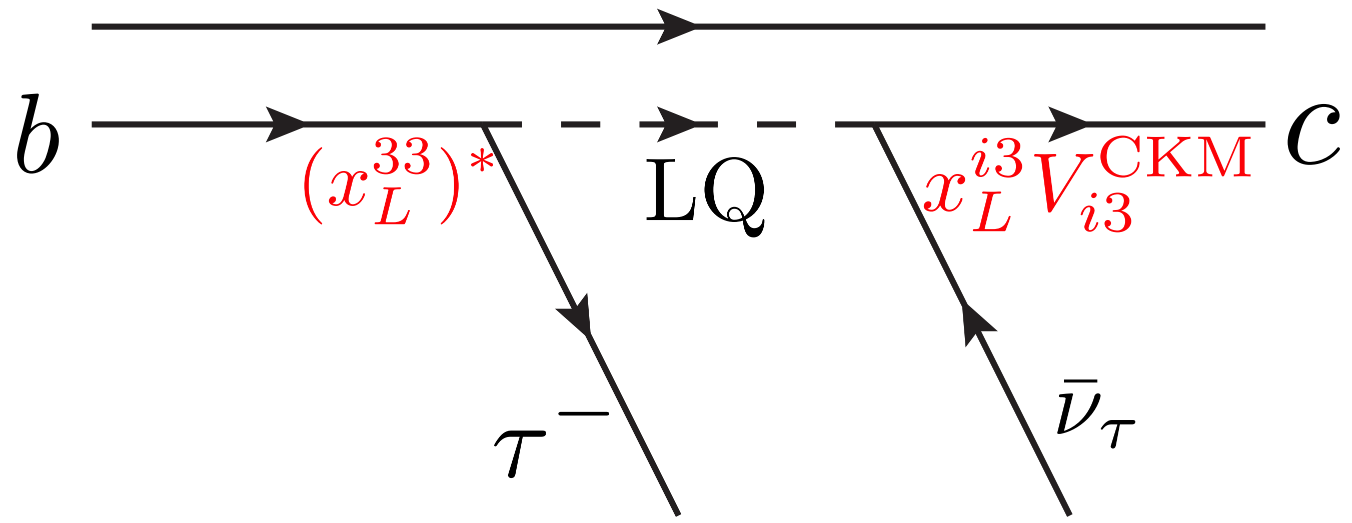


$$\frac{1}{\Lambda_2^2}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

$R_{K^{(*)}}$

$\mathrm{Br}(B_s \to \mu\mu)$

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



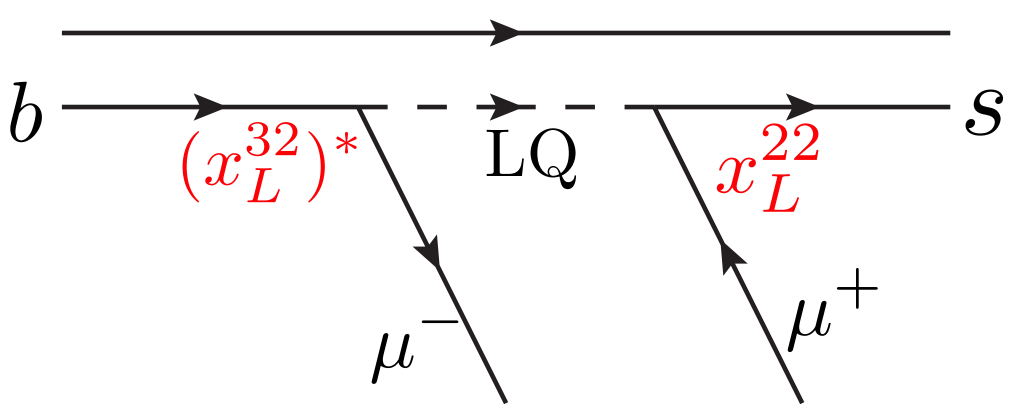
$$\frac{1}{\Lambda_3^2}(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$

$R_{D^{(*)}}$

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

Ballpark & Constraints

Ballpark for Anomalies(?)



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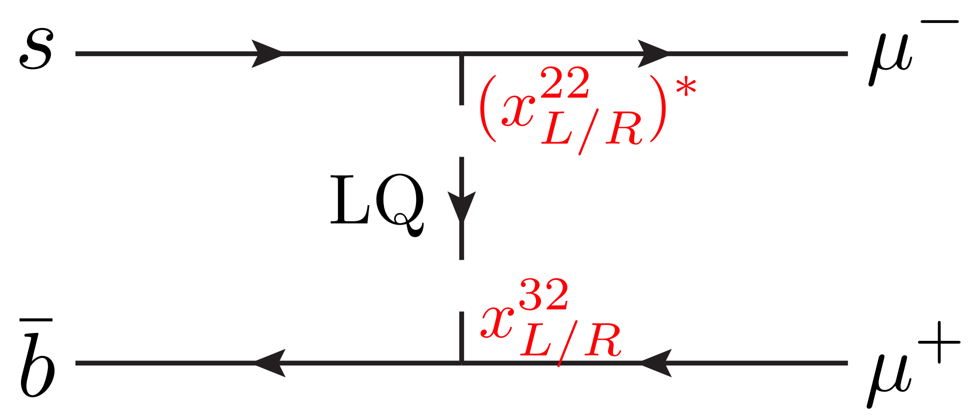


$$R_{K^{(*)}} \equiv \frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)}$$

$2.1 - 2.5\sigma\ (R_{K^{(*)}})$

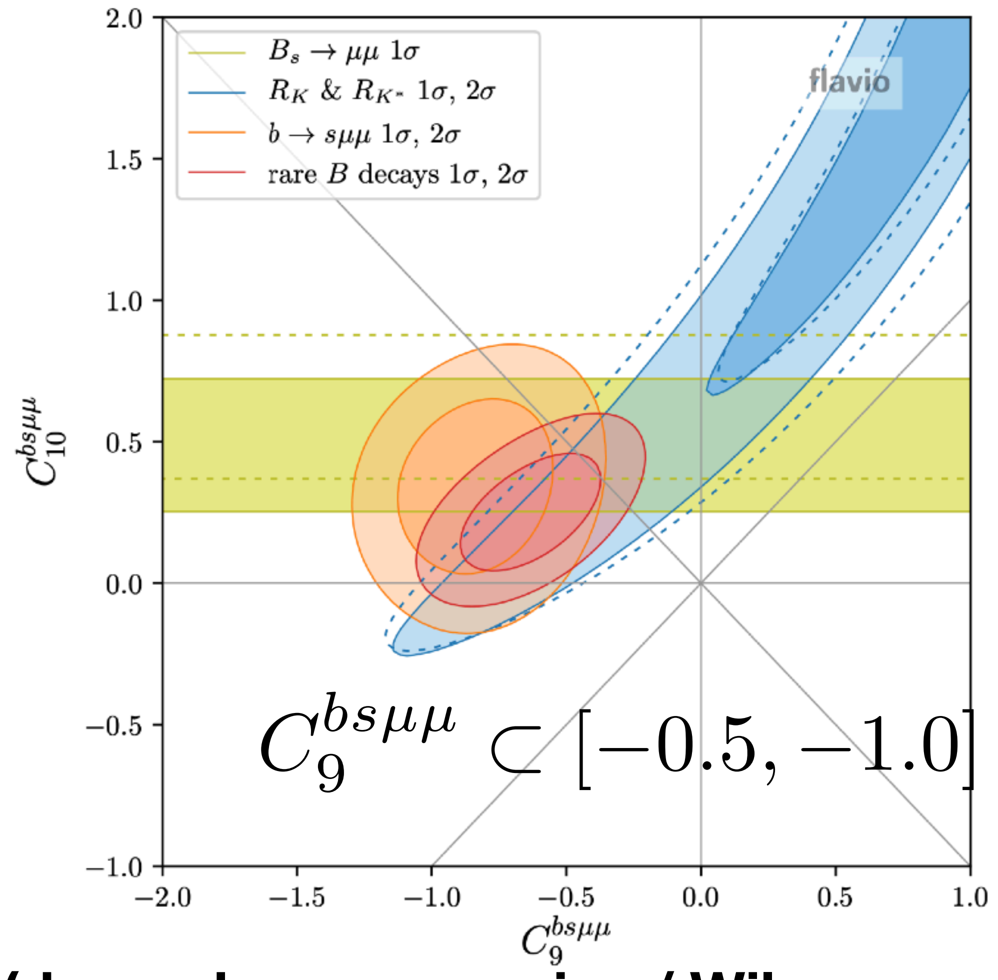
$3.1\sigma\ (R_K)$

$$\frac{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\rm exp}}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\rm SM}} = 0.73^{+0.13}_{-0.10}$$

$(2.1\sigma$ away from SM)

[ATLAS-CONF-2020-049]

W. Altmannshofer, P. Stangl [2103.13370]



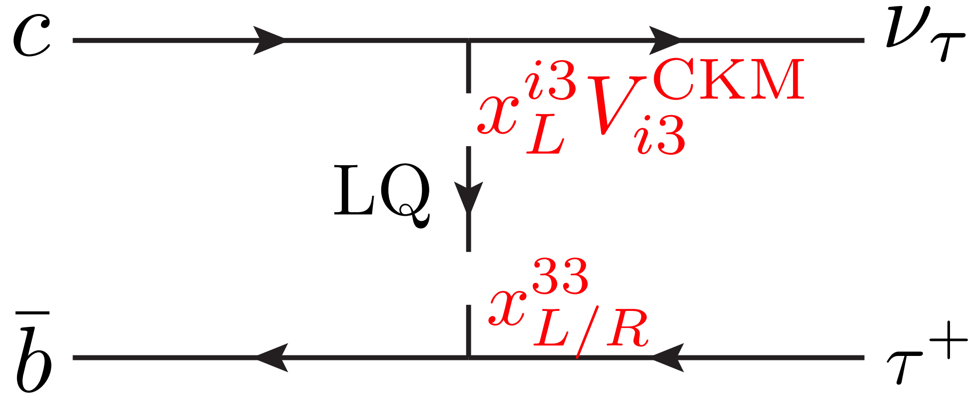
$C_9^{bs\mu\mu} \subset [-0.5, -1.0]$

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

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

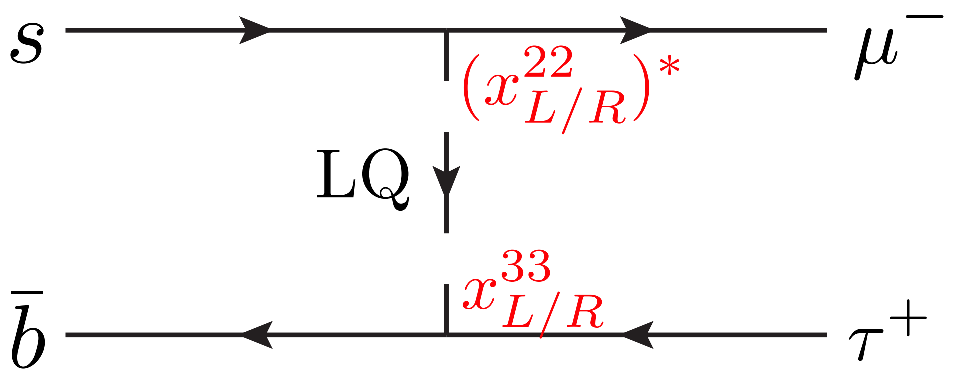
(depends on scenarios / Wilson coefficients)

Upper limits from LFV in B-meson decays



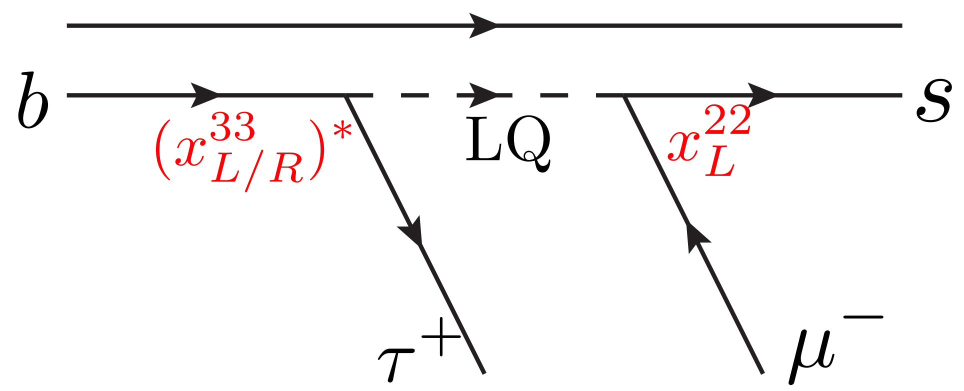
$\mathrm{Br}(B_c \to \tau^+\nu_\tau)_{\rm exp} \le 0.1$

A. G. Akeroyd et al.
[PRD 96 (2017) 075011]



$\mathrm{Br}(B_s \to \tau^+\mu^-)_{\rm exp} < 2.1 \times 10^{-5}$

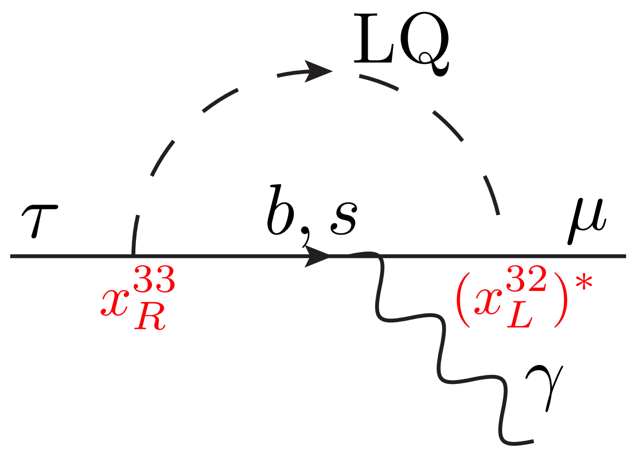
LHCb Collaboration
[PRL 123 (2019) 211801]



$\mathrm{Br}(B^+ \to K^+\tau^+\mu^-) < 2.8 \times 10^{-5}$

BaBar Collaboration
[PRD 86 (2012) 012004]

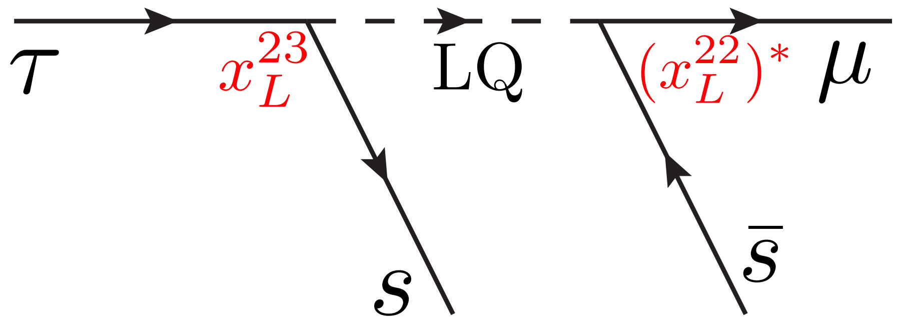
Upper limits from LFV in tau decays



$\mathrm{Br}(\tau \to \mu\gamma) < 3 \times 10^{-8}$

Belle Collaboration
[PLB 666 (2008) 16]

BaBar Collaboration
[PRL 104 (2010) 021802]



$\mathrm{Br}(\tau \to \mu\phi) < 5.1 \times 10^{-8}$

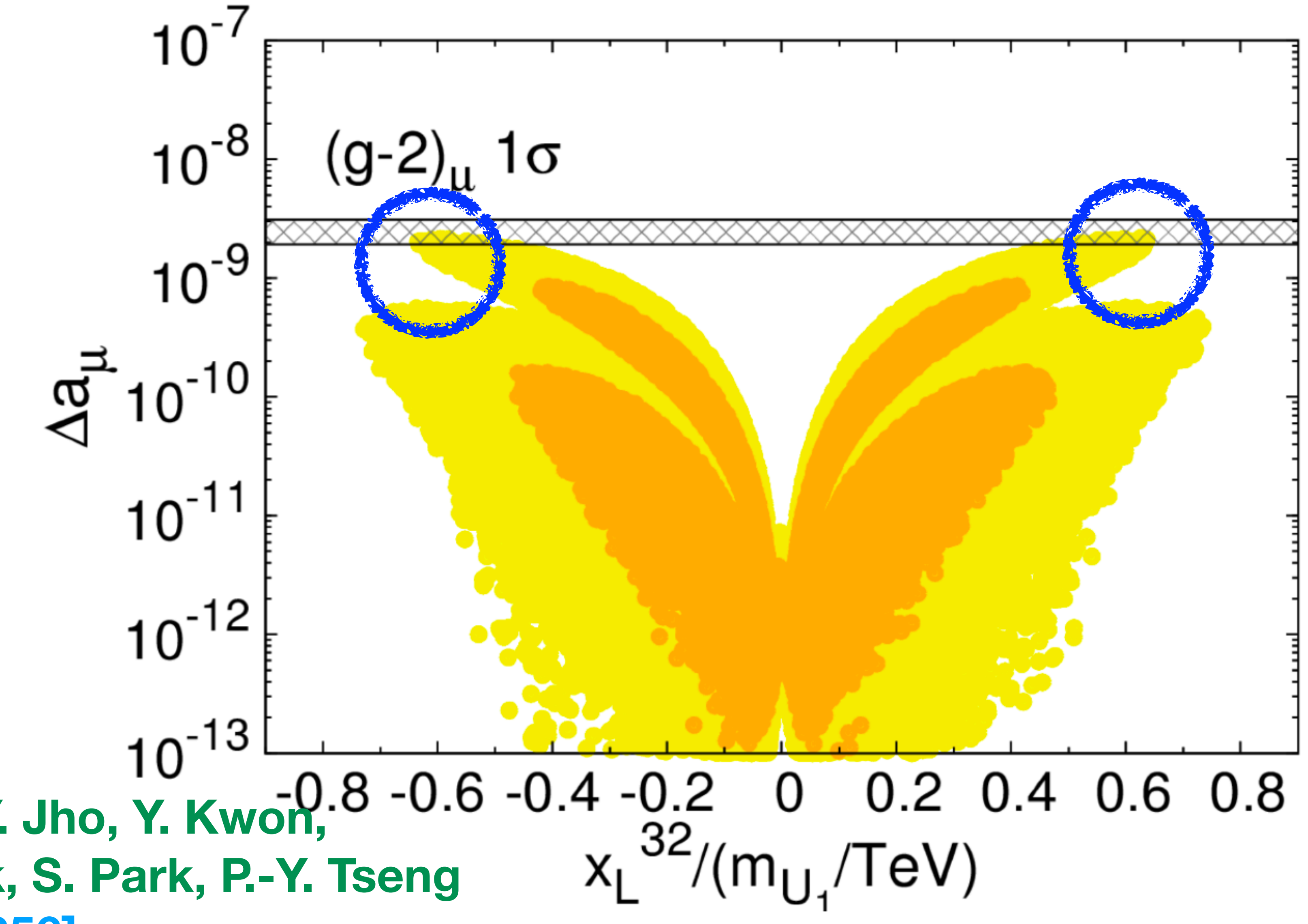
Belle Collaboration
[PLB 699 (2011) 251]

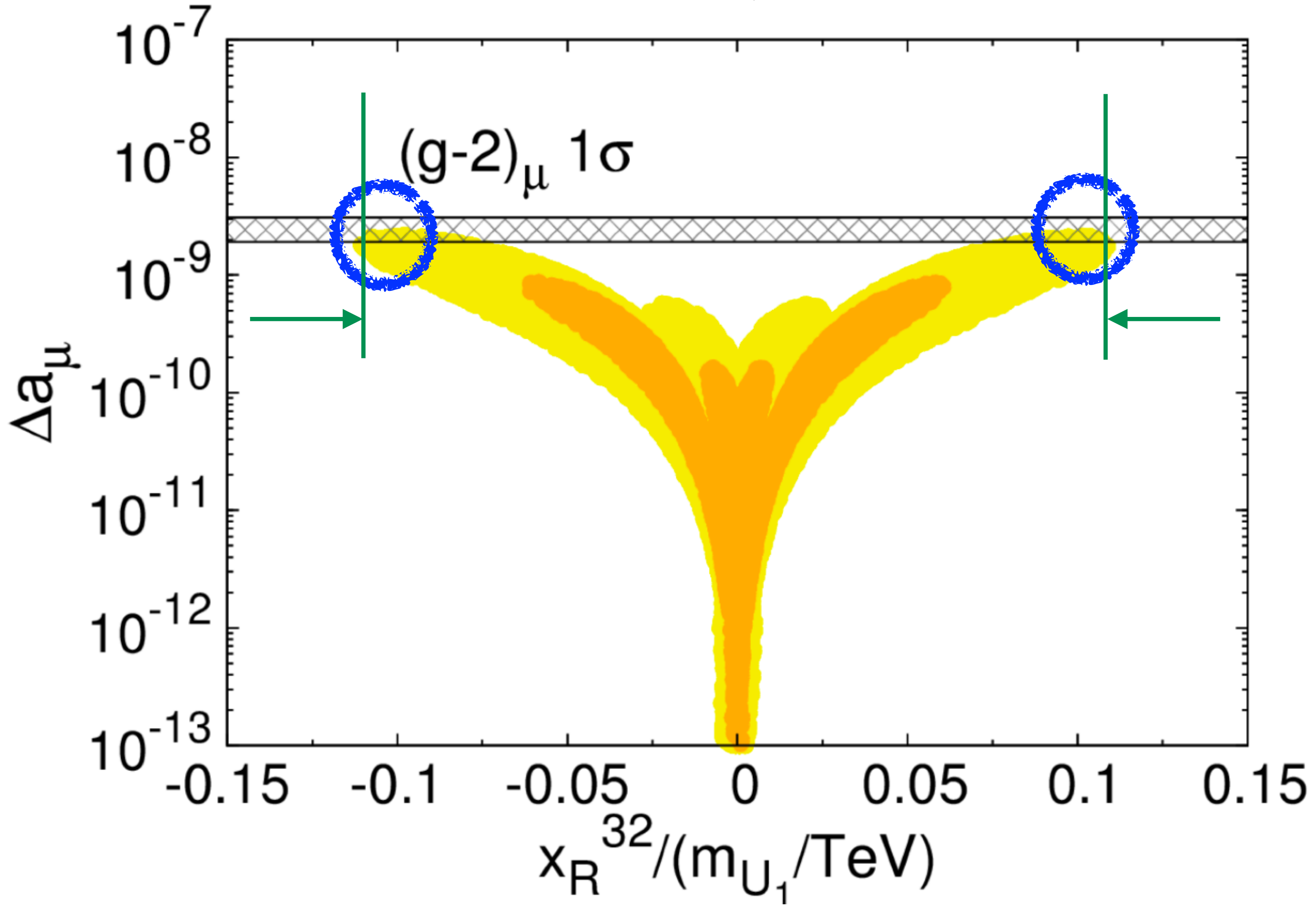
Result & best-fit parameters

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

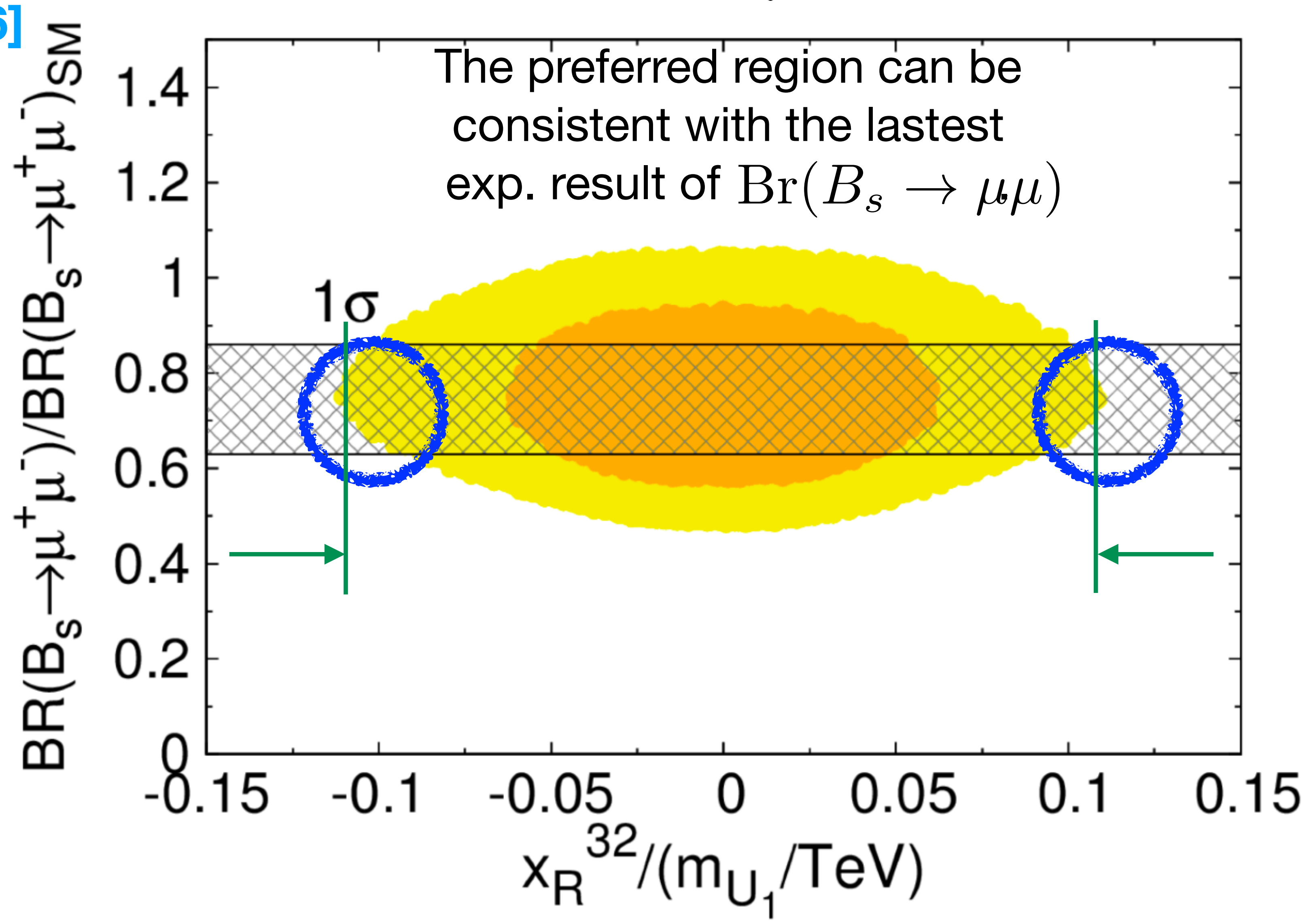
- $\Delta\chi \leq 5.99$
- $\Delta\chi \leq 2.30$

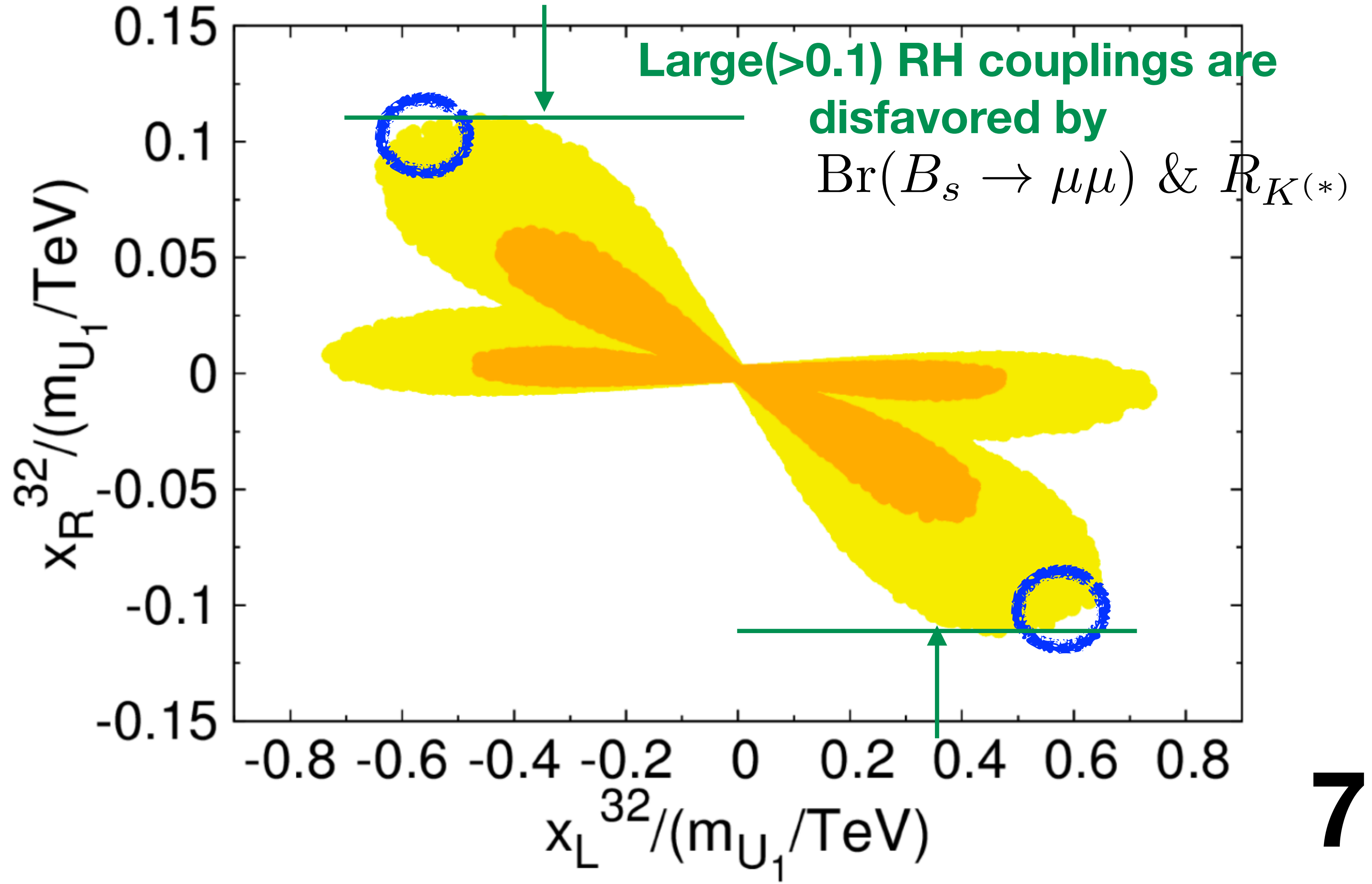
$x_L^{32} \simeq \pm 1.2,\ x_R^{32} \simeq \mp 0.18$ provides a simultaneous explanation for $(g-2)_\mu,\ R_{K^{(*)}},$ and $R_{D^{(*)}}$



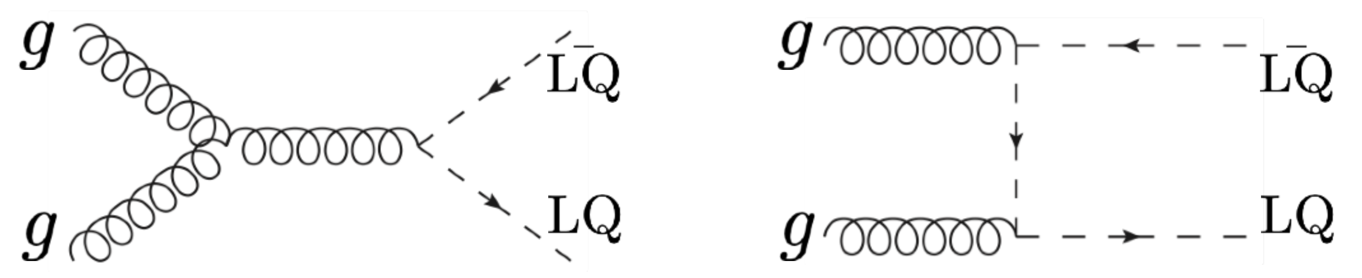


K. Ban, Y. Jho, Y. Kwon, S.C. Park, S. Park, P.-Y. Tseng [2104.06656]



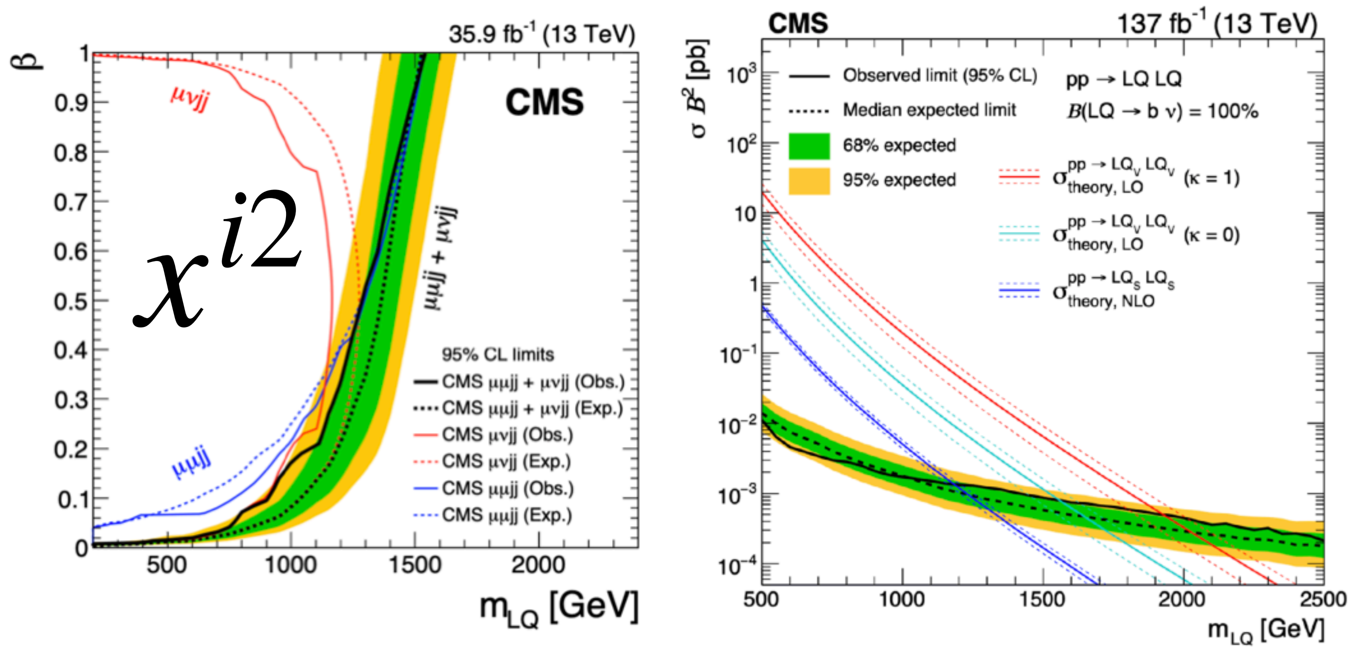


Searches for LQ at the LHC

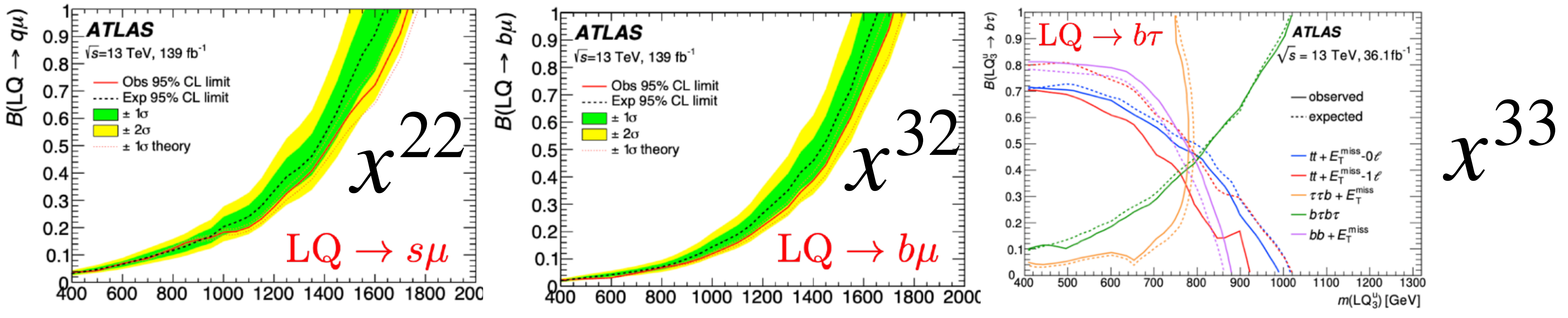


- **LQ can be pair-produced with a large cross section. (QCD process)**

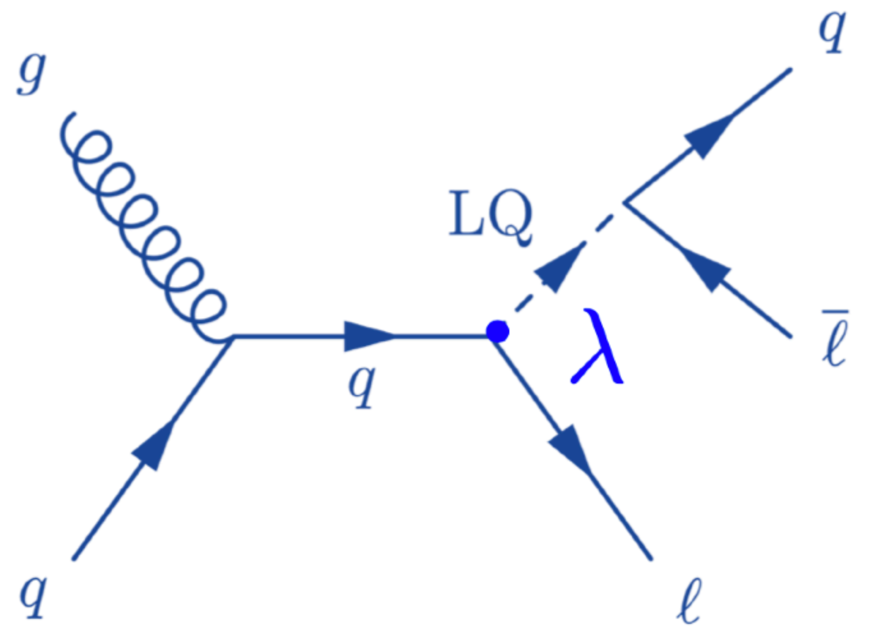
[PRD 99 (2019) 032014 (CMS Collab.)]

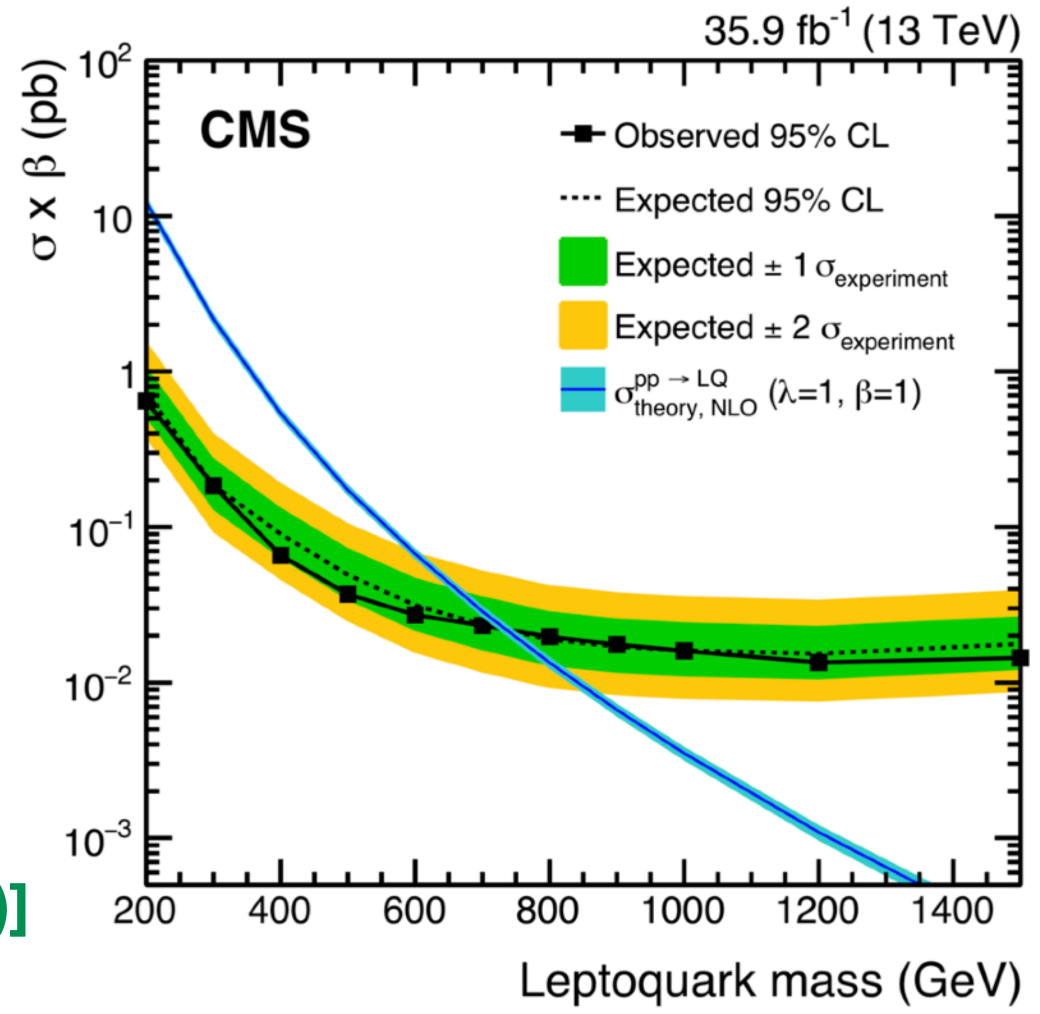


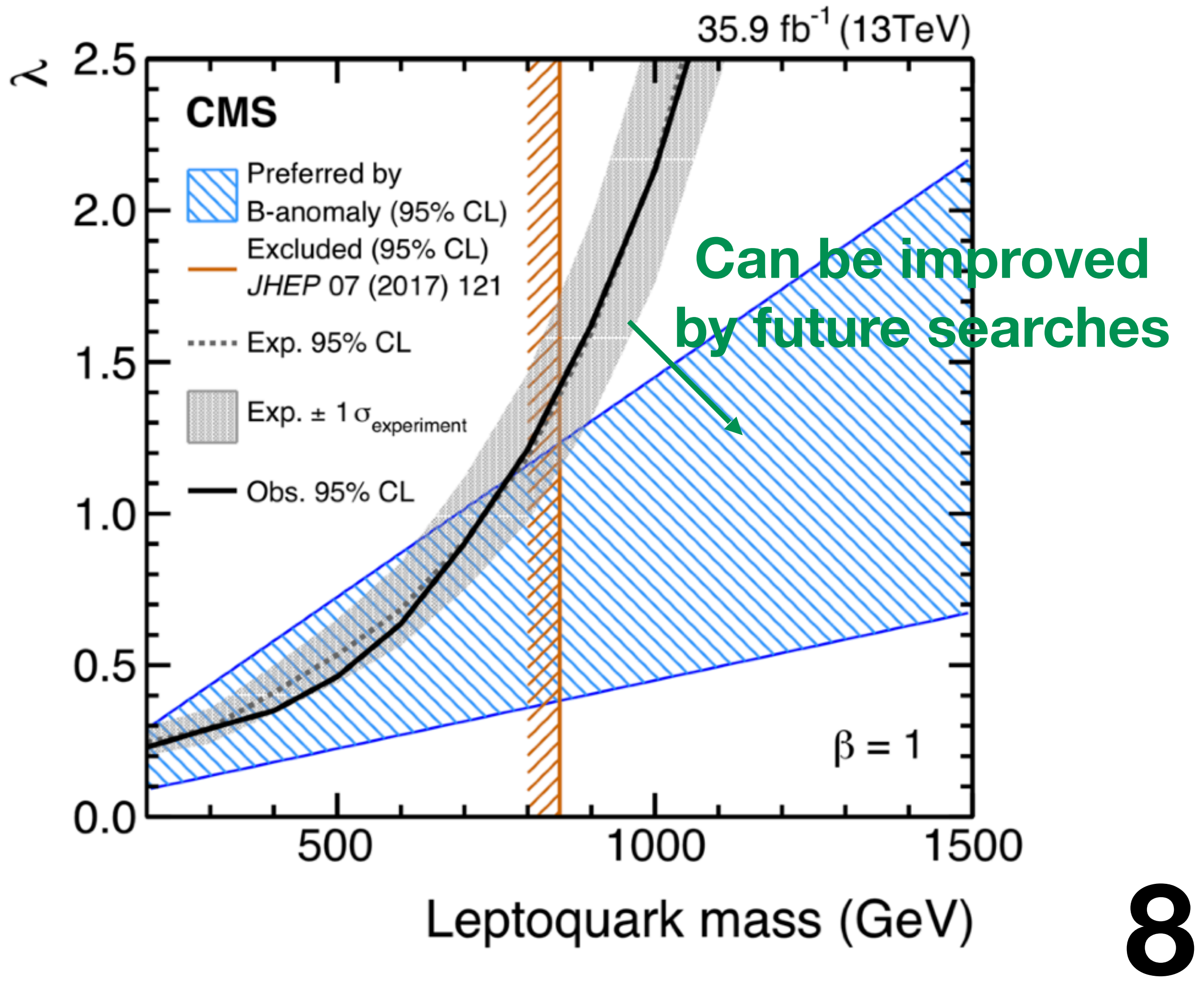
[JHEP 10 (2020) 112 (ATLAS Collab.)]



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







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

Future prospects (B-factory)

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

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

Belle II Collaboration
PTEP 2019 (2019) 12, 123C01

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

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

  - 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**

$$B^+ \to K^+\ell^+\ell'^- \qquad \tau \to \mu\gamma$$

$$B^0_{(s)} \to \mu^\pm\tau^\mp \qquad \tau \to \mu\phi$$

Future prospects (e+e-)

- **Z-factory**

  Z boson precision measurements are sensitive to LQ via loop corrections

Precision measurement/Lepton universality

[PDG 2020] $\Gamma(Z \to \mu^+\mu^-)/\Gamma(Z \to e^+e^-) = 1.0001 \pm 0.0022$

$\Gamma(Z \to \tau^+\tau^-)/\Gamma(Z \to \mu^+\mu^-) = 1.0010 \pm 0.0026$

$\Gamma(Z \to \tau^+\tau^-)/\Gamma(Z \to e^+e^-) = 1.0020 \pm 0.0032$

$\Gamma(Z \to b\bar{b})/\Gamma(Z \to \textbf{hadrons}) = 0.21629 \pm 0.00066$

Current experimental precision level: Δ**Br/Br** $\sim \mathcal{O}(10^{-3})$

LFV

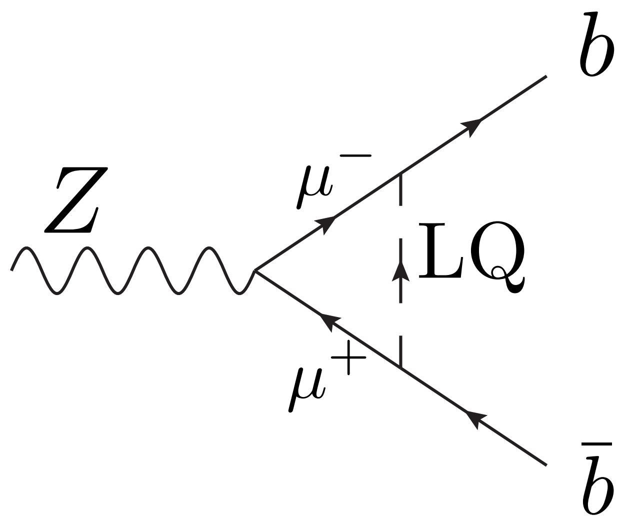
$\mathrm{Br}(Z \to \mu\tau) < 1.2 \times 10^{-5}$ (LEP-I)

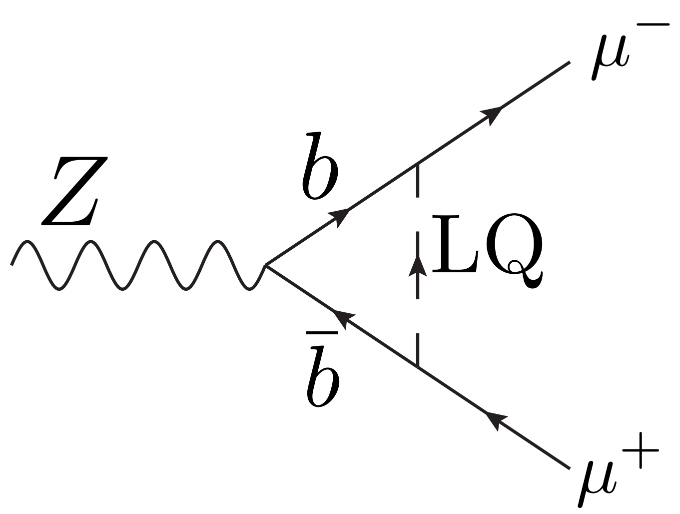
At Future colliders with $\sim 10^{12}\ Z$ **production,**
Br$(Z \to \mu\tau) < \mathcal{O}(10^{-8})$ **is expected**

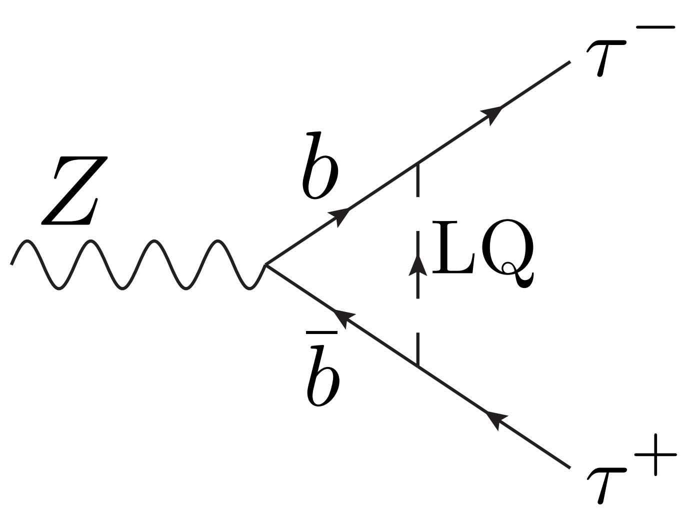
CEPC Conceptual Design Report [arXiv:1811.10545]

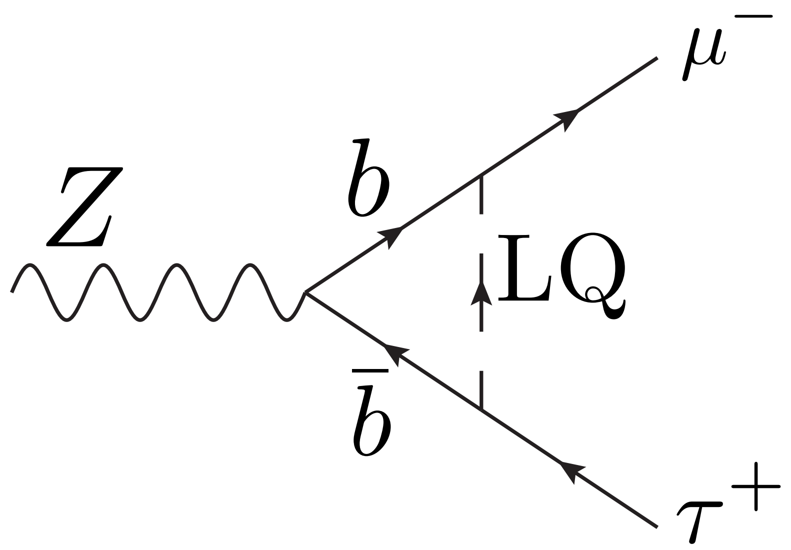
→ Both can be significantly improved at future e-e+ colliders (ILC/FCC-ee/CEPC)

- **LQ contributions to Lepton universality/LFV**









Precision measurement/Lepton universality

$$\Delta\mathrm{Br}_{LQ}/\mathrm{Br} \sim \frac{|x_{L/R}^{32,33}|^2}{16\pi^2} F(m_Z^2/m_{\mathrm{LQ}}^2) \sim \mathcal{O}(10^{-5})$$

logarithmic loop function

LFV

Br$(Z \to \mu\tau)_{LQ} \sim \mathcal{O}(10^{-7})$

For $x_{L/R} \sim \mathcal{O}(1), m_{LQ} \sim 2TeV$

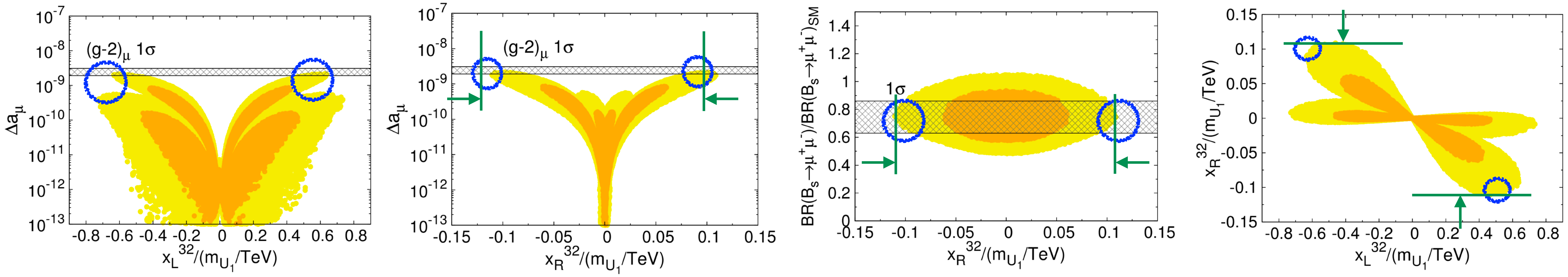
Summary

- 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

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

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 $R_{D^{(*)}}$