Interplay between flavor physics and (direct) search for new physics

Yuji Omura (KINDAI Univ.)

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2. The new physics interpretations of the $B \to K^{(*)} ll$ anomalies.
3. The new physics interpretations of the $B \to D^{(*)} l \nu$ anomalies.
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1. Introduction

Interesting points of flavor physics:

sensitive to very high-scale physics.

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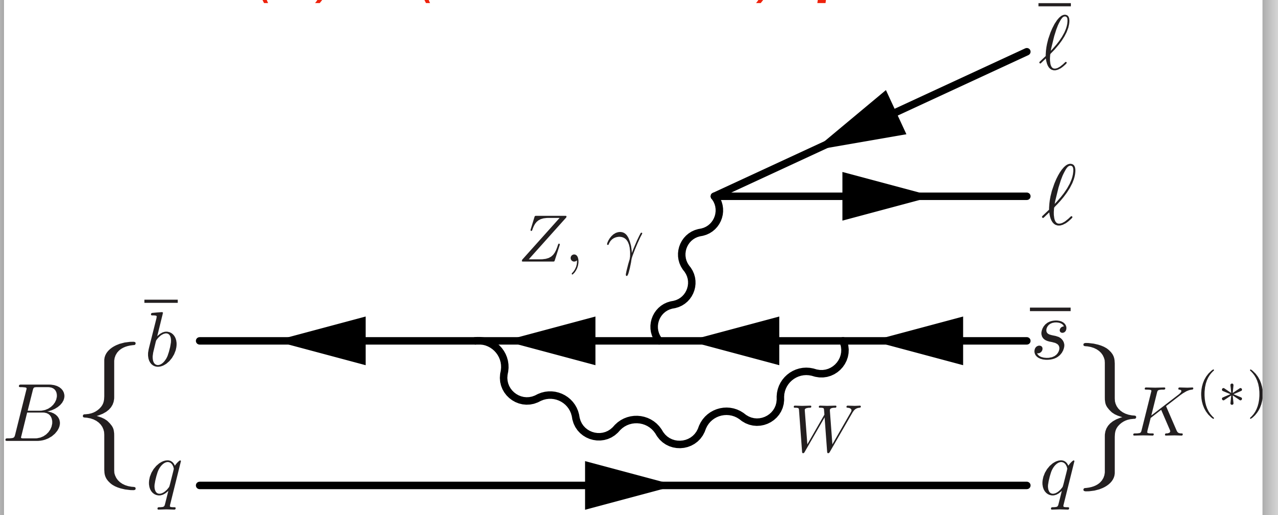
sensitive to very high-scale physics.

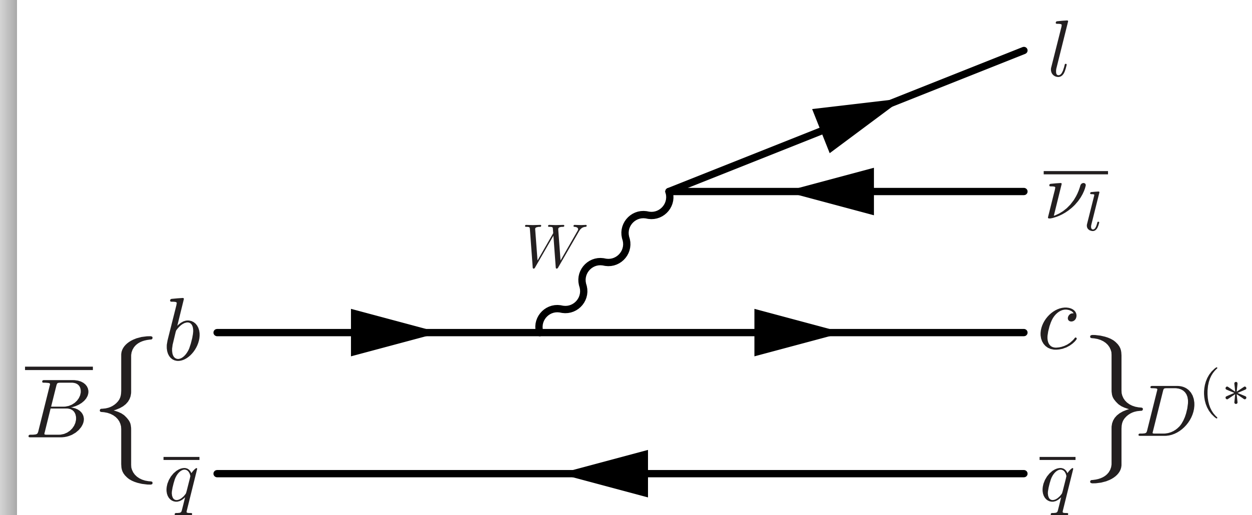
experimental results are deviated from the SM predictions in some observables relevant to 2nd and 3rd generations.

The processes where deviations are reported

B→K(*)ll (l = e, μ) processes



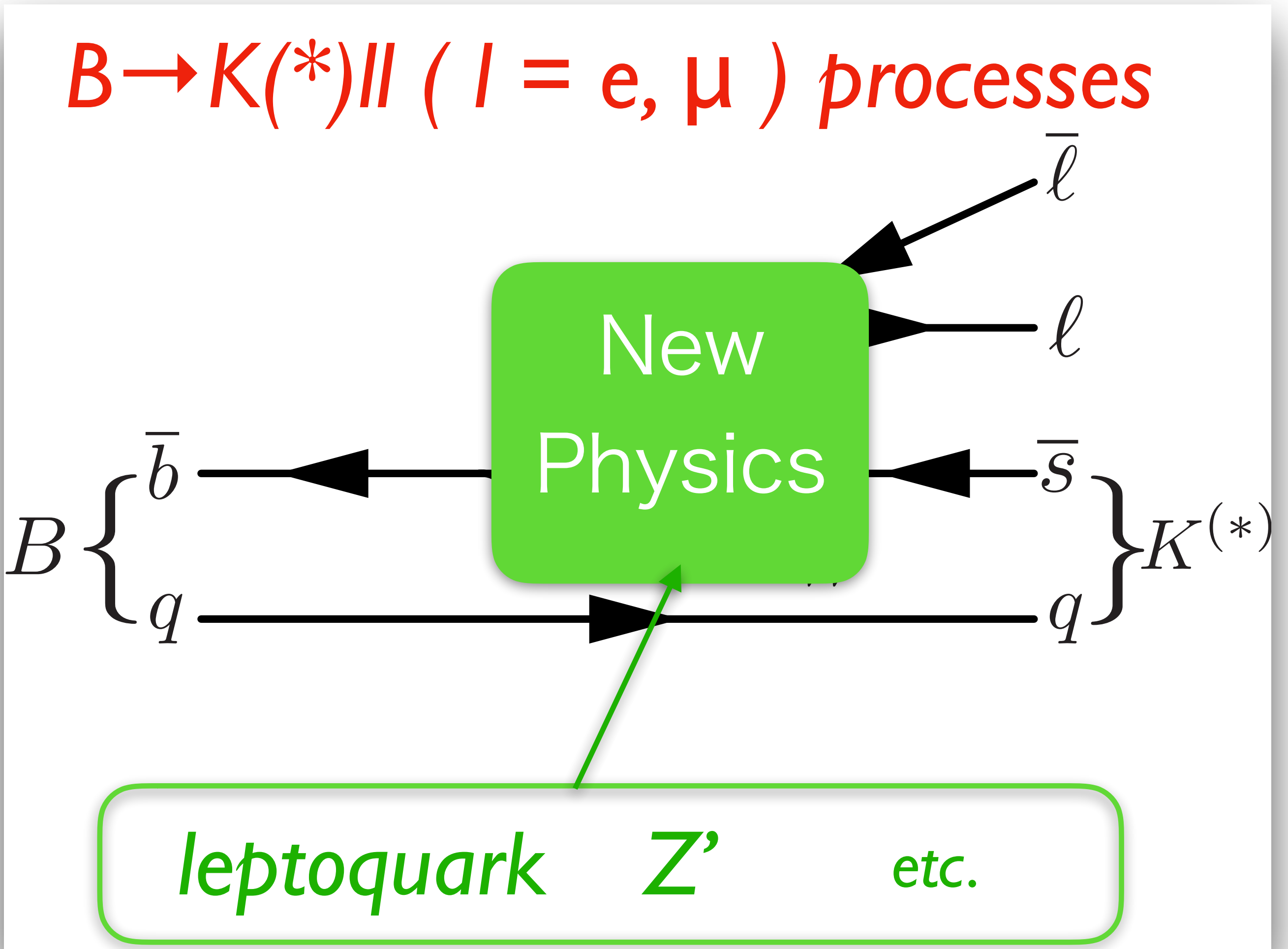
B→D(*)lν (l = e, μ, τ) processes

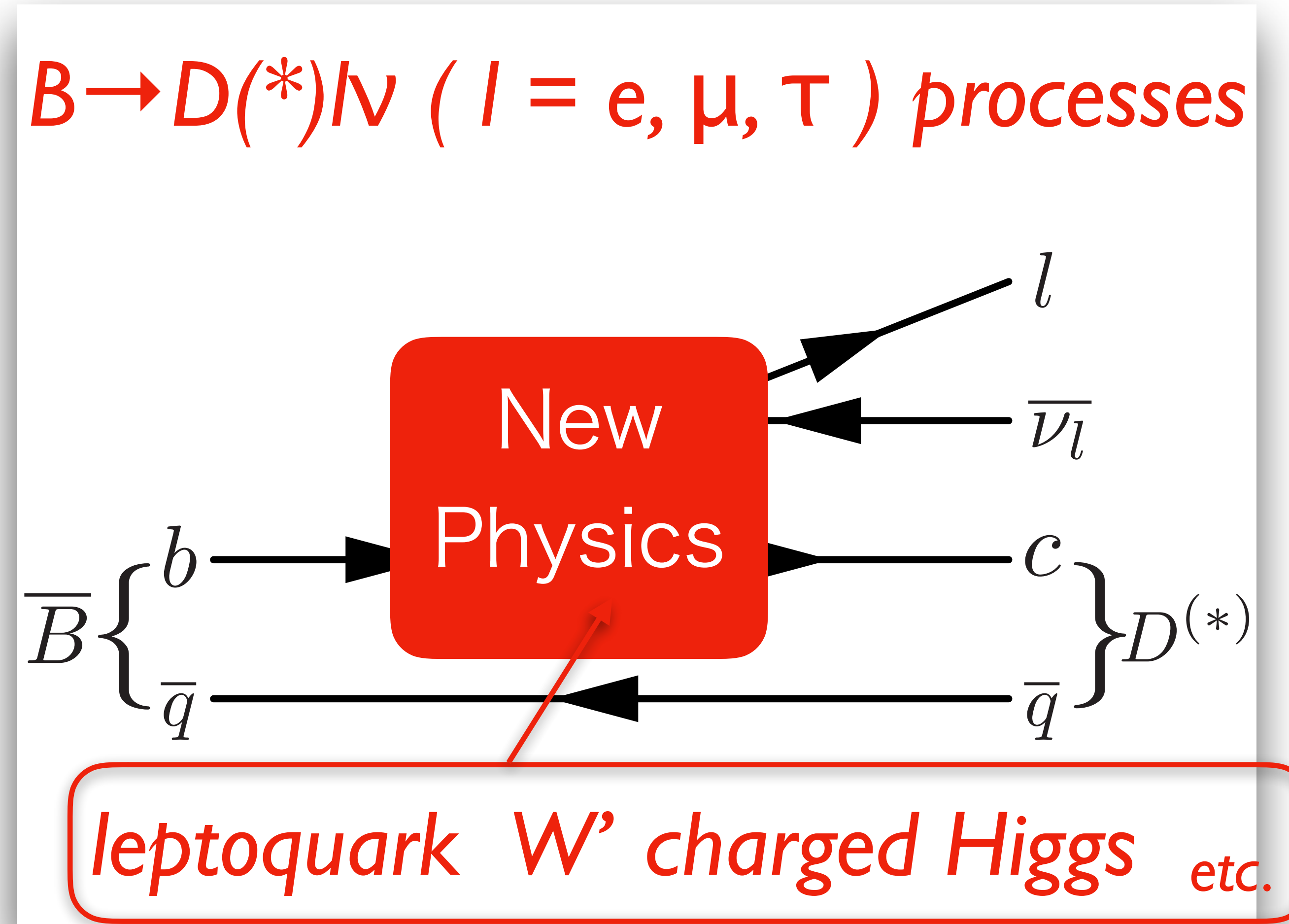


Excesses reported in the observables do not have large theoretical uncertainties.

(Other obs. such as (g-2)μ are also interesting, but I concentrate on these processes.)

There may be new physics!





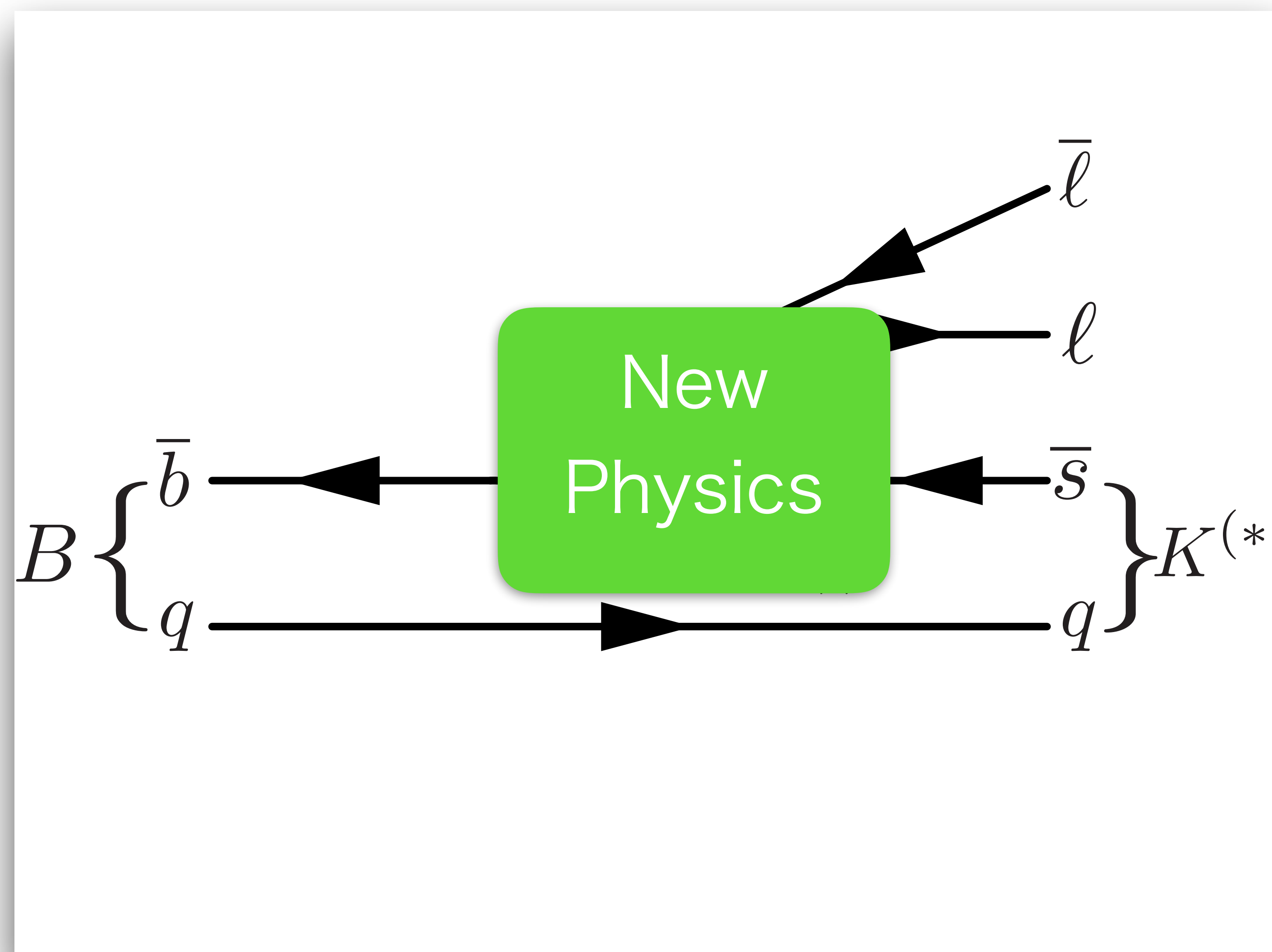
Interestingly, the required NP scale is as low as the direct search (LHC etc.) can reach

In my talk, I introduce

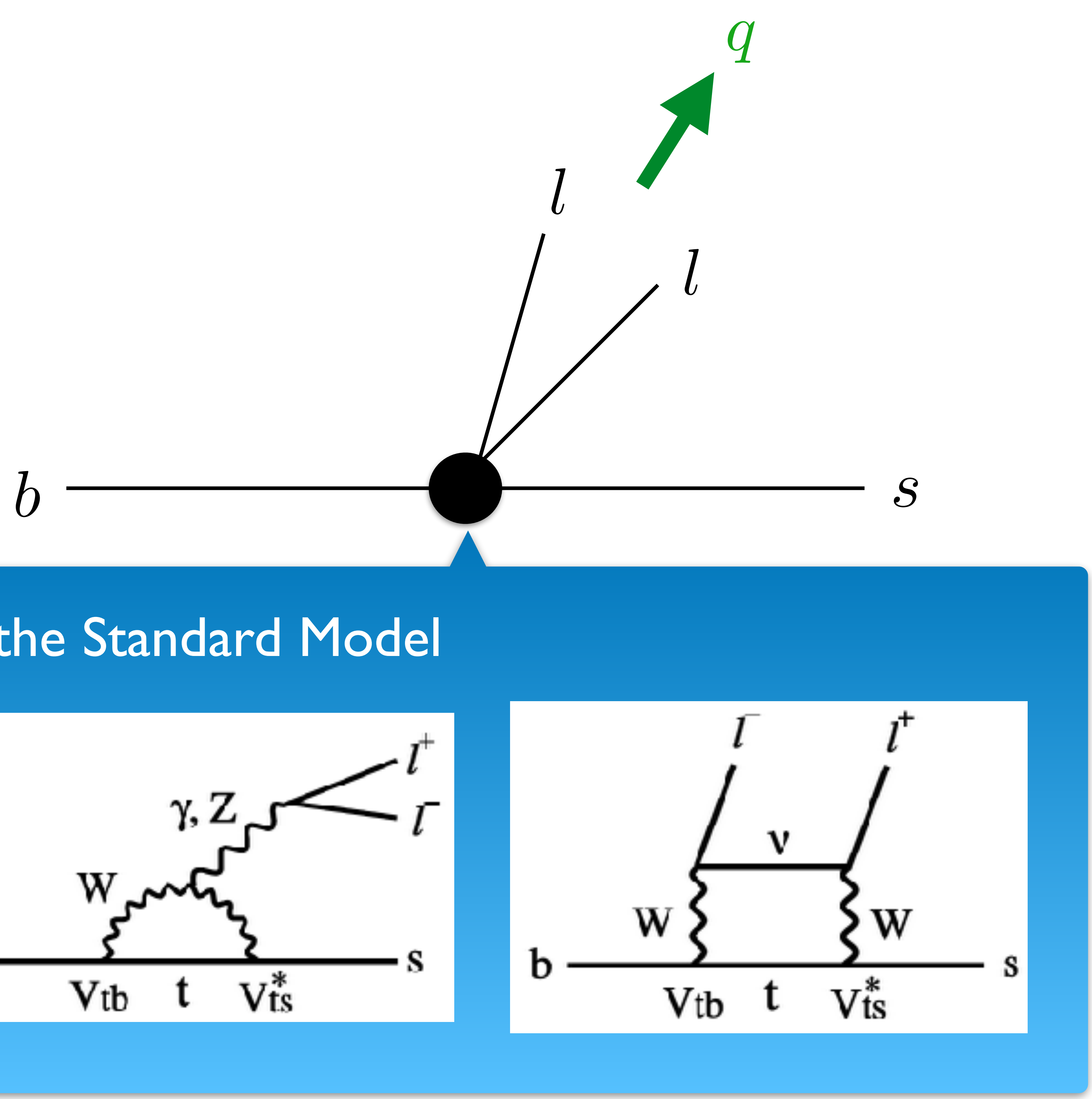
new physics possibilities

how to test them at the LHC etc..

2. The new physics interpretations of the B→K(*)ll anomalies



In the SM, the B ***to K(*) ll*** decays are caused by



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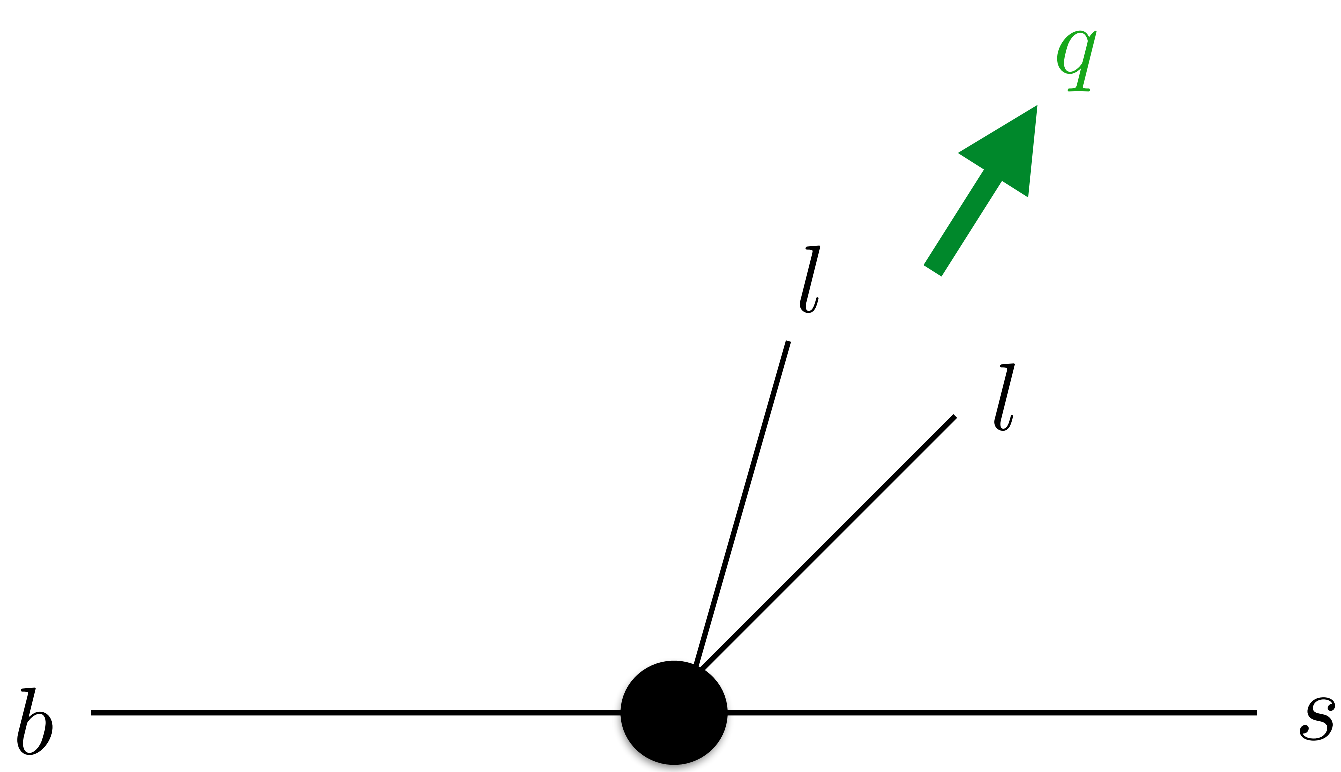
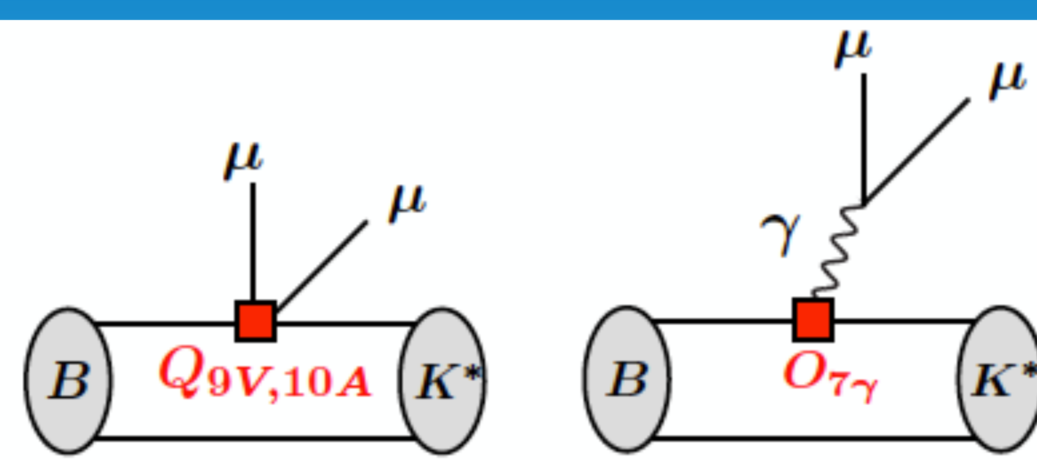


the operators in the Standard Model

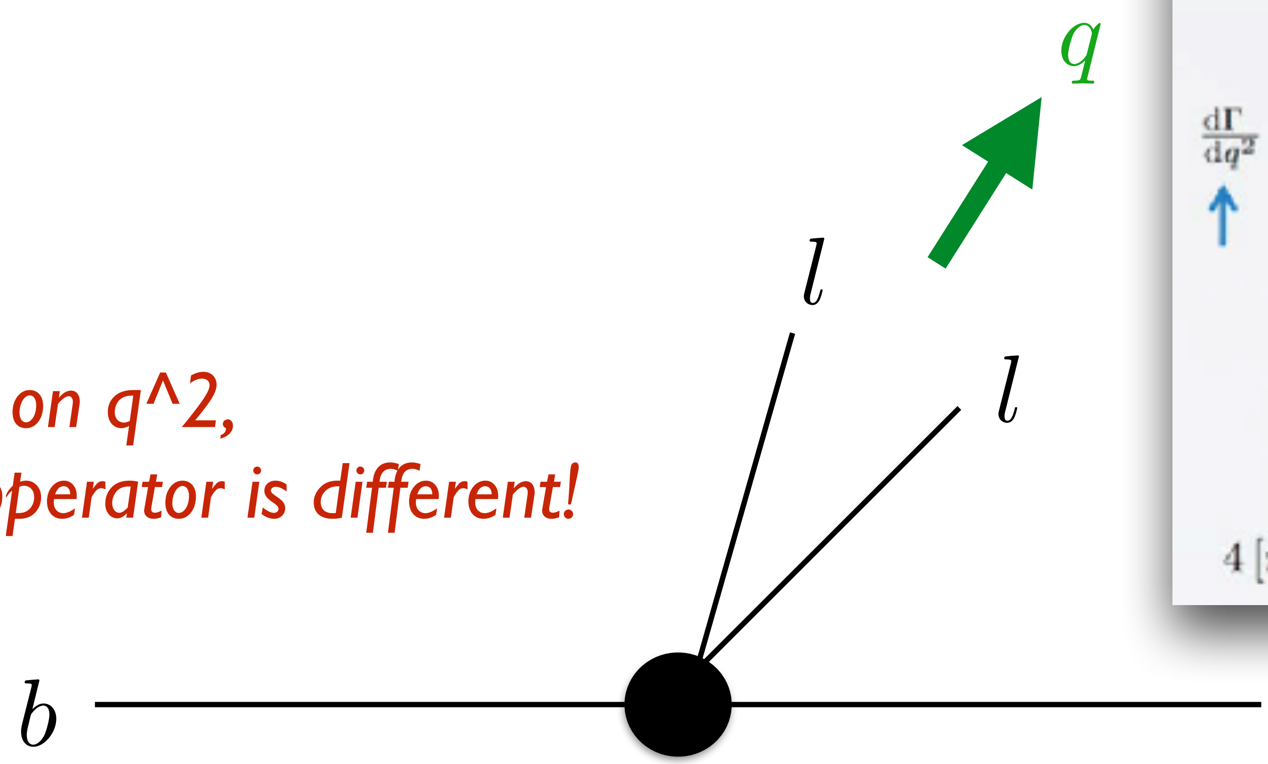
$$O_9 = \frac{e^2}{16\pi^2}(\bar{b}_L\gamma_\mu s_L)(\bar{\ell}\gamma^\mu\ell)$$

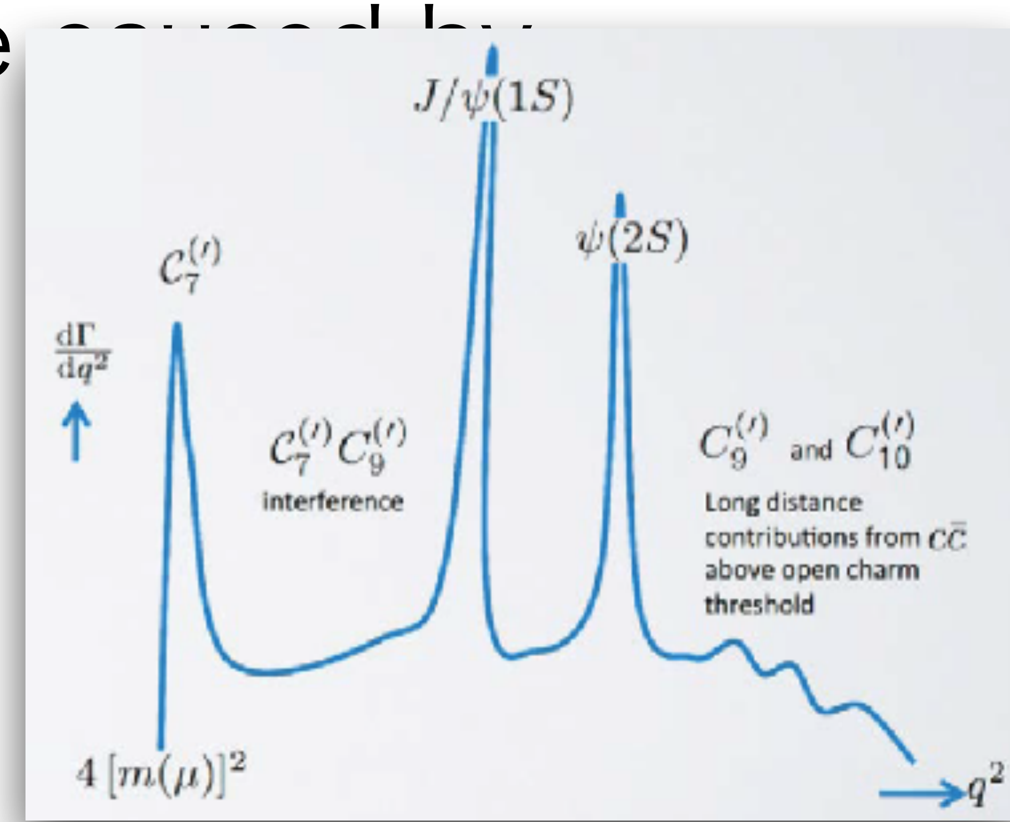
$$O_{10} = \frac{e^2}{16\pi^2}(\bar{b}_L\gamma_\mu s_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$O_{7\gamma} = \frac{e}{16\pi^2}m_b\bar{b}_R\sigma^{\mu\nu}s_L F_{\mu\nu}$$



In the SM, the B *to K(*) ll* decays are





Depending on q^2,
dominant operator is different!

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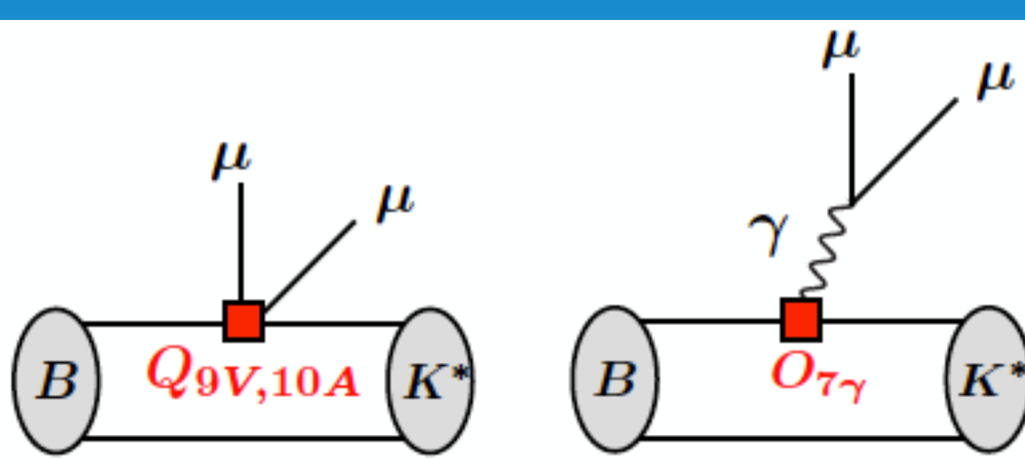
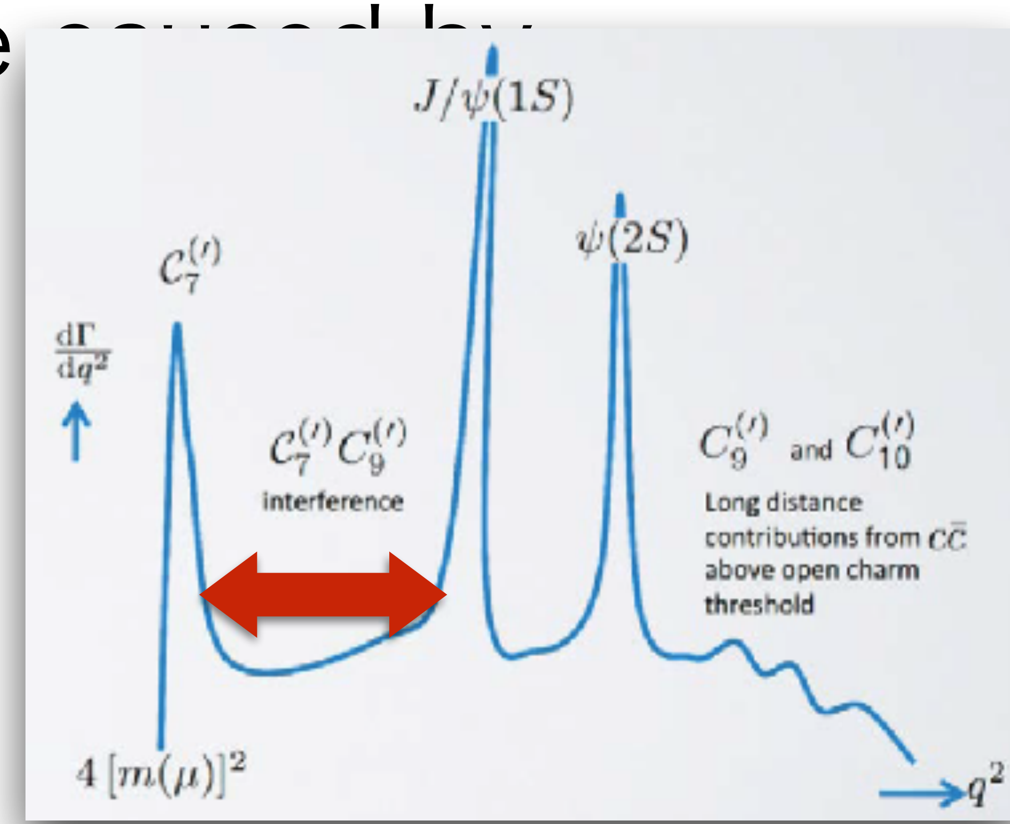


In the SM, the B *to K(*) ll* decays are



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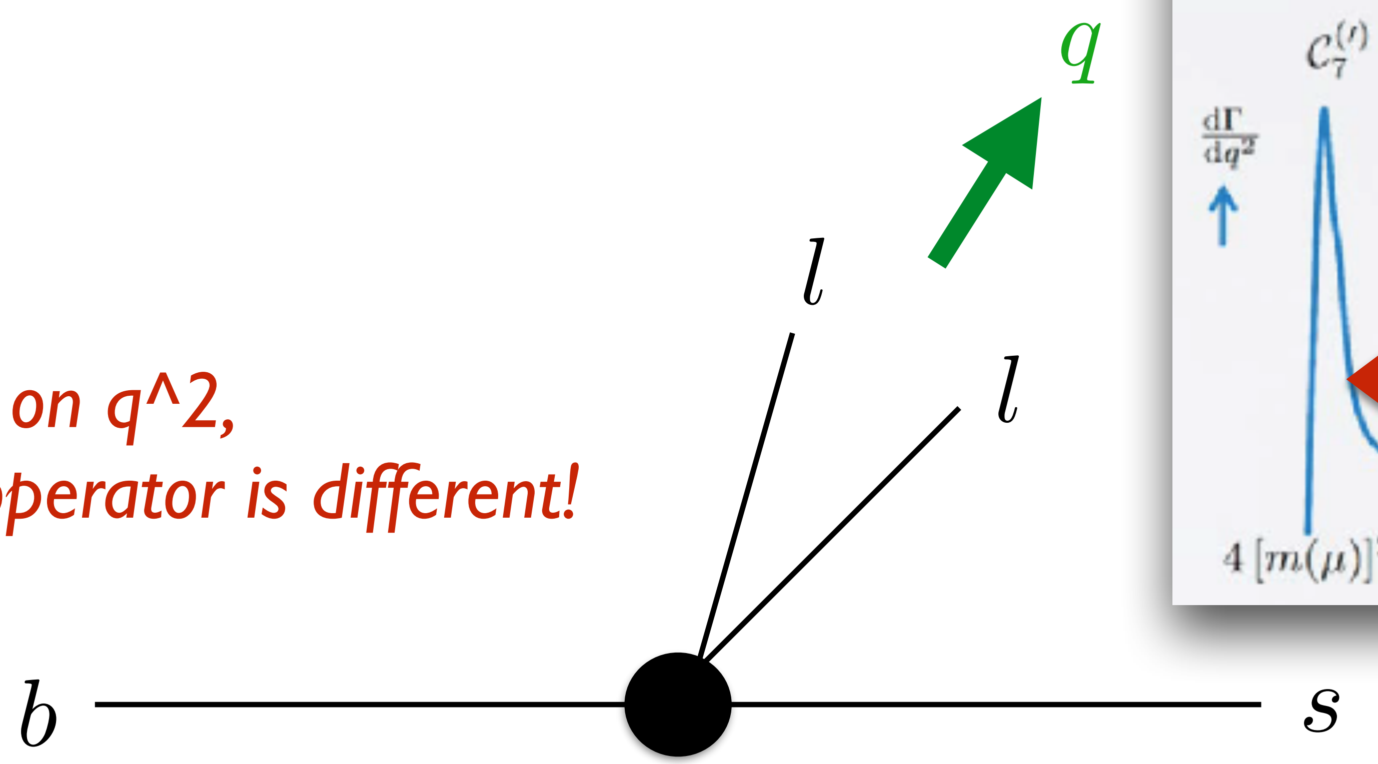

the operators in the Standard Model

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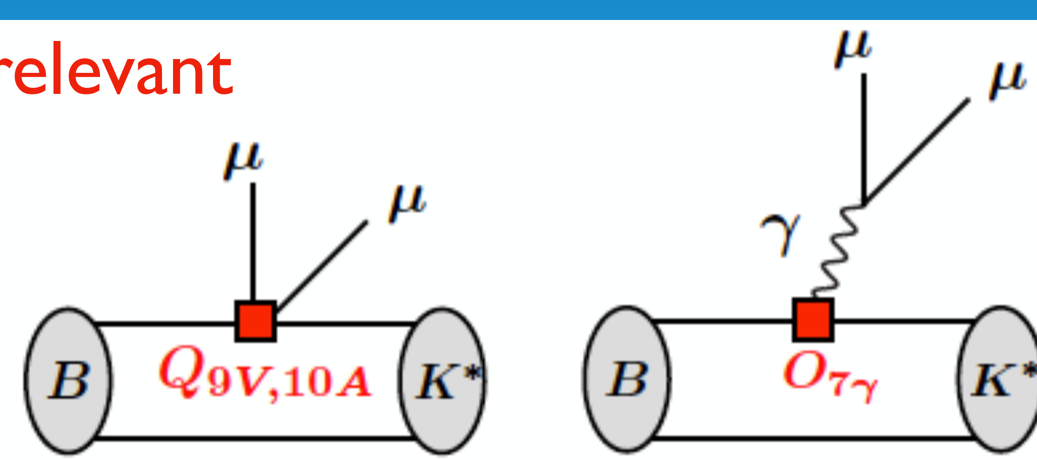
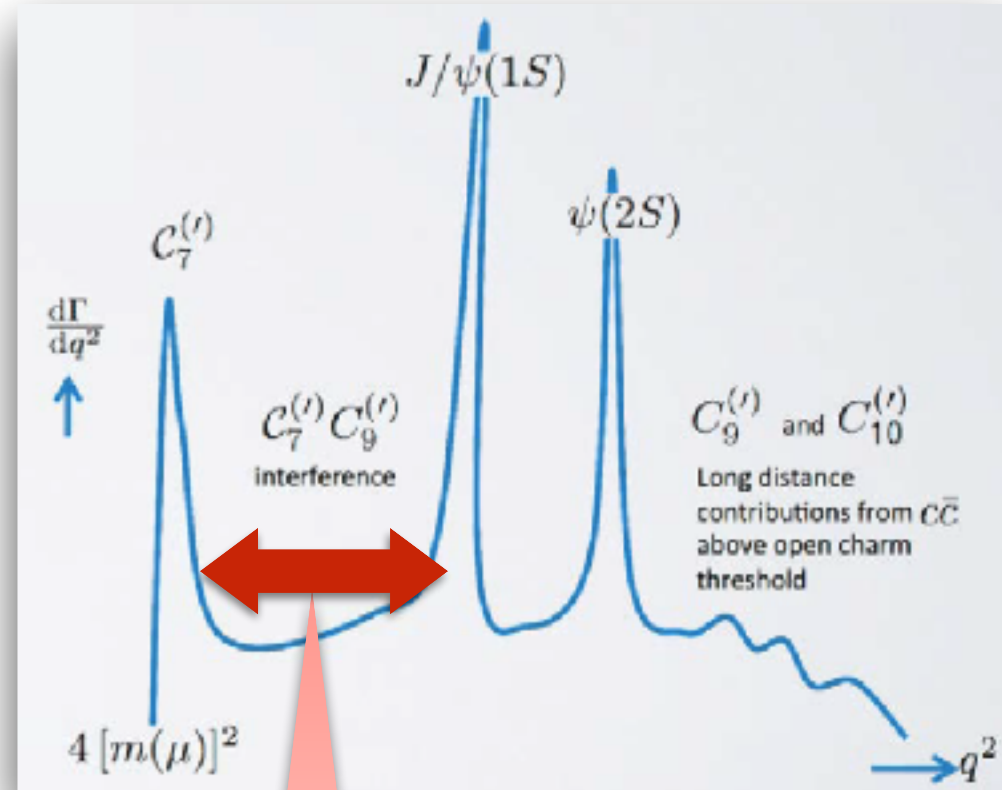
relevant

$$O_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}$$



The observables where the excesses are reported in this q^2 region:



Lepton universality in $B^+ \to K^+ l^+ l^-$ $(l = e,\ \mu)$ *(1406.6482,1903.09252)*

Lepton universality in $B_0 \to K_0^* l^+ l^-$ $(l = e,\ \mu)$ *(1705.05802)*

Angular analysis of $B_0 \to K_0^* \mu^+ \mu^-$ *(1308.1707; 1512.04442)*

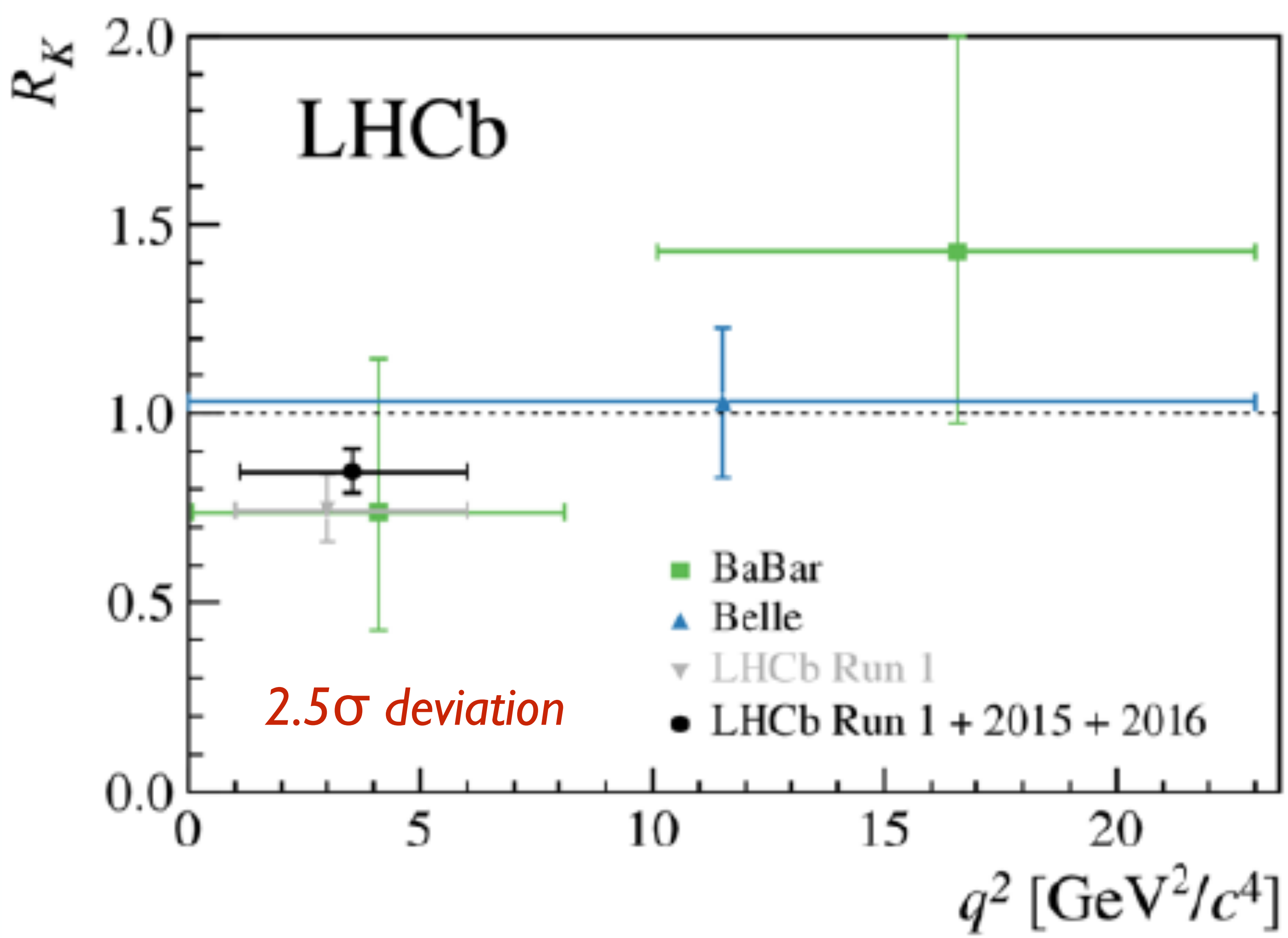
@LHCb experiment.

The deviations are reported in the observables that do not have large theoretical uncertainties.

Lepton universality in $B^+ \to K^+ l^+ l^- \;(l = e,\, \mu)$ *(1406.6482,1903.09252)*

observable

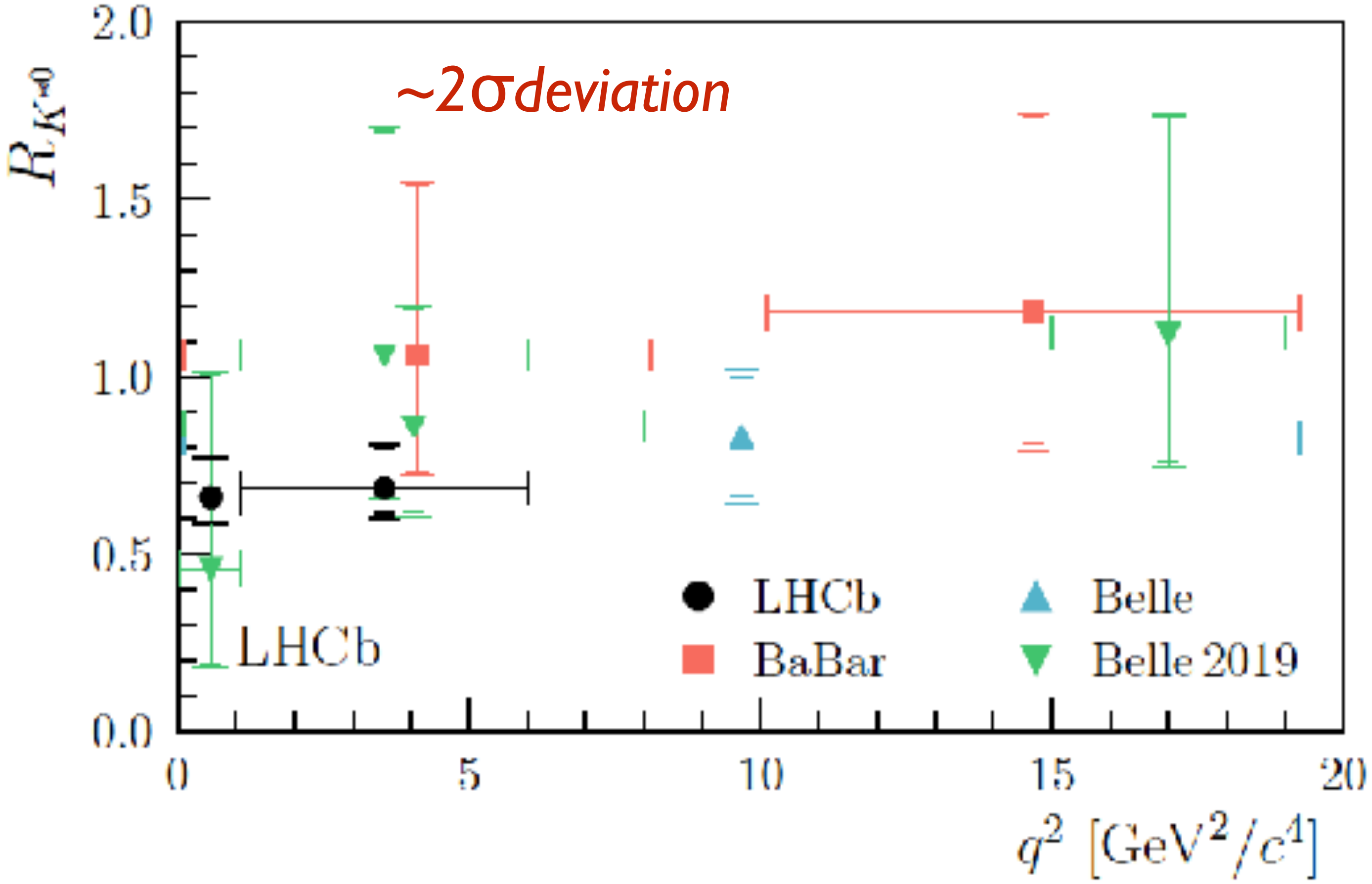
$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+ e^+ e^-]}{\mathrm{d}q^2} \mathrm{d}q^2}$$

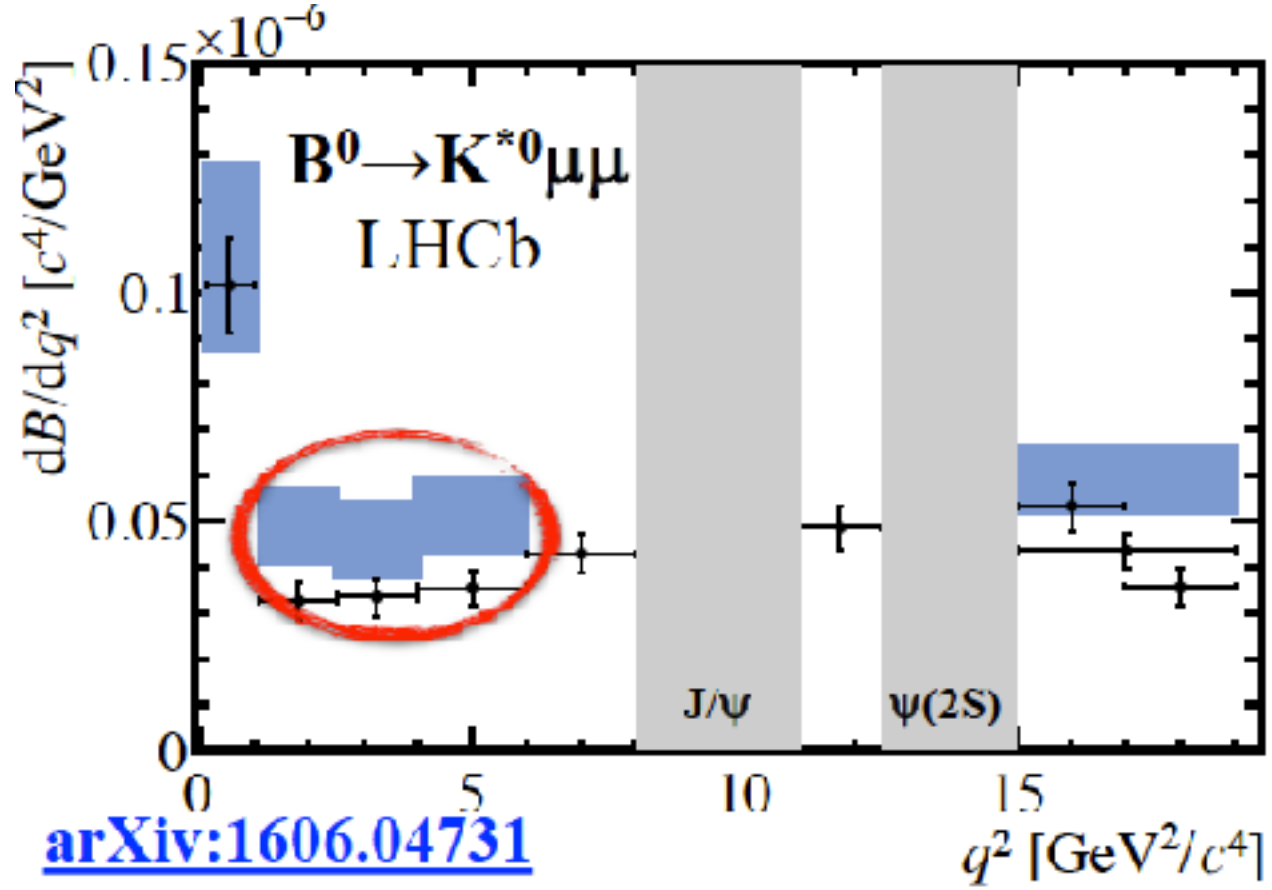


New result shows 2.5σ deviation@LHCb

$$R_K = 0.846^{+0.060}_{-0.054}(stat)^{+0.014}_{-0.016}(syst)$$ *(1903.09252)*

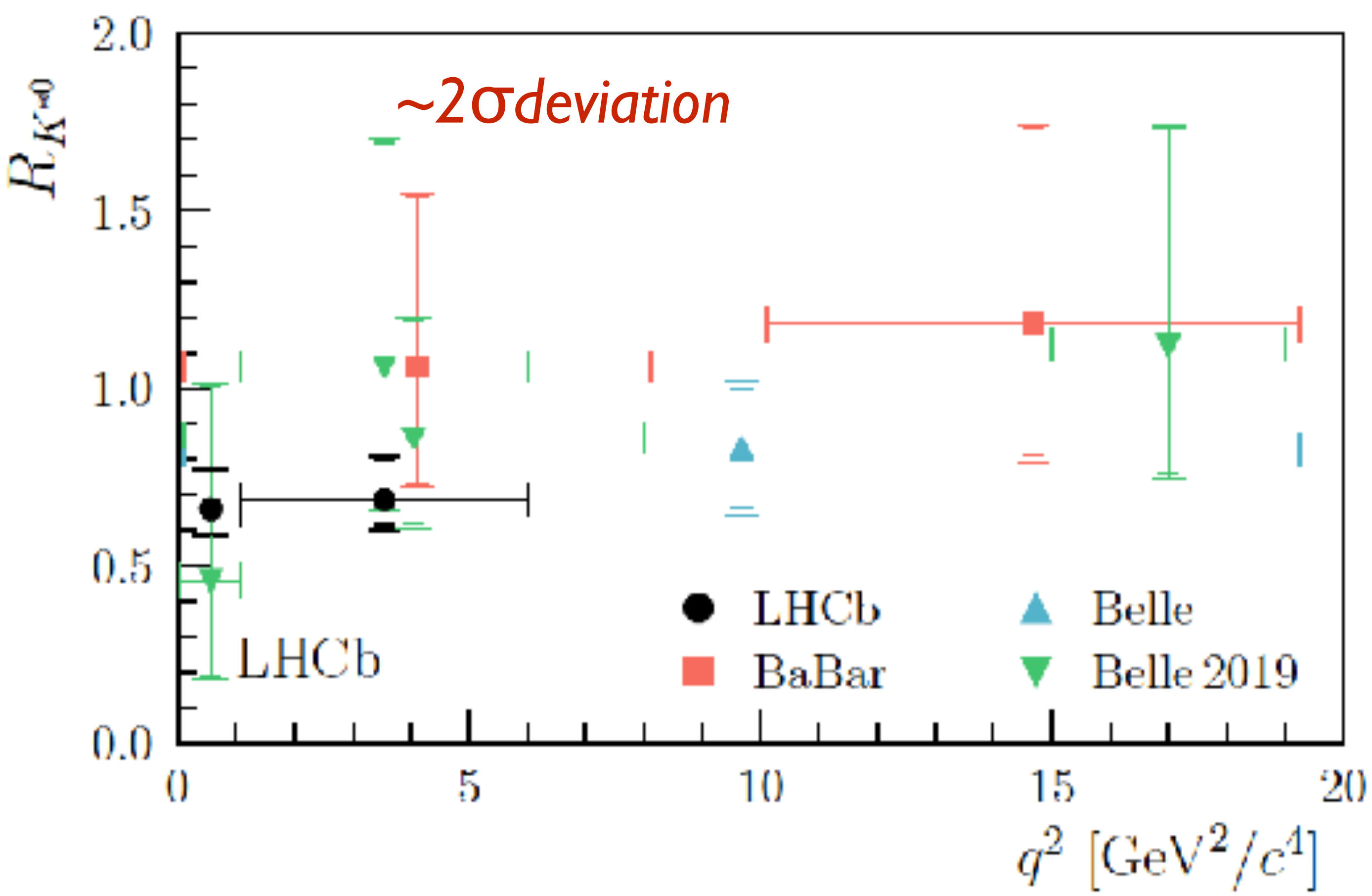
Lepton universality in $B_0 \to K_0^* \mu^+ \mu^-$

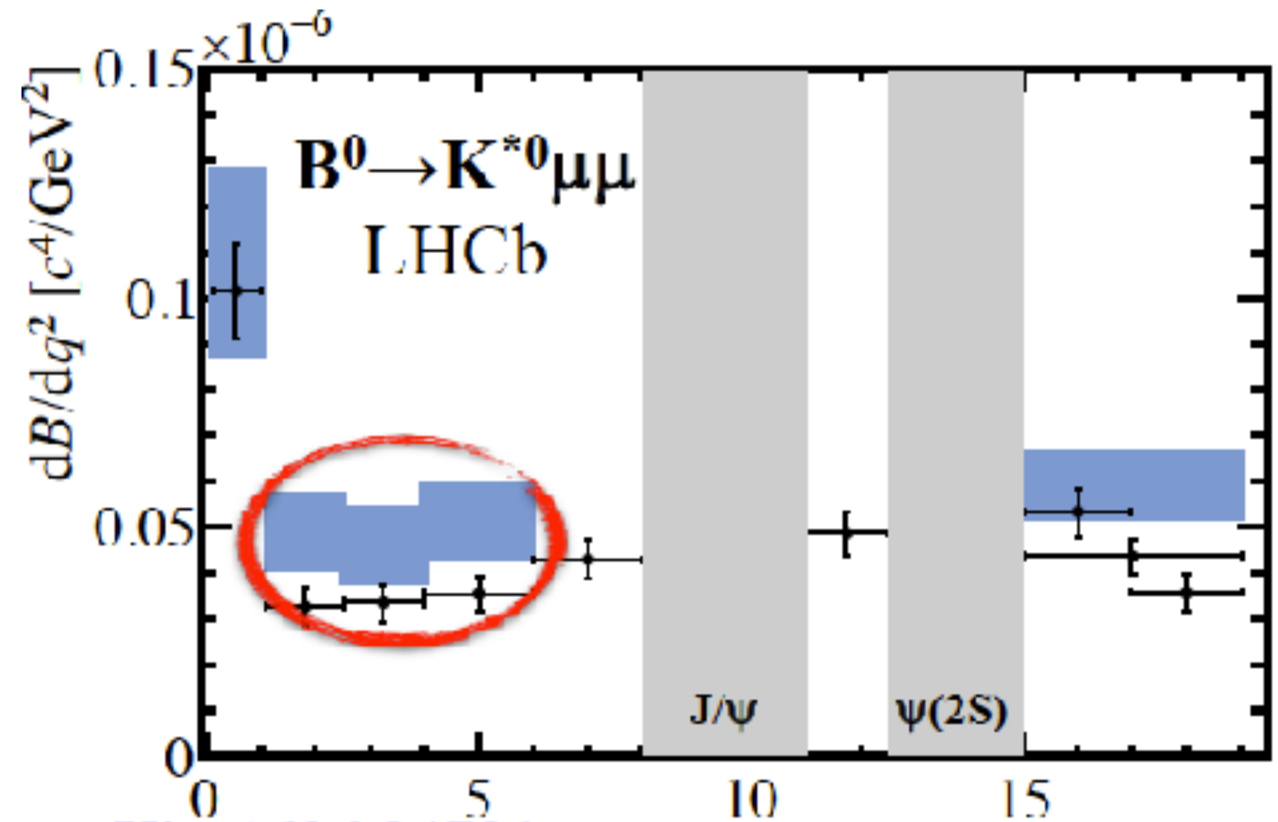




arXiv:1606.04731

Lepton universality in $B_0 \to K_0^* \mu^+ \mu^-$



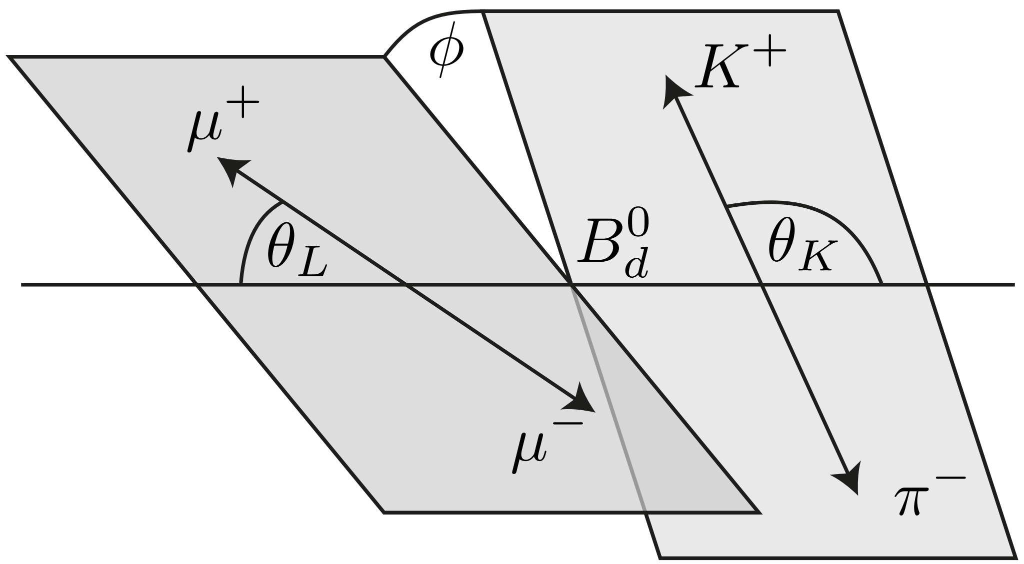


arXiv:1606.04731

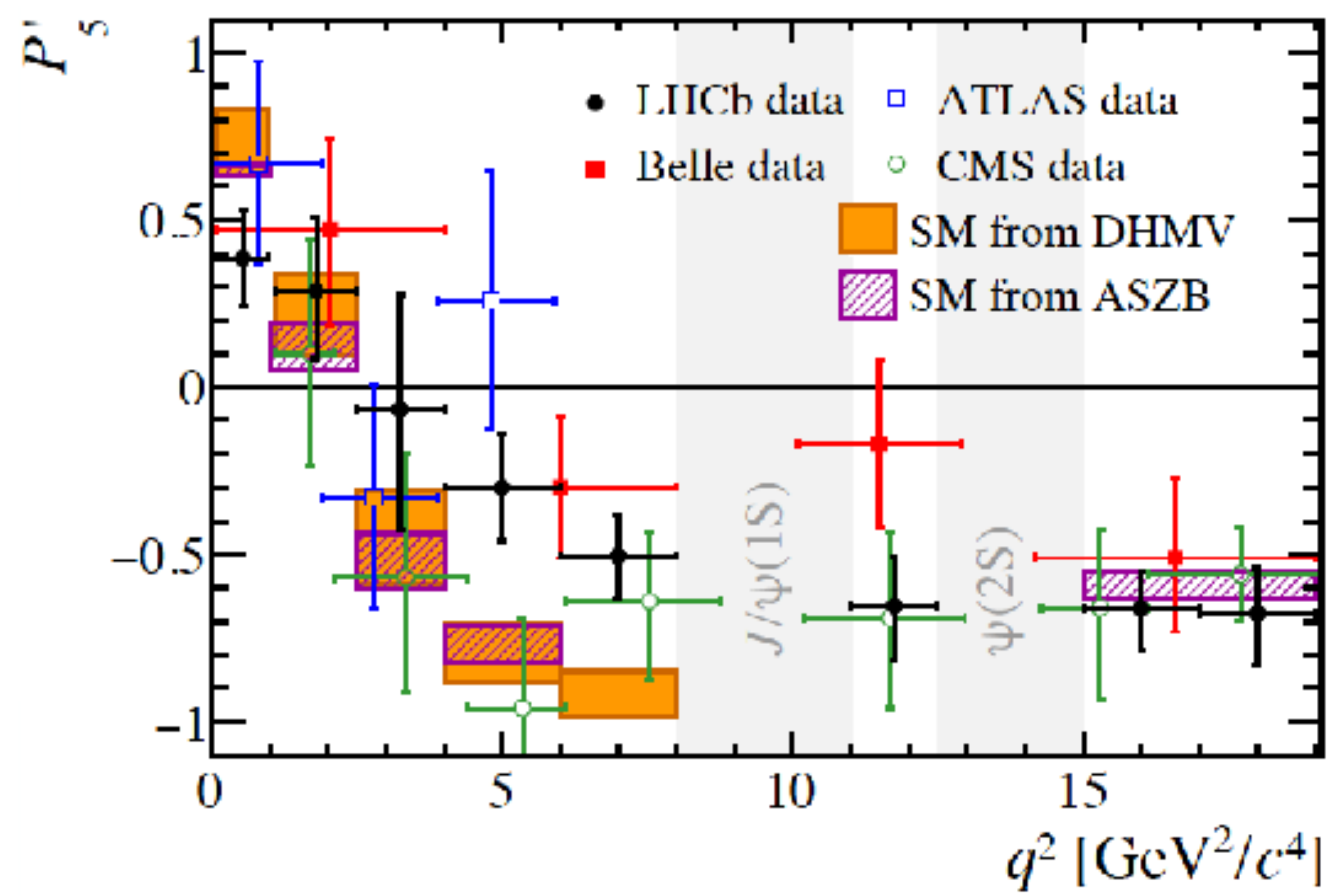
There are similar deviations in Bs→φμμ and Λb→Λμμ.

Angular analysis of $B_0 \to K_0^{*}\mu^{+}\mu^{-}$

(LHCb, JHEP02(2016)104;
Belle, PRL118(2017)111801;
CMS-PAS-BPH-15-008;JHEP10(2018047))

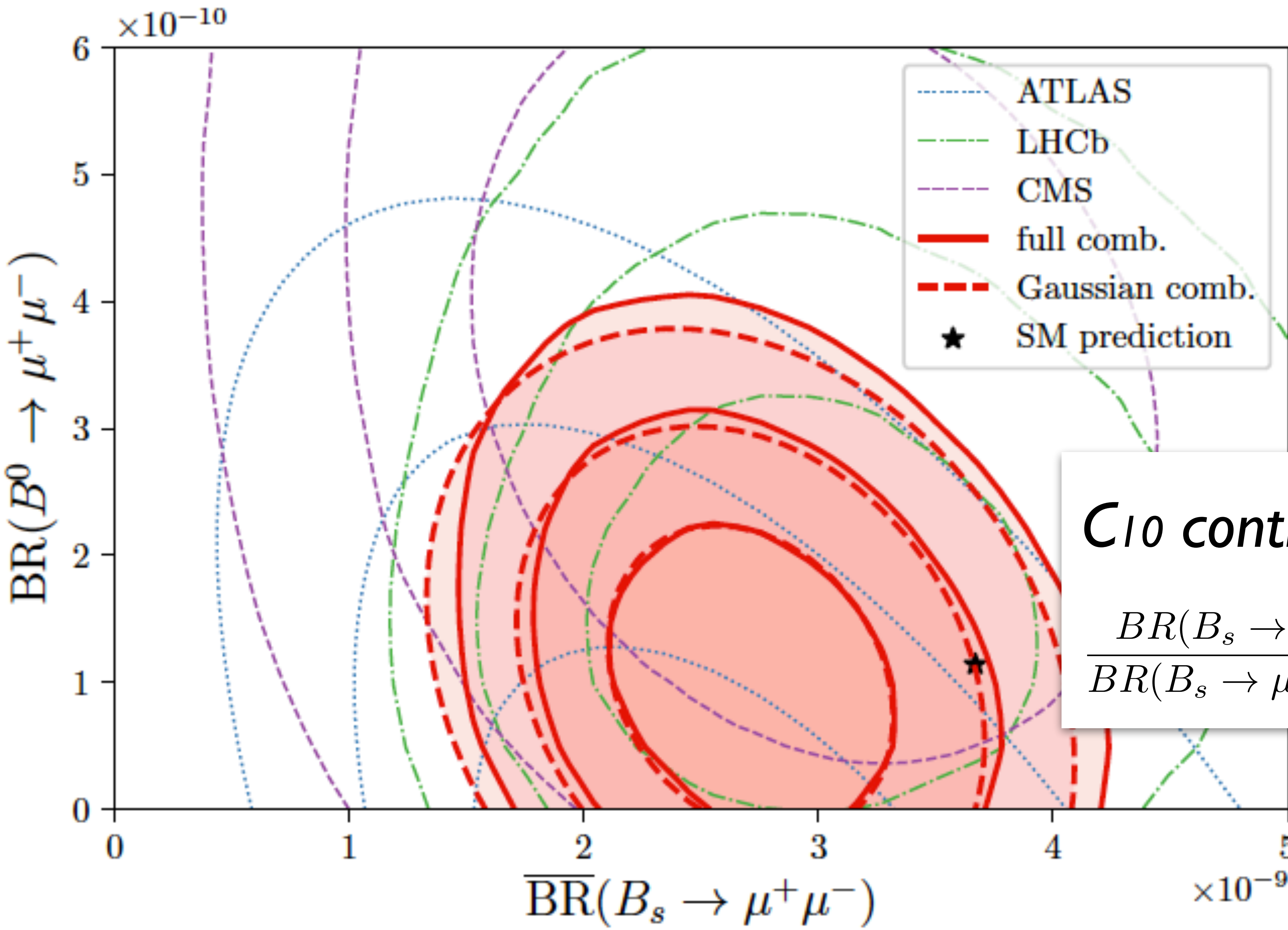


$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$



Bs→μμ, Bd→μμ

(J.Aebischer, et.al, 1903.10434)

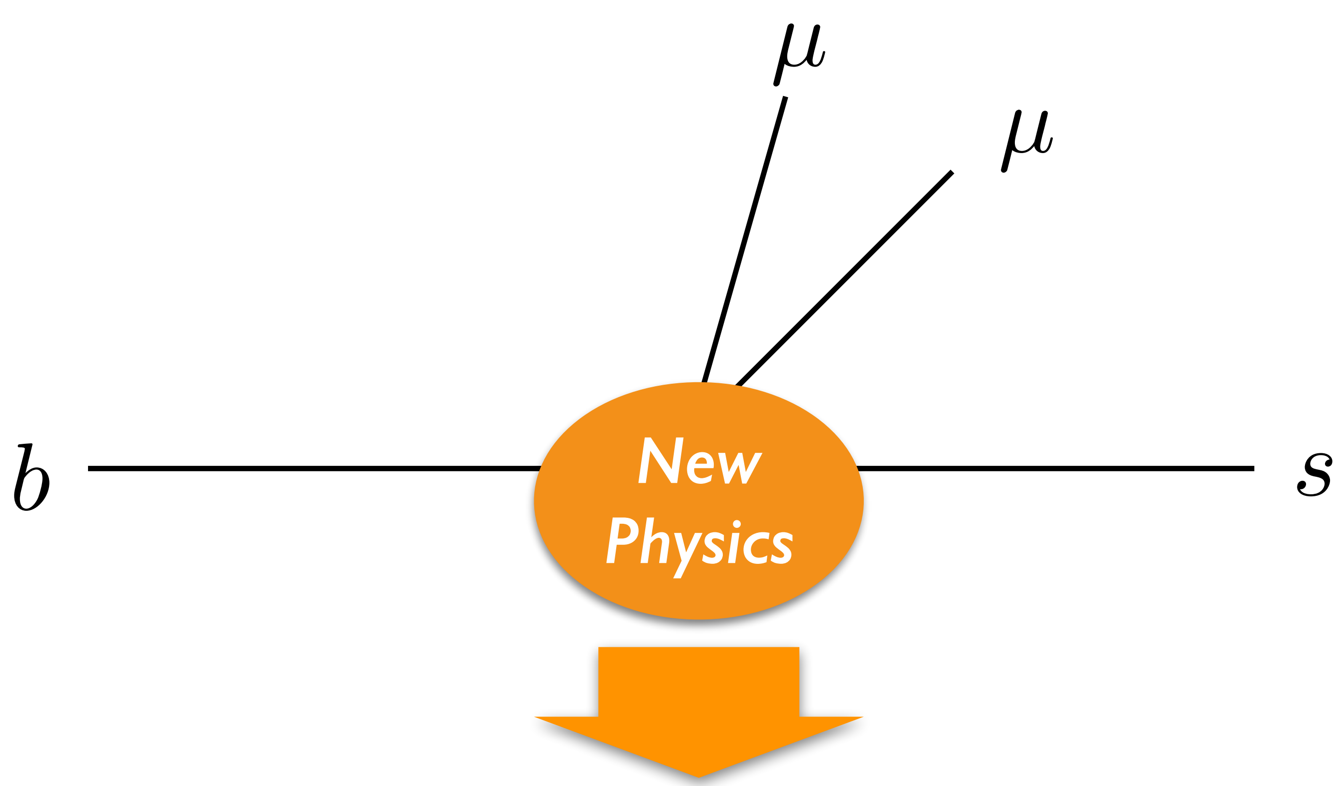


***C10* contributes to *Bs* →μμ:**

$$\frac{BR(B_s \to \mu\mu)}{BR(B_s \to \mu\mu)_{SM}} = |1 - 0.24\, C_{10}^{\mu}|^2$$

below the SM prediction

Many new physics interpretations have been proposed

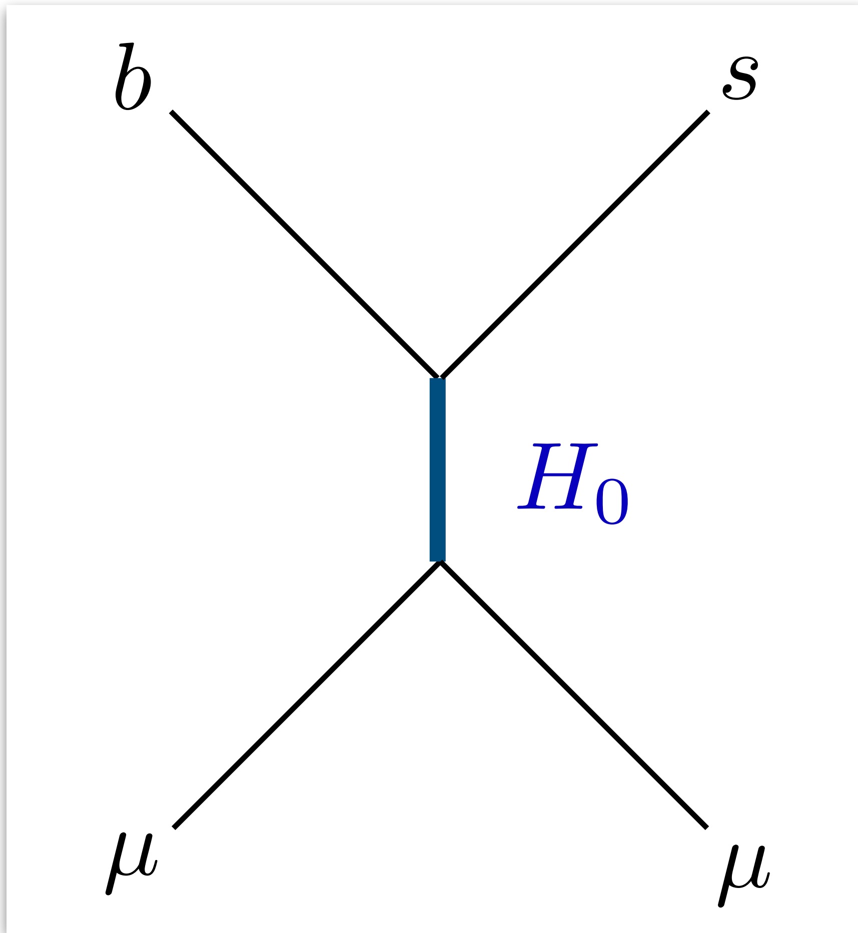


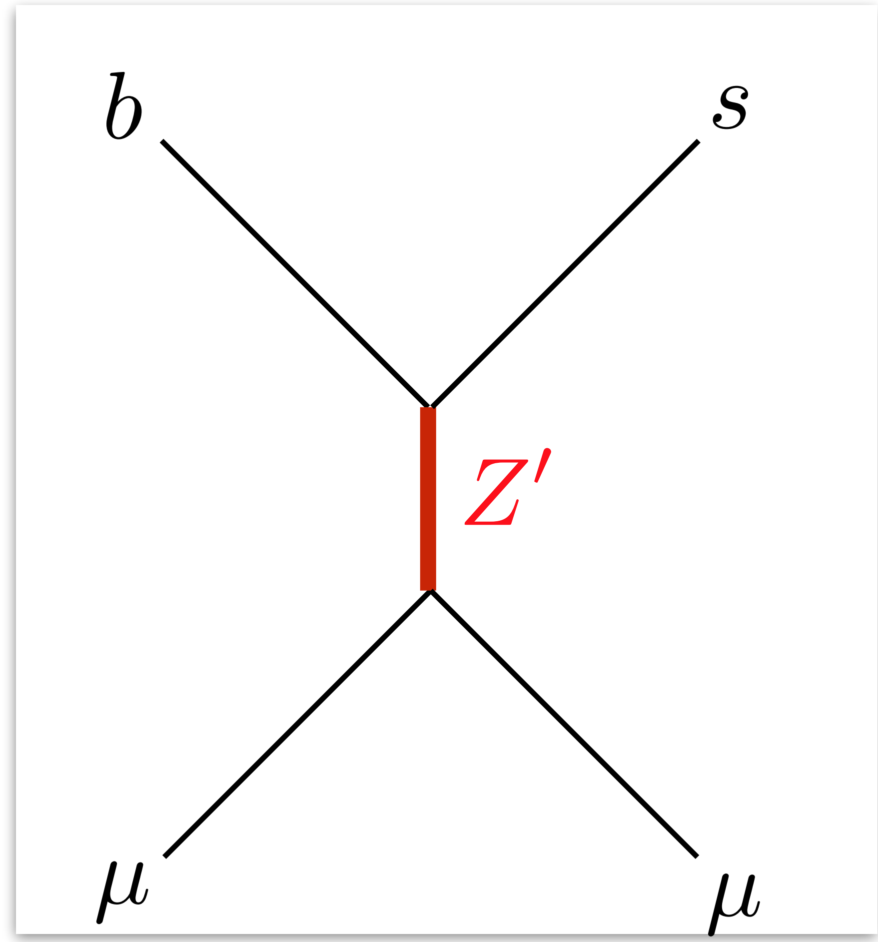
Depending on the new physics, the spin structure is different.

$$(\overline{s_I}\gamma_\mu b_I)(\overline{\mu}_J\gamma^\mu\mu_J)\ (I, J = L,\ R)$$ *etc.*

Which structure is favored?

<u>demonstration</u>





$$\frac{1}{\Lambda^2}(\overline{s_L} b_R)(\overline{\mu_R}\mu_L)$$

$$\frac{1}{\Lambda^2}(\overline{s_L}\gamma_\mu b_L)(\overline{\mu}\gamma^\mu \mu)$$

$$\frac{1}{\Lambda^2}(\overline{s_R}\gamma_\mu b_R)(\overline{\mu}\gamma^\mu \mu)$$ etc.

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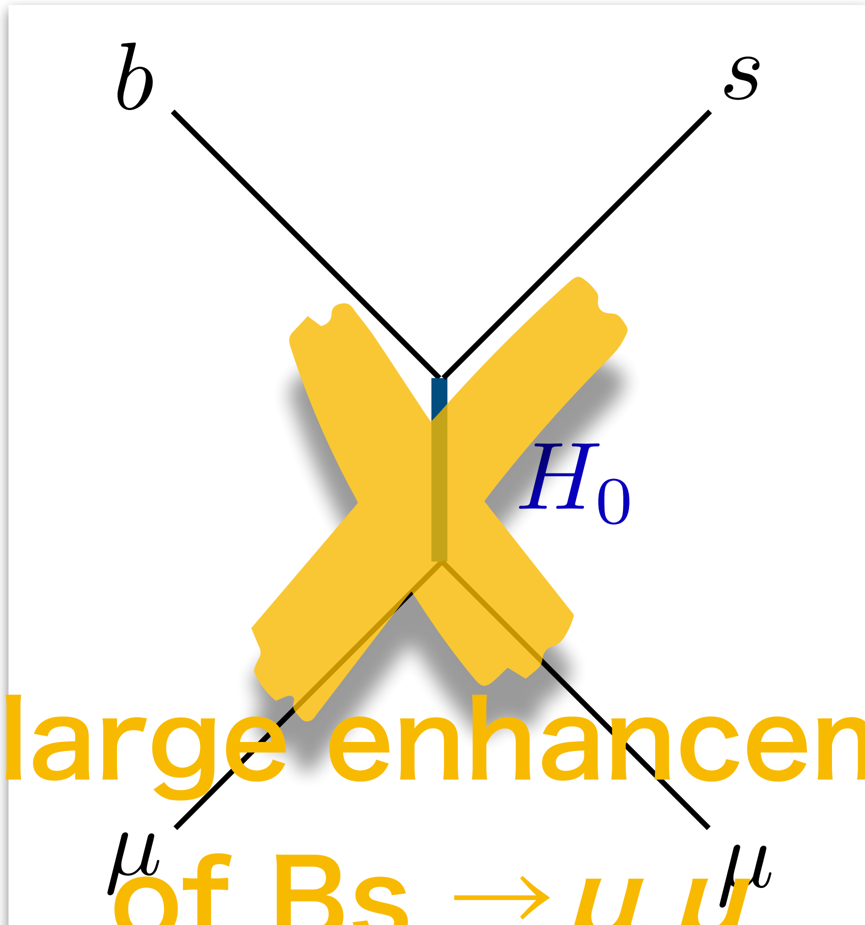
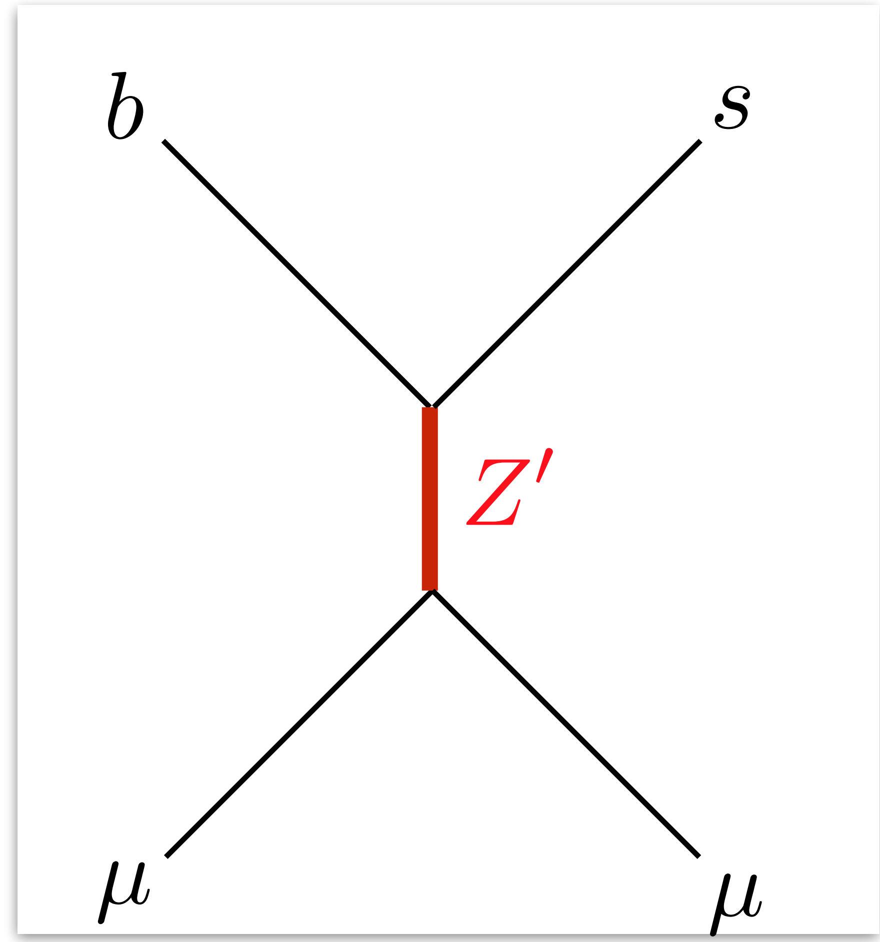


too large enhancement
of Bs $\rightarrow \mu\,\mu$

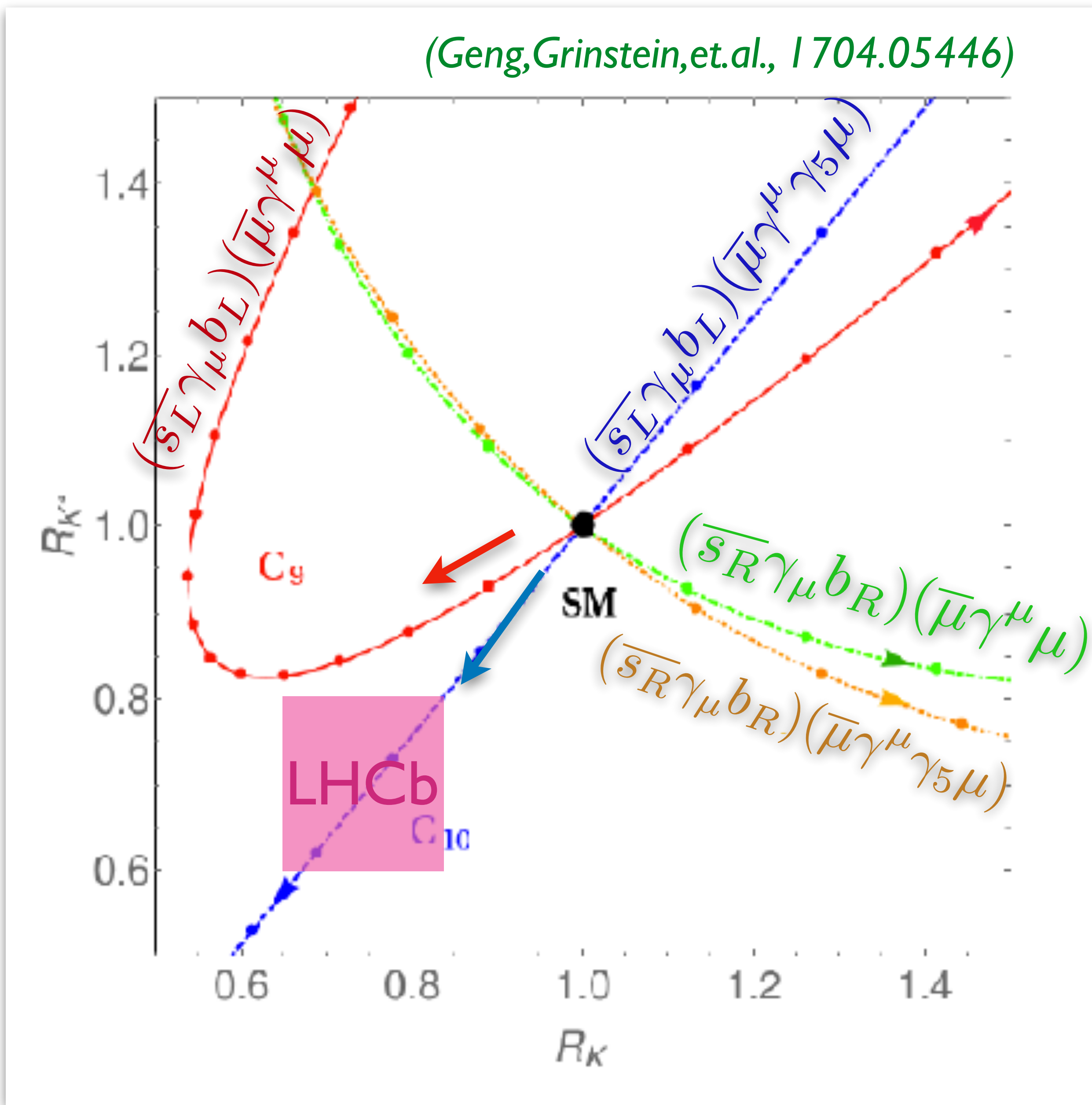
$$\cancel{\frac{1}{\Lambda^2}(\overline{s_L} b_R)(\overline{\mu_R}\mu_L)}$$

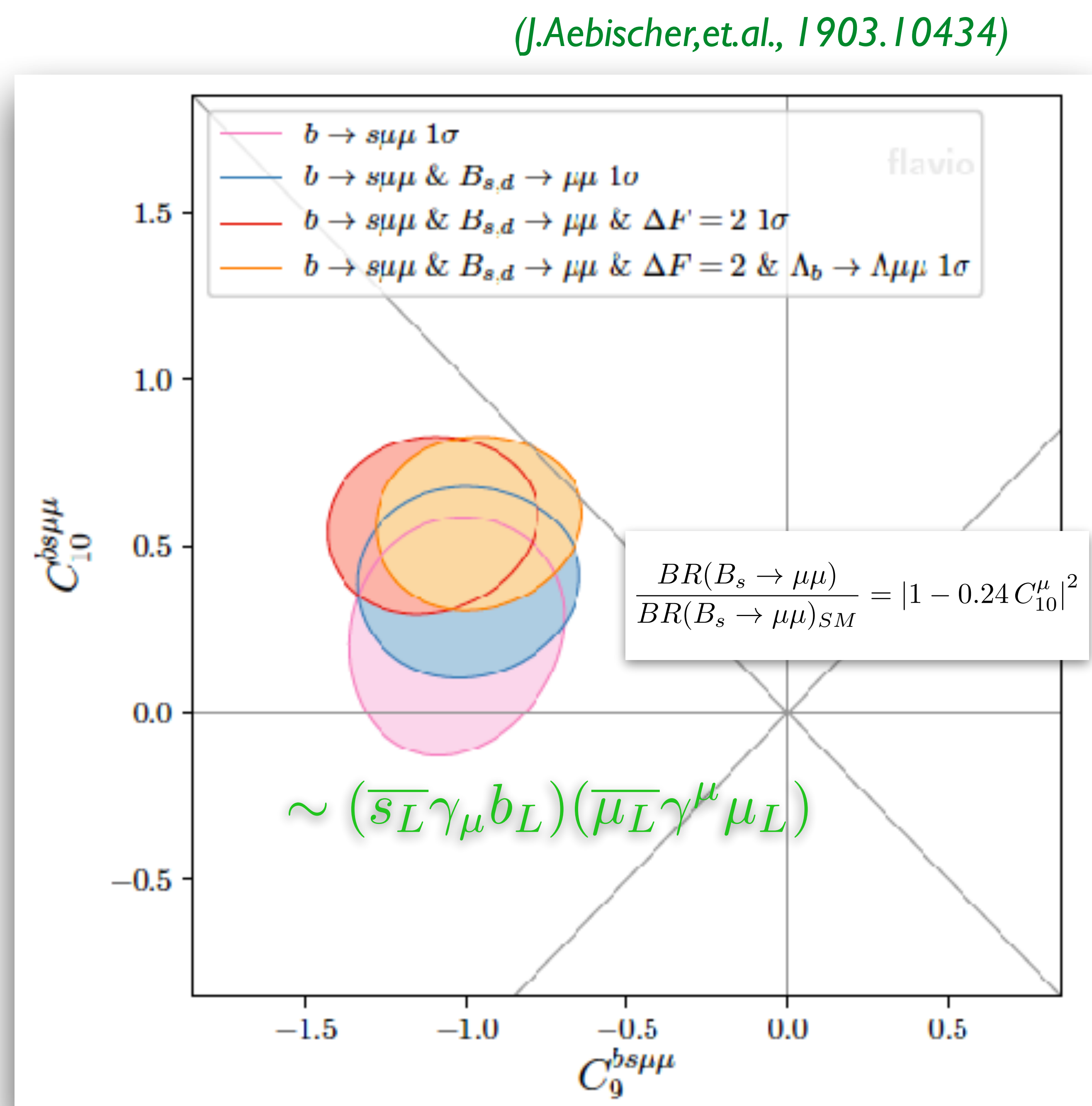


$$\frac{1}{\Lambda^2}(\overline{s_L}\gamma_\mu b_L)(\overline{\mu}\gamma^\mu \mu)$$

$$\frac{1}{\Lambda^2}(\overline{s_R}\gamma_\mu b_R)(\overline{\mu}\gamma^\mu \mu) \quad \text{etc.}$$

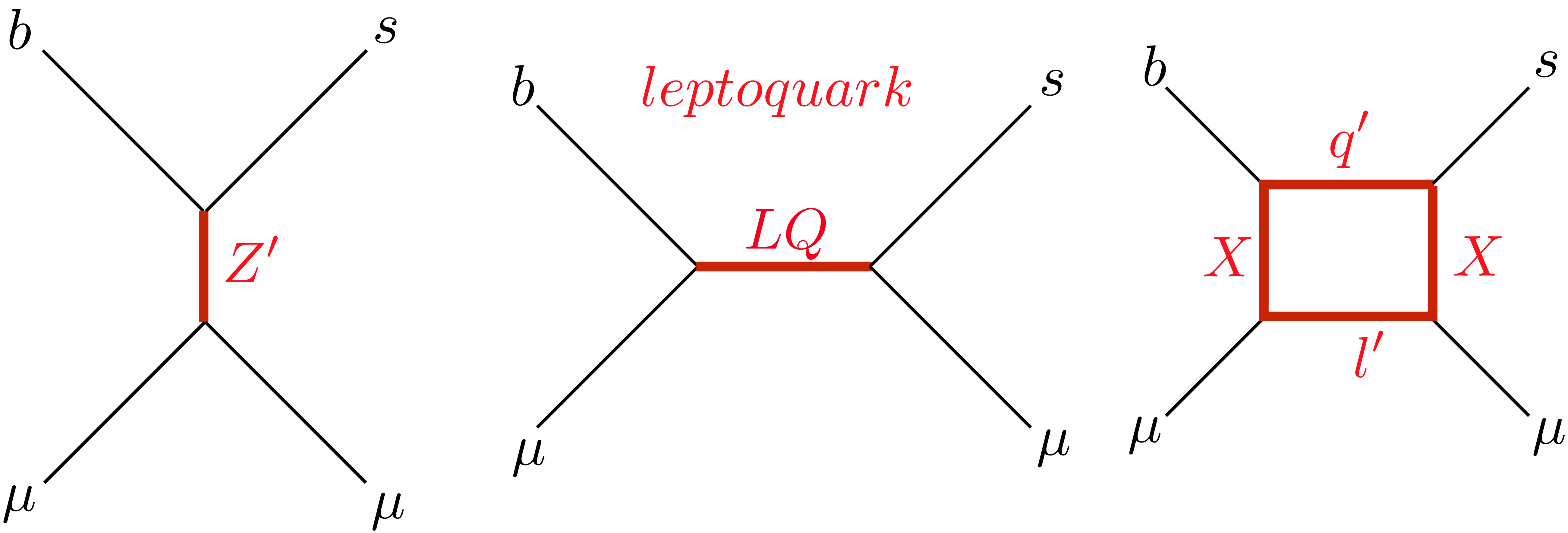
Which structure is favored?





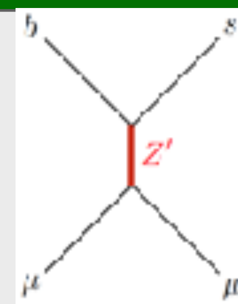
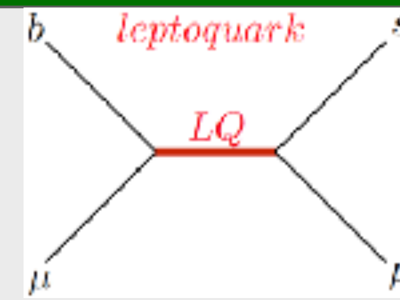
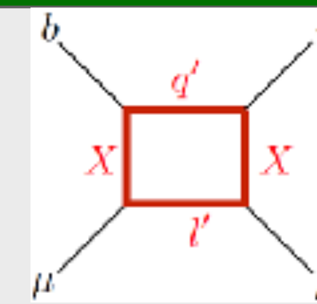
The SM-like operators (*quarks are left-handed*) are favored and destructive interference with the SM is required.

Many possible new physic have been proposed:



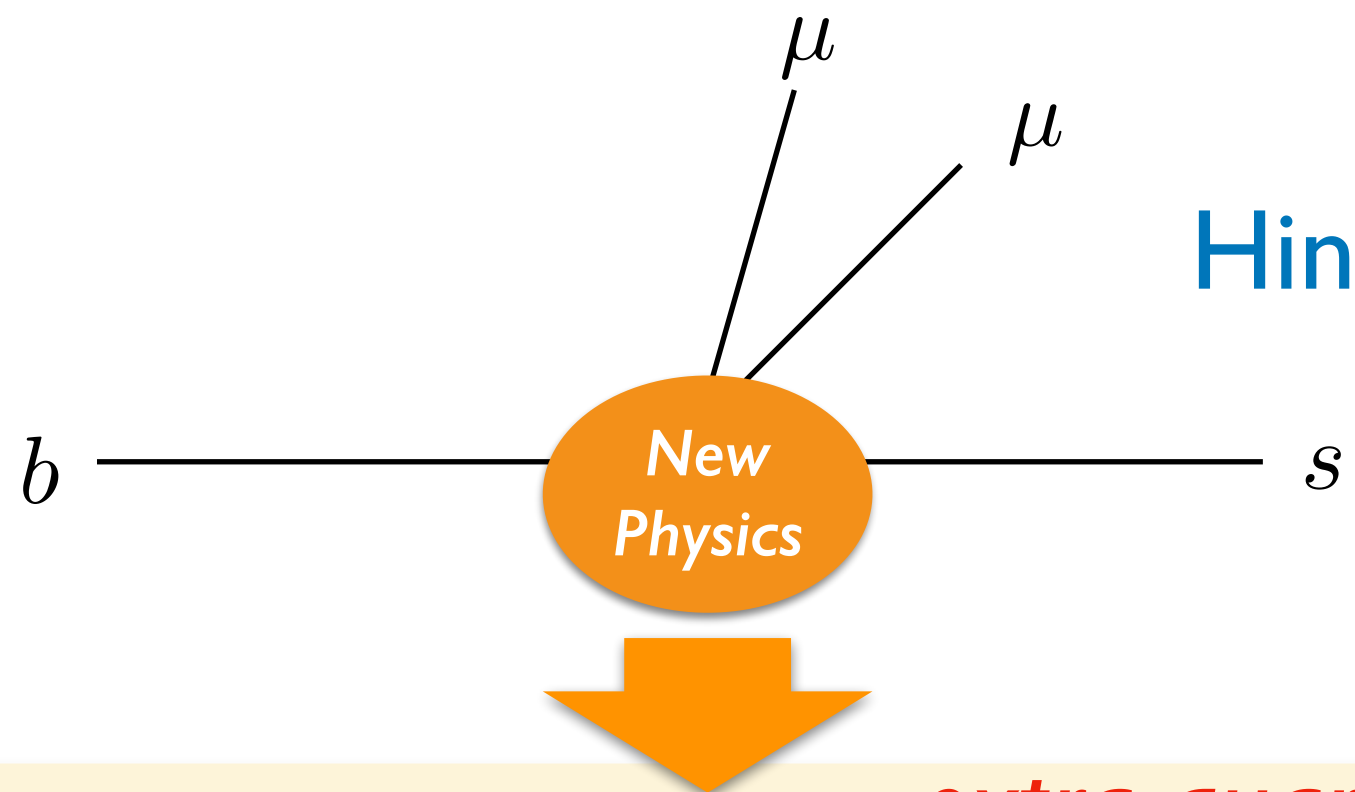
Required NW scale is about $\Lambda \approx 25\,\mathrm{TeV}$

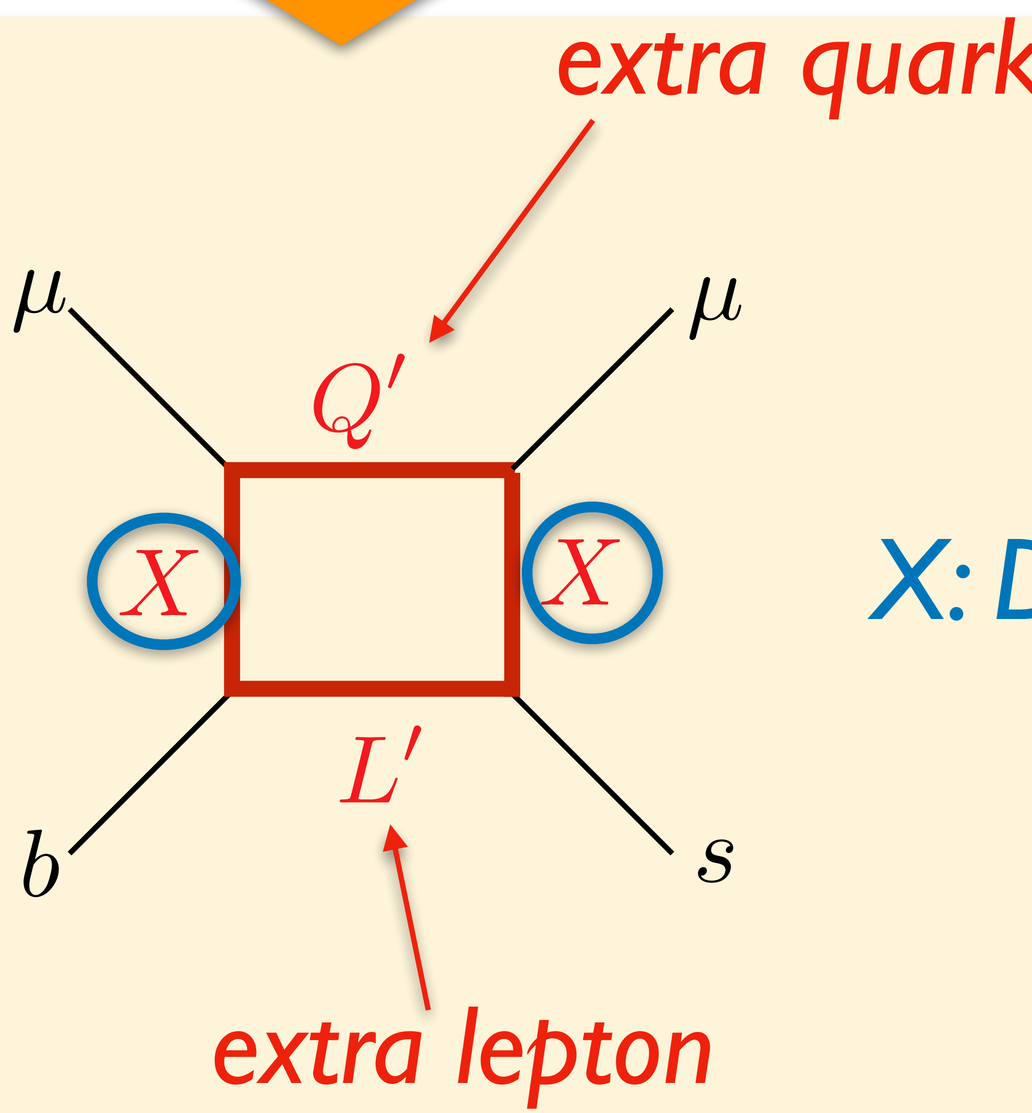
Rough sketch of BSMs motivated by *b→sll anomalies*

	Z'	Leptoquark	"Loop"
Contribution to $B \to K^{(*)}ll$			
Expected BSMs	For fermion masses *(Ko, Yu, Shigekami, YO,'17)* Motivated by GUT *(King, '17)* $U(1)_{\mu-\tau}$, $U(1)_{(B-L)_i}$ etc. *(Chen, Nomura, '18; Bian, Choi, et.al.'17; Ellis, et.al, 17'; Alonso, Cox, et.al., '17 etc.)*	Pati-Salam: $SU(4)\times SU(2)_L\times SU(2)_R$ *(Blanke, Crivellin,'18; Calibbi, Crivellin, Li,'17)* Composite *LQ* *(Gripaios, Nardecchia, Renner '14; Barbieri, et.al., '16; Matsuzaki, Nishiwaki, Watanabe, '17; Cline, '17)*	Inverse seesaw, Radiative seesaw *(Khalil, 17'; Cai, Gargalionis, et.al.,'17)* DM models *(Belanger, et.al,'15; Kawamura, Okawa, YO,'17)* SUSY *(Altmannshofer, Straub'13; Das, Hati, et.al.,'17)* LR gauged model *(Das, Hati, et.al.,'17)*
Bs-Bsbar mixing	Tree-level	1-loop	1-loop
signals@LHC	Z' →μμ/ττ	ττ search, *LQ* search	search for q'/l'/X
Refs. for $(g-2)_\mu$	*Bian, Choi, Kang, Lee, 1707.04811; Allanach, Queiroz, et.al., 1511.07447, etc.*	*Bauer, Neubert, 1511.01900; Calibbi, Crivellin, Li, 1709.00692, etc.*	*Gripaios, et.al., 1509.05020; Poh, Raby, 1705.07007, etc.*
Other issues	b→sττ (for $U(1)_{\mu-\tau}$) ν→νμμ (trident production) B→Kνν How to achieve anomaly-free	b→clν: R(D(*)) b→sττ, b→sτμ	Very large μ-couplings DM search

Dark matter interpretation

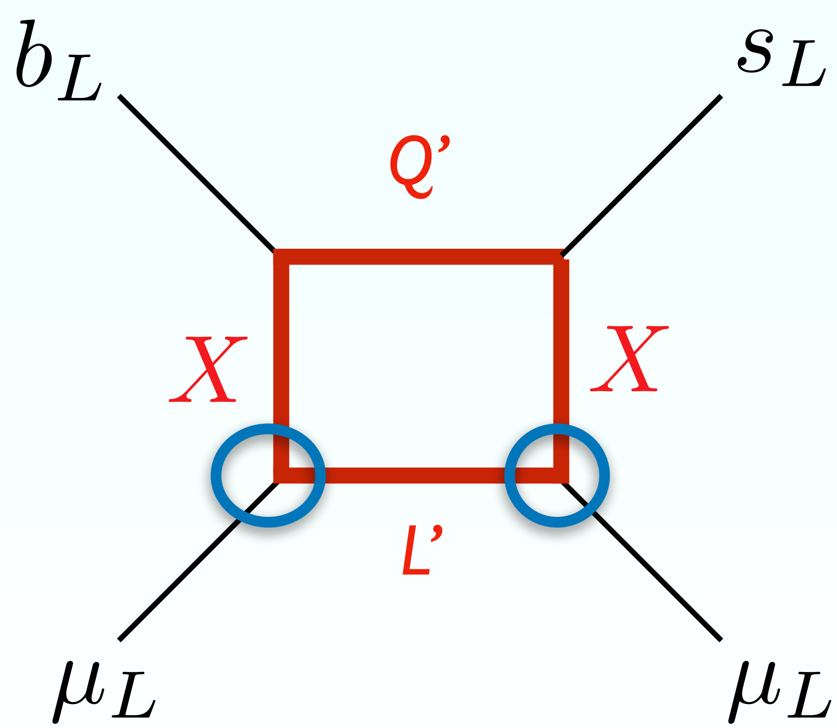
Hint for Dark Side?



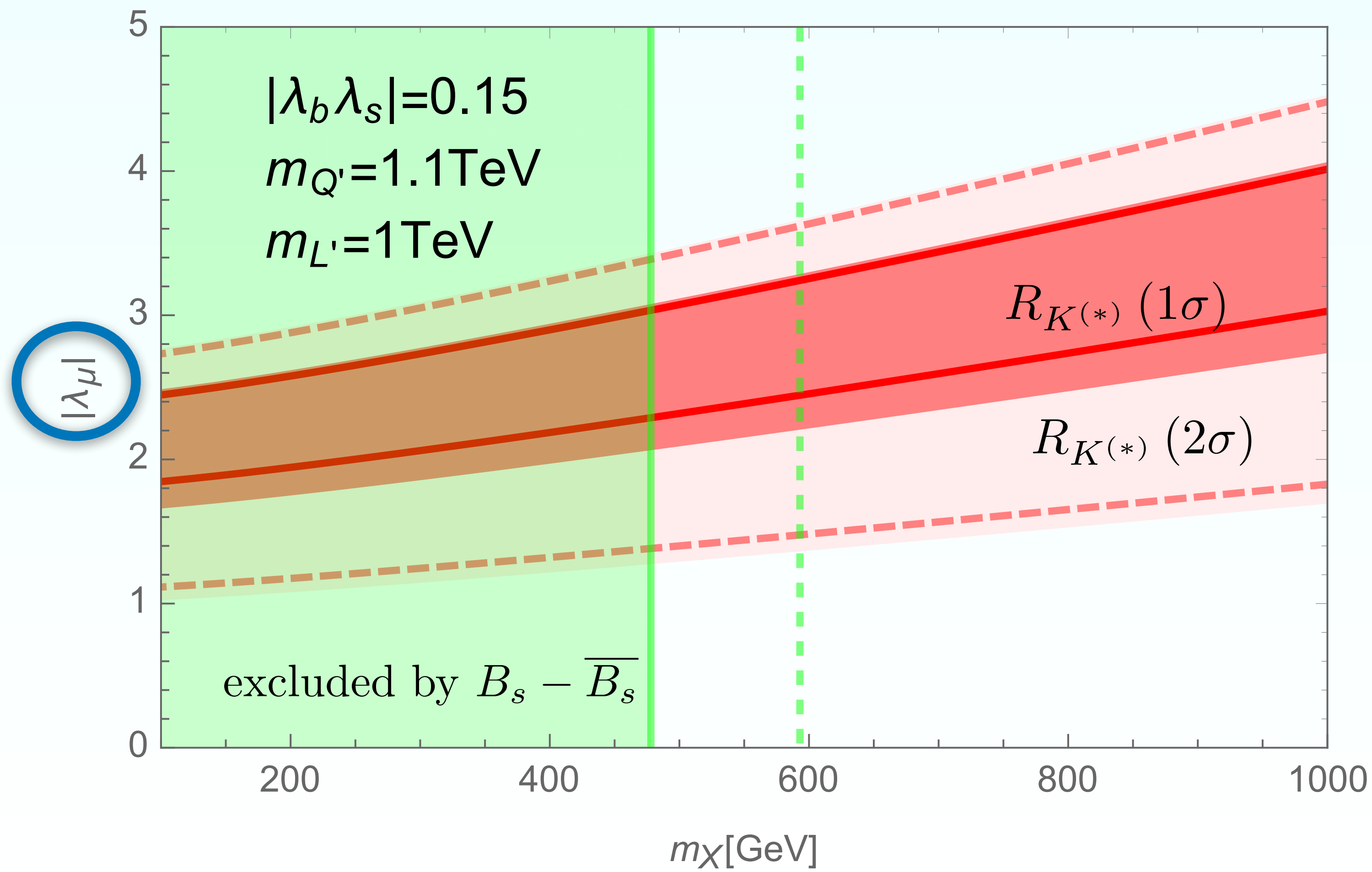


X: DM candidate

The explanation of the excesses



(Kawamura,Okawa,YO,1706.04344)

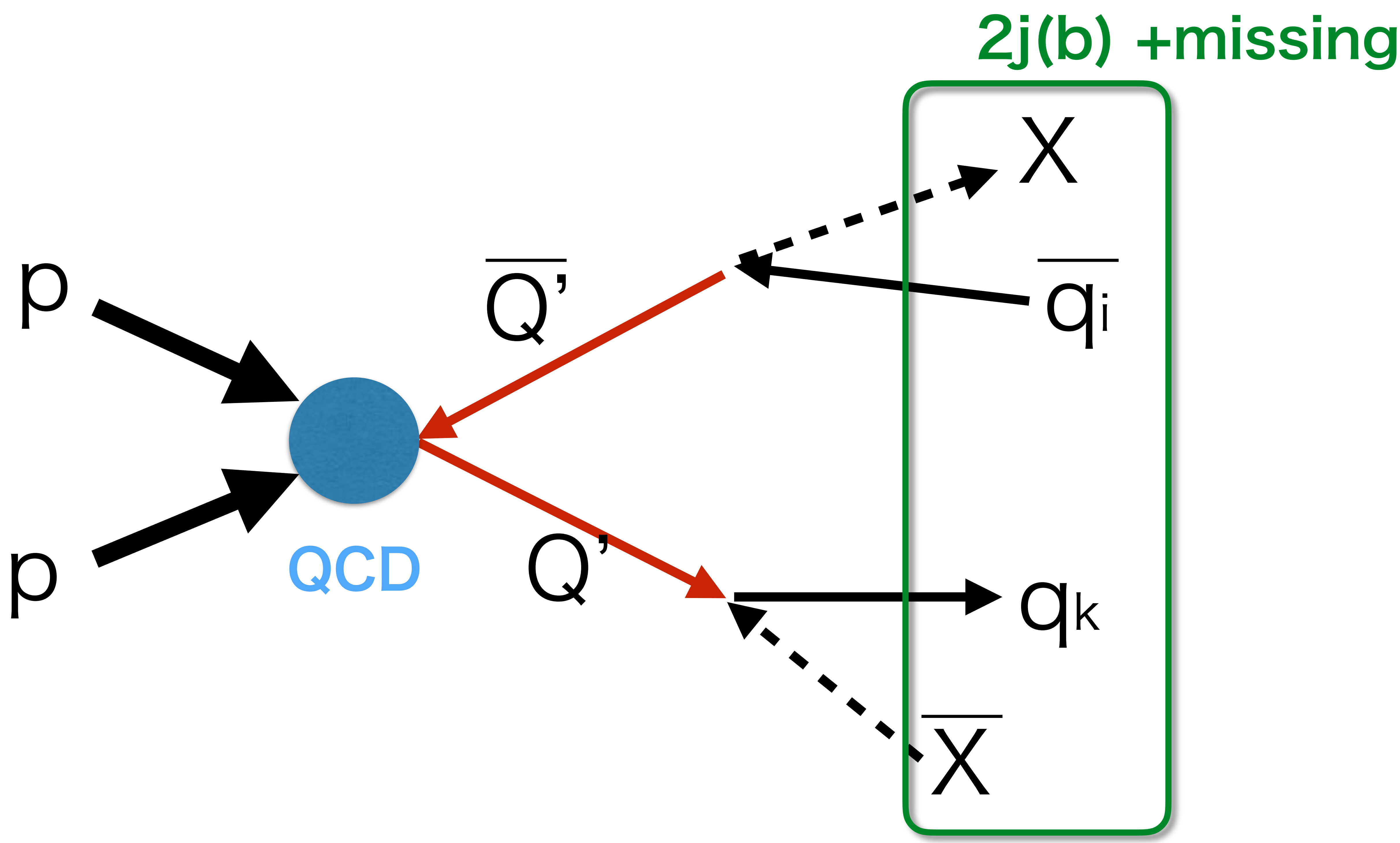


very large μ coupling required

We can search for Q', L' and DM (X) at the LHC and the XENON!

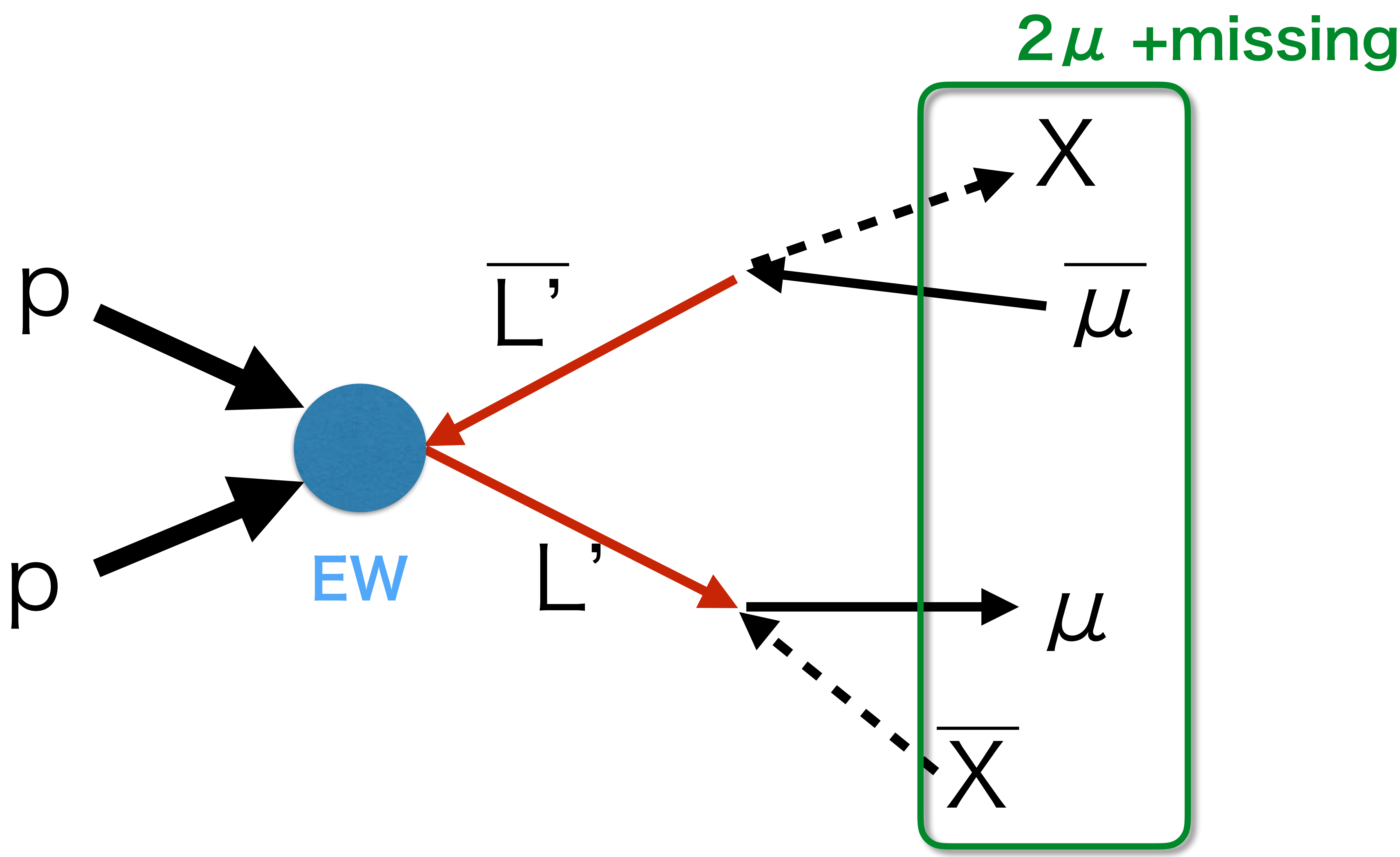
Search for Q' at the LHC

(Kawamura,Okawa,YO,1706.04344)



Search for L' at the LHC

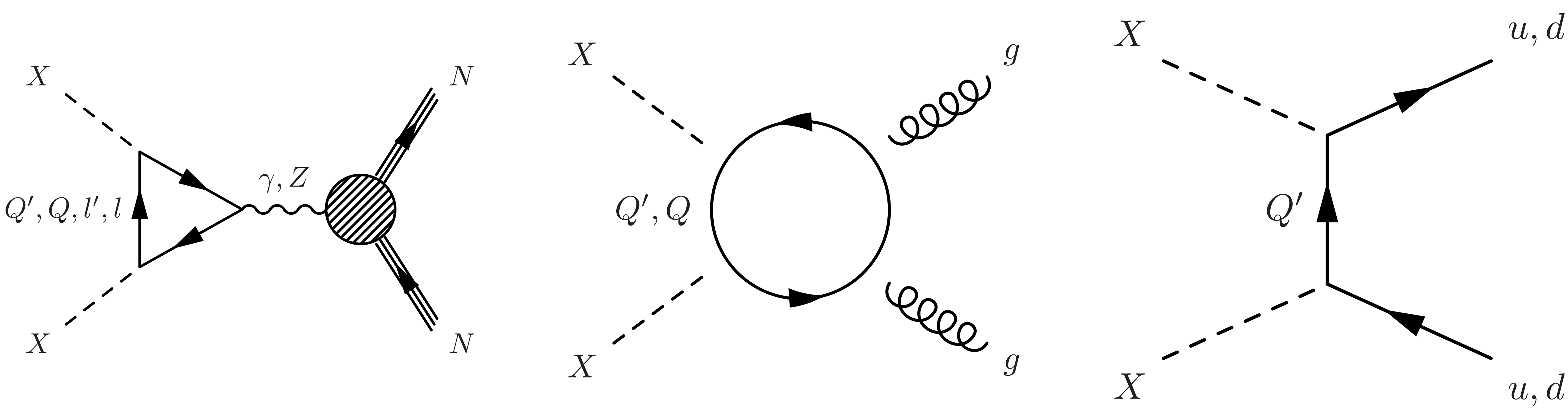
(Kawamura, Okawa, YO, 1706.04344)



Search for DM

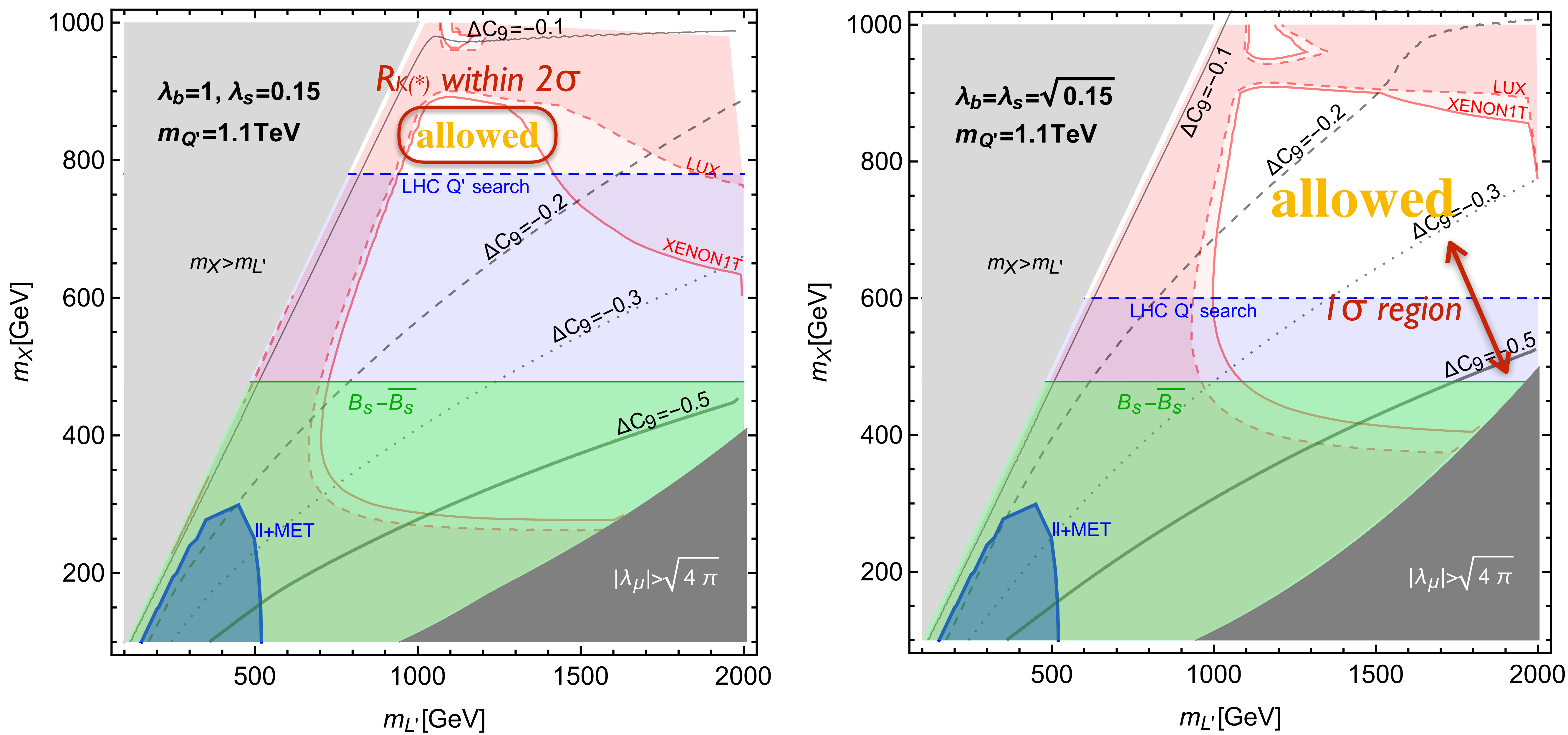
(Kawamura,Okawa,YO,1706.04344)

- *The relic density of DM (X) can be estimated.*
- *We can see the DM-nucleus scattering.*



Interplay with DM and LHC physics

(Kawamura,Okawa,YO,1706.04344)

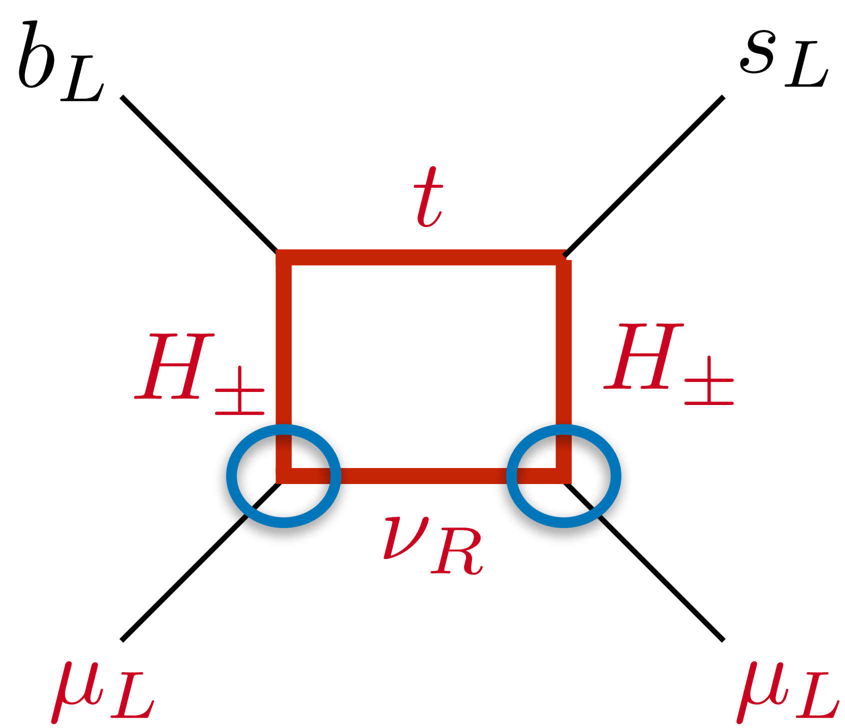


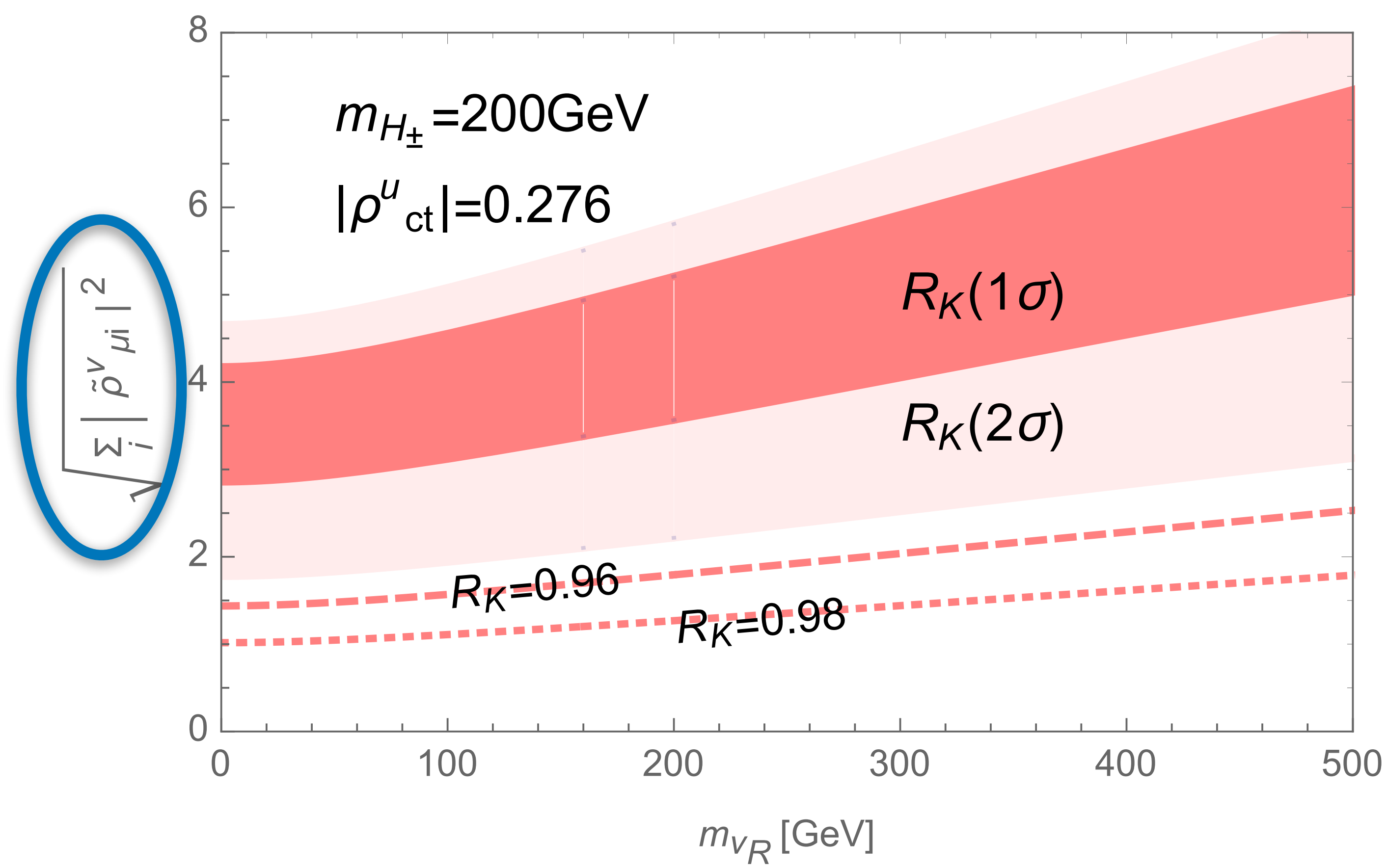
Possibility of the flavor-violating coupling involving νR.

(Iguro, YO, 1802.01732)

$$\overline{L_L^i}(V_\nu)^{ij}\widetilde{H}_2\rho_\nu^j\nu_R$$

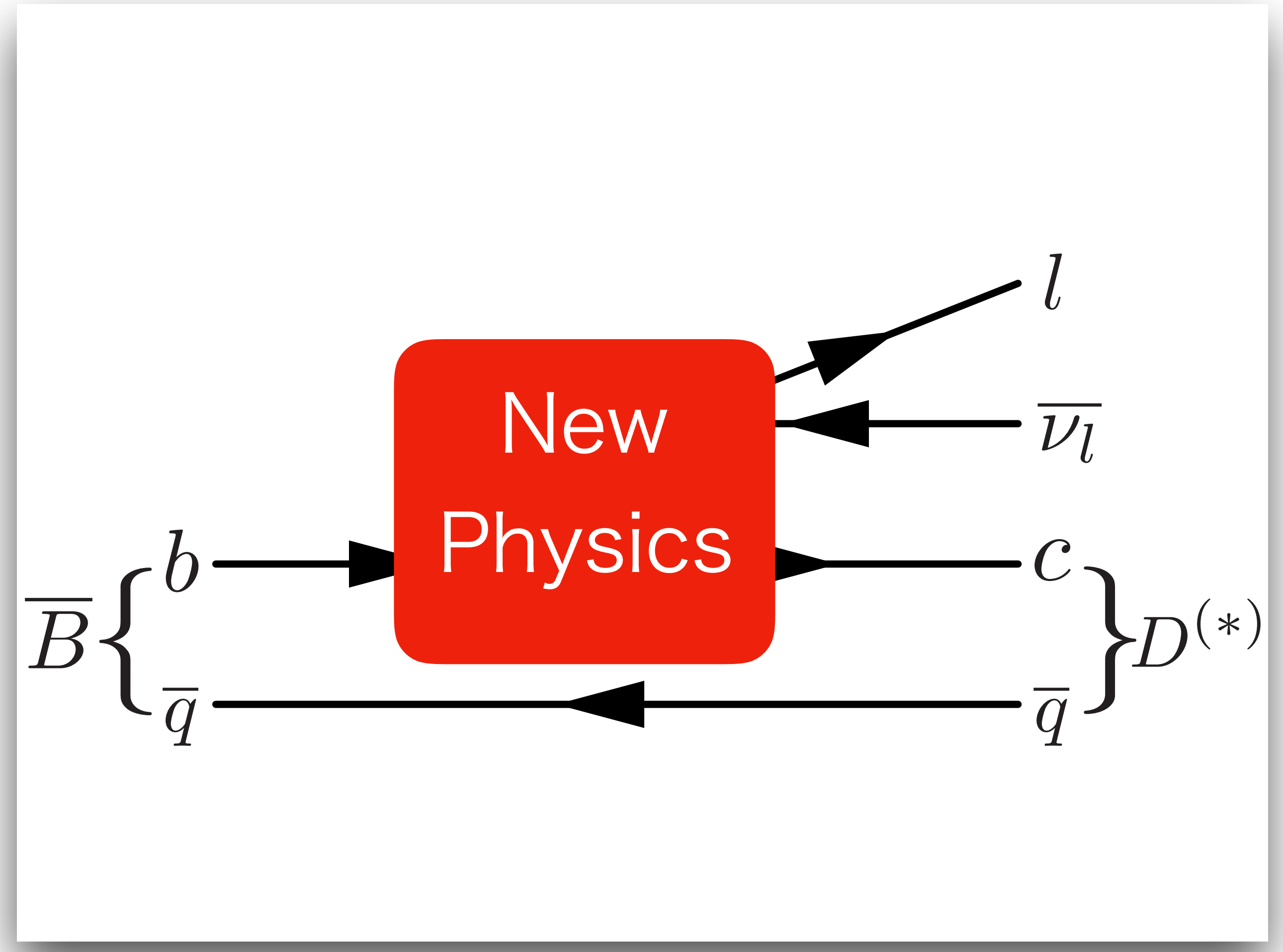
heavy Higgs instead of X



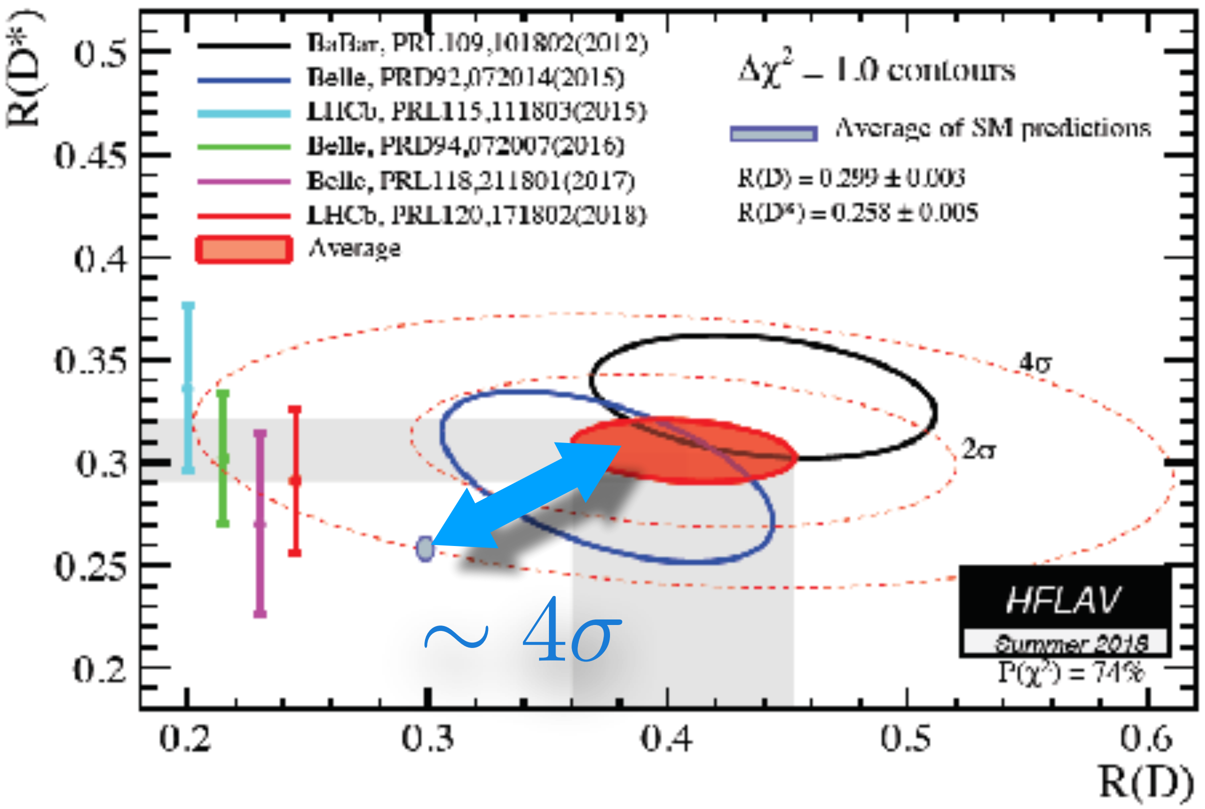


very large μ coupling required

3. The new physics interpretations of the B→D(*)lν anomalies



The violation of Lepton Flavor Universality (LFU) in B→D(*)lν is also deviated from the SM prediction.

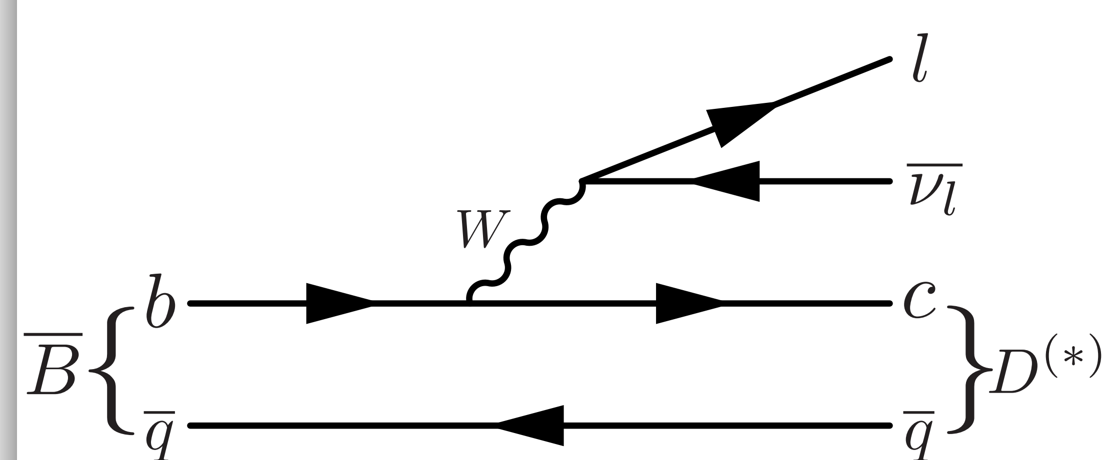


<u>*lepton universality of B→D(*)τν*</u>

$$R(D^{(*)}) \equiv \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$$

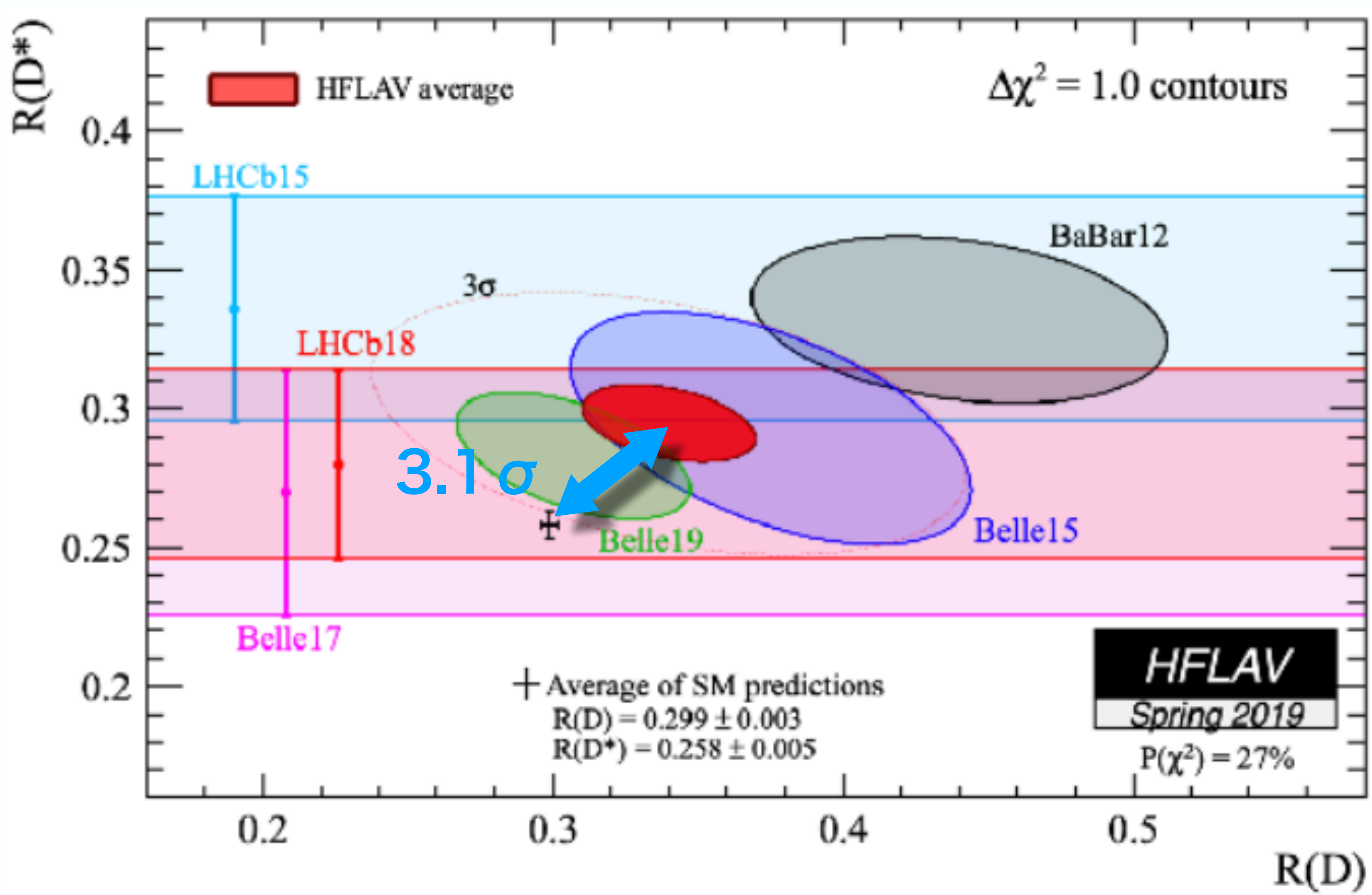
where $\ell = e, \mu$

In the SM,

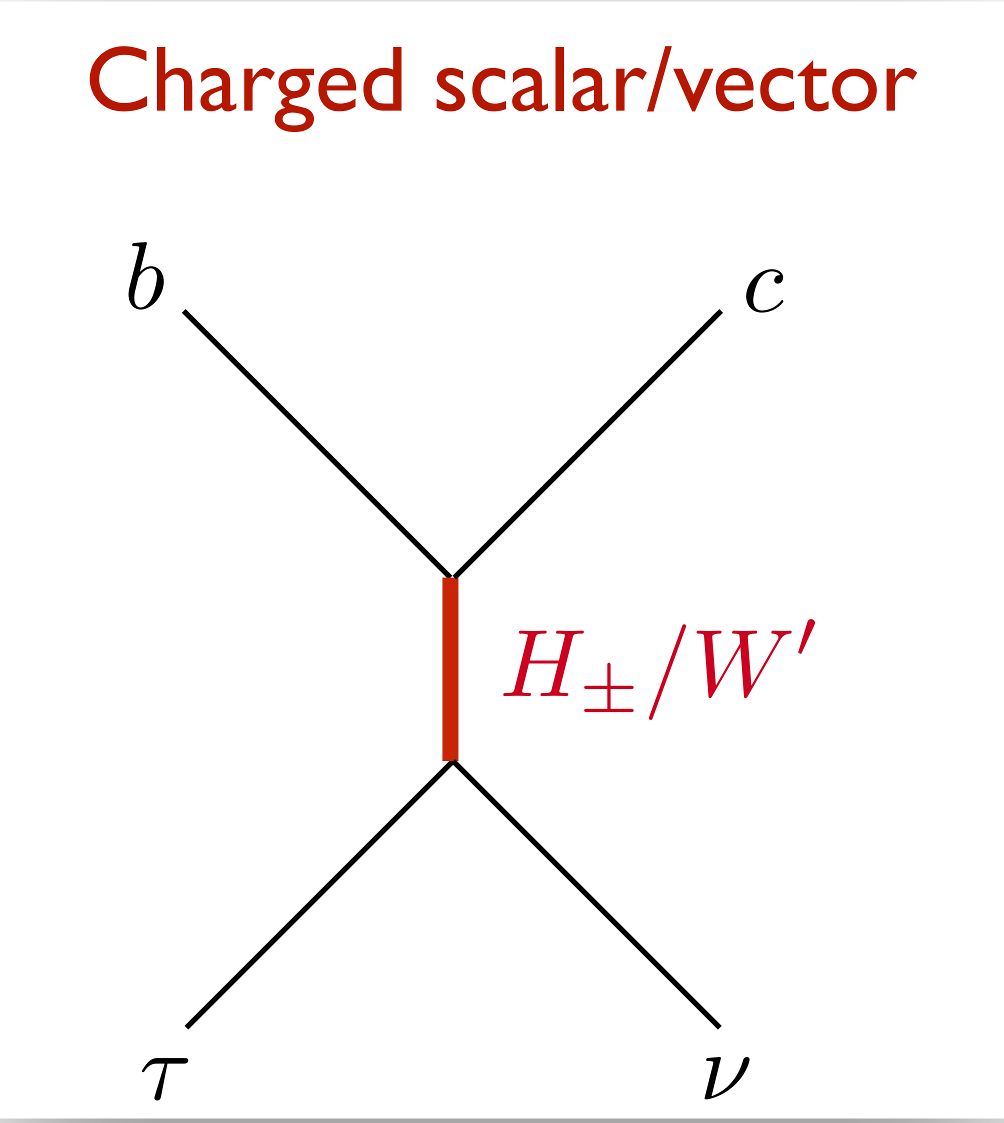


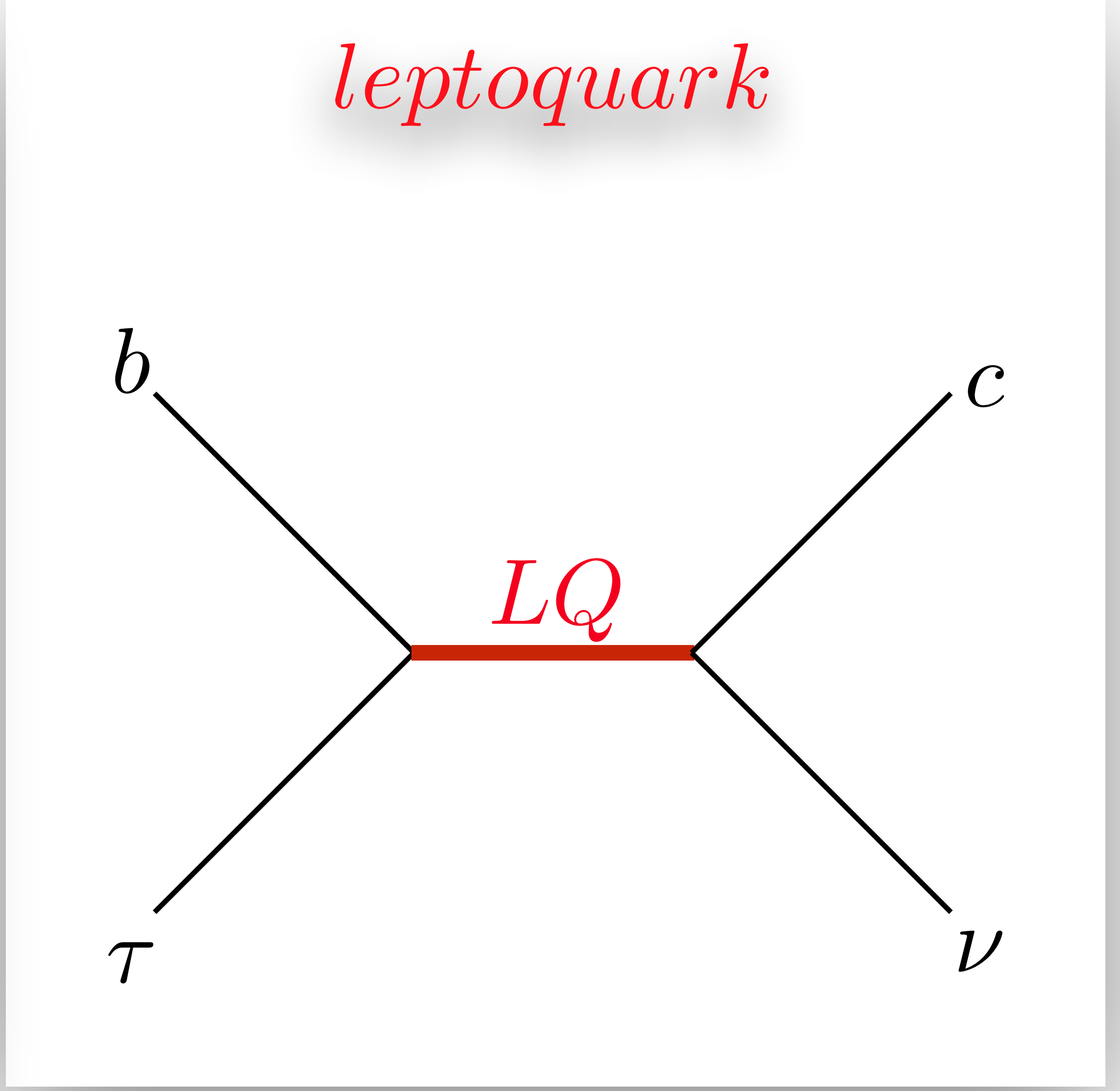
Including new result of Belle,

1904.08794



New charged particles that interact with heavy flavors may exist





B→D(*)τν anomaly requires $\Lambda \approx 2.4\,\mathrm{TeV}$

that comparable to the weak int..

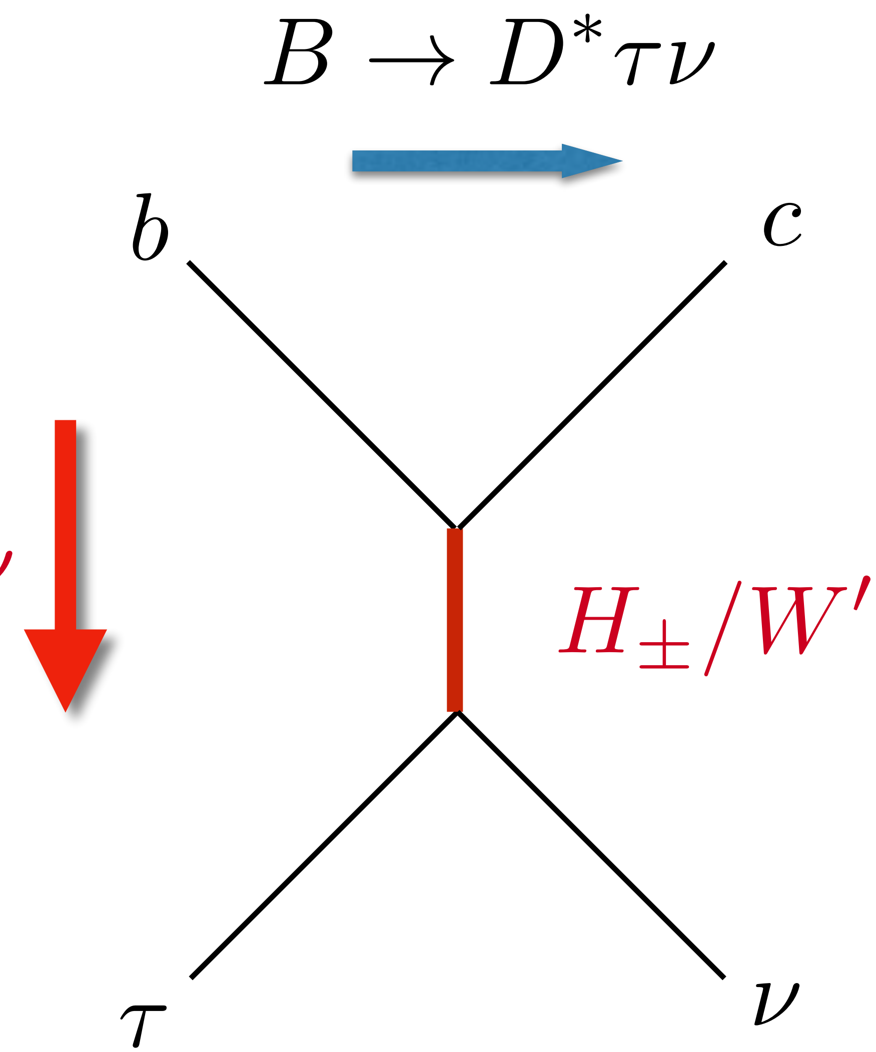
We could see them directly at the LHC!

Interestingly, we can test both W' and H+/- directly at the LHC!

(Iguro,YO, Takeuchi, 1810.05843)

$pp \to H_\pm/W' \to \tau\nu$

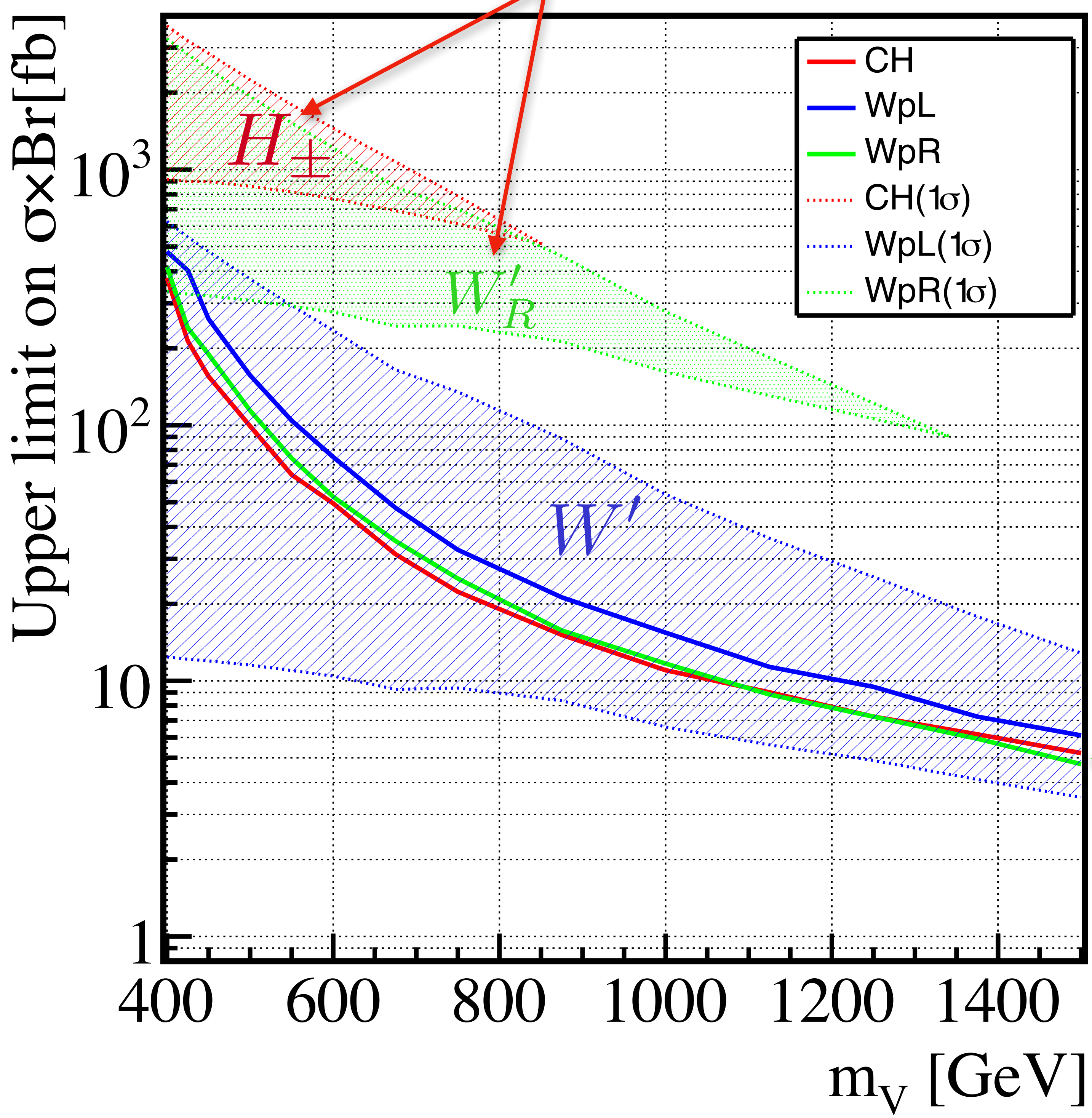
@LHC



Charged Higgs explanation is excluded if heavier than 400 GeV.

(Iguro, YO, Takeuchi, 1810.05843)

excluded!



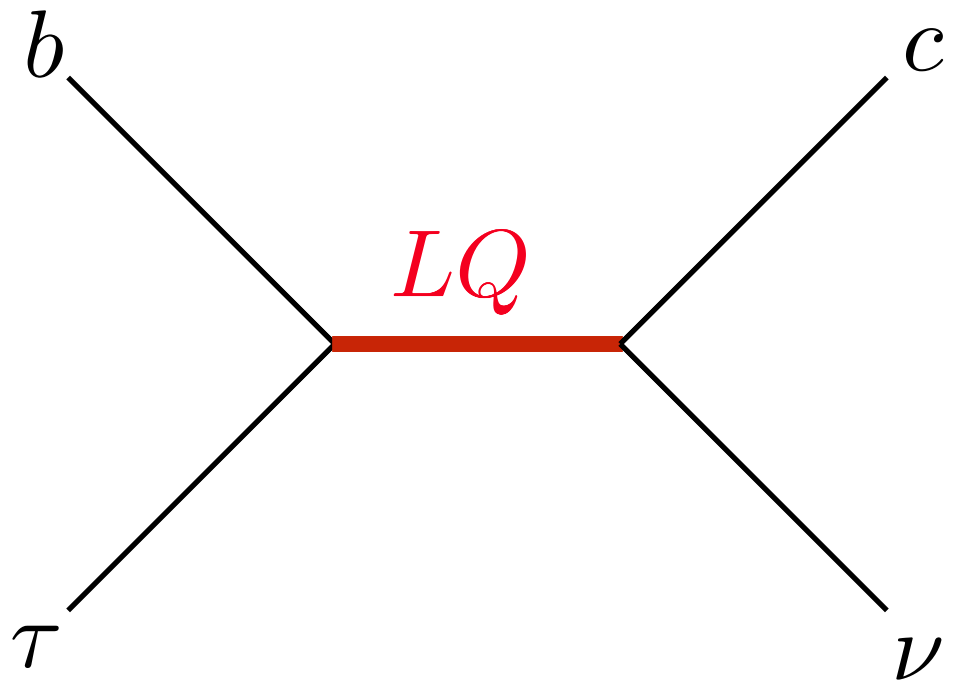
within 1σ
in the hatched region

exclusion lines

based on 1807.11421 (CMS)

stronger than the Bc bound

How about another candidate, leptoquark?



Leptoquark, for instance, predicted by an unified theory: $SU(4)\times SU(2)_L\times SU(2)_R$ (breaks down to the SM at the energy)

(Calibbi,Crivellin,Li,arXiv:1709.00692.)

$$\mathcal{L}_{SU(4)} = g_U \left(\overline{\hat{l}^I_L} \quad \overline{\hat{q}^{b\,I}_L}\right) \begin{pmatrix} B_\mu & \overset{LQ}{\boxed{U^{a\,\dagger}_\mu}} \\ \underset{LQ}{\boxed{U^{b}_\mu}} & G^{ba}_\mu \end{pmatrix} \gamma^\mu \begin{pmatrix} \hat{l}^I_L \\ \hat{q}^{a\,I}_L \end{pmatrix} \Rightarrow \kappa_{ij}\left(\overline{d^{b\,i}_L}\gamma_\mu e^j_L + (V_{CKM})_{ki}\overline{u^{b\,k}_L}\gamma_\mu \nu^j_L\right)\boxed{U^{b\,\mu}}$$

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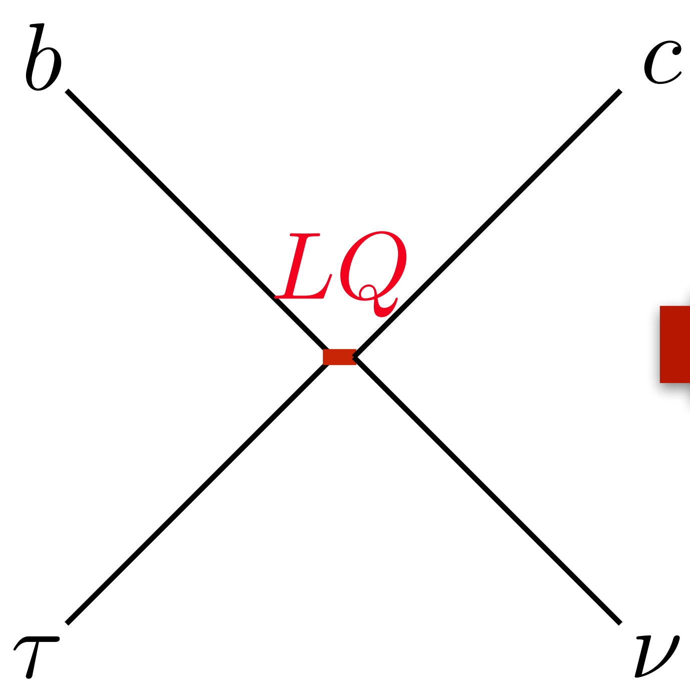
After integrating out the LQ, we obtain 4-fermi int.:



$$\Rightarrow (couplings) \times \frac{1}{M_U^2}$$

Test LQ, using the flavor observables

$$\frac{d\Gamma}{d\cos\theta_{hel}(\tau)} = \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{hel}(\tau))$$

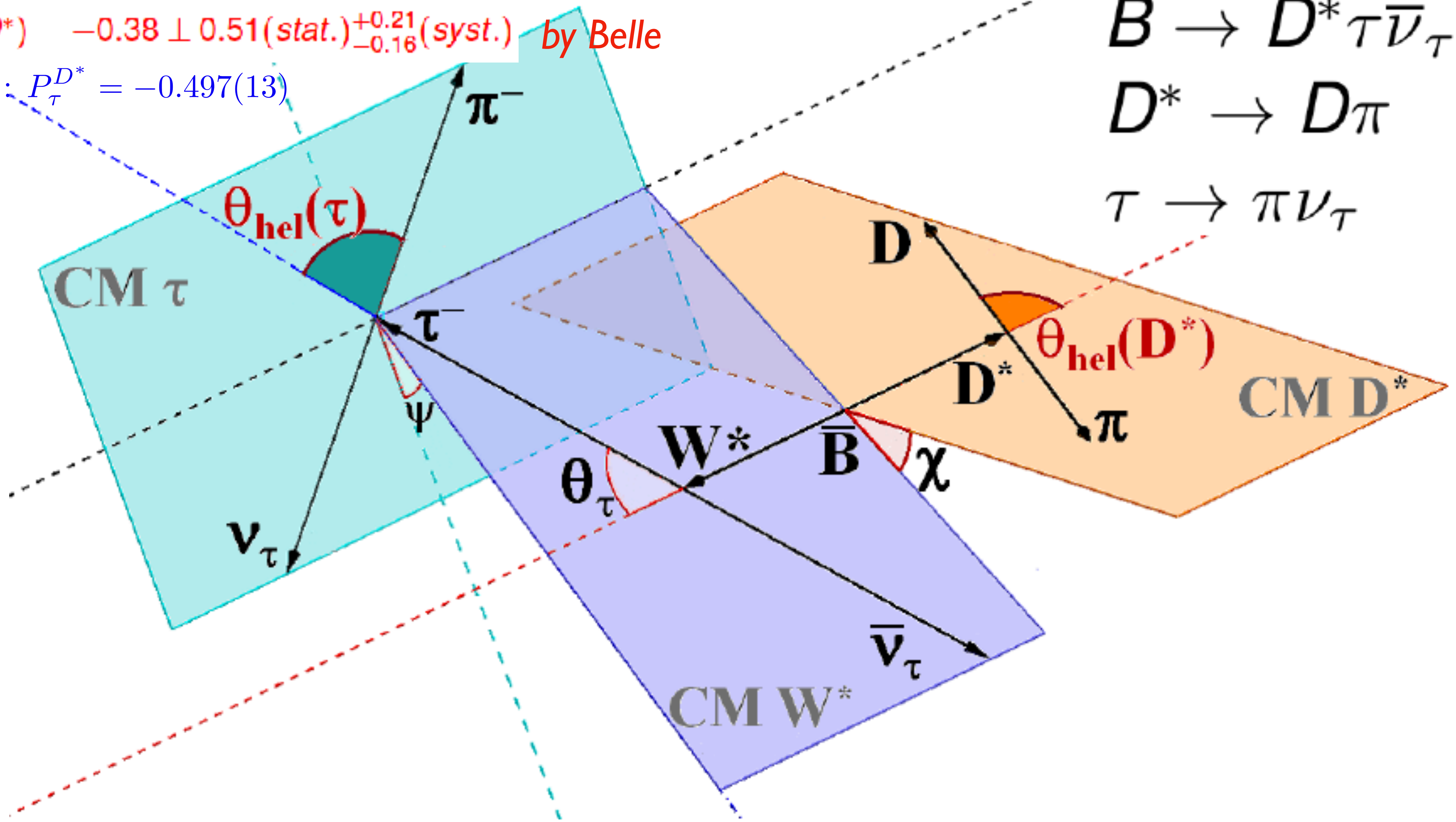
$P_\tau(D^*) \quad -0.38 \pm 0.51(stat.)^{+0.21}_{-0.16}(syst.)$ *by Belle*

$\mathrm{SM}: P_\tau^{D^*} = -0.497(13)$

$\overline{B} \to D^* \tau \overline{\nu}_\tau$

$D^* \to D\pi$

$\tau \to \pi \nu_\tau$



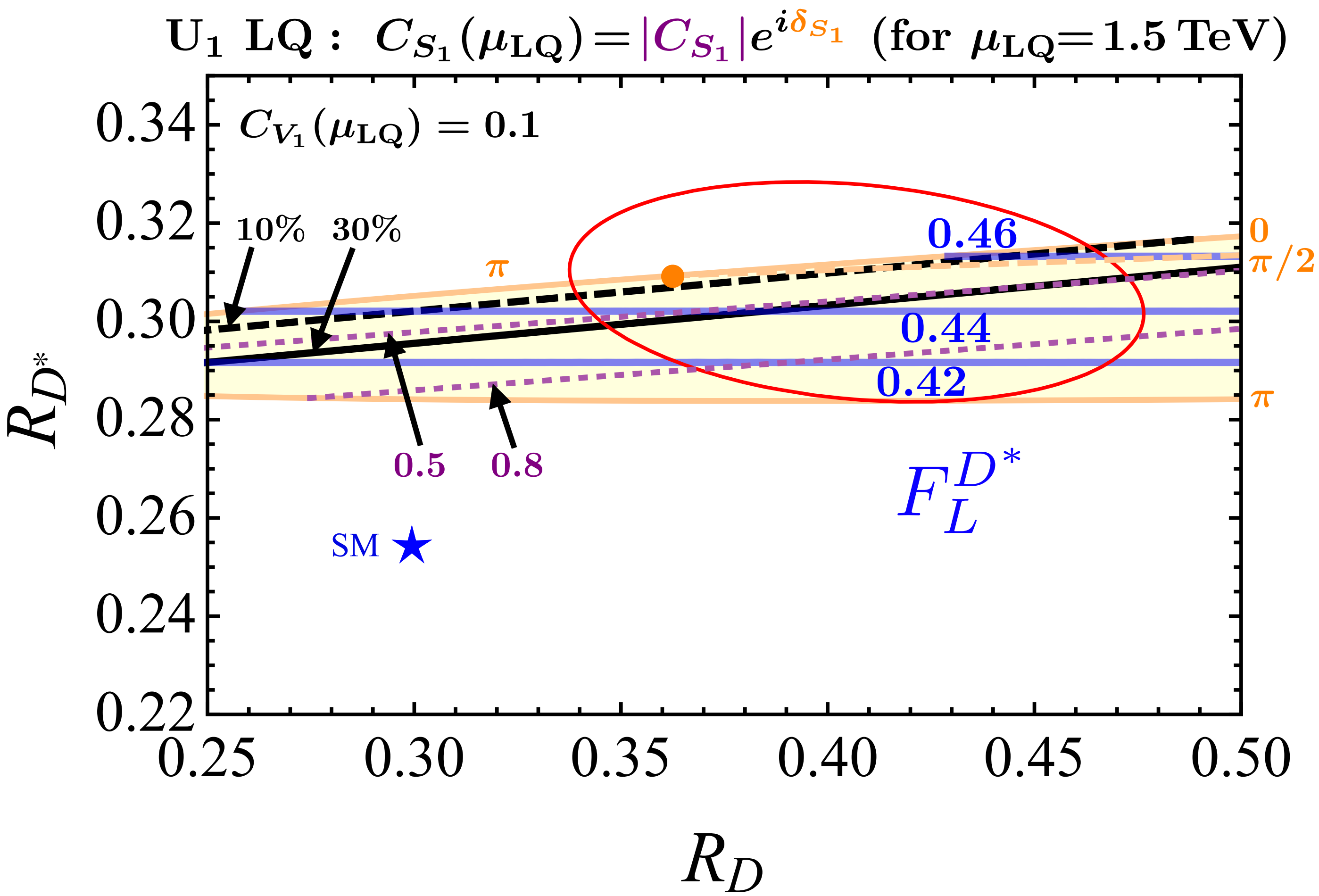
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}(D^*)} = \frac{3}{4}[2F_L^{D^*}\cos^2(\theta_{\rm hel}(D^*)) + (1 - F_L^{D^*})\sin^2(\theta_{\rm hel}(D^*))]$$

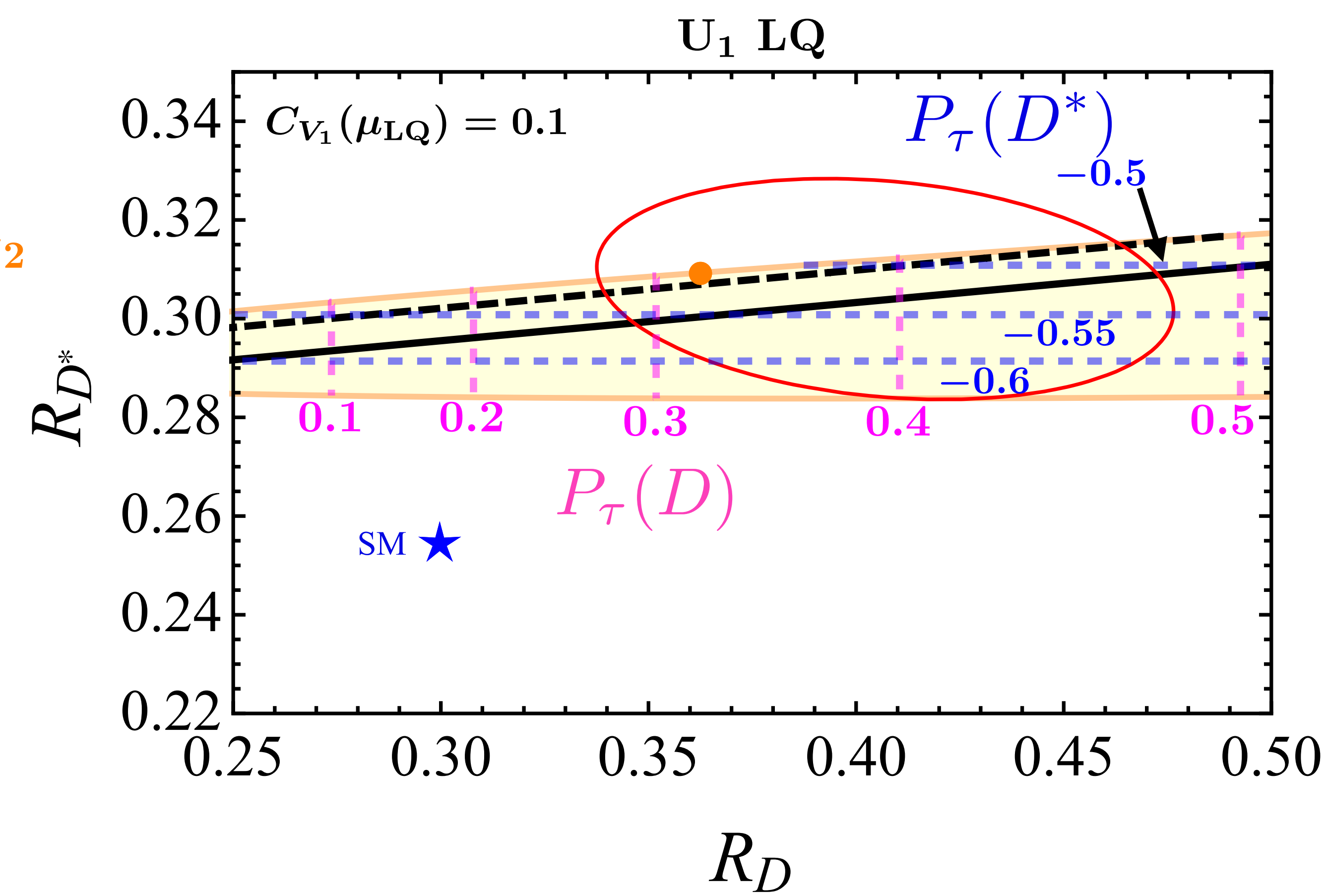
$F_L^{D^*} = 0.60 \pm 0.08(stat.) \pm 0.035(syst.)$ *by Belle*

SM: $F_L^{D^*} = 0.46 \pm 0.03$ (Phys. Rev. D **95**, 115038 (2017), A.K. Alok, et al) (1.5 σ)

Test LQ, using the flavor observables

(Iguro, Kitahara, YO, Watanabe, Yamamoto, 1811.08899)





$F_L^{D^*} = 0.60 \pm 0.08(stat.) \pm 0.035(syst.)$

$P_\tau(D^*)$ $-0.38 \pm 0.51(stat.)^{+0.21}_{-0.16}(syst.)$ by Belle

4. Summary

- Flavor physics play an important role in testing not only the SM but also new physics beyond the SM.

- Interestingly, the lepton flavor universality is deviated from the SM prediction in

  $B \to K(*)\ ll\ (\ l = e, \mu\ )$ *processes*

  $B \to D(*)\ l\nu\ (\ l = e, \mu, \tau\ )$ *processes*

- Motivated by these excesses, many new physics scenarios have been proposed. *They can be tested by many observables in flavor, LHC and DM experiments.*

  Charged Higgs is, for instance, almost killed by the LHC result.

  LQ is tested by the LHC and the flavor physics.

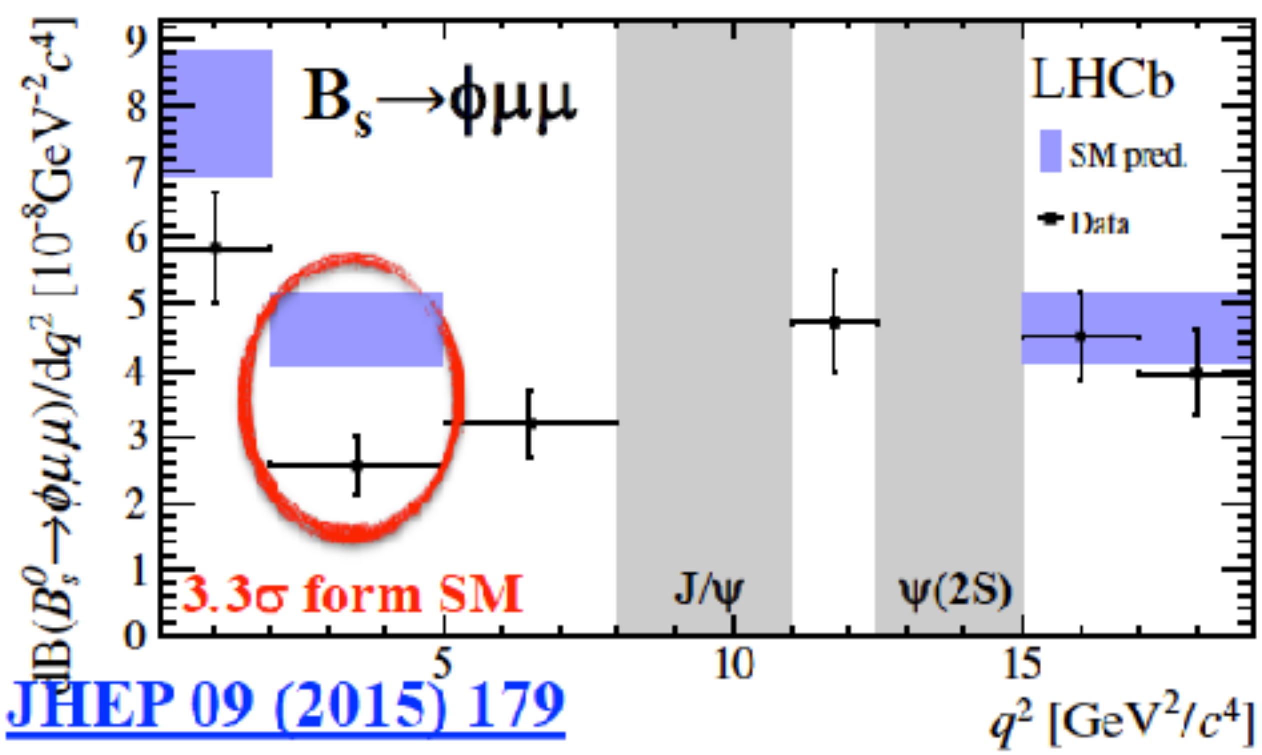
END

Backup

Other excesses caused by b→s$\mu\mu$

Branching ratio of $B_s \to \phi\mu^+\mu^-$

(1506.08777)



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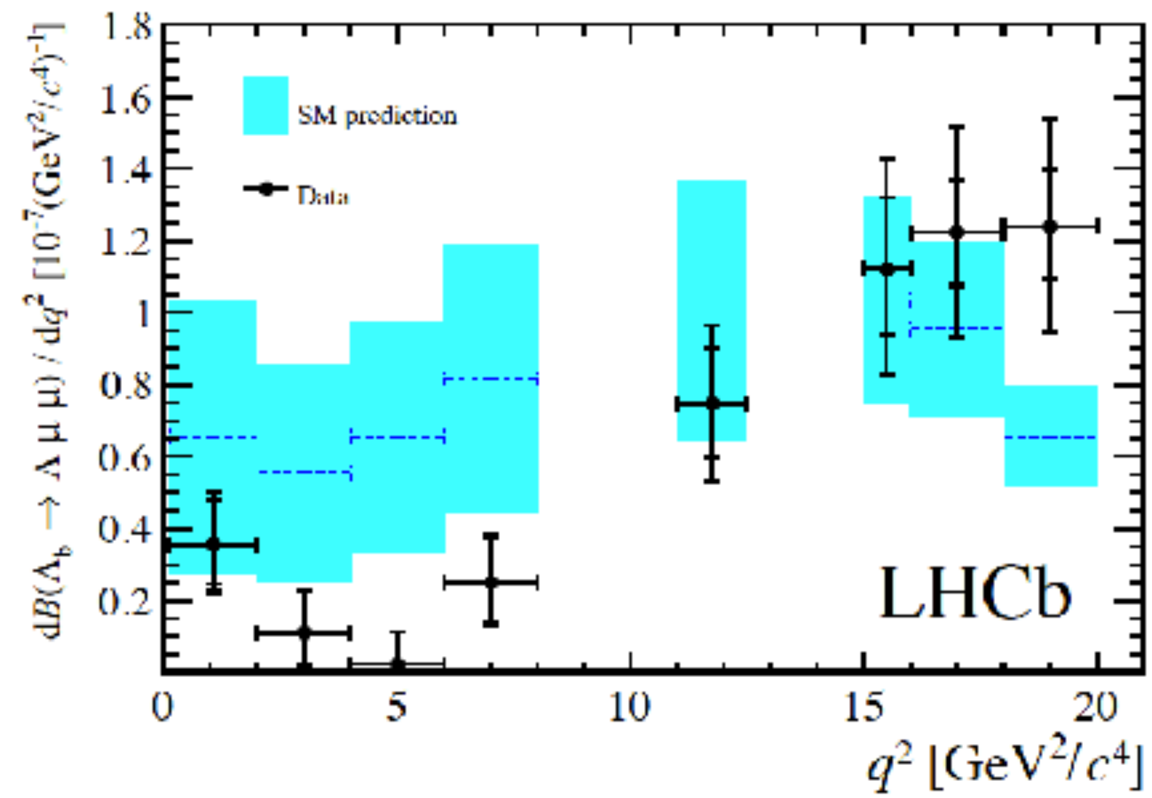
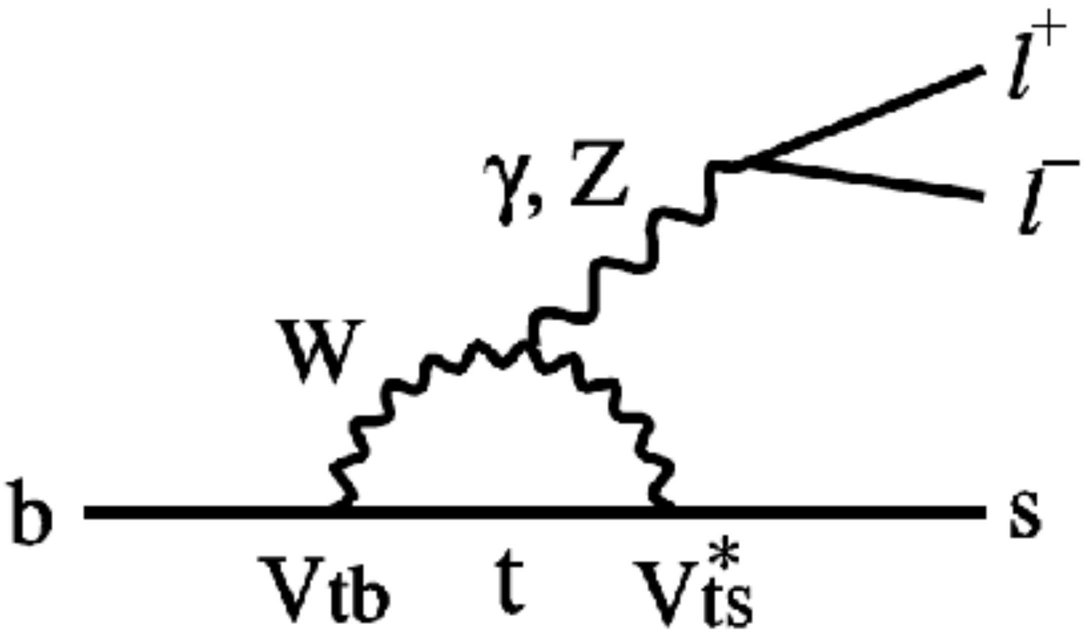
Branching ratio of $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

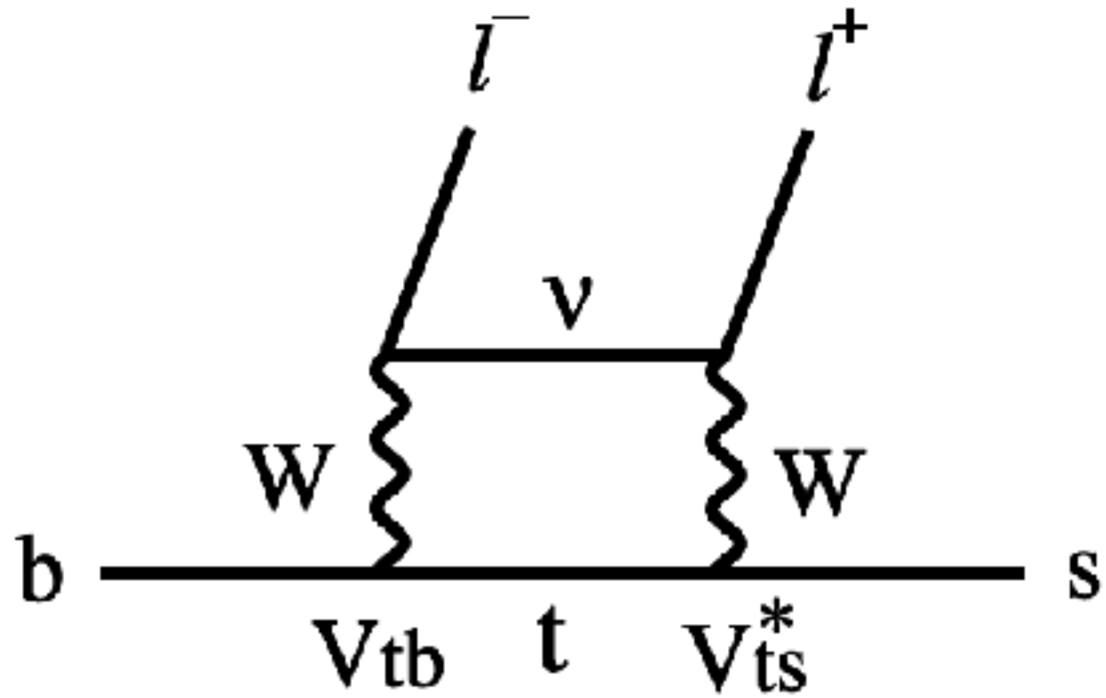
(1503.07138)



b→sμμ seems to be smaller.

In the Standard Model, the *b to s ll* is given by





effective Hamiltonian

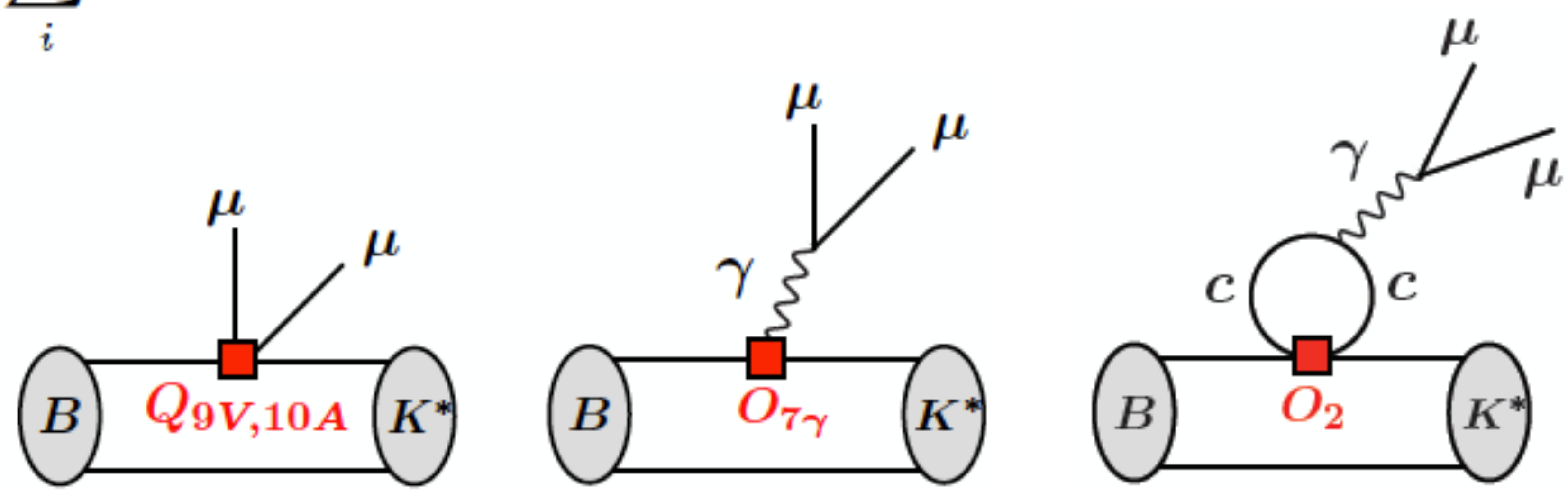
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i O_i$$

$$O_9 = \frac{e^2}{16\pi^2}(\bar{b}_L \gamma_\mu s_L)(\bar{\ell}\gamma^\mu \ell)$$

$$O_{10} = \frac{e^2}{16\pi^2}(\bar{b}_L \gamma_\mu s_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$O_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{b}_R \sigma^{\mu\nu} s_L F_{\mu\nu}$$

$$O_2 = (\bar{b}_L \gamma_\mu c_L)(c_L \gamma^\mu s_L)$$

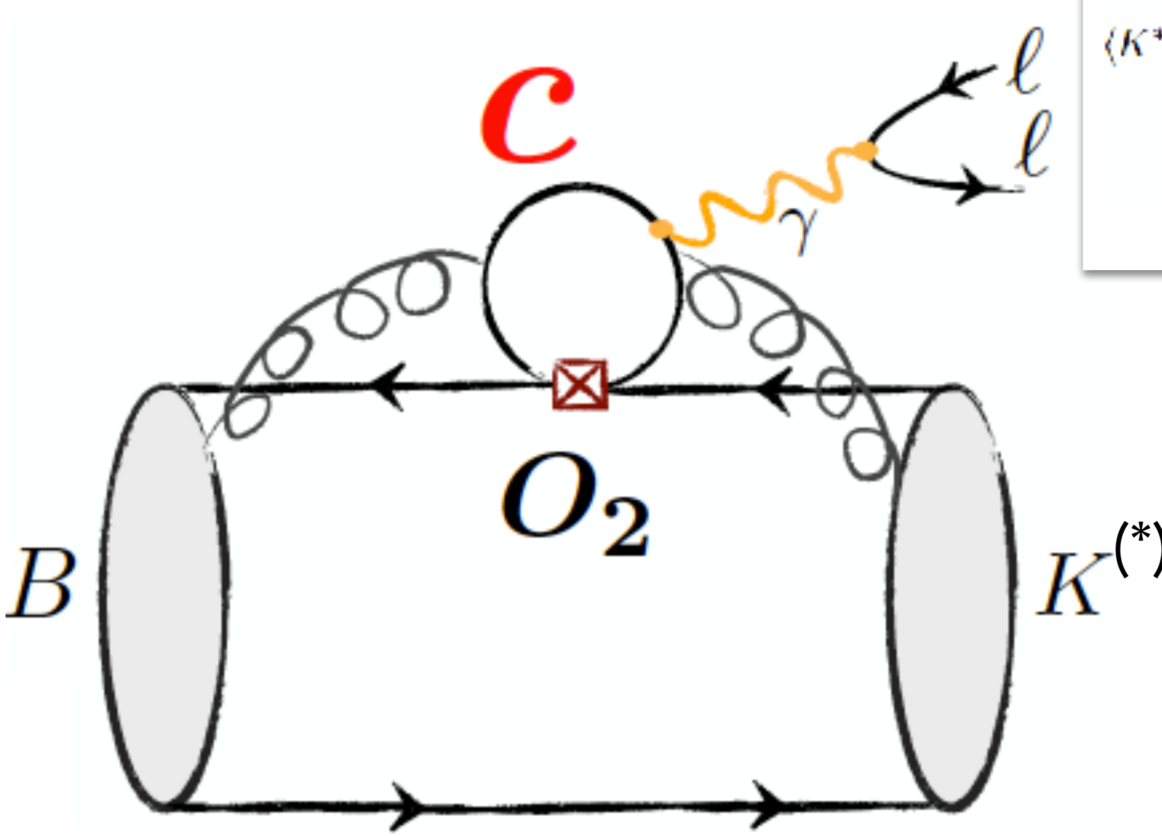


$$C_7 \sim -0.3, \; C_9 \sim 4, \; C_{10} \sim -4$$ in the SM.

Form factor in B→K(*)ll can be estimated in heavy quark and large E limit.

(hep-ph/9812358;1503.05534)

The 4-quark operator largely contributes via one-loop $\sim \mathcal{O}(10)\%$



$$\langle \bar{K}^*(k,\lambda)|\bar{s}\gamma_\mu b|\bar{B}(p)\rangle = \epsilon_{\mu\nu\rho\sigma}\epsilon_\lambda^{*\nu} p^\rho k^\sigma \frac{2}{m_B + m_{K^*}} V(q^2)\,,$$

$$\langle \bar{K}^*(k,\lambda)|\bar{s}\gamma_\mu\gamma_5 b|\bar{B}(p)\rangle = i(\epsilon_\lambda^* \cdot q)\frac{2m_{K^*}q_\mu}{q^2} A_0(q^2) + i(m_B + m_{K^*})\left(\epsilon^*_{\lambda,\mu} - \frac{(\epsilon^*_\lambda \cdot q)q_\mu}{q^2}\right) A_1(q^2)$$
$$- i(\epsilon_\lambda^* \cdot q)\left[\frac{(2p-q)_\mu}{m_B + m_{K^*}} - (m_B - m_{K^*})\frac{q_\mu}{q^2}\right] A_2(q^2)\,,$$

(Khodjamirian,et.al.,1006.4945)

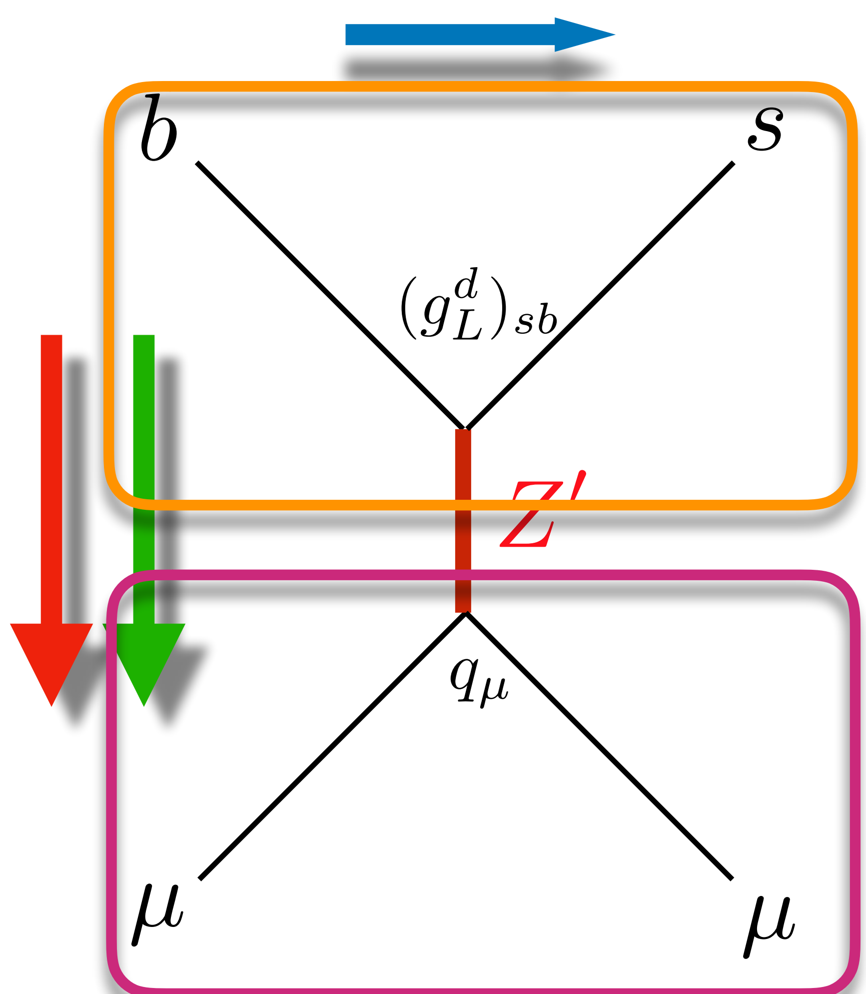
- But excesses are reported in flavor universalities of B→K(*)ll, that is not relevant to the ambiguity.

- Angular analysis would be relevant to the contribution.

Relation with the other processes

our interest

B→K(*)μμ



constrained by
Bs-$\overline{\text{B}}$s mixing

$B_s \to \mu\mu$

$pp \to Z' \to \mu\mu$

@LHC

constrained by

$\nu N \to \nu N \mu\mu^+$

B →D(*)lν processes

$$\mathcal{H}_{\text{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} \boxed{J_{bc,\mu}} \sum_{\ell=e,\mu,\tau} (\bar{\ell}\gamma^\mu P_L \nu_\ell) + \text{h.c.}$$

$$J_{bc}^{\mu} = \boxed{\bar{c}\gamma^\mu P_L b} + \boxed{g_{SL} i\partial^\mu (\bar{c}P_L b) + g_{SR} i\partial^\mu (\bar{c}P_R b)}$$

SM

leptoquark

charged Higgs appears

(Fajfer, et al., 1203.2654; Sakaki,Tanaka,1205.4908;Crivellin,et al., 1206.2634)

B →D*τν

$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |\mathbf{p}| q^2}{96\pi^3 m_B^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[(|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2) \left(1 + \frac{m_\tau^2}{2q^2}\right) + \boxed{\frac{3}{2}\frac{m_\tau^2}{q^2} |H_{0t}|^2} \right]$$

B →Dτν

$$H_{0t} = H_{0t}^{\text{SM}} \left[1 + (g_{SR} - g_{SL}) \frac{q^2}{m_b + m_c} \right]$$

$$\frac{d\Gamma(\bar{B} \to D l^- \bar{\nu})}{dq^2} = \frac{G_F^2 |V_{cb}|^2}{192\pi^3 m_B^3} \left(1 - \frac{m_l^2}{q^2}\right)^2 \sqrt{\lambda_D}$$

$$\times \left[\lambda_D \left(1 + \frac{m_l^2}{2q^2}\right)^2 f_+(q^2) + \frac{3m_l^2}{2q^2} (m_B^2 - m_D^2)^2 f_0^2(q^2) \left(1 + \boxed{\delta_{H^+}^{Dl}(q^2)}\right) \right]$$

where $\lambda_D = (m_B^2 - m_D^2 - q^2)^2 - 4m_D^2 q^2$.

(Iguro,Tobe,1708.06176)

Bc decay also limit the charged scalar scenario strongly.

(Alonso,Grinstein,et al., 1611.06676;Akeroyd,Chen,1708.04072)