Scalar Leptoquarks for B-meson Anomalies and Dark Matter.

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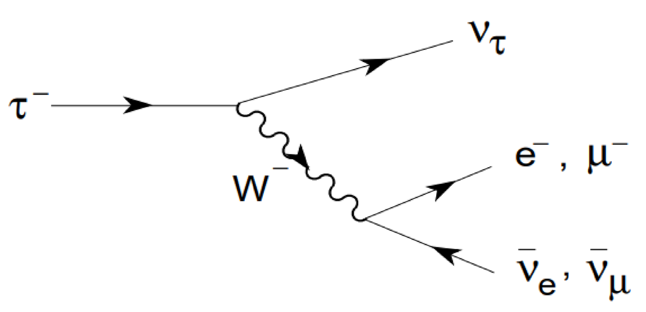
Abstract

The LHCb experiment has recently provided several new measurements to test the lepton flavor universality in the Standard Model (SM) and confirmed some of the prevailing anomalies from the B-meson decays in BaBar and/or Belle experiments. We consider the setup where scalar leptoquarks or extra U(1) gauge bosons have flavor-dependent couplings to the SM. In this work, we discuss the flavor structure for quarks and leptons and various constraints on the model and propose a natural candidate for dark matter.

B-meson Anomalies

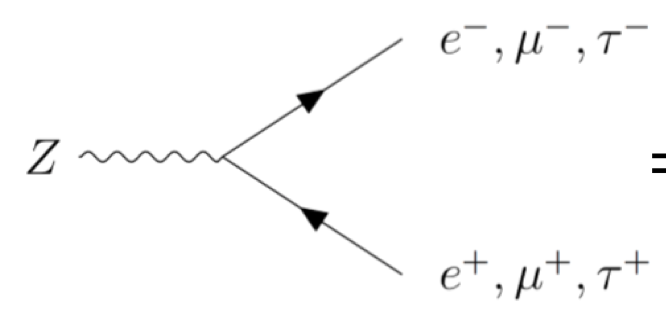
❖ Lepton Flavor Universality

Tau decay [1]



$$\frac{BR(\tau^- \to \nu_\tau \mu^- \bar{\upsilon}_\mu)}{BR(\tau^- \to \nu_\tau e^- \bar{\upsilon}_e)} = 0.9761 \pm 0.0028$$

Z boson decay [2]

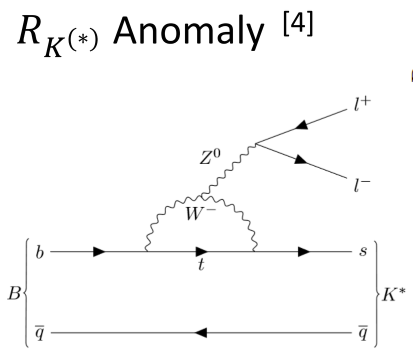


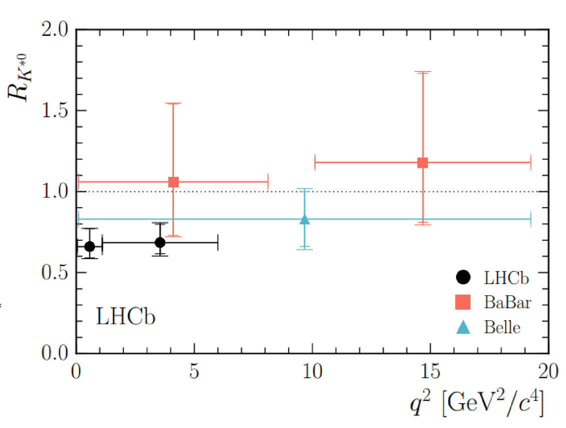
$B_e : B_\mu : B_\tau \approx 1:1:1$
where $B_l = BR(Z \to l^+ l^-)$

⇒ Lepton Flavor Universality for Weak interaction

❖ B-meson Decay [3]

$R_{K^{(*)}}$ Anomaly [4]





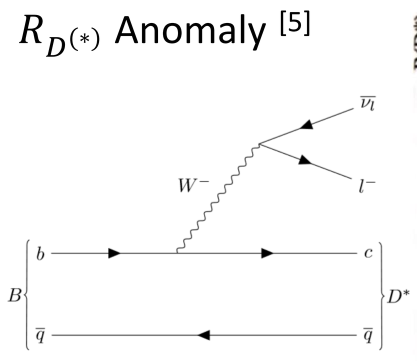
$$R_{K^{(*)}} = \frac{Br(B \to K^{(*)}\mu^+\mu^-)}{Br(B \to K^{(*)}e^+e^-)}$$

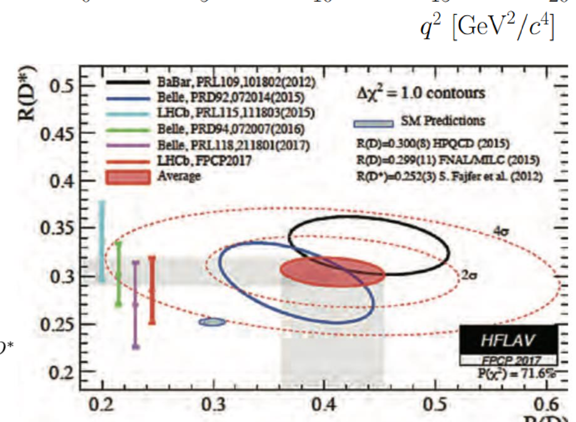
$R^{SM}_{K^{(*)}} \cong 1$

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

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

$R_{D^{(*)}}$ Anomaly [5]





$$R_{D^{(*)}} = \frac{Br(B \to D^{(*)}\bar{\nu}_\tau \tau^-)}{Br(B \to D^{(*)}\bar{\nu}_l l^-)}$$

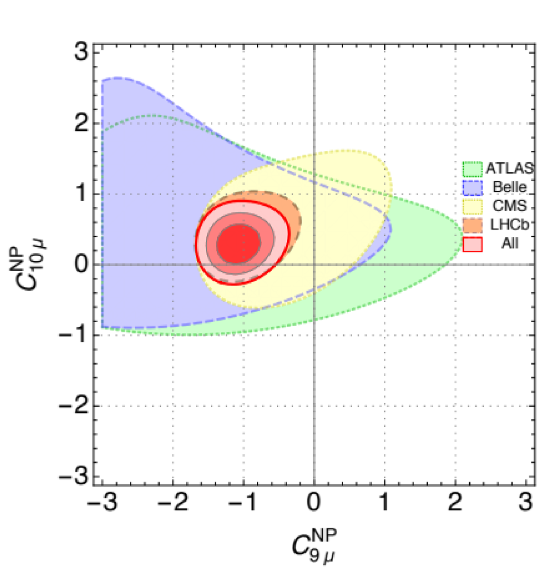
$R^{SM}_{D^{(*)}} = 0.257 \pm 0.003$

But, $R^{Exp}_{D^{(*)}} = 0.310 \pm 0.015 \pm 0.008$

SM expectations at 4σ

Leptoquarks Model [6], [7]

❖ Model Independent Interpretation



Effective Operator for $b \to s\mu^+\mu^-$ [8]

$$\mathcal{H}_{b\to s\mu^+\mu^-} = -\frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts} \textstyle\sum_i C_i \mathcal{O}_i$$

$$\mathcal{O}_{9l} = \frac{\alpha}{4\pi}(\bar{s}\gamma^\mu P_L b)(\bar{l}\gamma_\mu l)$$
$$\mathcal{O}_{10l} = \frac{\alpha}{4\pi}(\bar{s}\gamma^\mu P_L b)(\bar{l}\gamma_\mu \gamma_5 l)$$

Best fit

$$C^{NP}_{9\mu} = -C^{NP}_{10\mu} = -0.62$$

while taking $[-0.75, -0.49]$ with 1σ
and $[-0.88, -0.37]$ with 2σ

Effective Operator for $b \to c\tau^-\bar{\upsilon}_\tau$ [9]

$$\mathcal{H}_{b\to c\tau^-\bar{\upsilon}_\tau} = \frac{4G_F}{\sqrt{2}} V_{cb} C_{cb} (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \upsilon_\tau)$$

where $C_{cb} = 1$ in the SM
by charged current W^- - interactions

Best fit

$$\Delta C_{cb} = 0.1$$

while taking $[0.072, 0.127]$ with 1σ
and $[0.044, 0.153]$ with 2σ

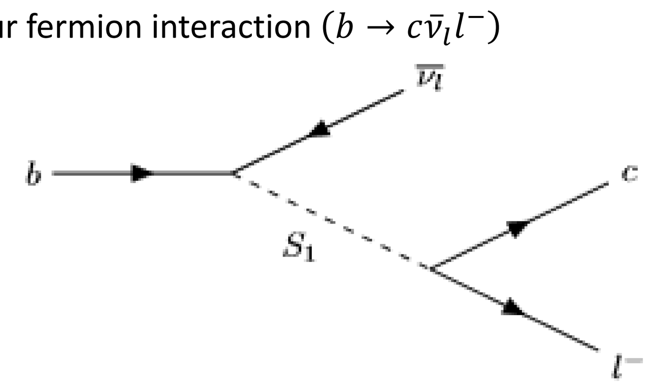
❖ Singlet Scalar Leptoquark $S_1(\bar{3},1,1/3)$

Lagrangian for a $SU(2)_L$ singlet scalar leptoquark S_1

$$\mathcal{L}_{S_1} = -\lambda_{ij}(\bar{Q}^c)^a_{Ri}\epsilon_{ab}S_1 L^b_{Lj} + h.c.$$

where $\epsilon_{ab} = (i\sigma^2)_{ab} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

Four fermion interaction ($b \to c\bar{\nu}_l l^-$)



$$\mathcal{L}_{S_1} \supset -\frac{\lambda_{2i}\lambda^*_{3j}}{2m^2_{S_1}}(\bar{b}_L\gamma^\mu c_L)(\bar{\nu}_{Lj}\gamma_\mu \nu_{Li})$$

$R_{D^{(*)}}$ effective operator coefficient

$$-\frac{\lambda_{2\tau}\lambda^*_{3\tau}}{2m^2_{S_1}} = \frac{4G_F}{\sqrt{2}} V_{cb}C_{cb} \equiv \frac{1}{\Lambda^2_D}$$

Best Fit

$\Lambda_D \sim 2.271\ TeV$

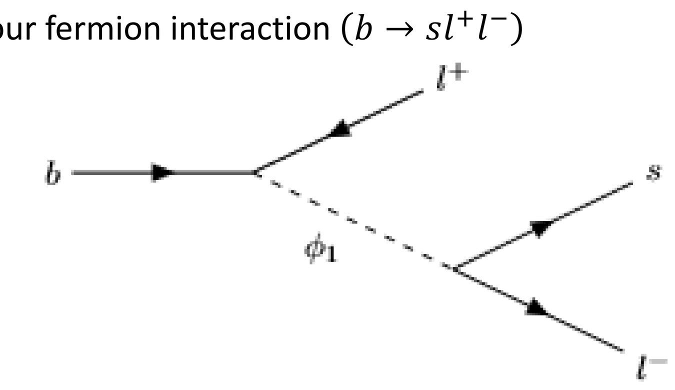
❖ Triplet Scalar Leptoquark $S_3(\bar{3},3,1/3)$

Lagrangian for a $SU(2)_L$ singlet scalar leptoquark S_3

$$\mathcal{L}_{S_3} = -\tilde{\lambda}_{ij}(\bar{Q}^c)^a_{Ri}S_{3ab} L^b_{Lj} + h.c.$$

where $S_{3ab} = \begin{pmatrix} \sqrt{2}\phi_3 & -\phi_2 \\ -\phi_2 & -\sqrt{2}\phi_1 \end{pmatrix}$

Four fermion interaction ($b \to s l^+ l^-$)



$$\mathcal{L}_{S_3} \supset \frac{\tilde{\lambda}_{2i}\tilde{\lambda}^*_{3j}}{m^2_{S_1}}(\bar{b}_L\gamma^\mu s_L)(\bar{l}_{Lj}\gamma_\mu l_{Li})$$

$R_{K^{(*)}}$ effective operator coefficient

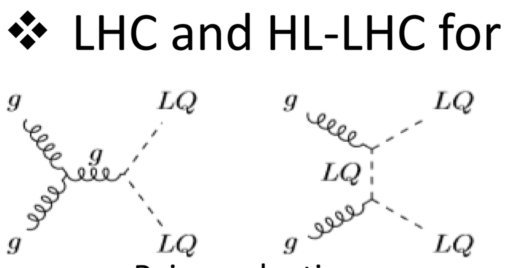
$$\frac{\tilde{\lambda}_{2\mu}\tilde{\lambda}^*_{3\mu}}{m^2_{S_1}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts}\frac{\alpha}{4\pi}C^{NP}_{9\mu} \equiv \frac{1}{\Lambda^2_K}$$

Best Fit

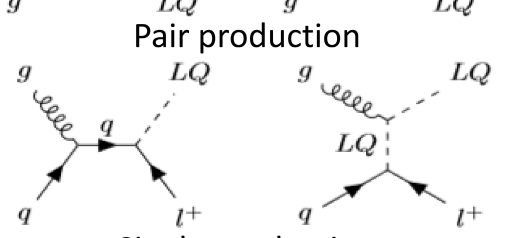
$\Lambda_K \sim 36.956\ TeV$

Leptoquarks Production [10],[11],[12],[13]

❖ LHC and HL-LHC for the Leptoquark production

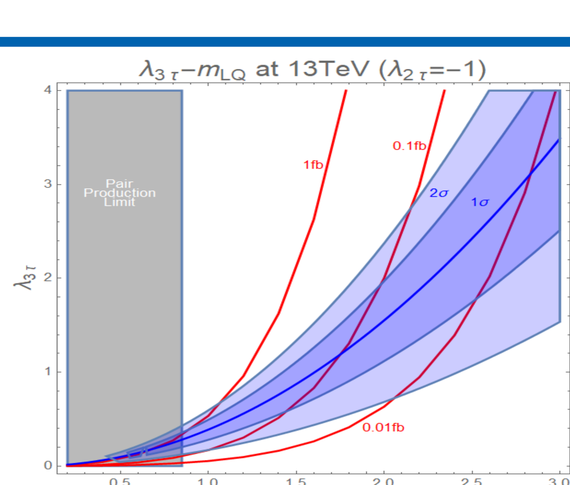


Pair production



Single production

Leptoquarks	BR$_1$	BR$_2$
S_1	$B(\bar{t}\bar{\tau}) = B(\bar{b}\nu_\tau) = \lambda^2_{33}/(\lambda^2_{33}+\lambda^2_{23})$	$B(\bar{c}\bar{\tau}) = B(\bar{s}\nu_\tau) = \lambda^2_{23}/(\lambda^2_{33}+\lambda^2_{23})$
$S_3(\phi_1)$	$B(\bar{b}\bar{\mu}) = \tilde{\lambda}^2_{32}/(\tilde{\lambda}^2_{32}+\tilde{\lambda}^2_{22})$	$B(\bar{s}\bar{\mu}) = \tilde{\lambda}^2_{22}/(\tilde{\lambda}^2_{32}+\tilde{\lambda}^2_{22})$
$S_3(\phi_2)$	$B(\bar{t}\bar{\mu}) = B(\bar{b}\bar{\nu}_\mu) = \tilde{\lambda}^2_{32}/(\tilde{\lambda}^2_{32}+\tilde{\lambda}^2_{22})$	$B(\bar{c}\bar{\mu}) = B(\bar{s}\bar{\nu}_\mu) = \tilde{\lambda}^2_{22}/(\tilde{\lambda}^2_{32}+\tilde{\lambda}^2_{22})$
$S_3(\phi_3)$	$B(\bar{t}\bar{\nu}_\mu) = \tilde{\lambda}^2_{32}/(\tilde{\lambda}^2_{32}+\tilde{\lambda}^2_{22})$	$B(\bar{c}\bar{\nu}_\mu) = \tilde{\lambda}^2_{22}/(\tilde{\lambda}^2_{32}+\tilde{\lambda}^2_{22})$



For $S_1(R_{D^{(*)}}\ anomaly)$
$m_{LQ} > 850GeV$ at $\sqrt{s} = 13TeV$

Scalar Dark Matter [14]

❖ Singlet real scalar dark matter

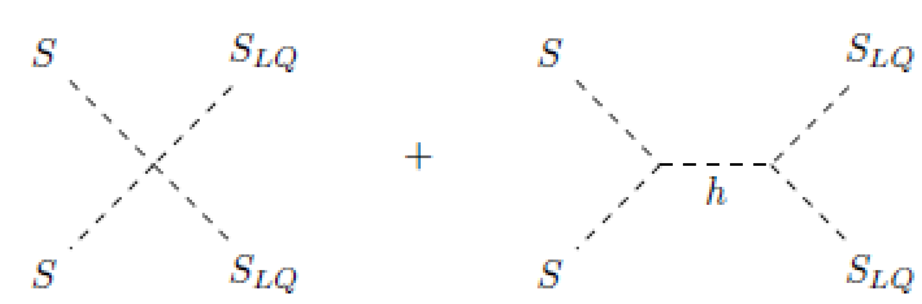
Lagrangian generalizes the Higgs portal interactions to those for leptoquarks.

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

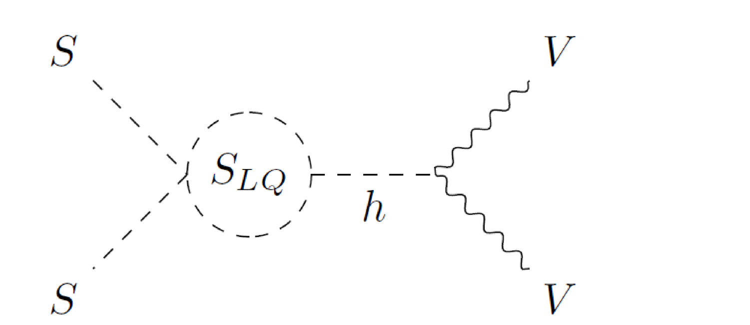
❖ Relic density for scalar dark matter

In this cases, Lagrangian includes term for λ_3 in contrast with general scalar dark matter (without leptoquarks).

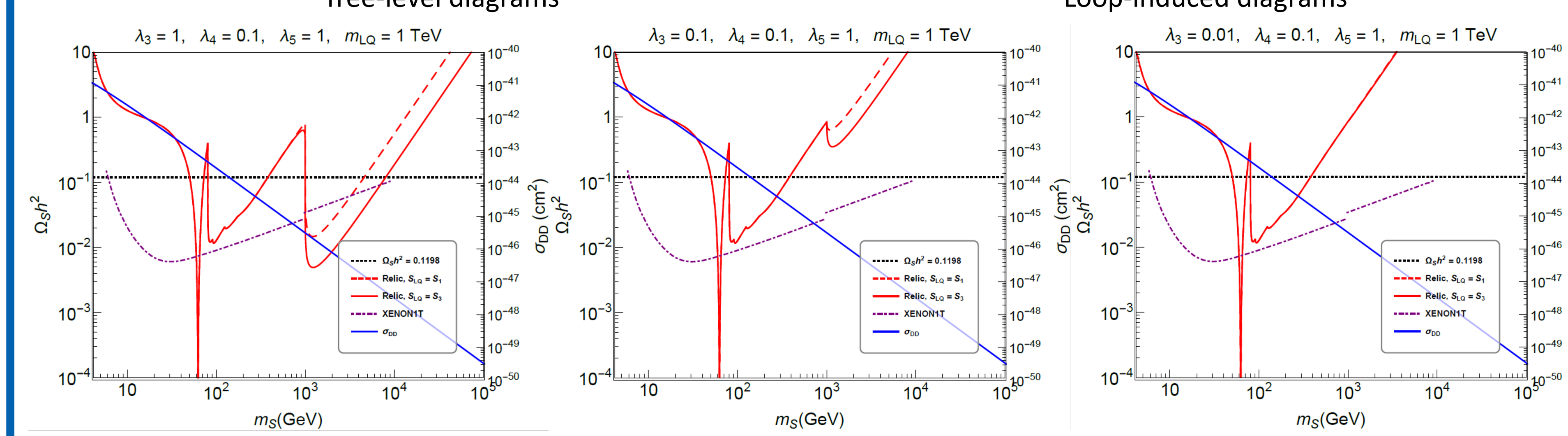
So, two diagrams for tree-level annihilation cross section are added. And we need to consider the loop-induced annihilation cross sections.



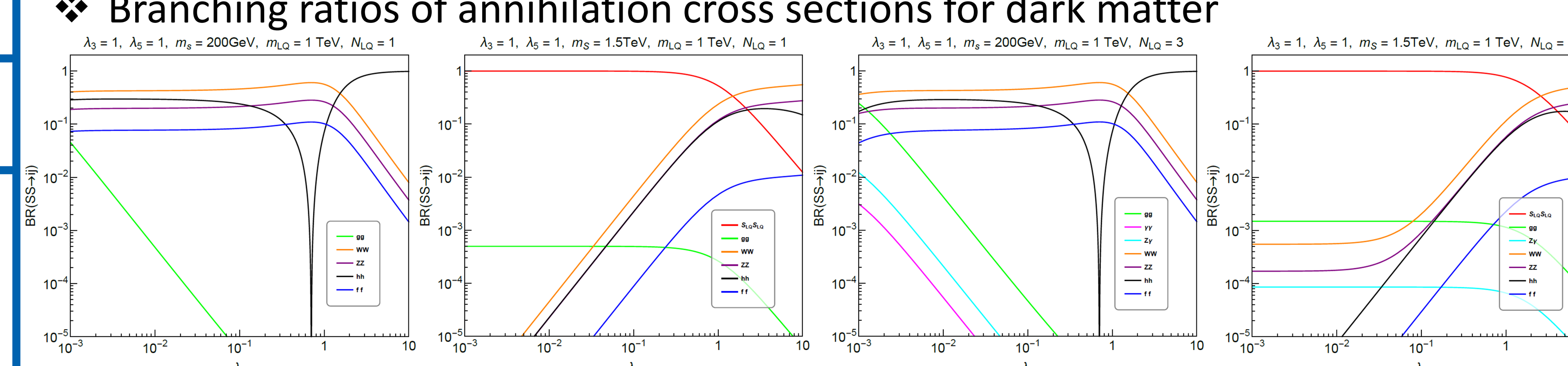
Tree-level diagrams



Loop-induced diagrams

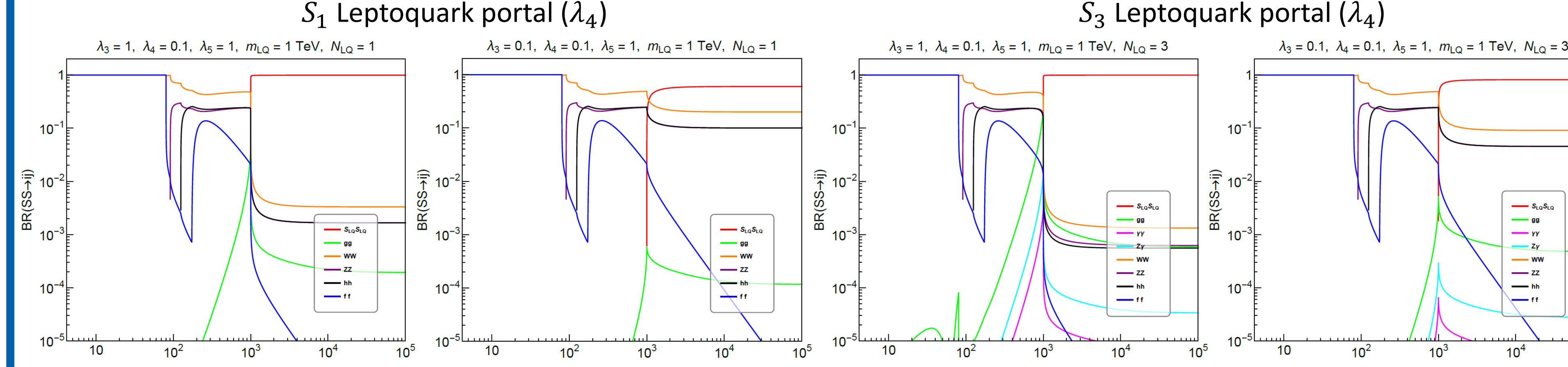


❖ Branching ratios of annihilation cross sections for dark matter



S_1 Leptoquark portal (λ_4)

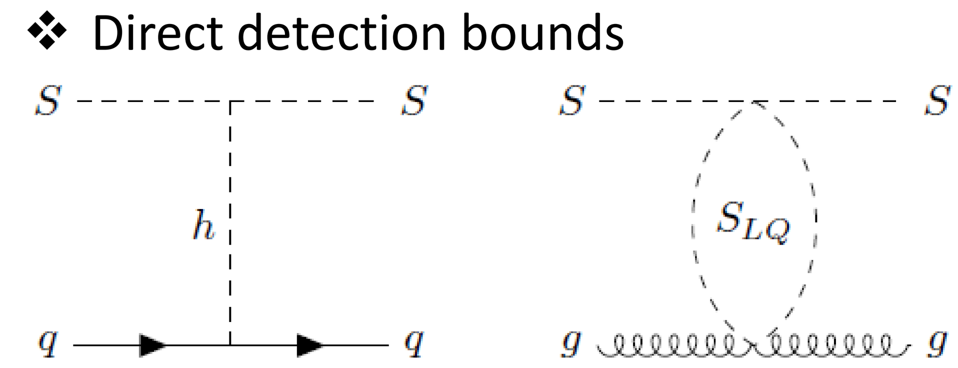
S_3 Leptoquark portal (λ_4)



S_1 Leptoquark portal (m_S)

S_3 Leptoquark portal (m_S)

❖ Direct detection bounds



$$\mathcal{L}_{eff,Sq\bar{q}} = \frac{\lambda_4 m_q}{m^2_h} S^2\bar{q}q\ , \mathcal{L}_{eff,Sgg} = \frac{\alpha_S\lambda_3}{96\pi m^2_{LQ}} l_3(S_{LQ})\, S^2 G_{\mu\nu}G^{\mu\nu}$$

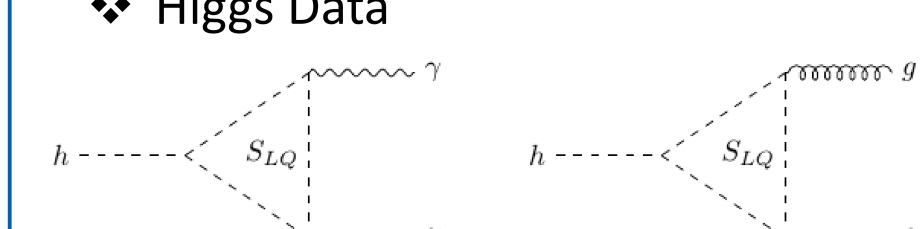
Spin-indep. cross section for DM-nucleon elastic scattering is given by

$$\sigma_{S-N} = \frac{\mu^2_N}{\pi m^2_S A^2}\left(Zf^S_p + (A-Z)f^S_n\right)^2$$

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

where mass fractions $f^{p,n}_{Tq}$, $f^{p,n}_{TG}$ are constants

❖ Higgs Data



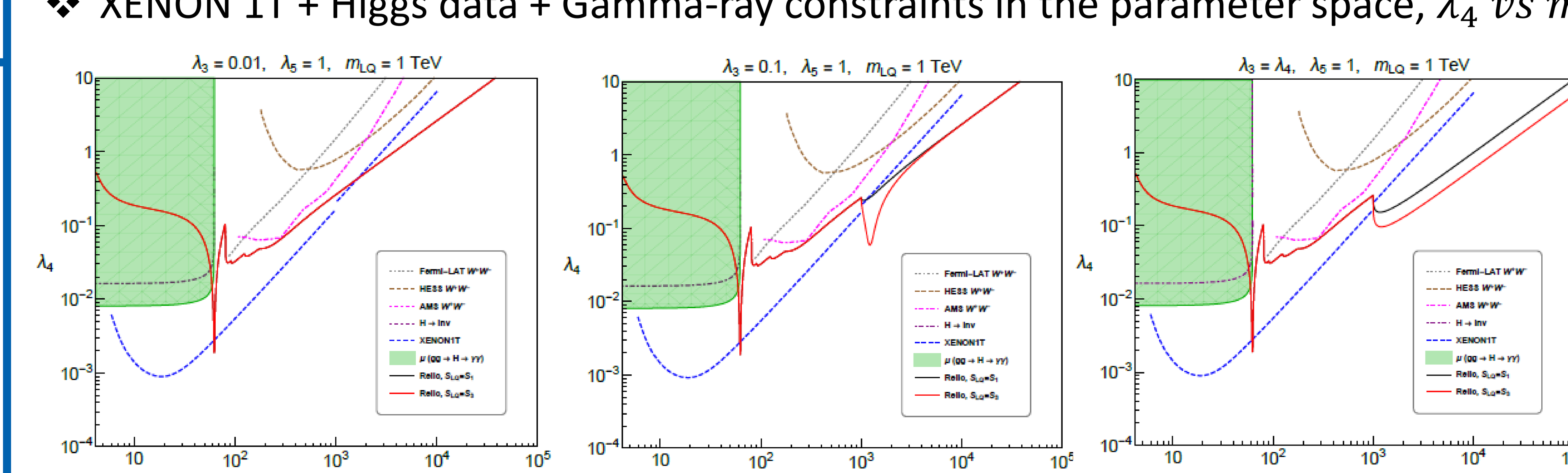
$$\Gamma(h\to\gamma\gamma) = \frac{G_F\alpha^2_{em}m^3_h}{128\sqrt{2}\pi^3}\left|\sum_f N_c Q^2_f A_{\frac{1}{2}}(x_f) + A_1(x_W) + N_c g^2_{LQ}\sum_{i=1,\cdots,N_{LQ}} Q^2_{LQ}A_0(x_{LQ})\right|^2$$

$$\Gamma(h\to gg) = \frac{G_F\alpha^2_s m^3_h}{36\sqrt{2}\pi^3}\left|\frac{3}{4}\sum_f A_{1/2}(x_f) + \frac{3}{4}N_{LQ}g^2_{LQ}A_0(x_{LQ})\right|^2$$

$$R_{\gamma\gamma,gg} \equiv \frac{\Gamma(h\to\gamma\gamma,gg)}{\Gamma_h\cdot BR(h\to\gamma\gamma,gg)_{SM}} \qquad \Gamma_h \approx \Gamma_{h,SM} + \Gamma(h\to SS)\ \ where\ \Gamma_{h,SM} = 4MeV$$

$$\mu_{\gamma\gamma} = R_{gg}R_{\gamma\gamma} = 1.10^{+0.23}_{-0.22}$$

❖ XENON 1T + Higgs data + Gamma-ray constraints in the parameter space, $\lambda_4\ vs\ m_S$



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