Leptonic new force for Muon (g-2) and B-anomalies

S.C.Park

Based on arXiv: 1904.13053, 2001.06572, 2006.13910, 2012.04190, 2104.06656, …

Collaboration with
Kayoung Ban, **Yongsoo Jho**, **Youngjoon Kwon** (Yonsei+KEK), **Yeji Park**, **Seokhee Park** (KEK)
Po-Yan Tseng (Yonsei -> Tsing Hua)

* **students @ Yonsei**
* **experiment**

Mini-workshop on BSM-related aspects at ILC and other proposed e+e- colliders

March 2 JST, 2022 https://agenda.linearcollider.org/event/9575/

It’s like making a good Tacoyaki!

Motivation

- The LHC is an excellent probe to discover new physics
  - ✓ if it couples with hadron
  - ✓ relatively heavy (>10 GeV) depending on channels
  - ✓ nothing beyond the SM is seen yet
- There are other types of new physics
  - ✓ couples to leptons (and possibly dark sector)
  - ✓ relatively light (<10 GeV) but feebly interacting
  - ✓ BELLE-II, XENONnT, COSINE …can cover this territory

Complementary

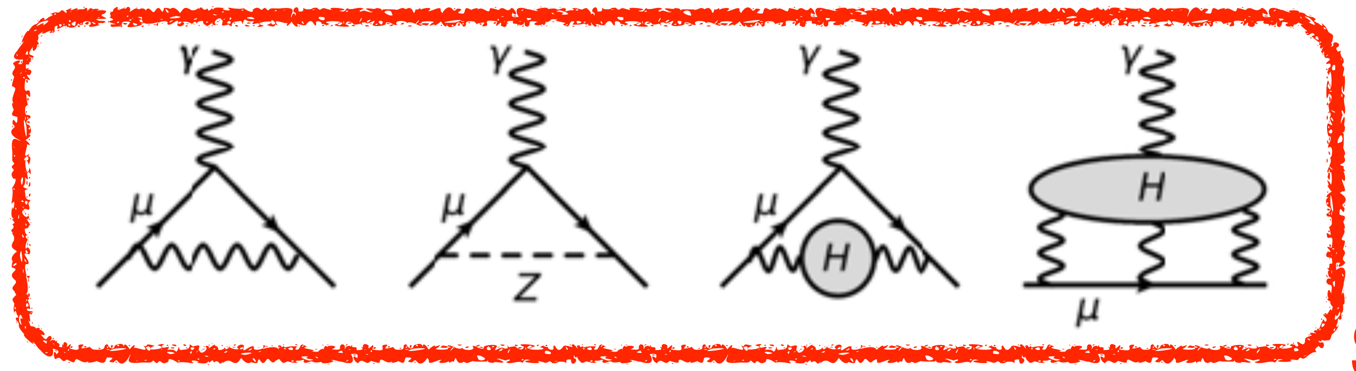
Motivation

- Indeed, there have been long standing problems…
  - (g-2) of muon remains anomalous for many years
  - Recent observation suggests violation of lepton universality

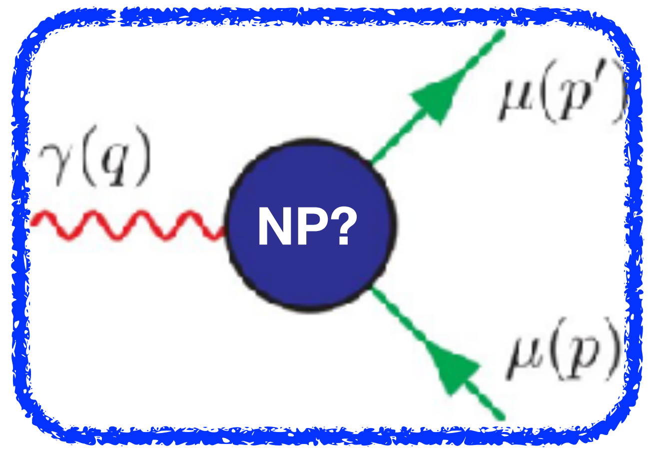
➡ New physics BSM may have contact (exclusively) with leptonic sector

➡We want to focus on this direction today

Muon g-2 and New Physics

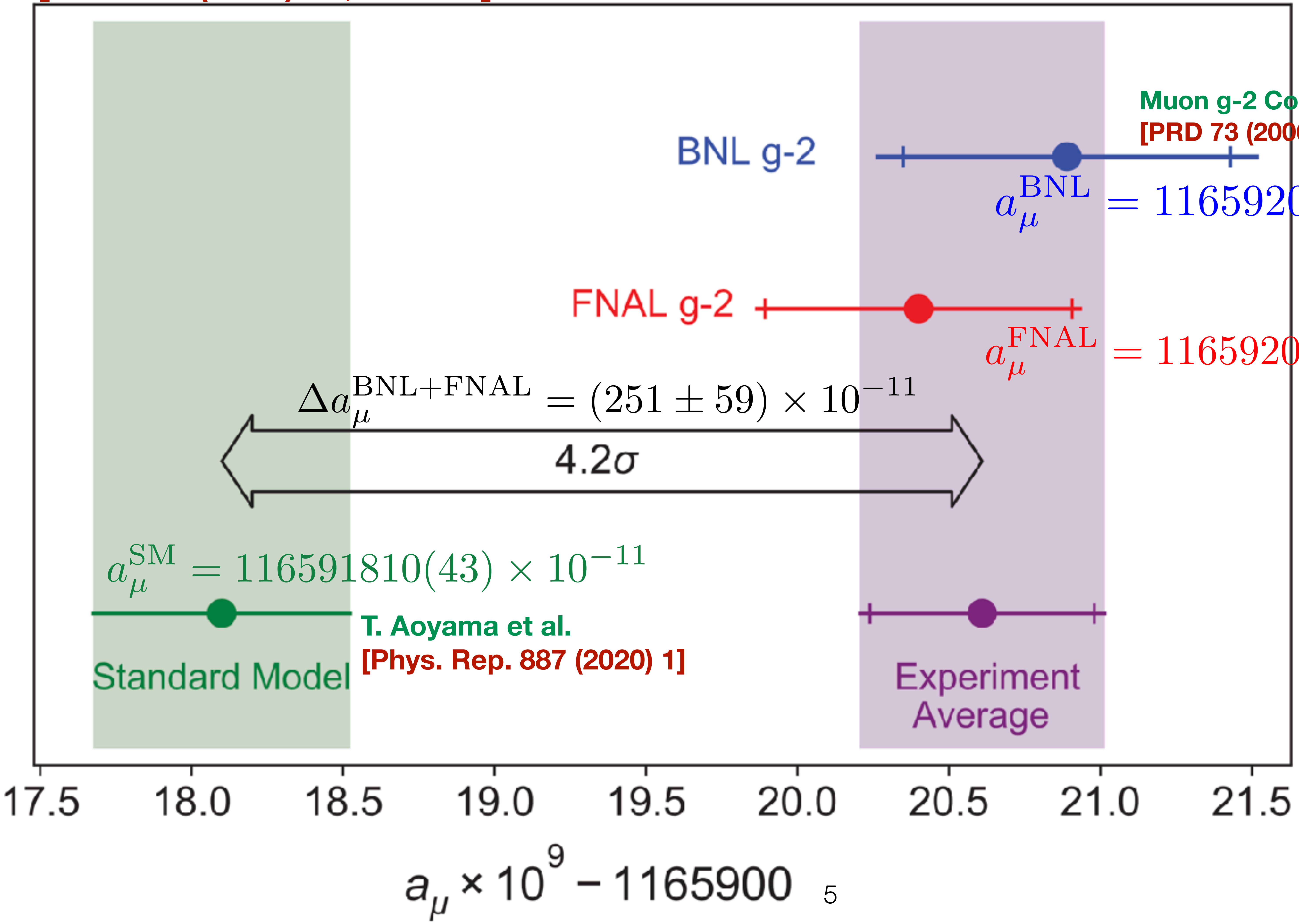


SM



NP?

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

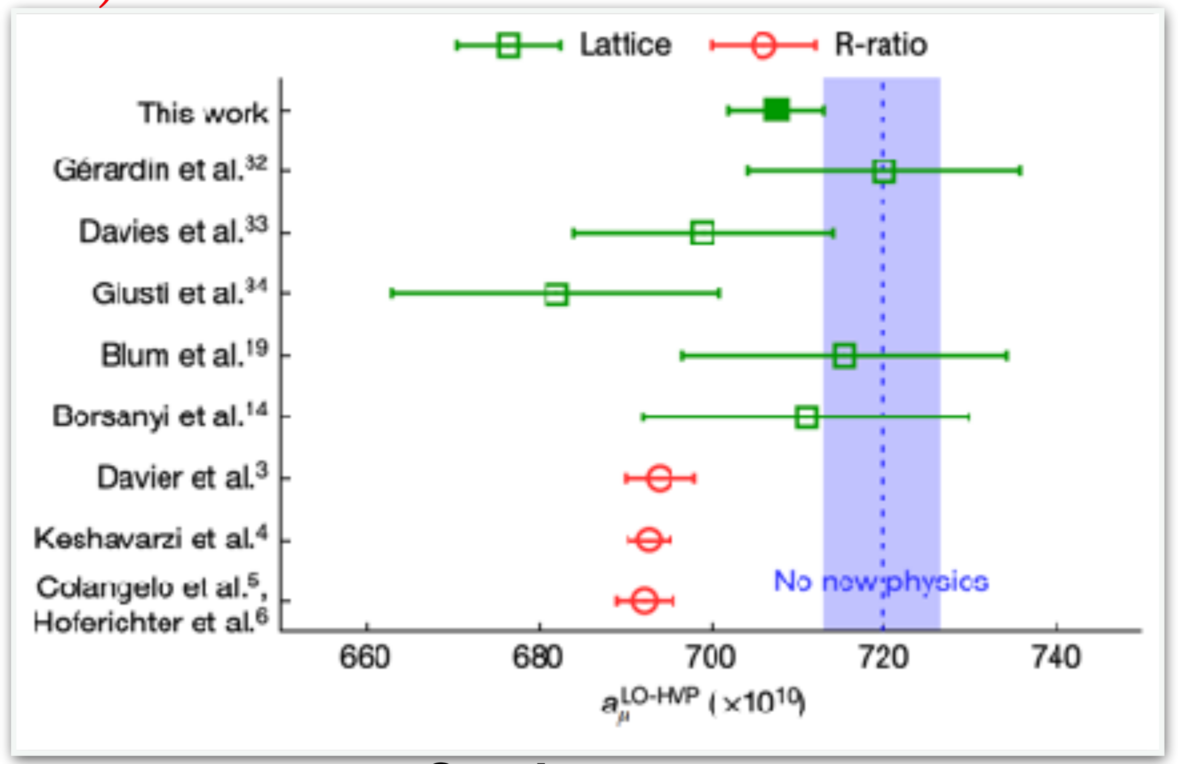


Muon g-2 Collaboration
[PRD 73 (2006) 072003]

$$a_\mu^{\rm BNL} = 116592080(63) \times 10^{-11}$$

$$a_\mu^{\rm FNAL} = 116592040(54) \times 10^{-11}$$

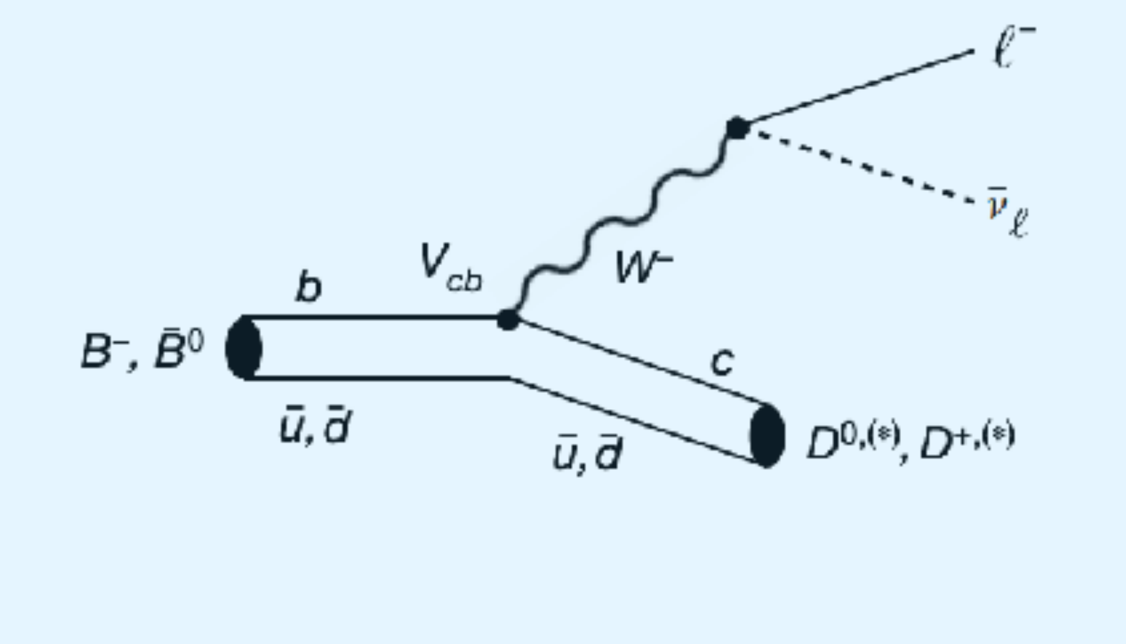
T. Aoyama et al.
[Phys. Rep. 887 (2020) 1]



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

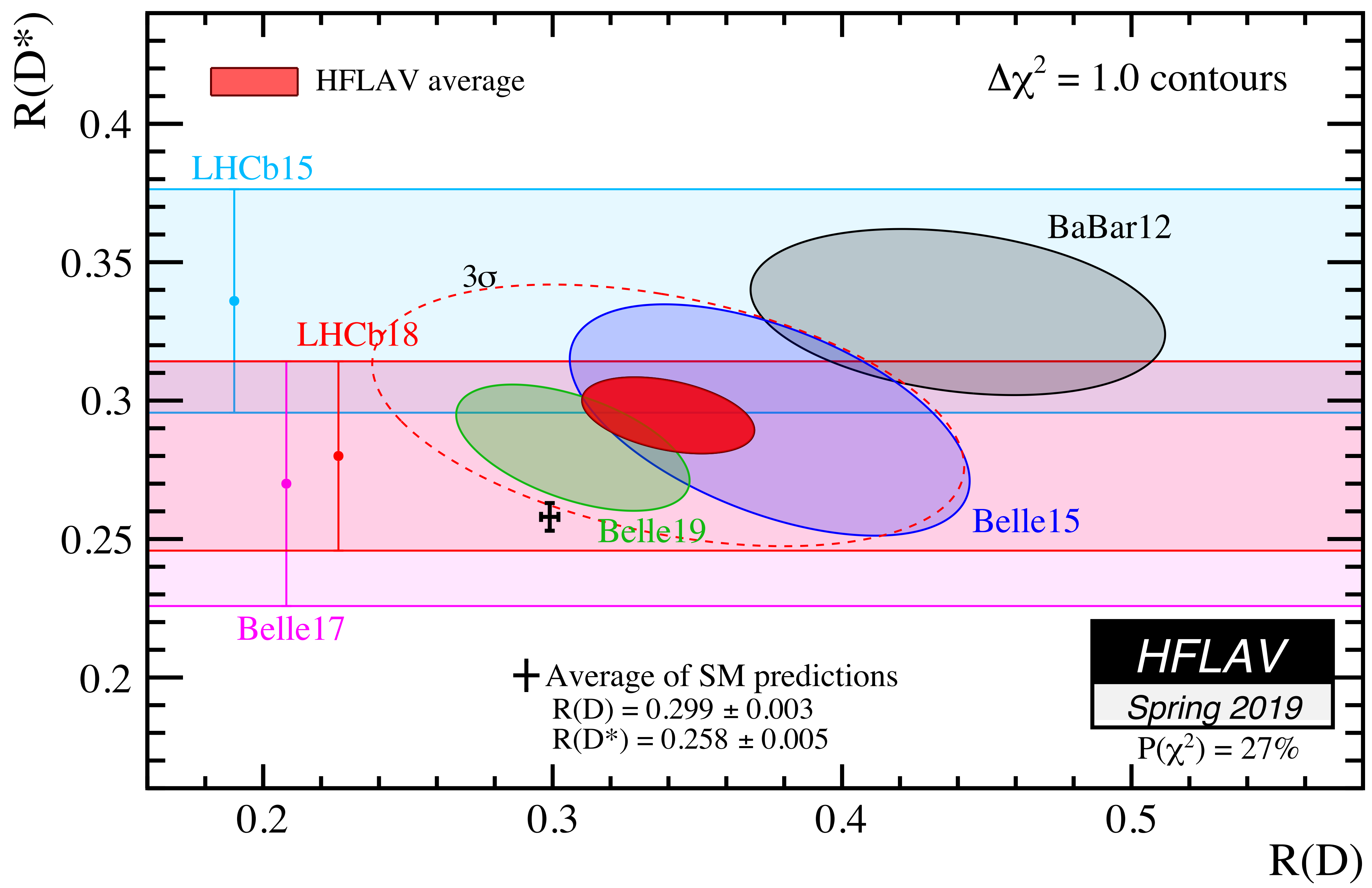
$+4.2\sigma$ larger $(g-2)_\mu$
than the SM expectation!

Lepton universality tests in B-meson decays (I)



$$R_D \equiv \frac{B(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{B(\bar{B} \to De^-\bar{\nu}_e)} = \begin{cases} 0.299 \pm 0.003 & \text{SM} \\ 0.340 \pm 0.027 \pm 0.013 & \text{exp} \end{cases} \qquad +1.4\sigma$$

$$R_{D*} \equiv \frac{B(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{B(\bar{B} \to D^*e^-\bar{\nu}_e)} = \begin{cases} 0.258 \pm 0.005 & \text{SM} \\ 0.295 \pm 0.011 \pm 0.008 & \text{exp} \end{cases} \qquad +2.5\sigma$$

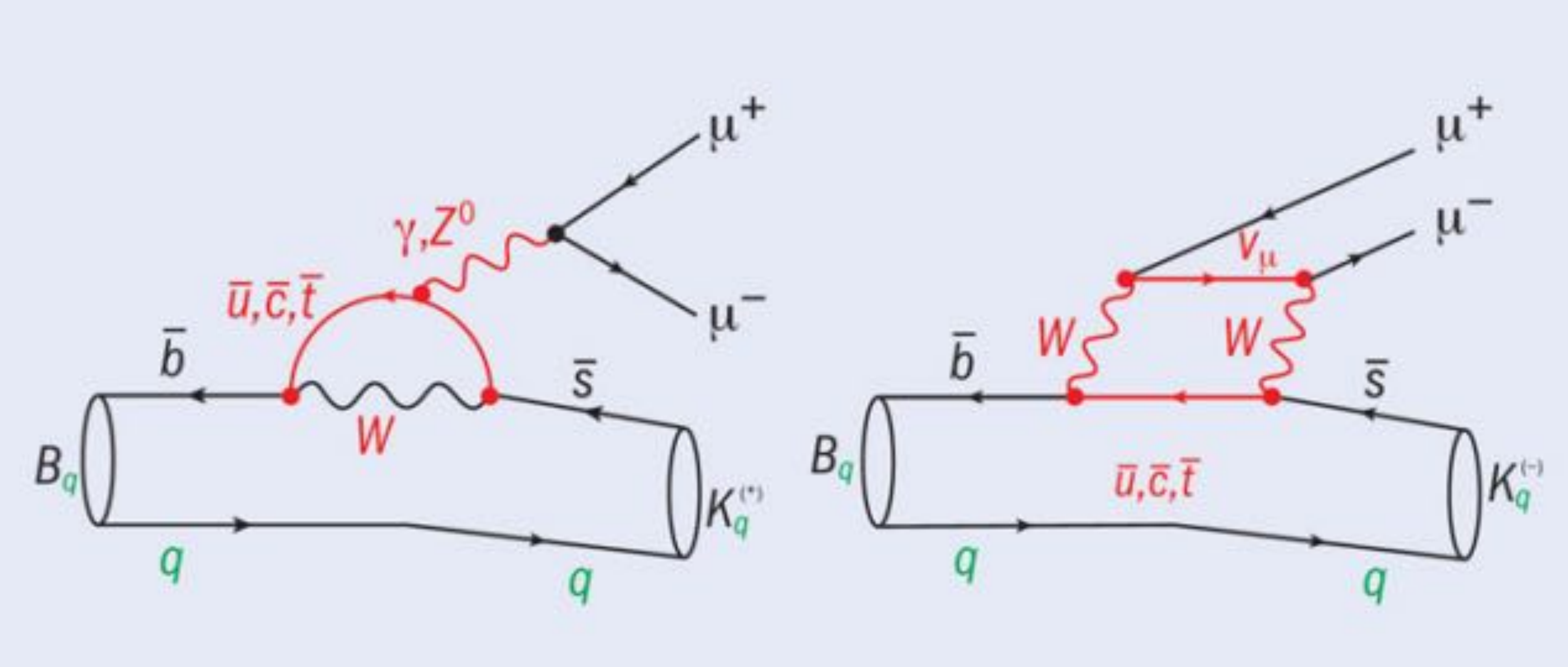


HFLAV average : https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html

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

$+3.1\sigma$ (combined) larger R_D, R_{D*} than the SM expectation!

Lepton universality tests in B-meson decays (2)



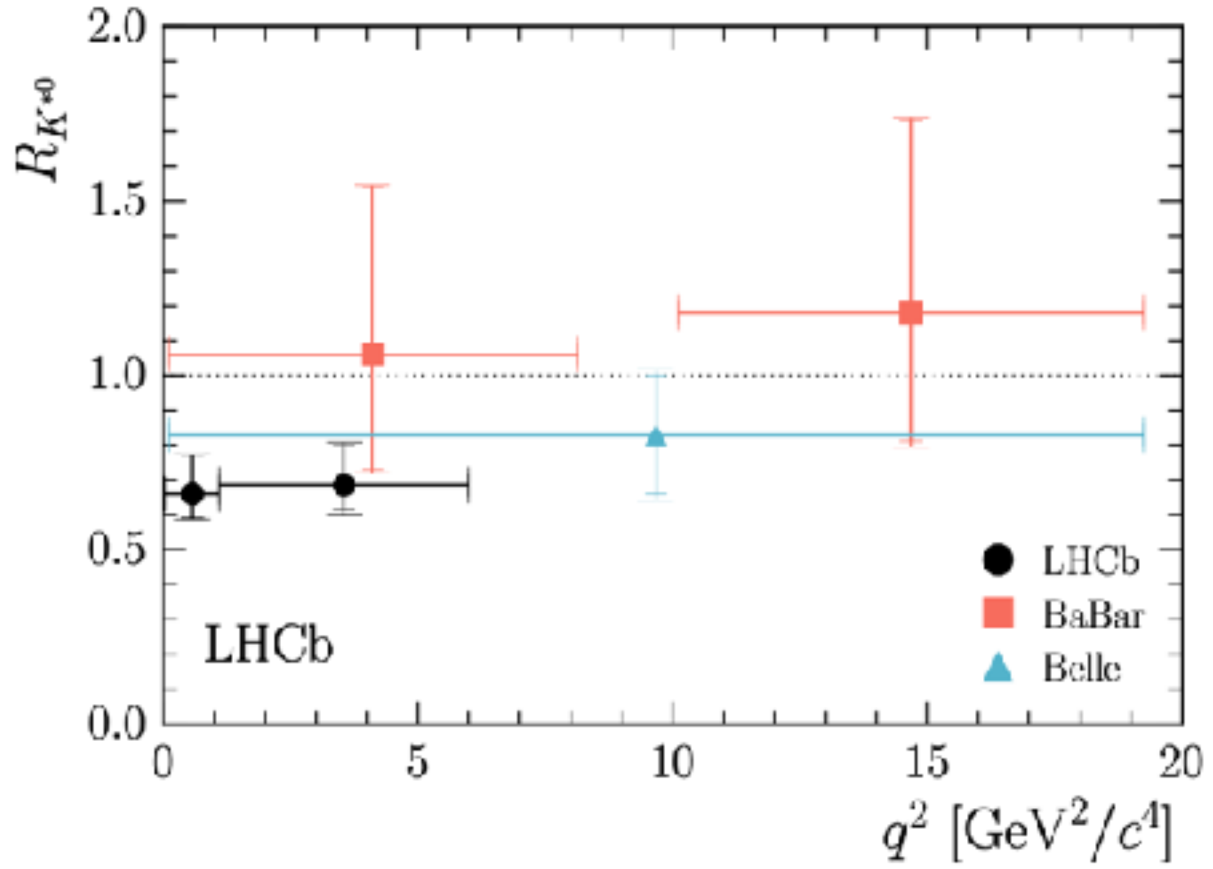
$$R_{K^{(*)}} \equiv \frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)} \approx 1.0 \text{ SM}$$

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

R_K
BaBar Collaboration
[PRD 86 (2012) 032012]

Belle Collaboration
[JHEP 03 (2021) 105]

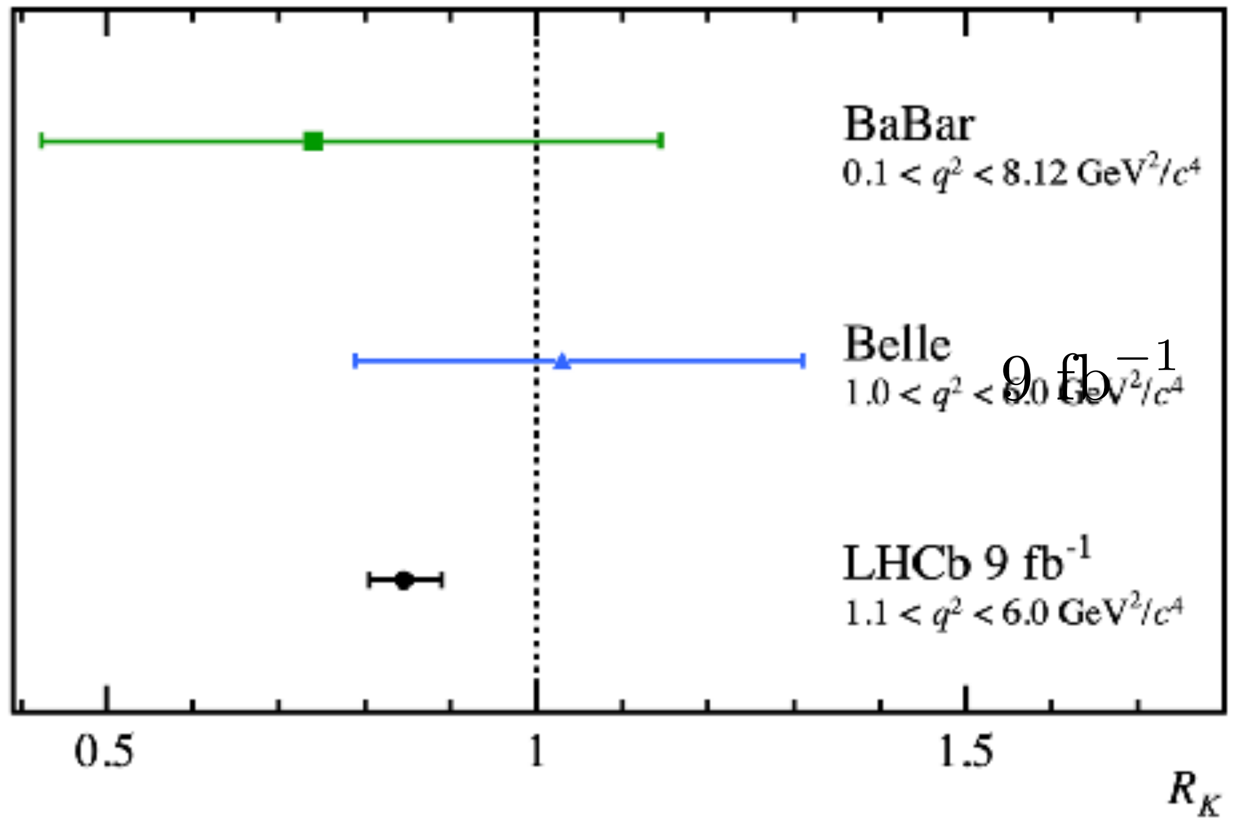
LHCb Collaboration
[2103.11769 (hep-ex)]



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

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

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

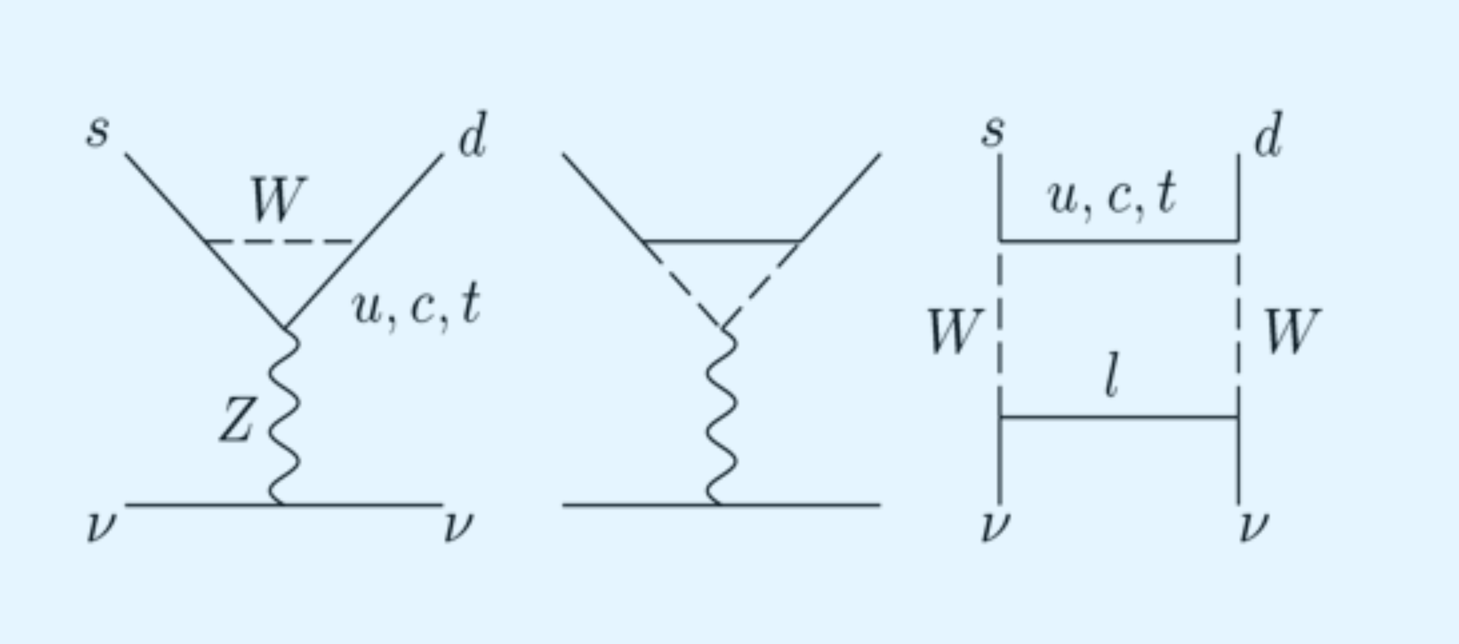


LHCb 2021, Run 1+2 full data set

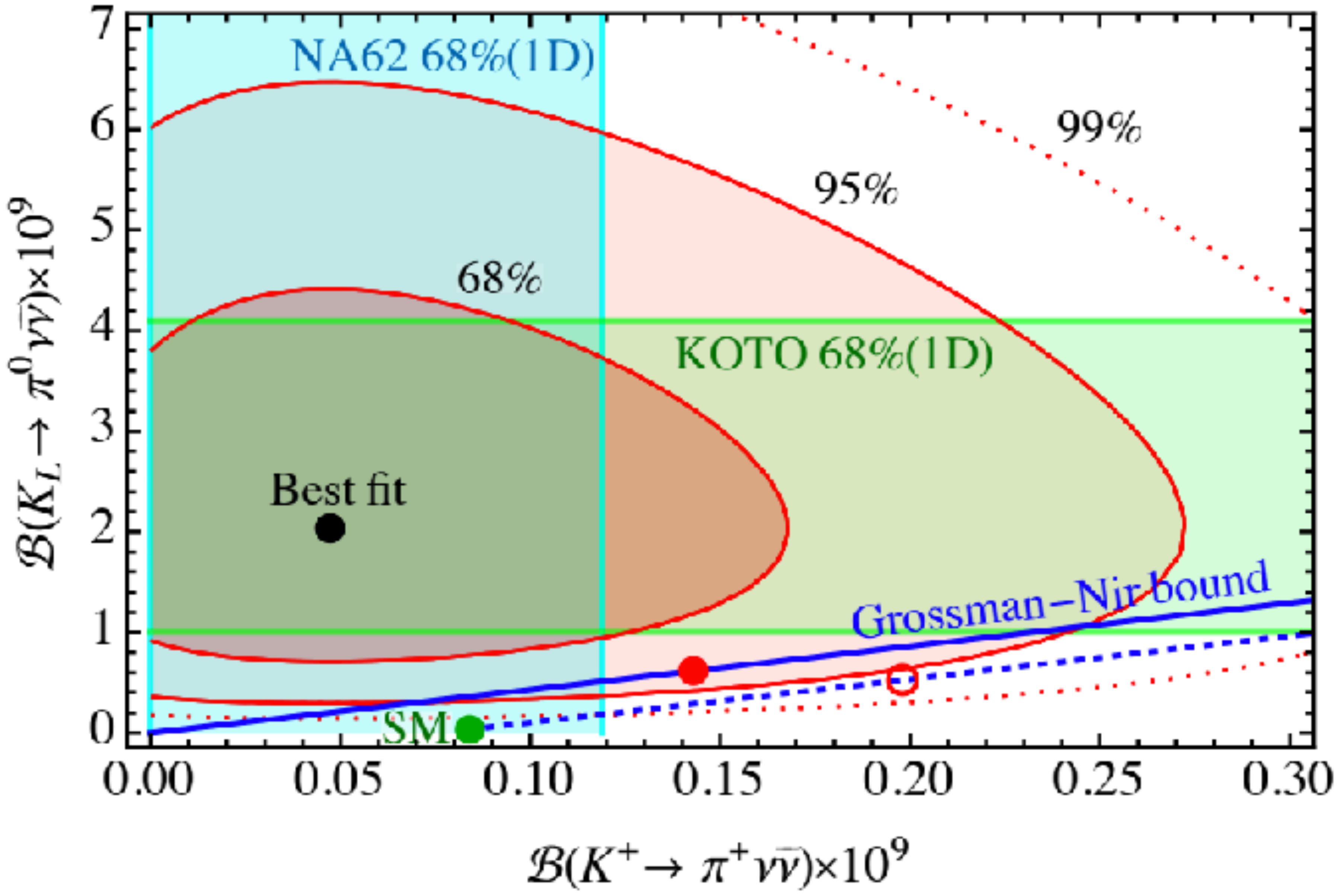
$$R_K^{[1.1,6.0]} = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

-3.1σ smaller R_K, R_{K^*} than the SM expectation!

J-PARC KOTO anomaly



$$B(K_L \to \pi^0 \nu \bar{\nu}) = \begin{cases} (2.1^{+2.0}_{-1.1}) \times 10^{-9} & \text{SM} \\ (3.0 \pm 0.3) \times 10^{-11} & \text{KOTO} \end{cases}$$

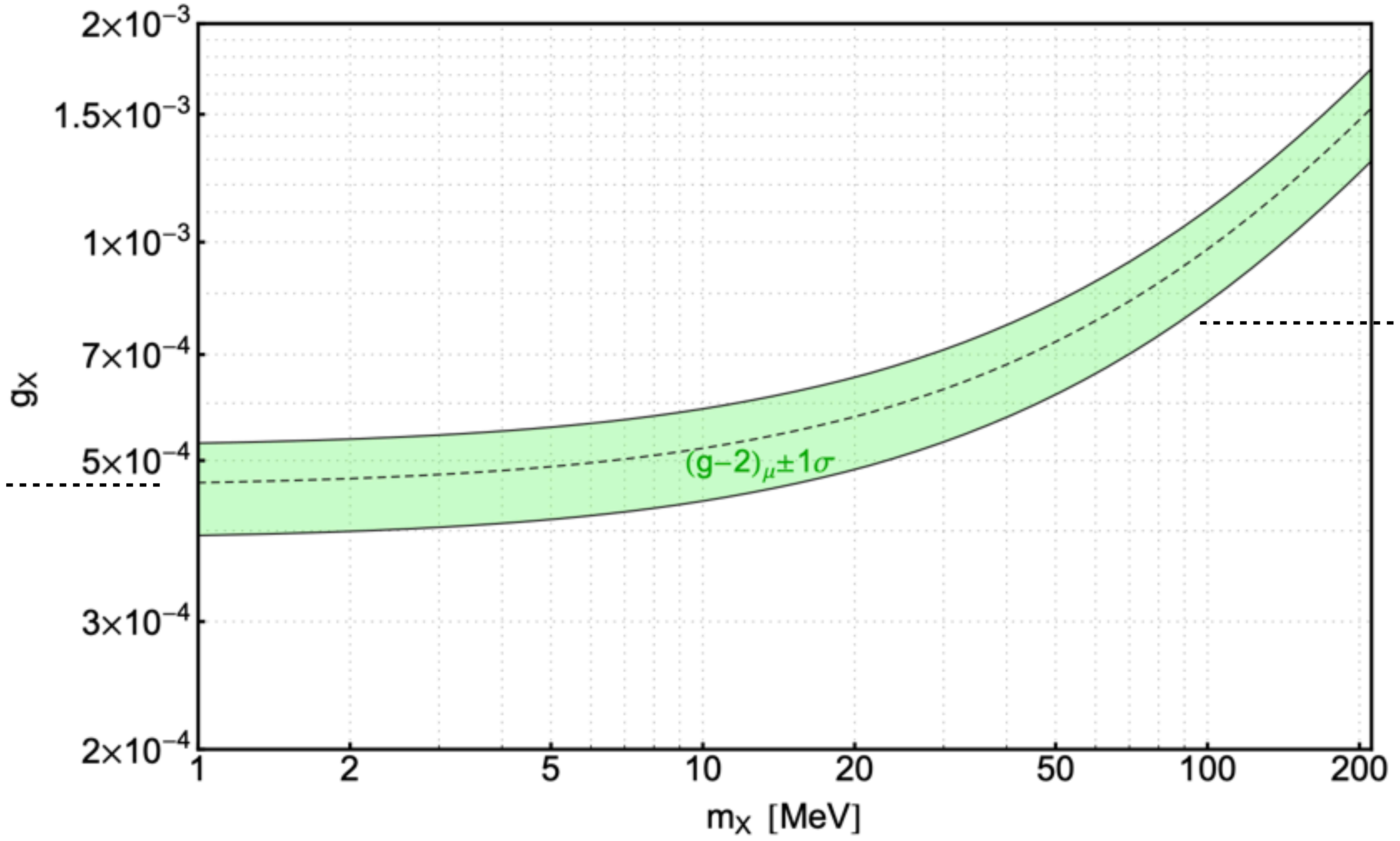


T. Kitahara et. al. 1909.11111

$\times\, 10^{-2}$ **smaller than the SM expectation!**

Muonic new force for (g-2) of muon: $\mathscr{L}_{\rm eff} \ni -g_X X_\alpha(\bar{\mu}\gamma^\alpha\mu) - \frac{1}{2}m_X^2 X_\mu X^\mu$

$$\Delta a_\mu^X = \frac{g_X^2}{8\pi^2}\int_0^1 dz\, \frac{2z(1-z)^2}{(1-z)^2 + (m_X/m_\mu)^2 z}$$ **@ 1-loop**



saturate when $m_X \ll m_\mu$

$$\Delta a_\mu^X \approx \frac{g_X^2}{8\pi^2}$$

$g_X \sim O(10^{-4})$ **preferred**

$m_X \sim (1-100)$ MeV **preferred**

'heavier, stronger'

Y.S. Jho, Y. Kwon, SCP, P-y. Tseng JHEP 10 (2019) 168 [1904.13053]

Leptonic new force

- Anomaly free extension of the SM
  - $L_i - L_j$
  - $B_i - L_j$
  - $a(B-L)_i - b(L_j - L_k)$
  - Vector LQ

$\oplus$ **Kinetic mixing of $U(1)_Y \times U(1)_X$**

$$\Delta \mathscr{L} = \epsilon B_{\mu\nu} X^{\mu\nu}$$

Typically, free parameters include

$m_X, q_X, \epsilon, (a/b)$

Effective Lagrangian for $U(1)_{\rm lepton}$

$$\mathscr{L}_{eff} \ni -X_\mu \left(g_e J_e^\mu + g_\nu J_\nu^\mu + g_\chi J_\chi^\mu \right) + \cdots$$

$$J_e^\mu = \bar{e}\gamma^\mu e$$
$$J_\nu^\mu = \bar{\nu}_L \gamma^\mu \nu_L$$
$$J_\chi^\mu = \bar{\chi}\gamma^\mu \chi$$

Controllable parameters : $g_e, g_\nu, m_X, g_\chi, m_\chi$

LQ models

$LQ \to q + \ell$

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	$\bar{q}^c_L \ell_L$ 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	$-1/6$	$\bar{u}^c_R \gamma^\mu \ell_L$
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]

LQ for $R_{D^{(*)}}, R_{K^{(*)}}$

All possible LQs couples to quark + lepton

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

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

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

U_1: isospin singlet vector leptoquark

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

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

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]

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

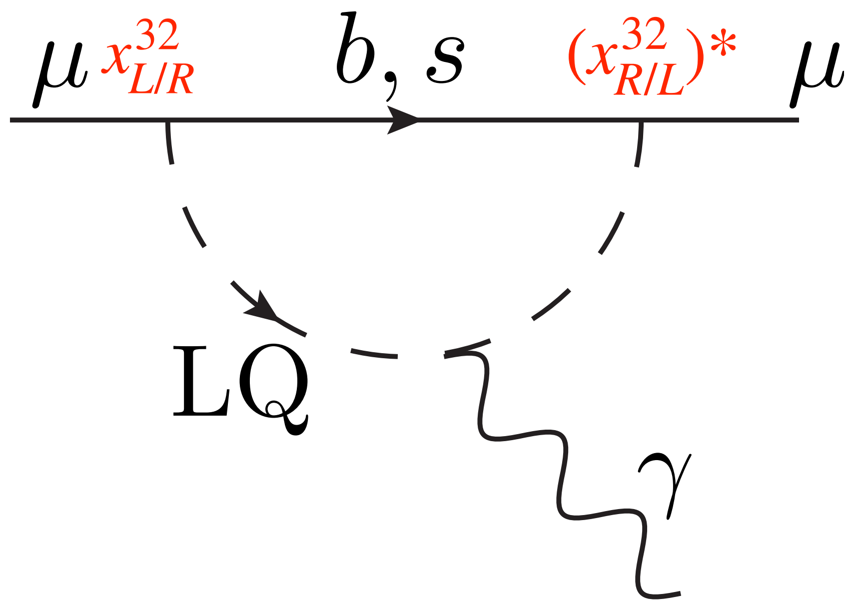
⊃ QCD&EM interactions

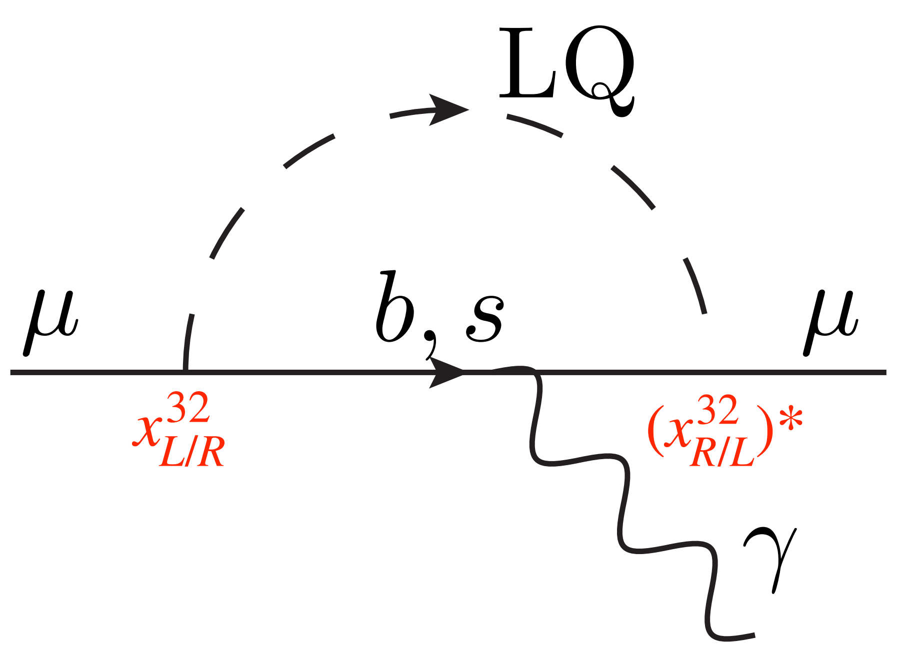
(effective) LQ interactions

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

$$D_\mu \equiv \partial_\mu - i g_s G^a_\mu T^a_{13} - i \frac{2}{3} g_Y B_\mu$$

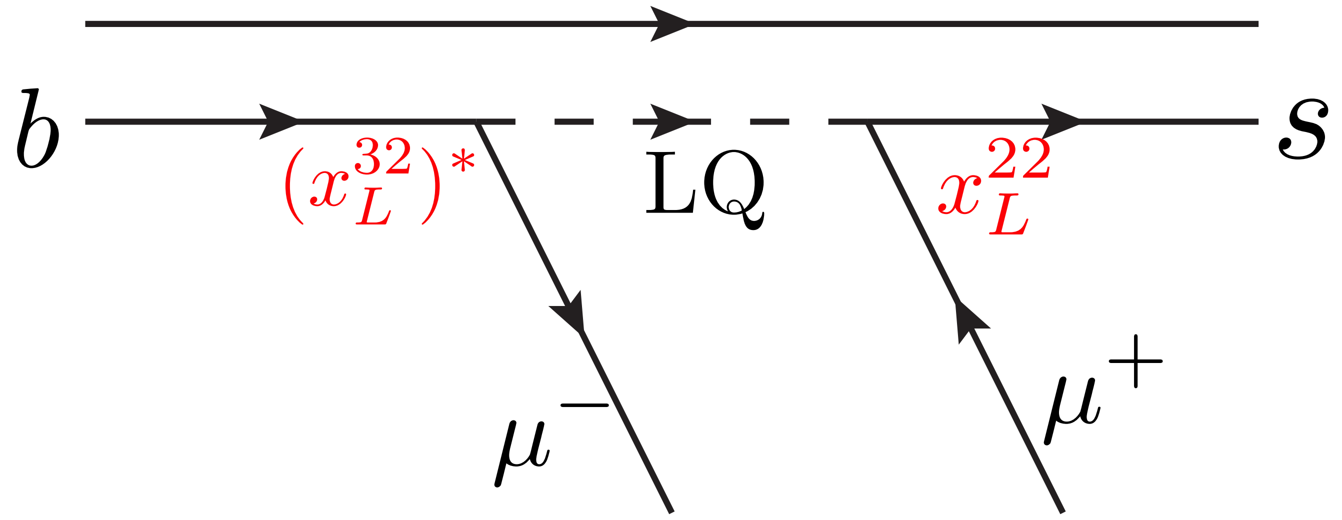
LQ contributions





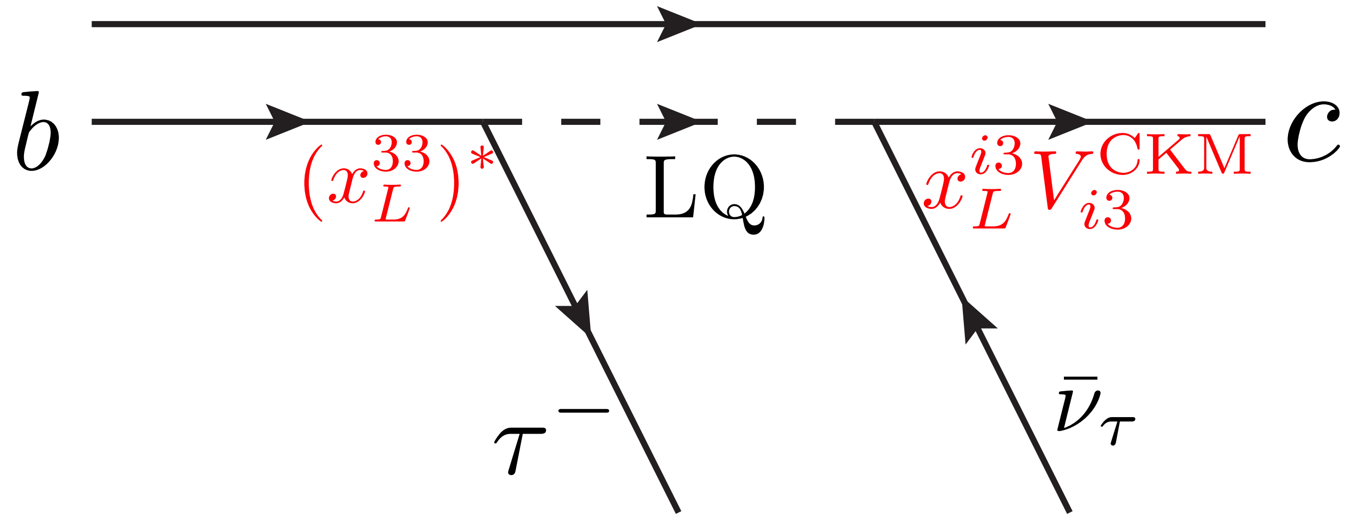
$$\frac{1}{\Lambda_1}(\bar{\mu}_L \sigma^{\mu\nu}\mu_R)F_{\mu\nu} \qquad (g-2)_\mu$$

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



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

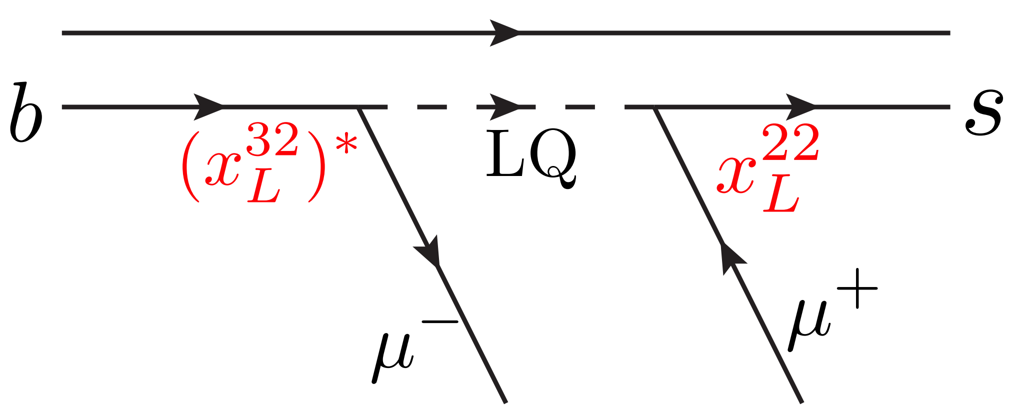
$$-\frac{x_L^{22}(x_L^{32})^*}{m_{\mathrm{LQ}}^2} \subset [0.83, 1.41] \times 10^{-3}\ \mathrm{TeV}^{-2}$$



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

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

Ballpark & Constraints

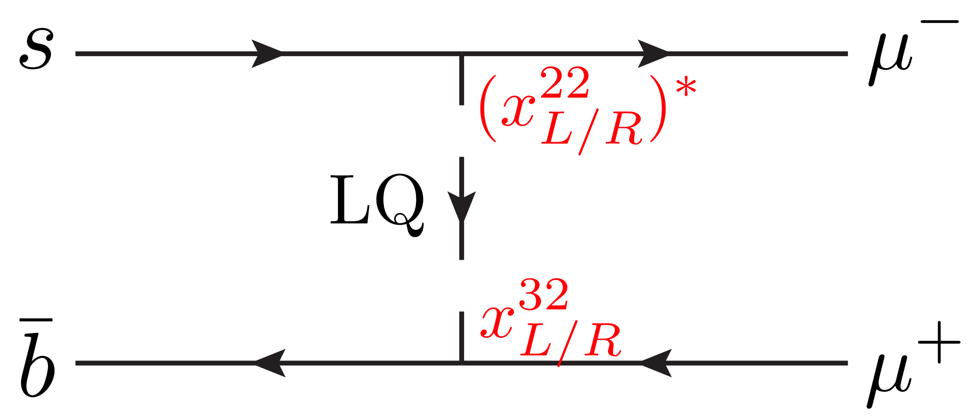


$$R_{K^{(*)}} \equiv \frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)}$$

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

3.1σ (R_K)

+

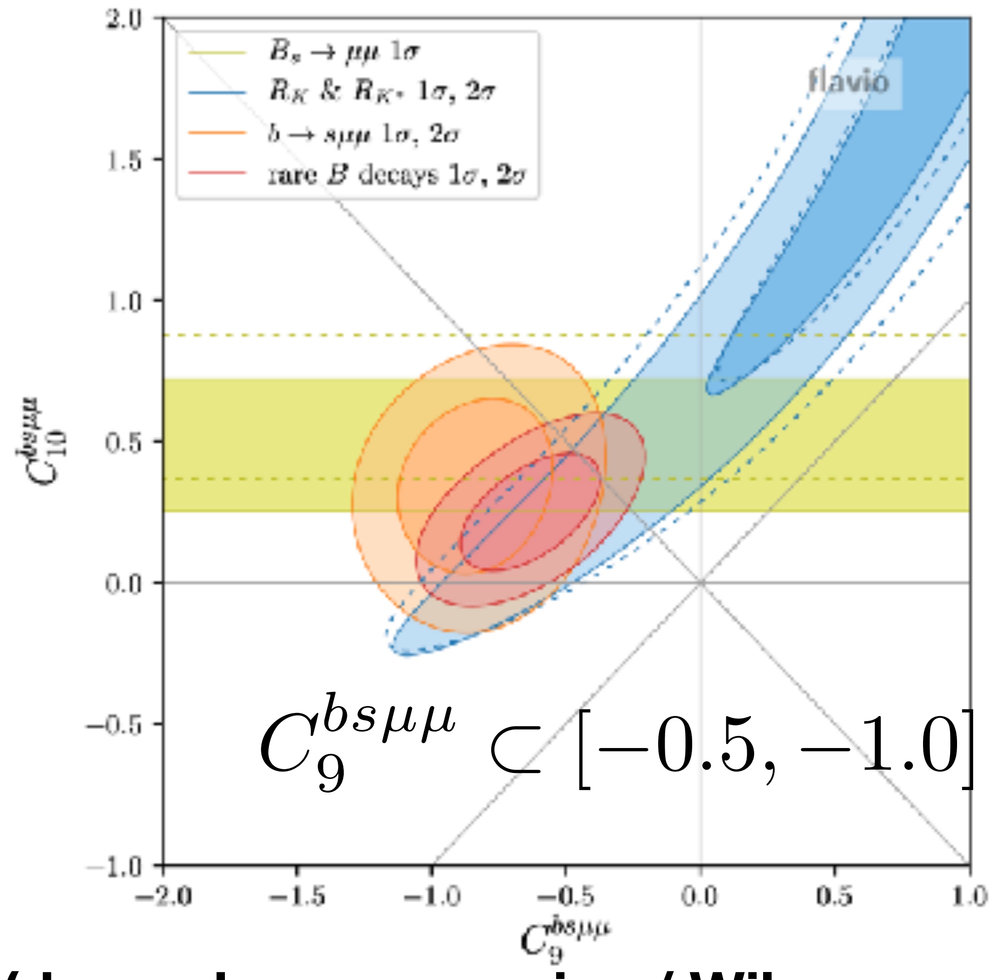


$$\frac{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{exp}}}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} = 0.73^{+0.13}_{-0.10}$$

(2.1σ away from SM)

[ATLAS-CONF-2020-049]

W. Altmannshofer, P. Stangl [2103.13370]

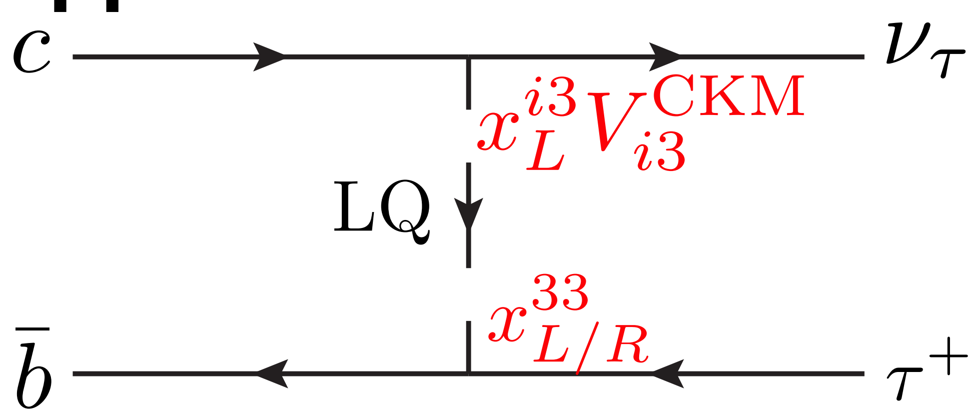


$$\mathcal{O}_9^{\ell_1\ell_2} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}_1\gamma^\mu\ell_2),$$

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

(depends on scenarios / Wilson coefficients)

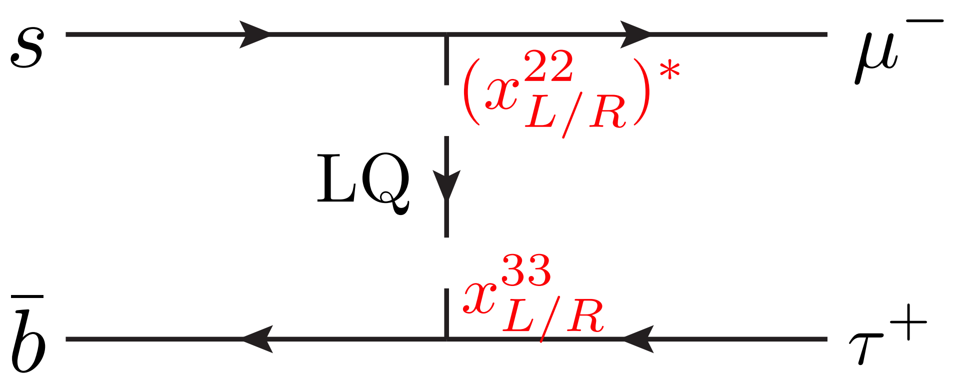
Upper limits from LFV in B-meson decays



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

A. G. Akeroyd et al.

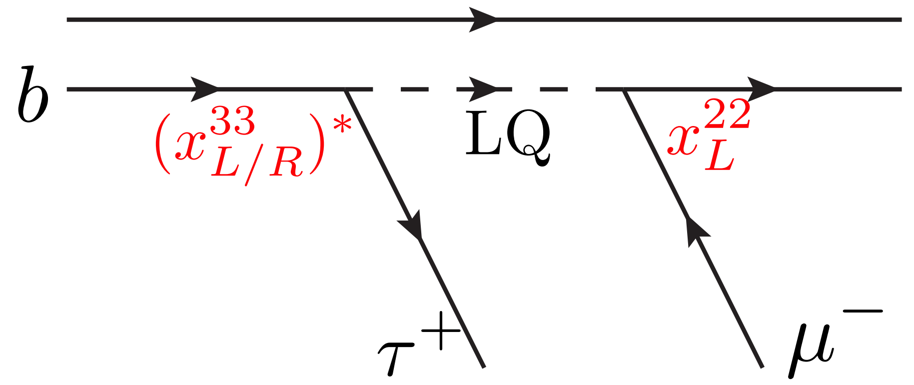
[PRD 96 (2017) 075011]



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

LHCb Collaboration

[PRL 123 (2019) 211801]

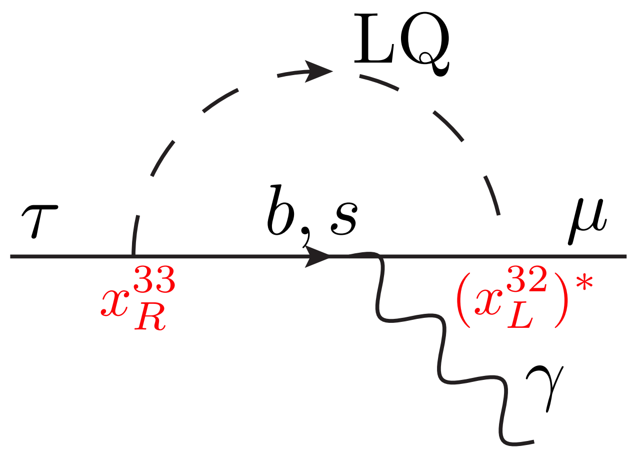


$$\mathrm{Br}(B^+ \to K^+\tau^+\mu^-) < 2.8 \times 10^{-5}$$

BaBar Collaboration

[PRD 86 (2012) 012004]

Upper limits from LFV in tau decays



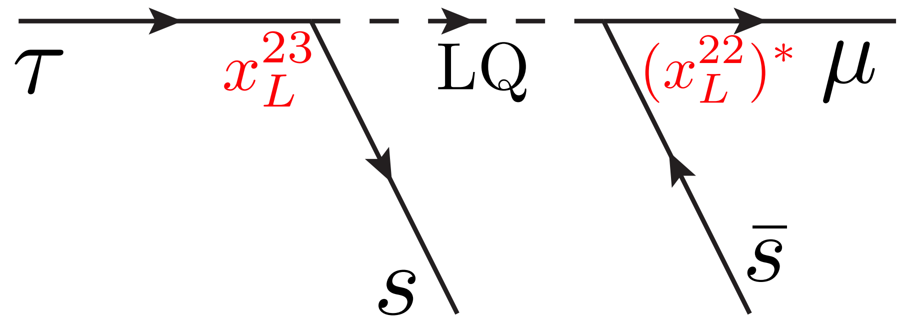
$$\mathrm{Br}(\tau \to \mu\gamma) < 3 \times 10^{-8}$$

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]

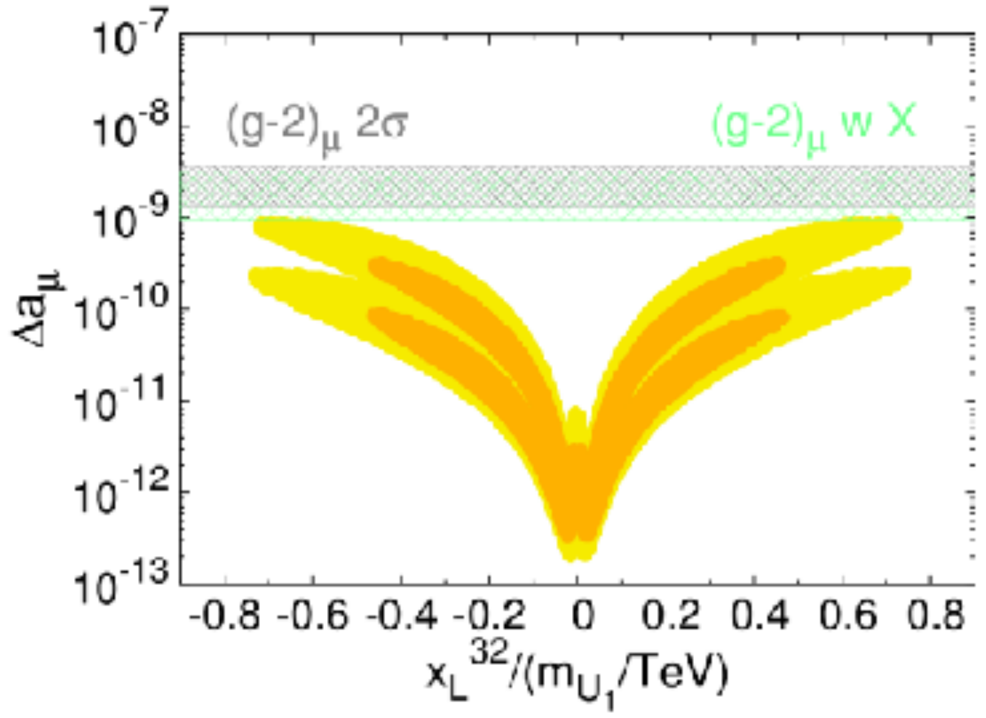
LQ + X for B-anomalies & (g-2)

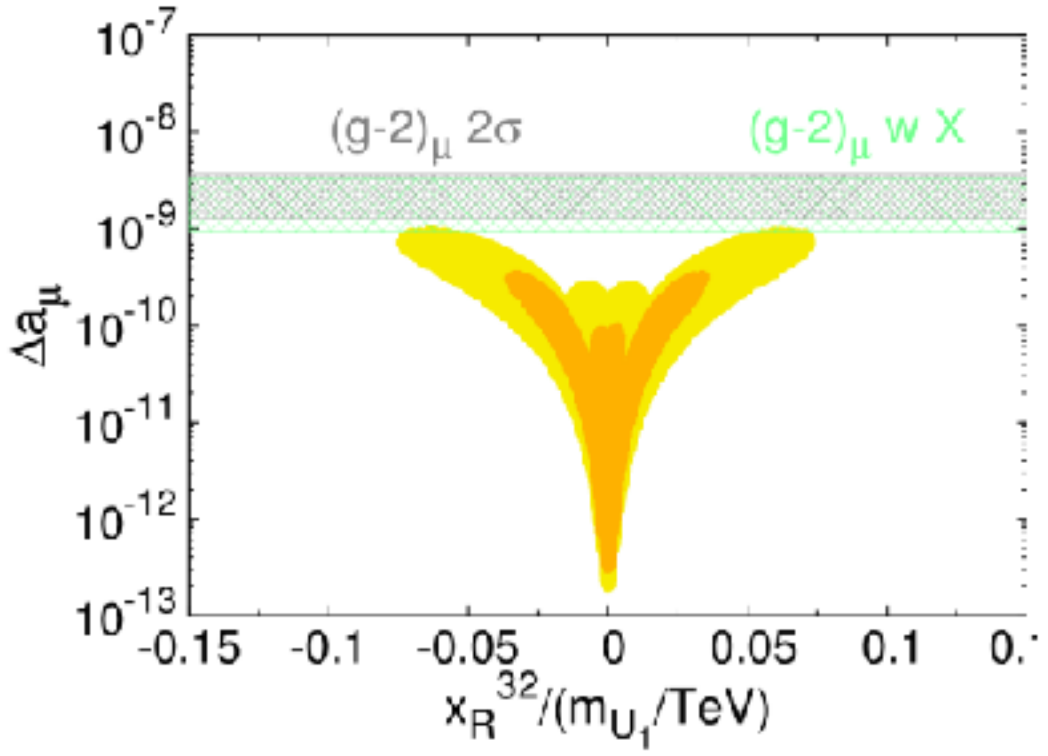
for B-anomalies

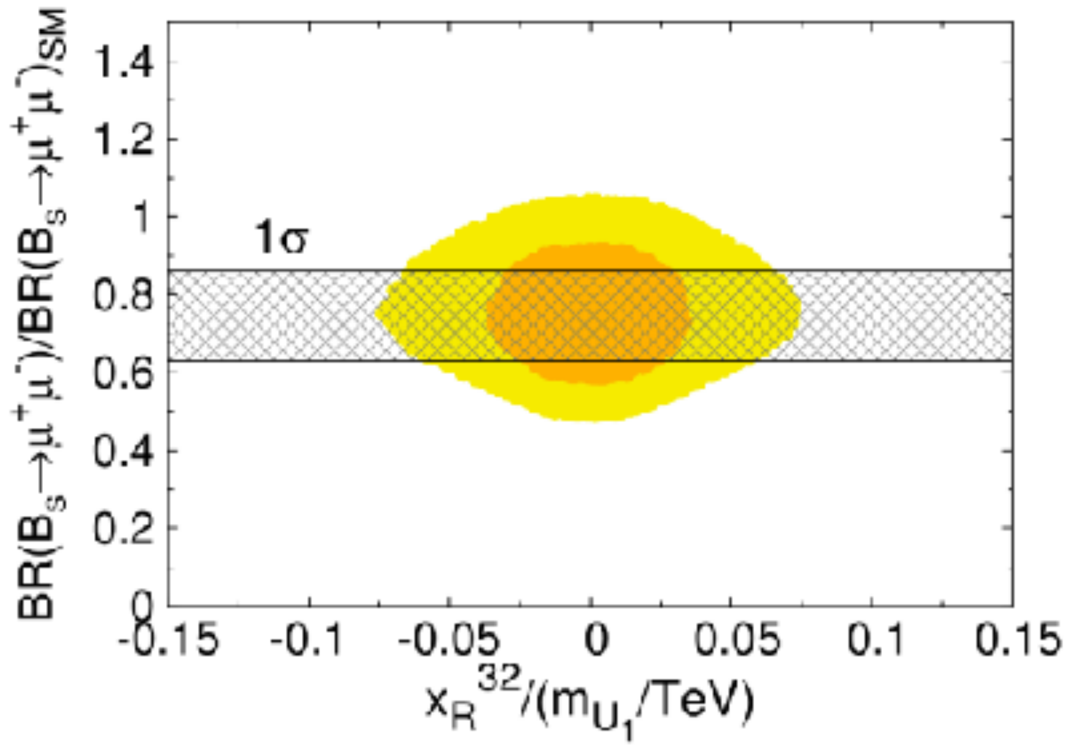
- $\Delta\chi \leq 5.99$
- $\Delta\chi \leq 2.30$

LQ only

$m_{LQ} = 2\text{TeV}$





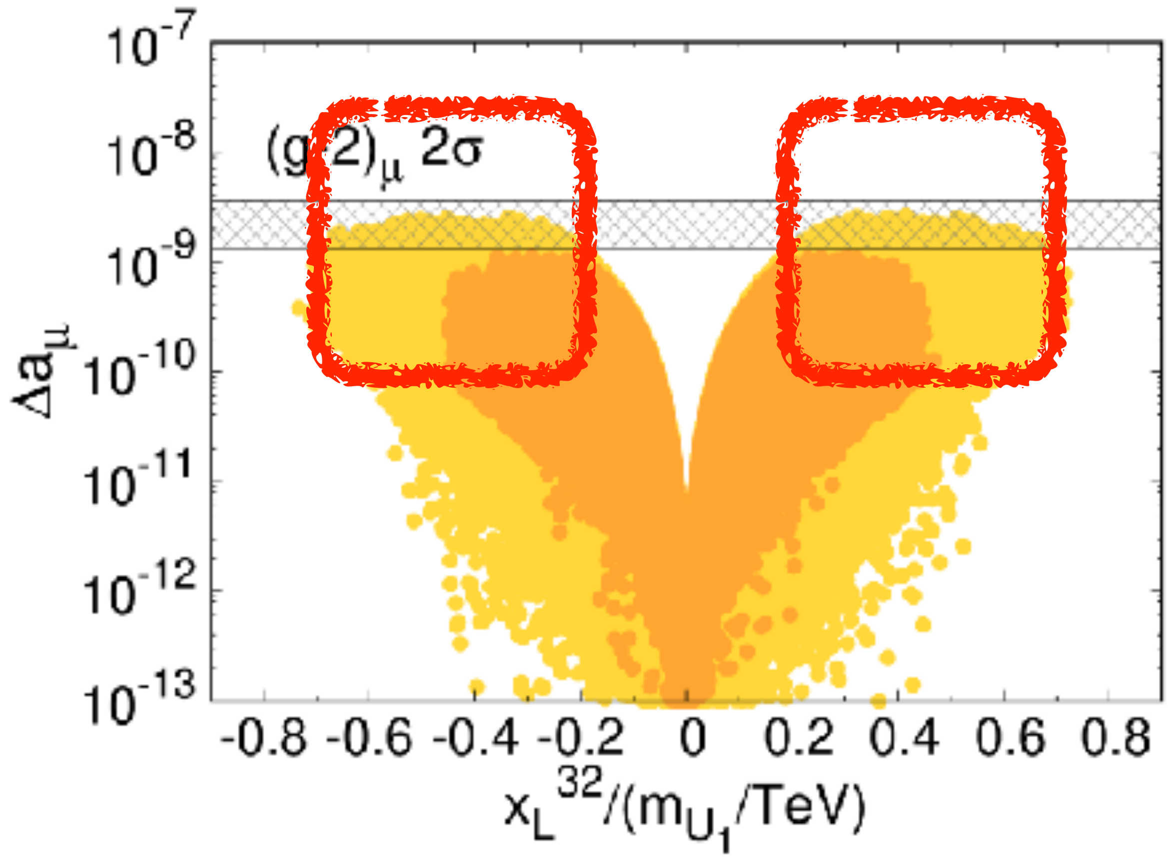


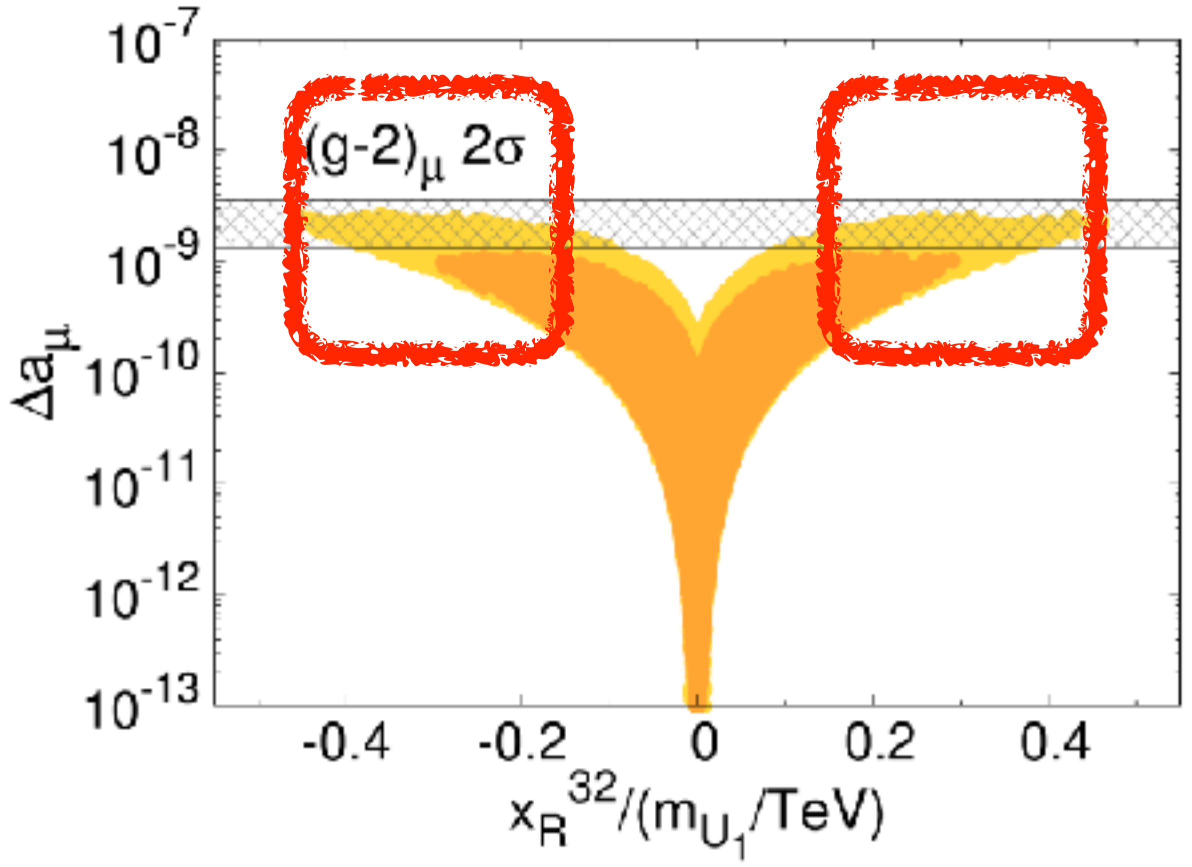
The couplings $x_L^{32} \sim x_R^{32} \sim 0.3$ & $U(1)_{B_3-L_2}$ X-boson provide an excellent explanation!

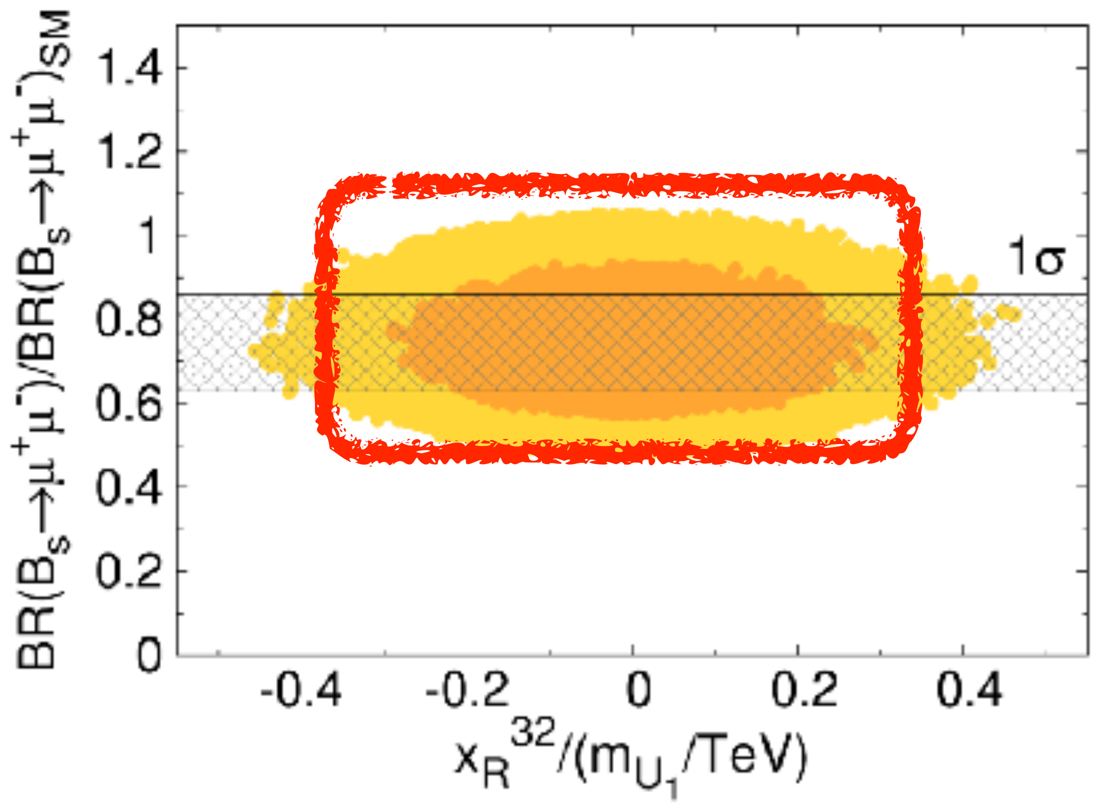
LQ +X

$m_{LQ} = 2\text{TeV}$

$m_X = 100\ \text{GeV}$



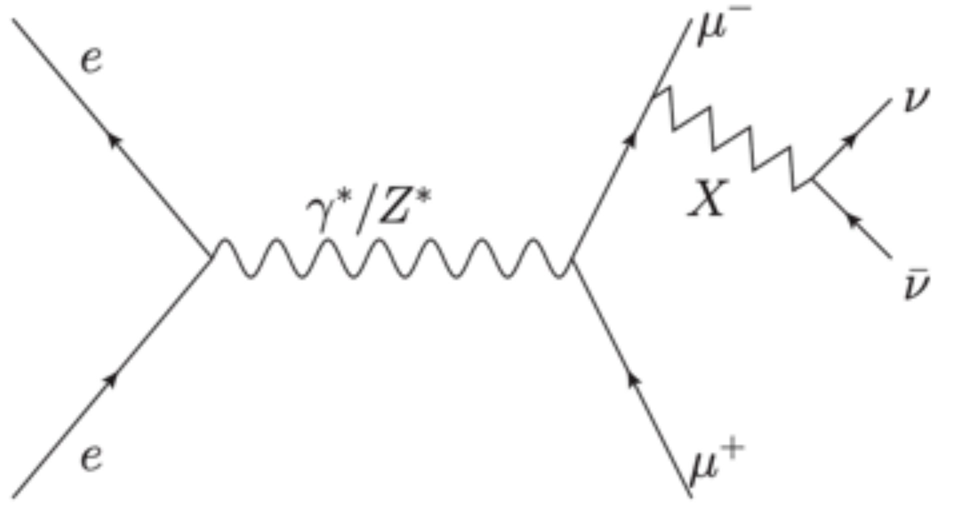


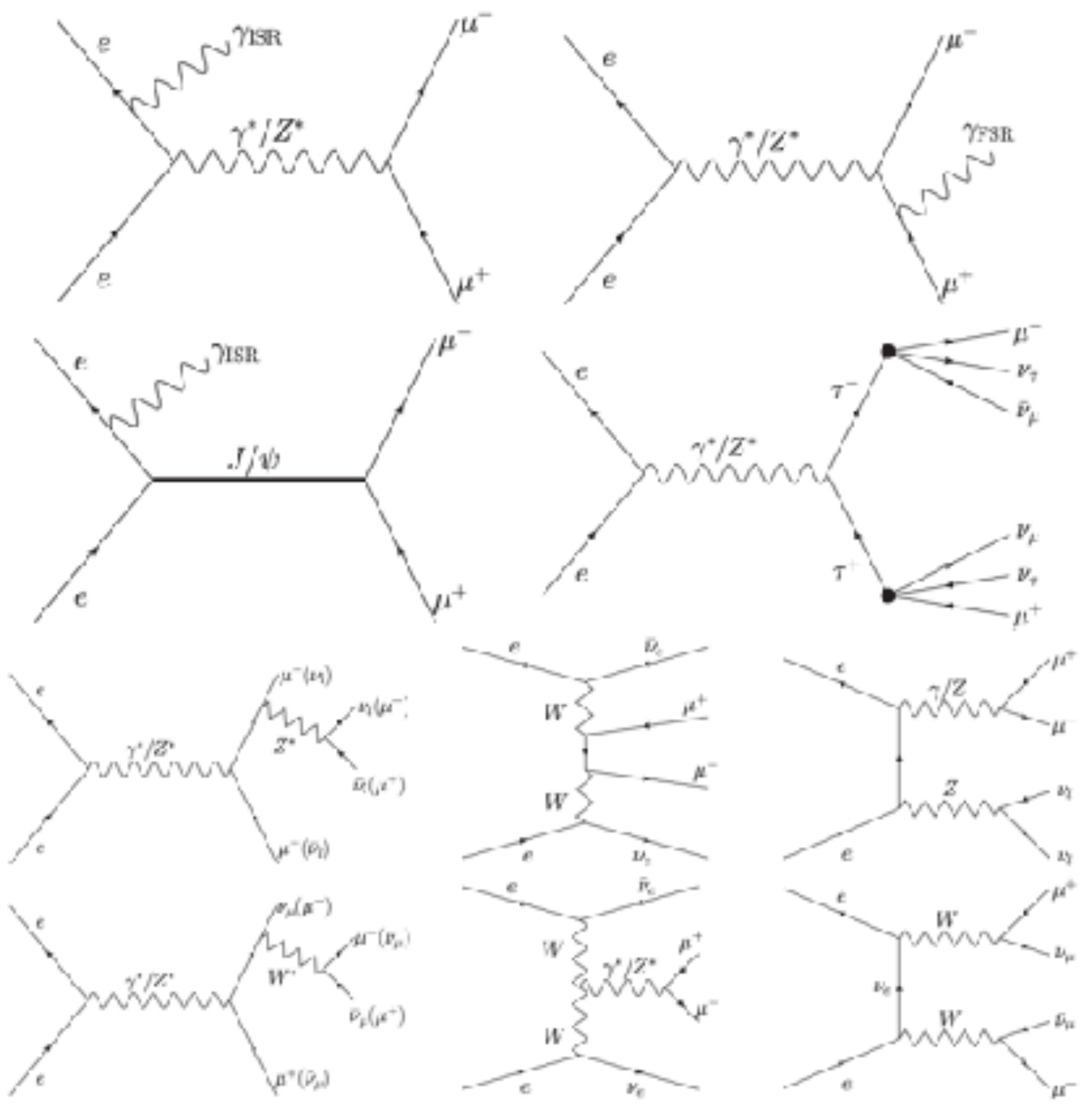


K. Ban, Y. Jho, Y. Kwon, SCP, S. Park, P.-Y. Tseng[2104.06656]

Searches of X at BELLE-II

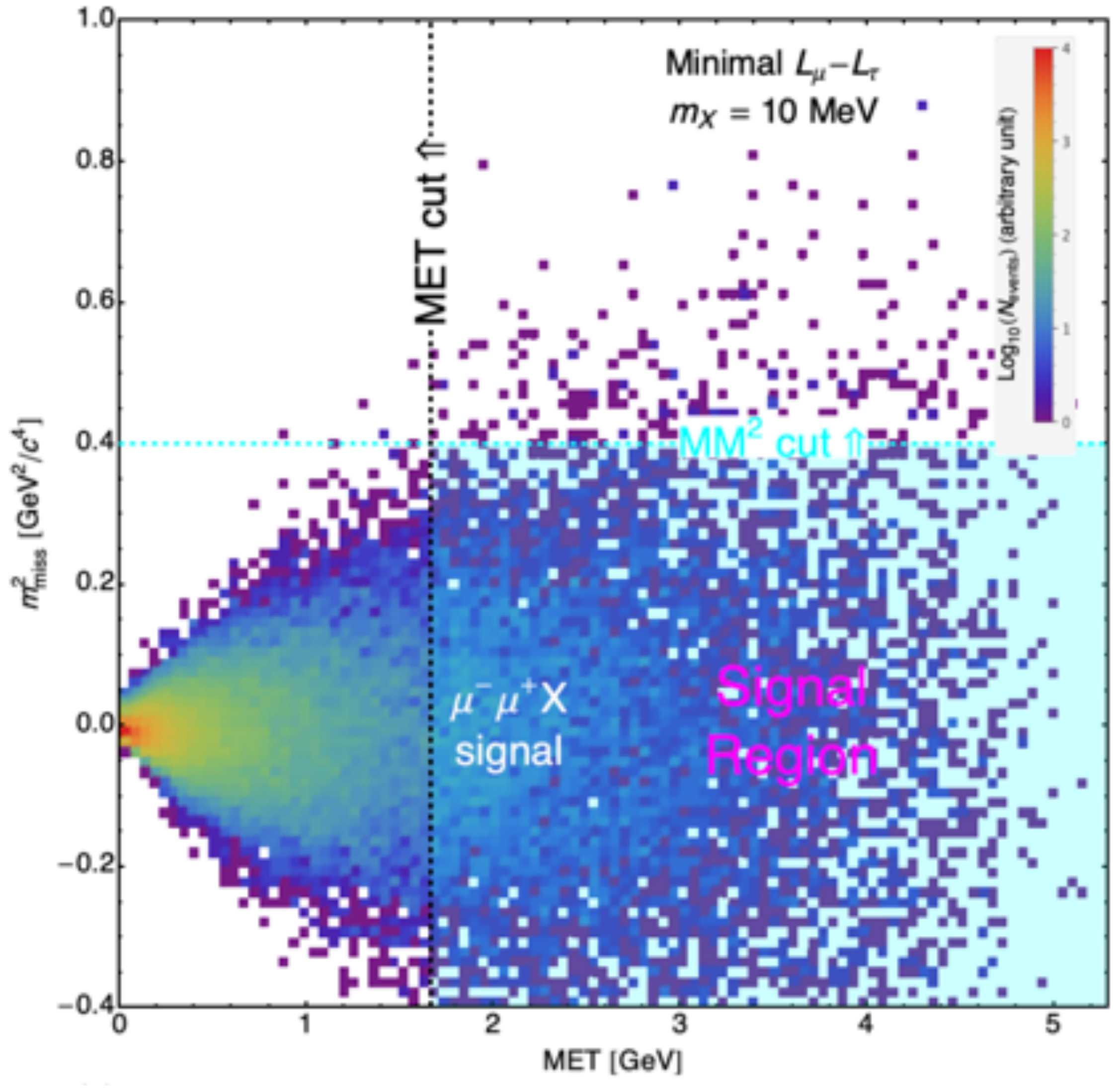
signal

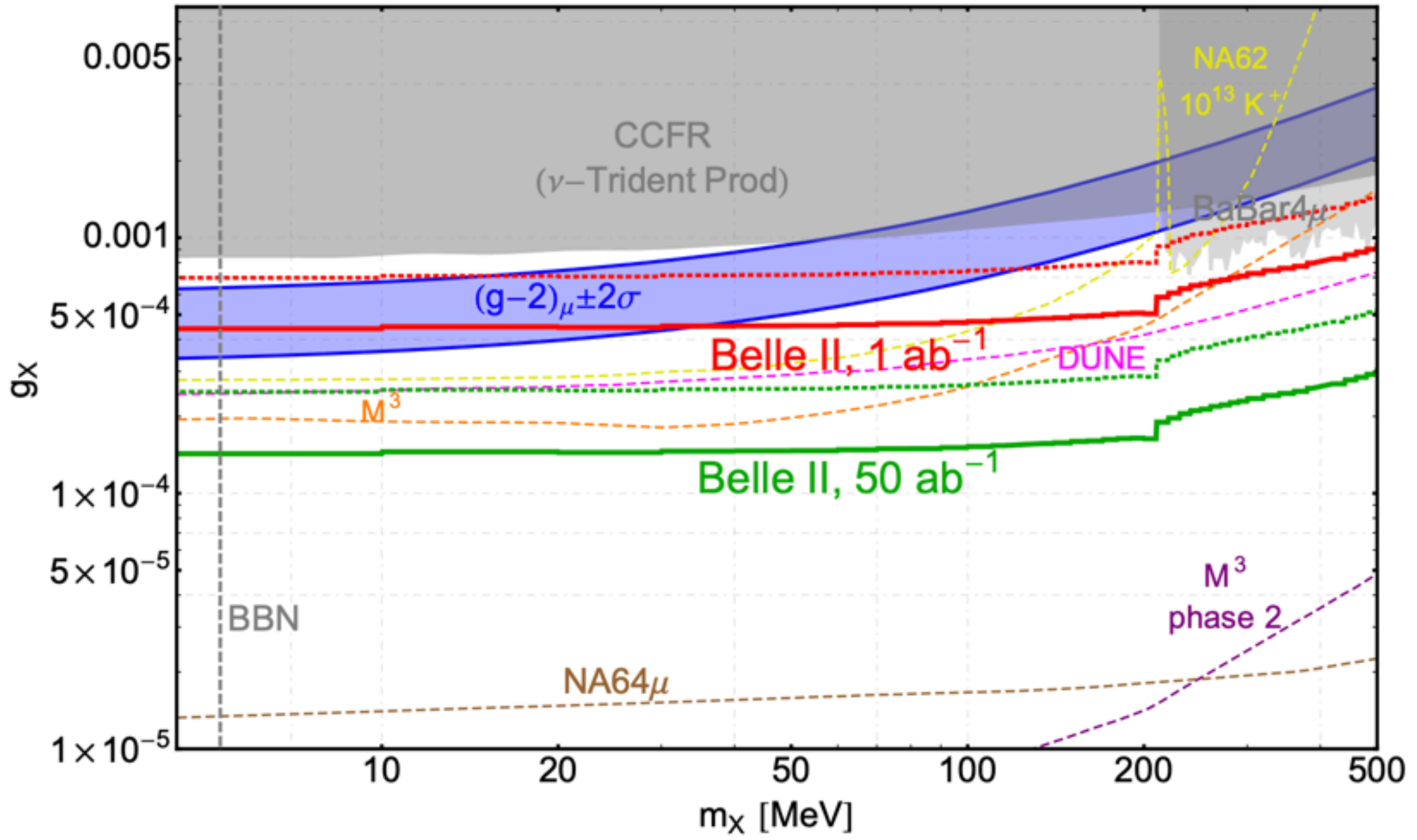




background

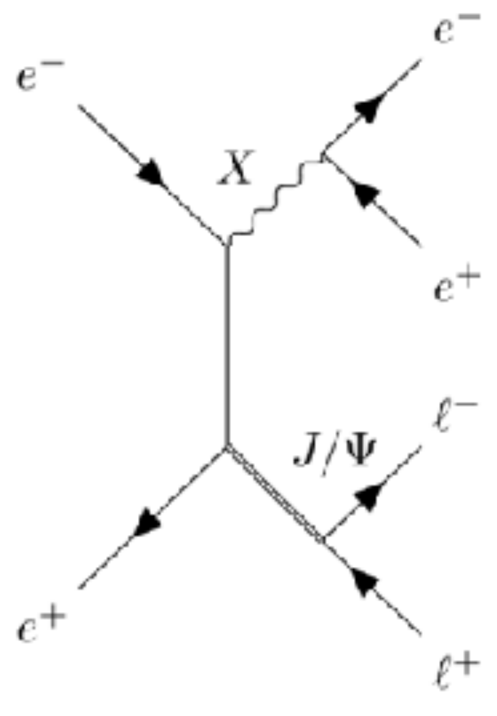
background rejection by MET, MM^{2}, etc

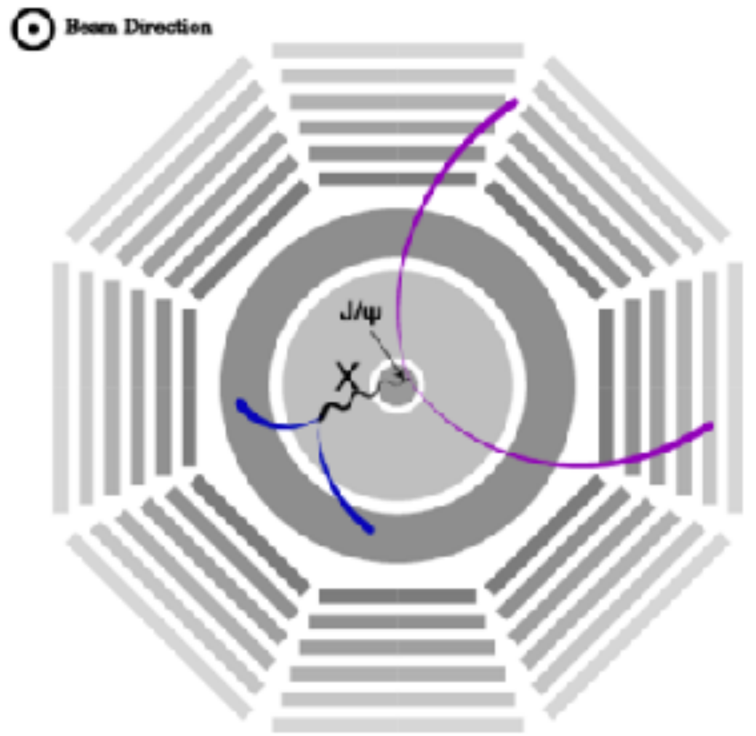




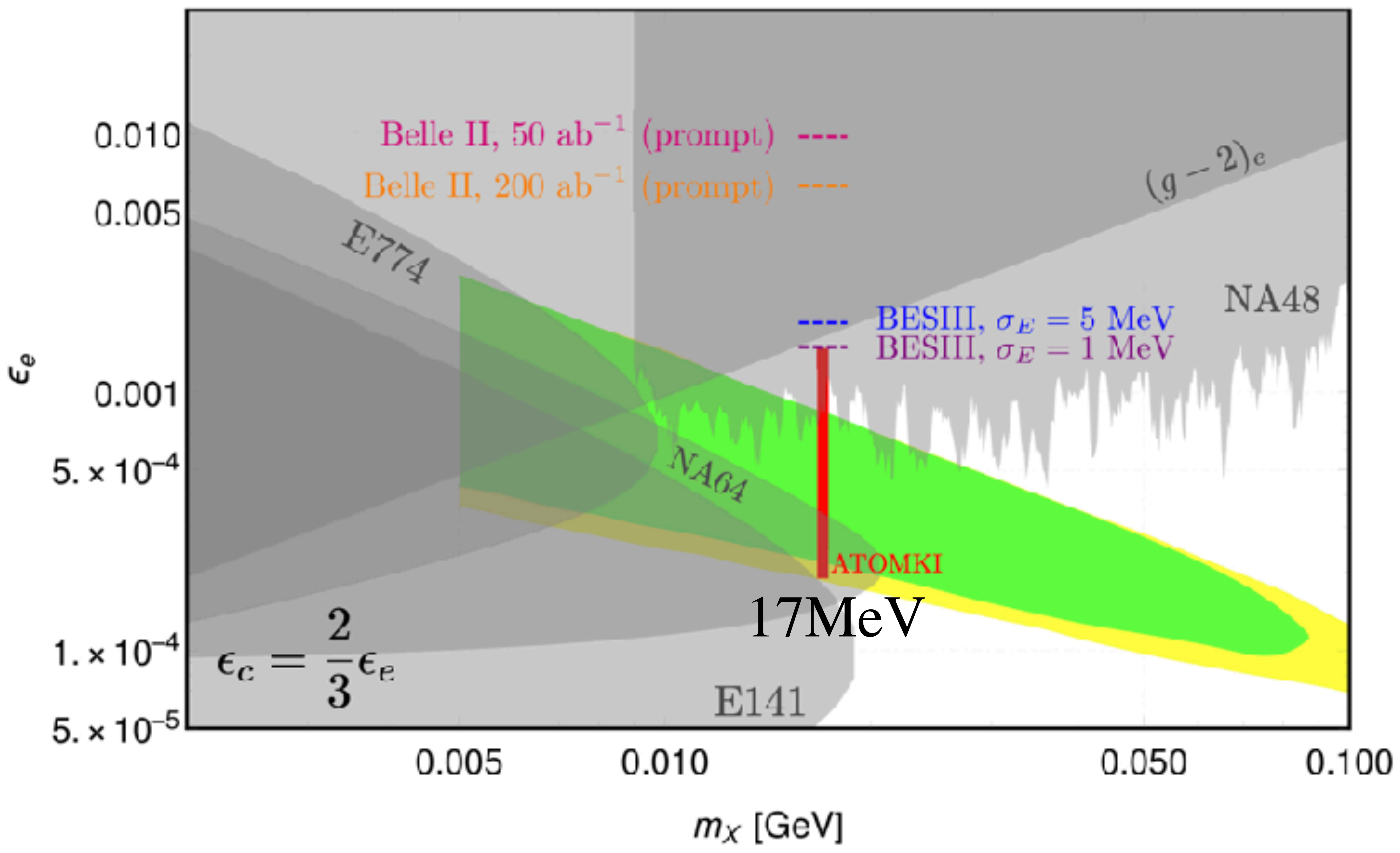
Y.S. Jho, Y.J.Kwon, SCP, P-y. Tseng, *JHEP* 10 (2019) 168 [1904.13053]

Searches of X at BELLE-II



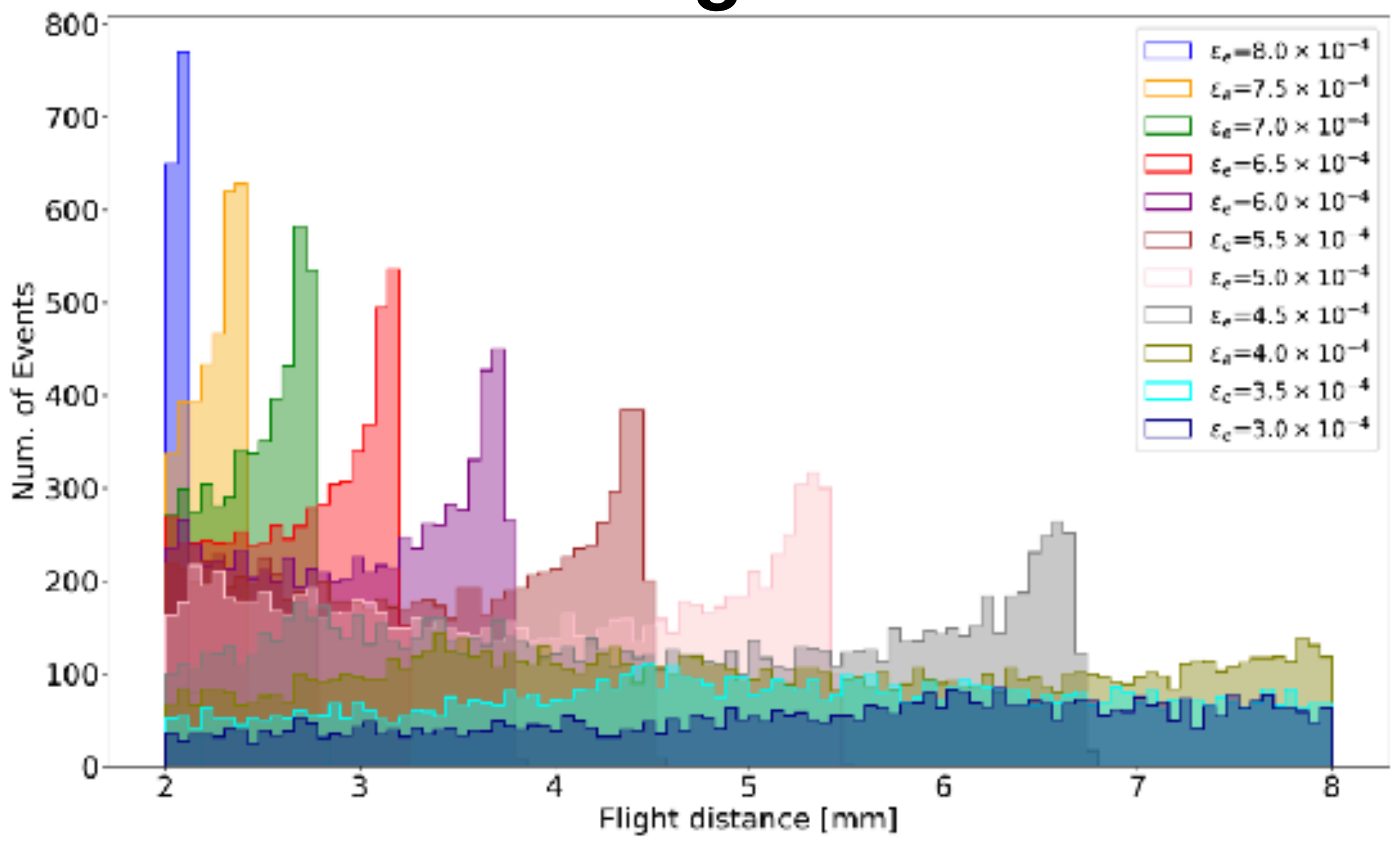


$g_X = e\epsilon_e$



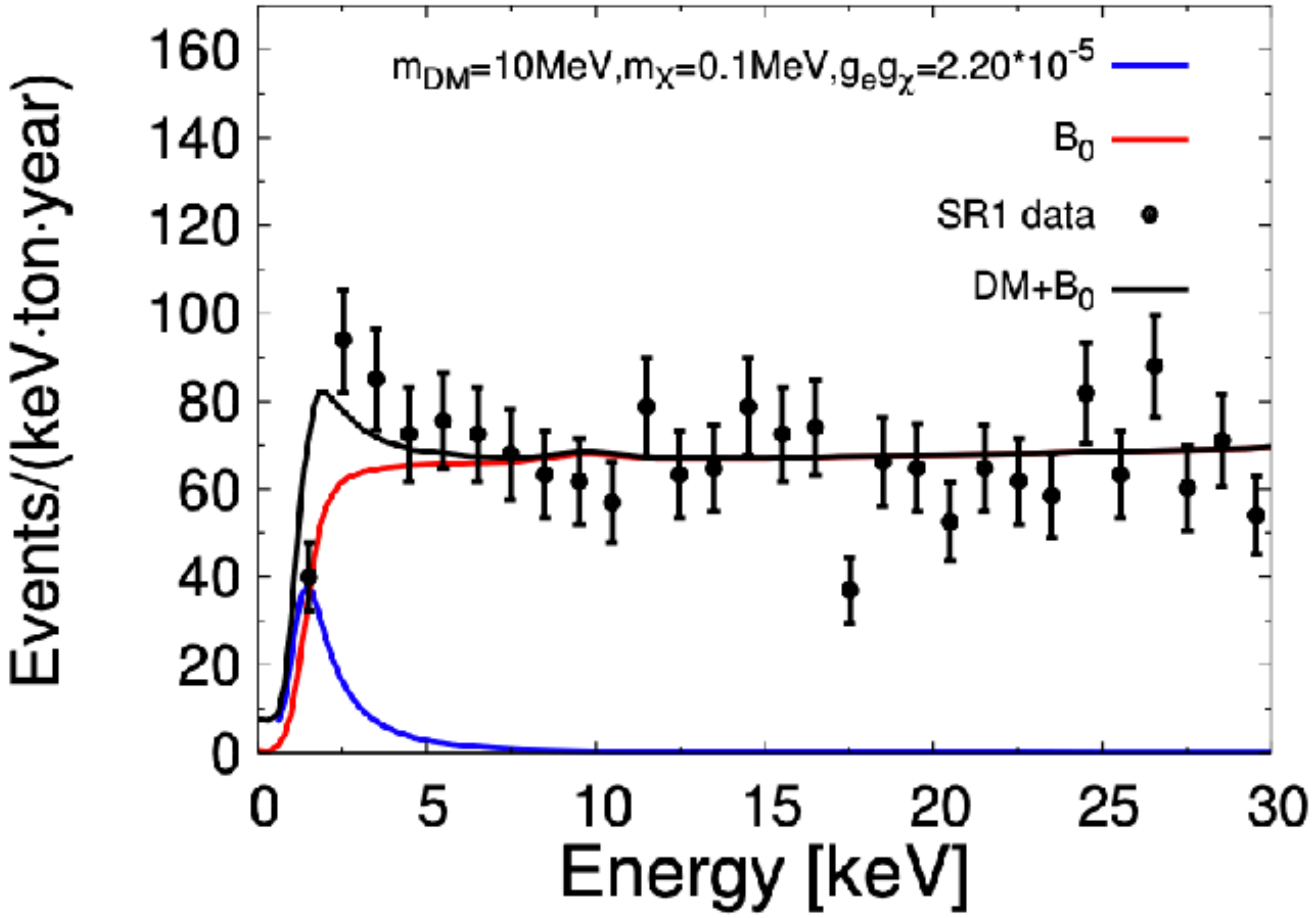
K. Ban, Y.S. Jho, Y.J.Kwon, SCP, S.Park *JHEP* 04 (2021) 091 [2012.04190]

if Long lived



New mediator for Dark sector

- The new force can be an excellent mediator for dark sector
- e.g. $\mathscr{L} \ni -X_\mu \left(g_\ell J^\mu_\ell + g_\chi J^\mu_\chi \right)$
- NEW Boost mechanism: CR electrons or CR neutrinos can boost DM and the boosted DM can be detected.
- e.g. Xenon1t_e O(1) keV electron recoil events with 3.5σ significance Xenon collab. PRD102 no 7, 072004 (2020)



Y.S. Jho, J.C.Park, SCP, P-y. Tseng, PLB811 (2020) 2006.13910

Summary

- We are motivated to consider new leptonic interactions : $(g-2)_\mu, R_{D,D*,K,K*}$, KOTO anomaly, DMe anomaly…

- Various theoretically well motivated possibilities exist : $L_i - L_j, B_i - L_j, (L_i - L_j) + x(B_i - L_j)$, and LQ etc…

- Using combinations of available models, we indeed can explain those anomalies (even though not necessarily by a single model)

- ‘Clean’ leptonic experiments (such as Belle-II, J-PARK, Xenon-nt, and **ILC**) are definitely helpful! Especially when MET/Missing Masses are involved and if New Physics only couples through leptons.