LHC phenomenology in light of $R(D)$ and $R(D^*)$ anomalies

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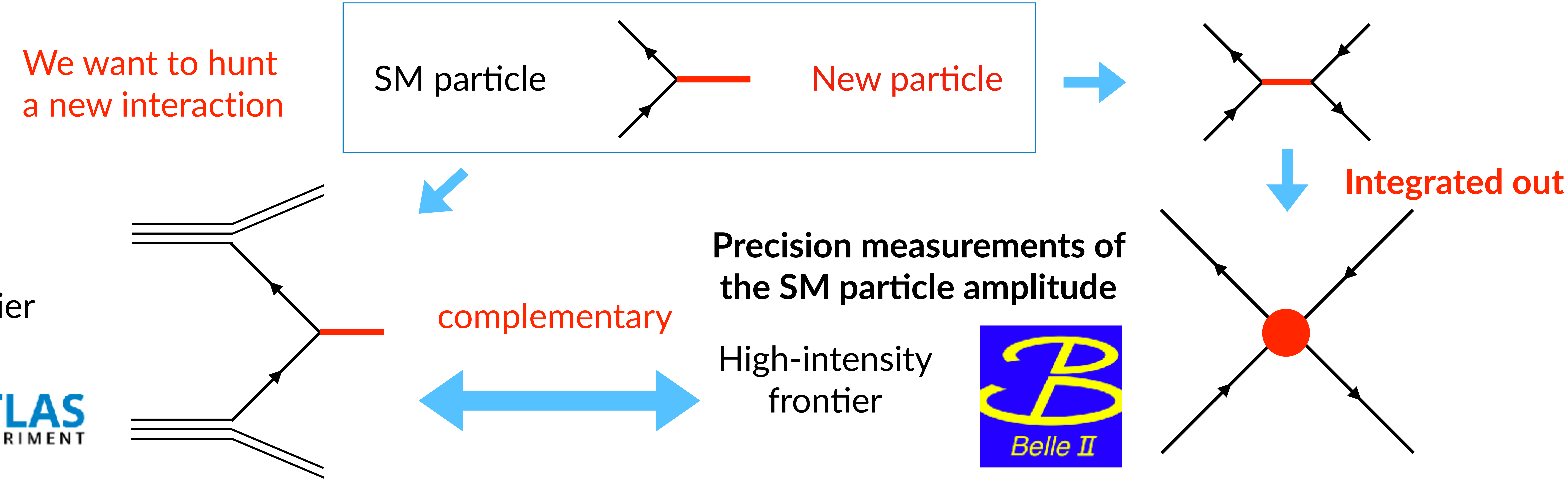
High-energy vs. high-precision

- The Standard Model (SM) is known to be an incomplete model that can not explain matter–antimatter asymmetry, dark matter, gauge hierarchy, quark mass hierarchy, neutrino mass, etc.
- Beyond the standard model (New Physics/NP) is, therefore, **required**

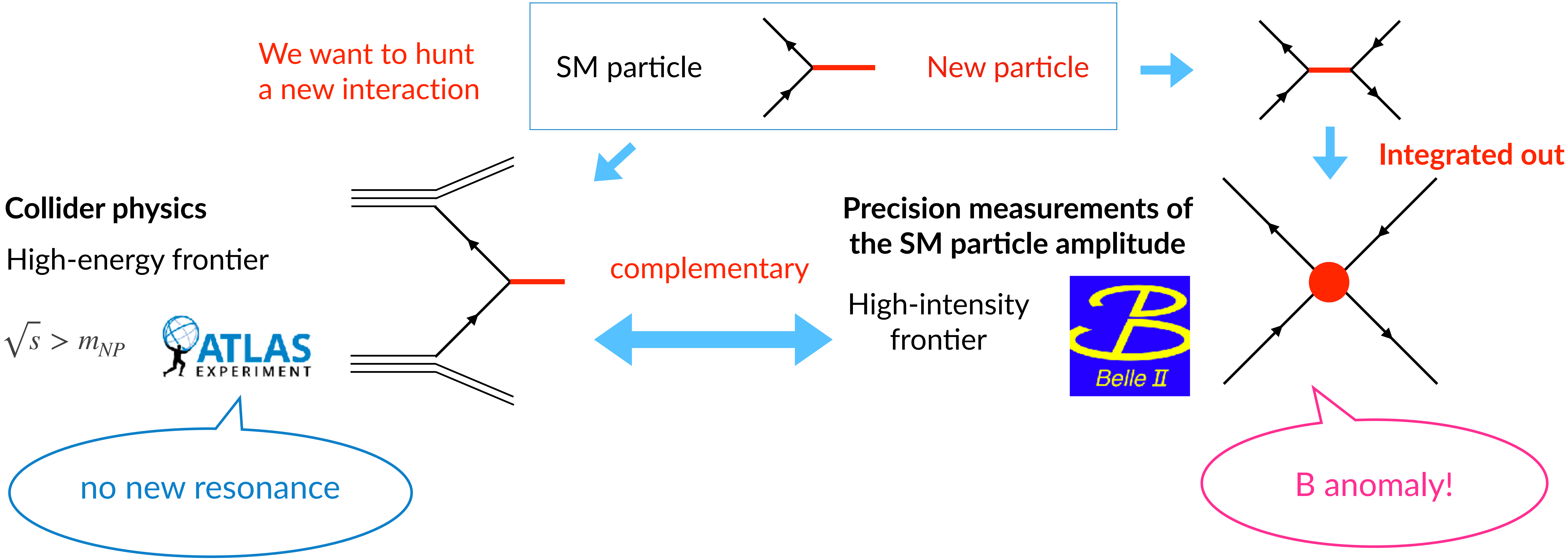


Collider physics

High-energy frontier

$\sqrt{s} > m_{NP}$

ATLAS EXPERIMENT


We want to hunt
a new interaction
SM particle
New particle
Integrated out
Collider physics
High-energy frontier
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ATLAS
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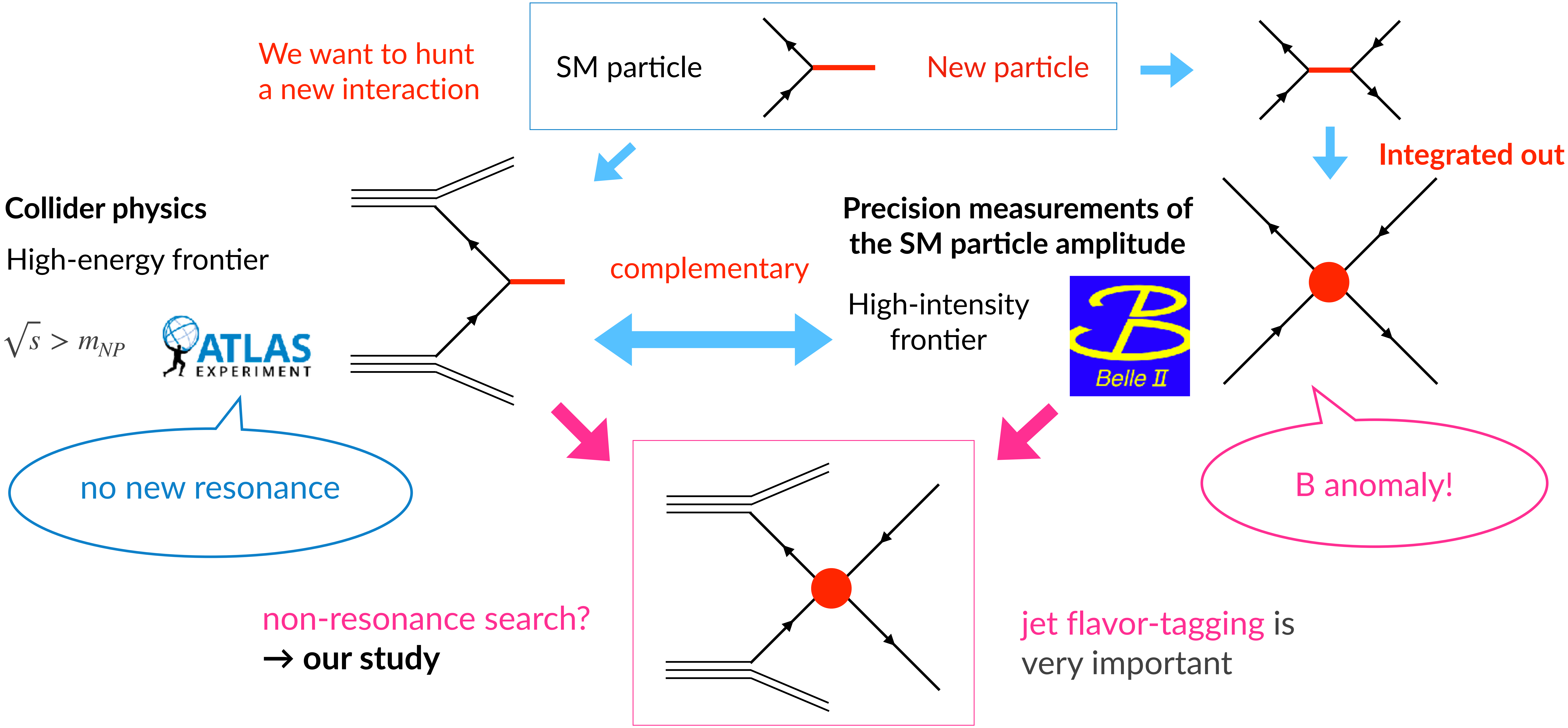
complementary
Precision measurements of
the SM particle amplitude
High-intensity
frontier
Belle II
no new resonance
B anomaly!



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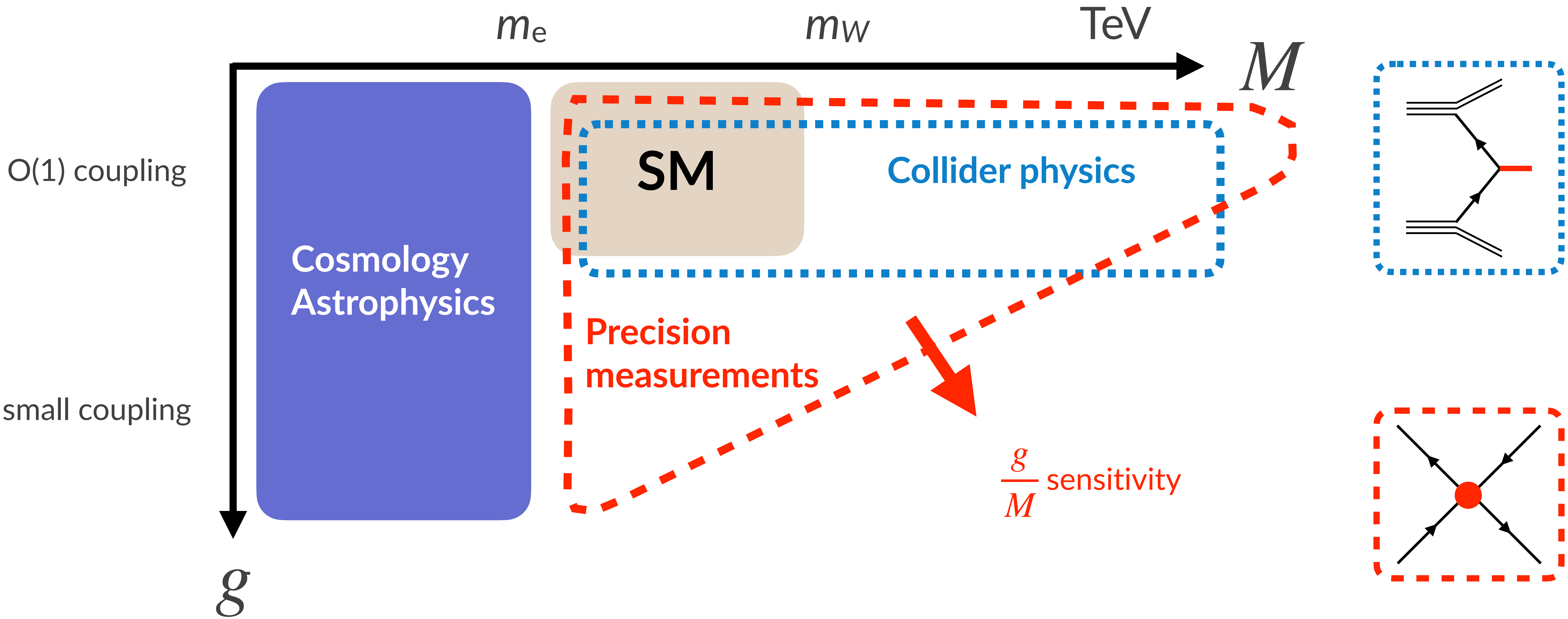
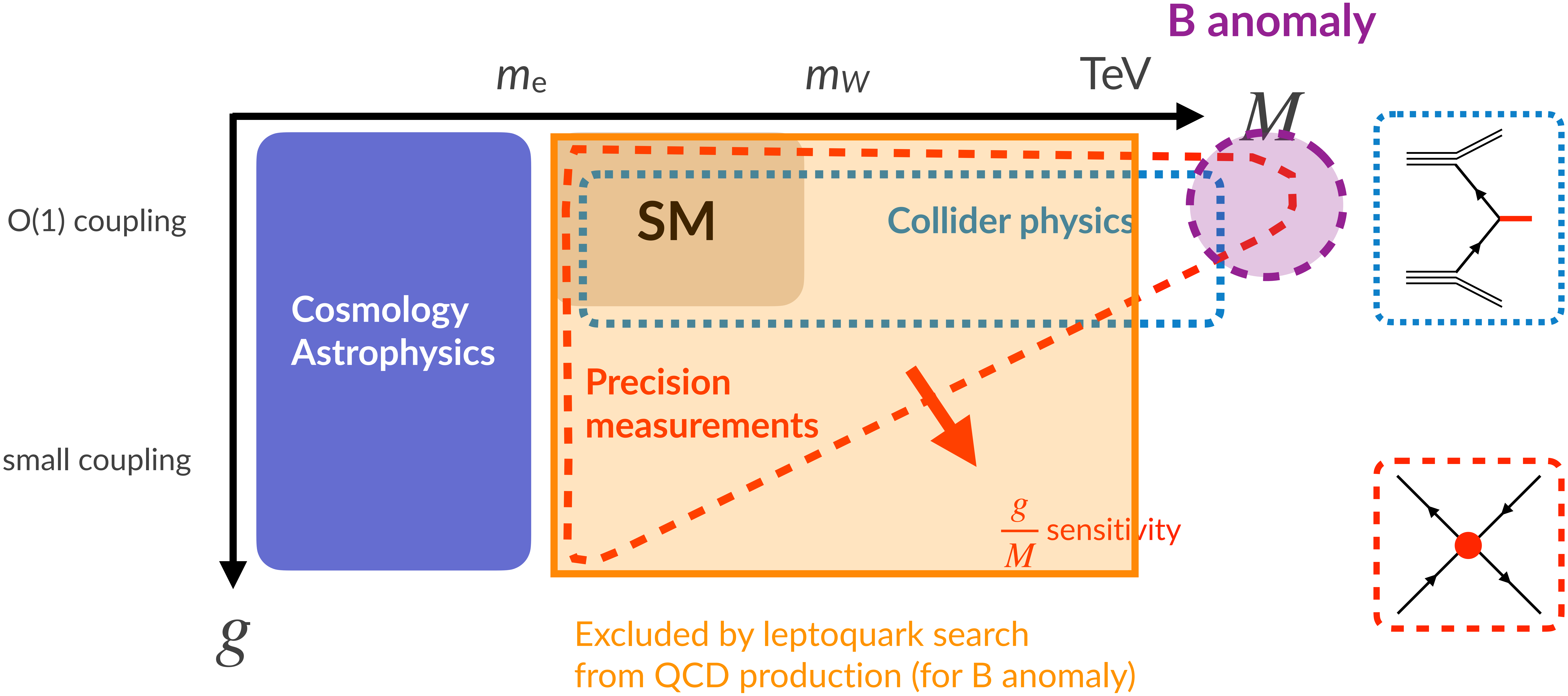
B anomaly!
non-resonance search?
→ our study
jet flavor-tagging is
very important



m_e
m_W
TeV
M
O(1) coupling
small coupling
g
Cosmology
Astrophysics
SM
Collider physics
Precision
measurements
$\frac{g}{M}$ sensitivity



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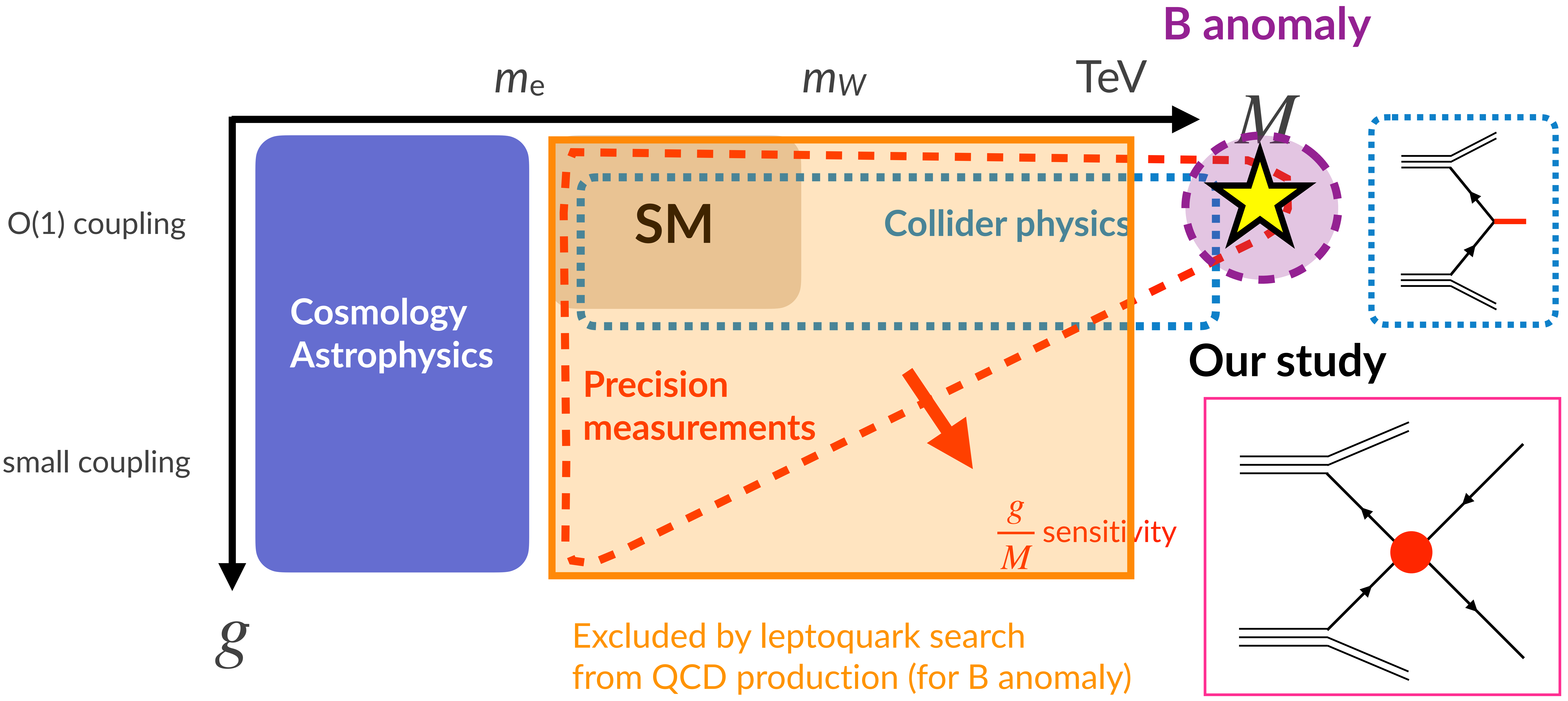
Excluded by leptoquark search
from QCD production (for B anomaly)



B anomaly
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Our study
Excluded by leptoquark search
from QCD production (for B anomaly)

B physics

- Rich phenomenology; CKM, FCNC, CP violation, tau lepton, **Lepton-flavor universality (LFU)**, Hadron spectroscopy, dark sector, etc
- **Three major B factories:**

BaBar experiment @ **SLAC**, physics run was **finished at 2008**

$e^+e^- \to \Upsilon \to B\bar{B}$ $10^8 B\bar{B}$ per year

Belle and Belle II experiments @ **KEK**, Belle II started at 2019

$e^+e^- \to \Upsilon \to B\bar{B}$ $10^{10} B\bar{B}$ per year

LHCb experiment @ **CERN**, Run 2 were done, Run 3 will start at **2022**

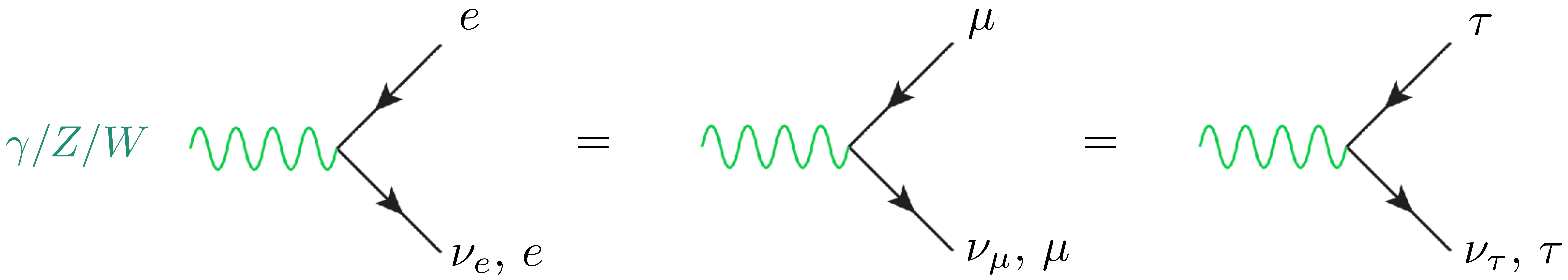
$pp \to b\bar{b} \to B\bar{B}$ $10^{12} b\bar{b}$ per year

newcomer

CMS experiment will become B factory at Run 3 (called B-parking),
Run 2 data [$10^{10}\,(b \to \mu X)\bar{b}$] will be shown near future [Takahashi, PPP2021]

Test of Lepton Flavor Universality (LFU)

- Gauge symmetry predicts lepton flavor universal phenomena



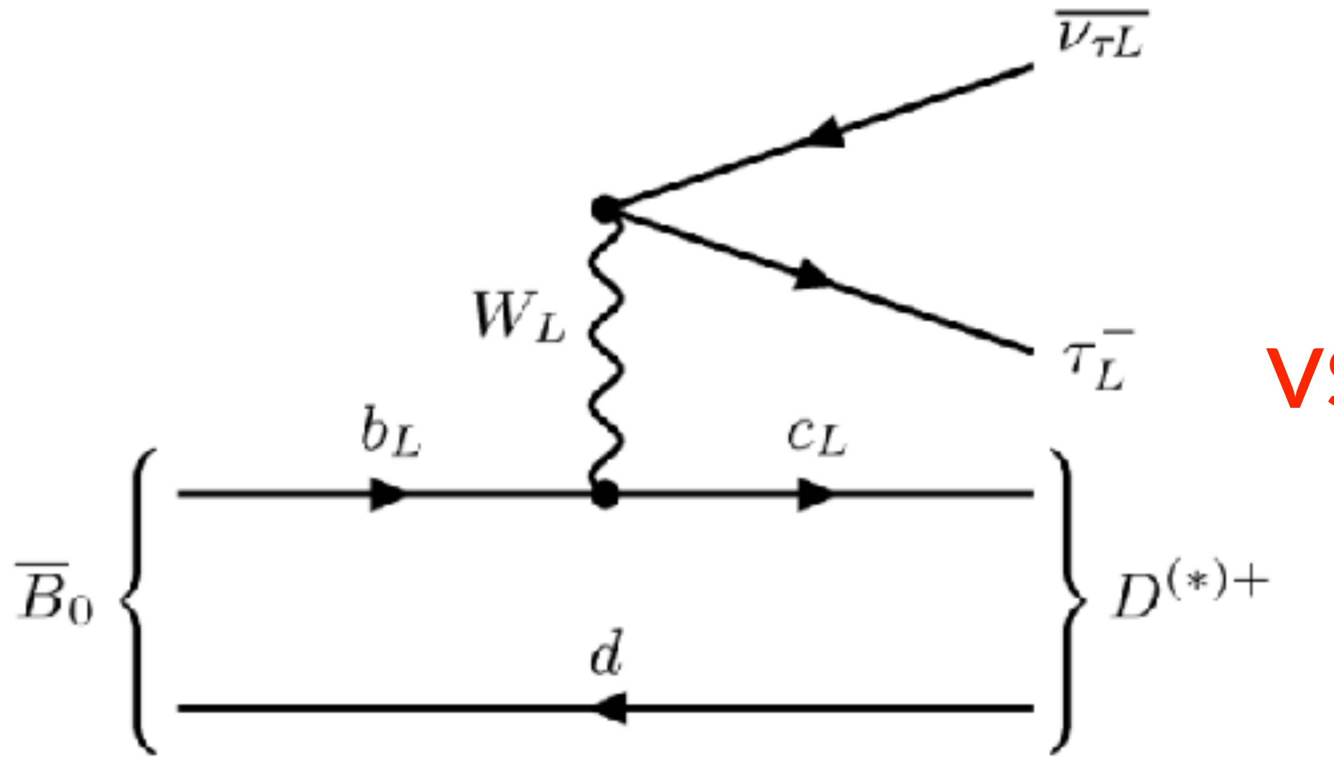
- **Charged lepton mass** changes **kinematics** and modifies **scalar form factors in the hadronization**, which eventually violates the lepton flavor universality

- Long-distance QED correction (beyond PHOTOS MC simulation) could violate the lepton flavor universality [de Boer, TK, Nisandzic, PRL '18; Isidori, Nabeebaccus, Zwicky, '20]

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

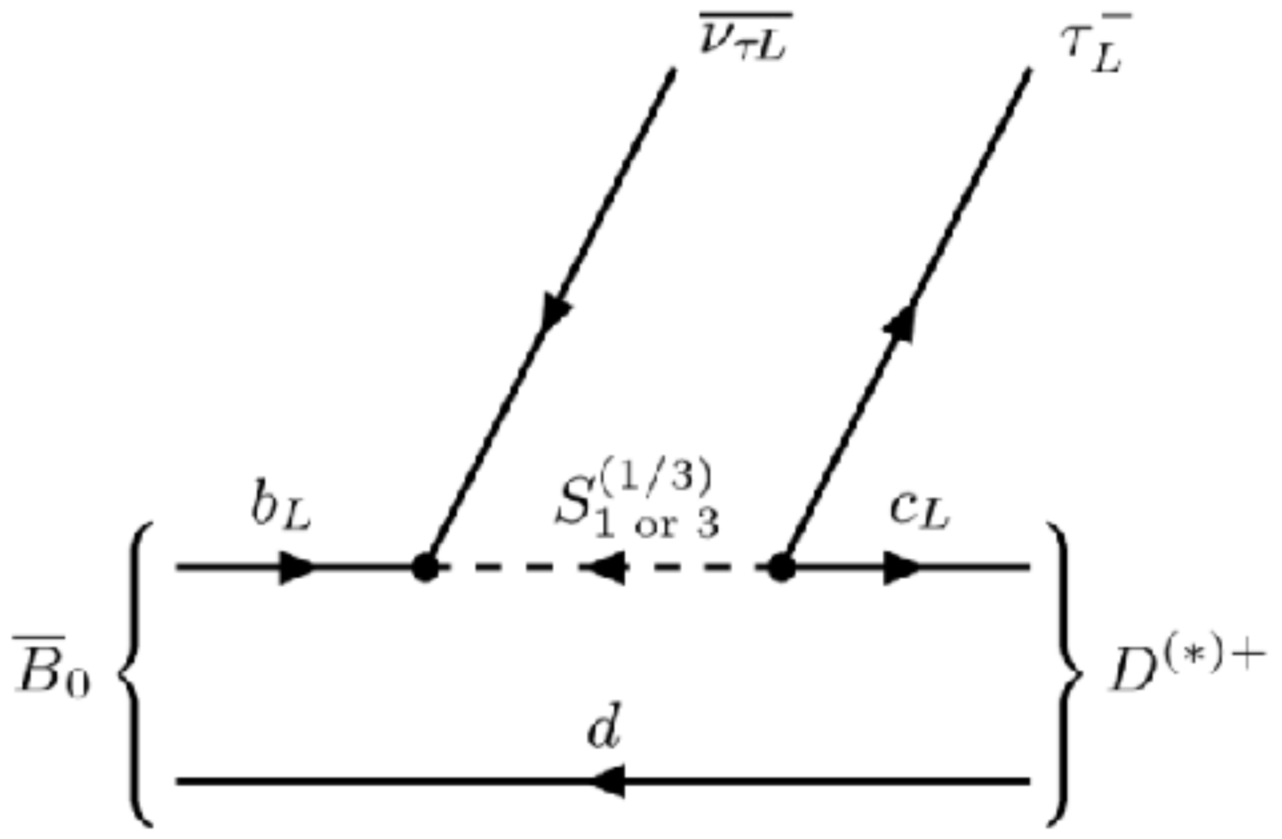
$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\bar{\tau}\nu_\tau)}{\mathrm{BR}(B \to D^{(*)}\bar{\ell}\nu_\ell)}$$

V_{cb} dropped



SM

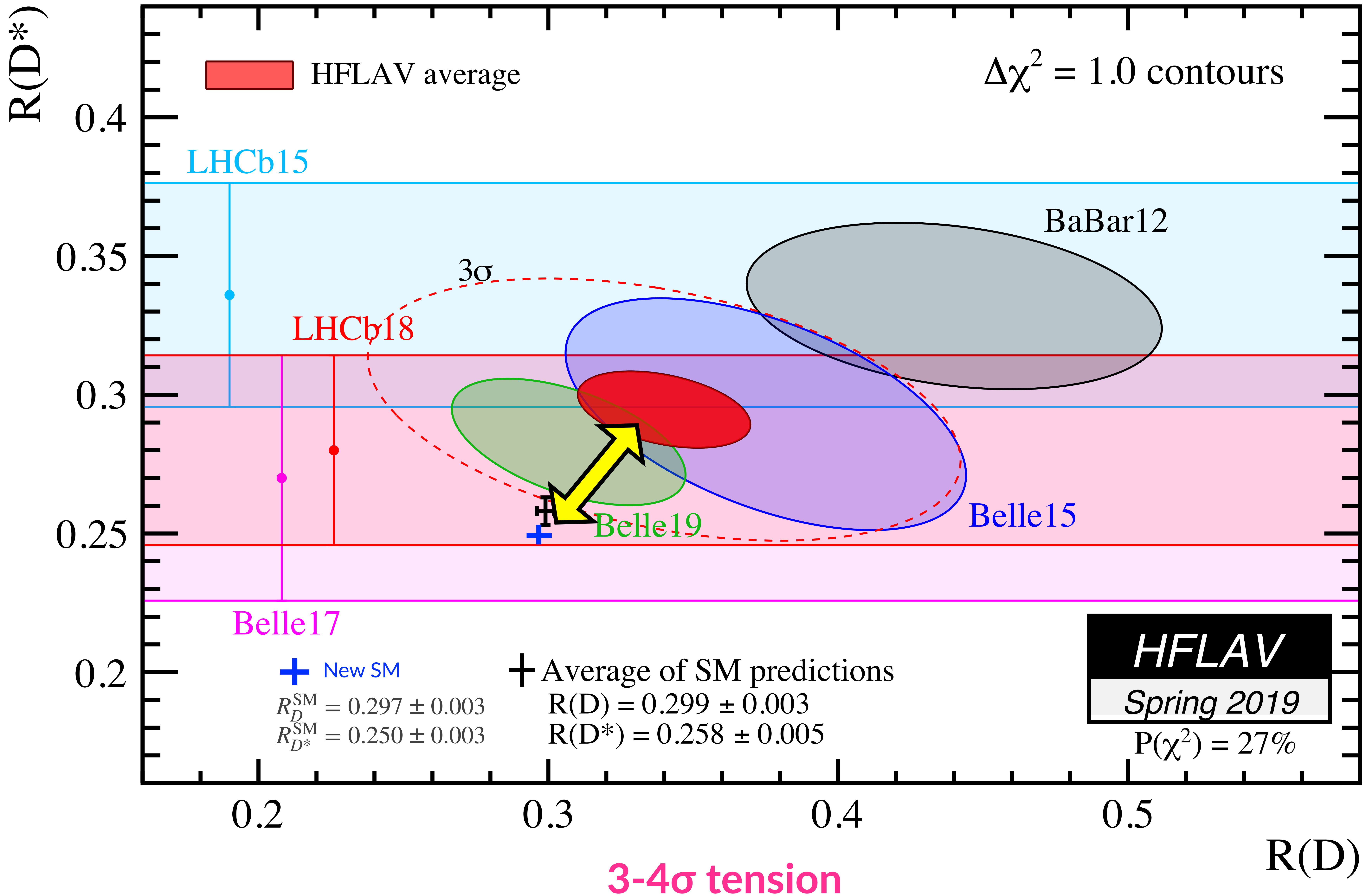
vs.



New physics, *e.g.*, Leptoquark

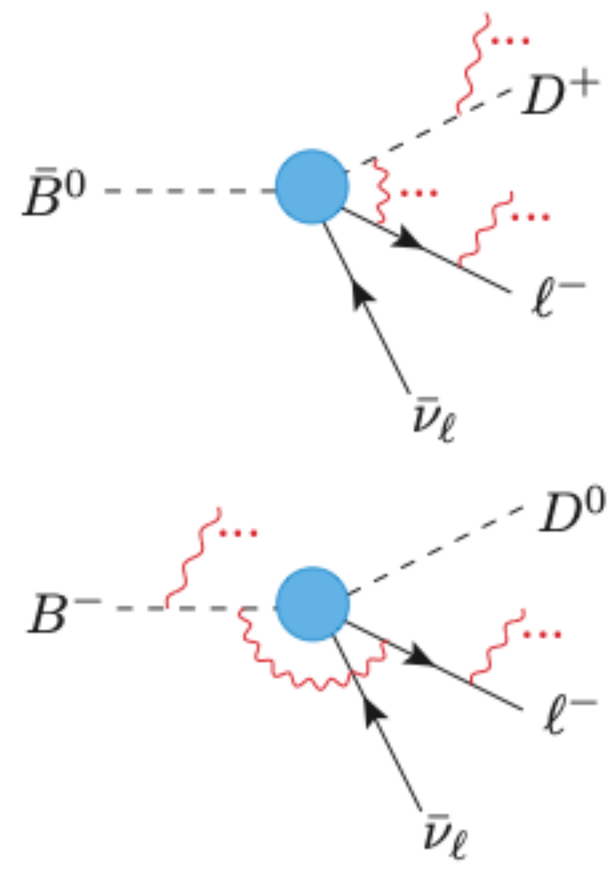
$\mathcal{B}(B \to D\ell\nu) = 2\%,\ \mathcal{B}(B \to D^*\ell\nu) = 5\%,$

[HFLAV 2019]



3-4σ tension

QED corrections could be missed at a few % level



Current plot: only included final-state radiations without the interference

[de Boer, TK, Nisandzic, PRL '18]

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]

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

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

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

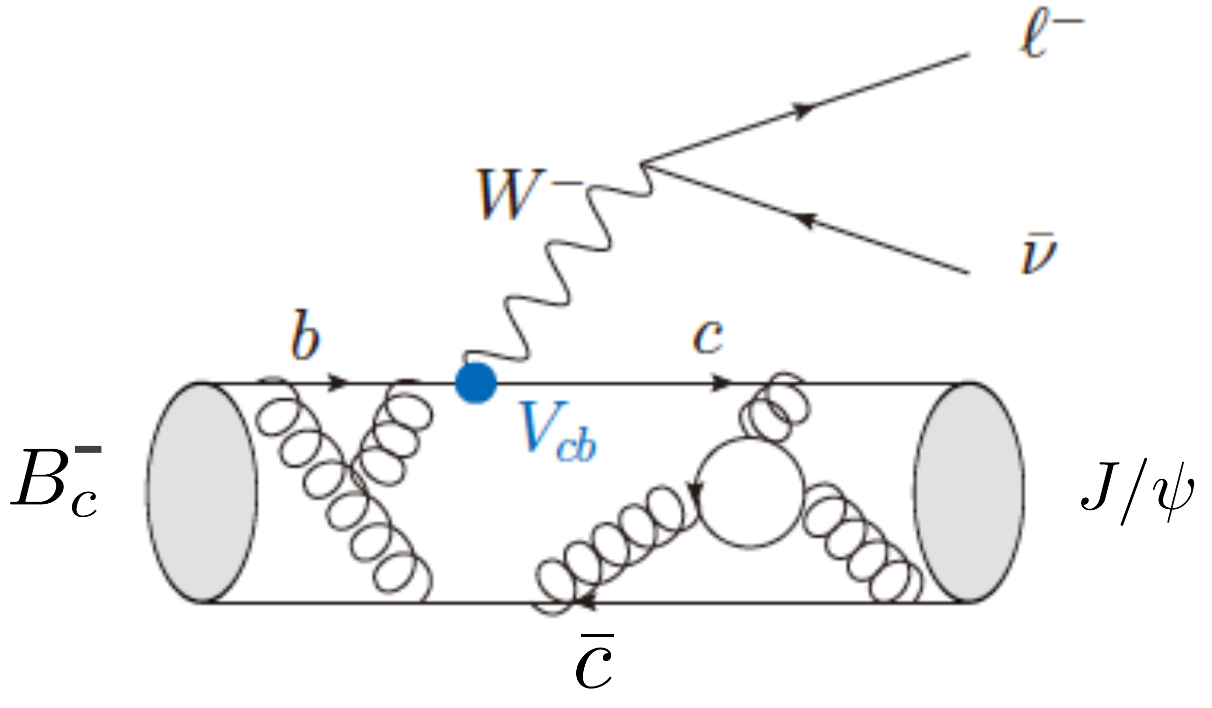
[Available Belle data 1510.03657; 1702.01521; 1809.03290]

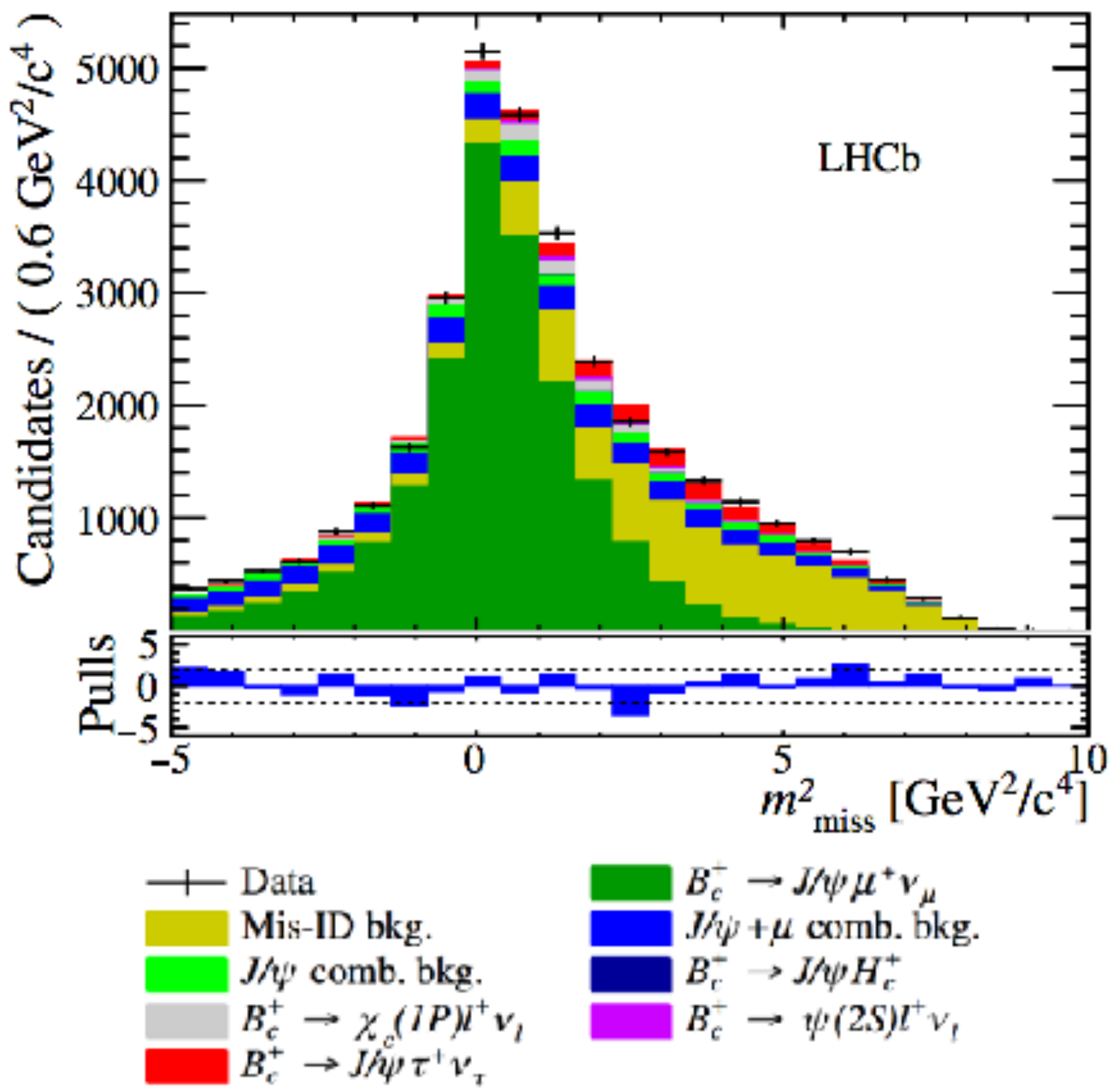
$R(D)$: **1.4** [HFLAV2019] → **1.4** [BJvD], **1.7 σ** [IW]
$R(D^*)$: **2.5** → **3.2, 3.4 σ**
combine: 3.1 → **3.9, 4.2 σ**

Other channel: $R(J/\psi)$

- The LFU violation was measured in $B_c^- \to J/\psi$ transitions

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^- \to J/\psi\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B_c^- \to J/\psi\ell^-\bar{\nu}_\ell)}$$





$R(J/\psi)_{\rm exp} = 0.71 \pm 0.17_{\rm stat} \pm 0.18_{\rm syst}$ [LHCb, 1711.05623]

$R(J/\psi)_{\rm SM} = 0.2582 \pm 0.0038$ Based on **first lattice result** [HPQCD, 2007.06956]

1.8σ consistent using N_f=2+1+1, with "HISQ" *c* and heavy quark *b*

Same-direction tension as R(D) and R(D*) anomalies

Early new physics study, *e.g.*, [Watanabe, PLB '18; Alok, Kumar, Kumar, Kumbhakar, Sankar, JHEP '18]

Signal reconstructed with tau leptonic decays and LHCb Run 1 data (3fb^{-1})

Let us consider New Physics

New physics interpretations

- New physics (NP) for R(D(*)) anomaly can be model-independently described by

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

- SM contribution is the first term
- C_{V_2} appears dimension-eight at the SMEFT
- Light right-handed neutrinos ($m_{\nu_R} < m_B$) can also be included, but constrained from the collider bounds

Single new particle interpretations (1/2)

- Single WC scenarios

C_{V_1} — W', SU(2)L-singlet **vector LeptoQuark (LQ)**, SU(2)L-triplet or -singlet **scalar LQ (S_1)**

C_{S_1} — Charged Higgs, SU(2)L-singlet or doublet **vector LQ (U_1, V_2)**

C_{S_2} — Charged Higgs with generic flavour structure

$C_{S_2} = 4C_T$ — scalar SU(2)L-**doublet LQ (R_2)**
("4" comes from Fierz identity
and is modified by RG evolution)

- Two WCs scenarios

$(C_{V_1}, C_{S_2} = -4C_T)$ — SU(2)L-singlet **scalar LQ (S_1)**

(C_{V_1}, C_{S_1}) — SU(2)L-singlet **vector LQ (U_1)**

(C_{S_1}, C_{S_2}) — Charged Higgs with generic flavour structure

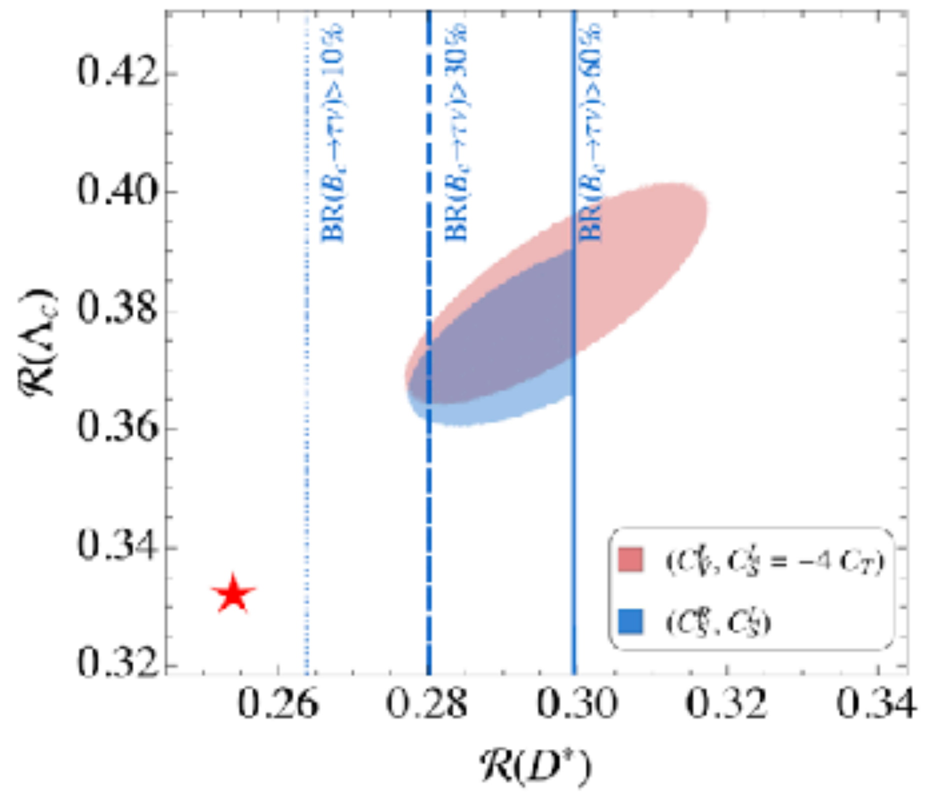
- There are so many detailed studies for **each** single particle scenario

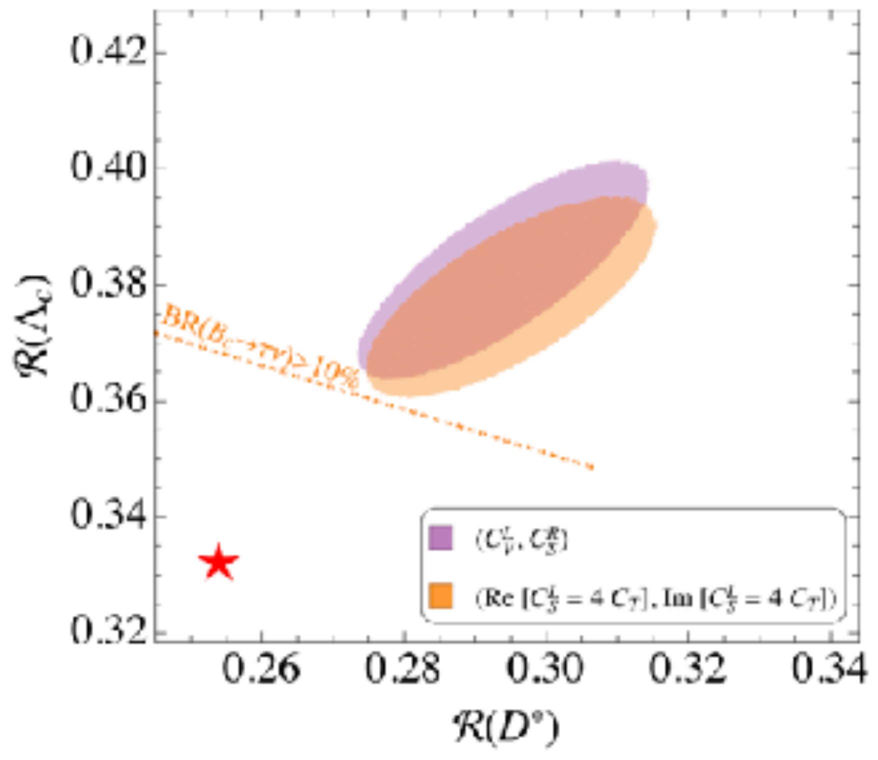
Model-independent prediction: $R(\Lambda_c)$

- Baryonic counterpart: $$\mathcal{R}(\Lambda_c) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}_\ell)}$$ @ LHCb [Bernlochner, Liegt, Robinson, Sutcliffe '18]

SU(2)$_L$-singlet scalar LQ (S_1)

Charged Higgs





SU(2)$_L$-singlet vector LQ (U_1)

SU(2)$_L$-doublet scalar LQ (R_2)

Similar ellipses!

- Sum rule for $R(\Lambda_c)$ prediction from the hadronic form-factor analysis

Model-independent sum rule
(also valid for light RH neutrino scenarios)

$$\frac{R(\Lambda_c)}{R(\Lambda_c)_{\rm SM}} \simeq 0.26 \frac{R(D)}{R(D)_{\rm SM}} + 0.74 \frac{R(D^*)}{R(D^*)_{\rm SM}}$$

Crosscheck of $R(D^{(*)})$ anomaly is possible by $R(\Lambda_c)$

$$R(\Lambda_c) = 0.38 \pm 0.01_{R(D^{(*)})} \pm 0.01_{\rm FF}$$

There is no data yet

$$R(\Lambda_c)_{\rm SM} = 0.324 \pm 0.004$$

[Blanke, Crivellin, TK, Moscati, Nierste, Nisandzic, '19]

Single new particle interpretations (2/2)

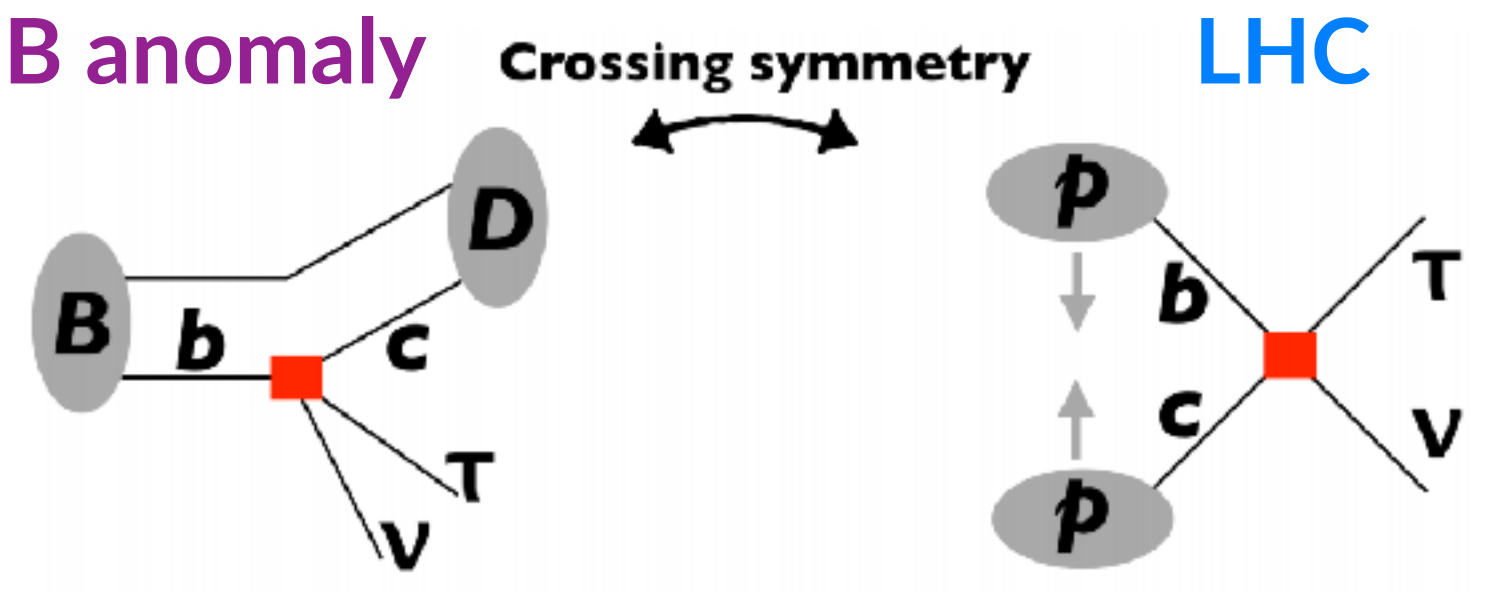
- **W'**
  - **Severely constrained** from $\Delta M_s,\ Z' \to \tau\tau$ search [Faroughy, Greljo, Kamenik '16], and $W' \to \tau\nu$ search [Abdullah, Calle, Dutta, Flores. Restrepo '18]
- **Charged Higgs with generic flavour structure**
  - **Severely constrained** from $B_c \to \tau\nu,\ H^\pm \to \tau\nu$ search [Iguro, Tobe '17; Iguro, Omura, Takeuchi '18]
- **Leptoquark**
  - Collider bound comes from direct search via QCD coupling $gg \to \mathrm{LQLQ}^*$, and broad parameter regions are still allowed when $M_{\mathrm{LQ}} \gtrsim 1$ TeV

→ We focus on (heavy) LQ scenarios

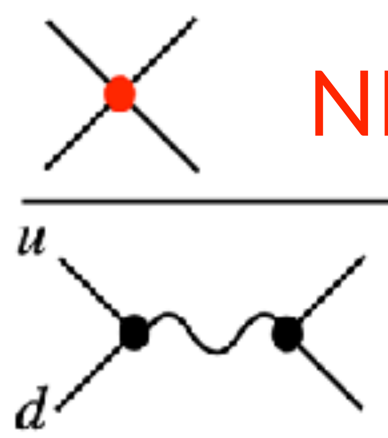
Collider search for $pp \to \tau\nu$

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

[Greljo, Camalich, Ruiz-Alvarez ’19; Marzocca, Min, Son, ’20; Iguro, Takeuchi, Watanabe ‘20]



$$\frac{\Delta\sigma}{\sigma} \sim \frac{\mathrm{L}_{c\bar{b}+b\bar{c}} \times |V_{cb}|^2 \times \left(\frac{m_W^2}{\hat{s}} - C_{V_1}\right)^2}{\mathrm{L}_{u\bar{d}+d\bar{u}} \times |V_{ud}|^2 \times \left(\frac{m_W^2}{\hat{s}}\right)^2} = \frac{\text{NP signal}}{\text{SM BG}} \propto \hat{s}^2 \times C_{V_1}^2$$



LQ signal/BG is amplified at large $\hat{s}$: hard τ with large missing transverse energy (ν_τ)

2σ upper bound from data (36fb^{-1})

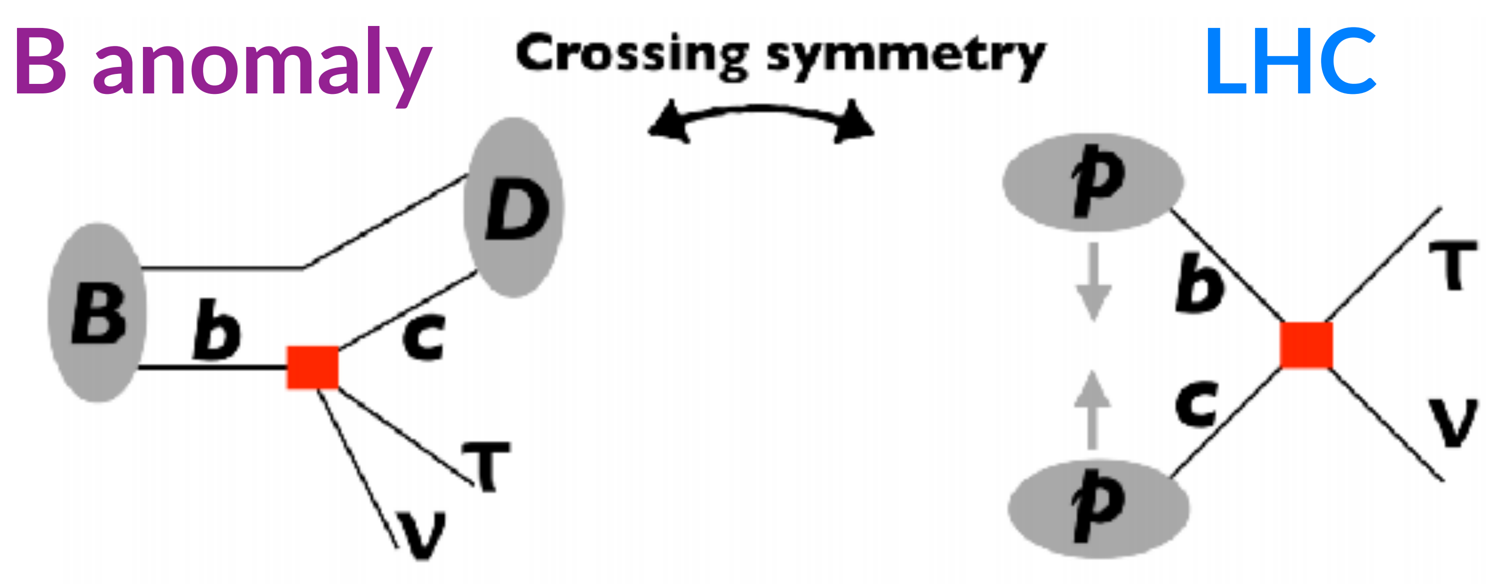
$$|C_{V_{1/2}}| < 0.32, \quad |C_{S_{1/2}}| < 0.57, \quad |C_T| < 0.16$$

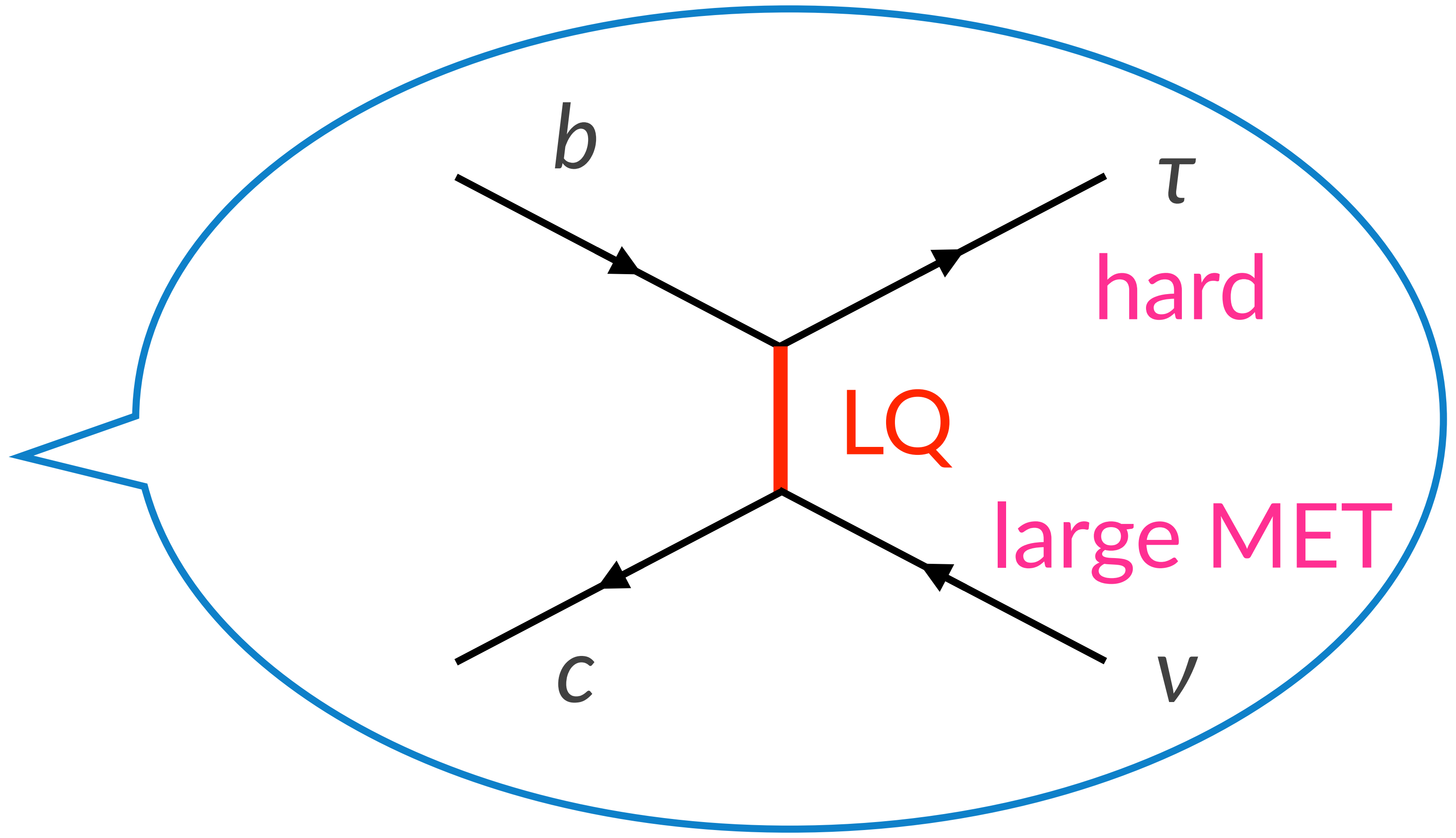
[Greljo, Camalich, Ruiz-Alvarez ’19]

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

What we did: LQ mass dependence

- We investigate LQ mass effects, which relax the collider bound [Iguro, Takeuchi, Watanabe '20]





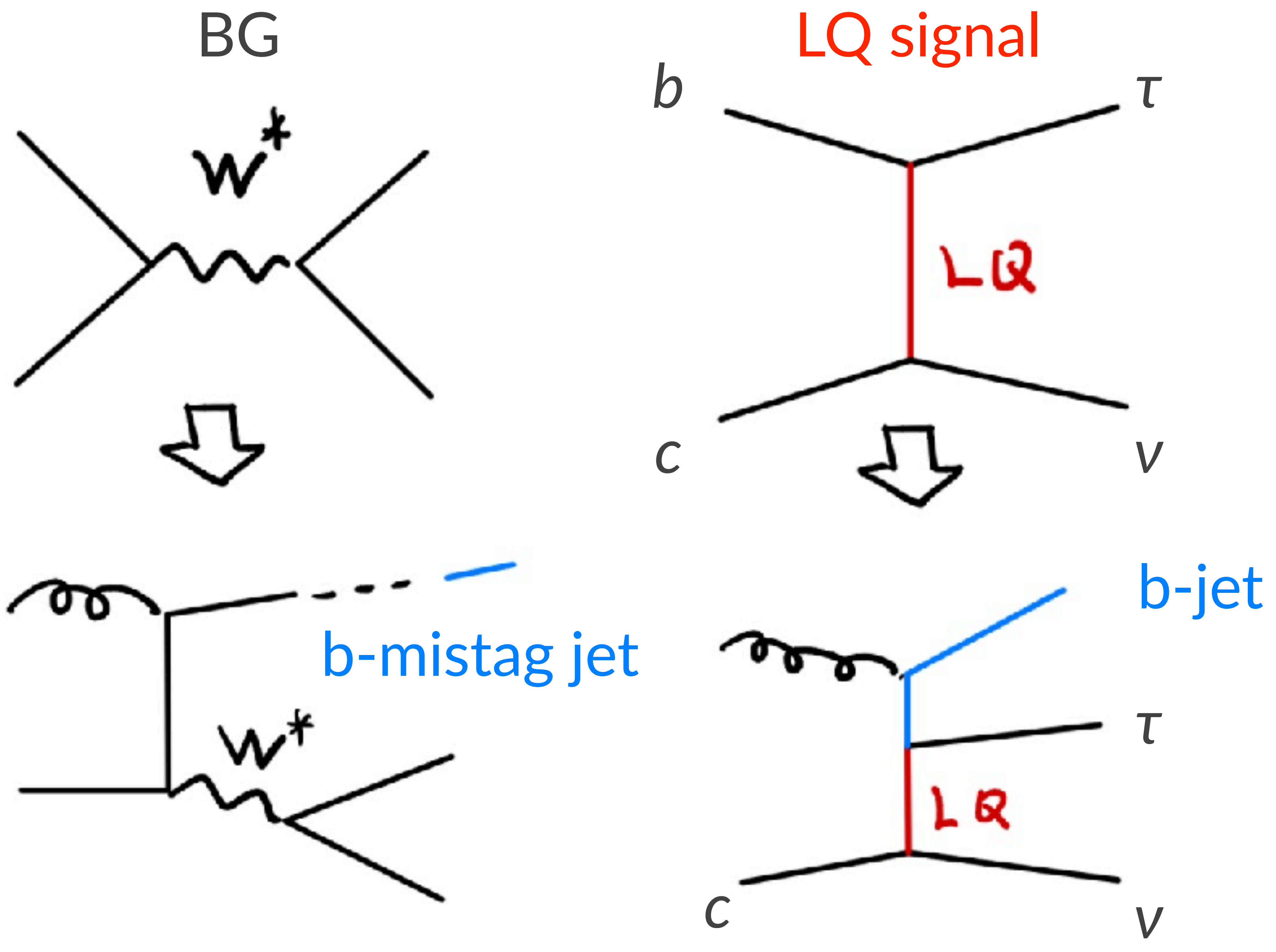
$$\propto \frac{1}{t - M_{\rm LQ}^2}$$

Here, to amplify the LQ signal/BG ratio, $t \sim -\mathcal{O}(1)\text{TeV}^2$ is expected.
Now, the LQ mass receives additional effective mass via the large t

➡ Collider bound should be relaxed when lighter LQ mass range

What we did: Additional b-jet tagging

- Requirement an additional b-jet would be powerful [Marzocca, Min, Son ’20]



Additional b-tag suppresses the BG by several of powers, because the b-tag comes from only the b-mistag from QCD jets

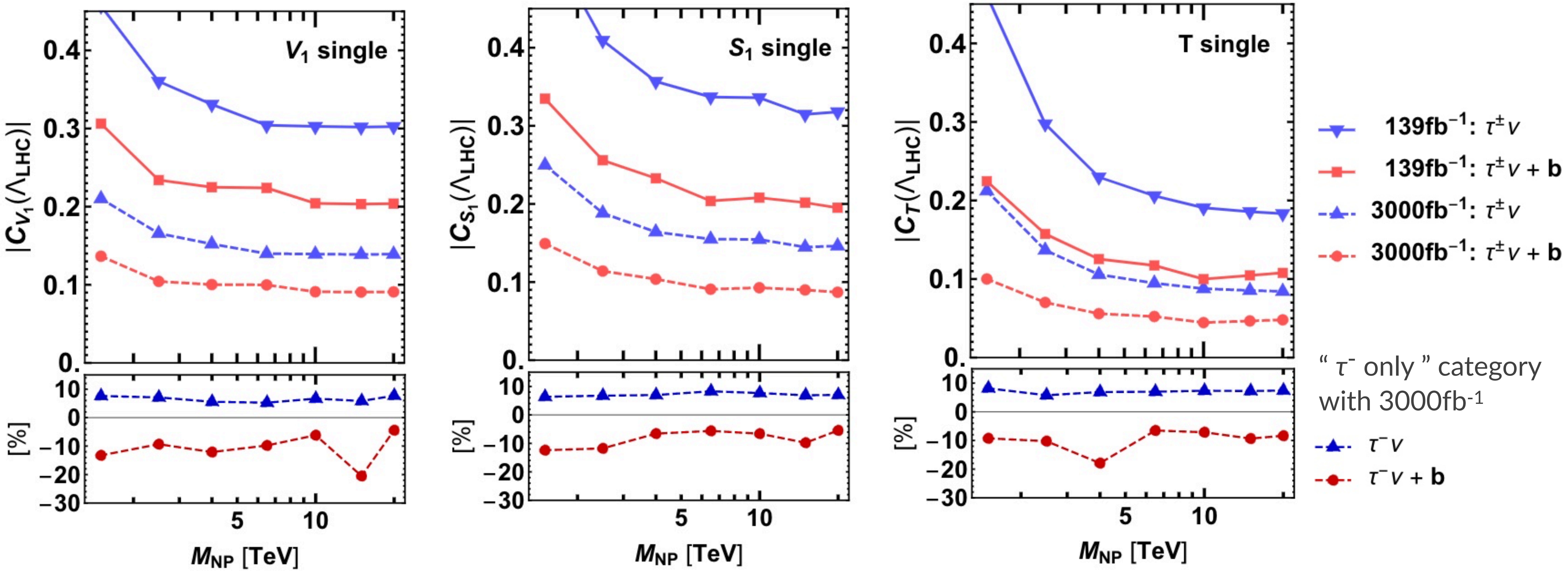
LQ signal suppresses only by a several factors

→ Signal/BG ratio can be amplified by the additional b-jet tagging

Note: stat. uncertainty becomes large

Single operator scenarios

[Endo, Iguro, TK, Takeuchi, Watanabe, PRELIMINARY]



R_2 leptoquark scenario

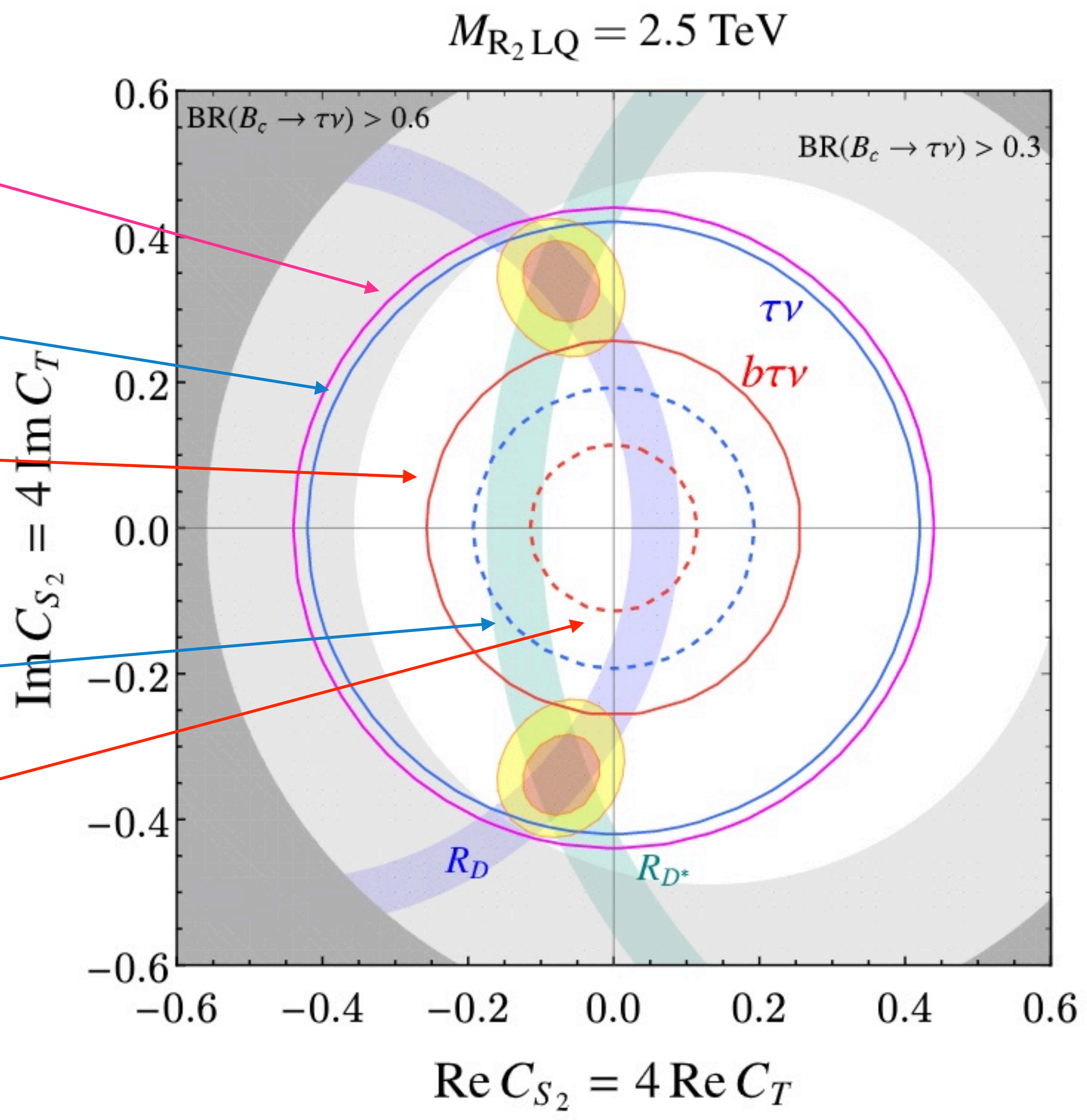
τ+MET search
36fb^{-1} exclusion

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

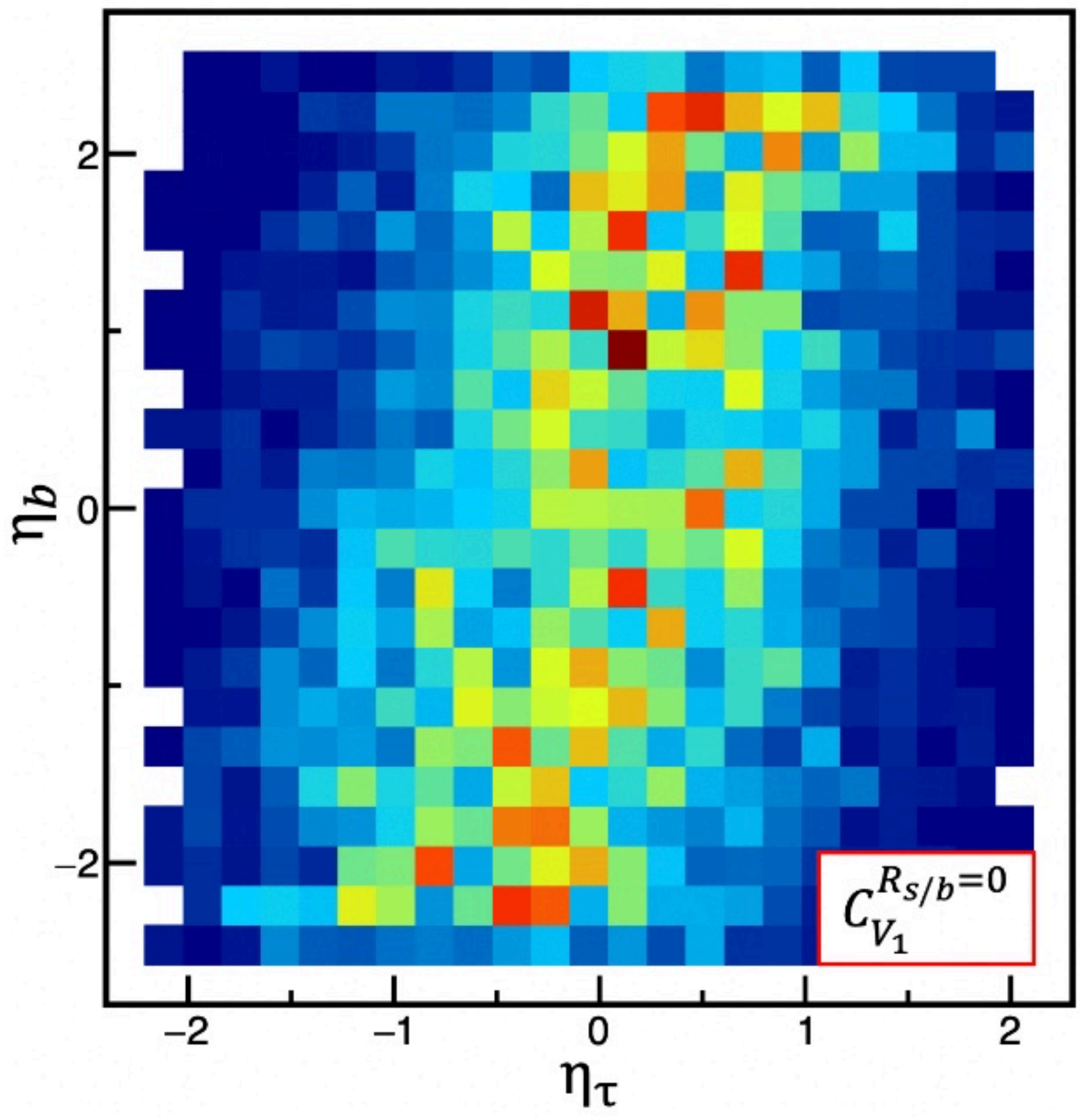


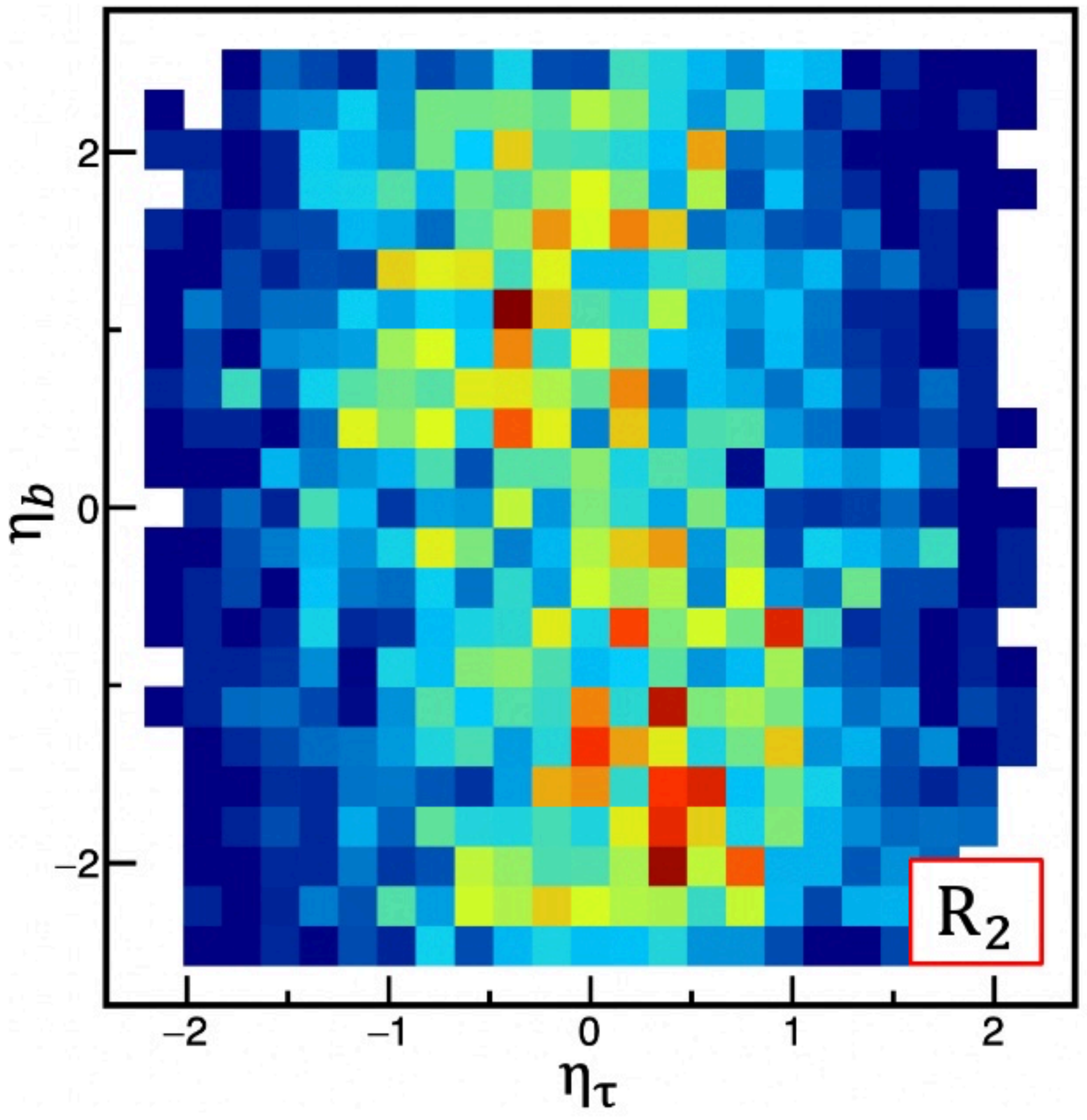
[Endo, Iguro, TK, Takeuchi, Watanabe, PRELIMINARY]

R_2 LQ scenario
can be probed
by b+tau+MET search
with Run 2 data (139fb^{-1})

Pseudorapidity distribution

[Endo, Iguro, TK, Takeuchi, Watanabe, PRELIMINARY]





Conclusions

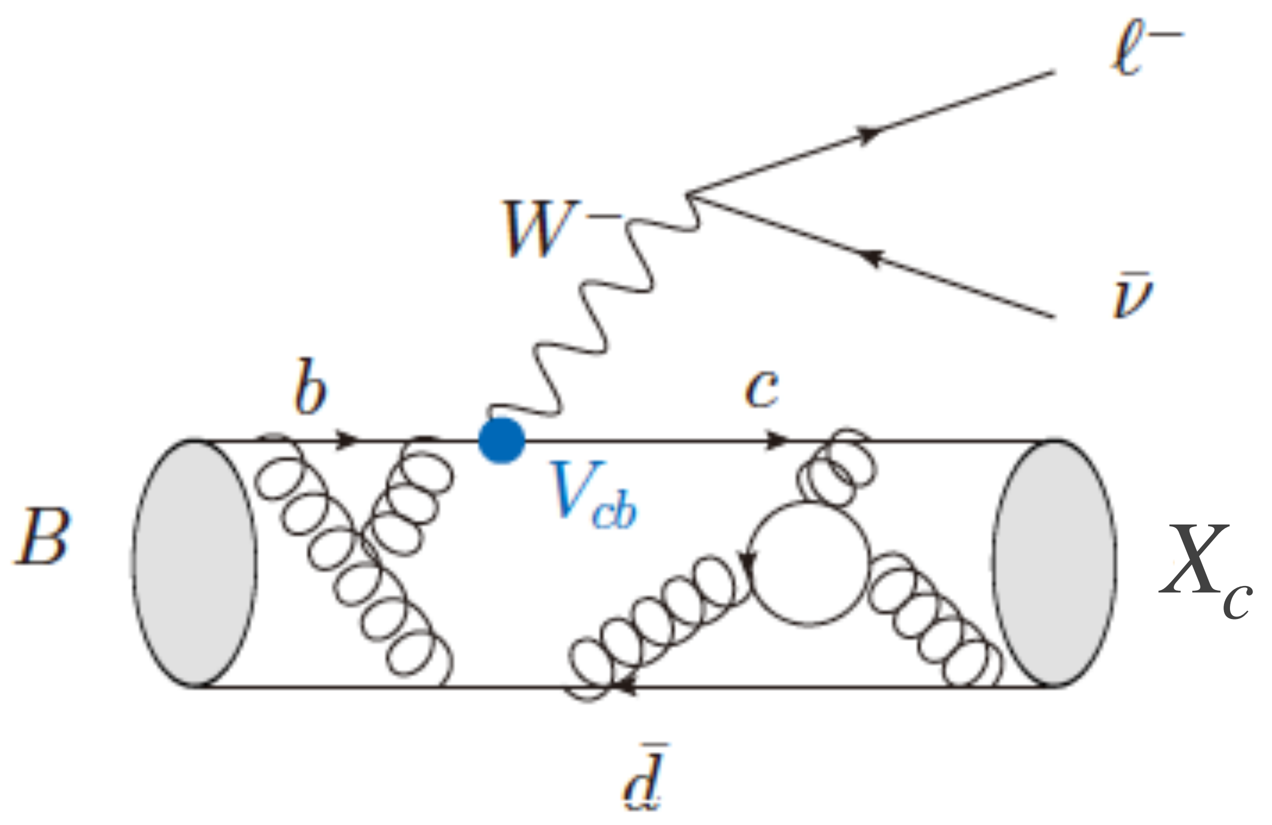
- Lepton-flavor universality violation [$R(D)$ and $R(D^{*})$ anomalies] is observed at ~4σ levels
- Several leptoquark can easily explain the $R(D)$ and $R(D^{*})$ anomalies
- We simulate the LHC sensitivity of the leptoquark indirect search via

  $pp \to \tau\nu$ and $pp \to \tau\nu + b$
- We show that additional b-jet tagging significantly improves the LHC sensitivity, and light LQ mass can relax the collider bounds.
- We also study the angular distributions of $pp \to \tau\nu + b$ to distinguish the LQ scenarios

Backup

Measurements of $|V_{cb}|$

- **For determination of $|V_{cb}|$**, one compares measured branching ratios and the theoretical formulae



$\ell = e, \mu$

Hadron states X_c
= D^{**}, D^*, D, $D\pi$, $D\pi\pi$...

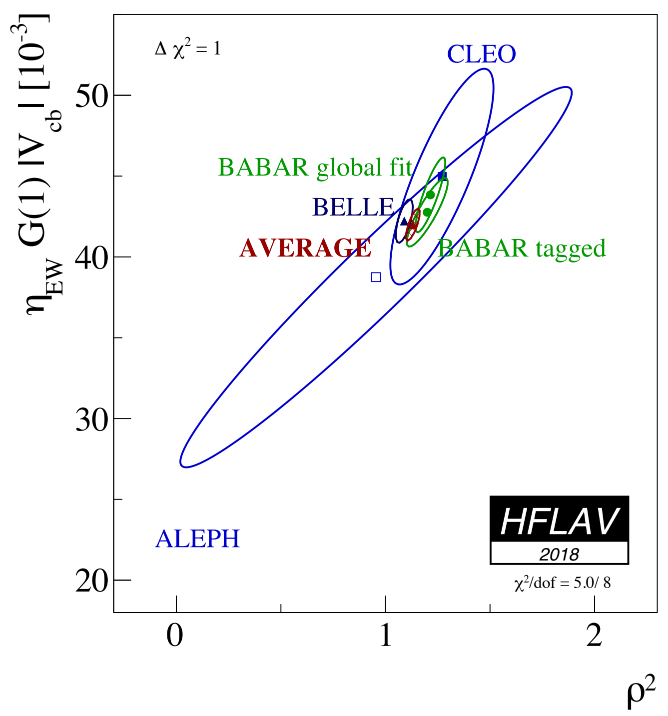
- Inclusive decays: $B \to X_c \ell \nu$
  - It corresponds to quark-level decay rate ($b \to c \ell \nu$) + α_s , Λ_{QCD}/m_b corrections
  - Last data in 2010 → Belle II result coming soon [Moriond2021, preliminary]
  - No lattice → the first lattice study [Gambino, Hashimoto, PRL '20]
- Exclusive decays: $B \to D \ell \nu, B \to D^* \ell \nu$
  - Many data with different schemes. One can use several lattice simulations.

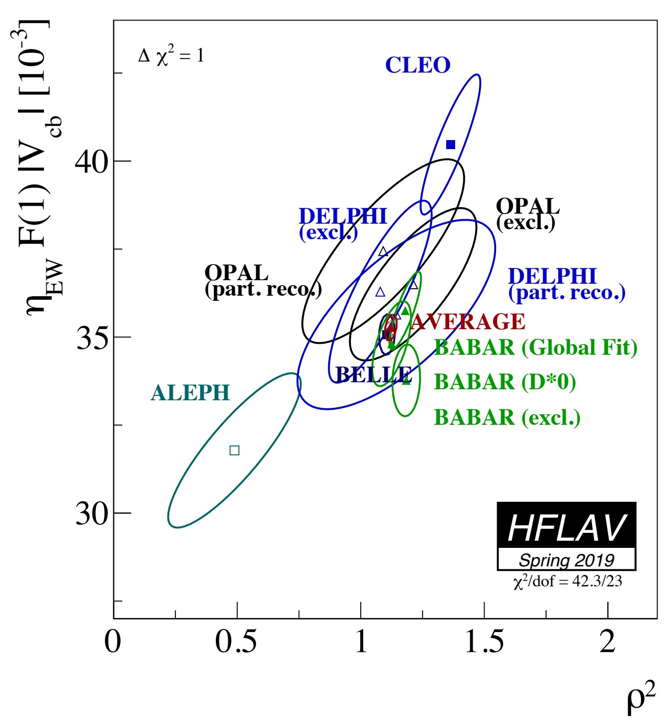
$\sim 3\sigma$ **tension** between inclusive vs. exclusive V_{cb} and V_{ub}

NP interpretation is difficult [Iguro, Watanabe, 2004.10208]

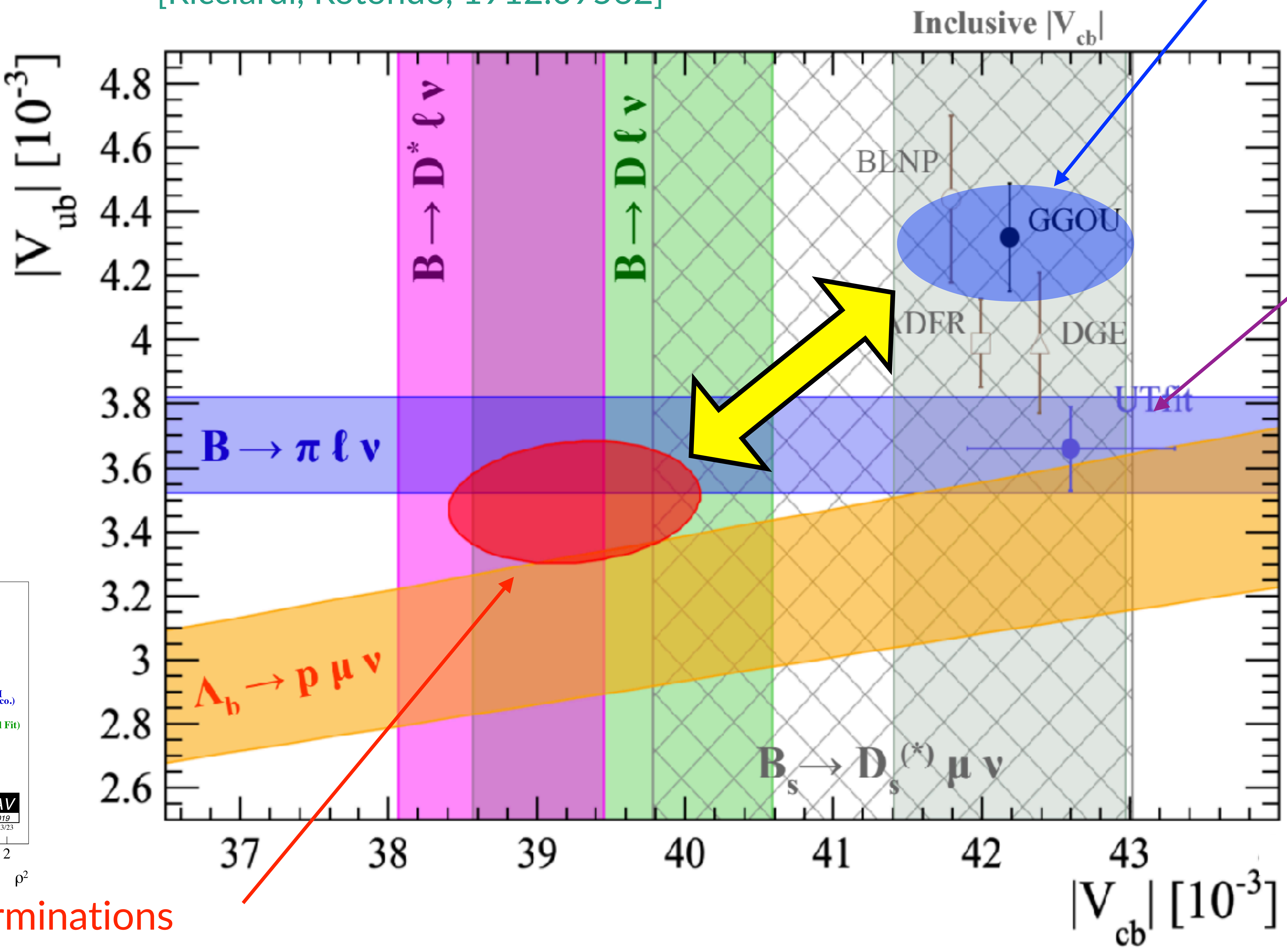
[HFLAV 2019, based on CLN]

$B \to D \ell \nu$ $\quad$ $B \to D^* \ell \nu$





[Ricciardi, Rotondo, 1912.09562]



Average of the inclusive determinations

Kaon physics prefers inclusive V_{cb}

CKM unitarity

Belle II preliminary result [Moriond2021]
Inclusive Vcb
$= 41.7\,(12) \times 10^{-3}$

Belle preliminary [ICHEP2020]
Inclusive Vub
$= 4.06\,(24) \times 10^{-3}$

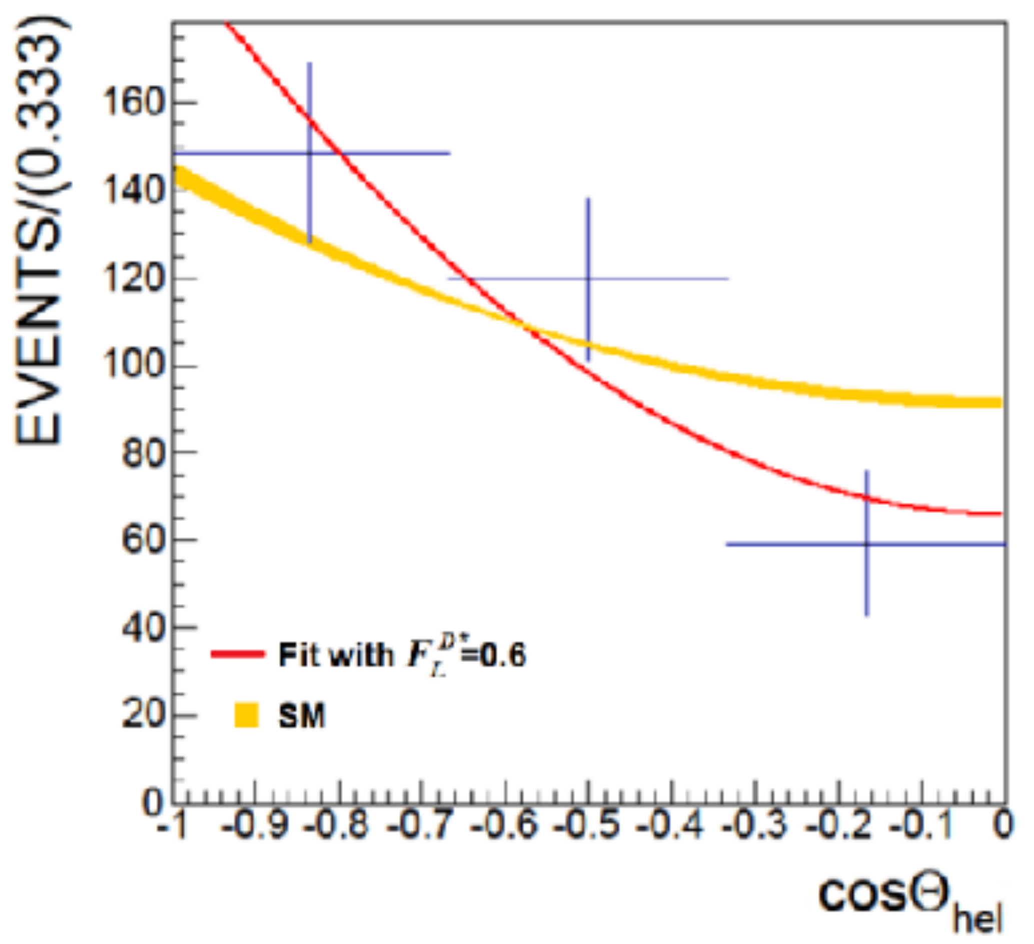
Average of the exclusive determinations

Polarization observables in $b \to c\tau\nu$

- The following two polarization observables could be important to confirm/distinguish new physics
  - Longitudinal D^* polarization ($D^* \to D\pi$)

$$F_L(D^*) = \frac{\Gamma(B \to D_L^* \tau\nu)}{\Gamma(B \to D^* \tau\nu)}$$

θ_{hel} is the angle between D and B in the D^* rest frame



[Belle, 1903.03102]

1.4 σ consistent

  - τ polarization asymmetry along the longitudinal directions of τ ($\tau \to \pi\nu,\ \rho\nu$) [Tanaka, ZPC '95]

$$P_\tau(D^{(*)}) = \frac{\Gamma\left(B \to D^{(*)}\tau^{\lambda=+1/2}\nu\right) - \Gamma\left(B \to D^{(*)}\tau^{\lambda=-1/2}\nu\right)}{\Gamma\left(B \to D^{(*)}\tau\nu\right)}$$

Fit of angle dependence: between π, ρ and $W^*(\tau\nu)$ in τ rest frame

Predicted ranges of polarization observables

- Polarization observables can discriminate these LQ scenarios
  [Iguro, TK, Omura, Watanabe, Yamamoto, '19, **UPDATED**]

[Predicted ranges]

		$F_L^{D^*}$	P_τ^D	$P_\tau^{D^*}$	R_D	R_{D^*}
[Predicted ranges]	R_2 LQ	[0.442, 0.447]	[0.336, 0.456]	[−0.464, −0.424]	1 σ data	1 σ data
	S_1 LQ	[0.436, 0.481]	[−0.006, 0.489]	[−0.512, −0.450]	1 σ data	1 σ data
	U_1 LQ	[0.440, 0.459]	[0.156, 0.422]	[−0.542, −0.488]	1 σ data	1 σ data
	SM	0.46(4)	0.325(9)	−0.497(13)	0.299(3)	0.258(5)
	data	0.60(9)	-	−0.38(55)	**0.340(30)**	**0.295(14)**
(50 ab^{-1})	Belle II	0.04	3%	0.07	3%	2%

- $P_\tau(D)$ can well discriminate the new physics

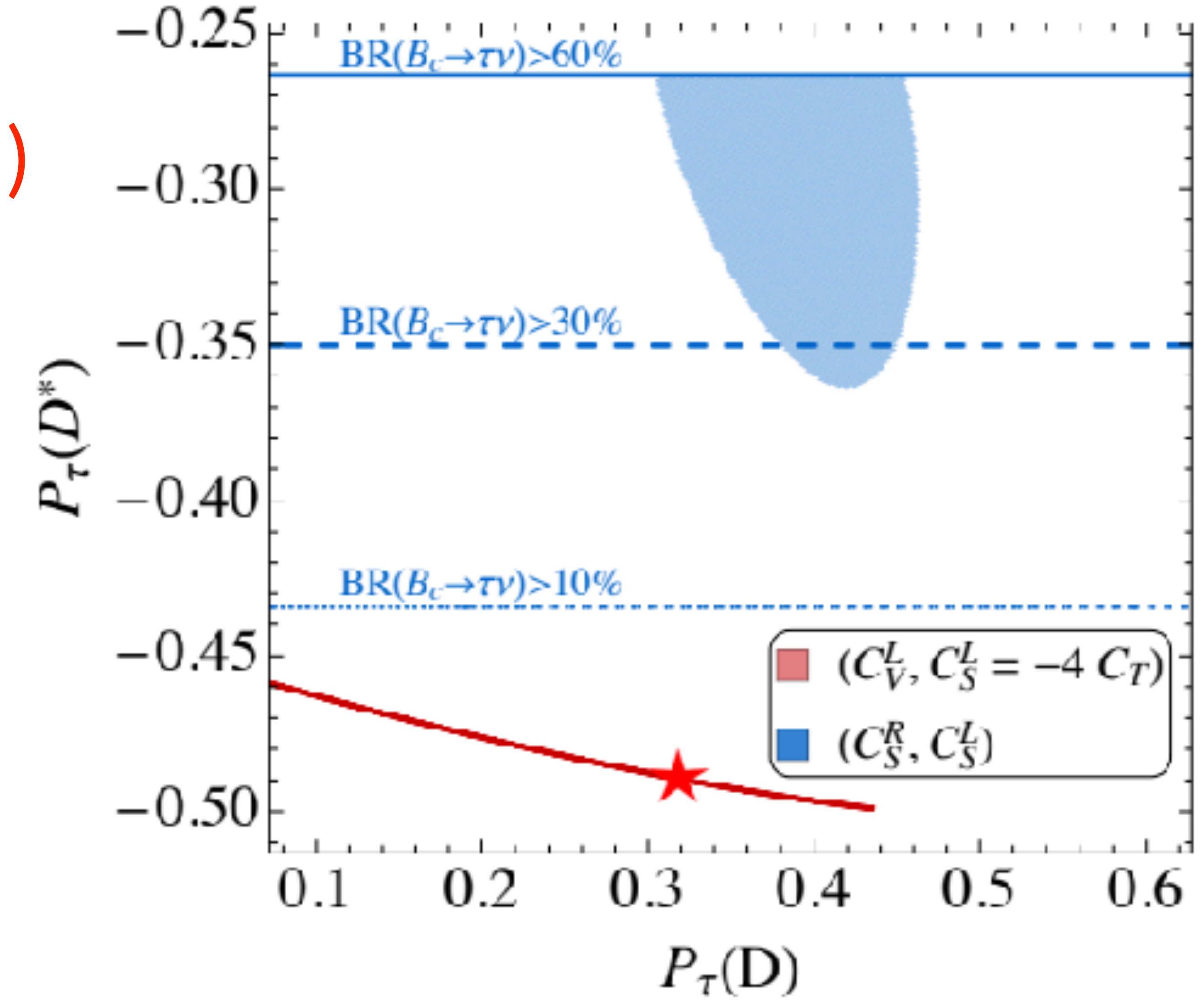
- LHC mono-τ search gives more severe bound than BR$(B_c^+ \to \tau^+\nu) < 30\,\%$

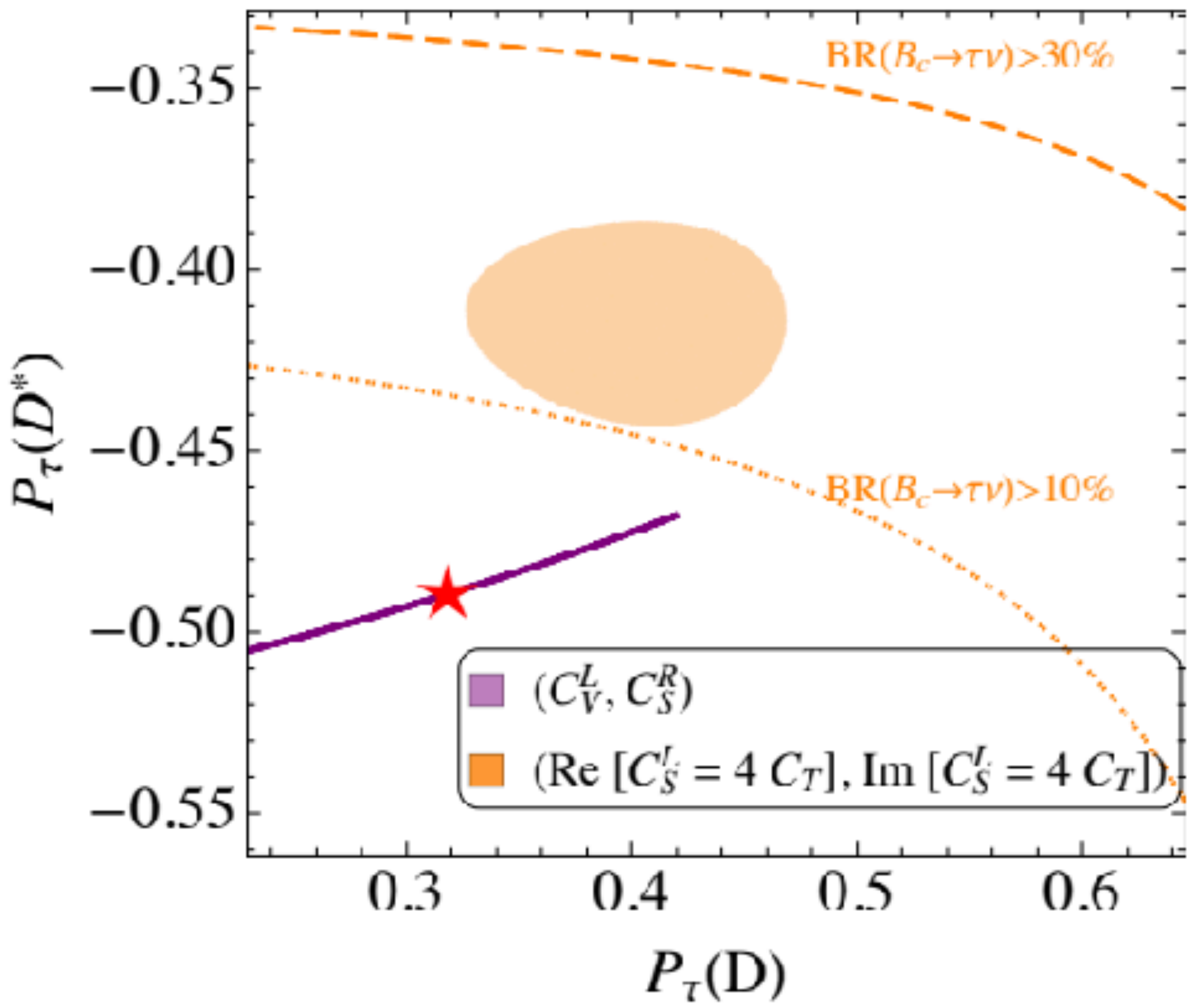
[Blanke, Crivellin, TK, Moscati, Nierste, Nisandzic, PRD ’19]

SU(2)L-singlet scalar LQ (S_1)

Charged Higgs

$\boldsymbol{P_\tau(D)}$ vs. $\boldsymbol{P_\tau(D^*)}$



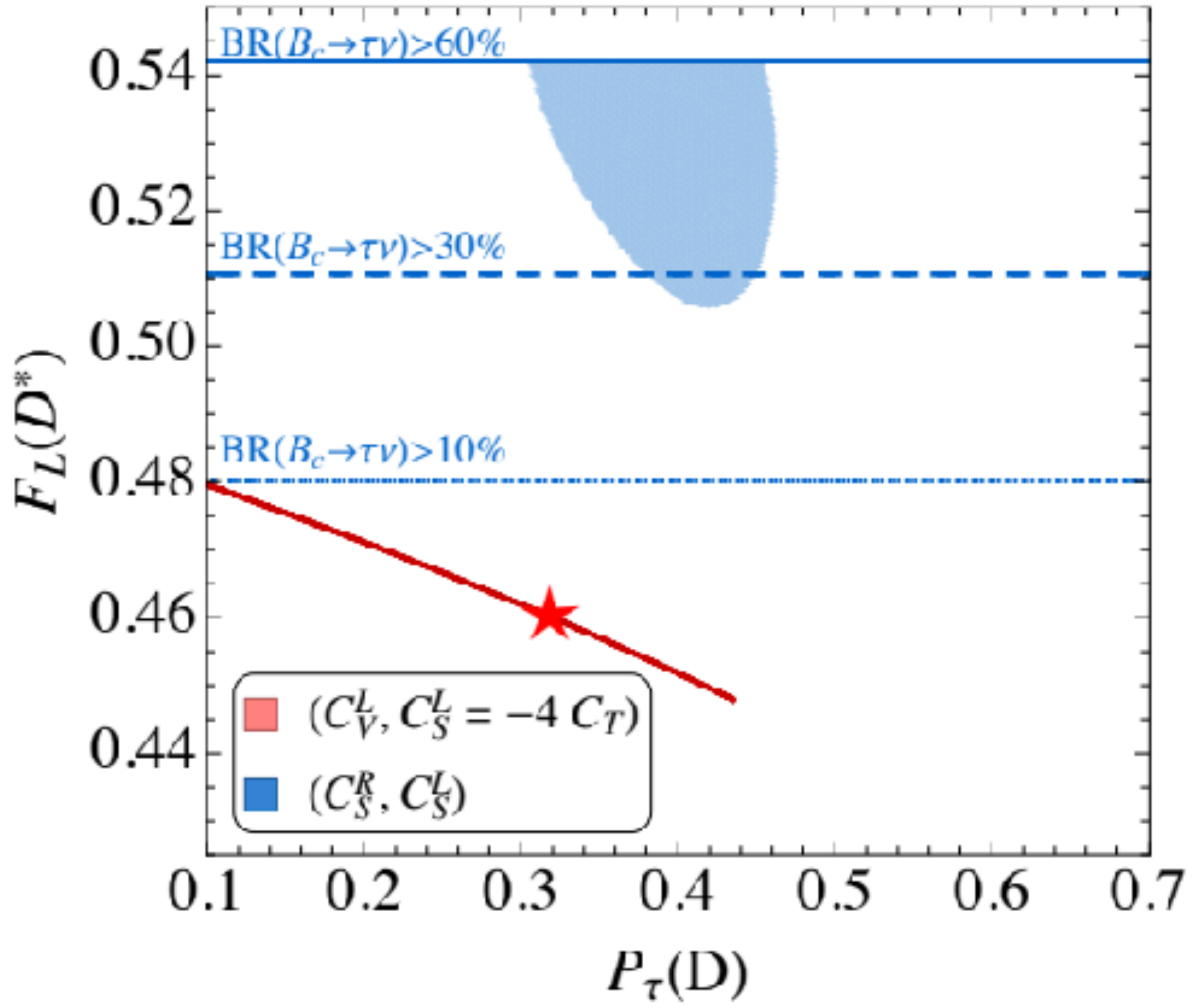


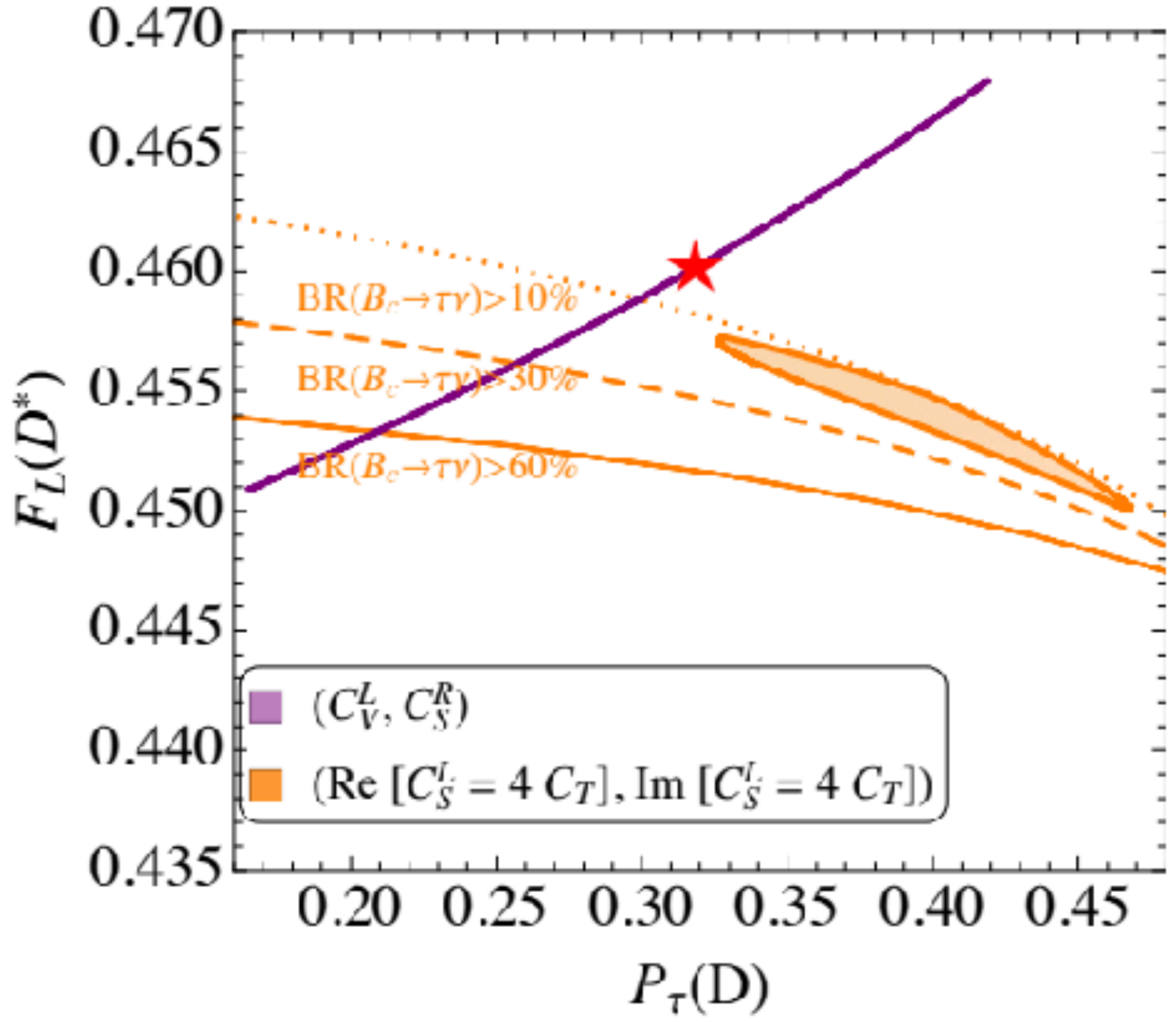
SU(2)L-singlet vector LQ (U_1)

SU(2)L-doublet scalar LQ (R_2)

$P_\tau(D)$ can discriminate the new physics

$\boldsymbol{P_\tau(D)}$ vs. $\boldsymbol{F_L(D^*)}$





$P_\tau(D^*)$ could discriminate the new physics

$F_L(D^*)$ is difficult to discriminate them

Tensor operator vs. $F_L(D^*)$

- Tensor operator in new physics scenario is significantly constrained by $F_L(D^*)$

[Iguro, TK, Omura, Watanabe, Yamamoto, '19, UPDATED]

$$\mathcal{H}_{\rm eff} = 2\sqrt{2} G_F V_{cb} C_T(\mu) \, (\bar{c}\sigma^{\mu\nu} P_L b)\, (\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$

$$C_{T,\,\rm SM} = 0$$

$$F_L(D^*) = 0.60 \pm 0.08 \pm 0.04$$

[Belle, 1903.03102]