Leptoquark and vector-like quark extended models as the explanation of the muon $g - 2$ anomaly

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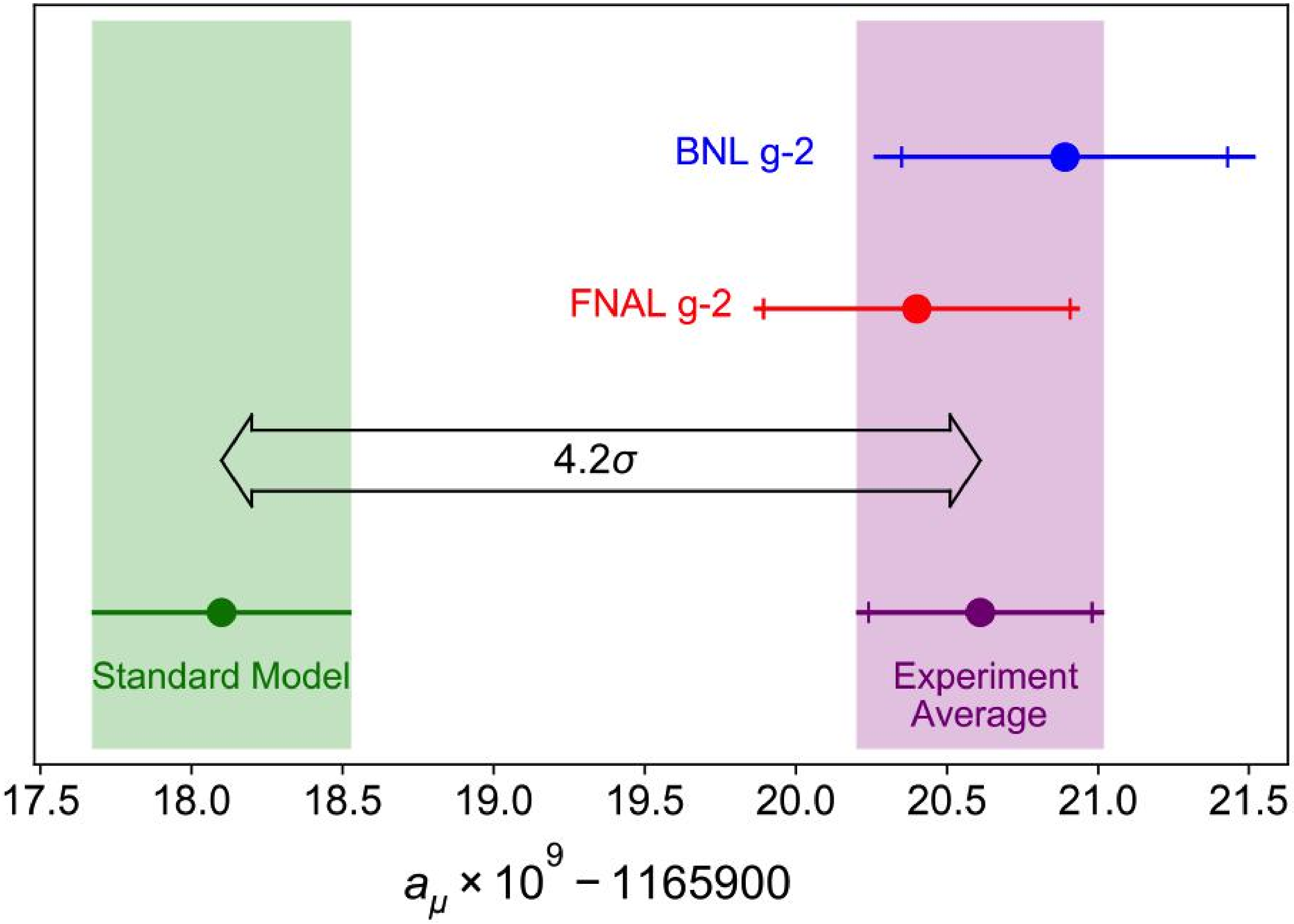
1. $(g-2)_\mu$ introduction



FNAL (2021)

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

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

$a_\mu(\mathrm{Exp}) = 116592061(41) \times 10^{-11}$

$a_\mu(\mathrm{SM}) = 116591810(43) \times 10^{-11}$

T. Aoyama et al. (2020)

$a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$

4.2 σ deviation?

$(g-2)_\mu$ prediction in the standard model (SM)

$$a_\mu(\text{SM}) = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{Had}}, \quad a_\mu^{\text{Had}} = a_\mu^{\text{HVP}} + a_\mu^{\text{HLbL}}$$

$$a_\mu^{\text{QED}} = 116584718.931(104) \times 10^{-11}$$

up to tenth order (5-loop)

$$a_\mu^{\text{EW}} = 153.6(1.0) \times 10^{-11}$$

up to 2-loop

$$a_\mu^{\text{HVP}} = a_\mu^{\text{HVP, LO}} + a_\mu^{\text{HVP, NLO}} + a_\mu^{\text{HVP, NNLO}} = 6845(40) \times 10^{-11}$$

$$a_\mu^{\text{HLbL}} = a_\mu^{\text{HLbL, LO}} + a_\mu^{\text{HLbL, NLO}} = 92(18) \times 10^{-11}$$

⬇

$$a_\mu(\text{SM}) = 116591810(43) \times 10^{-11}$$

T. Aoyama et al. (2020)

developments on this anomaly

- Pin down this anomaly
  - Reduce theoretical uncertainty:

    improve the HVP and HLbL calculations
  - Reduce experimental uncertainty

    FNAL run 2, J-PARC

- New physics (NP) explanations

NP implications of this anomaly

↓

our interest

2. New physics contributions

our interest

one-loop

two-loop: Barr-Zee diagrams

effective operator

$$O_{eB} = \overline{L^i_L}\sigma^{\mu\nu} e^j_R H B_{\mu\nu}$$

$$O_{eW} = \overline{L^i_L}\sigma^{\mu\nu}\sigma^a e^j_R H W^a_{\mu\nu}$$

$$-\frac{e a_\mu}{4m_\mu}\bar{\mu}\sigma^{\mu\nu}\mu F_{\mu\nu}$$

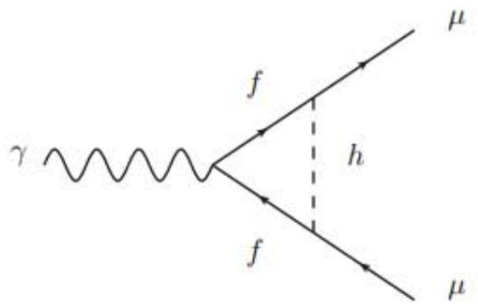
$SU_L(2) \otimes U_Y(1)$ invariant

New physics contributions at one-loop

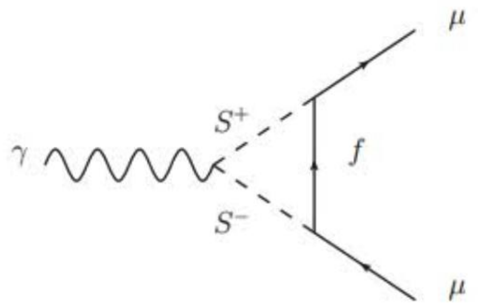
four basic topologies as the basis of new physics

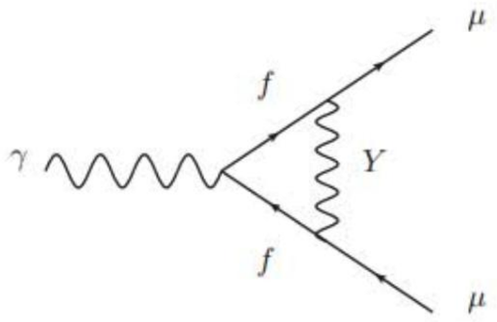
F. Jegerlehner and A. Nyffeler (2009)
M. Lindner, M. Platscher, and F. S. Queiroz (2016)

neutral scalar

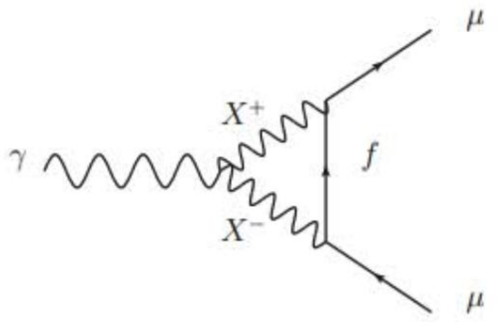


singly charged scalar





neutral vector

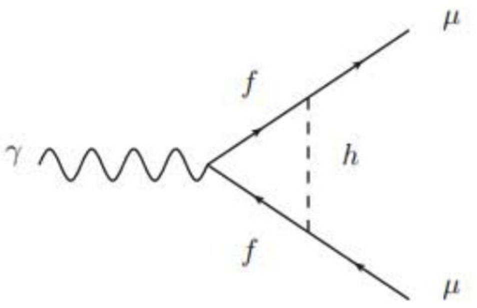


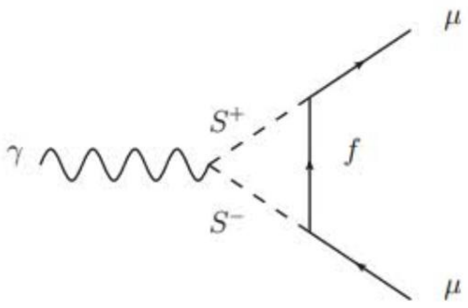
singly charged vector

combination →

- axion / dark photon
- doubly charged scalar / vector
- scalar / vector leptoquark (LQ)
- supersymmetric particles
- ...

analysis of the scalar mediator case





two topologies

four independent integrals as the basis

neutral scalar h (not SM Higgs) ↑

singly charged scalar S ↑

$$\Delta a_\mu = \frac{m_\mu^2}{8\pi^2}\left\{\frac{(|y_L^h|^2+|y_R^h|^2)I_{LL}^h + [(y_L^h)(y_R^h)^* + (y_R^h)(y_L^h)^*]I_{LR}^h}{m_h^2} + \frac{(|y_L^S|^2+|y_R^S|^2)I_{LL}^S + [(y_L^S)(y_R^S)^* + (y_R^S)(y_L^S)^*]I_{LR}^S}{m_S^2}\right\}$$

$$I_{LL}^h = \frac{1}{2}\int_0^1 dx \frac{x^2(1-x)m_h^2}{xm_f^2 + (1-x)m_h^2 - x(1-x)m_\mu^2}$$

$$I_{LR}^h = \frac{m_f}{2m_\mu}\int_0^1 dx \frac{x^2 m_h^2}{xm_f^2 + (1-x)m_h^2 - x(1-x)m_\mu^2}$$

$$I_{LL}^S = -\frac{1}{2}\int_0^1 dx \frac{x(1-x)^2 m_S^2}{xm_f^2 + (1-x)m_S^2 - x(1-x)m_\mu^2}$$

$$I_{LR}^S = -\frac{m_f}{2m_\mu}\int_0^1 dx \frac{x(1-x) m_S^2}{xm_f^2 + (1-x)m_S^2 - x(1-x)m_\mu^2}$$

properties of the four integrals

- chiral symmetry $\lim_{m_\mu \to 0} \frac{m_\mu^2}{m_S^2} * \{I^{h}_{LL}, I^{h}_{LR}, I^{S}_{LL}, I^{S}_{LR}\} = 0$

- decoupling behaviour $\lim_{m_S \to \infty} \frac{m_\mu^2}{m_S^2} * \{I^{h}_{LL}, I^{h}_{LR}, I^{S}_{LL}, I^{S}_{LR}\} = 0$

- threshold behaviour $m_\mu > m_{h/S} + m_f \Rightarrow \mathrm{Im}\{I^{h}_{LL}, I^{h}_{LR}, I^{S}_{LL}, I^{S}_{LR}\} \neq 0$

- expansion results — approximation choice depend on the specific models

one example: $m_\mu \ll m_{h/S}, m_f$ $\Rightarrow$

$$I^{h}_{LL} \to f^{q}_{LL}(x), \qquad I^{h}_{LR} \to \frac{m_f}{m_\mu} \cdot f^{q}_{LL}(x) \qquad x \equiv \frac{m_f^2}{m_h^2}$$

$$I^{S}_{LL} \to f^{S}_{LL}(x), \qquad I^{S}_{LR} \to \frac{m_f}{m_\mu} \cdot f^{S}_{LL}(x) \qquad x \equiv \frac{m_f^2}{m_S^2}$$

$$f^{q}_{LL}(x) = \frac{2 + 3x - 6x^2 + x^3 + 6x\log(x)}{12(1-x)^4}, \qquad f^{q}_{LR}(x) = -\frac{3 - 4x + x^2 + 2\log(x)}{4(1-x)^3}$$

$$f^{S}_{LL}(x) = -\frac{1 - 6x + 3x^2 + 2x^3 - 6x^2\log(x)}{12(1-x)^4}, \qquad f^{S}_{LR}(x) = -\frac{1 - x^2 + 2x\log(x)}{4(1-x)^3}$$

new physics models

- light scalar mediator: axion
- heavy scalar mediator

$m_\mu = m_f \ll m_{h/S}$ scenario

$$\Delta a_\mu \approx \frac{1}{8\pi^2}\{(|y_L^h|^2 + |y_R^h|^2)\frac{m_\mu^2}{6m_h^2} + [(y_L^h)(y_R^h)^* + (y_R^h)(y_L^h)^*]\frac{m_\mu^2}{m_h^2}(\log\frac{m_h}{m_\mu} - \frac{3}{4})$$

$$- (|y_L^S|^2 + |y_R^S|^2)\frac{m_\mu^2}{12m_S^2} - [(y_L^S)(y_R^S)^* + (y_R^S)(y_L^S)^*]\frac{m_\mu^2}{4m_S^2}\}$$

$m_\mu \ll m_f, m_{h/S}$ scenario

$$\Delta a_\mu \approx \frac{1}{8\pi^2}\{(|y_L^h|^2 + |y_R^h|^2)\frac{m_\mu^2}{m_h^2}f_{LL}^q(\frac{m_f^2}{m_h^2}) + [(y_L^h)(y_R^h)^* + (y_R^h)(y_L^h)^*]\frac{m_\mu m_f}{m_h^2}f_{LR}^q(\frac{m_f^2}{m_h^2})$$

$$+ (|y_L^S|^2 + |y_R^S|^2)\frac{m_\mu^2}{m_S^2}f_{LL}^S(\frac{m_f^2}{m_S^2}) + [(y_L^S)(y_R^S)^* + (y_R^S)(y_L^S)^*]\frac{m_\mu m_f}{m_S^2}f_{LR}^q(\frac{m_f^2}{m_S^2})\}$$

↓

$m_\mu \ll m_f \ll m_{h/S}$

$$f_{LL}^q(x) \to \frac{1}{6}, \qquad f_{LR}^q(x) \to -\frac{3 + 2\log(x)}{4}$$

$$f_{LL}^S(x) \to -\frac{1}{12}, \qquad f_{LR}^S(x) \to -\frac{1}{4}$$

numerical estimation of heavy mediator case

$\Delta a_\mu = (251 \pm 59) \times 10^{-11}$

$m_\mu = m_f \ll m_{h/S}$ scenario $O(\Delta a_\mu) \sim \frac{y^2}{16\pi^2}\frac{m_\mu^2}{m_{h/S}^2}$ ⇒ $\frac{m_{h/S}}{y} \sim O(100\text{GeV})$

- $m_{h/S} \sim$ GeV, $y \sim 0.01$
- $m_{h/S} \sim$ 10GeV, $y \sim 0.1$
- $m_{h/S} \sim$ 100GeV, $y \sim 1$
- $m_{h/S} \sim$ TeV is not favored, unitarity violation

$m_\mu \ll m_f, m_{h/S}$ scenario chiral enhancement $\frac{m_f}{m_\mu}$ $O(\Delta a_\mu) \sim \frac{y_L y_R}{16\pi^2}\frac{m_\mu m_f}{m_{h/S}^2}$

How is the chiral enhancement produced? ⇒

- vector-like lepton m_L/m_μ
- LQ m_q/m_μ
- ...

$m_f \sim$ GeV

$m_f \sim$ 10GeV

$m_f \sim$ 100GeV

...

$\frac{m_{h/S}}{\sqrt{y_L y_R}} \sim O(\text{TeV}) - O(10\text{TeV})$ } TeV and heavier mediator is viable

Note: logarithm can have some effects on the estimation

3. LQ extended models

minimal LQ models

$SU(3)_C \times SU(2)_L \times U(1)_Y$ representation	label	F	$y_L^{\mathrm{LQ}\mu t}$	$y_R^{\mathrm{LQ}\mu t}$
$(\bar{3}, 3, 1/3)$	S_3	-2	0	$\mathcal{O}(y)$
$(3, 2, 7/6)$	R_2	0	$\mathcal{O}(y)$	$\mathcal{O}(y)$
$(3, 2, 1/6)$	$\widetilde{R}_2$	0	0	0
$(\bar{3}, 1, 4/3)$	$\widetilde{S}_1$	-2	0	0
$(\bar{3}, 1, 1/3)$	S_1	-2	$\mathcal{O}(y)$	$\mathcal{O}(y)$

chiral enhancements

R_2 S_1

D. Chakraverty, D. Choudhury, and A. Datta (2001)
K. Cheung (2001)

two LQs

I. Dorsner, S. Fajfer, and O. Sumensari (2019)

D. Zhang (2021) $\widetilde{R}_2 + S_1$

three LQs

A. Crivellin, B. Fuks, and L. Schnell (2022) $R_2 + R_2 + R_2$

S. L. Chen, W. W. Jiang, and Z. K. Liu (2022) $\widetilde{R}_2 + S_1 + S_3$

B anomalies
neutrino mass

LQ+vector-like quark (VLQ) models

with up-type quark chiral enhancements

Shi-Ping He, Phys. Rev. D 105 (2022), 035017, arXiv:2112.13490

one LQ + one VLQ

$$\mathcal{L}_{F=0} \supset \bar{\mu}(y_L^{S_A\mu q_A}\omega_- + y_R^{S_A\mu q_A}\omega_+)q_A S_A + \text{h.c.}$$

$$\mathcal{L}_{F=2} \supset \bar{\mu}(y_L^{S_B\mu q_B}\omega_- + y_R^{S_B\mu q_B}\omega_+)q_B^C S_B + \text{h.c.}$$

third generation quark
heavy quark

LQ	VLQ	related input parameters	mixing angle relation
R_2	$T_{L,R}$	$y_L^{R_2\mu t},\ y_R^{R_2\mu t},\ y_R^{R_2\mu T},\ \theta_L,\ m_T$	$\tan\theta_R = \frac{m_t}{m_T}\tan\theta_L$
	$(X,T)_{L,R}$	$y_L^{R_2\mu t},\ y_R^{R_2\mu t},\ \theta_R,\ m_T$	$\tan\theta_L = \frac{m_t}{m_T}\tan\theta_R$
	$(T,B)_{L,R}$	$y_L^{R_2\mu t},\ y_R^{R_2\mu t},\ y_L^{R_2\mu T},\ \theta_R^t,\ \theta_R^b,\ m_T$	$\tan\theta_L^{t(b)} = \frac{m_{t(b)}}{m_{T(B)}}\tan\theta_R^{t(b)}$
	$(X,T,B)_{L,R}$	$y_L^{R_2\mu t},\ y_R^{R_2\mu t},\ y_R^{R_2\mu T},\ \theta_L,\ m_T$	$\tan\theta_R^{t(b)} = \frac{m_{t(b)}}{m_{T(B)}}\tan\theta_L^{t(b)},\ \sin 2\theta_L^b = \frac{\sqrt{2}(m_T^2-m_t^2)}{m_B^2-m_b^2}\sin 2\theta_L^t$
	$(T,B,Y)_{L,R}$	$y_L^{R_2\mu t},\ y_R^{R_2\mu t},\ \theta_L,\ m_T$	$\tan\theta_R^{t(b)} = \frac{m_{t(b)}}{m_{T(B)}}\tan\theta_L^{t(b)},\ \sin 2\theta_L^b = -\frac{m_T^2-m_t^2}{\sqrt{2}(m_B^2-m_b^2)}\sin 2\theta_L^t$
S_1	$T_{L,R}$	$y_L^{S_1\mu t},\ y_R^{S_1\mu t},\ y_L^{S_1\mu T},\ \theta_L,\ m_T$	$\tan\theta_R = \frac{m_t}{m_T}\tan\theta_L$
	$(X,T)_{L,R}$	$y_L^{S_1\mu t},\ y_R^{S_1\mu t},\ \theta_R,\ m_T$	$\tan\theta_L = \frac{m_t}{m_T}\tan\theta_R$
	$(T,B)_{L,R}$	$y_L^{S_1\mu t},\ y_R^{S_1\mu t},\ y_R^{S_1\mu T},\ \theta_R^t,\ \theta_R^b,\ m_T$	$\tan\theta_L^{t(b)} = \frac{m_{t(b)}}{m_{T(B)}}\tan\theta_R^{t(b)}$
	$(X,T,B)_{L,R}$	$y_L^{S_1\mu t},\ y_R^{S_1\mu t},\ \theta_L,\ m_T$	$\tan\theta_R^{t(b)} = \frac{m_{t(b)}}{m_{T(B)}}\tan\theta_L^{t(b)},\ \sin 2\theta_L^b = \frac{\sqrt{2}(m_T^2-m_t^2)}{m_B^2-m_b^2}\sin 2\theta_L^t$
	$(T,B,Y)_{L,R}$	$y_L^{S_1\mu t},\ y_R^{S_1\mu t},\ \theta_L,\ m_T$	$\tan\theta_R^{t(b)} = \frac{m_{t(b)}}{m_{T(B)}}\tan\theta_L^{t(b)},\ \sin 2\theta_L^b = -\frac{m_T^2-m_t^2}{\sqrt{2}(m_B^2-m_b^2)}\sin 2\theta_L^t$
S_3	$(X,T,B)_{L,R}$	$y_L^{S_3\mu T},\ y_R^{S_3\mu t},\ \theta_L,\ m_T$	$\tan\theta_R^{t(b)} = \frac{m_{t(b)}}{m_{T(B)}}\tan\theta_L^{t(b)},\ \sin 2\theta_L^b = \frac{\sqrt{2}(m_T^2-m_t^2)}{m_B^2-m_b^2}\sin 2\theta_L^t$

$$\begin{bmatrix} T & \sqrt{2}X \\ \sqrt{2}B & -T \end{bmatrix}$$

$-\sqrt{2}T$

$$\begin{bmatrix} B & \sqrt{2}T \\ \sqrt{2}Y & -B \end{bmatrix}$$

convention difference from other Refs.
But it has no effects on the physical quantities.

J. J. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, and M. P. Victoria (2013)

μ LQ Yukawa interactions with top and T quarks

LQ	VLQ	$\overline{\mu_R} t_L$	$\overline{\mu_L} t_R$	$\overline{\mu_R} T_L$	$\overline{\mu_L} T_R$
R_2	$T_{L,R}$	$y_L^{R_2\mu t} c_L$	$y_R^{R_2\mu t} c_R - y_R^{R_2\mu T} s_R$	$y_L^{R_2\mu t} s_L$	$y_R^{R_2\mu t} s_R + y_R^{R_2\mu T} c_R$
	$(X,T)_{L,R}$	$y_L^{R_2\mu t} c_L$	$y_R^{R_2\mu t} c_R$	$y_L^{R_2\mu t} s_L$	$y_R^{R_2\mu t} s_R$
	$(T,B)_{L,R}$	$y_L^{R_2\mu t} c_L - y_L^{R_2\mu T} s_L$	$y_R^{R_2\mu t} c_R$	$y_L^{R_2\mu t} s_L + y_L^{R_2\mu T} c_L$	$y_R^{R_2\mu t} s_R$
	$(X,T,B)_{L,R}$	$y_L^{R_2\mu t} c_L$	$y_R^{R_2\mu t} c_R - y_R^{R_2\mu T} s_R$	$y_L^{R_2\mu t} s_L$	$y_R^{R_2\mu t} s_R + y_R^{R_2\mu T} c_R$
	$(T,B,Y)_{L,R}$	$y_L^{R_2\mu t} c_L$	$y_R^{R_2\mu t} c_R$	$y_L^{R_2\mu t} s_L$	$y_R^{R_2\mu t} s_R$

LQ	VLQ	$\overline{\mu_R} (t_R)^C$	$\overline{\mu_L} (t_L)^C$	$\overline{\mu_R} (T_R)^C$	$\overline{\mu_L} (T_L)^C$
S_1	$T_{L,R}$	$y_L^{S_1\mu t} c_R - y_L^{S_1\mu T} s_R$	$y_R^{S_1\mu t} c_L$	$y_L^{S_1\mu t} s_R + y_L^{S_1\mu T} c_R$	$y_R^{S_1\mu t} s_L$
	$(X,T)_{L,R}$	$y_L^{S_1\mu t} c_R$	$y_R^{S_1\mu t} c_L$	$y_L^{S_1\mu t} s_R$	$y_R^{S_1\mu t} s_L$
	$(T,B)_{L,R}$	$y_L^{S_1\mu t} c_R$	$y_R^{S_1\mu t} c_L - y_R^{S_1\mu T} s_L$	$y_L^{S_1\mu t} s_R$	$y_R^{S_1\mu t} s_L + y_R^{S_1\mu T} c_L$
	$(X,T,B)_{L,R}$	$y_L^{S_1\mu t} c_R$	$y_R^{S_1\mu t} c_L$	$y_L^{S_1\mu t} s_R$	$y_R^{S_1\mu t} s_L$
	$(T,B,Y)_{L,R}$	$y_L^{S_1\mu t} c_R$	$y_R^{S_1\mu t} c_L$	$y_L^{S_1\mu t} s_R$	$y_R^{S_1\mu t} s_L$
S_3	$(X,T,B)_{L,R}$	$-y_L^{S_3\mu T} s_R$	$y_R^{S_3\mu t} c_L$	$y_L^{S_3\mu T} c_R$	$y_R^{S_3\mu t} s_L$

μ LQ Yukawa interactions with bottom and B quarks

LQ	VLQ	$\overline{\mu_R} b_L$	$\overline{\mu_L} b_R$	$\overline{\mu_R} B_L$	$\overline{\mu_L} B_R$
R_2	$T_{L,R}$	$y_L^{R_2\mu t}$	0	$\times$	$\times$
	$(X,T)_{L,R}$	$y_L^{R_2\mu t}$	0	$\times$	$\times$
	$(T,B)_{L,R}$	$y_L^{R_2\mu t} c_L^b - y_L^{R_2\mu T} s_L^b$	0	$y_L^{R_2\mu T} c_L^b + y_L^{R_2\mu t} s_L^b$	0
	$(X,T,B)_{L,R}$	$y_L^{R_2\mu t} c_L^b$	$-\sqrt{2} y_R^{R_2\mu T} s_R^b$	$y_L^{R_2\mu t} s_L^b$	$\sqrt{2} y_R^{R_2\mu T} c_R^b$
	$(T,B,Y)_{L,R}$	$y_L^{R_2\mu t} c_L^b$	0	$y_L^{R_2\mu t} s_L^b$	0

LQ	VLQ	$\overline{\mu_R}(b_R)^C$	$\overline{\mu_L}(b_L)^C$	$\overline{\mu_R}(B_R)^C$	$\overline{\mu_L}(B_L)^C$
S_1	$T_{L,R}$	0	0	$\times$	$\times$
	$(X,T)_{L,R}$	0	0	$\times$	$\times$
	$(T,B)_{L,R}$	0	0	0	0
	$(X,T,B)_{L,R}$	0	0	0	0
	$(T,B,Y)_{L,R}$	0	0	0	0
S_3	$(X,T,B)_{L,R}$	$-y_L^{S_3\mu T} s_R^b$	$\sqrt{2} y_R^{S_3\mu t} c_L^b$	$y_L^{S_3\mu T} c_R^b$	$\sqrt{2} y_R^{S_3\mu t} s_L^b$

Erratum xxx (2022)

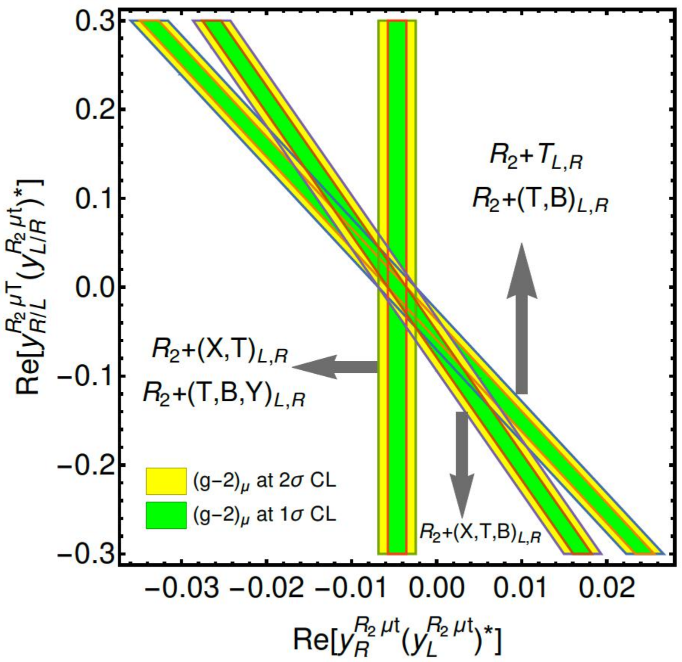
contributions to the $(g-2)_\mu$

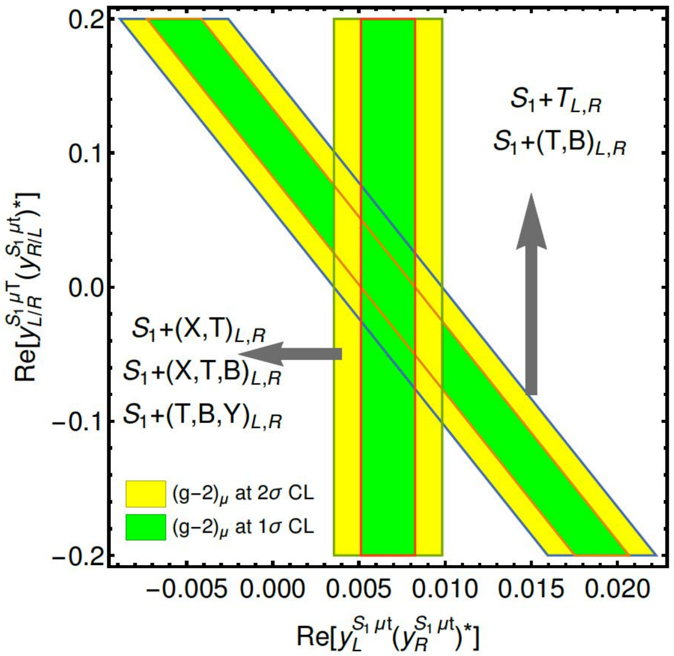
approximate results — chirally enhanced parts — $m_b \ll m_t \ll m_T \approx m_B$

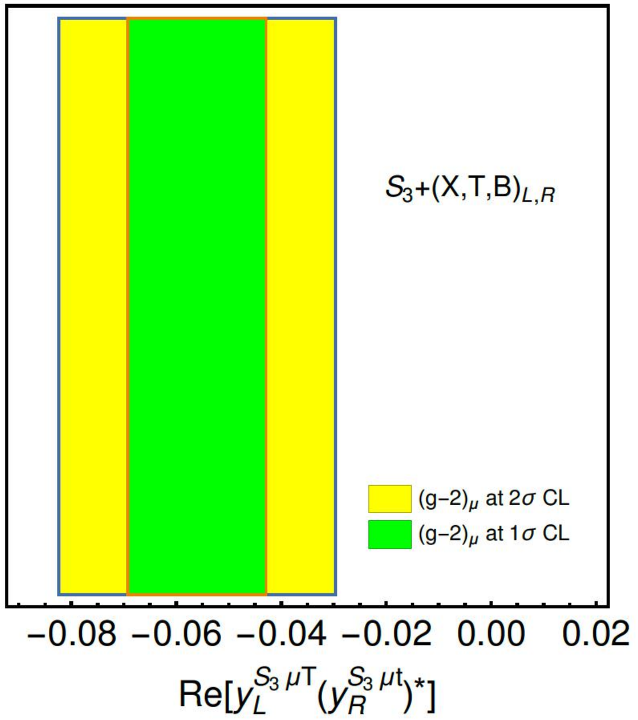
LQ	VLQ	the approximate expressions of $\Delta\overline{a_\mu}$	coupling product order of T compared to t
R_2	$T_{L,R}$	$\frac{m_T}{m_t} f_{LR}^{R_2}(m_T^2/m_{R_2}^2)\mathrm{Re}[y_R^{R_2\mu T}(y_L^{R_2\mu t})^*]s_L + (\frac{1}{4}+\log\frac{m_t^2}{m_{R_2}^2})\mathrm{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]$	s_L
	$(X,T)_{L,R}$	$\frac{m_T}{m_t} f_{LR}^{R_2}(m_T^2/m_{R_2}^2)\mathrm{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]s_L s_R + (\frac{1}{4}+\log\frac{m_t^2}{m_{R_2}^2})\mathrm{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]$	$m_t s_R^2/m_T$
	$(T,B)_{L,R}$	$\frac{m_T}{m_t} f_{LR}^{R_2}(m_T^2/m_{R_2}^2)\mathrm{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu T})^*]s_R + (\frac{1}{4}+\log\frac{m_t^2}{m_{R_2}^2})\mathrm{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]$	s_R
	$(X,T,B)_{L,R}$	$\frac{m_T}{m_t}[f_{LR}^{R_2}(m_T^2/m_{R_2}^2) + 2\widetilde{f}_{LR}^{R_2}(m_T^2/m_{R_2}^2)]\cdot\mathrm{Re}[y_R^{R_2\mu T}(y_L^{R_2\mu t})^*]s_L$ $+(\frac{1}{4}+\log\frac{m_t^2}{m_{R_2}^2})\mathrm{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]$	s_L
	$(T,B,Y)_{L,R}$	$\frac{m_T}{m_t} f_{LR}^{R_2}(m_T^2/m_{R_2}^2)\mathrm{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]s_L s_R + (\frac{1}{4}+\log\frac{m_t^2}{m_{R_2}^2})\mathrm{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]$	$m_t s_L^2/m_T$
S_1	$T_{L,R}$	$\frac{m_T}{m_t} f_{LR}^{S_1}(m_T^2/m_{S_1}^2)\mathrm{Re}[y_L^{S_1\mu T}(y_R^{S_1\mu t})^*]s_L - (\frac{7}{4}+\log\frac{m_t^2}{m_{S_1}^2})\mathrm{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]$	s_L
	$(X,T)_{L,R}$	$\frac{m_T}{m_t} f_{LR}^{S_1}(m_T^2/m_{S_1}^2)\mathrm{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]s_L s_R - (\frac{7}{4}+\log\frac{m_t^2}{m_{S_1}^2})\mathrm{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]$	$m_t s_R^2/m_T$
	$(T,B)_{L,R}$	$\frac{m_T}{m_t} f_{LR}^{S_1}(m_T^2/m_{S_1}^2)\mathrm{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu T})^*]s_R - (\frac{7}{4}+\log\frac{m_t^2}{m_{S_1}^2})\mathrm{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]$	s_R
	$(X,T,B)_{L,R}$	$\frac{m_T}{m_t} f_{LR}^{S_1}(m_T^2/m_{S_1}^2)\mathrm{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]s_L s_R - (\frac{7}{4}+\log\frac{m_t^2}{m_{S_1}^2})\mathrm{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]$	$m_t s_L^2/m_T$
	$(T,B,Y)_{L,R}$	$\frac{m_T}{m_t} f_{LR}^{S_1}(m_T^2/m_{S_1}^2)\mathrm{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]s_L s_R - (\frac{7}{4}+\log\frac{m_t^2}{m_{S_1}^2})\mathrm{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]$	$m_t s_L^2/m_T$
S_3	$(X,T,B)_{L,R}$	$\frac{m_T}{m_t}[f_{LR}^{S_3}(m_T^2/m_{S_3}^2) + 2\widetilde{f}_{LR}^{S_3}(m_T^2/m_{S_3}^2)]\cdot\mathrm{Re}[y_L^{S_3\mu T}(y_R^{S_3\mu t})^*]s_L$ $+(\frac{7}{4}+\log\frac{m_t^2}{m_{S_3}^2})\mathrm{Re}[y_L^{S_3\mu T}(y_R^{S_3\mu t})^*]s_R$	m_T/m_t

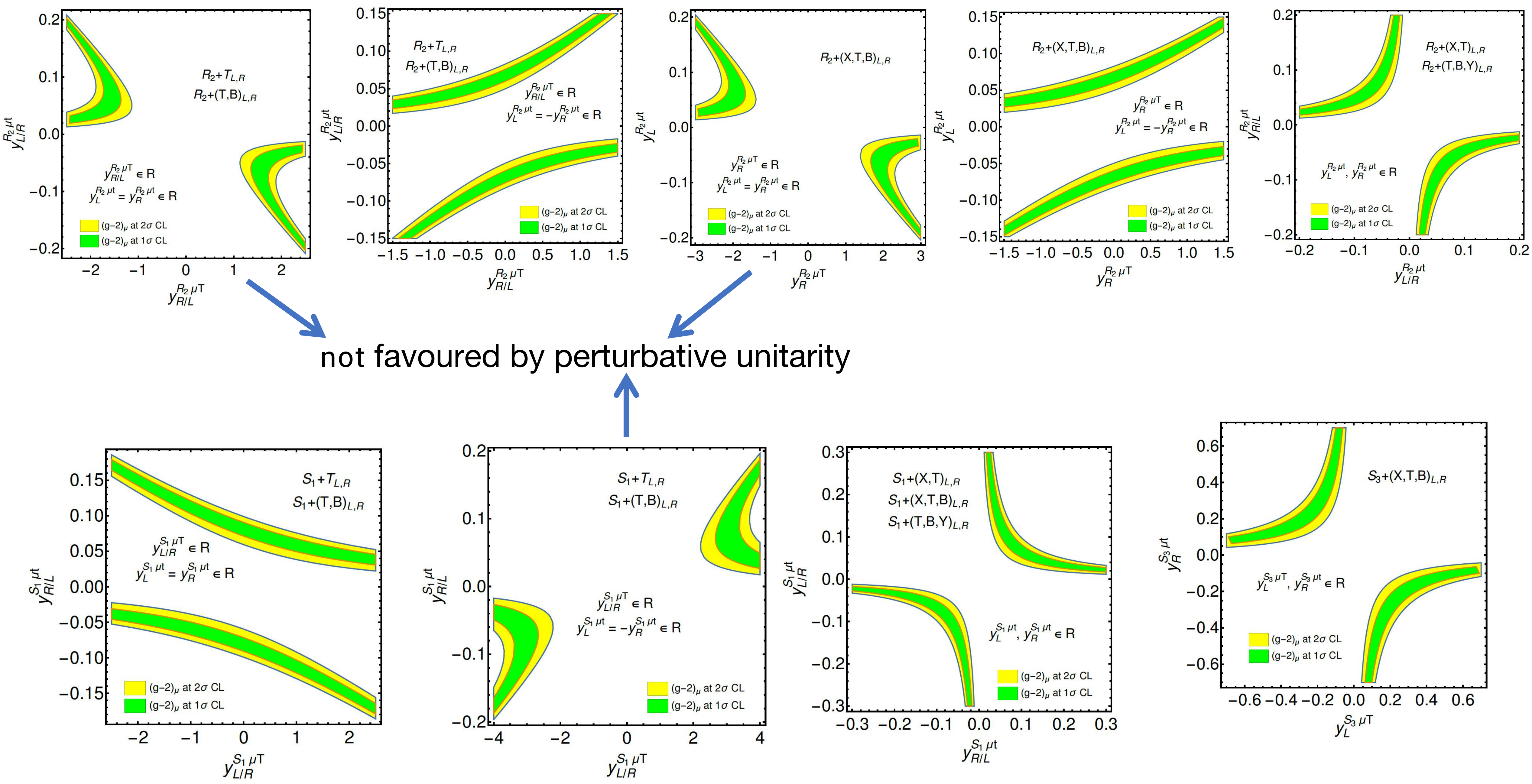
numerical results

LQ	VLQ	the leading order expressions of $\Delta a_\mu \times 10^7$
R_2	$T_{L,R}$	$-0.5238\text{Re}[y_R^{R_2\mu T}(y_L^{R_2\mu t})^*] - 5.393\text{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]$
	$(X,T)_{L,R}$	$-5.397\text{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]$
	$(T,B)_{L,R}$	$-0.5238\text{Re}[y_L^{R_2\mu T}(y_R^{R_2\mu t})^*] - 5.393\text{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]$
	$(X,T,B)_{L,R}$	$-0.3923\text{Re}[y_R^{R_2\mu T}(y_L^{R_2\mu t})^*] - 5.397\text{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]$
	$(T,B,Y)_{L,R}$	$-5.397\text{Re}[y_R^{R_2\mu t}(y_L^{R_2\mu t})^*]$
S_1	$T_{L,R}$	$0.2331\text{Re}[y_L^{S_1\mu T}(y_R^{S_1\mu t})^*] + 3.754\text{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]$
	$(X,T)_{L,R}$	$3.756\text{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]$
	$(T,B)_{L,R}$	$0.2331\text{Re}[y_R^{S_1\mu T}(y_L^{S_1\mu t})^*] + 3.754\text{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]$
	$(X,T,B)_{L,R}$	$3.756\text{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]$
	$(T,B,Y)_{L,R}$	$3.756\text{Re}[y_L^{S_1\mu t}(y_R^{S_1\mu t})^*]$
S_3	$(X,T,B)_{L,R}$	$-0.4478\text{Re}[y_L^{S_3\mu T}(y_R^{S_3\mu t})^*]$







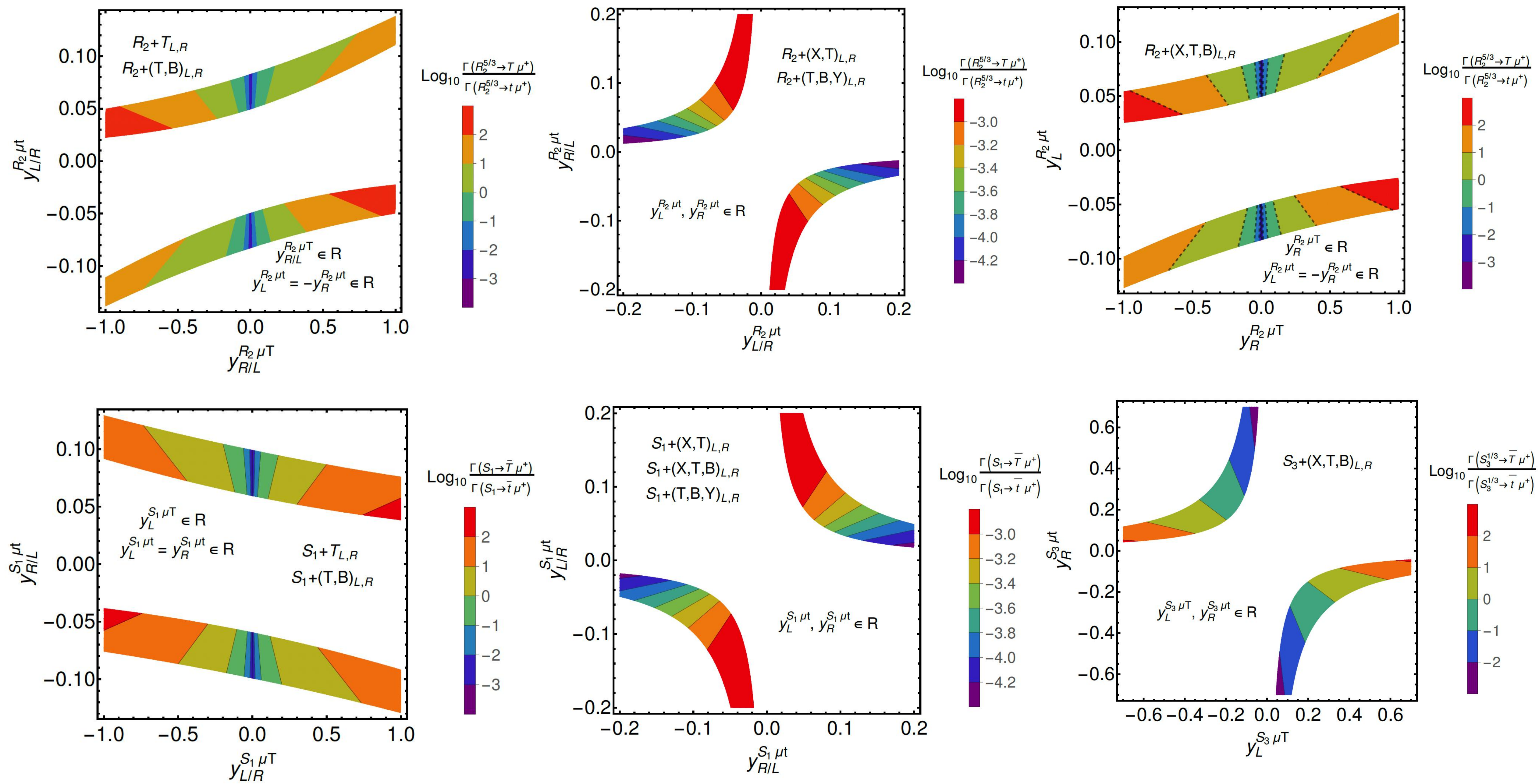

$R_2+T_{L,R}$
$R_2+(T,B)_{L,R}$
$R_2+(X,T,B)_{L,R}$
$R_2+(X,T)_{L,R}$
$R_2+(T,B,Y)_{L,R}$
$y^{R_2\,\mu T}_{R/L} \in R$
$y^{R_2\,\mu t}_{L} = y^{R_2\,\mu t}_{R} \in R$
$y^{R_2\,\mu t}_{L} = -y^{R_2\,\mu t}_{R} \in R$
$y^{R_2\,\mu T}_{R} \in R$
$y^{R_2\,\mu t}_{L},\ y^{R_2\,\mu t}_{R} \in R$
$(g-2)_\mu$ at 2σ CL
$(g-2)_\mu$ at 1σ CL
not favoured by perturbative unitarity
$S_1+T_{L,R}$
$S_1+(T,B)_{L,R}$
$S_1+(X,T)_{L,R}$
$S_1+(X,T,B)_{L,R}$
$S_1+(T,B,Y)_{L,R}$
$S_3+(X,T,B)_{L,R}$
$y^{S_1\,\mu T}_{L/R} \in R$
$y^{S_1\,\mu t}_{L} = y^{S_1\,\mu t}_{R} \in R$
$y^{S_1\,\mu t}_{L} = -y^{S_1\,\mu t}_{R} \in R$
$y^{S_1\,\mu t}_{L},\ y^{S_1\,\mu t}_{R} \in R$
$y^{S_3\,\mu T}_{L},\ y^{S_3\,\mu t}_{R} \in R$

Collider phenomenology

one LQ + one VLQ

new LQ decay channel
$T\mu$

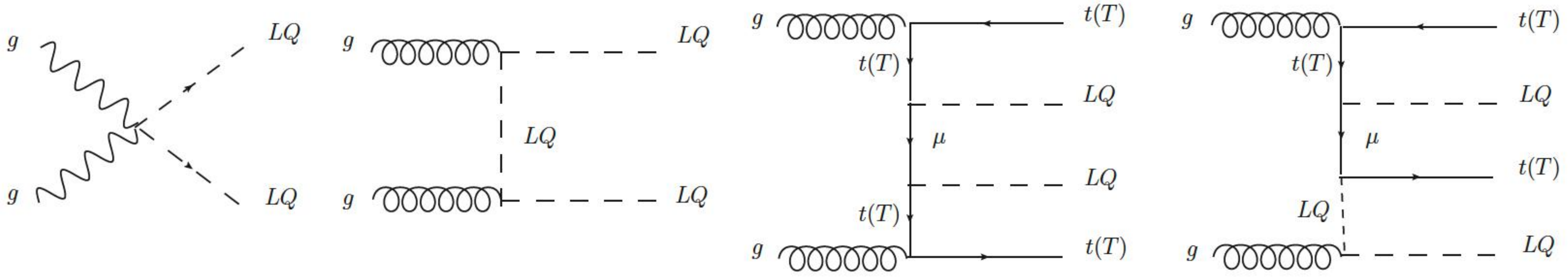
LQ	VLQ	the approximate expressions of $\frac{\Gamma(\mathrm{LQ}\to T\mu)}{\Gamma(\mathrm{LQ}\to t\mu)}$	suppress or not
R_2	$T_{L,R}$	$(1-\frac{m_T^2}{m_{R_2}^2})^2\lvert y_R^{R_2\mu T}\rvert^2/(\lvert y_L^{R_2\mu t}\rvert^2+\lvert y_R^{R_2\mu t}\rvert^2)$	No
	$(X,T)_{L,R}$	$(1-\frac{m_T^2}{m_{R_2}^2})^2\lvert y_R^{R_2\mu t}\rvert^2 s_R^2/(\lvert y_L^{R_2\mu t}\rvert^2+\lvert y_R^{R_2\mu t}\rvert^2)$	s_R^2
	$(T,B)_{L,R}$	$(1-\frac{m_T^2}{m_{R_2}^2})^2\lvert y_L^{R_2\mu T}\rvert^2/(\lvert y_L^{R_2\mu t}\rvert^2+\lvert y_R^{R_2\mu t}\rvert^2)$	No
	$(X,T,B)_{L,R}$	$(1-\frac{m_T^2}{m_{R_2}^2})^2\lvert y_R^{R_2\mu T}\rvert^2/(\lvert y_L^{R_2\mu t}\rvert^2+\lvert y_R^{R_2\mu t}\rvert^2)$	No
	$(T,B,Y)_{L,R}$	$(1-\frac{m_T^2}{m_{R_2}^2})^2\lvert y_L^{R_2\mu t}\rvert^2 s_L^2/(\lvert y_L^{R_2\mu t}\rvert^2+\lvert y_R^{R_2\mu t}\rvert^2)$	s_L^2
S_1	$T_{L,R}$	$(1-\frac{m_T^2}{m_{S_1}^2})^2\lvert y_L^{S_1\mu T}\rvert^2/(\lvert y_L^{S_1\mu t}\rvert^2+\lvert y_R^{S_1\mu t}\rvert^2)$	No
	$(X,T)_{L,R}$	$(1-\frac{m_T^2}{m_{S_1}^2})^2\lvert y_L^{S_1\mu t}\rvert^2 s_R^2/(\lvert y_L^{S_1\mu t}\rvert^2+\lvert y_R^{S_1\mu t}\rvert^2)$	s_R^2
	$(T,B)_{L,R}$	$(1-\frac{m_T^2}{m_{S_1}^2})^2\lvert y_R^{S_1\mu T}\rvert^2/(\lvert y_L^{S_1\mu t}\rvert^2+\lvert y_R^{S_1\mu t}\rvert^2)$	No
	$(X,T,B)_{L,R}$	$(1-\frac{m_T^2}{m_{S_1}^2})^2\lvert y_R^{S_1\mu t}\rvert^2 s_L^2/(\lvert y_L^{S_1\mu t}\rvert^2+\lvert y_R^{S_1\mu t}\rvert^2)$	s_L^2
	$(T,B,Y)_{L,R}$	$(1-\frac{m_T^2}{m_{S_1}^2})^2\lvert y_R^{S_1\mu t}\rvert^2 s_L^2/(\lvert y_L^{S_1\mu t}\rvert^2+\lvert y_R^{S_1\mu t}\rvert^2)$	s_L^2
S_3	$(X,T,B)_{L,R}$	$(1-\frac{m_T^2}{m_{S_3}^2})^2\lvert y_L^{S_3\mu T}\rvert^2/\lvert y_R^{S_3\mu t}\rvert^2$	No



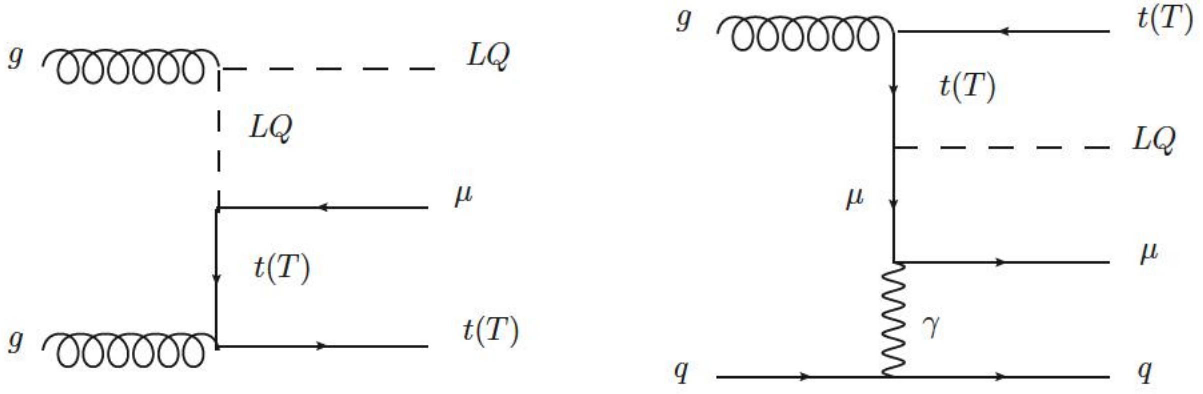
For detailed numerical results of one LQ + two VLQs, refer to our paper ➡ Shi-Ping He (2022)

LQ production channels

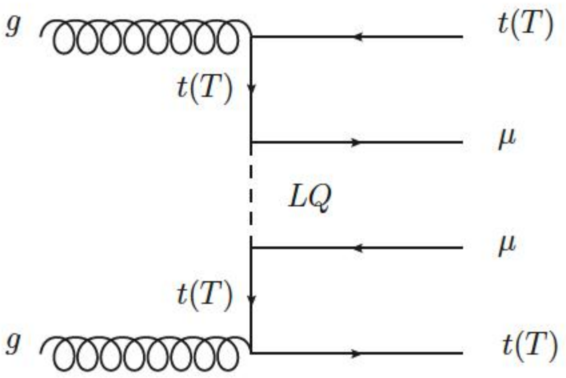
LQ pair



single LQ



off-shell LQ



collider signatures:
multi-t and multi-μ

$R_2^{5/3} \rightarrow t\ \mu^+$

$R_2^{5/3} \rightarrow T\,\mu^+$ → $bW^+, t\,Z, t\,\mathrm{h}$

$S_1/S_3^{1/3} \rightarrow \bar{t}\ \mu^+$

$S_1/S_3^{1/3} \rightarrow \bar{T}\,\mu^+$ → $bW^+, t\,Z, t\,\mathrm{h}$

$R_2^{2/3} \rightarrow b/B\,\mu^+$
$S_3^{4/3} \rightarrow \bar{b}/\bar{B}\,\mu^+$
$S_3^{-2/3} \rightarrow \bar{X}\,\mu^+$

Summary

- introduction to the $(g-2)_\mu$

  light scalar mediator
  heavy scalar mediator → chiral enhancement

- one LQ + one VLQ models

  $R_2 + \mathrm{T}_{L,R}/(\mathrm{X},\mathrm{T})_{L,R}/(\mathrm{T},\mathrm{B})_{L,R}/(\mathrm{X},\mathrm{T},\mathrm{B})_{L,R}/(\mathrm{T},\mathrm{B},\mathrm{Y})_{L,R}$
  $S_1 + \mathrm{T}_{L,R}/(\mathrm{X},\mathrm{T})_{L,R}/(\mathrm{T},\mathrm{B})_{L,R}/(\mathrm{X},\mathrm{T},\mathrm{B})_{L,R}/(\mathrm{T},\mathrm{B},\mathrm{Y})_{L,R}$
  $S_3 + (\mathrm{X},\mathrm{T},\mathrm{B})_{L,R}$

- phenomenology under the constraints from $(g-2)_\mu$

  LQ→ Tμ

  multi-t and multi-μ signatures

Further studies

LQ contributions
VLQ contributions → W mass

- $S_3 + (X,T,B)_{L,R}$ model for $(g-2)_\mu$ and W mass simultaneously

Shi-Ping He, arXiv:2205.02088

Thank you!

谢谢!

Grazie!

Backups

$$\bar{\mu}(y_L^{S_A\,\mu\,q_A}\omega_- + y_R^{S_A\,\mu\,q_A}\omega_+)q_A S_A + \mathrm{h.}c.$$

$$\Delta a_\mu = -\frac{N_C\, m_\mu^2}{8\pi^2 m_{S_A}^2}\{(|y_L^{S_A\,\mu\,q_A}|^2 + |y_R^{S_A\,\mu\,q_A}|^2)[Q_{q_A} f_{LL}^q(\frac{m_{q_A}^2}{m_{S_A}^2}) + Q_{S_A} f_{LL}^S(\frac{m_{q_A}^2}{m_{S_A}^2})]$$

$$+\frac{2m_{q_A}}{m_\mu} Re[y_L^{S_A\,\mu\,q_A}(y_R^{S_A\,\mu\,q_A})^*]\cdot[Q_{q_A} f_{LR}^q(\frac{m_{q_A}^2}{m_{S_A}^2}) + Q_{S_A} f_{LR}^S(\frac{m_{q_A}^2}{m_{S_A}^2})]\}$$

$\bar{\mu}\, t\,(R_2^{5/3})^*, \bar{\mu}\, T(R_2^{5/3})^*$ $\quad Q_{q_A} = \frac{2}{3}, Q_{S_A} = -\frac{5}{3}$

$\bar{\mu}\, b(R_2^{2/3})^*, \bar{\mu}\, B(R_2^{2/3})^*$ $\quad Q_{q_A} = -\frac{1}{3}, Q_{S_A} = -\frac{2}{3}$

$$\bar{\mu}(y_L^{S_B\,\mu\,q_B}\omega_- + y_R^{S_B\,\mu\,q_B}\omega_+)q_B^C S_B + \mathrm{h.}c.$$

$$\Delta a_\mu = -\frac{N_C\, m_\mu^2}{8\pi^2 m_{S_B}^2}\{(|y_L^{S_B\,\mu\,q_B}|^2 + |y_R^{S_B\,\mu\,q_B}|^2)[-Q_{q_B} f_{LL}^q(\frac{m_{q_B}^2}{m_{S_B}^2}) + Q_{S_B} f_{LL}^S(\frac{m_{q_B}^2}{m_{S_B}^2})]$$

$$+\frac{2m_{q_B}}{m_\mu} Re[y_L^{S_A\,\mu\,q_B}(y_R^{S_A\,\mu\,q_B})^*]\cdot[-Q_{q_B} f_{LR}^q(\frac{m_{q_B}^2}{m_{S_B}^2}) + Q_{S_B} f_{LR}^S(\frac{m_{q_B}^2}{m_{S_B}^2})]\}$$

$\bar{\mu}\, t^C(S_1^{1/3})^*, \bar{\mu}\, T^C(S_1^{1/3})^*$

$\bar{\mu}\, t^C(S_3^{1/3})^*, \bar{\mu}\, T^C(S_3^{1/3})^*$ $\quad Q_{q_B} = \frac{2}{3}, Q_{S_A} = -\frac{1}{3}$

$\bar{\mu}\, X^C(S_3^{-2/3})^*$ $\quad Q_{q_B} = \frac{5}{3}, Q_{S_A} = \frac{2}{3}$

$\bar{\mu}\, t\, (R_2^{5/3})^*$ interaction related functions

$$f_{LL}^{R_2}(x) \equiv -2 f_{LL}^{q}(x) + 5 f_{LL}^{S}(x) = -\frac{3 - 8x + x^2 + 4x^3 + 2x(2-5x)\log(x)}{4(1-x)^4}$$

$$f_{LR}^{R_2}(x) \equiv -2 f_{LR}^{q}(x) + 5 f_{LR}^{S}(x) = \frac{1 - 8x + 7x^2 + (4-10x)\log(x)}{4(1-x)^3}$$

$\bar{\mu}\, t^C (S_1^{1/3})^*$ interaction related functions

$$f_{LL}^{S_1}(x) \equiv 2 f_{LL}^{q}(x) + f_{LL}^{S}(x) = \frac{1 + 4x - 5x^2 + 2x(2+x)\log(x)}{4(1-x)^4}$$

$$f_{LR}^{S_1}(x) \equiv 2 f_{LR}^{q}(x) + f_{LR}^{S}(x) = -\frac{7 - 8x + x^2 + (4+2x)\log(x)}{4(1-x)^3}$$

$\bar{\mu}\, b (R_2^{2/3})^*$ interaction related functions

$$\bar{f}_{LL}^{R_2}(x) \equiv f_{LL}^{q}(x) + 2 f_{LL}^{S}(x) = \frac{x[5 - 4x - x^2 + (2+4x)\log(x)}{4(1-x)^4}$$

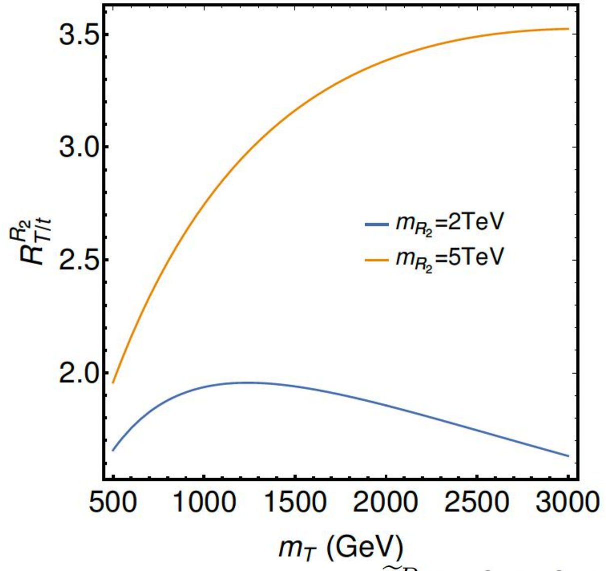
$$\bar{f}_{LR}^{R_2}(x) \equiv f_{LR}^{q}(x) + 2 f_{LR}^{S}(x) = -\frac{5 - 4x - x^2 + (2+4x)\log(x)}{4(1-x)^3}$$

$\bar{\mu}\, b^C (S_3^{4/3})^*$ interaction related functions

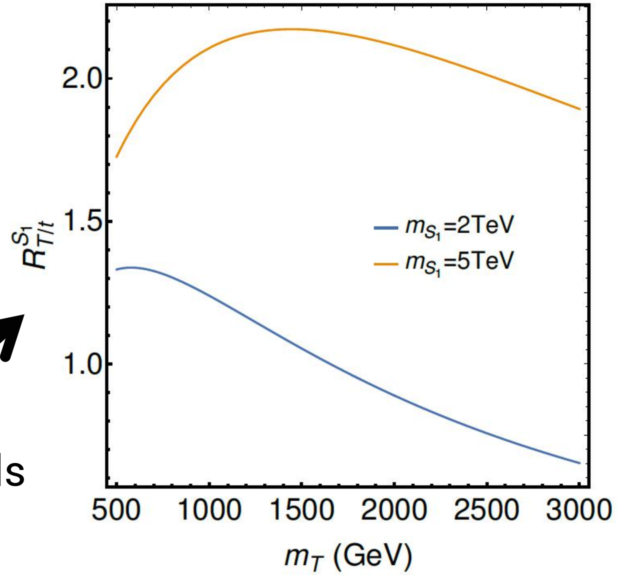
$$\bar{f}_{LL}^{S_3}(x) \equiv -f_{LL}^{q}(x) + 4 f_{LL}^{S}(x) = -\frac{2 - 7x + 2x^2 + 3x^3 + 2x(1-4x)\log(x)}{4(1-x)^4}$$

$$\bar{f}_{LR}^{S_3}(x) \equiv -f_{LR}^{q}(x) + 4 f_{LR}^{S}(x) = -\frac{1 + 4x - 5x^2 - (2-8x)\log(x)}{4(1-x)^3}$$

$$R^{R_2}_{T/t}(m_T, m_{R_2}) \equiv \frac{m_T f^{R_2}_{LR}(m_T^2/m_{R_2}^2)}{m_t f^{R_2}_{LR}(m_t^2/m_{R_2}^2)}$$



$$R^{S_1}_{T/t}(m_T, m_{S_1}) \equiv \frac{m_T f^{S_1}_{LR}(m_T^2/m_{S_1}^2)}{m_t f^{S_1}_{LR}(m_t^2/m_{S_1}^2)}$$

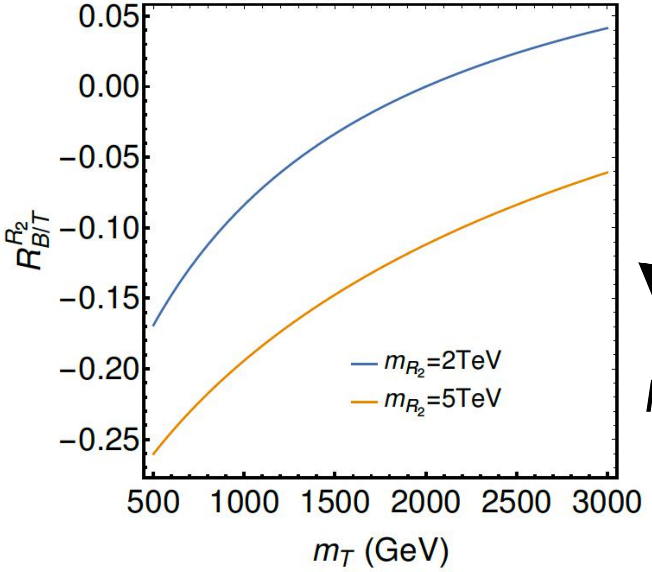


the ratio of T loop integral to the top one

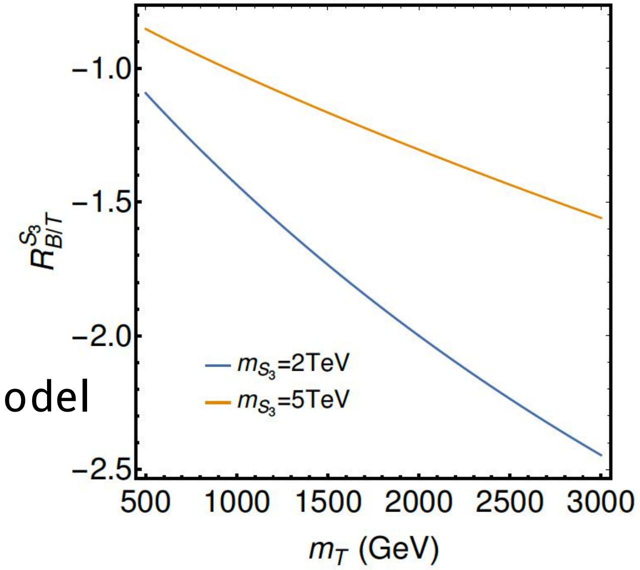
R_2 + VLQ models

S_1 + VLQ models

$$R^{R_2}_{B/T}(m_T, m_{R_2}) \equiv \frac{\widetilde{f}^{R_2}_{LR}(m_T^2/m_{R_2}^2)}{f^{R_2}_{LR}(m_T^2/m_{R_2}^2)}$$



$$R^{S_3}_{B/T}(m_T, m_{S_3}) \equiv \frac{\widetilde{f}^{S_3}_{LR}(m_T^2/m_{S_3}^2)}{f^{S_3}_{LR}(m_T^2/m_{S_3}^2)}$$



the ratio of B loop integral to the T one

R_2 + $(X, T, B)_{L,R}$ model

S_3 + $(X, T, B)_{L,R}$ model

one LQ + two VLQs

$R_2/S_1 + T_{L,R} + (T,B)_{L,R}$

turn off the LQ μt interactions

turn off the $t - T$ mixings

μ only interacts with heavy quarks

$$\Delta a_\mu^{R_2+T_{L,R}+(T,B)_{L,R}} \approx \frac{m_\mu^2}{4\pi^2 m_{R_2}^2}\mathrm{Re}[y_R^{R_2\mu T_1}(y_L^{R_2\mu T_2})^*][-\frac{m_T}{m_\mu}f_{LR}^{R_2}(\frac{m_T^2}{m_{R_2}^2})s_L^T c_R^T + \frac{m_{T'}}{m_\mu}f_{LR}^{R_2}(\frac{m_{T'}^2}{m_{R_2}^2})s_R^T c_L^T]$$

$$\Delta a_\mu^{S_1+T_{L,R}+(T,B)_{L,R}} \approx \frac{m_\mu^2}{4\pi^2 m_{S_1}^2}\mathrm{Re}[y_L^{S_1\mu T_1}(y_R^{S_1\mu T_2})^*][-\frac{m_T}{m_\mu}f_{LR}^{S_1}(\frac{m_T^2}{m_{S_1}^2})s_L^T c_R^T + \frac{m_{T'}}{m_\mu}f_{LR}^{S_1}(\frac{m_{T'}^2}{m_{S_1}^2})s_R^T c_L^T]$$

cancellation if $m_T = m_T'$ and $\theta_L^T = \theta_R^T$

constructive interference if $m_T = m_T'$ and $\theta_L^T = -\theta_R^T$

For detailed numerical results, refer to our paper → Shi-Ping He (2022)