New physics interpretations of $R(D^{(*)})$ anomaly and their exciting predictions

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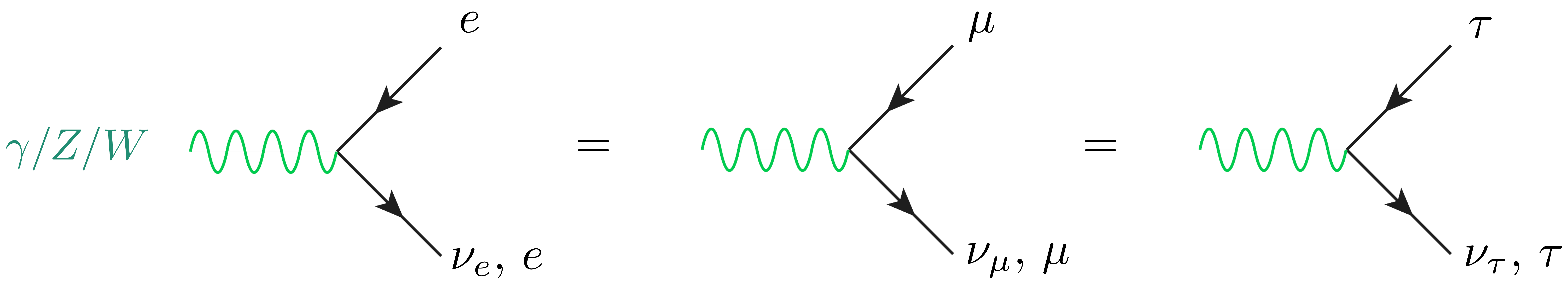
Test of Lepton Flavor Universality (LFU)

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



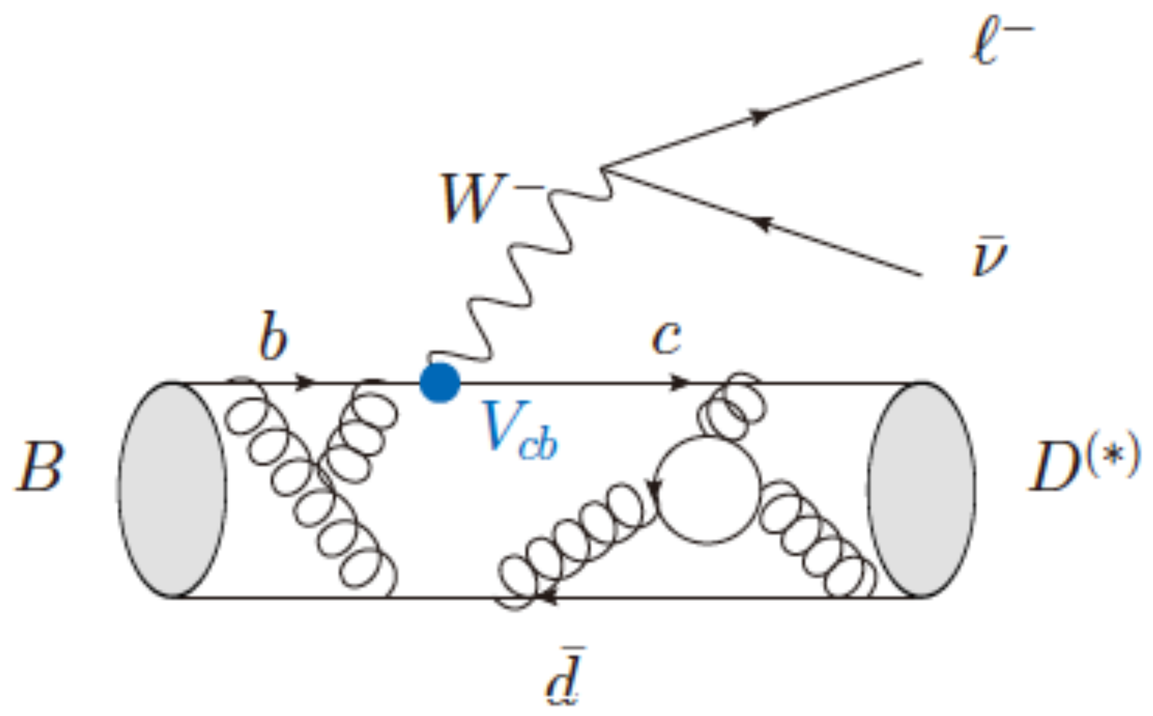
- Only **charged-lepton mass** (+QED corrections) violates the LFU within the SM

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

Lepton-flavor-universality observables: *R*(*D*) and *R*(*D**)

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

$(\ell = e\,,\mu)$



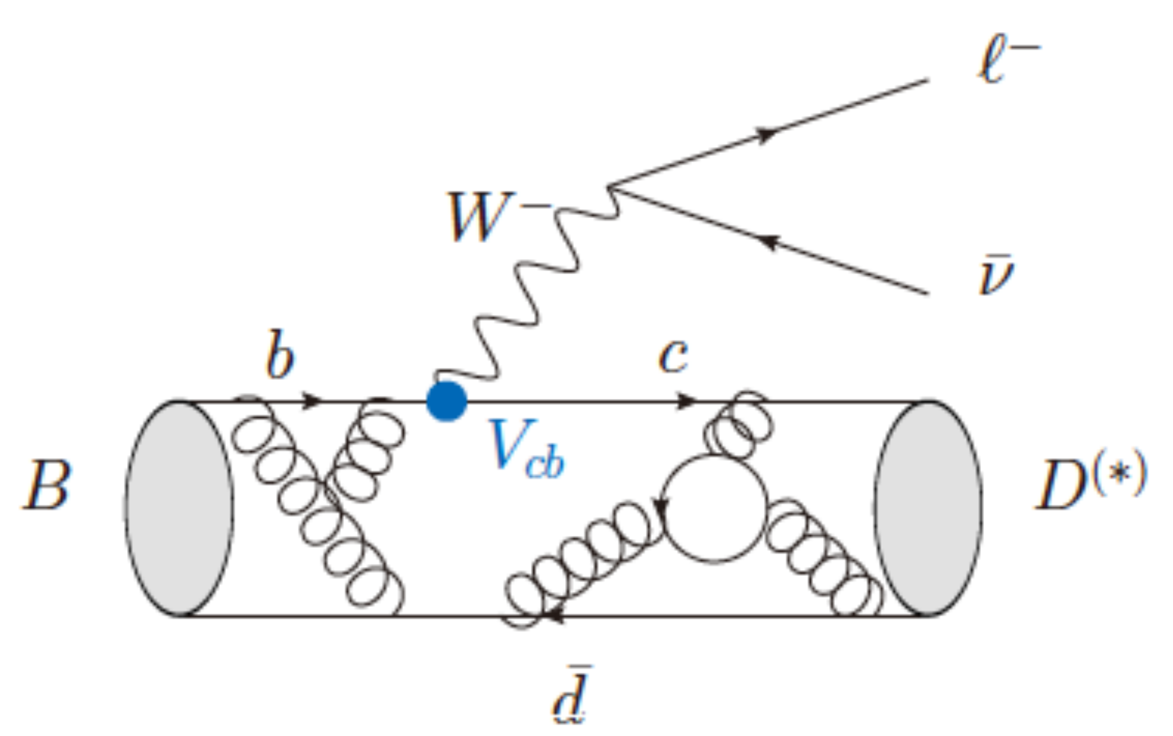
Experiment	R_{D^*}	R_D	Correlation
BaBar	$0.332 \pm 0.024 \pm 0.018$	$0.440 \pm 0.058 \pm 0.042$	-0.27
Belle	$0.293 \pm 0.038 \pm 0.015$	$0.375 \pm 0.064 \pm 0.026$	-0.49
Belle	$0.270 \pm 0.035^{+0.028}_{-0.025}$	–	–
Belle	$0.283 \pm 0.018 \pm 0.014$	$0.307 \pm 0.037 \pm 0.016$	-0.51
LHCb 2022Oct	$0.281 \pm 0.018 \pm 0.024$	$0.441 \pm 0.060 \pm 0.066$	-0.43
LHCb 2023Mar	$0.257 \pm 0.012 \pm 0.018$	–	–
World average	$0.284 \pm 0.008 \pm 0.010$	$0.356 \pm 0.024 \pm 0.016$	-0.37

P-value= 0.25; implying data are consistent

Lepton-flavor-universality observables: *R*(*D*) and *R*(*D**)

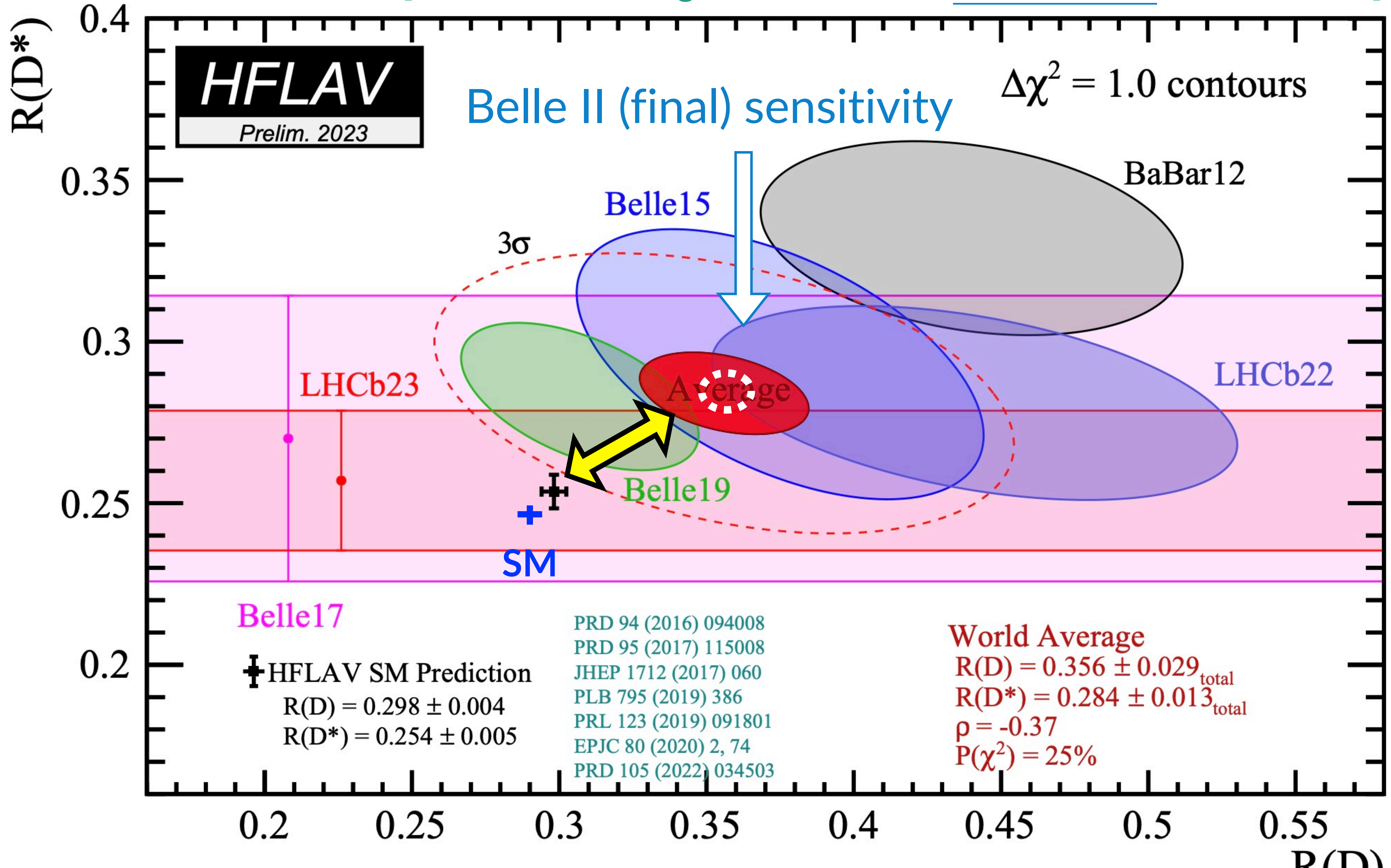
$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\bar{\tau}\nu_\tau)}{\mathrm{BR}(B \to D^{(*)}\bar{\ell}\nu_\ell)}$$

$(\ell = e\,,\mu)$



$b \to c\tau\nu$ anomaly

[HFLAV 2023 + Iguro, Watanabe, 2004.10208 for SM value]



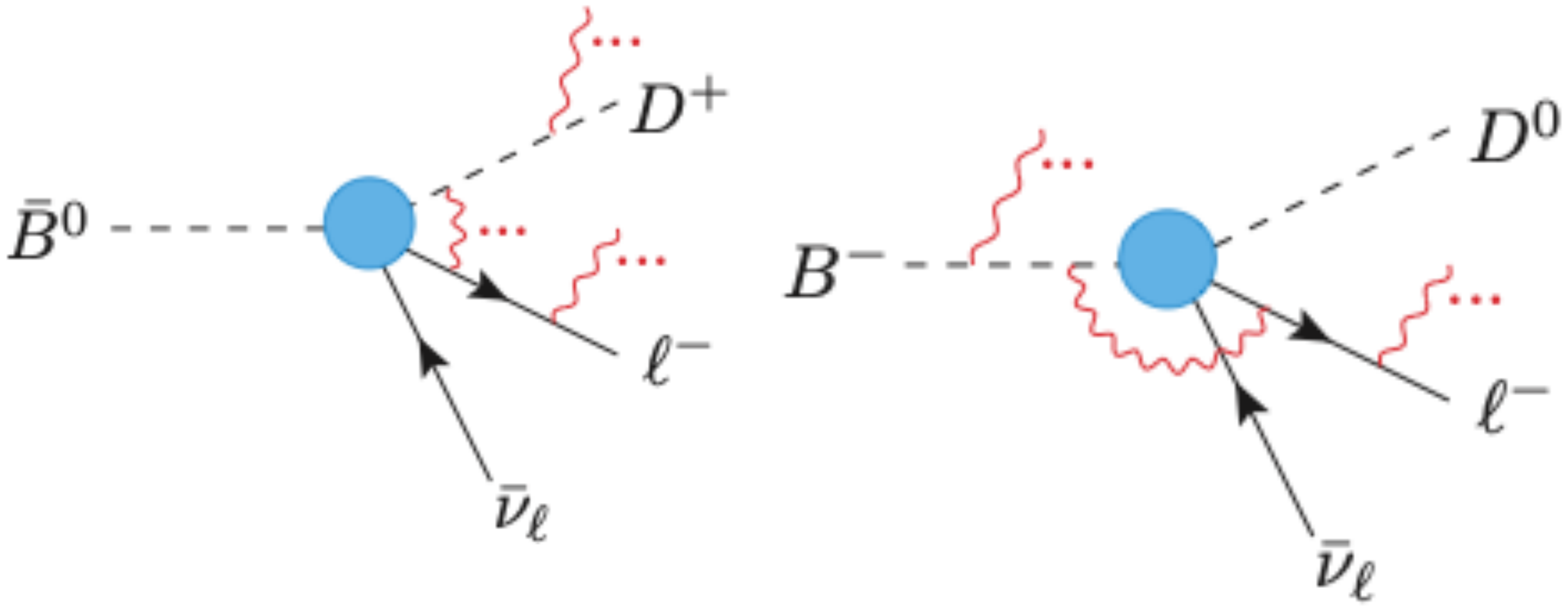
3.2–4σ tension *B* anomaly; violation of LFU

QED correction within the SM

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

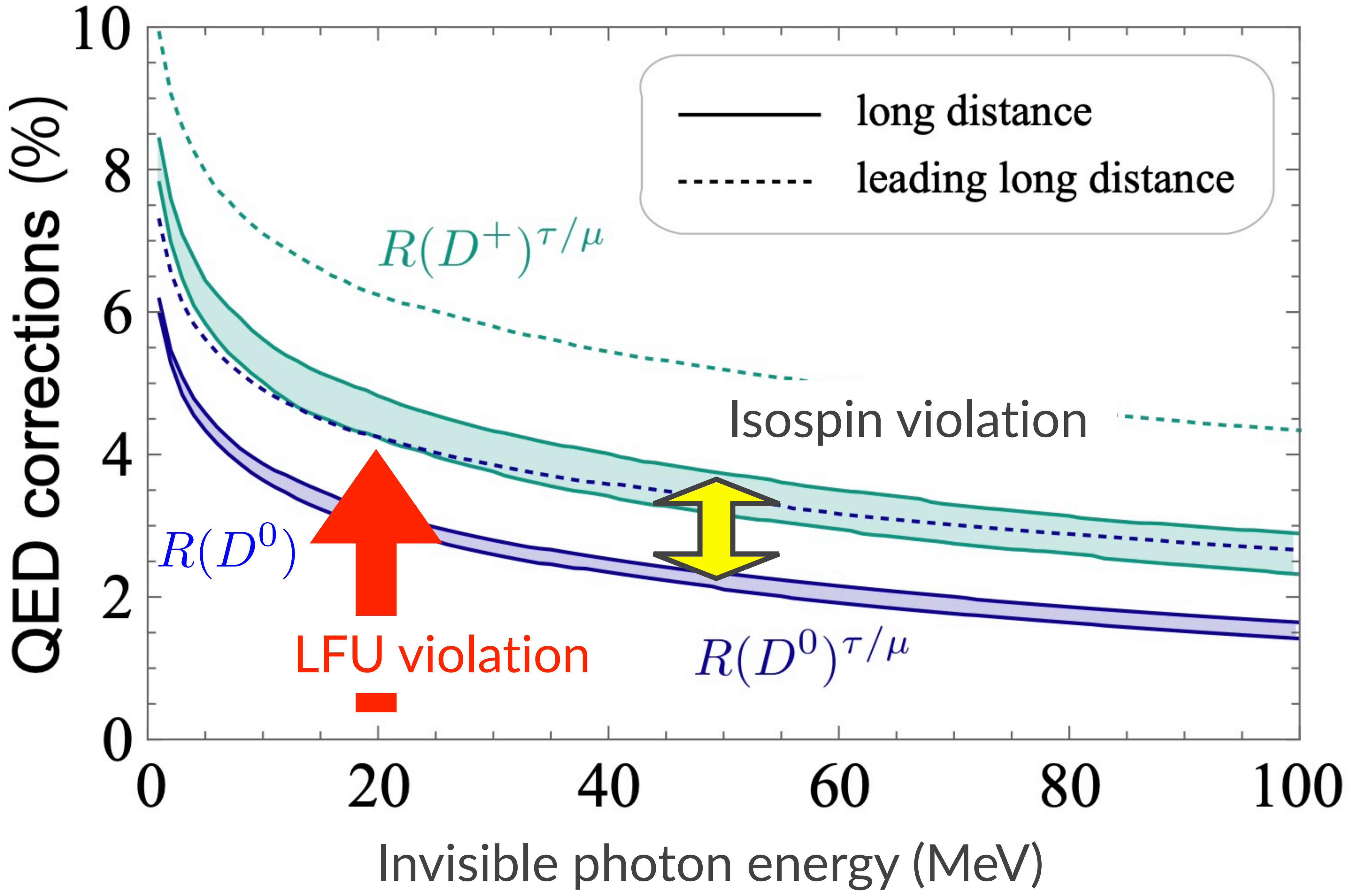
  [de Boer, TK, Nisandzic, 1803.05881; Calí, et al, 1905.02702; Isidori, Nabeebaccus, Zwicky, 2009.00929]

  Note that $B \to D\ell\nu$ measurements are not soft-photon inclusive



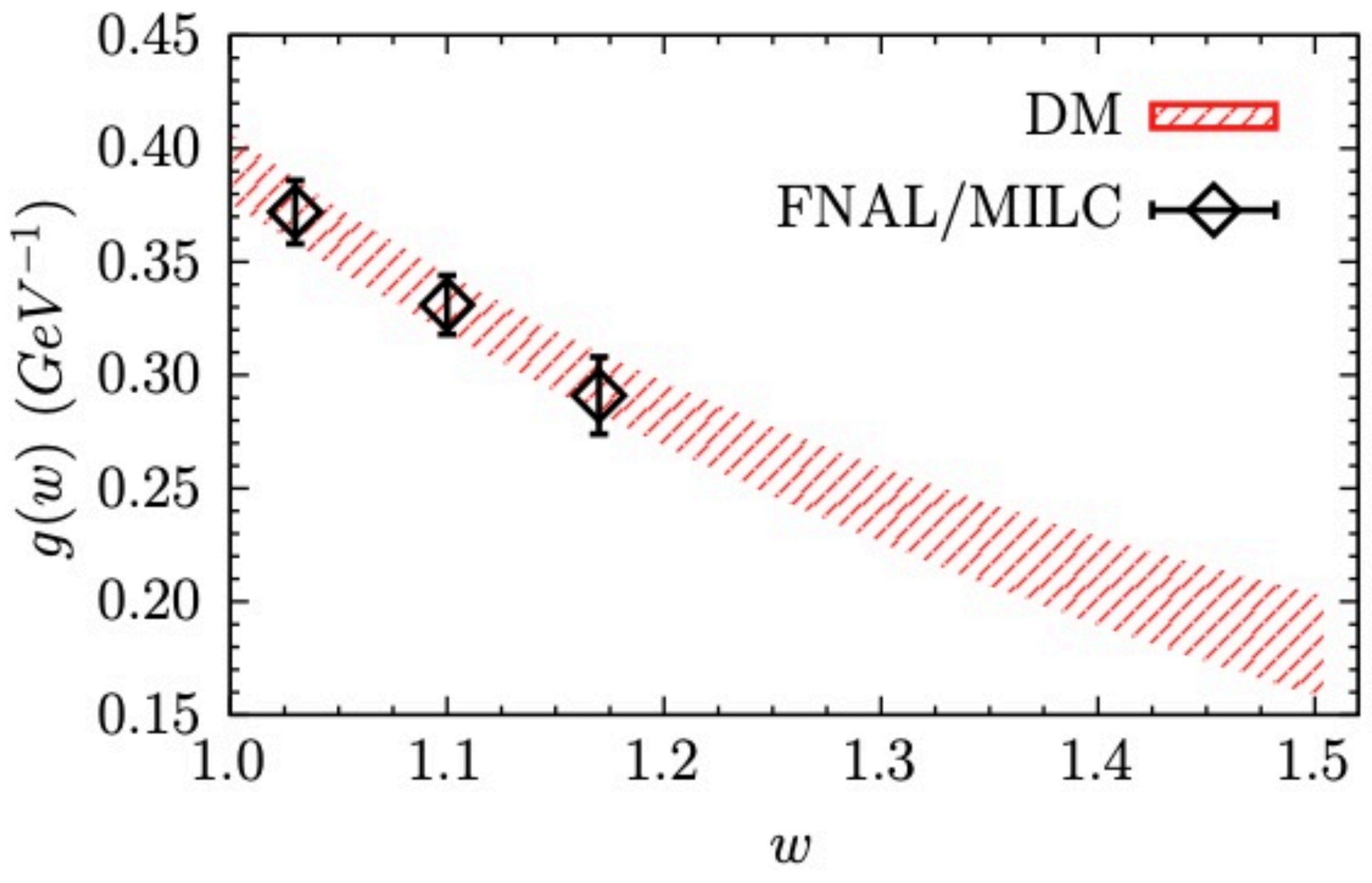
The QED corrections depend on the lepton velocities; non-rela τ vs relativistic $\mu \to$ *opposite sign*

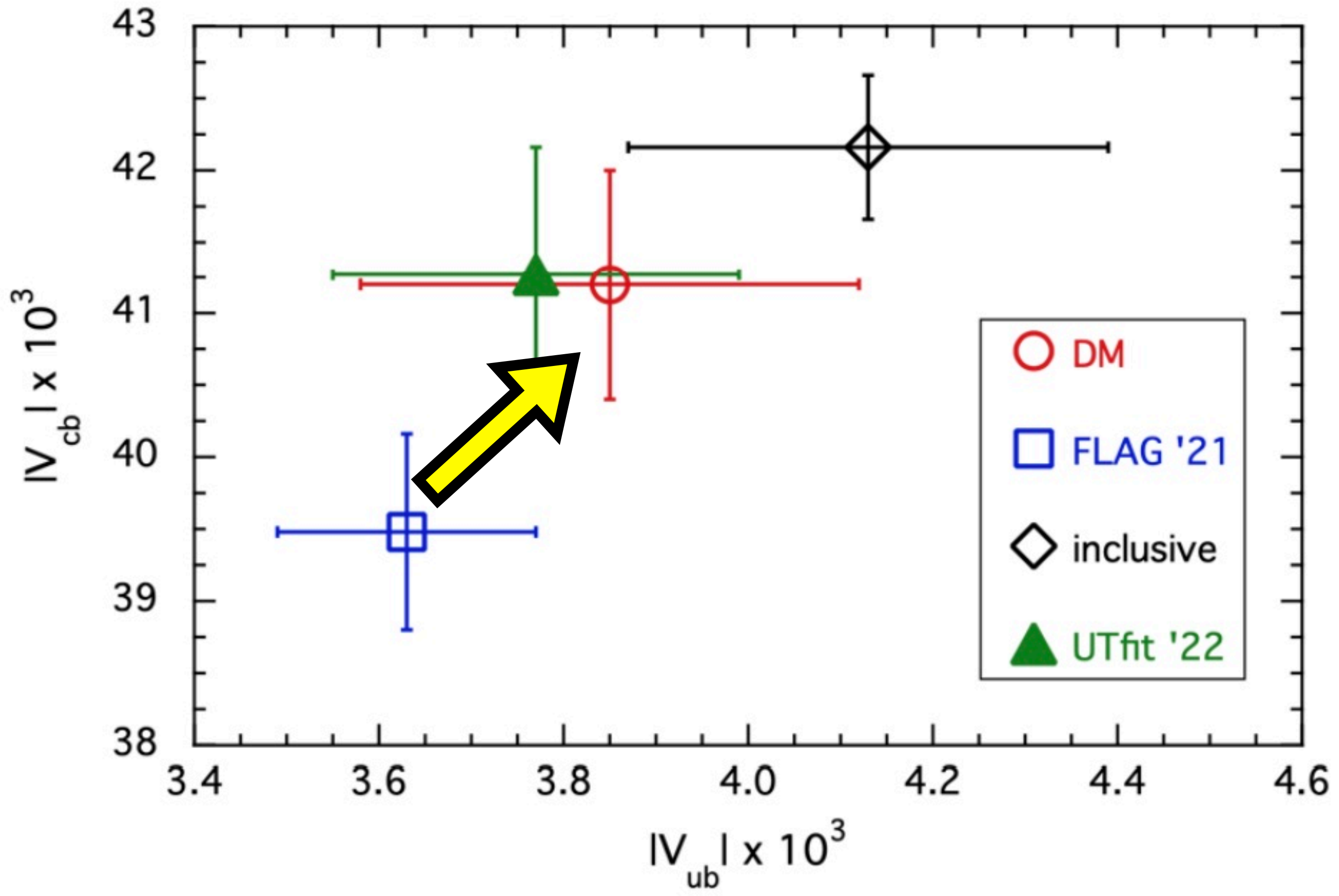
Soft-photon interference (FS-FS & IS-FS) is significant, see slide

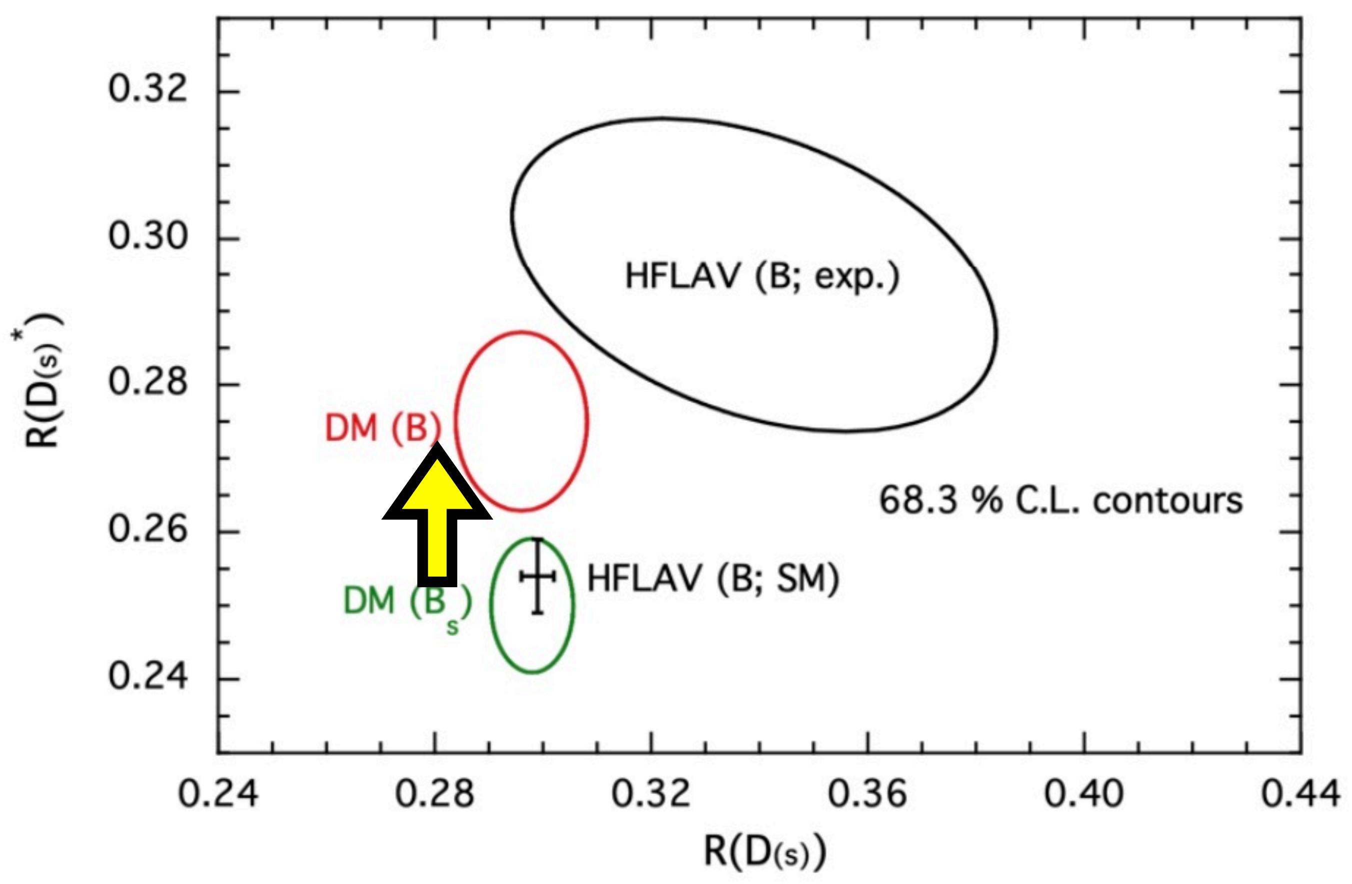


Recent progress in SM: Dispersion matrix approach

- Dispersion matrix approach is novel form factor's description for $B \to D^{(*)}$
- Based on the lattice QCD data only. By applying the unitarity condition, one can extract the form factors for all q^2 region with non-perturbative and model-independent manner
- No experimental data are needed [Di Carlo, et al, 2105.02497; Martinelli, et al, 2105.07851]



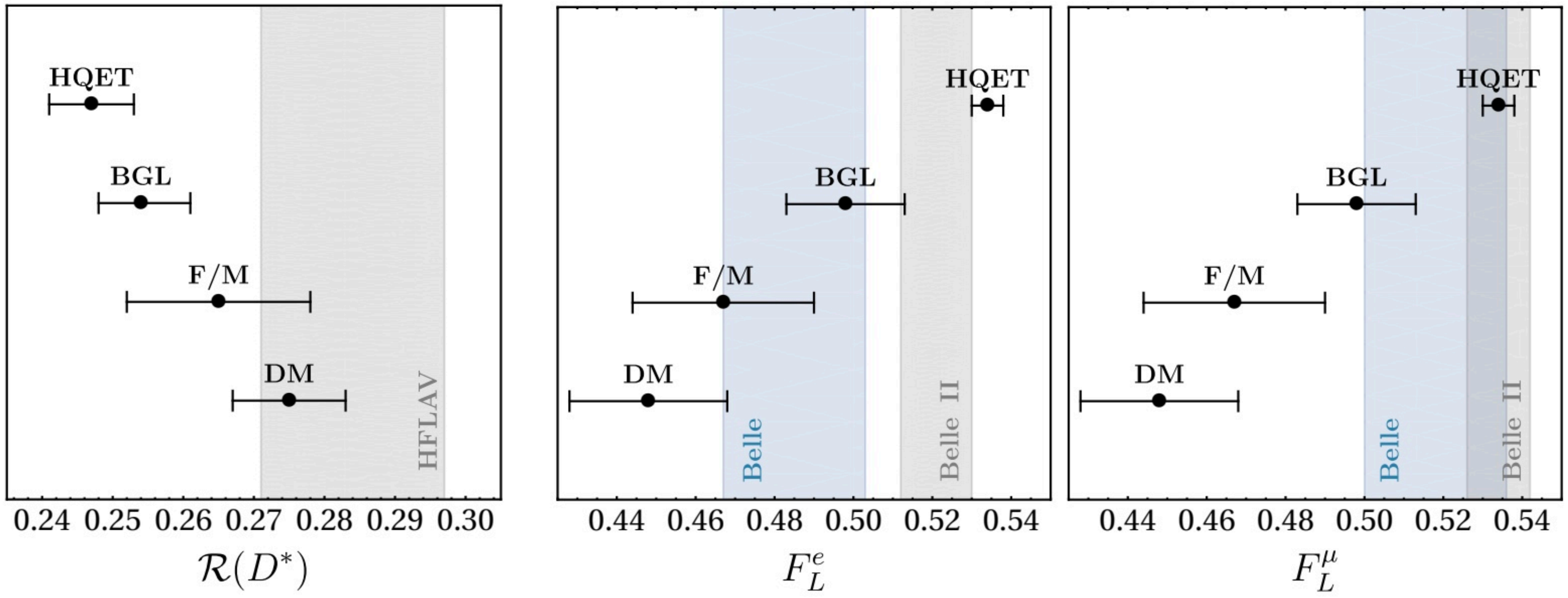


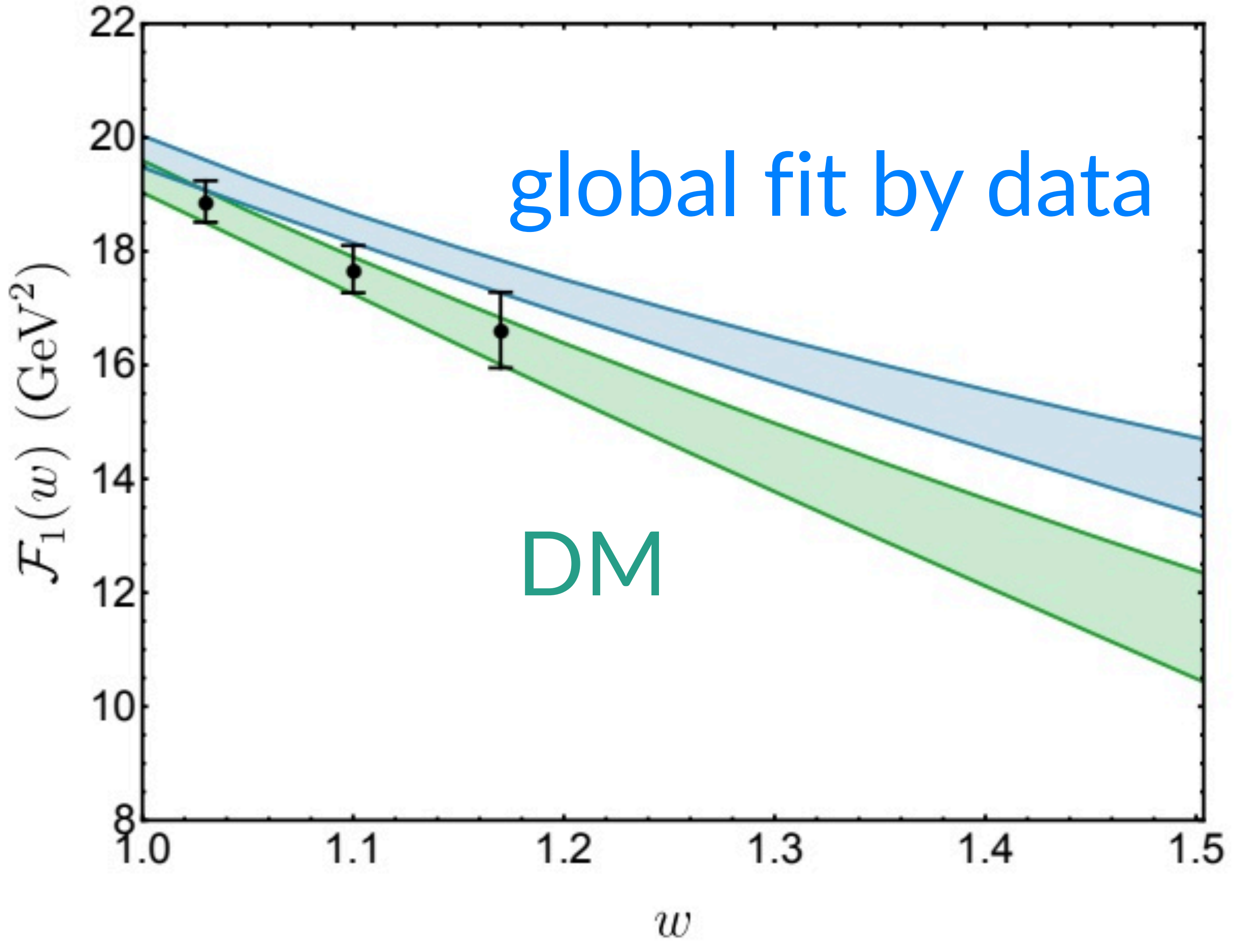


Recent progress in SM: Dispersion matrix approach

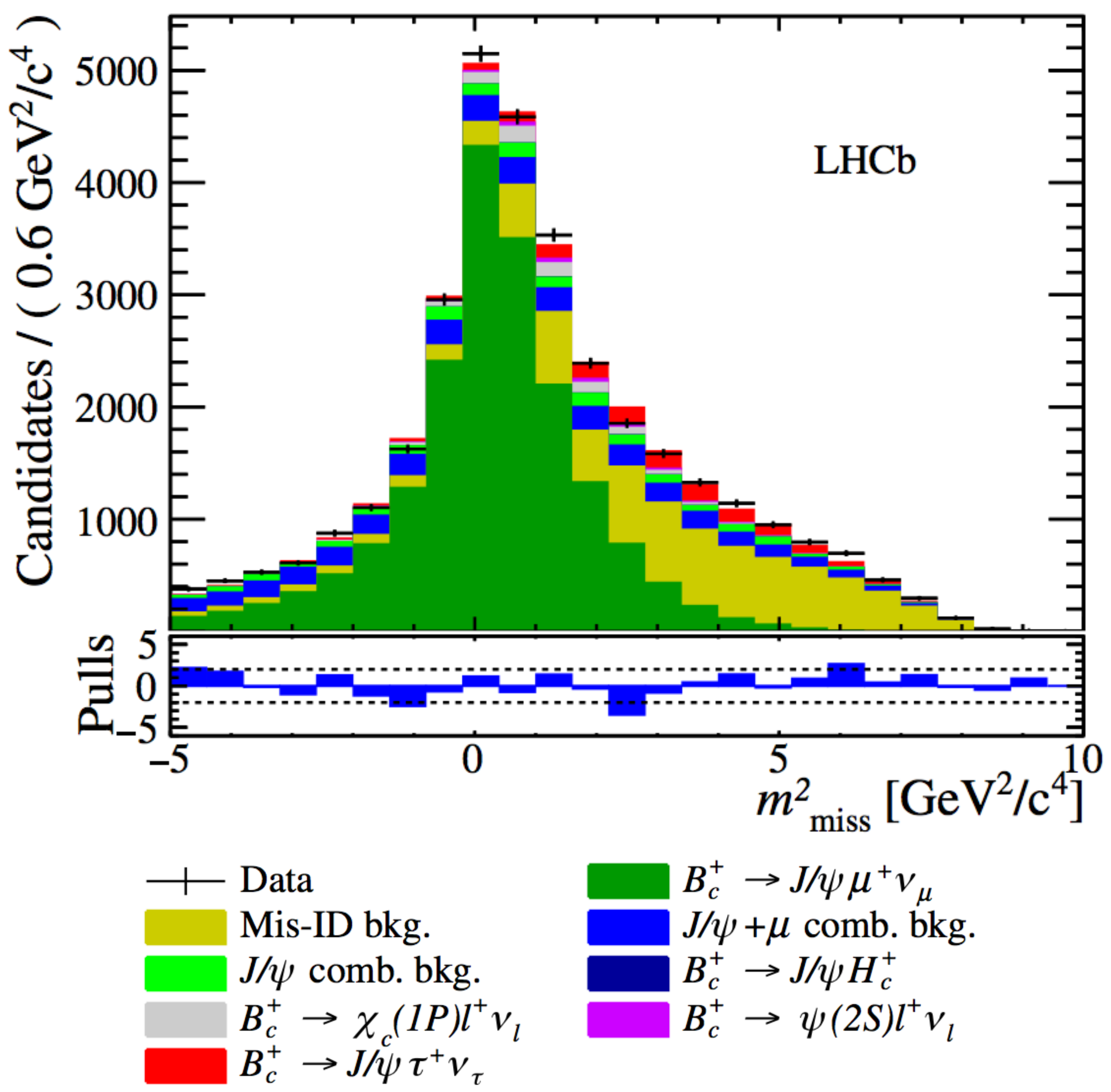
- It is pointed out that there are 3σ tension in the dispersion matrix approach with light-lepton data [Fedele, et al, 2305.15457]

D^* longitudinal polarization fraction



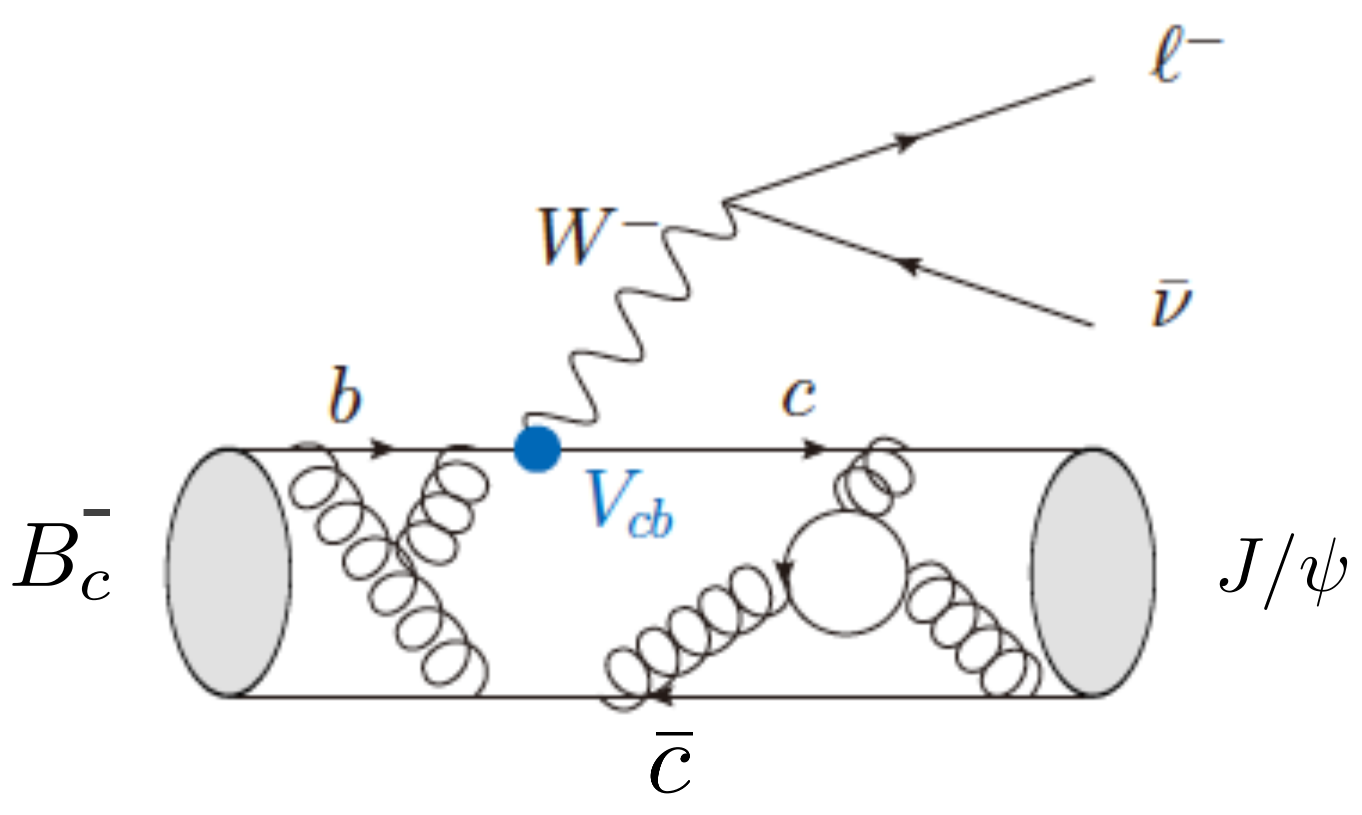


Related channel: *R(J/ψ)*



- The LFU violation was also observed in $B_c^- \to J/\psi$

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



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

$R(J/\psi)_{\rm SM} = 0.258 \pm 0.004$ Based on first lattice result [HPQCD, 2007.06956]

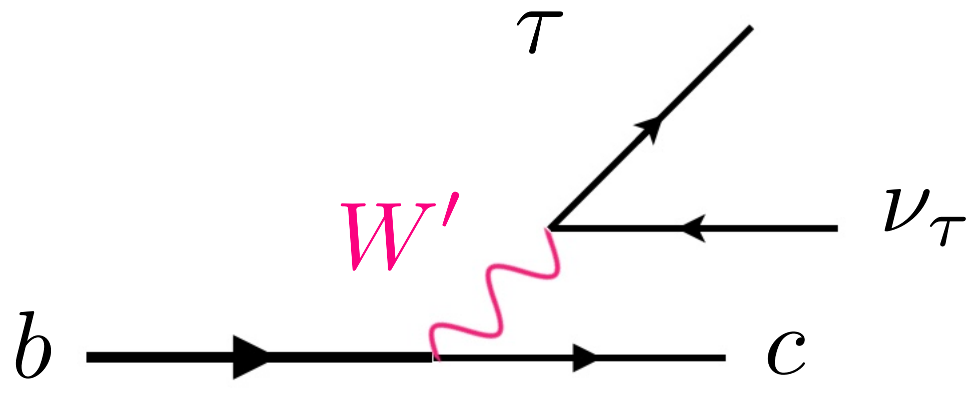
using N_f=2+1+1, with "HISQ" *c* and heavy quark *b*

1.8σ consistent

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

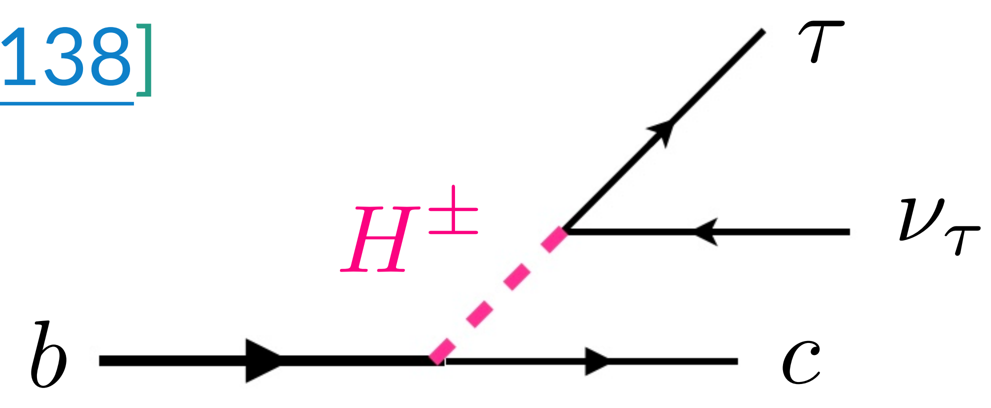
New physics interpretations of $b \to c\tau\nu$ anomaly

- **W' (additional SU(2) gauge symmetry)**



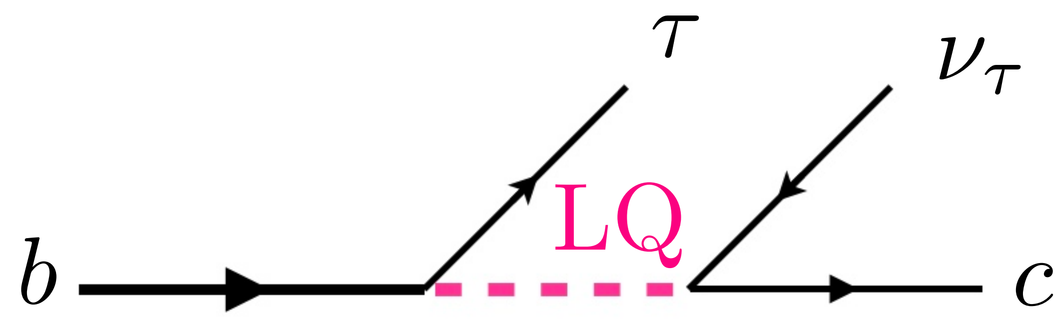
  - Severely constrained from ΔM_s (B_s^0-$\bar{B}_s^0$ mixing), $W' \to \tau\nu$ search [Abdullah, et al, 1805.01869] and $Z' \to \tau\tau$ search [Faroughy, Greljo, Kamenik, 1609.07138]

- **Charged-Higgs with generic flavor structure**



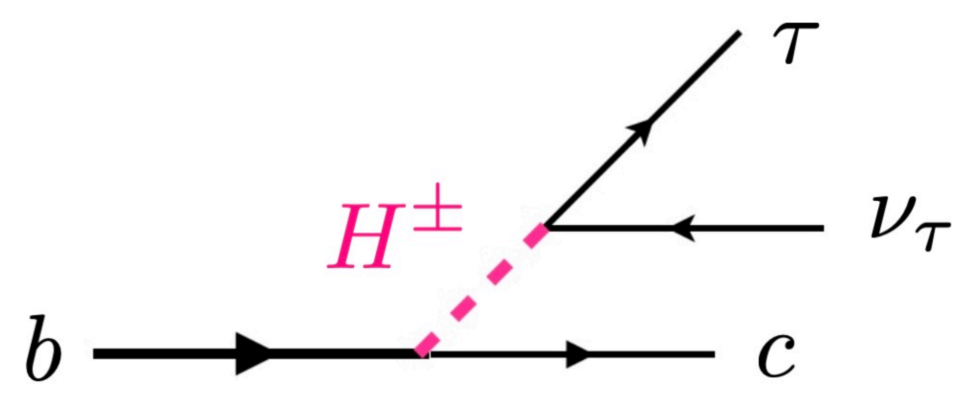
  - Constrained from BR($B_c \to \tau\nu$) and $H^\pm \to \tau\nu$ search, but still allowed [Blanke, Iguro, Zhang, 2202.10468; Iguro,2201.06565, 2302.08935] (next slide)

- **Leptoquark (LQ)**

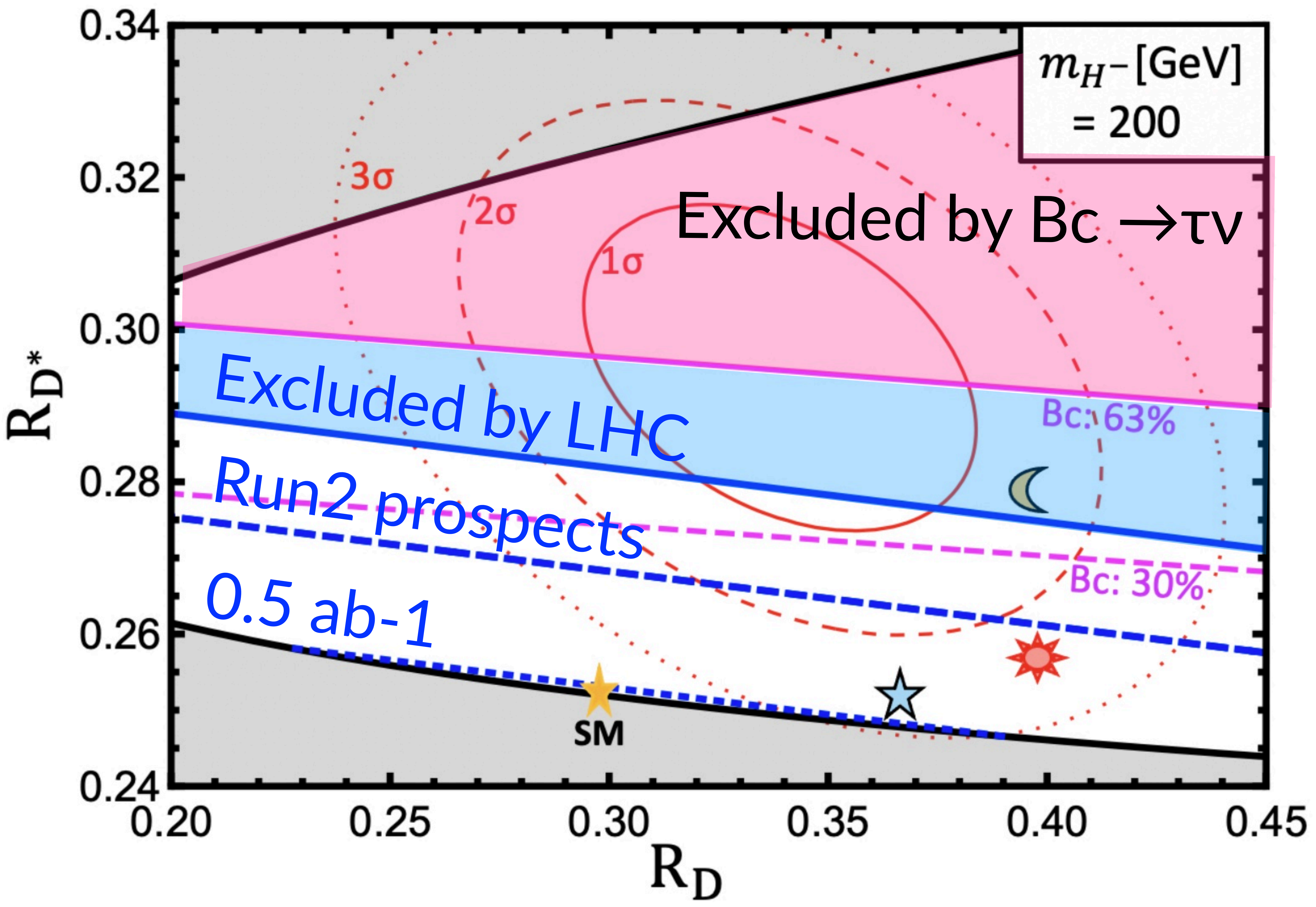


  - Collider bound comes from $pp \to$ LQ LQ*, and broad parameter regions are still allowed

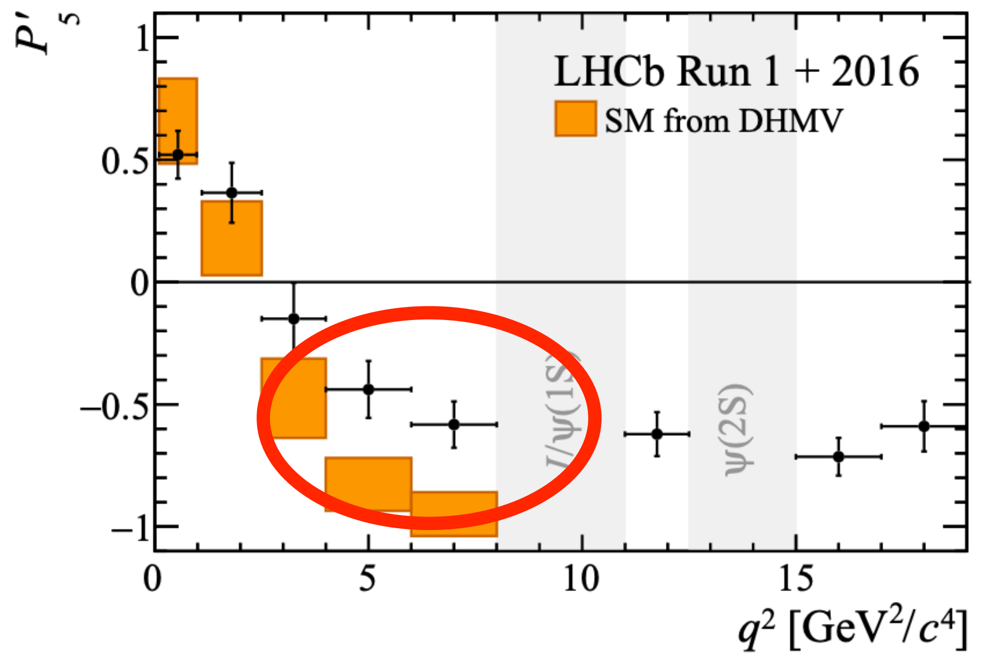
Charged-Higgs scenario



- For heavy charged Higgs, strong LHC bounds come from 2τ +MET, 2b (+γ), 2j, τ +MET (+b); $m_{H^\pm} \leq 250$ GeV is allowed [Blanke, Iguro, Zhang, 2202.10468; Iguro,2201.06565, 2302.08935]

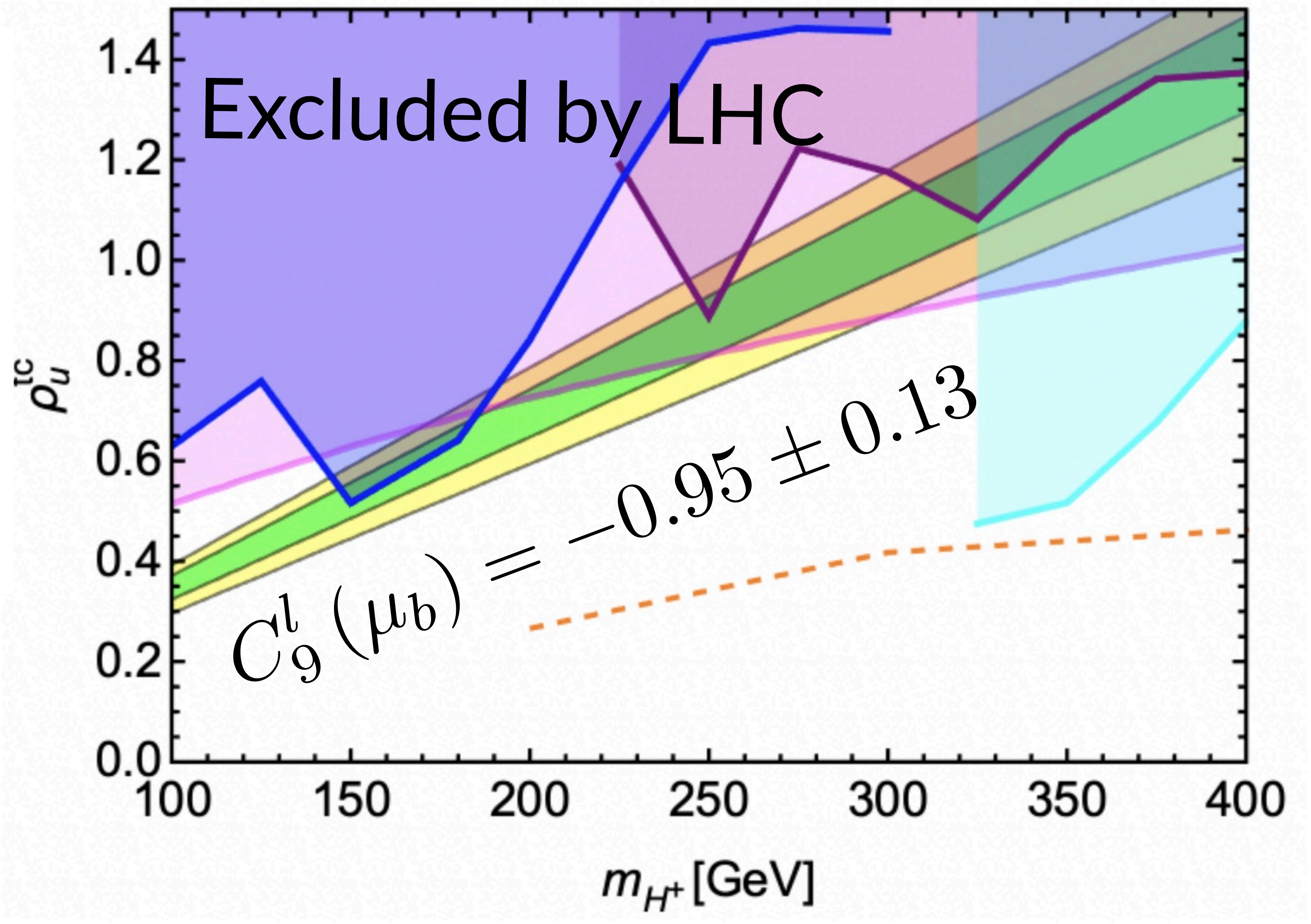


- Unique prediction
  $F_L(D^*) \gtrsim 0.5,\ P_\tau(D^*) \gtrsim -0.35$
- P'_5 anomaly can be solved simultaneously



in $B \to K^* \mu^+ \mu^-$

[LHCb, 2003.04831]



New physics interpretations of $b \to c\tau\nu$ anomaly

[Iguro, TK, Watanabe, 2210.10751 + Iguro, Omura, 2306.00052]

		Spin	Charge	Operators	R_D	R_{D^*}	LHC	Flavor
	$H^\pm$	0	$(\mathbf{1}, \mathbf{2}, 1/2)$	O_{S_L}	✓	✓	$b\tau\nu$	$B_c \to \tau\nu$, $F_L^{D^*}$, $P_\tau^{D^*}$, M_W
LQ	S_1	0	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	O_{V_L}, O_{S_L}, O_T	✓	✓	$\tau\tau$	ΔM_s, P_τ^D, $B \to K^{(*)}\nu\nu$
LQ	$\mathrm{R}_2^{(2/3)}$	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	O_{S_L}, O_T, (O_{V_R})	✓	✓	$b\tau\nu$, $\tau\tau$	$R_{\Upsilon(nS)}$, $P_\tau^{D^*}$, M_W
LQ	U_1	1	$(\mathbf{3}, \mathbf{1}, 2/3)$	O_{V_L}, O_{S_R}	✓	✓	$b\tau\nu$, $\tau\tau$	$R_{K^{(*)}}$, $R_{\Upsilon(nS)}$, $B_s \to \tau\tau$
LQ	$\mathrm{V}_2^{(1/3)}$	1	$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	O_{S_R}	✓	2σ	$\tau\tau$	$B_s \to \tau\tau$, $B_u \to \tau\nu$, M_W

Can be deviated from SM

Leptoquark (LQ)

One can distinguish each model by these observables

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

  [LQ* requires additional symmetry that forbids the proton decay, see 1603.04993]

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	✓	✓
V_2 LQ (*)	1	$(\bar{3}, 2, 5/6)$	only R(D)	Small	Small	✓
S_3 LQ (*)	0	$(\bar{3}, 3, 1/3)$	✗	✓	✗	With S_1
U_3 LQ	1	(3, 3, 2/3)	✗	✓	✗	?

Polarization obserbavles

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

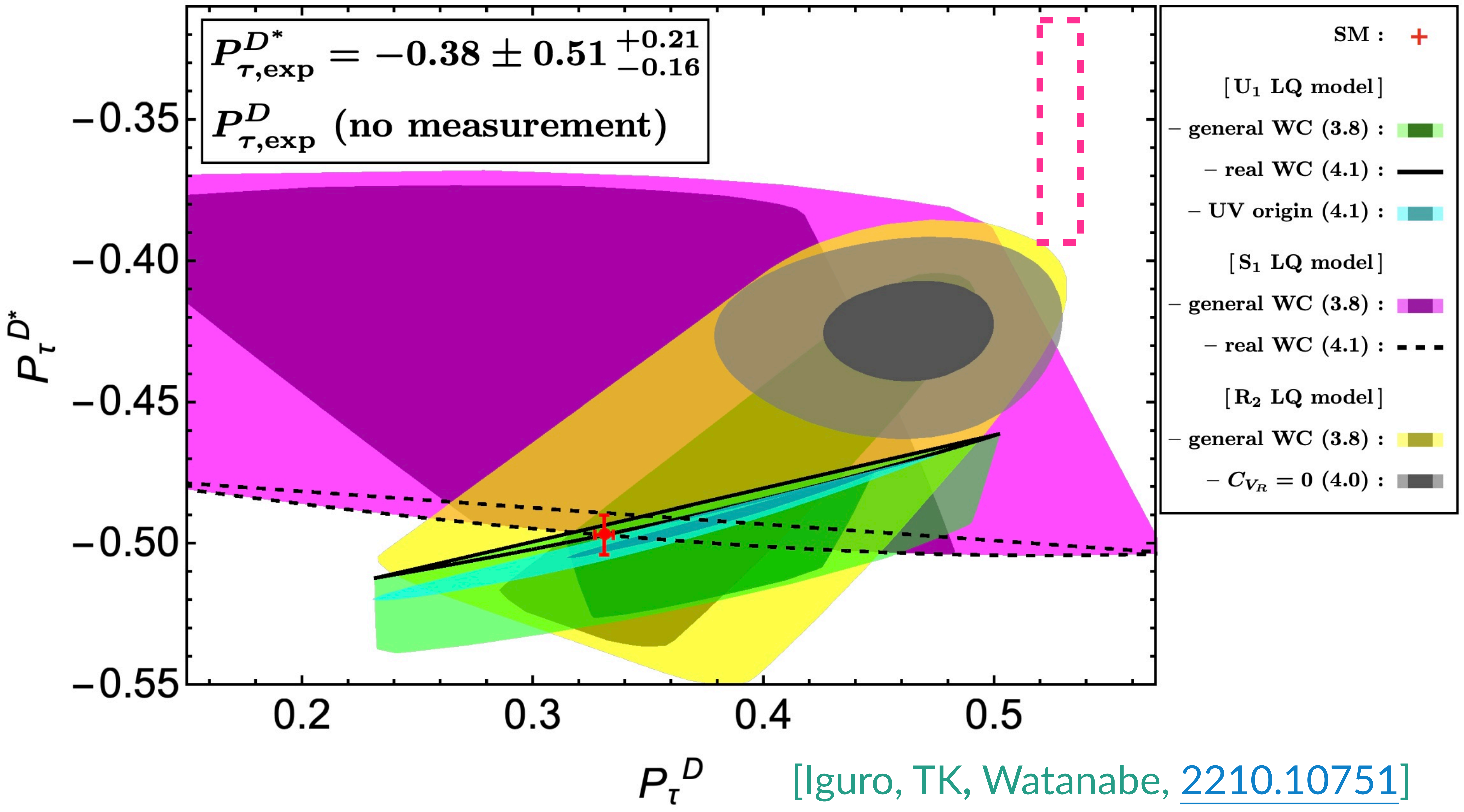
- τ polarization asymmetry along the longitudinal directions of τ [$\tau \to \pi\nu,\ \rho\nu$]

  [Tanaka, hep-ph/9411405]

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

- Belle II sensitivity is enough to distinguish NP models

Belle II (final) sensitivity



[Iguro, TK, Watanabe, 2210.10751]

New idea: LFU violation in Upsilon decay

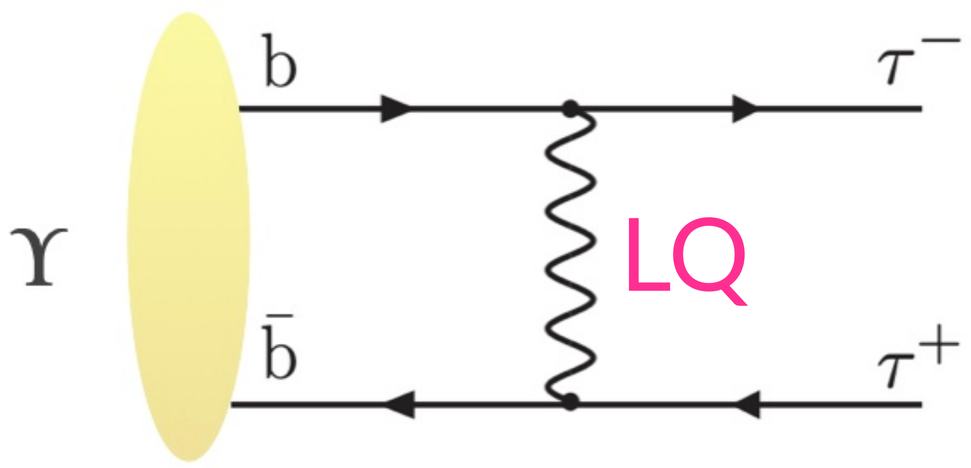
- Υ(nS) [n=1,2,3] leptonic decays can provide new LFU observable ($b\bar{b} \to \tau\bar{\tau}$)

$$R_{\Upsilon(nS)} = \frac{\mathcal{B}(\Upsilon(nS) \to \tau^+\tau^-)}{\mathcal{B}(\Upsilon(nS) \to \ell^+\ell^-)},$$

$$R^{\rm SM}_{\Upsilon(3S)} = 0.9948 \pm \mathcal{O}(10^{-5}),$$

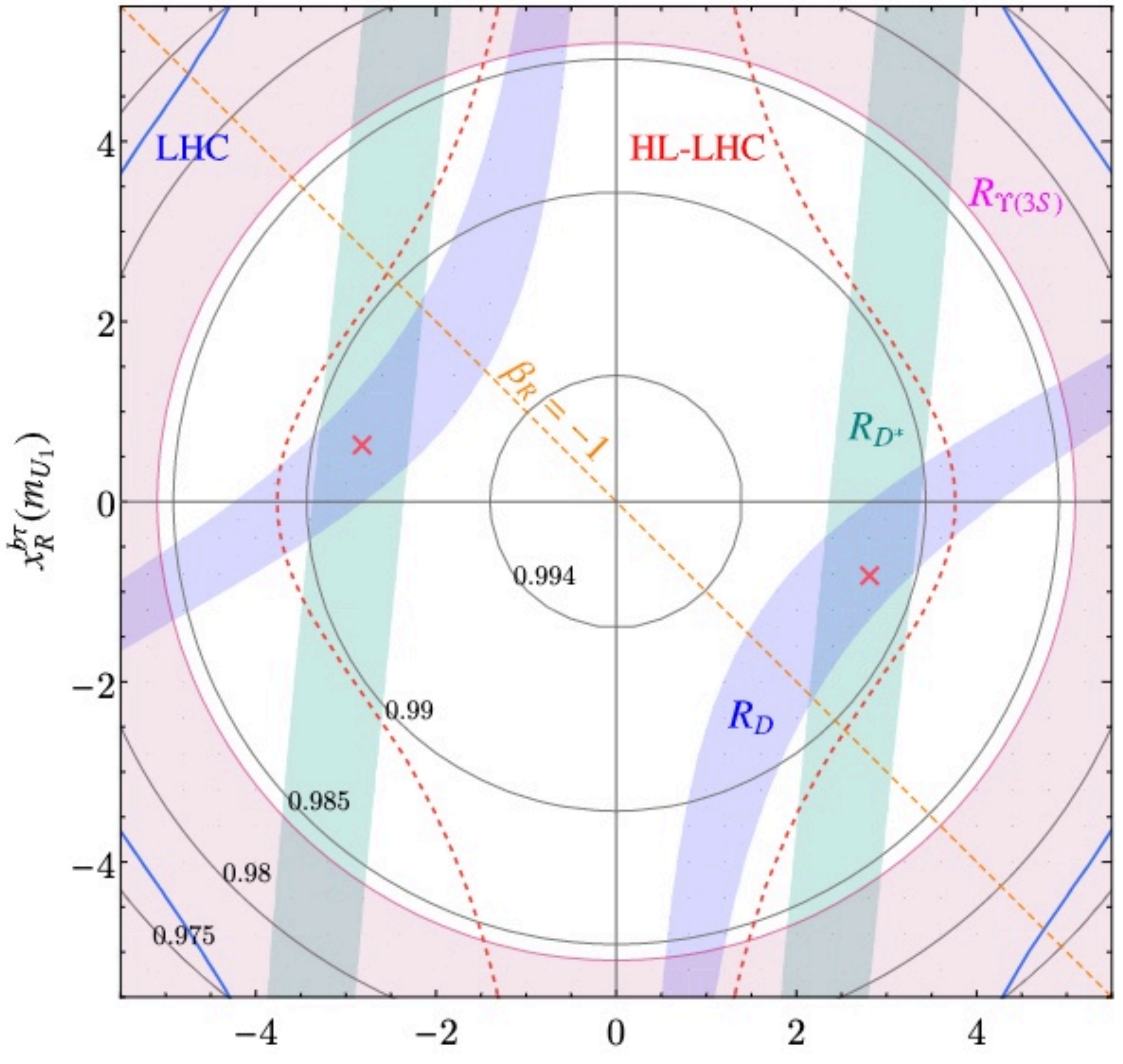
$$R^{\rm exp}_{\Upsilon(3S)} = 0.968 \pm 0.016.$$

[CLEO+BaBar data]



- Belle II can measure R_Υ precisely
- less than 1% accuracy is needed

Correlation in the U₁ LQ scenario



$x_L^{b\tau}(m_{U_1})$ [Iguro, TK, Watanabe, 2210.10751]

New idea: sum-rule between $R(\Lambda_c)$ and $R(D^{(*)})$

- Baryonic counterpart ($b \to c\tau\nu$) : $\mathcal{R}(\Lambda_c) = \dfrac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}_\ell)}$

- There is a **model-independent sum-rule** for R(D), R(D*), and $R(\Lambda_c)$, through new physics form factor analysis (originated from heavy quark symmetry)

$$\frac{R(\Lambda_c)}{R(\Lambda_c)_{\rm SM}} \simeq 0.28 \frac{R(D)}{R(D)_{\rm SM}} + 0.72 \frac{R(D^*)}{R(D^*)_{\rm SM}}$$

[Fedele, et al, 2211.14172]

It can crosscheck of $R(D^{(*)})$ anomaly by coherent amplification of $R(\Lambda_c)$

R(D(*)) anomaly data ⇒

$$R(\Lambda_c) = 0.380 \pm 0.012_{R(D^{(*)})} \pm 0.005_{\rm FF}$$

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

$$R(\Lambda_c)_{\rm exp} = 0.242 \pm 0.075$$

[LHCb, 2201.03497]

Currently, a slight (~2σ) inconsistency appeared

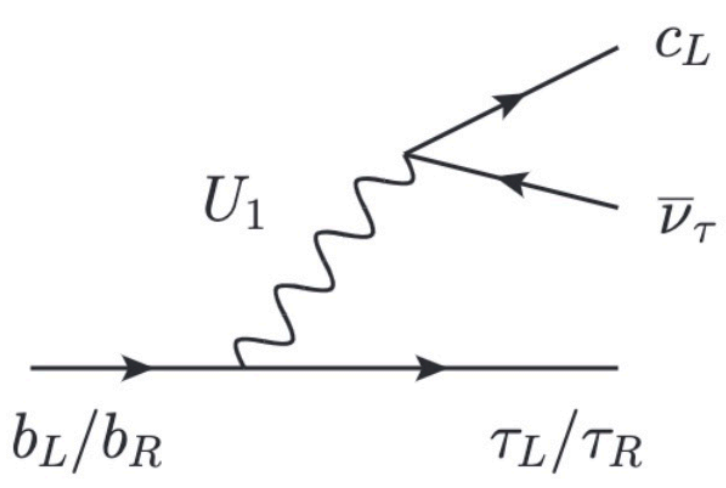
CPV from U₁ vector LQ [Iguro, TK, in progress]

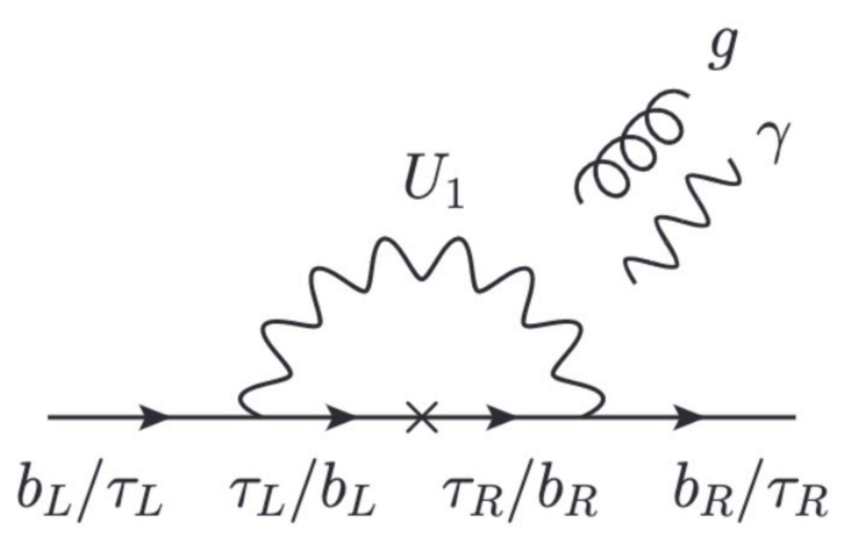
- In general, LQ-Yukawa coupling contains CPV phase: $\mathcal{L} = \left(Y_L \bar{Q}_i \gamma_\mu P_L L_3 + Y_R \bar{b} \gamma_\mu P_R \tau\right) U_1^\mu$
- Interestingly, U1 LQ provides robust correlation of the CPV phase with $R(D^{(*)})$

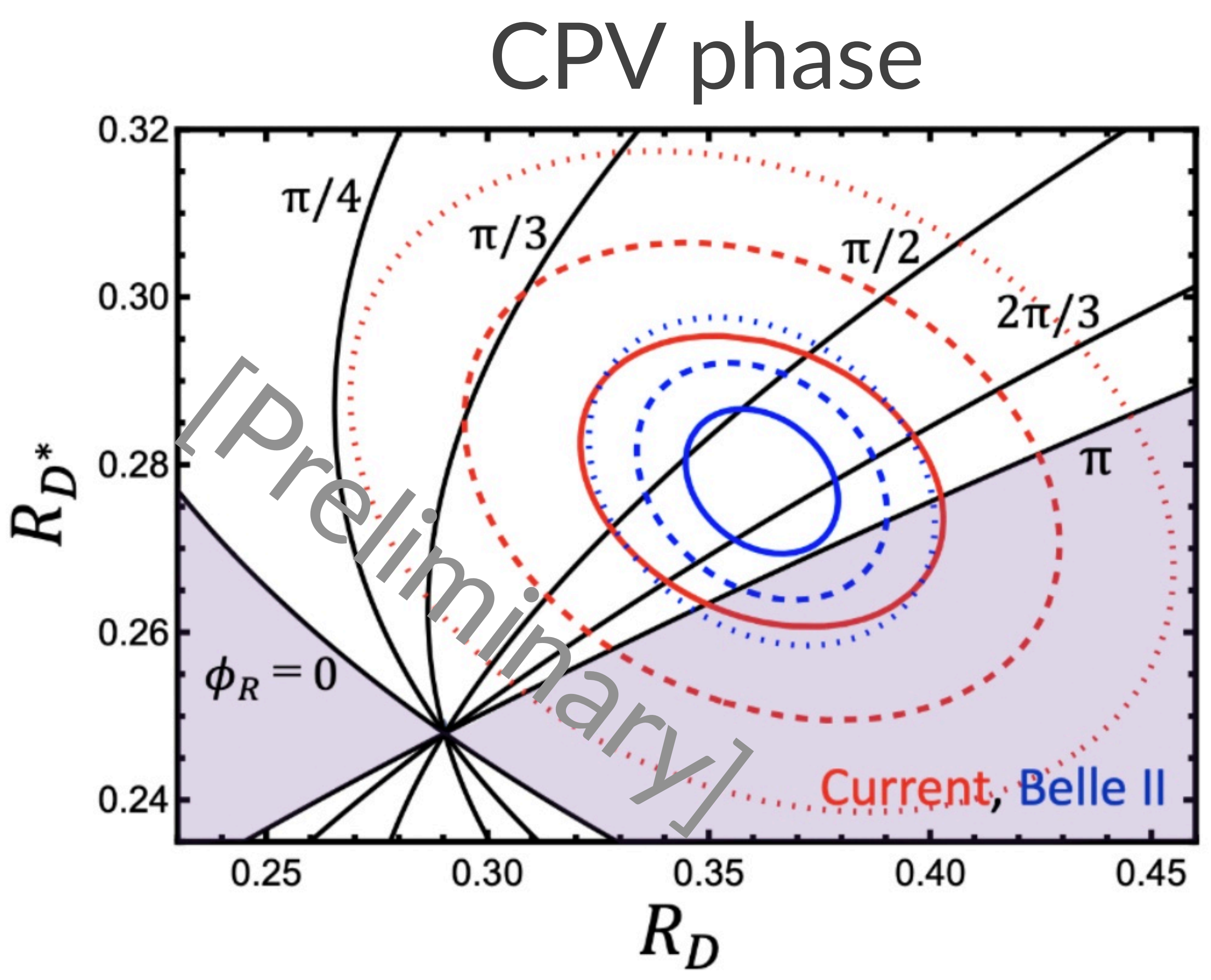
When UV model is 3rd generation-philic gauge symmetry with universal gauge coupling:

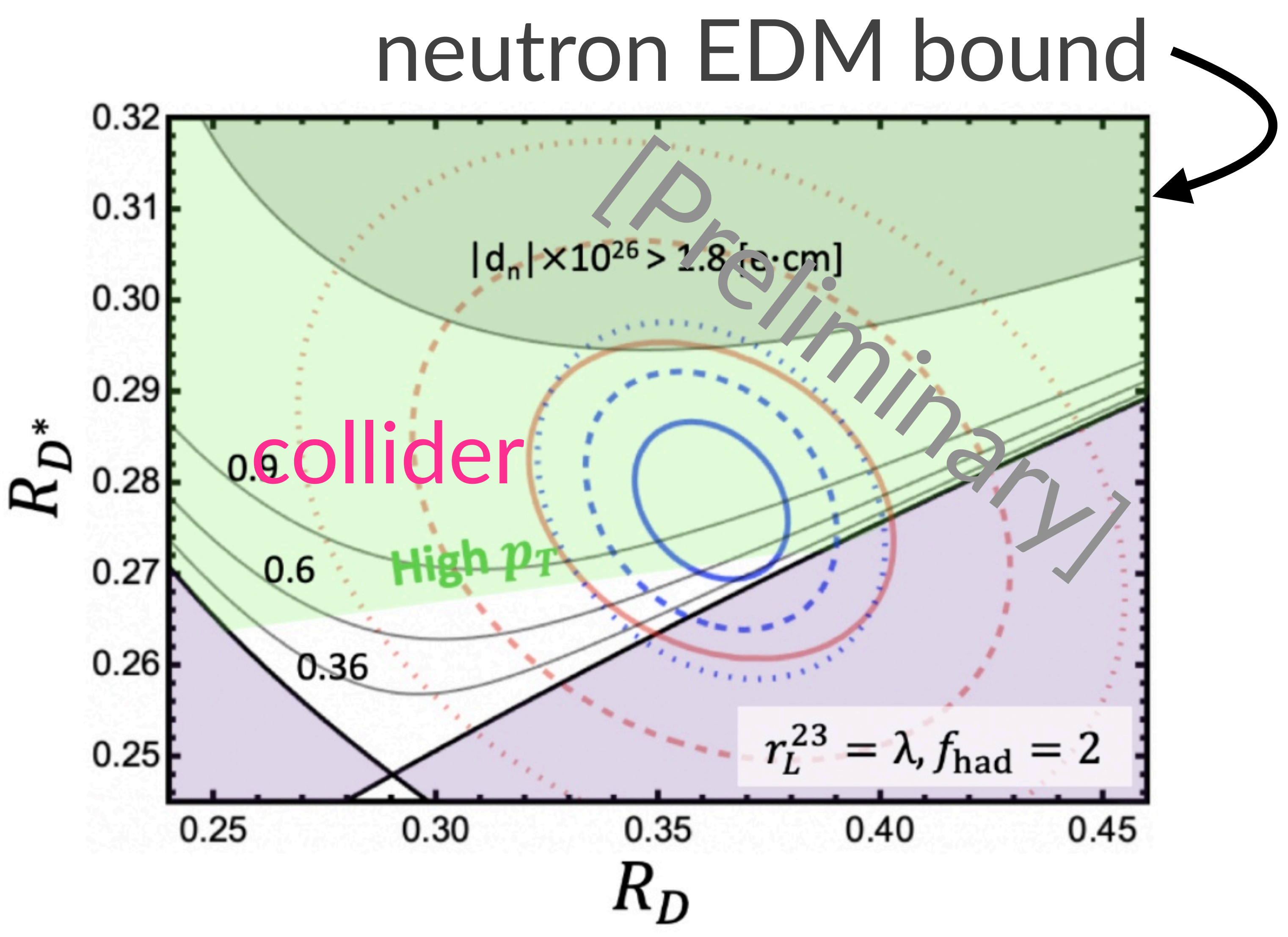
$$C_{S_R}\left(\Lambda_{\rm LQ}\right) = -2 e^{i\phi_R} C_{V_L}\left(\Lambda_{\rm LQ}\right)$$

single CPV phase ϕ_R is predicted



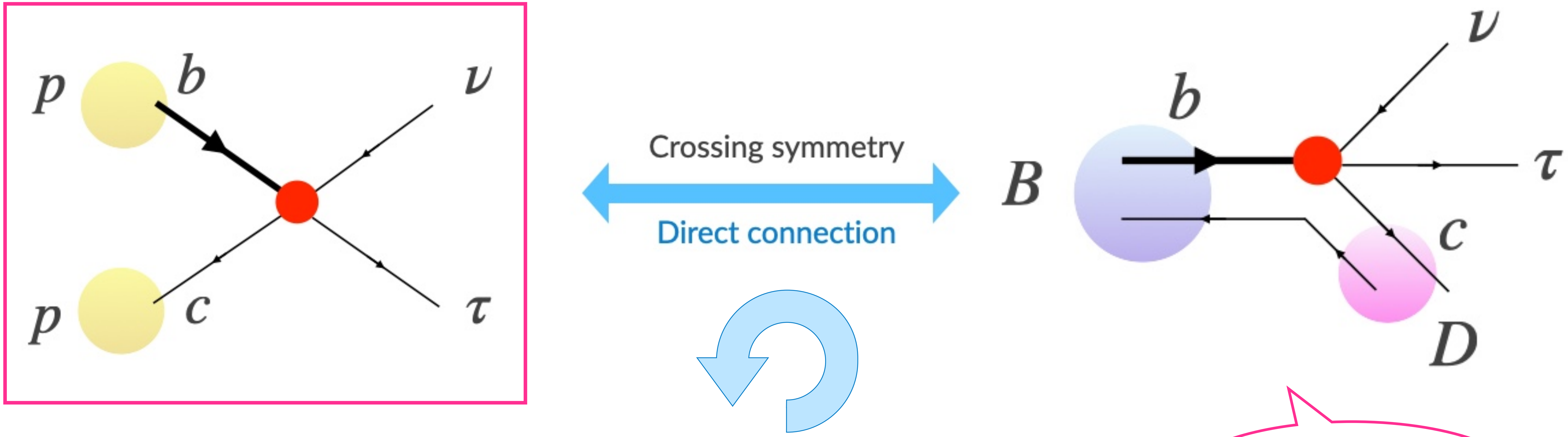






(CPV in $b \to s\gamma$ would be interesting as well)

neutron/proton EDMs can probe the allowed region



non-resonance search

→ **new study direction**

B anomaly!

Leptoquark indirect collider search

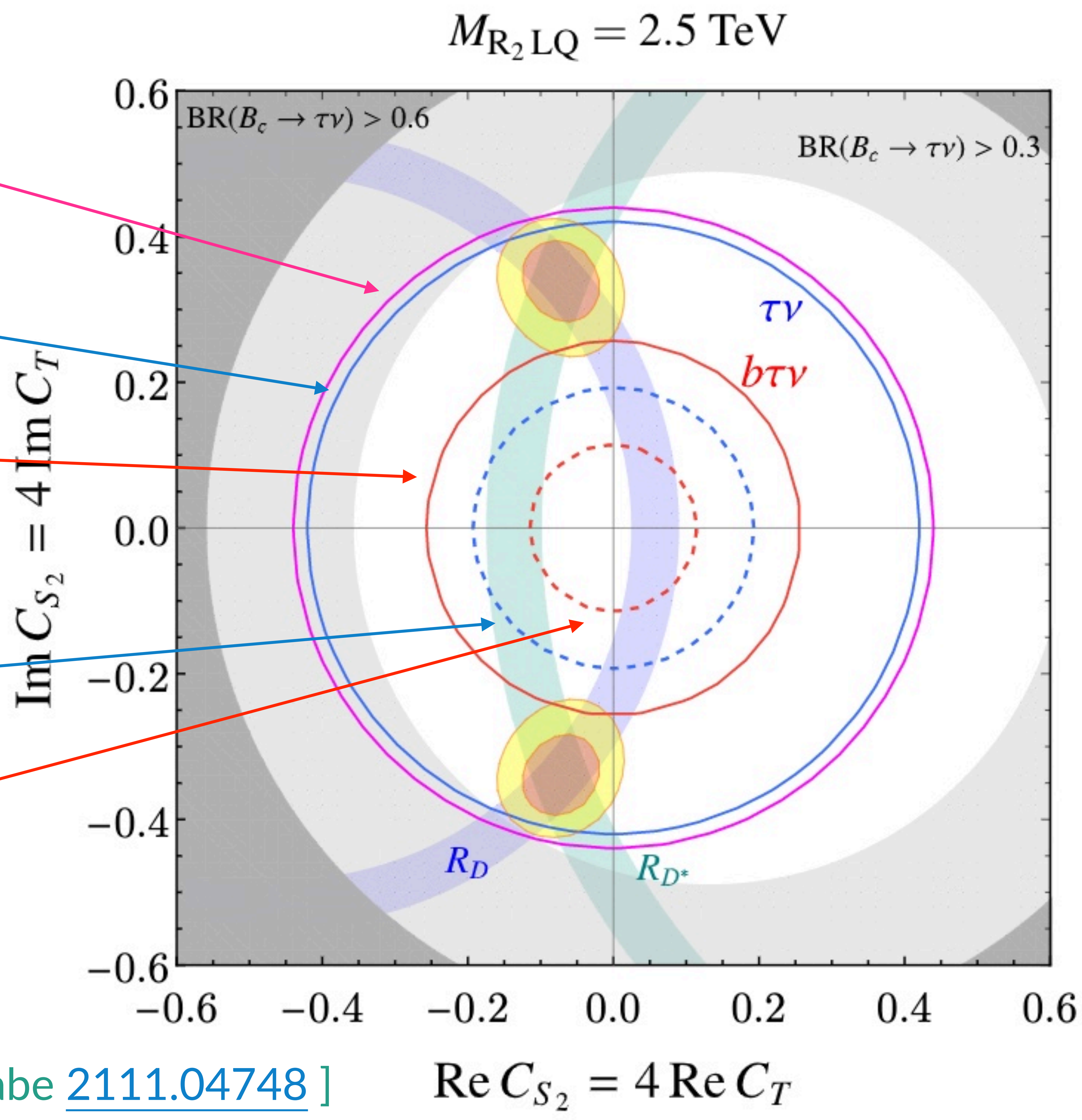
τ+MET search
36fb^{-1} exclusion

τ+MET search
139fb^{-1} sensitivity

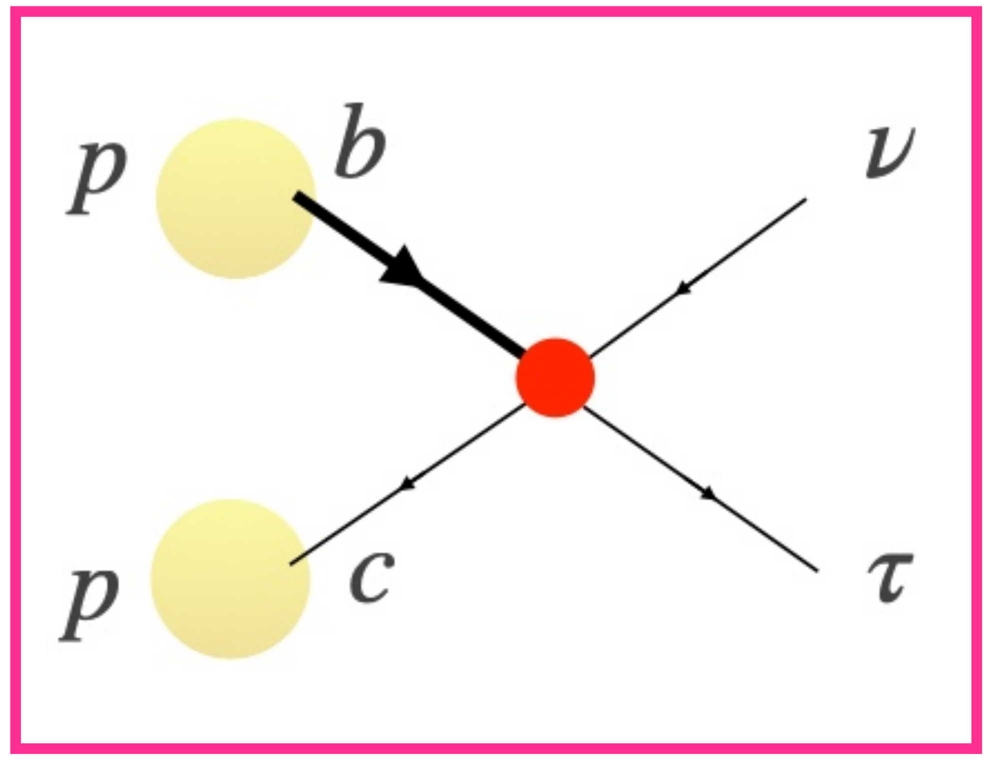
τ+MET+b search
139fb^{-1} sensitivity

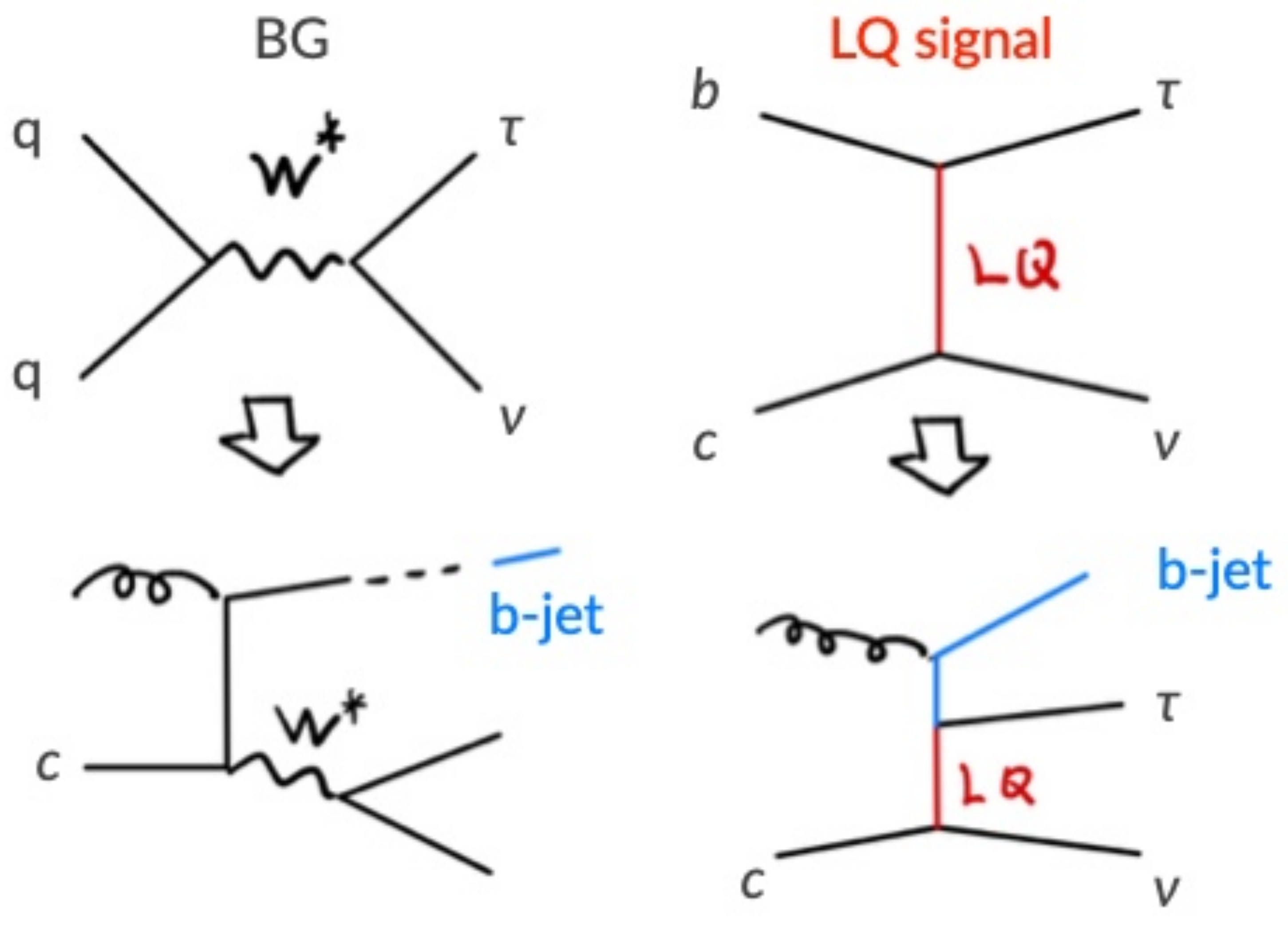
τ+MET search
3000fb^{-1} sensitivity

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



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

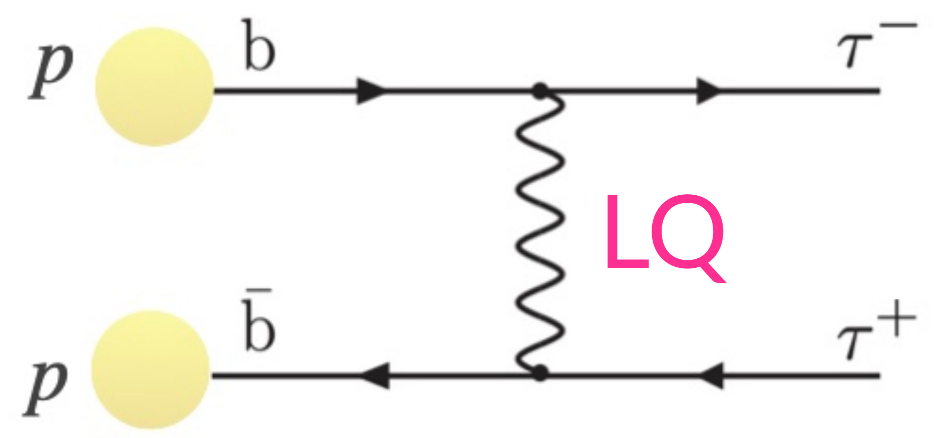


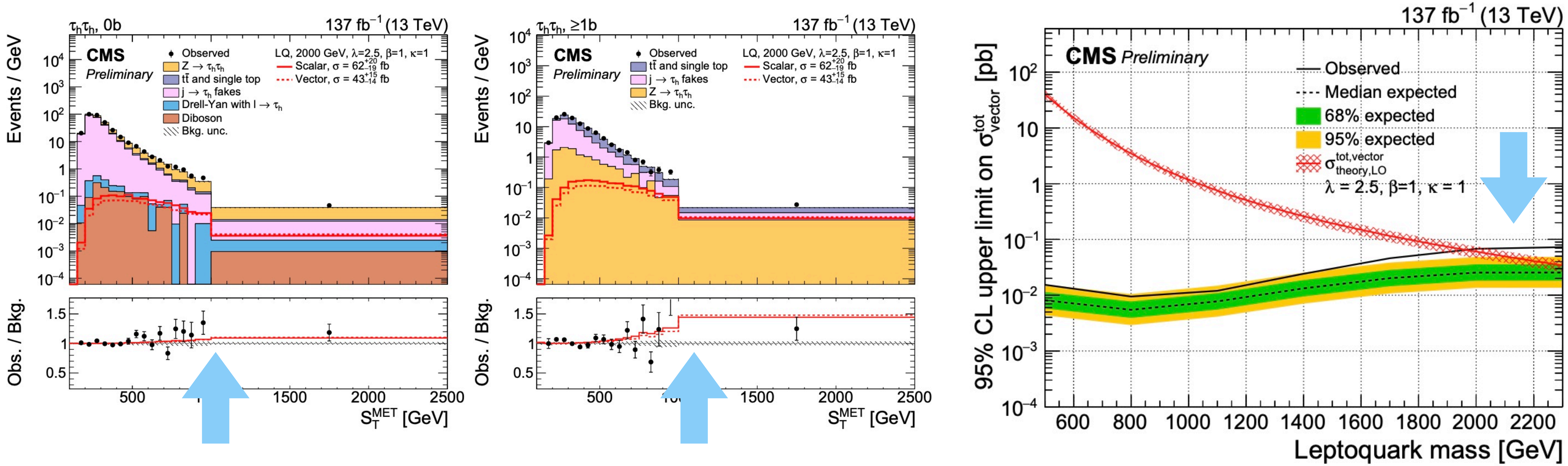


+b jet suppresses only bkg

R2 LQ scenario can be probed by bτ+MET search with Run 2 data

New LQ anomaly from CMS @ICHEP2022

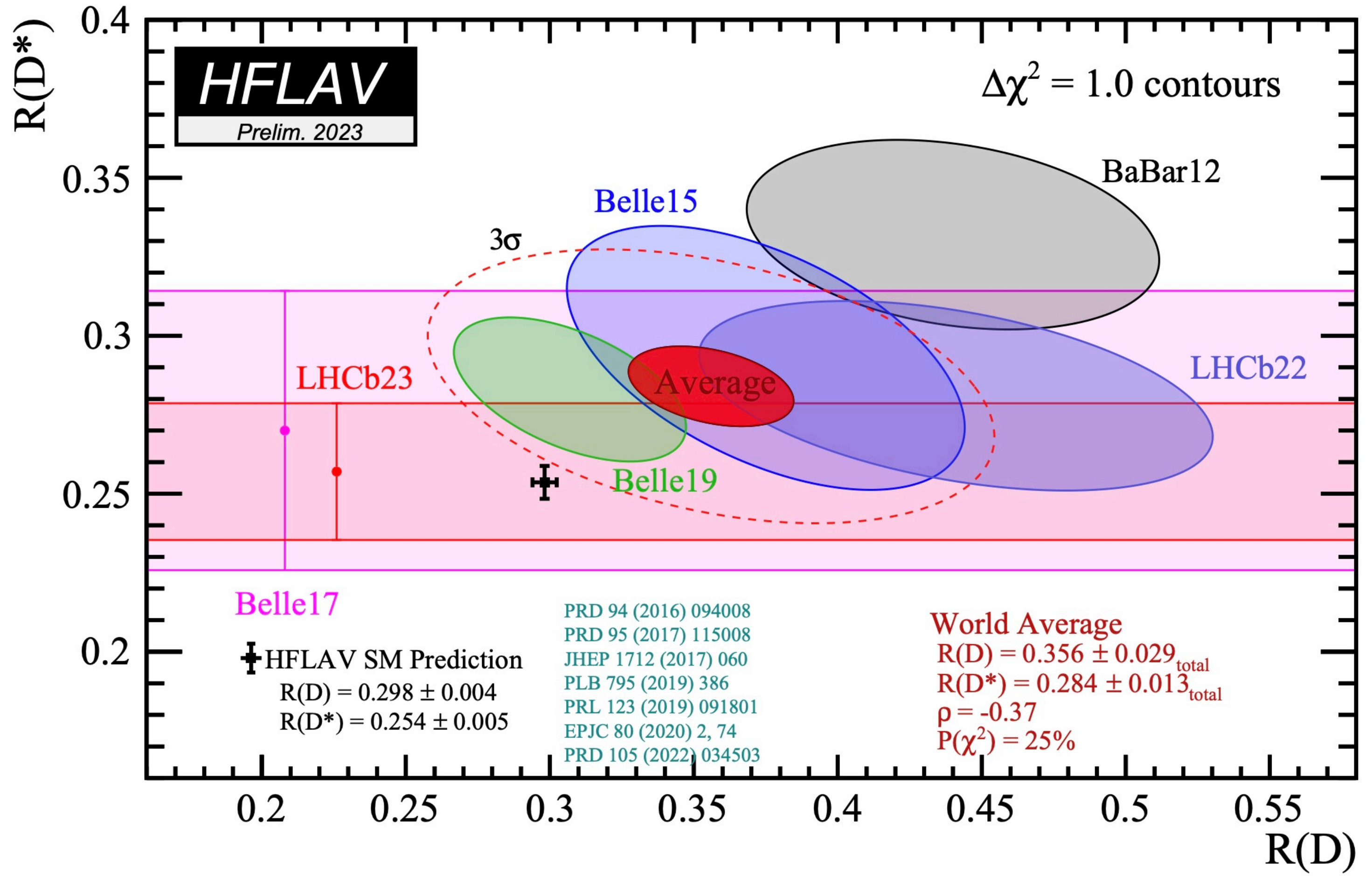




3.4σ level excess at $M_{LQ} \sim 2$ TeV was reported from CMS [CMS, CMS-PAS-EXO-19-016 (2022)]

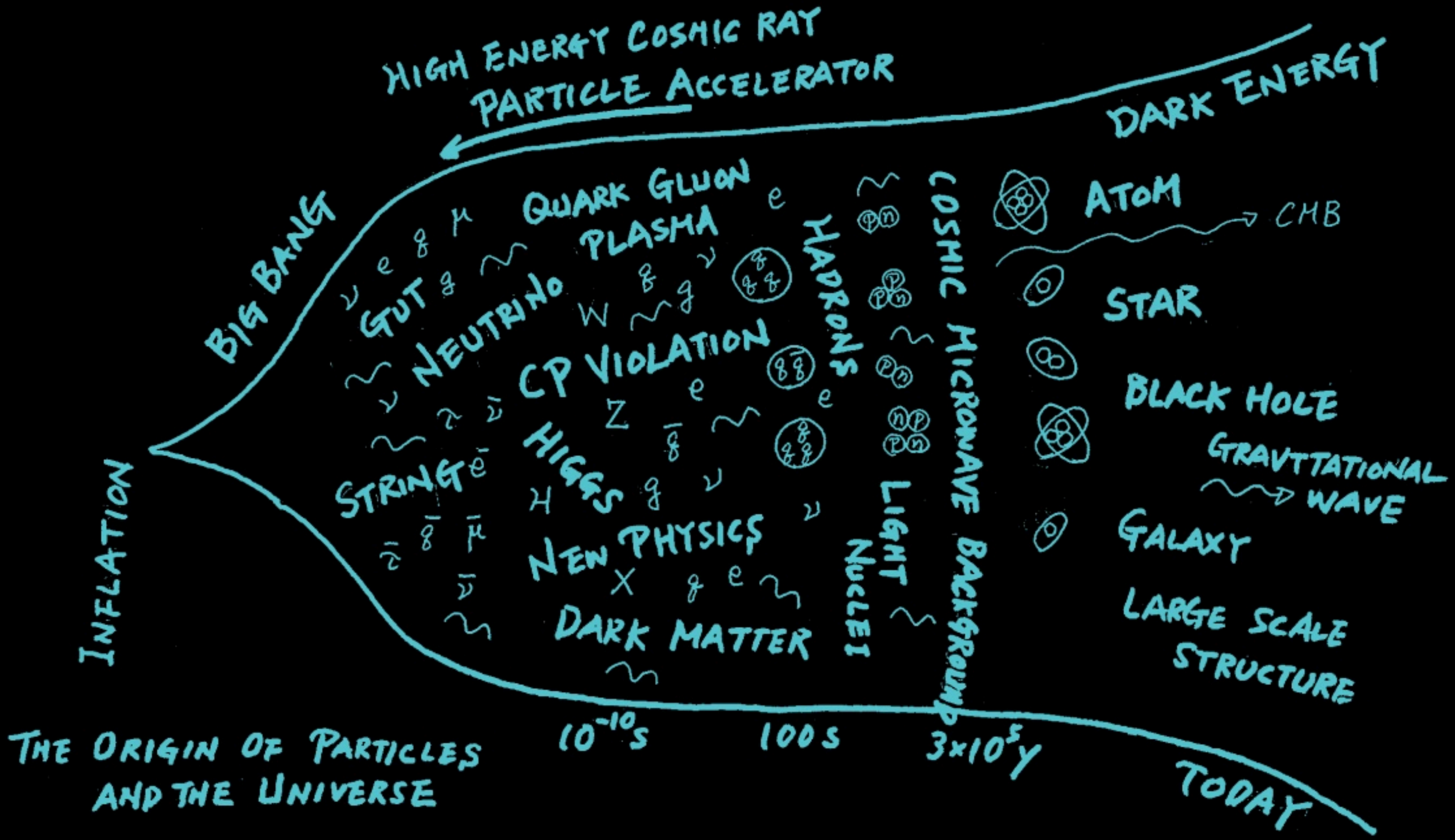
Conclusions

- $R(D^{(*)})$ anomaly persists in $b \to c\tau\nu, c\ell\nu$ processes at 3.2-4σ level
- The charged Higgs boson and Leptoquark models can accommodate the anomaly
- The crosschecks of the new physics are very important by
  $P_\tau(D^{(*)})$, $F_L(D^*)$, $R(\Lambda_c)$, $R(\Upsilon)$, $R(D^{(*)})(q^2)$ and LHC indirect search, see table:



		Spin	Charge	Operators	R_D	R_{D^*}	LHC	Flavor
	$H^\pm$	0	$(\mathbf{1}, \mathbf{2}, 1/2)$	O_{S_L}	✓	✓	$b\tau\nu$	$B_c \to \tau\nu$, $F_L^{D^*}$, $P_\tau^{D^*}$, M_W
LQ	S_1	0	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	O_{V_L}, O_{S_L}, O_T	✓	✓	$\tau\tau$	ΔM_s, P_τ^D, $B \to K^{(*)}\nu\nu$
LQ	$R_2^{(2/3)}$	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	O_{S_L}, O_T, (O_{V_R})	✓	✓	$b\tau\nu$, $\tau\tau$	$R_{\Upsilon(nS)}$, $P_\tau^{D^*}$, M_W
LQ	U_1	1	$(\mathbf{3}, \mathbf{1}, 2/3)$	O_{V_L}, O_{S_R}	✓	✓	$b\tau\nu$, $\tau\tau$	$R_{K^{(*)}}$, $R_{\Upsilon(nS)}$, $B_s \to \tau\tau$
LQ	$V_2^{(1/3)}$	1	$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	O_{S_R}	✓	2σ	$\tau\tau$	$B_s \to \tau\tau$, $B_u \to \tau\nu$, M_W

Backup slides



(c) KMI/Nagoya-U