Flavor Structure of Leptoquark Couplings in Light of B-meson Anomalies, Muon g-2 Constraints and Dark Matter

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arXiv : 1807.06547, in press JHEP10(2018)104

The 3rd IBS-KIAS Joint Workshop / Feb. 12, 2019

High 1 Resort

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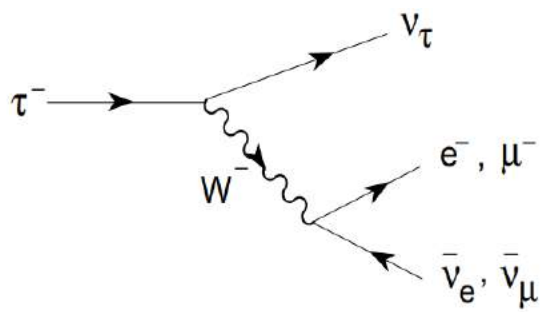
Lepton Flavor Universality

- Tau decay

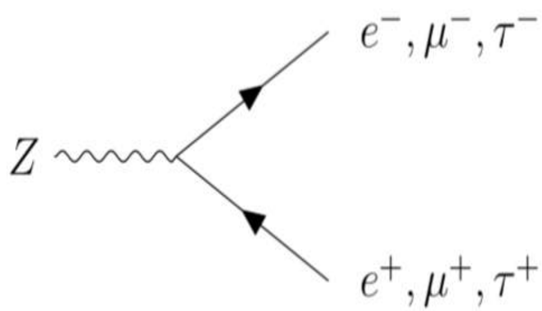


[A. Pich, arXiv:1310.7922]

$$BR(\tau^- \to \nu_\tau e^- \overline{\nu_e}) = (17.818 \pm 0.041)\,\%$$
$$BR(\tau^- \to \nu_\tau \mu^- \overline{\nu_\mu}) = (17.392 \pm 0.040)\,\%$$

$$\Longrightarrow \quad \frac{BR(\tau^- \to \nu_\tau \mu^- \overline{\nu_\mu})}{BR(\tau^- \to \nu_\tau e^- \overline{\nu_e})} = 0.9761 \pm 0.0028$$

- Z boson decay



[“Z decay modes”, pdg.lbl.gov/2012]

$$BR(Z \to e^+ e^-) = (3.363 \pm 0.004)\,\%$$
$$BR(Z \to \mu^+ \mu^-) = (3.366 \pm 0.007)\,\%$$
$$BR(Z \to \tau^+ \tau^-) = (3.370 \pm 0.008)\,\%$$

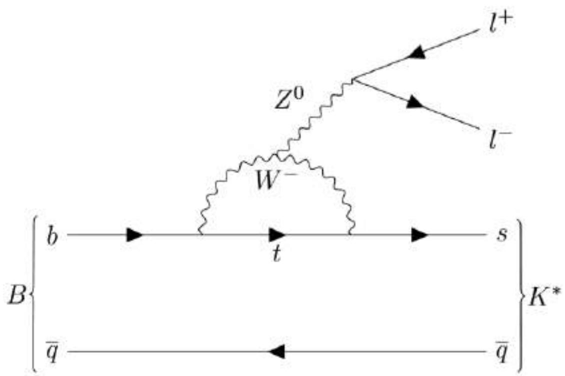
$$\Longrightarrow \quad B_e : B_\mu : B_\tau \approx 1 : 1 : 1$$

where $B_l = BR(Z \to l^+ l^-)$

<u>Lepton Flavor Universality for Weak interaction</u>

B-meson Anomalies

- B-meson decay to K*



The measurement is the ratio of the branching fractions of decay to muon and decay to electron.

$$R_{K*} = \frac{BR(B \to K * \mu^+\mu^-)}{BR(B \to K * e^+e^-)}$$

SM predictions for R_{K*}

$$R_{K*}^{SM} \approx 1$$

B-meson Anomalies

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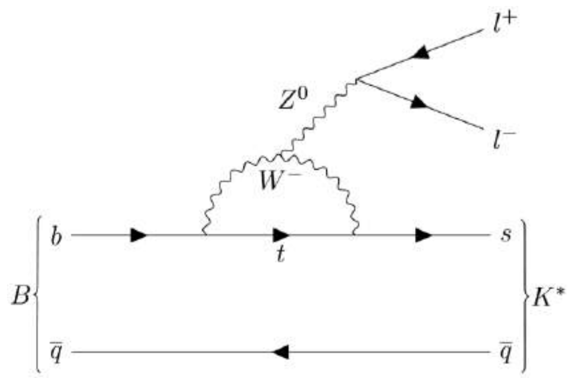

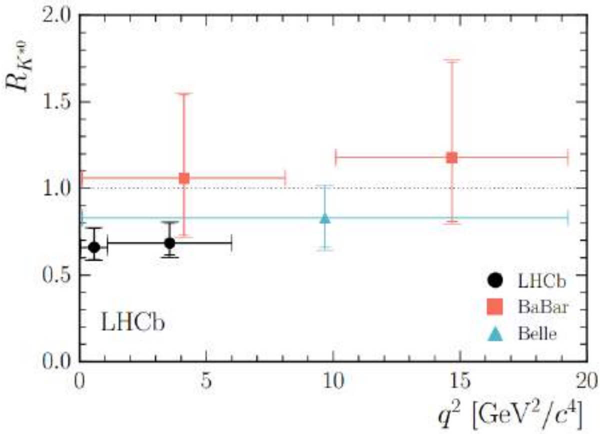

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$$R_{K*} = \frac{BR(B \to K*\mu^+\mu^-)}{BR(B \to K*e^+e^-)}$$

SM predictions for R_{K*}

$$R^{SM}_{K*} \approx 1$$

[LHCb Collaboration, arXiv:1705.05802]

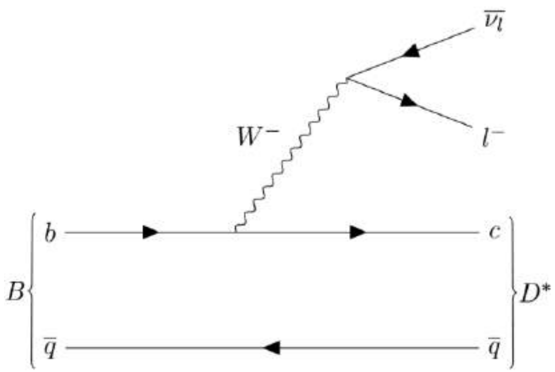
But, Experiments result differs from the SM prediction

$$R^{Exp}_{K*} = \begin{cases} 0.66\ ^{+0.11}_{-0.07}(\text{stat})\ \pm 0.03(\text{syst}), & 0.045\ \text{GeV}^2 < q^2 < 1.1\ \text{GeV}^2 \\ 0.69\ ^{+0.11}_{-0.07}(\text{stat})\ \pm 0.05(\text{syst}), & 1.1\ \text{GeV}^2 < q^2 < 6.0\ \text{GeV}^2 \end{cases}$$

$$\text{Deviations from SM at} \begin{cases} 2.1 - 2.3\ \sigma & 0.045\ \text{GeV}^2 < q^2 < 1.1\ \text{GeV}^2 \\ 2.4 - 2.5\ \sigma & 1.1\ \text{GeV}^2 < q^2 < 6.0\ \text{GeV}^2 \end{cases}$$

B-meson Anomalies

- B-meson decay to D*



The measurement is the ratio of the branching fractions of decay to tau and decay to muon/electron.

$$R_{D*} = \frac{BR(B \to D * \tau \overline{\nu}_\tau)}{BR(B \to D * l \overline{\nu}_l)} \quad \text{with } l = e, \mu$$

SM predictions for R_{D*}

$$R_{D*}^{SM} = 0.260 \pm 0.010$$

B-meson Anomalies

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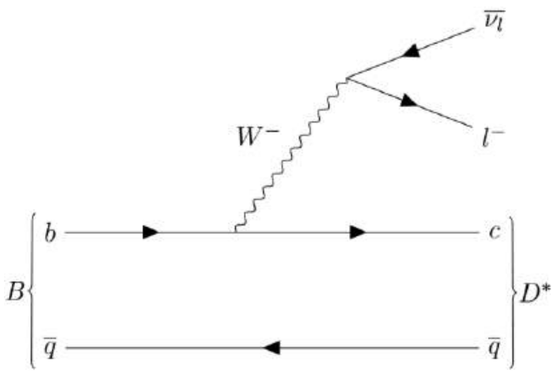

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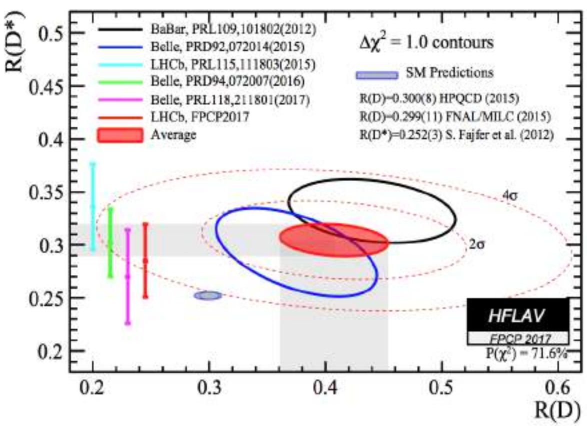
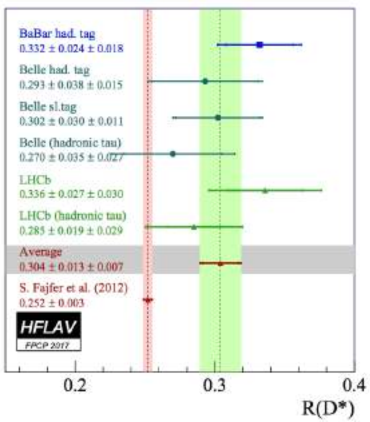
[EPJ Web Conf., DOI:10.1051/epjconf/201817501004]





Experiments result differs from the SM

$$R_{D*}^{Exp} = 0.310 \pm 0.015 \pm 0.008$$

The combined derivation between the measurement and the SM prediction is about 4.1σ

New Physics for B-anomalies

- Effective Hamiltonian for $b \to s\mu^+\mu^-$ [Bernat Capdevila et al, arXiv:1704.05340]

$$\mathscr{H}_{eff,\, b\to s\mu^+\mu^-} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha_{em}}{4\pi} \sum_i C_i \mathcal{O}_i$$

where
$$\mathcal{O}_{9\mu} = (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu \mu), \qquad \mathcal{O}_{10\mu} = (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu \gamma_5 \mu)$$
$$\mathcal{O}'_{9\mu} = (\bar{s}\gamma^\mu P_R b)(\bar{\mu}\gamma_\mu \mu), \qquad \mathcal{O}'_{10\mu} = (\bar{s}\gamma^\mu P_R b)(\bar{\mu}\gamma_\mu \gamma_5 \mu)$$

In the SM, the wilson coefficients are given by $C_{9\mu}^{SM} = -C_{10\mu}^{SM} = 4.27$ and $C_{9\mu}^{'SM} = -C_{10\mu}^{'SM} \approx 0$

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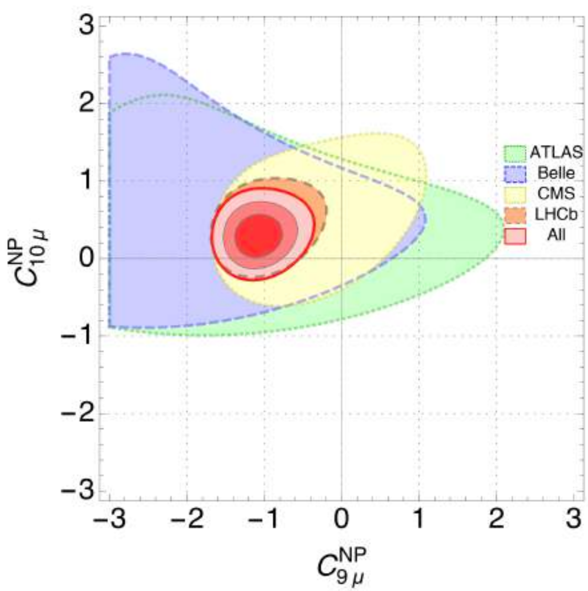

For $C_{10\mu}^{NP} = C_{9\mu}^{\prime NP} = C_{10\mu}^{\prime NP} = 0$ case, the best-fit value is given by

$C_{9\mu}^{NP} = -1.11$, while taking $[-1.28, -0.94]$ with 1σ and $[-1.45, -0.75]$ with 2σ

For $C_{9\mu}^{NP} = -C_{10\mu}^{NP}$ (V-A structure), $C_{9\mu}^{\prime NP} = C_{10\mu}^{\prime NP} = 0$ case, the best-fit value is given by

$C_{9\mu}^{NP} = -0.62$, while taking $[-0.75, -0.49]$ with 1σ and $[-0.88, -0.37]$ with 2σ

New Physics for B-anomalies

- Effective Hamiltonian for $b \to c\tau\nu$ [Hyun Min Lee, DOI:10.22661/AAPPSBL.2018.28.2.02]

$$\mathscr{H}_{eff,\, b\to c\tau\nu} = \frac{4G_F}{\sqrt{2}} V_{cb} C_{cb} (\bar{c}\gamma^{\mu} P_L b)(\bar{\tau}\gamma_{\mu} P_L \nu_{\tau})$$

where $C_{cb} = 1$ in the SM with $V_{cb} \approx 0.04$ by charged current W^- interactions.

The wilson coefficient for the new physics contribution should be $\Delta C_{cb} = 0.1$ while taking $[0.072,\, 0.127]$ with 1σ and $[0.044,\, 0.153]$ with 2σ

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- Effective cutoff scale

R_{K*} anomaly and Λ_K

$$\frac{1}{\Lambda_K^2} \equiv -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha_{em}}{4\pi} C_{9\mu}^{NP}$$

Best fit for $C_{9\mu}^{NP} = -C_{10\mu}^{NP} = -0.62$ (V - A structure)

$$\Lambda_K \sim 30 \text{ TeV}$$

R_{D*} anomaly and Λ_D

$$\frac{1}{\Lambda_D^2} \equiv \frac{4G_F}{\sqrt{2}} V_{cb} \Delta C_{cb}$$

Best fit for $\Delta C_{cb} = 0.1$

$$\Lambda_D \sim 3.5 \text{ TeV}$$

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$\Longrightarrow$ For explaining R_{K*} and R_{D*} anomalies, we considered singlet and triplet scalar leptoquarks.

Leptoquarks Model

- Singlet Scalar Leptoquark

Lagrangian for an $SU(2)_L$ singlet leptoquark S_1 with $Y = +\frac{1}{3}$

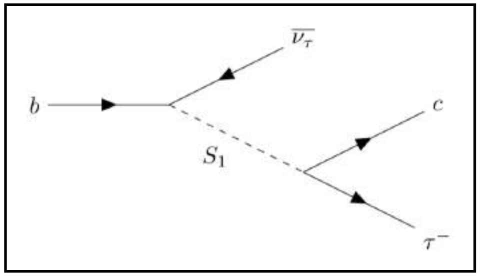
$$\mathscr{L}_{S_1} = -\lambda_{ij}\overline{(Q^C)}^a_{Ri}\left(i\sigma^2\right)_{ab} S_1 L^b_{Lj} + \text{h.c.} \qquad \text{where } \left(i\sigma^2\right)_{ab} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

After integrating out the leptoquark S_1, we obtain the effective Hamiltonian relevant for $\underline{b \to c\tau\bar{\nu}_\tau}$ R_{D^*}

$$\mathscr{H}^{S_1}_{b\to c\tau\bar{\nu}_\tau} = -\frac{\lambda^*_{33}\lambda_{23}}{m^2_{S_1}}\left(\overline{(c^C)}_R\tau_L\right)\left(\bar{\nu}_{\tau L}\left(b^C\right)_R\right) + \text{h.c.}$$

$$= -\frac{\lambda^*_{33}\lambda_{23}}{2m^2_{S_1}}\left(\bar{b}_L\gamma^\mu c_L\right)\left(\bar{\nu}_{\tau L}\gamma_\mu\tau_L\right) + \text{h.c.}$$

by using Fierz identity



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$R_D{}^*$

$$\mathscr{H}^{S_1}_{b\to c\tau\bar{\nu}_\tau} = -\frac{\lambda^*_{33}\lambda_{23}}{m^2_{S_1}}\left(\overline{(c^C)_R}\tau_L\right)\left(\bar{\nu}_{\tau L}(b^C)_R\right) + \text{h.c.}$$

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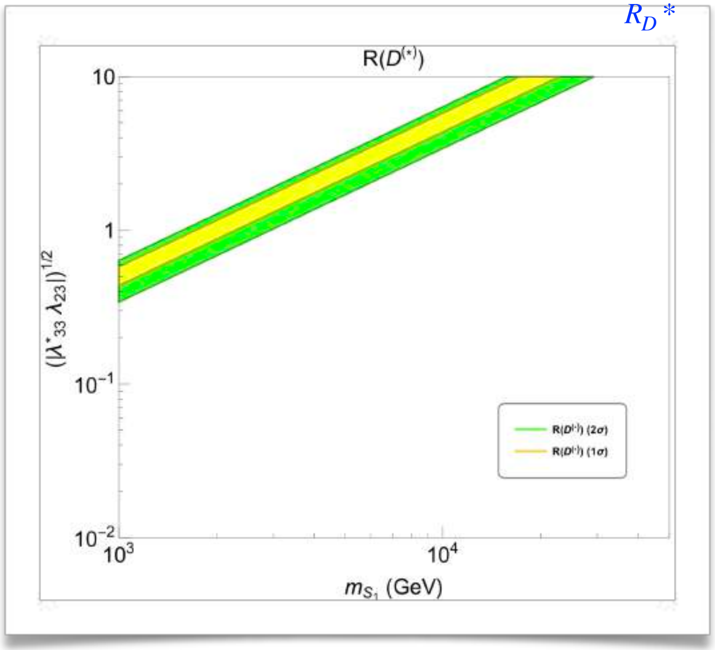

$\therefore$ S_1 gives rise to the effective operator for explaining the R_{D^*} anomalies and the effective cutoff scale Λ_D.

Thus, for $m_{S_1} \gtrsim 1$ TeV, we need $\sqrt{\left|\lambda^*_{33}\lambda_{23}\right|} \gtrsim 0.4$

Leptoquarks Model

- Triplet Scalar Leptoquark

Lagrangian for an $SU(2)_L$ triplet leptoquark S_3 where (ϕ_1, ϕ_2, ϕ_3) forms an isospin triplet with $T_3 = +1, 0, -1$ and $Q = +\frac{4}{3}, +\frac{1}{3}, -\frac{2}{3}$.

$$\mathscr{L}_{S_3} = -\kappa_{ij}\overline{\left(Q^C\right)^a_{Ri}}\Phi_{ab}L^b_{Lj} + \text{h.c.} \qquad \text{where } \Phi_{ab} = \begin{pmatrix} \sqrt{2}\phi_3 & -\phi_2 \\ -\phi_2 & -\sqrt{2}\phi_1 \end{pmatrix}$$

After integrating out the leptoquark ϕ_1, we obtain the effective Hamiltonian relevant for $\underline{b \to s\mu^+\mu^-}$ R_{K^*}

$$\mathscr{H}^{S_3}_{b\to s\mu^+\mu^-} = -\frac{2\kappa^*_{32}\kappa_{22}}{m^2_{\phi_1}}\left(\overline{\left(s^C\right)_R}\mu_L\right)\left(\overline{\mu}_L\left(b^C\right)_R\right) + \text{h.c.}$$

$$= -\frac{\kappa^*_{32}\kappa_{22}}{m^2_{\phi_1}}\left(\overline{b}_L\gamma^\mu s_L\right)\left(\overline{\mu}_L\gamma_\mu\mu_L\right) + \text{h.c.}$$

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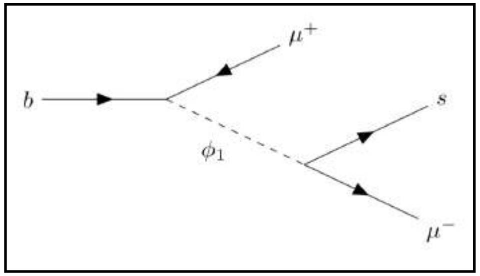

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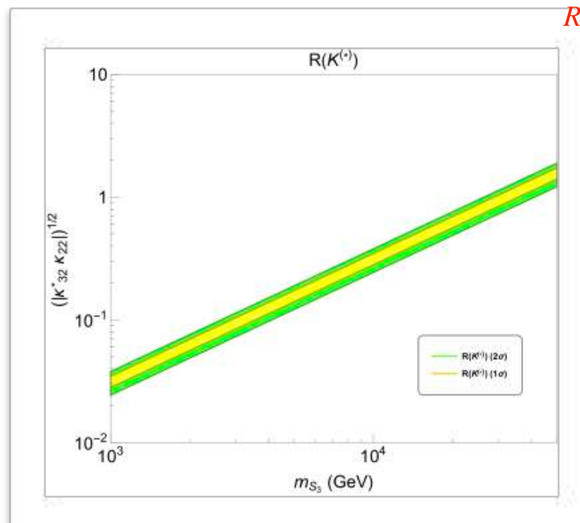
by using Fierz identity

$\therefore$ ϕ_1 gives rise to the effective operator of the $(V-A)$ structure as favored by the R_{K^*} anomalies and the effective cutoff scale Λ_K.

Thus, for $m_{\phi_1} \gtrsim 1$ TeV, we need $\sqrt{\left|\kappa^*_{32}\kappa_{22}\right|} \gtrsim 0.03$



Constraints

- Flavor Structure for Leptoquark couplings

For $m_{S_3} \sim m_{S_1} \gtrsim 1$ TeV,

$$\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \lambda_{23} \\ 0 & \lambda_{32} & \lambda_{33} \end{pmatrix}, \qquad \kappa = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \kappa_{22} & \kappa_{23} \\ 0 & \kappa_{32} & \kappa_{33} \end{pmatrix}$$

Constraints

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For $m_{S_3} \sim m_{S_1} \gtrsim 1$ TeV,

★ $\sqrt{\left|\kappa_{32}^{*}\kappa_{22}\right|} \gtrsim 0.03$ to explain R_{K^*} anomaly

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[A. K. Alok et al, arXiv:1703.09247]

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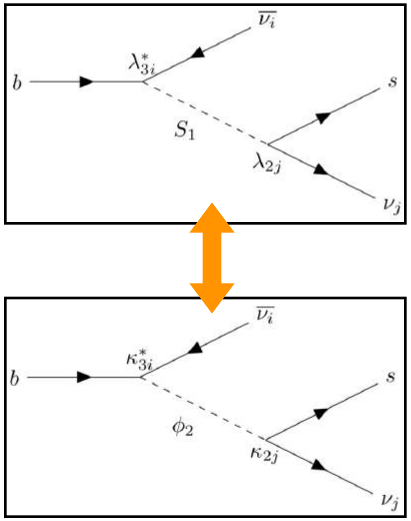
★ $\sqrt{\left|\kappa_{33}^{*}\kappa_{23}\right|} \approx \sqrt{\left|\lambda_{33}^{*}\lambda_{23}\right|} \gtrsim 0.4$ to explain rare meson decays



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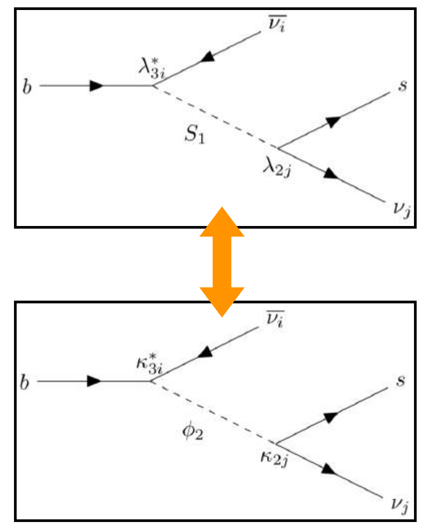

★ $\sqrt{\left|\kappa^*_{32}\kappa_{22}\right|} \gtrsim 0.03$ to explain R_{K^*} anomaly

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★ $\sqrt{\left|\kappa^*_{33}\kappa_{23}\right|} \approx \sqrt{\left|\lambda^*_{33}\lambda_{23}\right|} \gtrsim 0.4$ to explain rare meson decays

★ $\sqrt{\left|\kappa^*_{32}\kappa_{23}\right|} \approx \sqrt{\left|\lambda^*_{32}\lambda_{23}\right|}$ to explain rare meson decays

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Constraints

- $(g-2)_\mu$ and $BR(\tau \to \mu\gamma)$

We discussed the deviation in $(g-2)_\mu$ to get a sizable λ_{32} coupling.

[A. Crivellin et al, arXiv:1703.09226]

For the singlet scalar leptoquark, Yukawa couplings for $(g-2)_\mu$ with an additional Yukawa coupling.

$$\mathscr{L}_{S_1} \supset -\lambda_{ij}\, \overline{\left(Q^C\right)^a_{Ri}}\, \left(i\sigma^2\right)_{ab} S_1\, L^b_{jL} \;-\lambda'_{ij}\, \overline{\left(u^C\right)_{Li}}\, S_1\, e_{jR} \;+\; \text{h.c.}$$

Constraints

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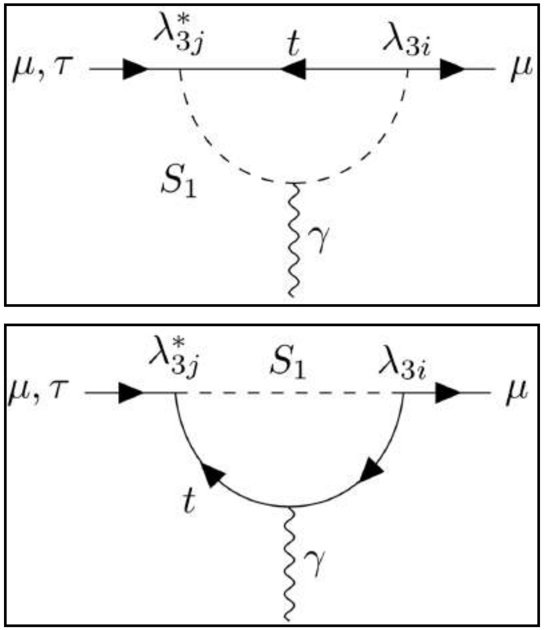
Chirality-enhanced effect from top quark contributes (right diagrams)



$$a_\mu^{S_1} = \frac{m_\mu}{4\pi^2} Re[C_R^{22}]$$

$$BR(\tau \to \mu\gamma) = \frac{\alpha m_\tau^3}{256\pi^4}\tau_\tau \left(\left|C_R^{23}\right|^2 + \left|C_L^{23}\right|^2 \right)$$

where $C_R^{ij} \equiv -\dfrac{N_c}{12 m_{S_1}^2} m_t \lambda_{3i} \lambda'^*_{3j} \left[7 + 4\log\left(\dfrac{m_t^2}{m_{S_1}^2}\right)\right]$

$$C_L^{ij} = C_R^{ij}\,\left(\lambda_{3i} \to \lambda'_{3i}\,,\ \lambda'_{3j} \to \lambda_{3j}\right)$$

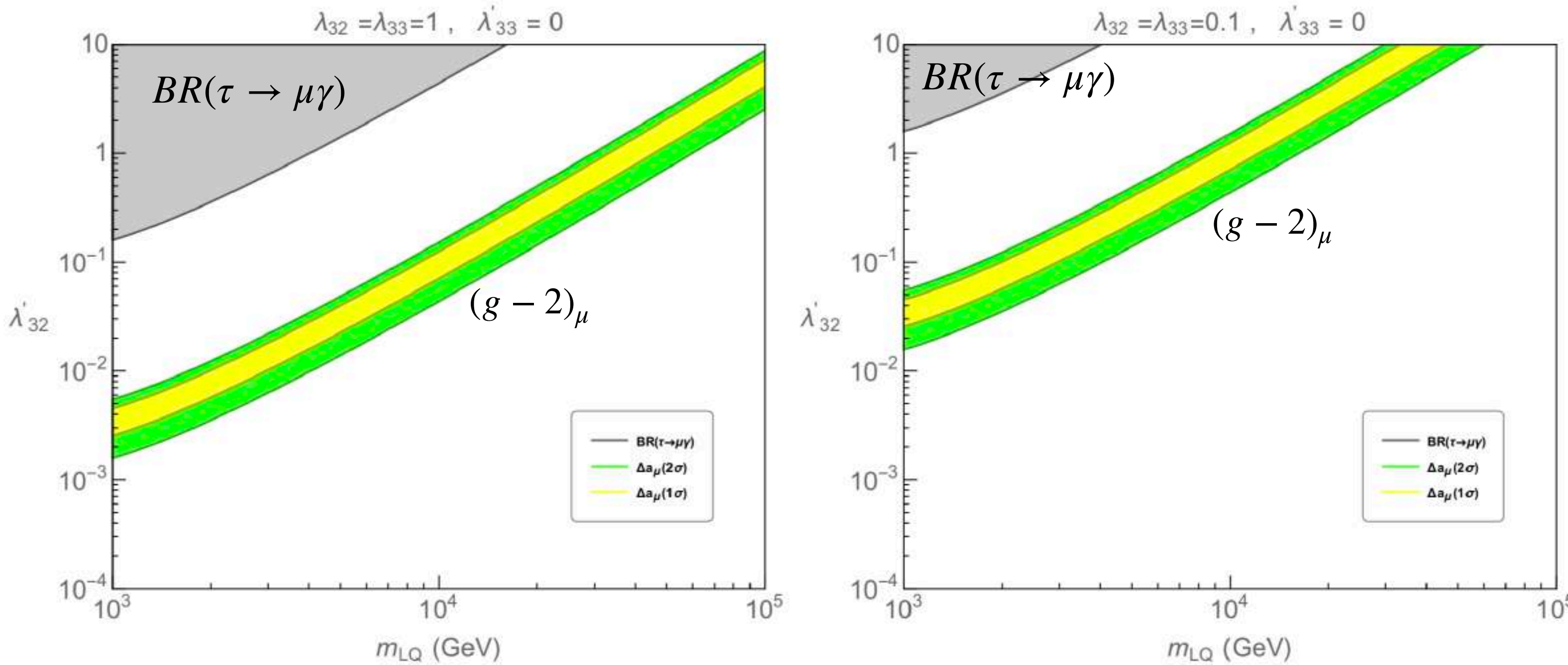
Constraints

- $(g-2)_\mu$ and $BR(\tau \to \mu\gamma)$

The current experimental bounds

$$\Delta a_\mu = a^{exp} - a^{SM} = 288(80) \times 10^{-11}, \qquad BR(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

[PDG(2016), DOI:10.1088/1674-1137/40/10/100001] [BaBar Collaboration, arXiv:0908.2381]



Constraints

- Flavor Structure for Leptoquark couplings

For $m_{S_3} \sim m_{S_1} \gtrsim 1$ TeV, $\lambda_{32} = \lambda_{33} = 1,\ \kappa_{23} = 0.1$ case

★ $\sqrt{\left|\kappa^*_{32}\kappa_{22}\right|} \gtrsim 0.03$ to explain R_{K^*} anomaly

★ $\sqrt{\left|\lambda^*_{33}\lambda_{23}\right|} \gtrsim 0.4$ to explain R_{D^*} anomaly

★ $\sqrt{\left|\kappa^*_{33}\kappa_{23}\right|} \approx \sqrt{\left|\lambda^*_{33}\lambda_{23}\right|} \gtrsim 0.4$ to explain rare meson decays

★ $\sqrt{\left|\kappa^*_{32}\kappa_{23}\right|} \approx \sqrt{\left|\lambda^*_{32}\lambda_{23}\right|}$ to explain rare meson decays

$$\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \lambda_{23} \\ 0 & 1 & 1 \end{pmatrix}, \qquad \kappa = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \kappa_{22} & 0.1 \\ 0 & \kappa_{32} & \kappa_{33} \end{pmatrix}$$

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$$\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \gtrsim 0.16 \\ 0 & 1 & 1 \end{pmatrix}, \qquad \kappa = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \kappa_{22} & 0.1 \\ 0 & \kappa_{32} & \kappa_{33} \end{pmatrix}$$

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$$\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \gtrsim 0.16 \\ 0 & 1 & 1 \end{pmatrix}, \qquad \kappa = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \gtrsim 5.6 \times 10^{-4} & 0.1 \\ 0 & \gtrsim 1.6 & \gtrsim 1.6 \end{pmatrix}$$

Leptoquark Portal Dark Matter

- Singlet Real Scalar Dark Matter

Lagrangian generalizes the Higgs portal interactions to those for leptoquarks $(S_{LQ} = S_{1,3})$.

$$\mathscr{L}_S = |D_\mu S_{LQ}|^2 - m_{LQ}^2 |S_{LQ}|^2 + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_1 S^4 - \lambda_2 |S_{LQ}|^4 - \frac{1}{2}\lambda_3 S^2 |S_{LQ}|^2 - \frac{1}{2}\lambda_4 S^2 |H|^2 - \lambda_5 |H|^2 |S_{LQ}|^2$$

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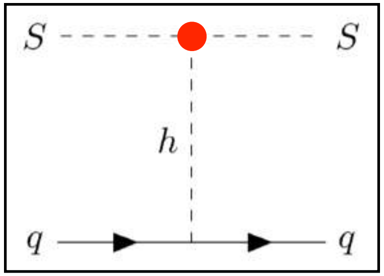
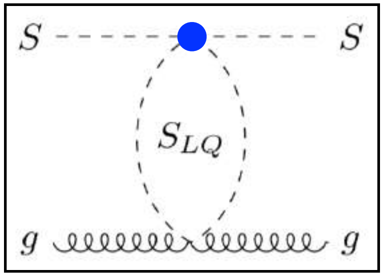
- Direct Detection Bounds

Spin-independent cross section for DM-nucleon elastic scattering is given by

$$\sigma_{S-N} = \frac{\mu_N^2}{\pi m_s^2 A^2}\left(Z f_P^S + (A-Z) f_n^S\right)^2$$

$$f_{p,n}^S = \frac{\lambda_4 m_{p,n}}{m_h^2}\left(\sum_{q=u,d,s} f_{Tq}^{p,n} + \frac{2}{9} f_{TG}^{p,n}\right) - \frac{\lambda_3 m_{p,n}}{108 m_{LQ}^2} l_3\left(S_{LQ}\right) f_{TG}^{p,n}$$





Leptoquark Portal Dark Matter

- Higgs Data in Collider

The bound from invisible Higgs decay,

$$\Gamma\left(h \to SS\right) = \frac{\lambda_4^2 v^2}{32\pi m_h}\sqrt{1 - \frac{4m_S^2}{m_h^2}} \qquad BR\left(h \to SS\right) = \frac{\Gamma\left(h \to SS\right)}{\Gamma_{h,SM} + \Gamma\left(h \to SS\right)} < 0.24$$

Leptoquark Portal Dark Matter

- ## Higgs Data in Collider

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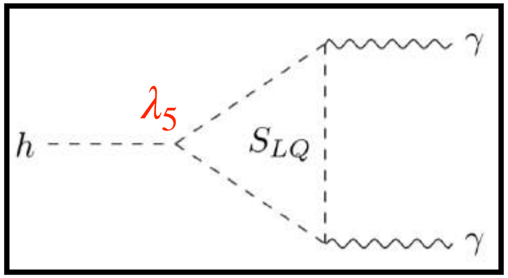
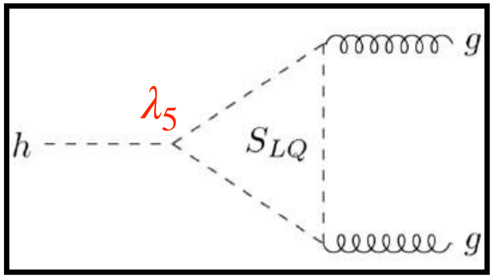
The diphoton signal strength for gluon-fusion production is given by

$$R_{gg} = \frac{\sigma\left(gg \to h\right)}{\sigma\left(gg \to h\right)_{SM}} \quad , \quad R_{\gamma\gamma} = \frac{\sigma\left(h \to \gamma\gamma\right)}{\sigma\left(h \to \gamma\gamma\right)_{SM}} \quad \Rightarrow \quad \mu_{\gamma\gamma} = R_{gg}R_{\gamma\gamma} = 1.10^{+0.23}_{-0.22}$$





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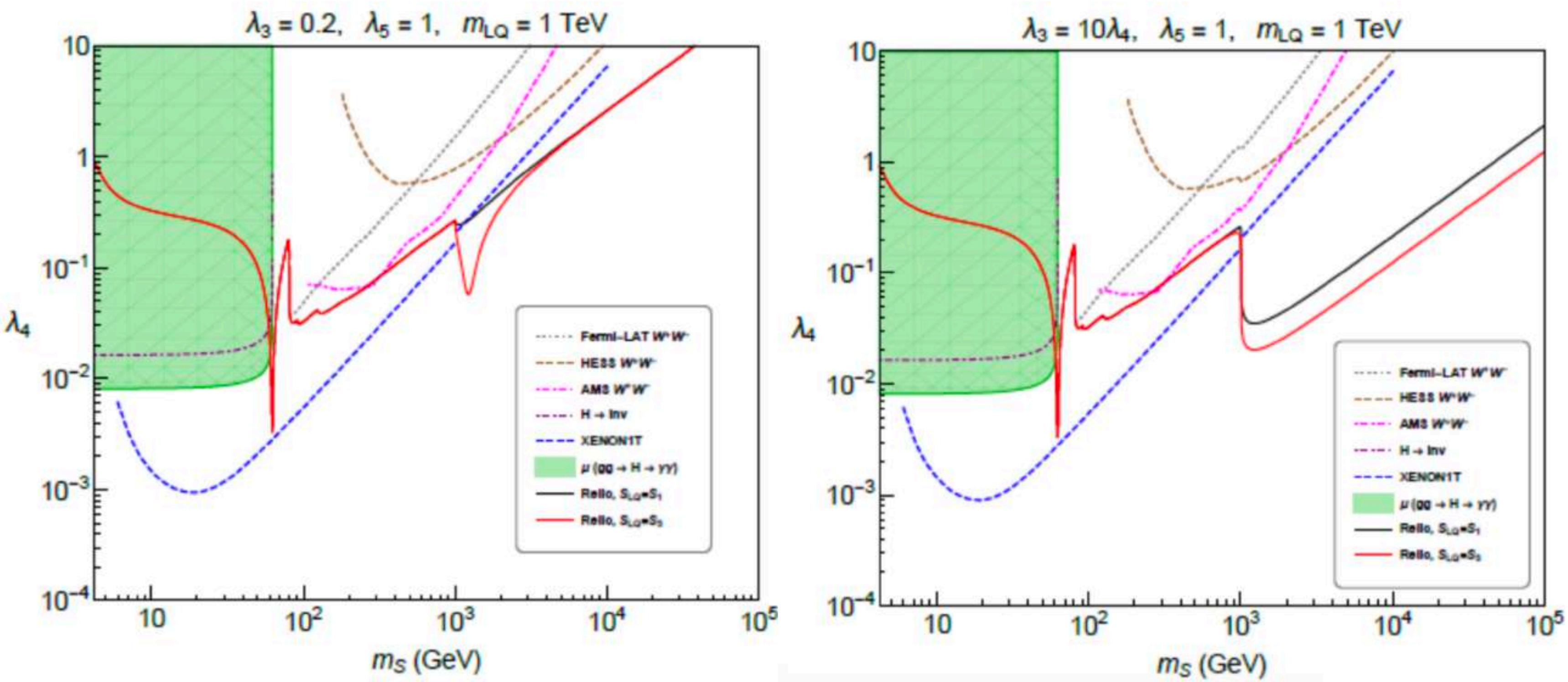
In our model, as far as $|\lambda_5| < 10$, the decay rate into a diphoton or a digluon can be ignored, but the diphoton signal strength is modified by the enhanced total decay width of Higgs boson due to the invisible decay mode

Leptoquark Portal Dark Matter

- Indirect Detection Bounds

DM annihilations into $hh, WW, ZZ, t\bar{t}, b\bar{b}$ from Higgs portal (or quartic coupling) are constrained by Fermi-LAT, HESS and AMS-02



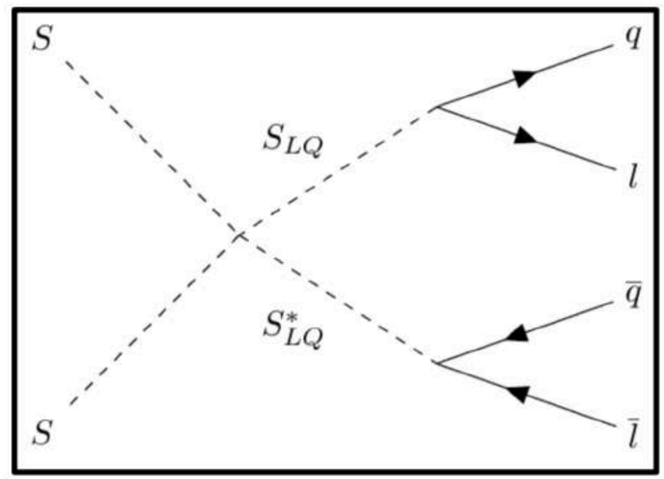
Leptoquark Portal Dark Matter

- Indirect Detection Bounds (Cascade Decay)

If $m_S > m_{LQ}$, dark matter can annihilate into LQs and LQ decays into quark and lepton in cascade decay.

LQs	BRs	BRs	BRs
$S_1 S_1^*$	$\mathrm{B}(\lvert \bar{t}\bar{\tau} + b\nu_\tau \rvert^2) = \beta^2$	$\mathrm{B}(\lvert \bar{c}\bar{\tau} + s\nu_\tau \rvert^2) = (1-\beta)^2$	$\mathrm{B}((\bar{t}\bar{\tau} + b\nu_\tau)^*(\bar{c}\bar{\tau} + s\nu_\tau) + \mathrm{h.c.}) = 2\beta(1-\beta)$
$\phi_1 \phi_1^*$	$\mathrm{B}(\bar{b}b\bar{\mu}\mu) = \gamma^2$	$\mathrm{B}(\bar{s}s\bar{\mu}\mu) = (1-\gamma)^2$	$\mathrm{B}(\bar{b}s\bar{\mu}\mu + \mathrm{h.c.}) = 2\gamma(1-\gamma)$
$\phi_2 \phi_2^*$	$\mathrm{B}(\lvert \bar{t}\bar{\mu} + b\nu_\mu \rvert^2) = \gamma^2$	$\mathrm{B}(\lvert \bar{c}\bar{\mu} + s\nu_\mu \rvert^2) = (1-\gamma)^2$	$\mathrm{B}((\bar{t}\bar{\mu} + b\nu_\mu)^*(\bar{c}\bar{\mu} + s\nu_\mu) + \mathrm{h.c.}) = 2\gamma(1-\gamma)$
$\phi_3 \phi_3^*$	$\mathrm{B}(\bar{t}t\bar{\nu}_\mu \nu_\mu) = \gamma^2$	$\mathrm{B}(\bar{c}c\bar{\nu}_\mu \nu_\mu) = (1-\gamma)^2$	$\mathrm{B}(\bar{t}c\bar{\nu}_\mu \nu_\mu + \mathrm{h.c.}) = 2\gamma(1-\gamma)$

$\beta \equiv \lambda_{33}^2/(\lambda_{33}^2 + \lambda_{23}^2)$ and $\gamma \equiv \kappa_{32}^2/(\kappa_{32}^2 + \kappa_{22}^2)$



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$\phi_3 \phi_3^*$	$B(\bar{t}t\bar{\nu}_\mu\nu_\mu) = \gamma^2$	$B(\bar{c}c\bar{\nu}_\mu\nu_\mu) = (1-\gamma)^2$	$B(\bar{t}c\bar{\nu}_\mu\nu_\mu + \text{h.c.}) = 2\gamma(1-\gamma)$

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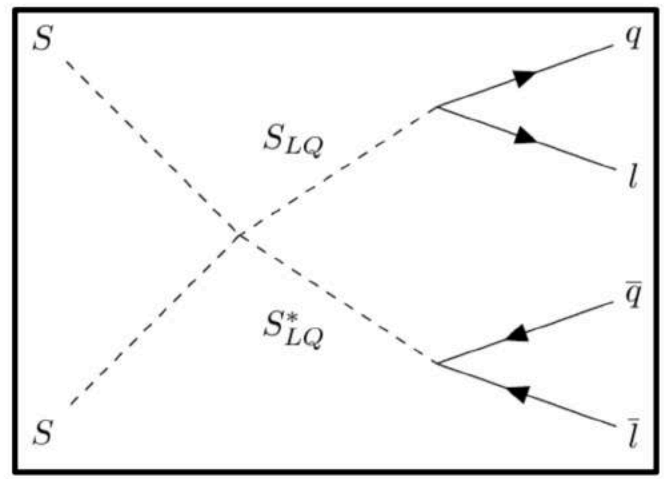


- $S_1 : \lambda_{33} \gg \lambda_{23}$ or $\beta \approx 1$

$$B(\bar{t}t\bar{\tau}\tau) : B(\bar{b}b\bar{\nu}_\tau\nu_\tau) : B(\bar{t}b\bar{\tau}\nu_\tau \ + \ h.c.) = \frac{1}{2} : \frac{1}{2} : 1$$

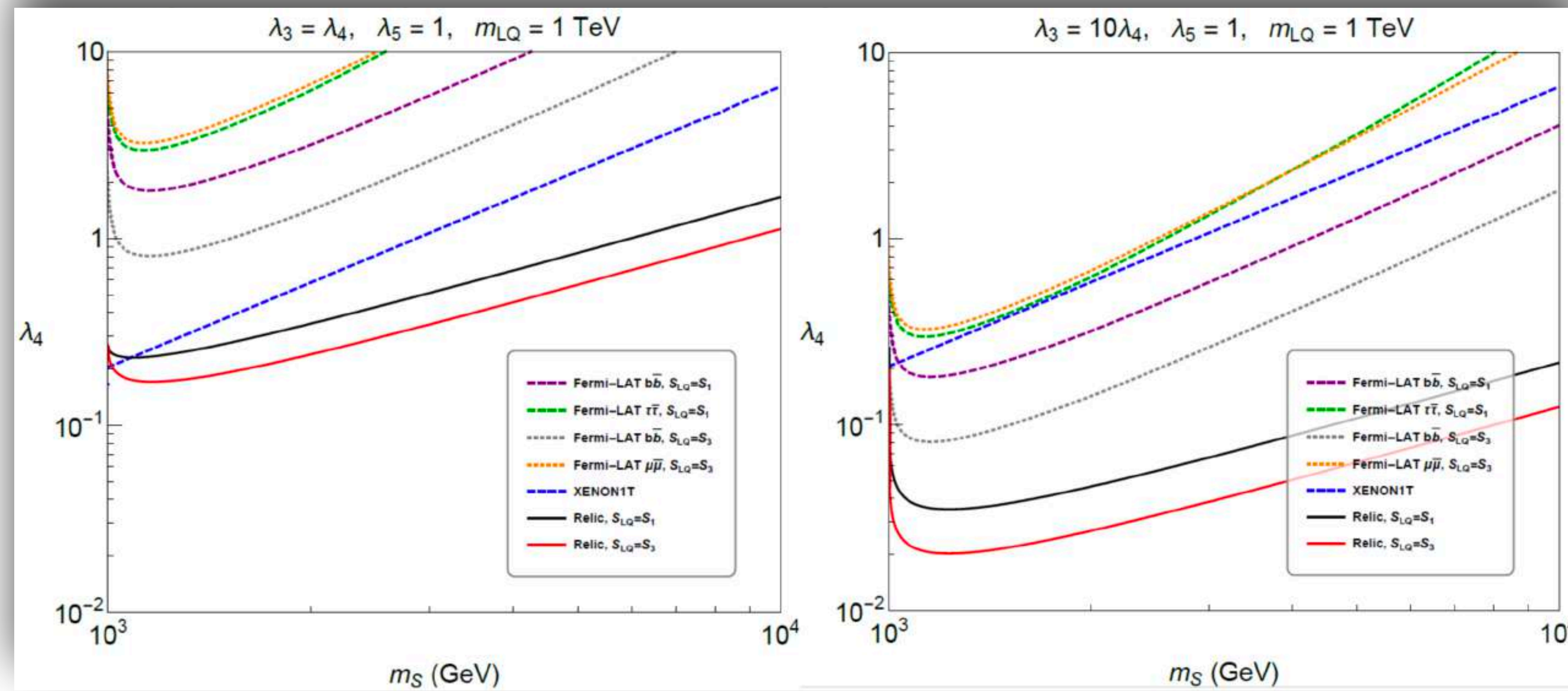
- $S_3 : \kappa_{32} \gg \kappa_{22}$ or $\gamma \approx 1$

$$B(\bar{b}b\bar{\mu}\mu) : B(\bar{t}t\bar{\mu}\mu) : B(\bar{b}b\bar{\nu}_\mu\nu_\mu) : B(\bar{t}b\bar{\mu}\nu_\mu \ + \ h.c.) : B(\bar{t}t\bar{\nu}_\mu\nu_\mu) = 1 : \frac{1}{4} : \frac{1}{4} : \frac{1}{2} : 1$$

Leptoquark Portal Dark Matter

- Indirect Detection Bounds (Cascade Decay)

If $m_S > m_{LQ}$, dark matter can annihilate into LQs and LQ decays into quark and lepton in cascade decay.



$$B(\bar{b}b\bar{\mu}\mu) : B(\bar{t}t\bar{\mu}\mu) : B(\bar{b}b\bar{\nu}_\mu\nu_\mu) : B(\bar{t}b\bar{\mu}\nu_\mu + h.c.) : B(\bar{t}t\bar{\nu}_\mu\nu_\mu) = 1 : \frac{1}{4} : \frac{1}{4} : \frac{1}{2} : 1$$

Conclusion

We have proposed Leptoquark models to explain R_K* and R_D* anomalies.

We discussed the constraints on scalar leptoquark models, due to rare meson decays, muon $(g-2)_\mu$ and $BR(\tau \to \mu\gamma)$. And we considered flavor structure for leptoquark couplings.

We considered the scalar dark matter with leptoquark portal. And we discussed bounds about direct detection (XENON1T), indirect detection (Fermi-LAT, HESS and AMS-02) and collider data.

Back up Slide

Constraints

- Rare meson decays and mixing

Effective Hamiltonian relevant for $\overline{b} \to \overline{s}\nu\overline{\nu}$

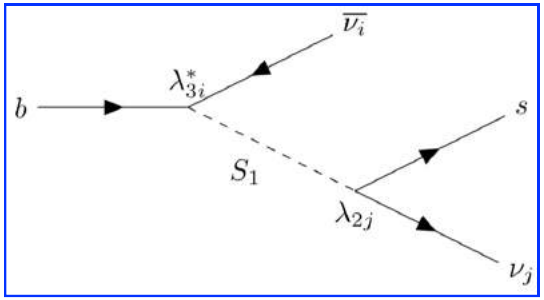
$$\mathscr{H}_{\overline{b}\to\overline{s}\nu\overline{\nu}} = -\frac{\sqrt{2}\alpha_{em}G_F}{\pi}V_{tb}V_{ts}^* \sum_l C_L^l \left(\overline{b}\gamma^\mu P_L s\right)\left(\overline{\nu_l}\gamma_\mu P_L \nu_l\right)$$

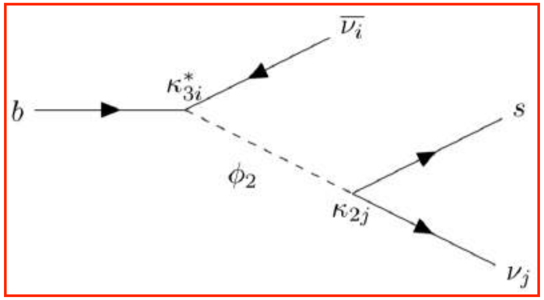
where $C_L^l = C_L^{SM} + C_\nu^{l,NP}$.

[A. K. Alok et al, arXiv:1703.09247]

We calculate the $C_\nu^{l,NP}$ by using right diagram's couplings.

$$C_\nu^{l,NP} = -\left(\frac{\lambda_{3i}^*\lambda_{2j}}{2m_{S_1}^2} + \frac{\kappa_{3i}^*\kappa_{2j}}{2m_{\phi_2}^2}\right)\frac{\pi}{\sqrt{2}\alpha_{em}G_F V_{tb}V_{ts}^*}$$





The ratio of the branching ratios are given by

$$R_{K^*\nu} \equiv \frac{BR(B \to K^*\nu\overline{\nu})}{BR(B \to K^*\nu\overline{\nu})\big|_{SM}} = \frac{2}{3} + \frac{1}{3}\frac{\left|C_L^{SM} + C_\nu^{l,NP}\right|^2}{\left|C_L^{SM}\right|^2}$$

Constraints

- Rare meson decays and mixing

Comparing the experimental bounds on $BR(B \to K^* \nu\bar{\nu})$

$BR(B \to K^* \nu\bar{\nu}) < 2.7 \times 10^{-5}$ [Belle Collaboration, arXiv:1702.03224]

$BR(B \to K^* \nu\bar{\nu})\Big|_{SM} = (9.19 \pm 0.86 \pm 0.50) \times 10^{-6}$ [A. J. Buras et al, arXiv:1409.4557]

Ignoring the imaginary part of $C_\nu^{l,NP}$, we get the $R_{K^*\nu}$ bound as

$$-10.1 < Re(C_\nu^{l,NP}) < 22.8$$

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$$-10.1 < Re(C_\nu^{l,NP}) < 22.8$$

We considered the necessary flavor structure for leptoquark couplings.

Flavor structure for leptoquark couplings is given by the following,

$$\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda_{22} & \lambda_{23} \\ 0 & \lambda_{32} & \lambda_{33} \end{pmatrix}, \qquad \kappa = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \kappa_{22} & \kappa_{23} \\ 0 & \kappa_{32} & \kappa_{33} \end{pmatrix}$$

Constraints

- Rare meson decays and mixing

From R_{K^*} anomaly,

$$\frac{\pi}{\sqrt{2}\alpha_{em}G_F V_{tb}V_{ts}^*} \sim (20\ \text{TeV})^2 \qquad \Longleftrightarrow \qquad \Lambda_K^2 \sim (30\ \text{TeV})^2$$

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Taking into account κ_{32} and κ_{22} satisfies the $R_{K^*\nu}$ bound on its own easily nevertheless on $\lambda_{22} = 0$

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Taking into account κ_{32} and κ_{22} satisfies the $R_{K^*\nu}$ bound on its own easily nevertheless on $\lambda_{22} = 0$

Ignoring the mass splitting generated within S_1 and S_3, So, we get $m_{\phi_1} = m_{\phi_2} = m_{\phi_3} \equiv m_{S_1}$

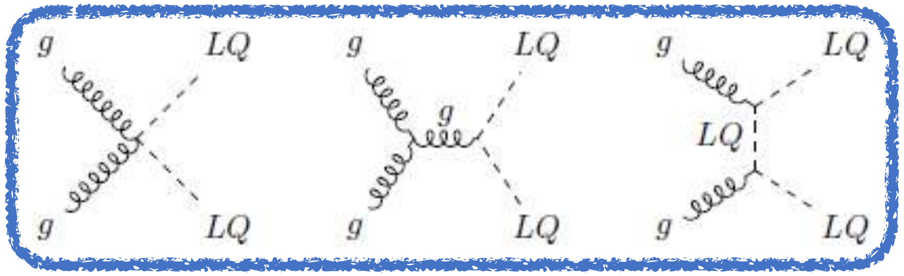
$$\frac{\lambda_{3i}^* \lambda_{2j}}{2m_{S_1}^2} + \frac{\kappa_{3i}^* \kappa_{2j}}{2m_{\phi_2}^2} \approx 0 \qquad \Longrightarrow \qquad \sqrt{\left|\lambda_{3i}^* \lambda_{2j}\right|} \approx \sqrt{\left|\kappa_{3i}^* \kappa_{2j}\right|}$$

$$\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \lambda_{23} \\ 0 & \lambda_{32} & \lambda_{33} \end{pmatrix}, \qquad \kappa = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \kappa_{22} & \kappa_{23} \\ 0 & \kappa_{32} & \kappa_{33} \end{pmatrix}$$

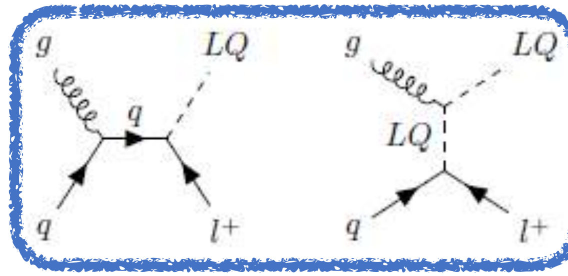
Constraints

- LHC searches

Collider productions channel (pair & single)



Pair production



Single production

Decay branching ratios of Leptoquark and LHC bounds on Leptoquark masses

LQs	BRs	$m_{LQ,\min}$	BRs	$m_{LQ,\min}$
S_1	$\mathrm{B}(\bar{t}\bar{\tau}/b\nu_\tau) = \frac{1}{2}\beta$	$1.22\,\mathrm{TeV}(b\nu_\tau)$ [32]	$\mathrm{B}(\bar{c}\bar{\tau}/s\nu_\tau) = \frac{1}{2}(1-\beta)$	$950\,\mathrm{GeV}(\nu_\tau j)$ [33]
$S_3(\phi_1)$	$\mathrm{B}(\bar{b}\bar{\mu}) = \gamma$	$1.4\,\mathrm{TeV}$ [34]	$\mathrm{B}(\bar{s}\bar{\mu}) = 1-\gamma$	$1.08\,\mathrm{TeV}\ (\bar{\mu}j)$ [35]
$S_3(\phi_2)$	$\mathrm{B}(\bar{t}\bar{\mu}/\bar{b}\bar{\nu}_\mu) = \frac{1}{2}\gamma$	$1.45\,\mathrm{TeV}\ (\bar{t}\bar{\mu})$ [36]	$\mathrm{B}(\bar{c}\bar{\mu}/\bar{s}\bar{\nu}_\mu) = \frac{1}{2}(1-\gamma)$	$850\,\mathrm{GeV}\ (\bar{\mu}\bar{\nu}_\mu jj)$ [37]
$S_3(\phi_3)$	$\mathrm{B}(\bar{t}\bar{\nu}_\mu) = \gamma$	$1.12\,\mathrm{TeV}$ [38]	$\mathrm{B}(\bar{c}\bar{\nu}_\mu) = 1-\gamma$	$950\,\mathrm{GeV}\ (\bar{\nu}_\mu j)$ [33]

where $\beta \equiv \lambda_{33}^2/\left(\lambda_{33}^2 + \lambda_{23}^2\right)$ and $\gamma \equiv \kappa_{32}^2/\left(\kappa_{32}^2 + \kappa_{22}^2\right)$

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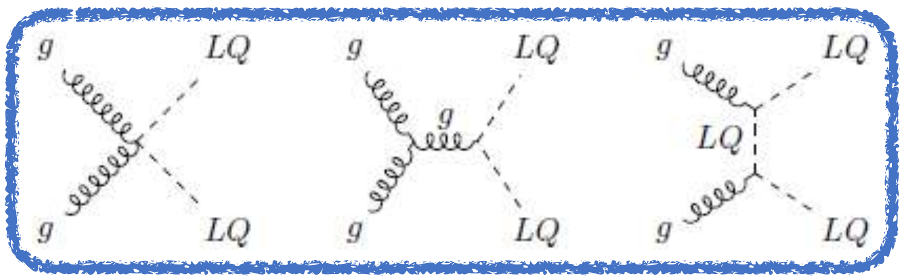
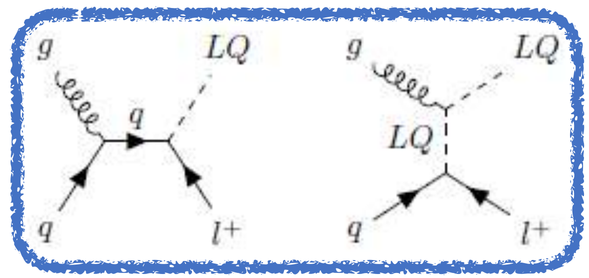
- LHC searches

Collider productions channel (pair & single)



Pair production



Single production

Decay branching ratios of Leptoquark and LHC bounds on Leptoquark masses

LQs	BRs	$m_{LQ,\min}$	BRs	$m_{LQ,\min}$
S_1	$B(\bar{t}\bar{\tau}/b\nu_\tau) = \frac{1}{2}\beta$	$1.22\,\text{TeV}(b\nu_\tau)$ [32]	$B(\bar{c}\bar{\tau}/s\nu_\tau) = \frac{1}{2}(1-\beta)$	$950\,\text{GeV}(\nu_\tau j)$ [33]
$S_3(\phi_1)$	$B(\bar{b}\bar{\mu}) = \gamma$	$1.4\,\text{TeV}$ [34]	$B(\bar{s}\bar{\mu}) = 1-\gamma$	$1.08\,\text{TeV}\ (\bar{\mu}j)$ [35]
$S_3(\phi_2)$	$B(\bar{t}\bar{\mu}/\bar{b}\bar{\nu}_\mu) = \frac{1}{2}\gamma$	$1.45\,\text{TeV}\ (t\bar{\mu})$ [36]	$B(\bar{c}\bar{\mu}/\bar{s}\bar{\nu}_\mu) = \frac{1}{2}(1-\gamma)$	$850\,\text{GeV}\ (\bar{\mu}\bar{\nu}_\mu jj)$ [37]
$S_3(\phi_3)$	$B(\bar{t}\bar{\nu}_\mu) = \gamma$	$1.12\,\text{TeV}$ [38]	$B(\bar{c}\bar{\nu}_\mu) = 1-\gamma$	$950\,\text{GeV}\ (\bar{\nu}_\mu j)$ [33]

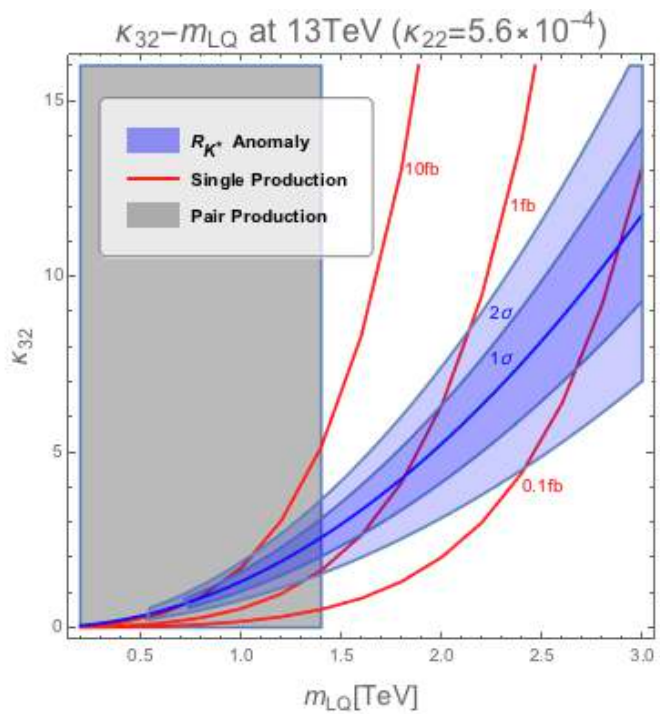
decay to b-quark

where $\beta \equiv \lambda_{33}^2/(\lambda_{33}^2 + \lambda_{23}^2)$ and $\gamma \equiv \kappa_{32}^2/(\kappa_{32}^2 + \kappa_{22}^2)$

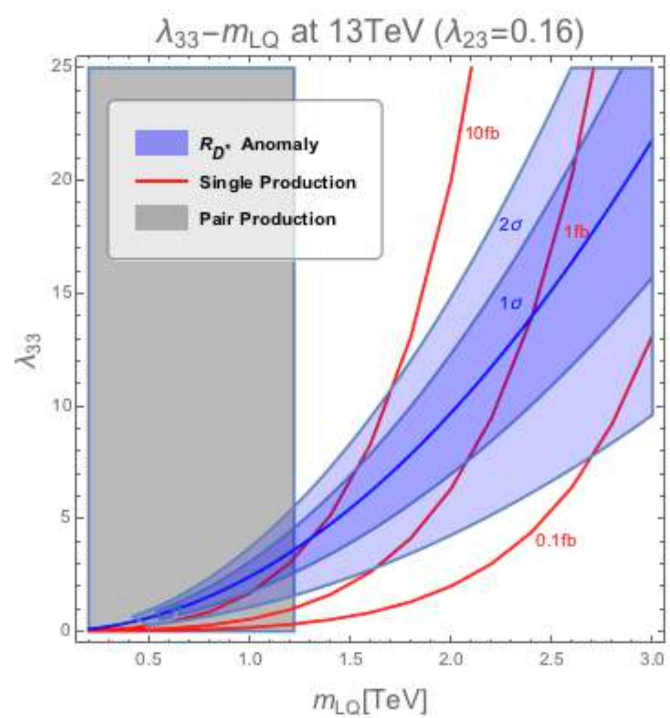
Constraints

- LHC searches

Leptoquark couplings vs. mass plot (decay to b-quark)



R_K* anomaly



R_D* anomaly