B anomaly hunting at the LHC: tau *b* + missing search for leptoquarks

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with
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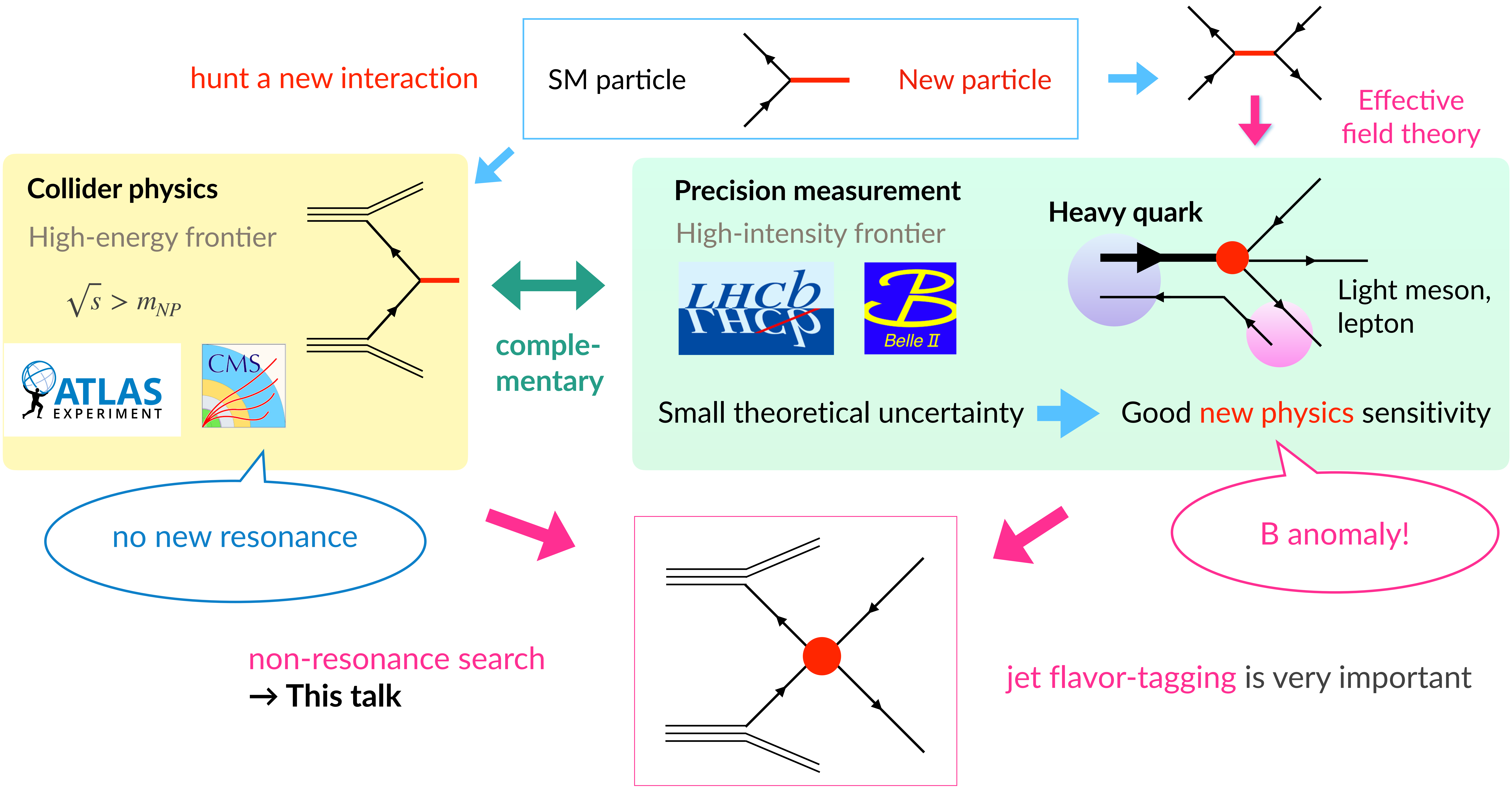
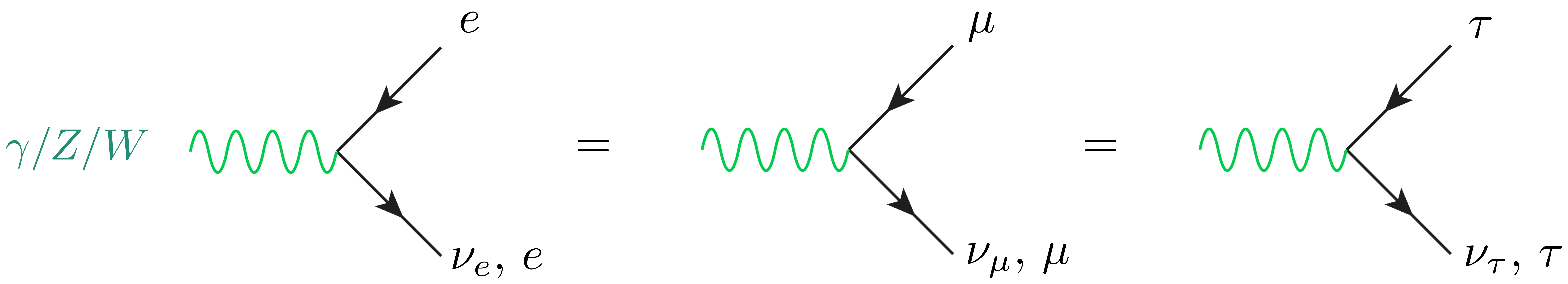

hunt a new interaction
SM particle
New particle
Effective field theory
Collider physics
High-energy frontier
$\sqrt{s} > m_{NP}$
ATLAS EXPERIMENT
CMS
comple-mentary
Precision measurement
High-intensity frontier
LHCb
Belle II
Heavy quark
Light meson, lepton
Small theoretical uncertainty
Good new physics sensitivity
no new resonance
B anomaly!
non-resonance search
→ This talk
jet flavor-tagging is very important

Test of Lepton Flavor Universality (LFU)

- Gauge symmetry predicts lepton flavor universal (LFU) phenomena:

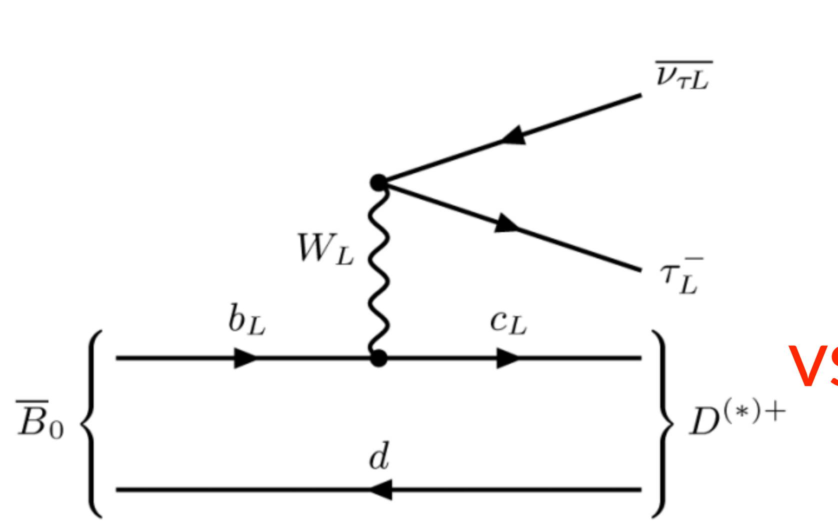


- Only **charged-lepton mass** violates the LFU within the SM

$$m_e = 0.5\,\text{MeV}\,, \qquad m_\mu = 105\,\text{MeV}\,, \qquad m_\tau = 1776\,\text{MeV}$$

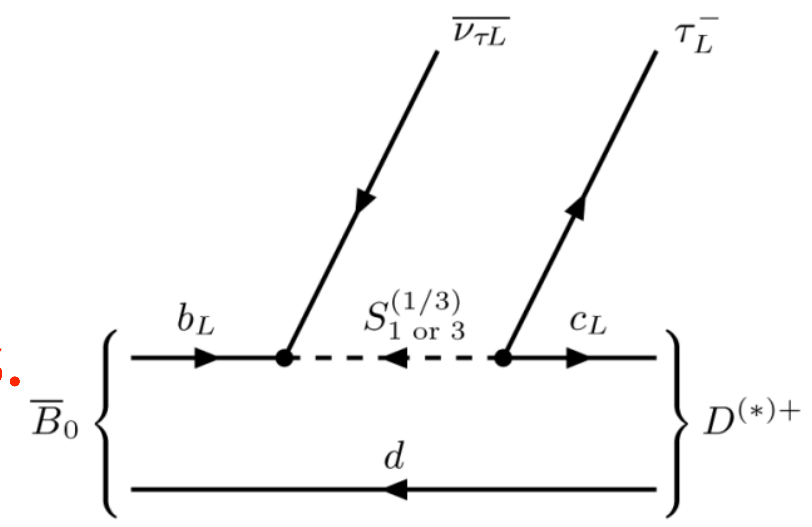
LFU observables $R(D)$ and $R(D^*)$

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\bar{\tau}\nu_\tau)}{\mathrm{BR}(B \to D^{(*)}\bar{\ell}\nu_\ell)} \quad (\ell = e, \mu)$$



SM

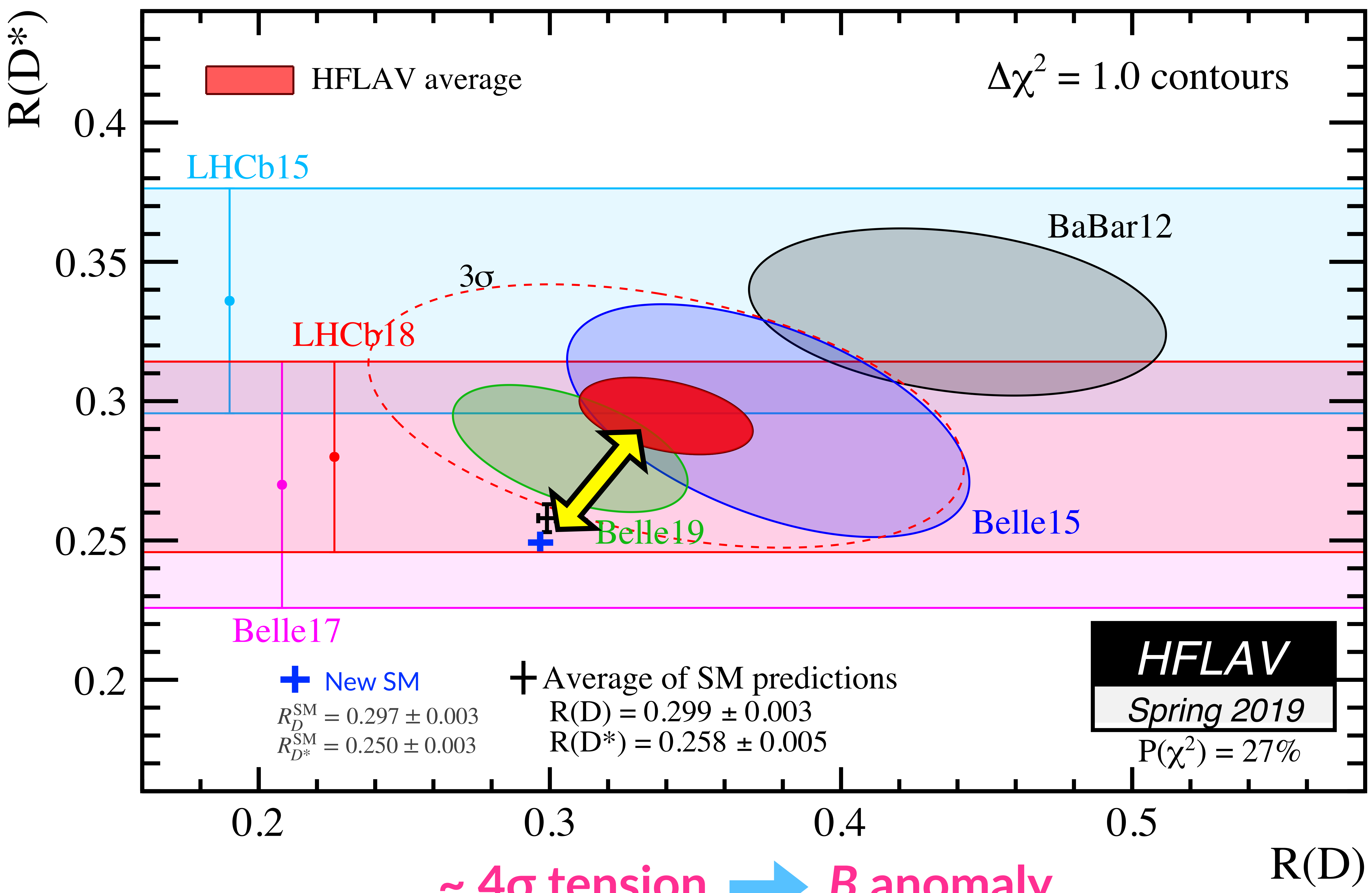
vs.



New physics, *e.g.*, Leptoquark

cf. $\mathcal{B}(B \to D\ell\nu) = 2\%,\ \mathcal{B}(B \to D^*\ell\nu) = 5\%,$

[HFLAV 2019, New SM= Iguro, Watanabe, 2004.10208]

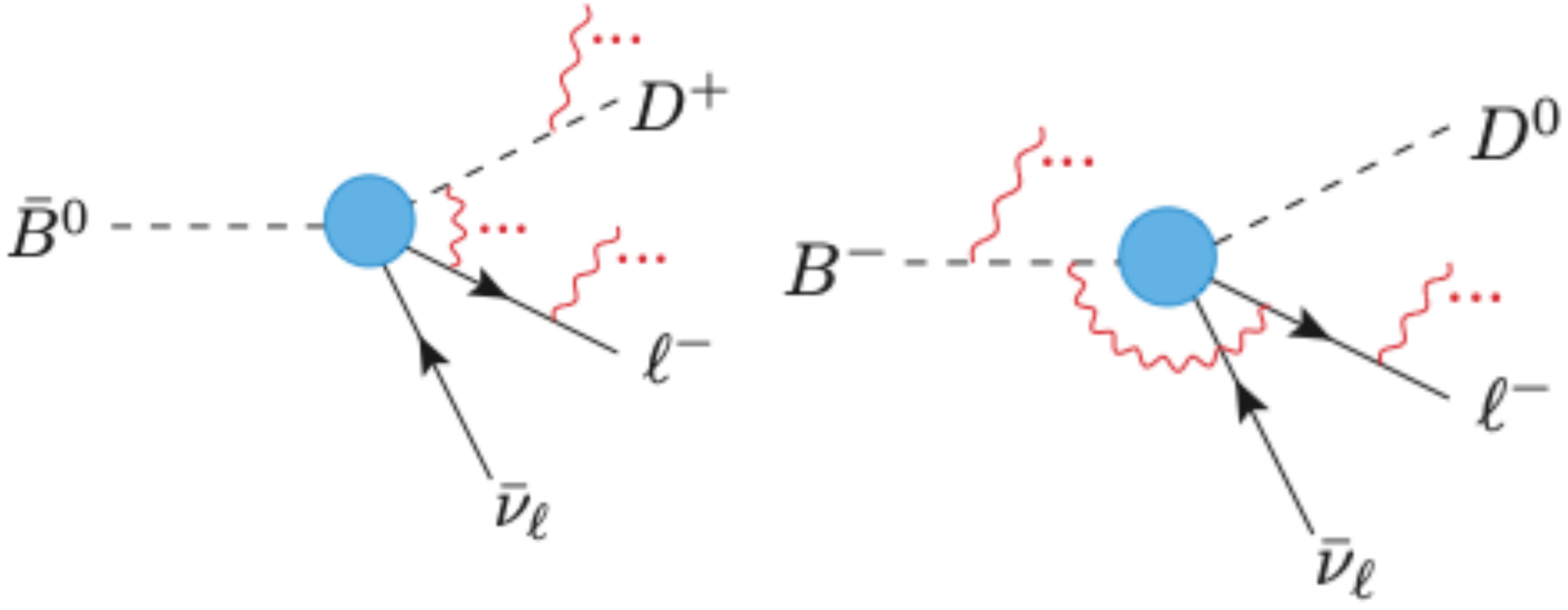


~ 4σ tension → *B* anomaly

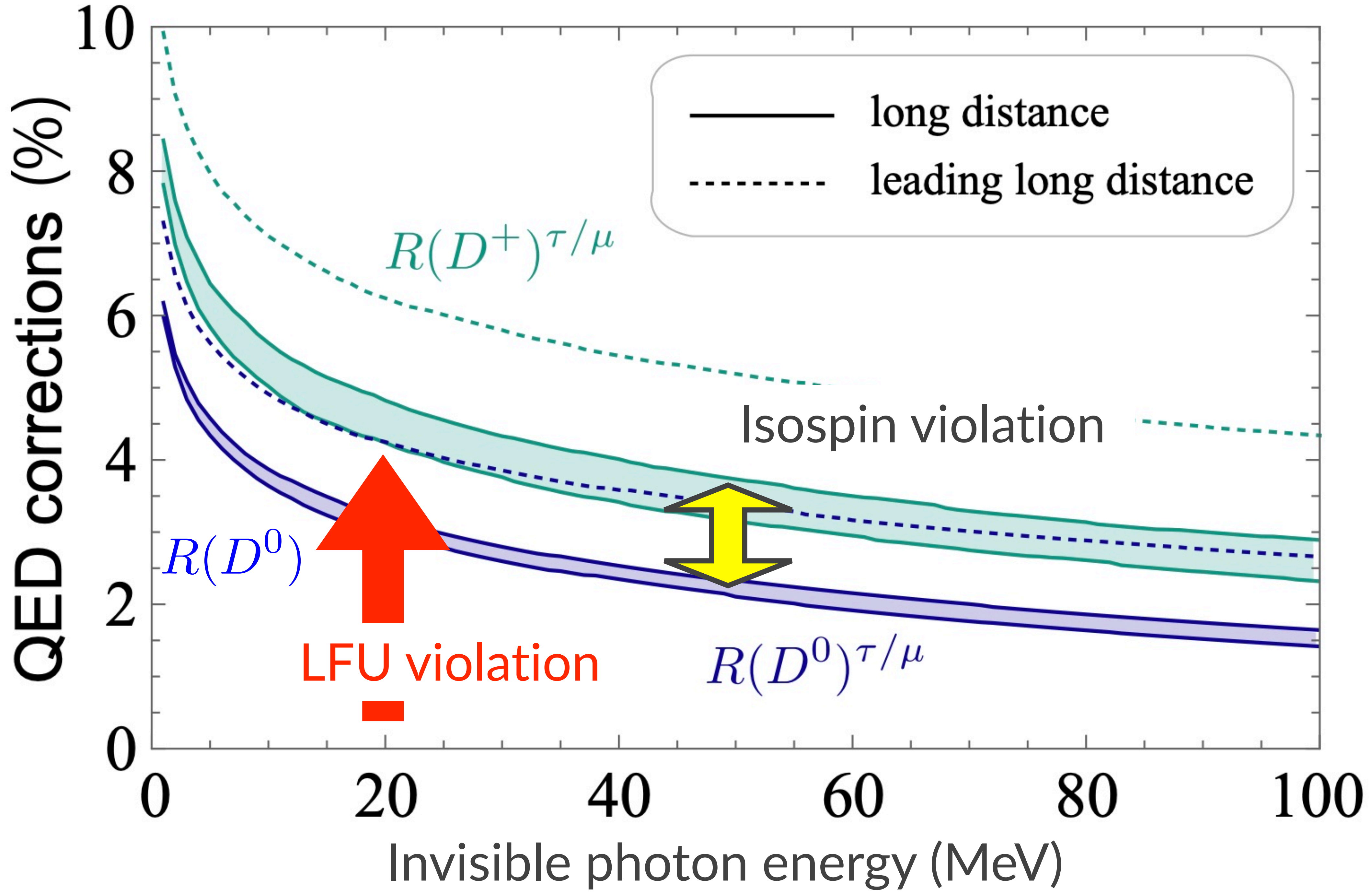
Comment on QED correction within the SM

- Long-distance QED correction could violate the lepton flavor universality

  [de Boer, **TK**, Nisandzic, 1803.05881] + [Calí, Klaver, Rotondo, Sciascia, 1905.02702; Isidori, Nabeebaccus, Zwicky, 2009.00929]



It is found that the QED corrections depend on the lepton velocity (=the lepton masses) with opposite sign (light lepton vs heavy lepton)



[de Boer, **TK**, Nisandzic, 1803.05881]

General operator basis

- General NP for $R(D^{(*)})$ anomaly can be model-independently described by

SM ↓

$$\mathcal{H}_{\rm eff} = 2\sqrt{2} G_F V_{cb} \Big[(1 + C_{V_1}) (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) + C_{V_2} (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu_\tau)$$
$$+ C_{S_1} (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau) + C_{S_2} (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau)$$
$$+ C_T (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau) \Big] + \text{h.c.}\,,$$

- C_{V_2} appears dimension-eight at the SMEFT, while others are dimension-six

- Light right-handed neutrinos ($m_{\nu_R} < m_B$) can also be included, but are constrained from the collider bounds

Single new-particle interpretations

- **W' :** C_{V_1}
    - **Severely constrained** from ΔM_s, $Z' \to \tau\tau$ search [Faroughy, Greljo, Kamenik, 1609.07138], and $W' \to \tau\nu$ search [Abdullah, Calle, Dutta, Flores, Restrepo, 1805.01869]
- **Charged Higgs with generic flavor structure :** C_{S_1} , C_{S_2}
    - **Severely constrained** from $B_c \to \tau\nu$ and $H^\pm \to \tau\nu$ search [Iguro, Tobe, 1708.06176; Iguro, 2201.06565]
- **Leptoquark :** C_{V_1} , C_{V_2} , C_{S_1} , C_{S_2} , C_T
    - Collider bound comes from $gg \to$ LQ LQ*, and broad parameter regions are still allowed

→ We will focus on heavy LQ scenarios, then there is no direct bound from LHC

Leptoquark catalogue

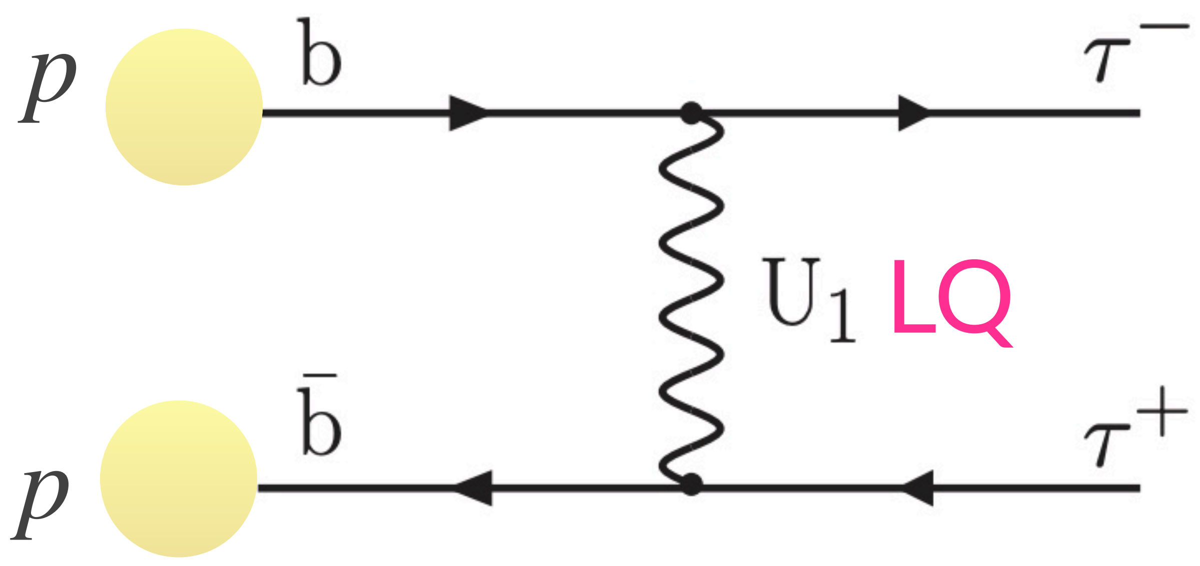
[*cf.* Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, 2103.12504; Athron, Balazs , Jacob , Kotlarski, Stockinger , Stockinger-Kim, 2104.03691]

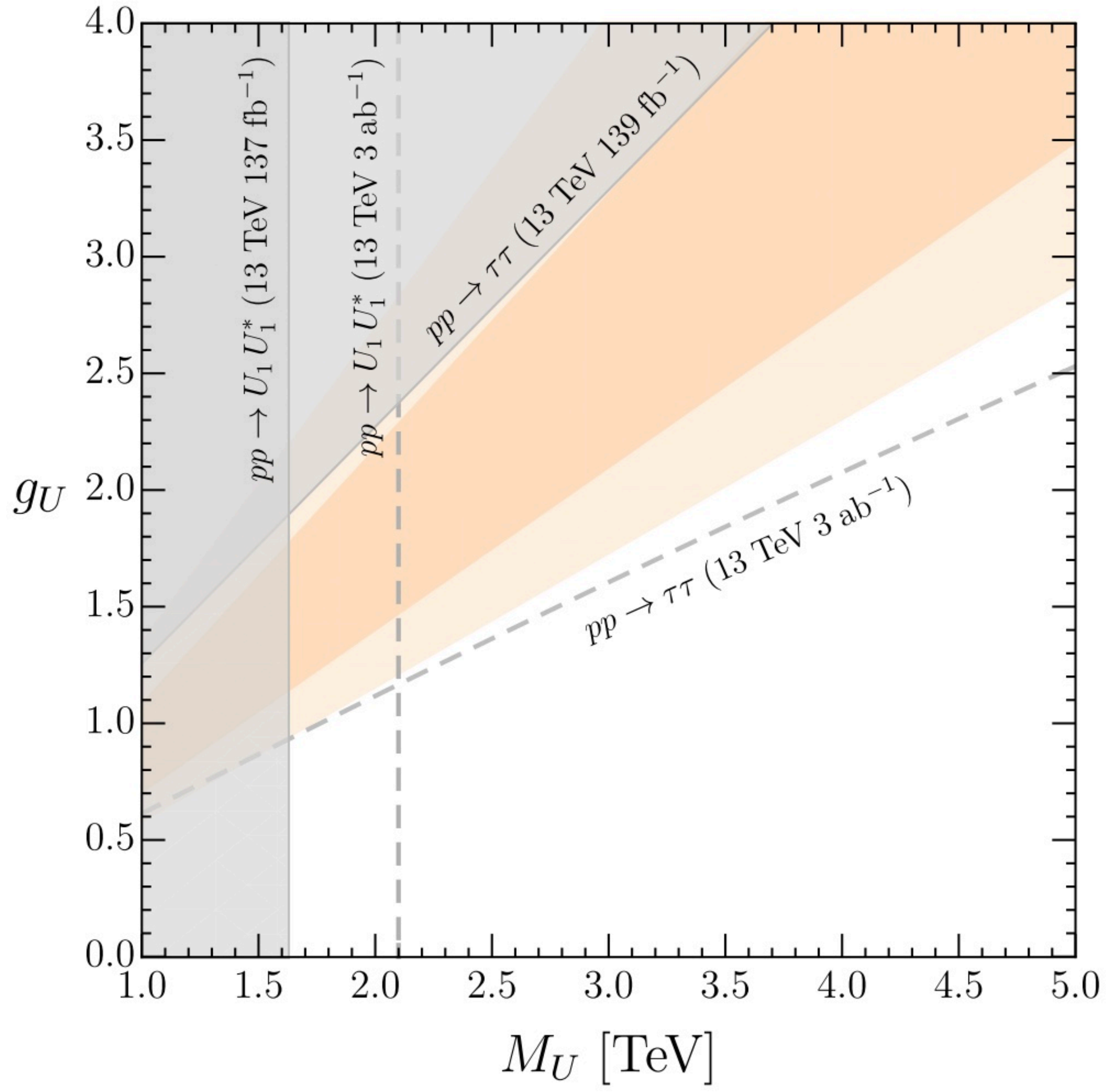
- Leptoquarks that do not lead to proton decay and can contribute precision measurements

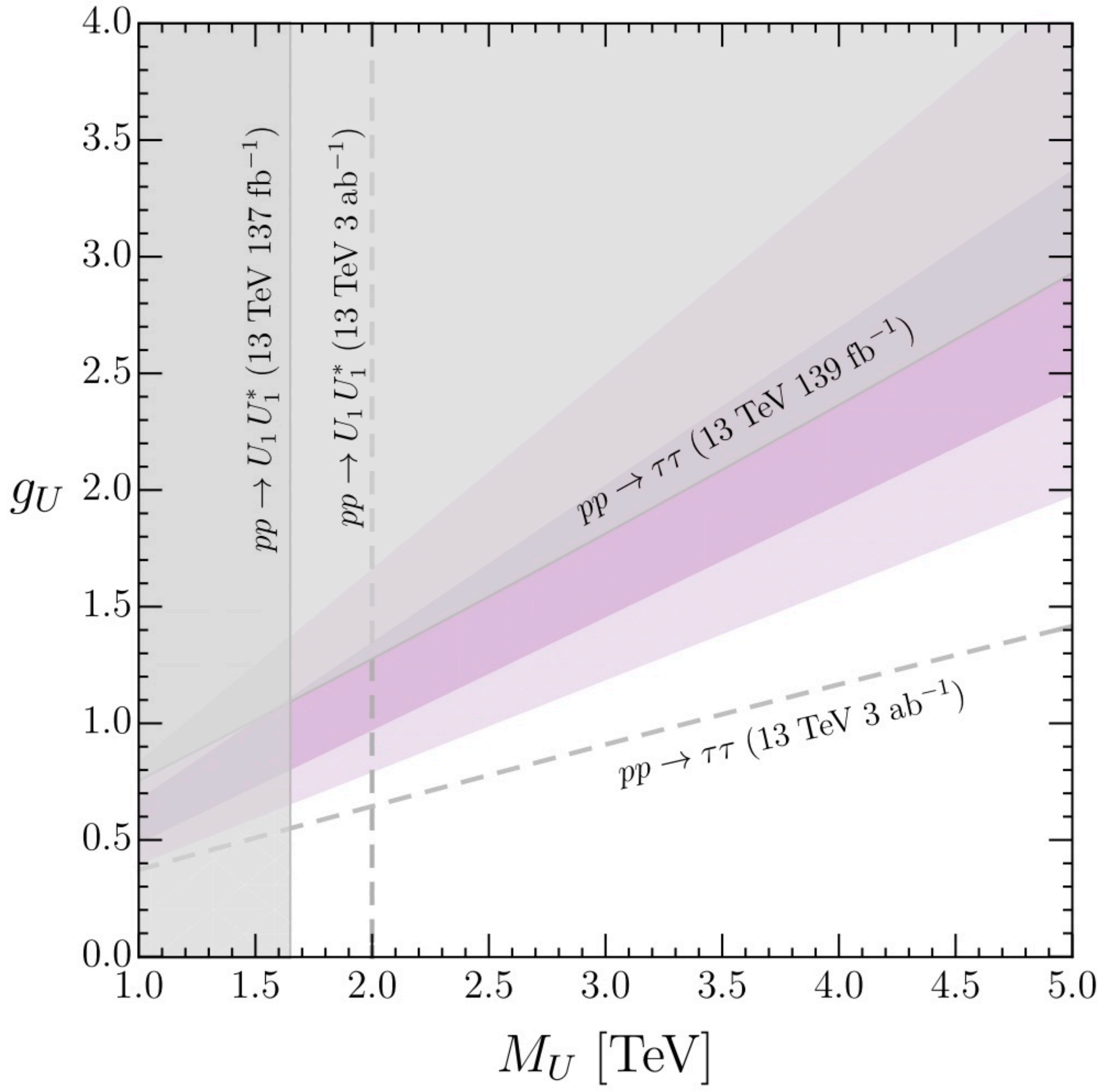
Label	Spin	Charge	$R(D^{(*)})$	$R(K^{(*)})$	muon g-2	M_W
S_1 LQ	0	$(\bar{3}, 1, 1/3)$	✓	Loop	✓	With S_3
U_1 LQ	1	$(3, 1, 2/3)$	✓	✓	✗	✗
R_2 LQ	0	$(3, 2, 7/6\ [1/6])$	✓	Loop	✓	Small
V_2 LQ	1	$(\bar{3}, 2, 5/6)$	Small	Electron	Small	✓
S_3 LQ	0	$(\bar{3}, 3, 1/3)$	✗	✓	✗	With S_1
U_3 LQ	1	$(3, 3, 2/3)$	✗	✓	✗	?

← different model points →

Thanks Hirose-san

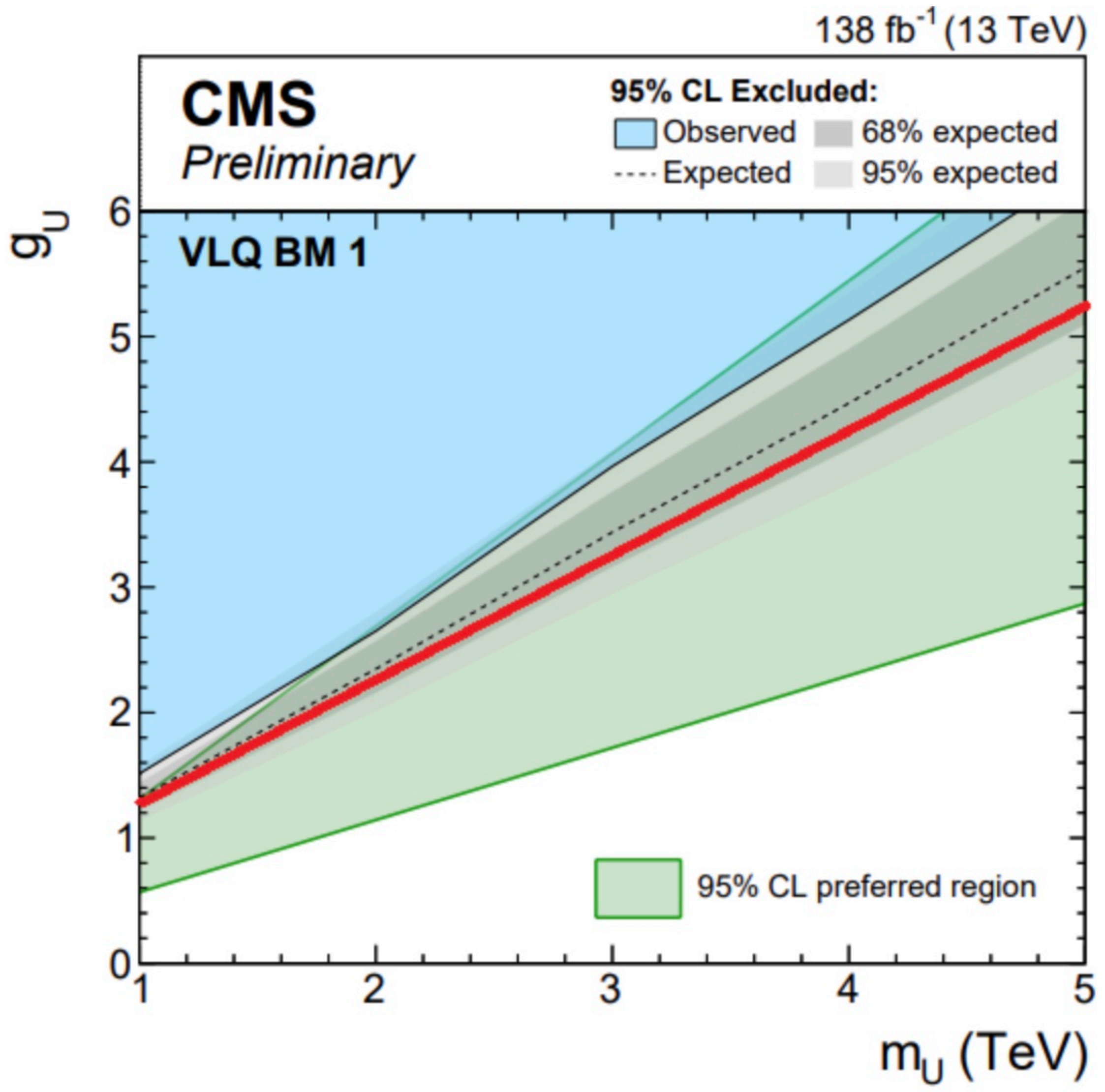


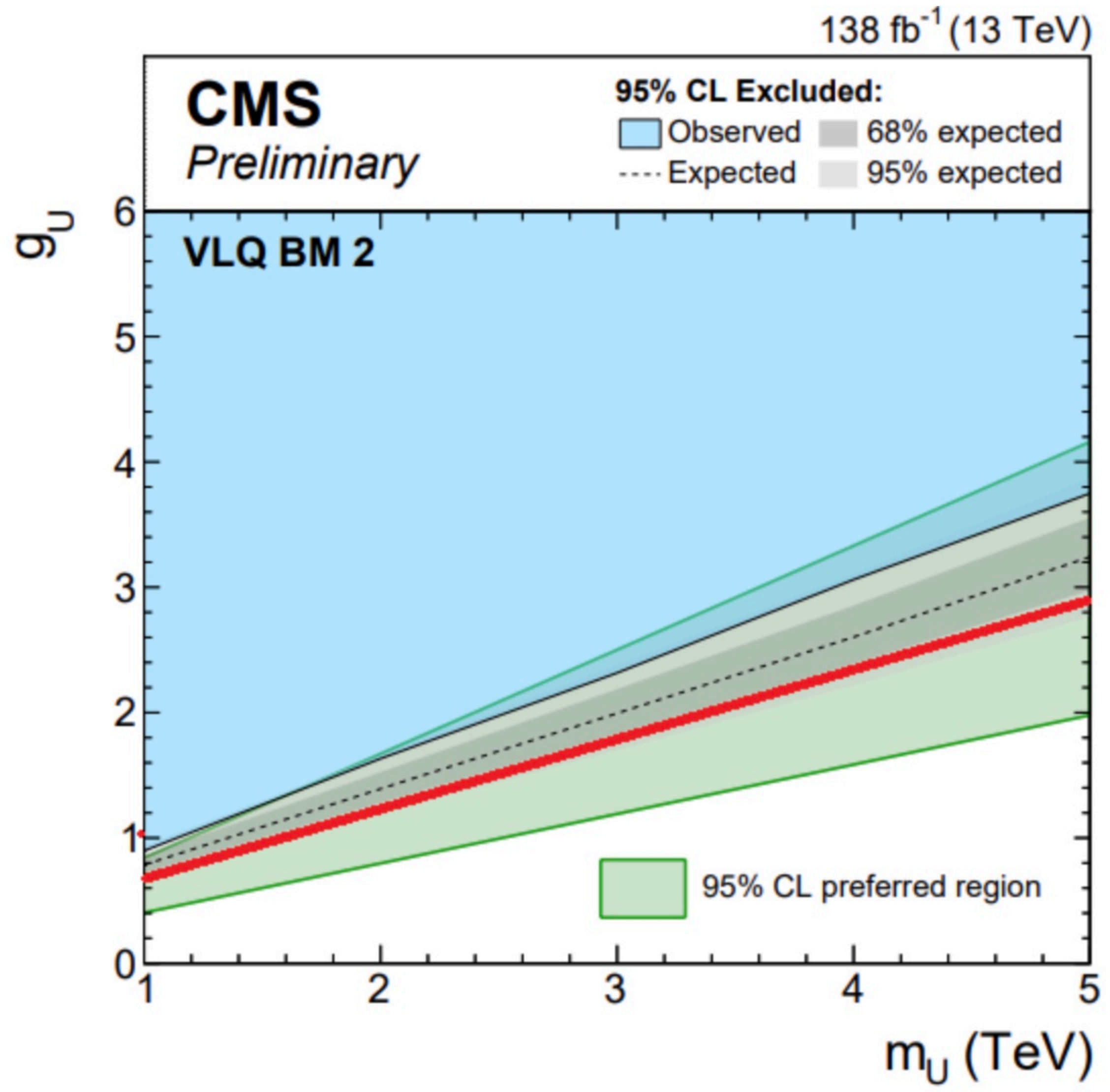




Recast the ATLAS data of $\tau^+\tau^-$ resonant search

[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558; ATLAS, 2002.12223]





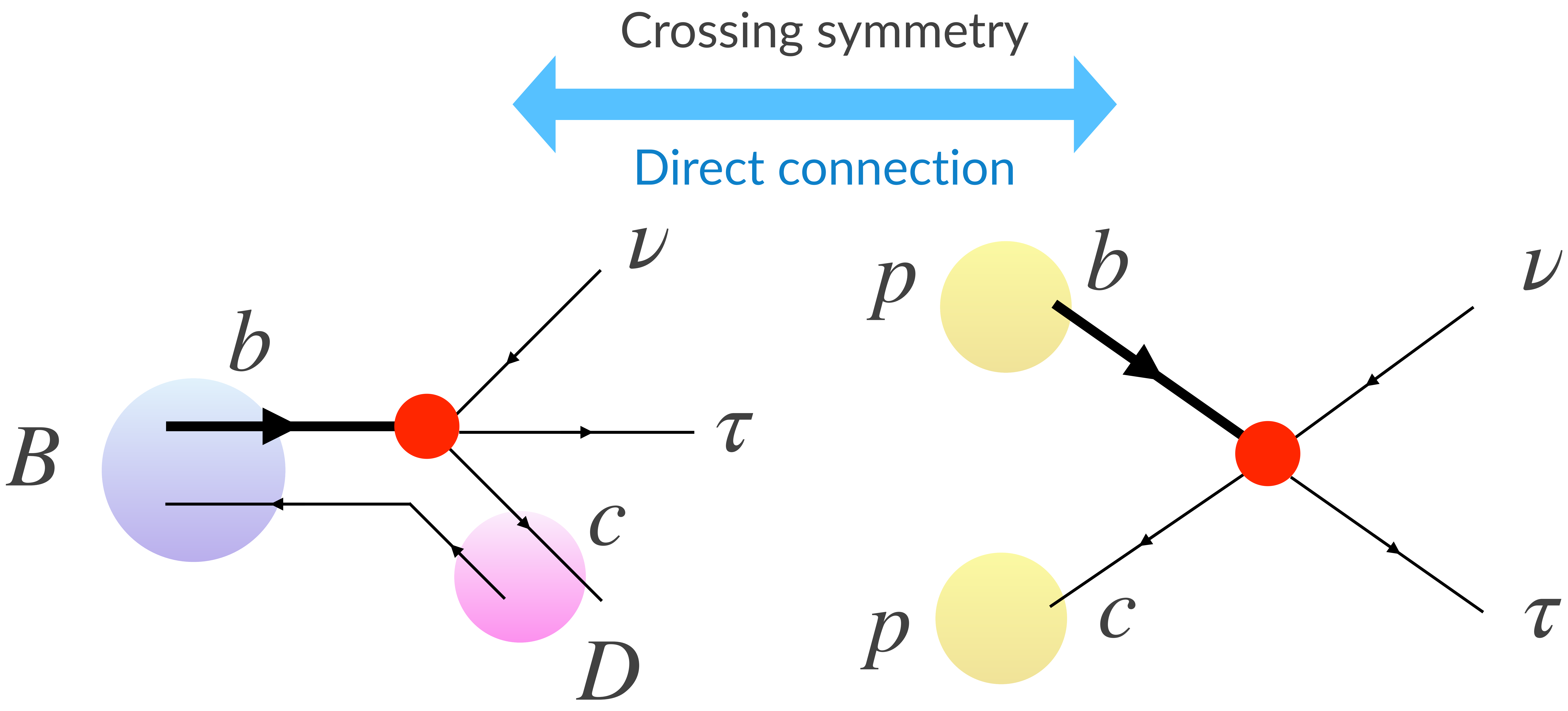
The CMS data of $\tau^+\tau^-$ non-resonant search

[CMS, CMS PAS HIG-21-001]

ATLAS

B anomaly

Unfortunately, the LHC sensitivity depends on the flavor structure of the leptoquark, significantly



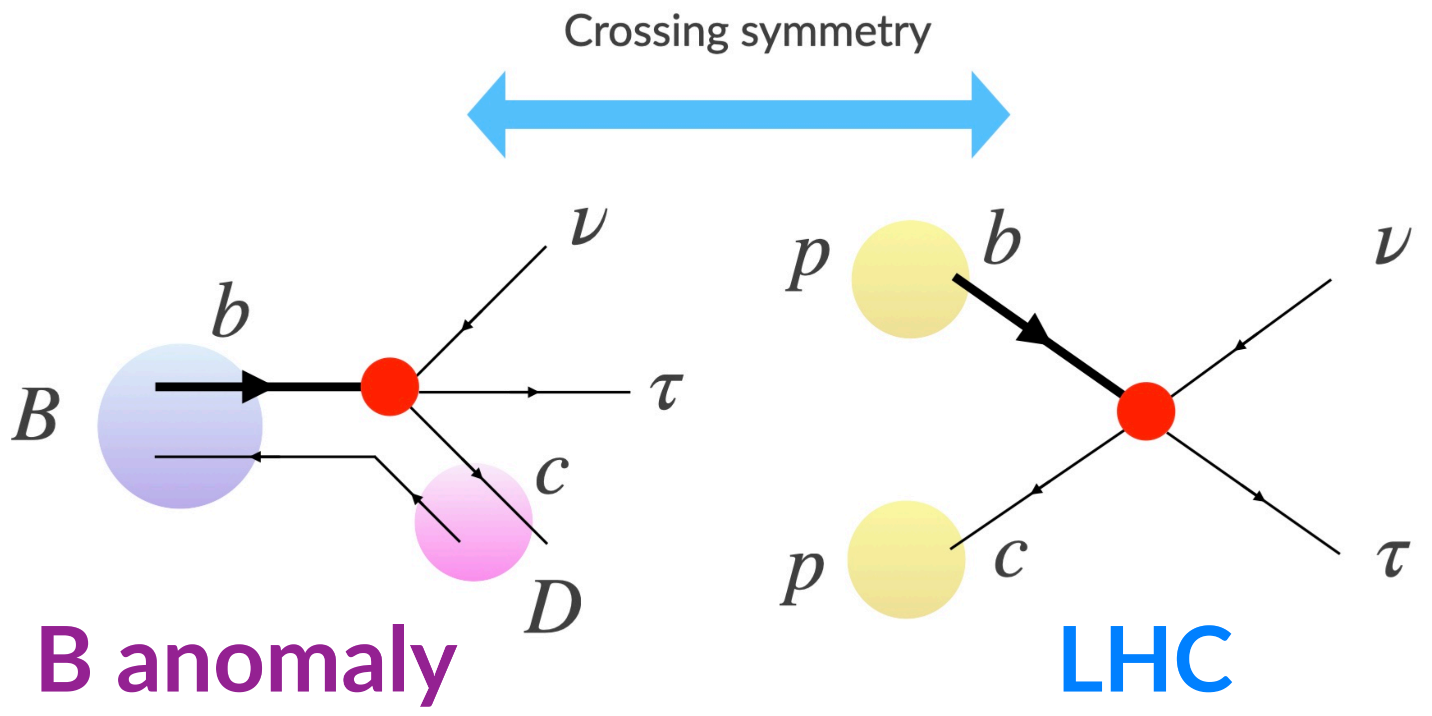
B anomaly

LHC event

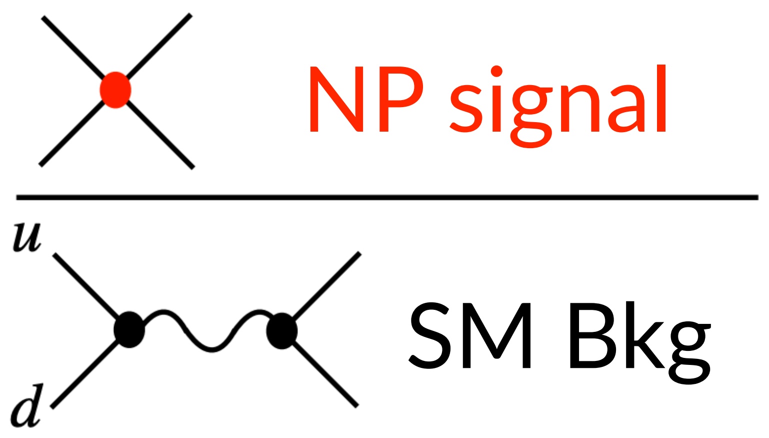
Collider search for $pp \to \tau\nu$

- The direct collider bound comes from high-p_T tails in mono-τ searches

  [Greljo, Camalich, Ruiz-Alvarez, 1811.07920; Marzocca, Min, Son, 2008.07541; Iguro, Takeuchi, Watanabe, 2011.02486]



$$\frac{\Delta\sigma}{\sigma} \sim \frac{L_{c\bar b + b\bar c} \times |V_{cb}|^2 \times \left(\frac{m_W^2}{\hat s} - C_{V_1}\right)^2}{L_{u\bar d + d\bar u} \times |V_{ud}|^2 \times \left(\frac{m_W^2}{\hat s}\right)^2} =$$



$$\propto \hat s^2 \times C_{V_1}^2$$

LQ signal over Bkg is amplified at large $\hat s$: hard τ with large missing transverse energy (= ν_τ)

[Greljo, Camalich, Ruiz-Alvarez, 1811.07920]

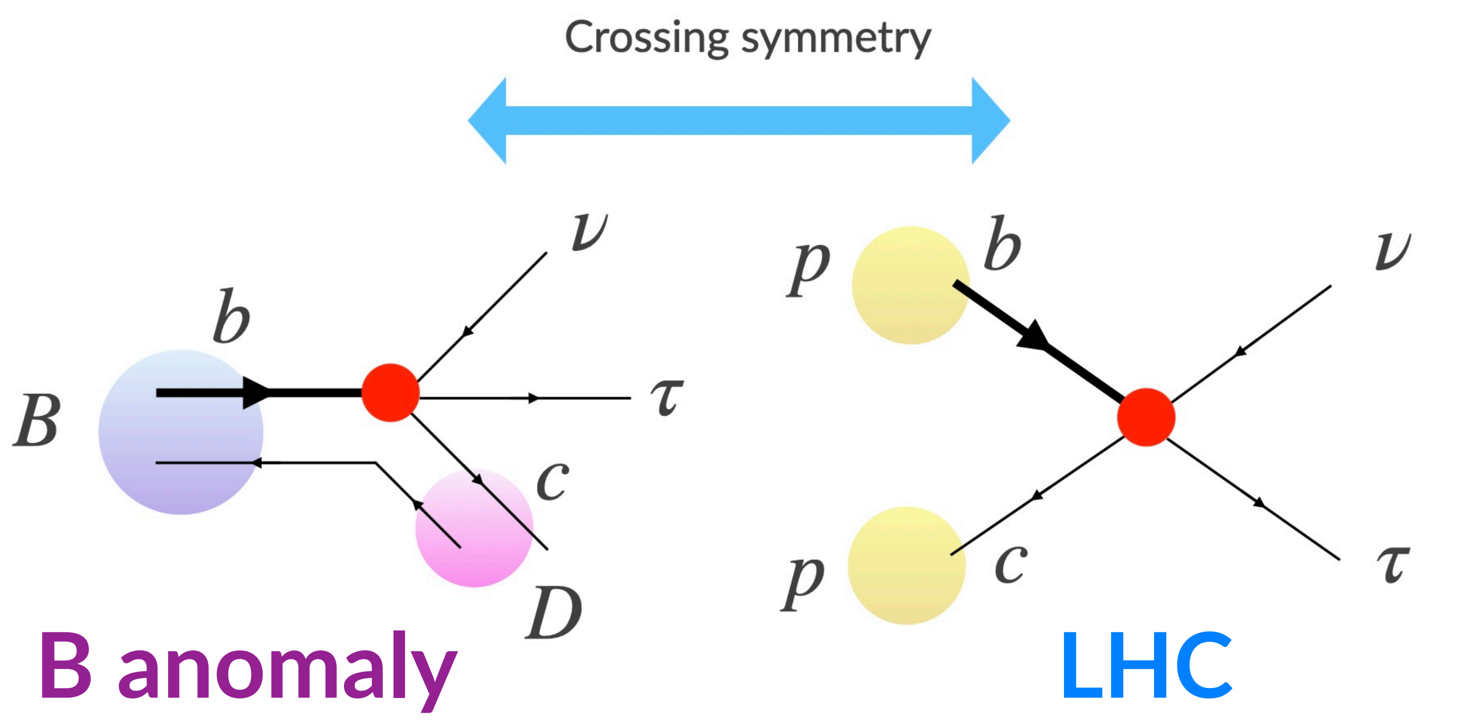
2σ upper bound from data (36fb^{-1})

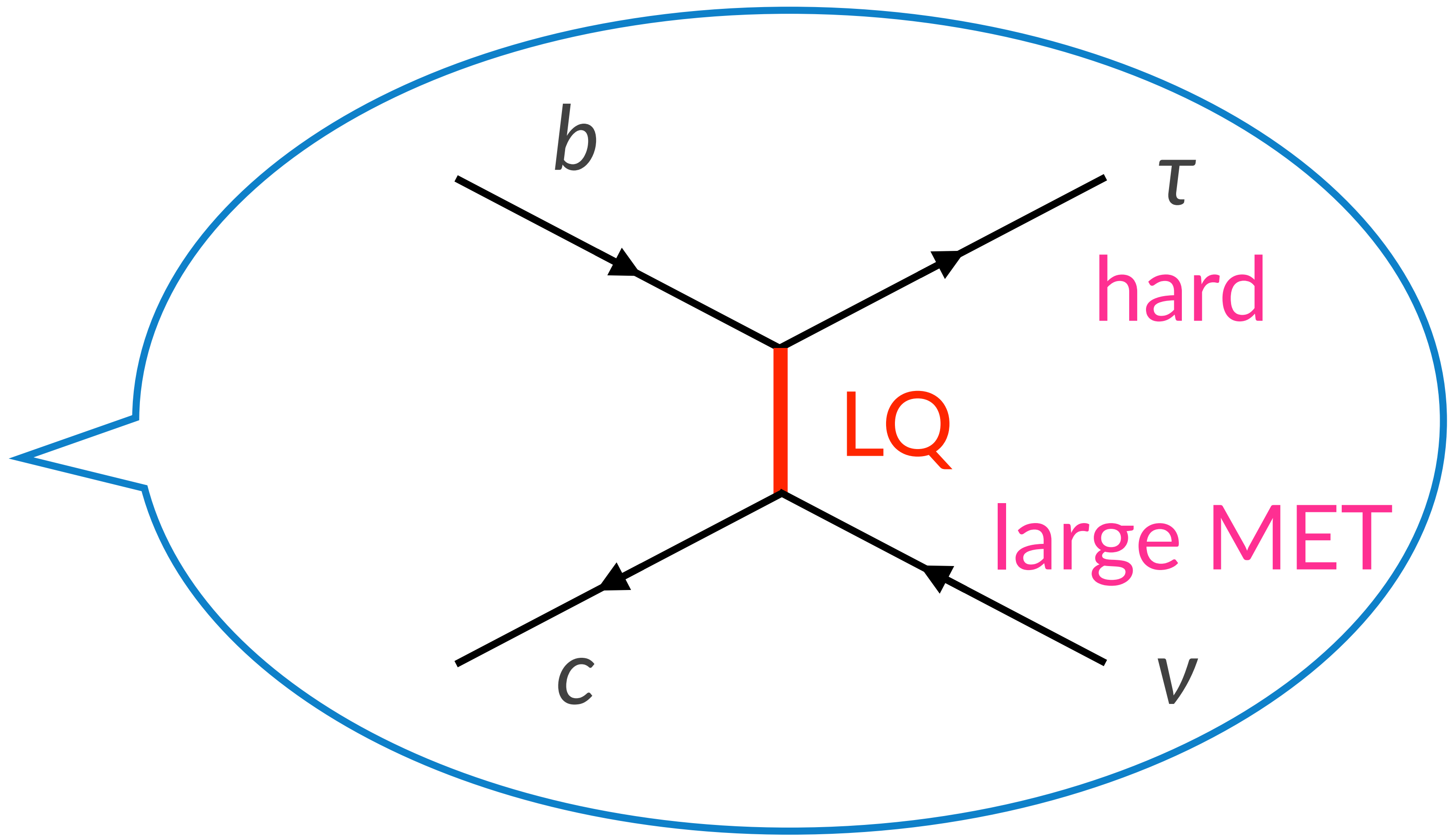
$$|C_{V_{1/2}}| < 0.32, \quad |C_{S_{1/2}}| < 0.57, \quad |C_T| < 0.16$$

Assuming EFT limit, namely $M_{\rm LQ} \to \infty$

Leptoquark mass dependence

- We investigate LQ mass effects, which relax the collider bound [Iguro, Takeuchi, Watanabe, 2011.02486]





$$\propto \frac{1}{t - M_{\mathrm{LQ}}^2}$$

with $t < 0$

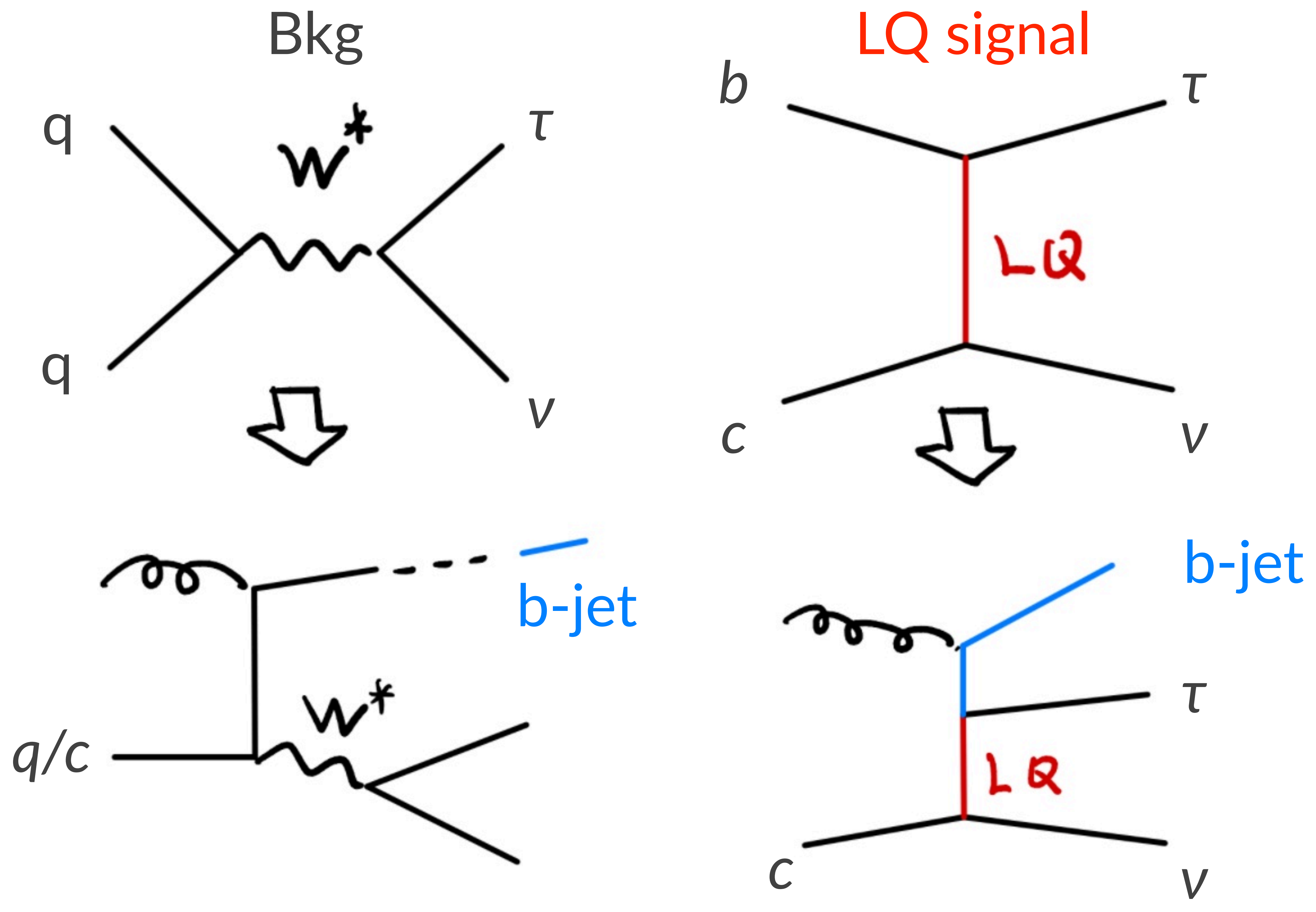
To amplify the LQ signal over Bkg ratio, $t \sim -\mathcal{O}(1)\mathrm{TeV}^2$ is expected.
Now, the LQ mass receives additional effective mass via the large negative t

$$\mathcal{M}_{\mathrm{LQ}} \approx \frac{g_{\mathrm{LQ}}^2}{\left|t - M_{\mathrm{LQ}}^2\right|} < \frac{g_{\mathrm{LQ}}^2}{M_{\mathrm{LQ}}^2} \approx \mathcal{M}_{\mathrm{EFT}}$$

Collider bound should be relaxed when LQ mass is light

Additional *b-jet* in the final state

- Furthermore, a requirement of an additional *b*-jet is powerful [Marzocca, Min, Son, 2008.07541]



Additional *b*-jet tagging suppresses the Bkg by several of powers

LQ signal suppresses only by a several factors

Signal over Bkg ratio can be amplified by the additional b-jet tagging

MC simulation (MadGraph5 + Pythia8 + Delphes) of both SM Bkg and leptoquark signal

SM Bkg (that mimics τ b + missing)

BG (**cut b**)	Wjj	Zjj $(Z \to \nu\bar{\nu})$	$t\bar{t}$	Z, γ DY	VV	single t
number of jets	6693.4	235099	346.7	1813.2	125.8	151.8
number of τ	3173.5	5617.1	73.9	894.9	59.7	34.0
number of b	90.6	305.5	35.9	163.9	5.28	18.8
isolated lepton	90.5	305.5	29.7	10.4	1.38	17.0
τ kinematics	78.8	20.8	23.6	9.19	1.13	14.0
MET cut	71.2	4.62	20.9	2.52	0.98	12.7
back-to-back	7.84	3.61	1.67	0.57	0.18	0.54
$0.7 < m_T < 1$ TeV	0.58	0.37	0.056	0.28	0.018	0.029
1 TeV $< m_T$	0.16	0.06	0.01	0.007	0.005	0.005
1 TeV $< m_T$ [34]	0.18(5)	0.21(12)	0.29(3)	$4.2(4)\times10^{-5}$	0.35(5)	0.067(7)

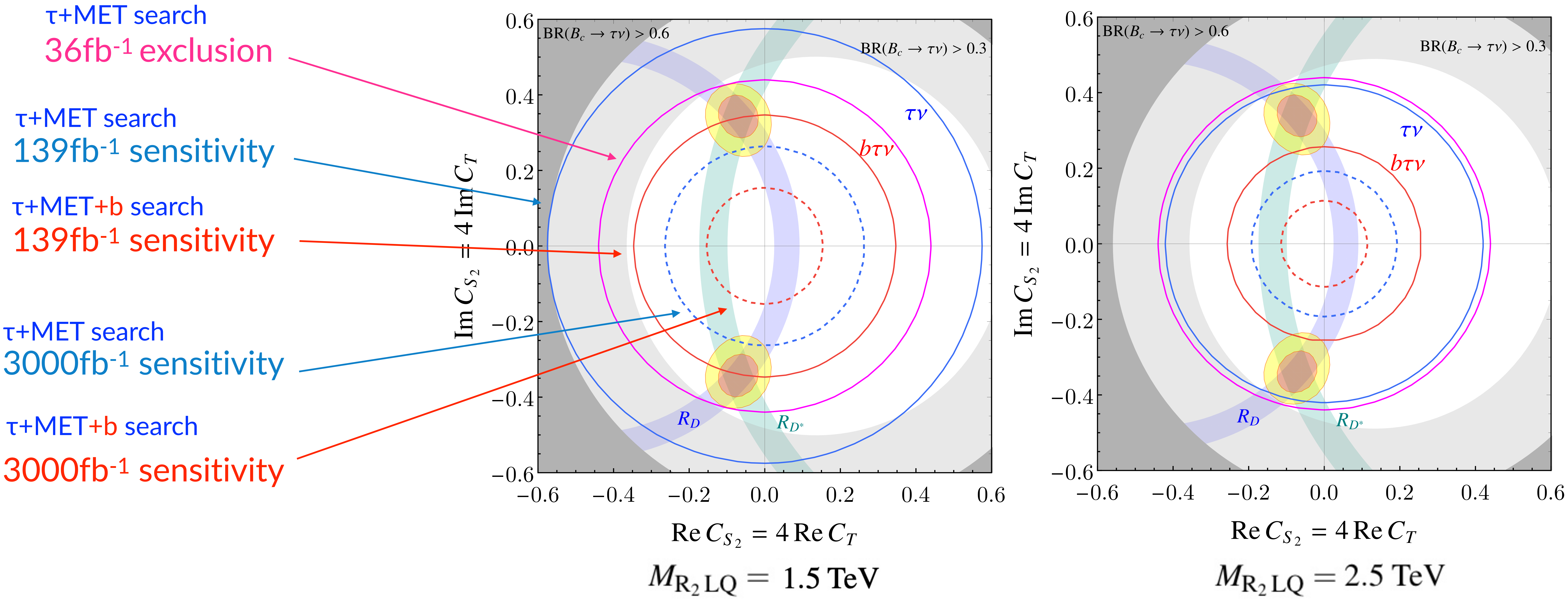
Examples of LQs [U₁ LQ scenarios]

	$U^{R_{s/b}=0}_{1,1.5\,\text{TeV}}$	$U^{R_{s/b}=0}_{1,\text{EFT}}$	$U^{R_{s/b}=1}_{1,1.5\,\text{TeV}}$	$U^{R_{s/b}=1}_{1,\text{EFT}}$	BG
number of jets	4245	6085	5966	8376	244230
number of τ	2024	2941	2898	4168	9853
number of b	460	692	535	754	620.0
isolated lepton	454	685	485	747	454.5
τ kinematics	424	637	451	692	147.5
MET cut	350	540	371	590	112.9
back-to-back	258	402	263	443	14.4
$0.7 < m_T < 1$ TeV	53.9	86.4	55.8	92.0	1.33
1 TeV $< m_T$	26.0	71.6	30.7	101	0.25

A transverse mass defined as: $m_T = \sqrt{2 p_T^{\tau} E_T^{\text{miss}} \left[1 - \cos\Delta\phi(\vec{p}_T^{\,\tau}, \vec{p}_T^{\,\text{miss}})\right]}$

R_2 Leptoquark scenario

[Endo, Iguro, **TK**, Takeuchi, Watanabe, 2111.04748]



Light LQ

Heavy LQ

U_1 Leptoquark scenario

[Endo, Iguro, **TK**, Takeuchi, Watanabe, 2111.04748]

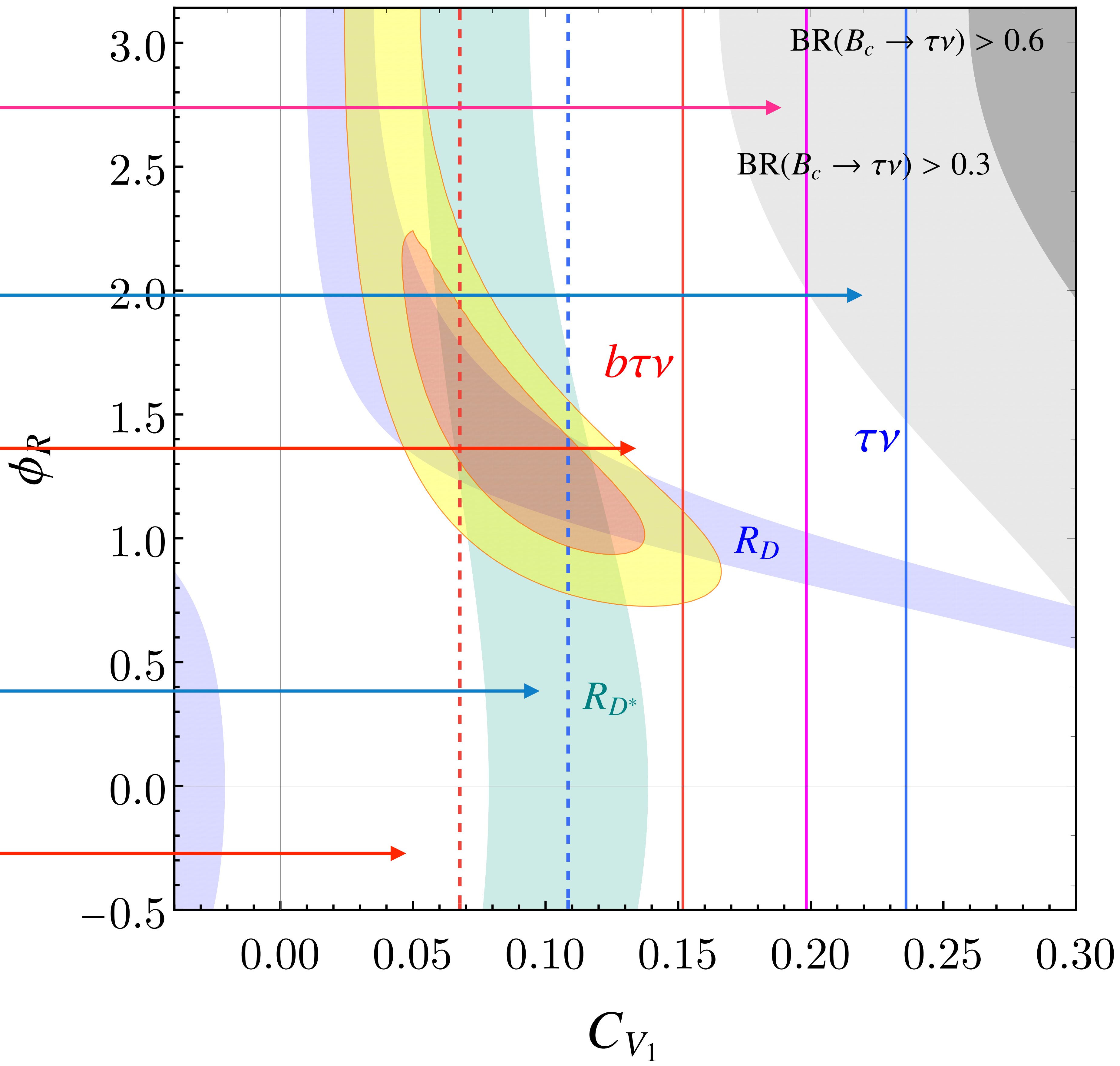
τ+MET search
36fb^{-1} exclusion

τ+MET search
139fb^{-1} sensitivity

τ+MET+b search
139fb^{-1} sensitivity

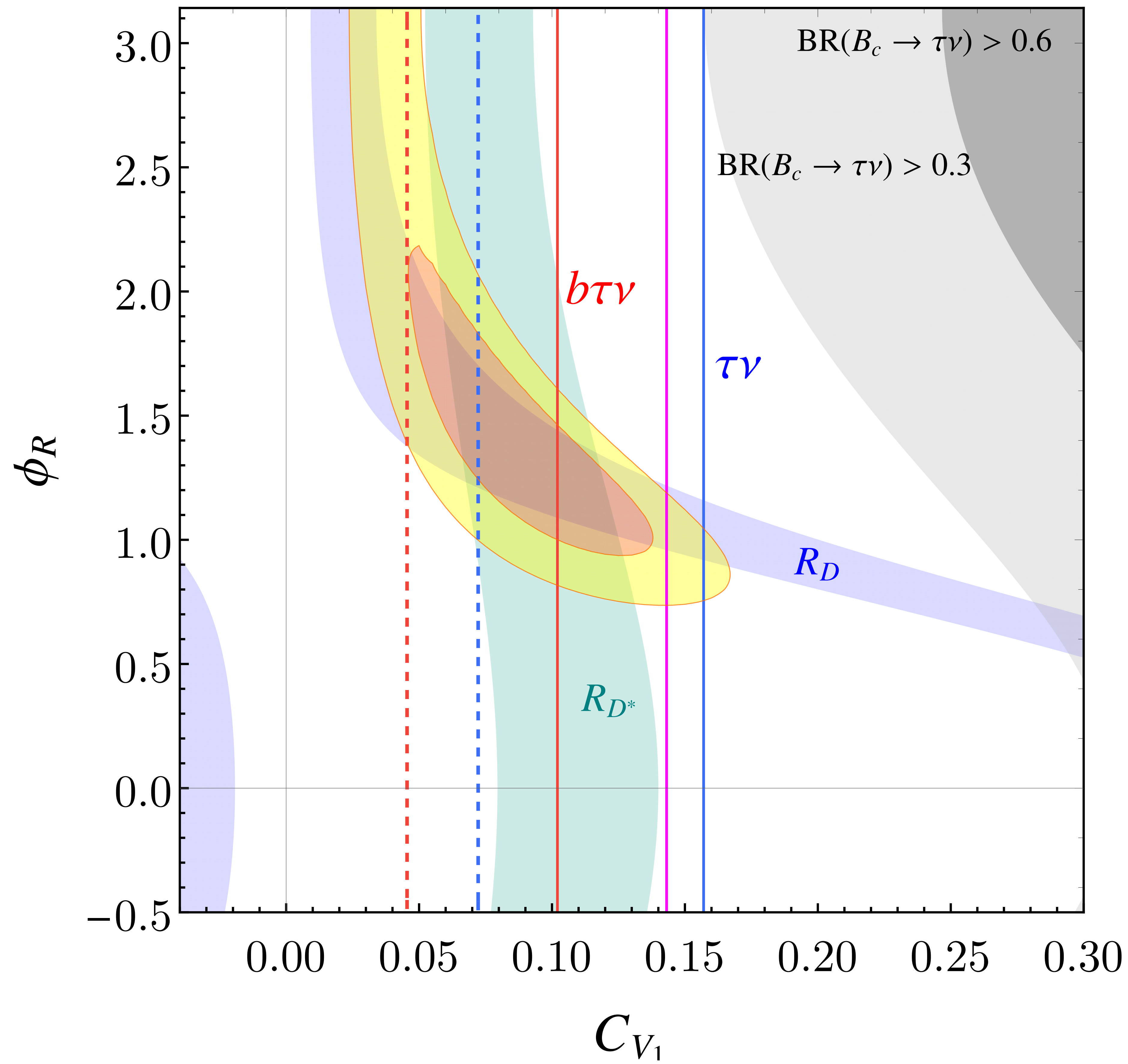
τ+MET search
3000fb^{-1} sensitivity

τ+MET+b search
3000fb^{-1} sensitivity



$M_{U_1\,LQ} = 1.5$ TeV

Light LQ



$M_{U_1\,LQ} = 4.0$ TeV

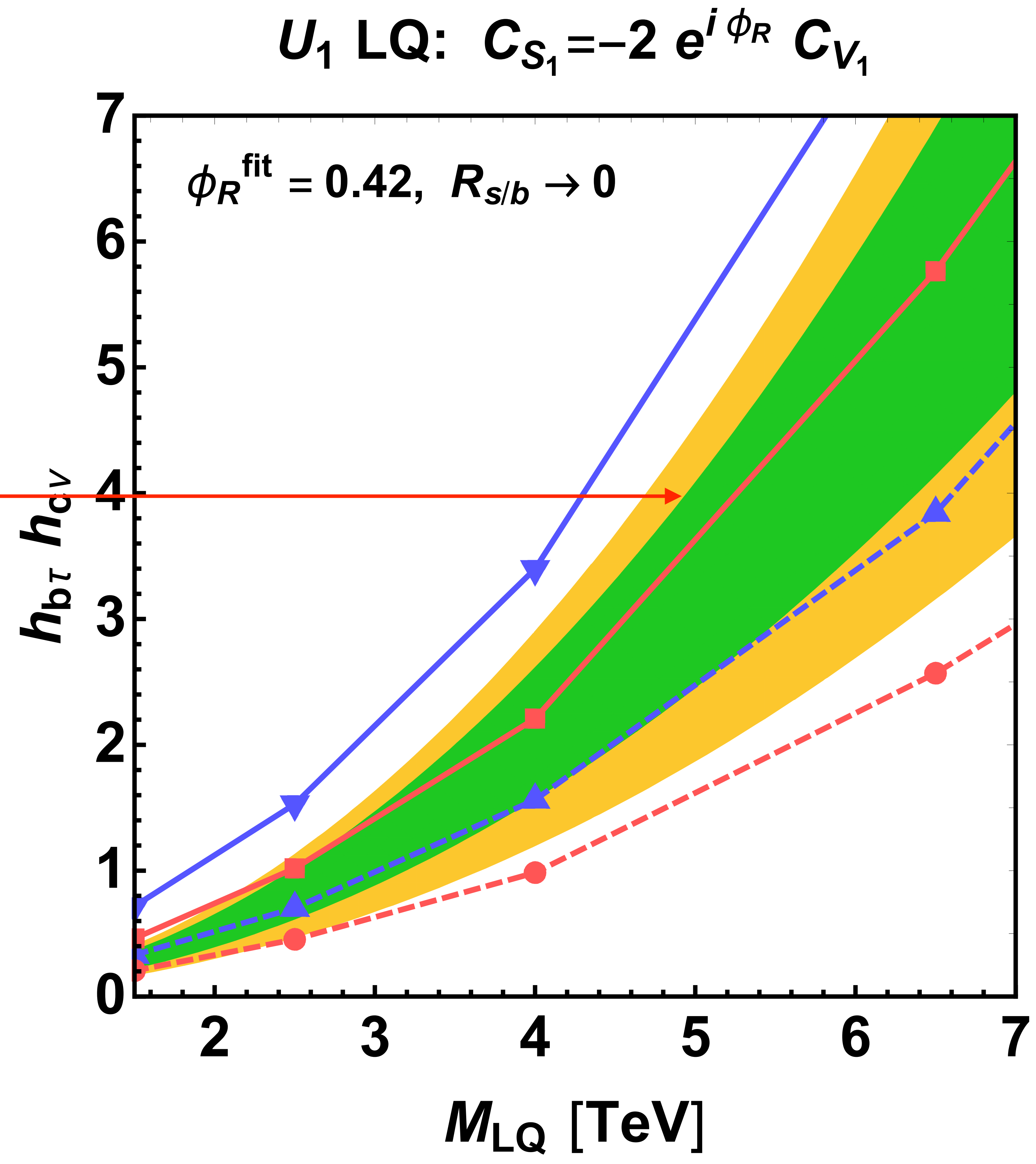
Heavy LQ

U_1 Leptoquark scenario: comparison

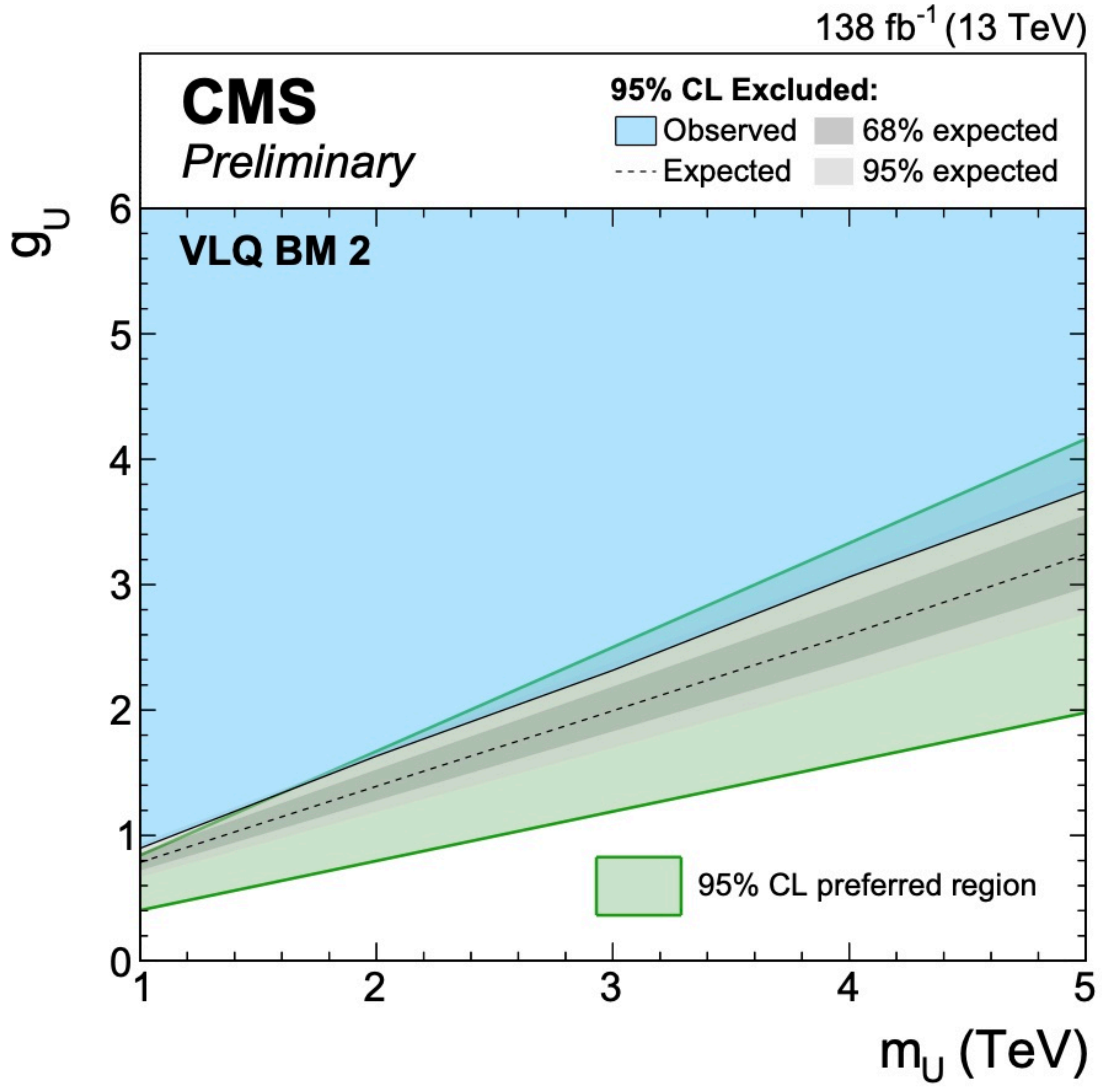
[Endo, Iguro, **TK**, Takeuchi, Watanabe, 2111.04748]

[CMS, CMS PAS HIG-21-001]

τ+MET+b search
139fb^{-1} sensitivity



$\tau\ b +$ missing sensitivity $(139\,\text{fb}^{-1})$



$\tau\tau +$ excluded region $(138\,\text{fb}^{-1})$

Conclusion

- Several leptoquark can easily explain both $R(D)$ and $R(D^*)$ 4σ levels anomalies
- We simulate the (HL-)LHC sensitivity of the leptoquark indirect search via

  $pp \to \tau\nu + b$ as well as $pp \to \tau\nu$
- We show that additional b-jet tagging significantly improves the LHC sensitivity **by ≈40%**
- We show the EFT breakdown behavior in light leptoquark region (see paper)
- We investigate the angular correlations to discriminate the LQ scenarios (see paper)

Backup

Latest SM predictions of $R(D)$ and $R(D^*)$

HFLAV theory average2019 $R(D)_{\rm SM} = 0.299 \pm 0.003$ $R(D^*)_{\rm SM} = 0.258 \pm 0.005$

New analyses

- + All lattice data, QCD sum rule, and the latest LCSR result [Gubernari, Kokulu, van Dyk '18]
  $@q^2 = q^2_{\rm max}$ $@q^2 \leq 0$
- + All $\mathcal{O}(\Lambda^2/m_c^2)$ corrections in the heavy quark effective theory in all form factors [Jung, Straub '18]
- + Momentum distributions from Belle data [Bordone, Jung, van Dyk '19]

$R(D)_{\rm SM} = 0.297 \pm 0.003$ $R(D^*)_{\rm SM} = 0.250 \pm 0.003$ [BJvD]

- + Angular distributions from Belle data [Iguro Watanabe '20]

[Available Belle data 1510.03657; 1702.01521; 1809.03290]

$R(D)_{\rm SM} = 0.289 \pm 0.004$ $R(D^*)_{\rm SM} = 0.248 \pm 0.001$ [IW]

$R(D)$: **1.4** [HFLAV2019] → **1.4** [BJvD], **1.7 σ** [IW]
$R(D^*)$: **2.5** → **3.2, 3.4 σ**
combine: **3.1** → **3.9, 4.2 σ**