重味物理前沿论坛研讨会

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RD(*) anomaly: theoretical overview

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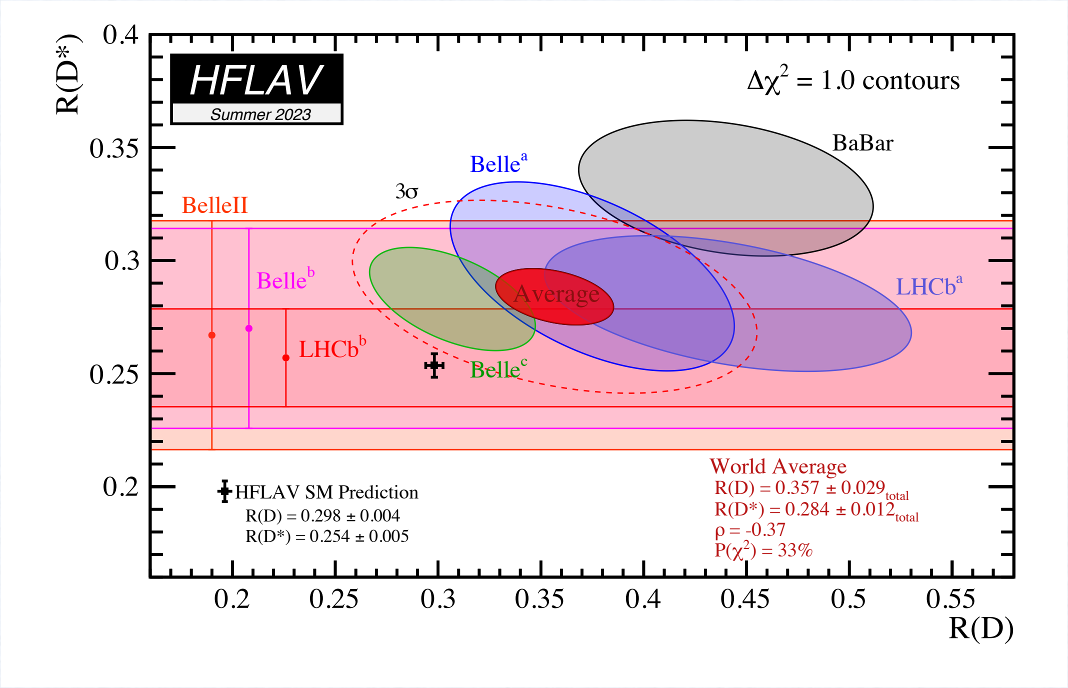
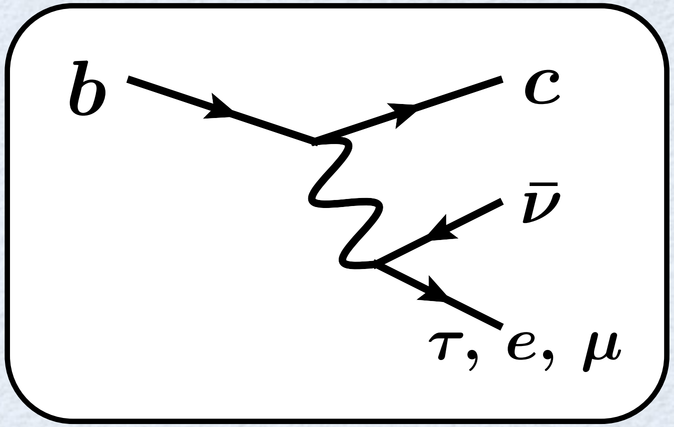
“Anomaly”

has been observed since 2012 in $R_{D^{(*)}} = \dfrac{\mathcal{B}(\bar{B} \to D^{(*)} \tau \bar{\nu})}{\mathcal{B}(\bar{B} \to D^{(*)} \ell \bar{\nu})}$

Measurements:



SM process:



Official consensus:

- **~ 3σ deviation from the “official” SM value**
- **Some NP interpretations are possible, but not conclusive**

RD(*): experiments

Experiment	R_{D^*}	R_D	Correlation
BaBar (2012)	$0.332 \pm 0.024 \pm 0.018$	$0.440 \pm 0.058 \pm 0.042$	-0.31
Belle (2015)	$0.293 \pm 0.038 \pm 0.015$	$0.375 \pm 0.064 \pm 0.026$	-0.50
Belle (2016)	$0.270 \pm 0.035^{+0.028}_{-0.025}$	–	–
Belle (2019)	$0.283 \pm 0.018 \pm 0.014$	$0.307 \pm 0.037 \pm 0.016$	-0.52
LHCb (2015)	$0.336 \pm 0.027 \pm 0.030$	–	–
LHCb (2017)	$0.280 \pm 0.018 \pm 0.029$	–	–
Previous average	0.297 ± 0.013	0.338 ± 0.030	-0.39
LHCb (2022)	$0.280 \pm 0.018 \pm 0.024$	$0.441 \pm 0.060 \pm 0.066$	-0.43
New average	0.284 ± 0.013	0.356 ± 0.029	-0.37

Latest status:

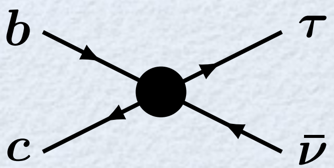
Belle (2019) ➡ no update in 4 years / LHCb run1 (2017) ➡ updated in 2022

Waiting lists:

CMS with “B-parking” / Belle II (first result ➡ in 2023!) / LHCb run2

RD(*): usual interpretations

NP EFT: $\mathcal{L}_X = 2\sqrt{2} G_F V_{cb} C_X^\tau (\bar{c}\,\Gamma b)(\bar{\tau}\,\Gamma' \nu)$



— Solutions to the RD(*) anomaly

$C^\tau_{\rm VLL} \approx 0.09$ $(\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu)$

$C^\tau_{\rm VRL} \approx 0.42 i$ $(\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu)$

$C^\tau_T \approx 0.15 + i\,0.19$ $(\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu)$

$C^\tau_{\rm SLL} \approx -0.82 + 0.78 i$ $(\bar{c} P_L b)(\bar{\ell} P_L \nu)$

Right-handed neutrino scenarios are skipped here:

1802.01732, 1804.04135, 1804.04642, 1807.04753, 1811.04496

— Models of the mediator particle

Vector boson (W'): $C^\tau_{\rm VLL}, C^\tau_{\rm VRL}$

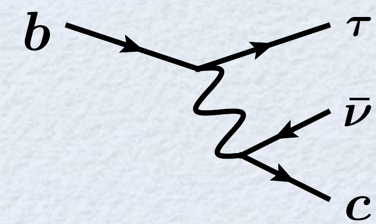
➡ **SU(2) model inevitably includes Z' that is very constrained due to tree-level FCNC**

Charged Higgs: $C^\tau_{\rm SLL}$

➡ **typical models (type-I, II) do not give desired SLL and so type-III is the last hope**

RD(*): usual interpretations

Leptoquarks (LQ): S_1, R_2, U_1



$\mathrm{S}_1\ (\bar{3}, 1, 1/3)$ scalar: C_{VLL}, $C_{\mathrm{SLL}} = -4C_T \approx 0.13$

➡ **VLL & SLL-T type couplings are independent and both has the solution**

➡ **S1-S3 mixture was discussed for RK** 1703.09226

$\mathrm{R}_2\ (3, 2, 7/6)$ scalar: $C_{\mathrm{SLL}} = +4C_T \approx 0.40\, i$

➡ **could be related to GUT and neutrino mass generation** 1701.08322

$\mathrm{U}_1\ (3, 1, 2/3)$ vector: C_{VLL}, C_{SLL} 1709.00692, 1808.07492, 1812.01603, 2103.11889

➡ **VLL and SLL are independent unless UV is discussed**

➡ **Famous Pati-Salam UV induces Z' that has to be managed (model dependent)**

➡ **Another UV from U(2) flavor symmetry gives** $C_{\mathrm{SLL}} = -2\, e^{I\phi}\, C_{\mathrm{VLL}}$

Content

- Status on related observables/measurements to RD(*)
- Impacts on the NP solutions

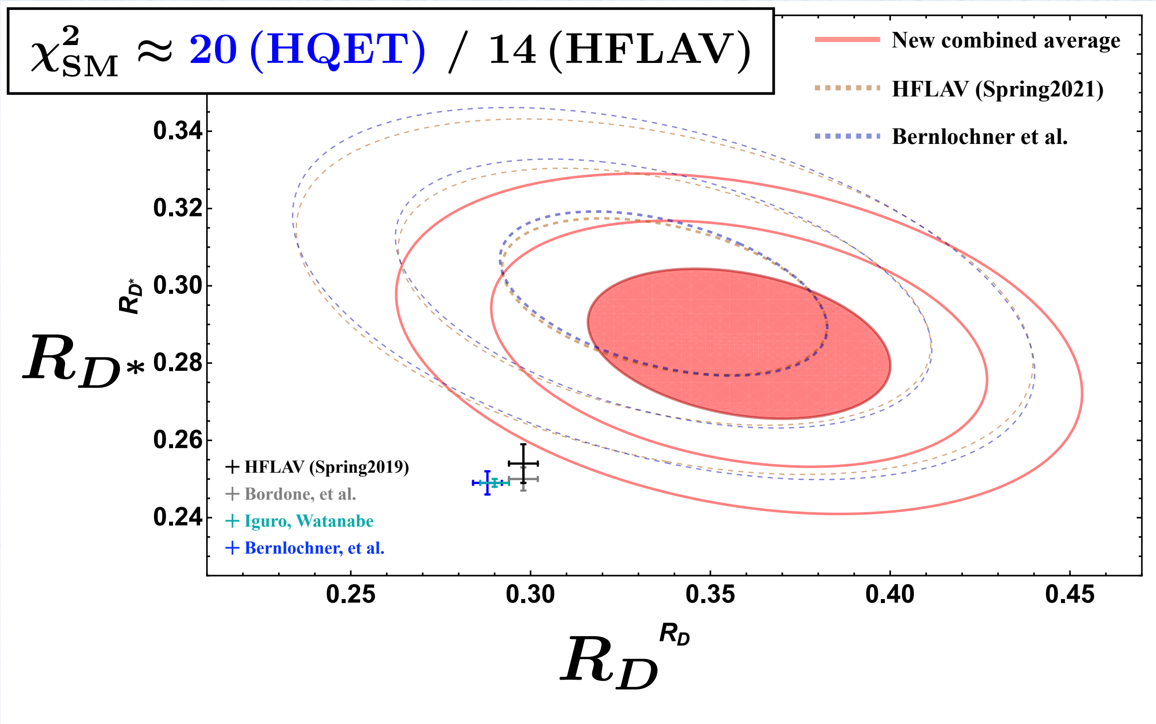
— SM predictions

— NP in the light lepton modes?

— Flavor signals: B_c, Λ_b, Tau polarizations

— Collider signals: Tau + missing (+b jet)

SM predictions (Form Factors)



BGL parameterization:

+ HFLAV (Spring2019)

HQET parameterization:

+ EPJC80(2020)74 [3/2/1 model]
+ JHEP08(2020)006 [3/2/1 model]
+ Phys,Rev.D106(2022)096015 [CLN base]

Why do we have different SM values?:

— FF shape fit is still **unstable** ➡ FF model dependences

— Lattice was available only for $B \to D$ until last year

New lattice results for $B \to D^*$!!:

— Fermilab-MILC (2022 published) / HPQCD (2023) / JLQCD (2023)

EPJC 82, 1141 (2022) 2304.03137 2306.05657

SM predictions (Form Factors)

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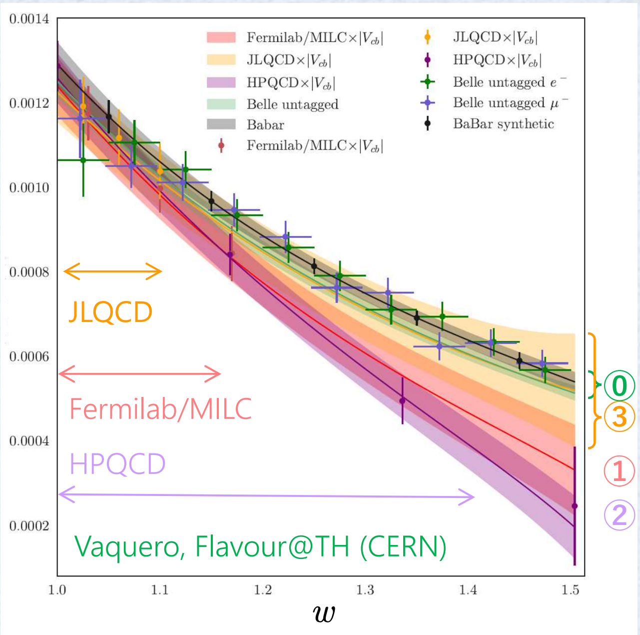
— Fermilab-MILC (2022 published) / HPQCD (2022) / JLQCD (2023)



JLQCD:

good consistency with exp ⁄ small recoil bins

HPQCD:

steeper slope ⁄ large recoil bins

⓪ extracted from Belle data
③ JLQCD
① Fermilab-MILC
② HPQCD

deviations

New issue: how should we combine the lattice results?

Effect on RD*:

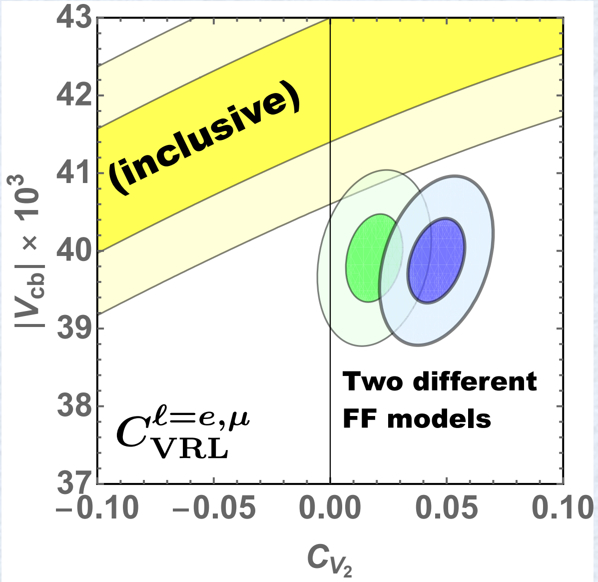
[0.252(22) JLQCD] vs [0.279(13) HPQCD] vs [0.265(13) MILC]

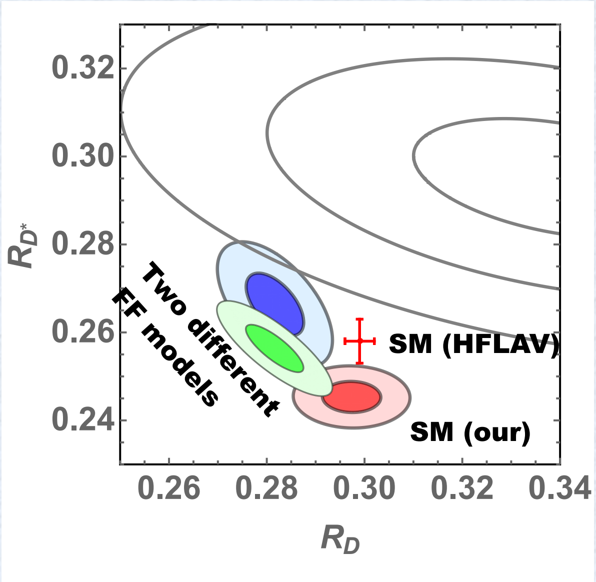
— JLQCD consistent with the present status [0.254(5) HFLAV]

— HPQCD & MILC larger value / reducing the B anomaly [0.285(13) exp]

NP in the light lepton modes?

Simultaneous fit of FF + Vcb + NP in $B \to D^{(*)}\mu\nu\,,\ D^{(*)}e\nu$





2004.10208 (RW)

— **assuming LFU type NP in e/μ:** $C^e_X = C^\mu_X$

— **taking Belle full angular data (2017,2018) & all available theory**

— **NP can be hidden behind the Vcb measurement**

➡ **possible size is < 5% of the "SM size"** $\equiv 2\sqrt{2}G_F V_{cb}$

— **Impact on RD(*), NP in denominator, is mild**

➡ **RD* increases while RD decreases in case of VRL type NP**

Flavor signals

(1) B_c lifetime

excluded the scalar NP solution (SLL):

— **Difference in experiment/theory is room for NP contribution** hep-ph/9601249, 1611.06676

$$[\tau_{B_c}^{\text{exp}} \approx 0.5\text{ps}] \text{ vs. } [0.4\text{ps} < \tau_{B_c}^{\text{th}} < 0.7\text{ps}] \quad \Rightarrow \quad \text{Br}(B_c \to \underbrace{\text{induced by NP}}_{\tau\nu}) < 30\%$$

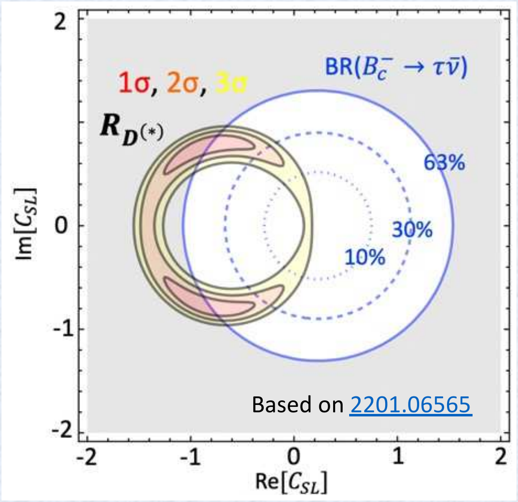
➡ **killed all the scalar NP solutions to the anomaly**

— **The present calculation (OPE) is sensitive to charm mass input**

➡ **1811.09603 pointed out a conservative bound should be <60%**

➡ **2105.02988 provides update concerning charm mass: th. could reach <1.0ps (<50%)**

➡ **theory calculation is not conclusive, need further update...**



2201.06565

— **This update significantly affects the SLL scenario**

➡ **Scalar type solution revived, but on the edge!**

➡ **Type-III charged Higgs is now viable!**

➡ **Good news for several LQ scenarios as well**

Flavor signals

(2) Λ_b decay

Another R proposal from b-baryon: $R_{\Lambda_c} = \mathcal{B}(\Lambda_b \to \Lambda_c\,\tau\,\nu)\Big/\mathcal{B}(\Lambda_b \to \Lambda_c\,\ell\,\nu)$

— light lepton modes were measured by DELPHI/CDF/LHCb since 2004

— the first result for tau together with R was reported by LHCb in this year!

2201.03497

$$\mathrm{LHCb\ (2022)}: 0.242 \pm 0.026 \pm 0.04 \pm 0.059 \quad \Leftrightarrow \quad \mathrm{SM\ (2018)}: 0.324 \pm 0.004$$

Heavy Quark Symmetry ensures sum rule: $\dfrac{R_{\Lambda_c}}{R_{\Lambda_c}^{\mathrm{SM}}} = 0.28\dfrac{R_D}{R_D^{\mathrm{SM}}} + 0.72\dfrac{R_{D^*}}{R_{D^*}^{\mathrm{SM}}} + \delta$

1811.09603, 1905.08253

— δ can be negligible under any NP existence as long as $|C_T| \ll 1$

➡ Recall the T solution: $|C_T| \approx |0.15 + i\,0.19| = 0.24 \quad \Rightarrow \delta = -0.03$

— measured RD(*) provides model-independent fit: $R_{\Lambda_c}^{\mathrm{fit}} = 0.380 \pm 0.013 \pm 0.005$

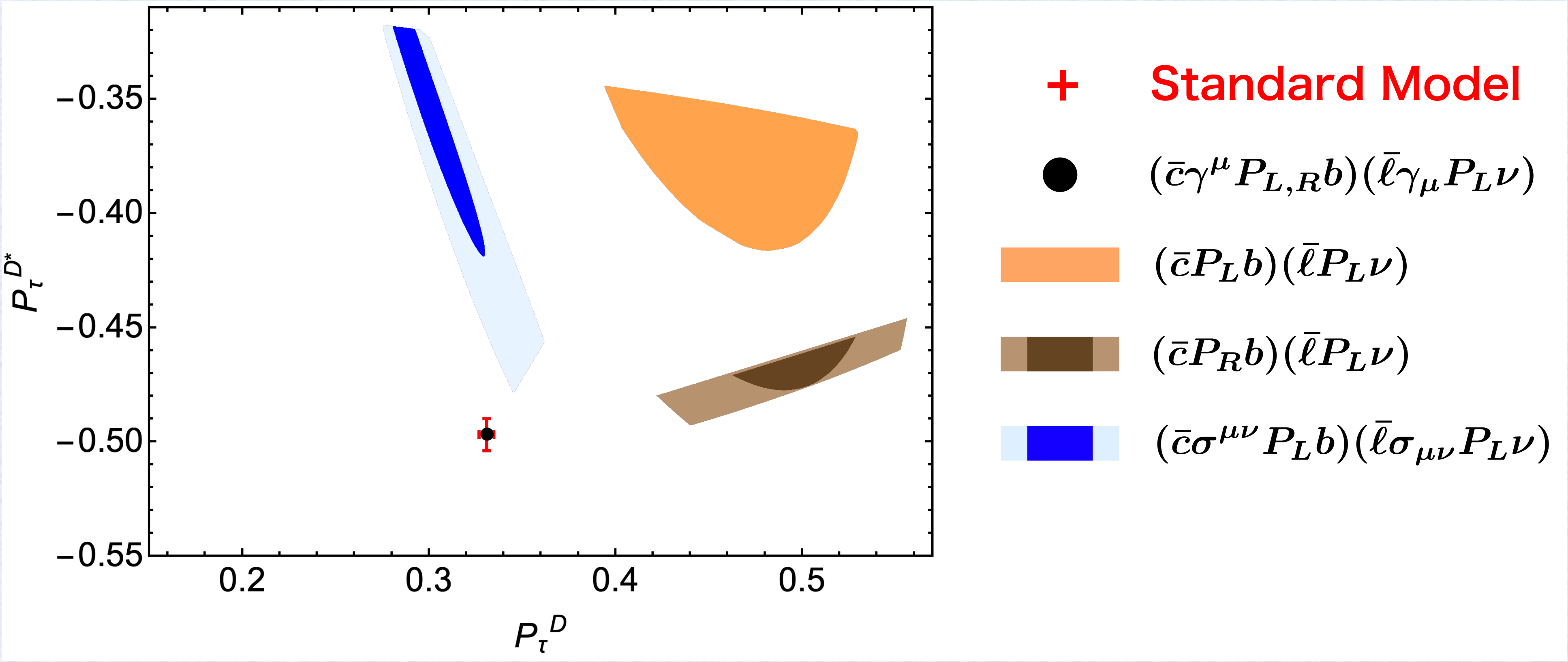
➡ is another index to test the anomaly

➡ IOW, this R cannot identify NP but is a unique value for every NP solution and for SM

➡ the measured RΛc is not consistent with the RD(*) anomaly: potentially another problem

Flavor signals

(3) Tau spin polarization



— **NP solutions for RD(*) anomaly predict distinct signals**

➡ **could identify T/SLL/SRL solution (blue/yellow/cyan)**

➡ **Current experimental measurement**

Belle (2017) 1709.00129

D* mode: $P^{D^*}_{\tau,\mathrm{exp}} = -0.38 \pm 0.51\,^{+0.21}_{-0.16}$ **D mode: not measured yet**

Collider signals

W boson resonance:

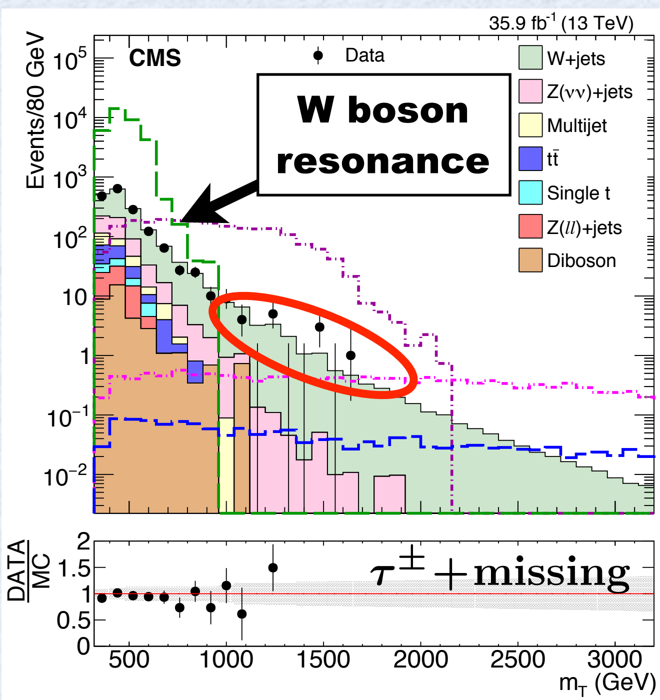
— has been observed with missing transverse mass

— its tail can be interpreted as NP contribution responsible for the RD(*) anomaly

— minimal NP process is bc → τν

➡ W' is severely constrained: < 2TeV excluded (bc PDF suppressed) / < 5TeV (SSM)

➡ EFT based analysis is also available and gives very crucial bound



1811.07920

— competitive with the NP solutions that require large WCs:

$$|C_{\mathrm{VLL}}^{\mathrm{LHC\text{-}EFT}}| < 0.32 \quad \Leftrightarrow \quad C_{\mathrm{VLL}}^{R_{D^{(*)}}} \approx 0.09$$

$$|C_{\mathrm{VRL}}^{\mathrm{LHC\text{-}EFT}}| < 0.33 \quad \Leftrightarrow \quad C_{\mathrm{VRL}}^{R_{D^{(*)}}} \approx 0.42\, i$$

$$|C_{T}^{\mathrm{LHC\text{-}EFT}}| < 0.20 \quad \Leftrightarrow \quad |C_{T}^{R_{D^{(*)}}}| \approx |0.15 + i\, 0.19| = 0.24$$

$$|C_{\mathrm{SLL}}^{\mathrm{LHC\text{-}EFT}}| < 0.32 \quad \Leftrightarrow \quad |C_{\mathrm{SLL}}^{R_{D^{(*)}}}| \approx |-0.82 + i\, 0.78| = 1.13$$

— Charged Higgs is very excluded, but has an exception

➡ tail pT < 500GeV is less sensitive to NP signal

➡ mass window 180GeV < mH < 400GeV is not accessible

Collider signals

t-channel case:

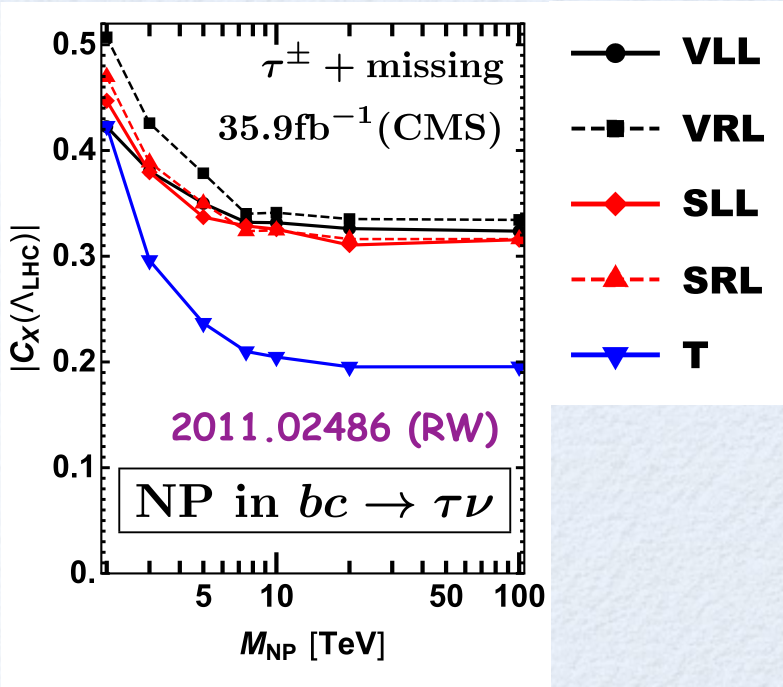
— EFT approximation is not good at high-mT

➡ if NP mass is close to mT bin ~ 1TeV applicable for bound

➡ In particular, it overestimates the signal in the case of t-channel

➡ Large t(<0) generates large mT and reduces the contribution

— ex) $\mathcal{L}_U = h_U^{ij}\left(\bar{q}_L^i \gamma^\mu \ell_L^j\right) U_\mu + \text{h.c.} \quad \Rightarrow \quad \frac{h_U^{b\tau} \cdot h_U^{c\nu}}{t - m_{\rm LQ}^2} \neq -\frac{h_U^{b\tau} \cdot h_U^{c\nu}}{m_{\rm LQ}^2} \equiv C_{\rm VLL}$



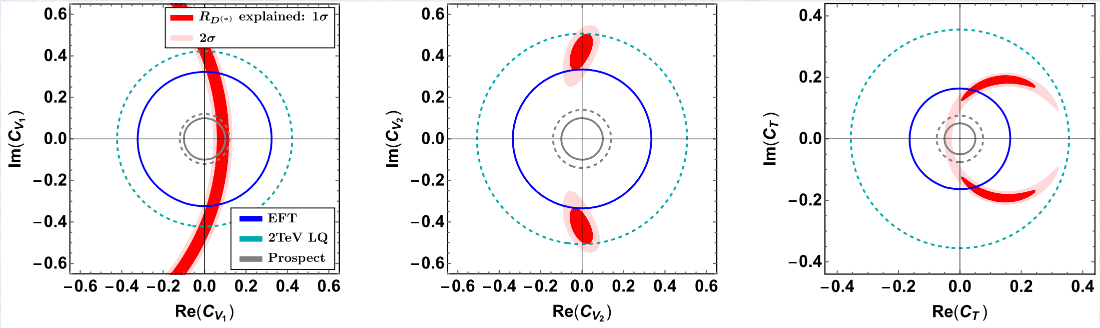
Proper bound for t-channel NP:

➡ 2TeV LQ: EFT bound is 40~100% overestimated

➡ 5TeV LQ: 10~20% overestimated

➡ T solution is still viable in the case of LQ type

$$|C_T^{\text{LHC-LQ}}| < 0.42 \quad \Leftrightarrow \quad |C_T^{R_{D^{(*)}}}| \approx |0.15 + i\,0.19| = 0.24$$



Collider signals

proposal of improvement:

— **Requiring additional b-jet greatly reduces the SM background** 2008.07541

➡ **comes from** $gq \to b\,\ell\,\nu \quad (q = u, c)$ **suppressed by |Vqb|^2 in the SM**

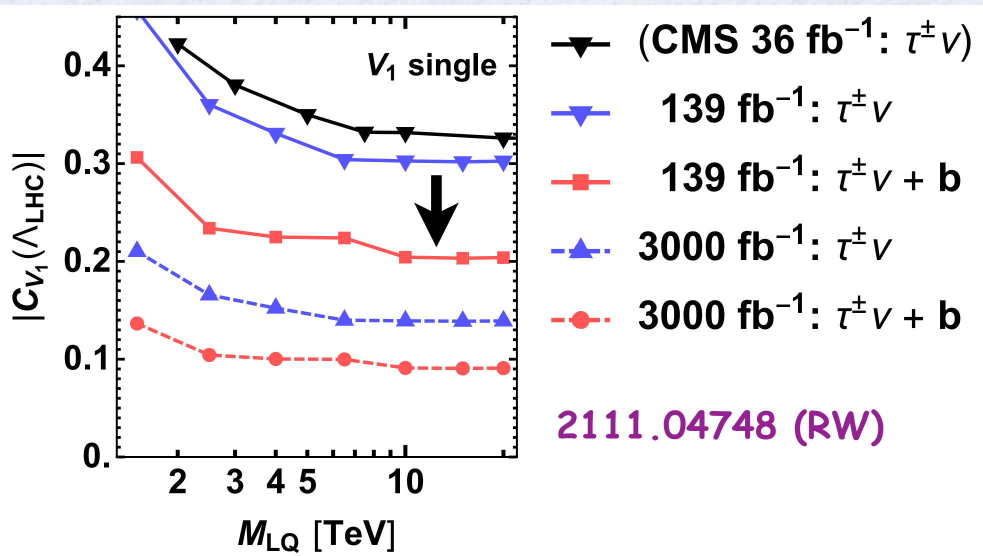
➡ **simulation shows +b search could improve the LHC bound by ~50%**

➡ **3ab^-1 LHC could reach the VLL solution:** $|C_{\rm VLL}^{\rm 3ab^{-1}\,+\,b}| \lesssim 0.1$

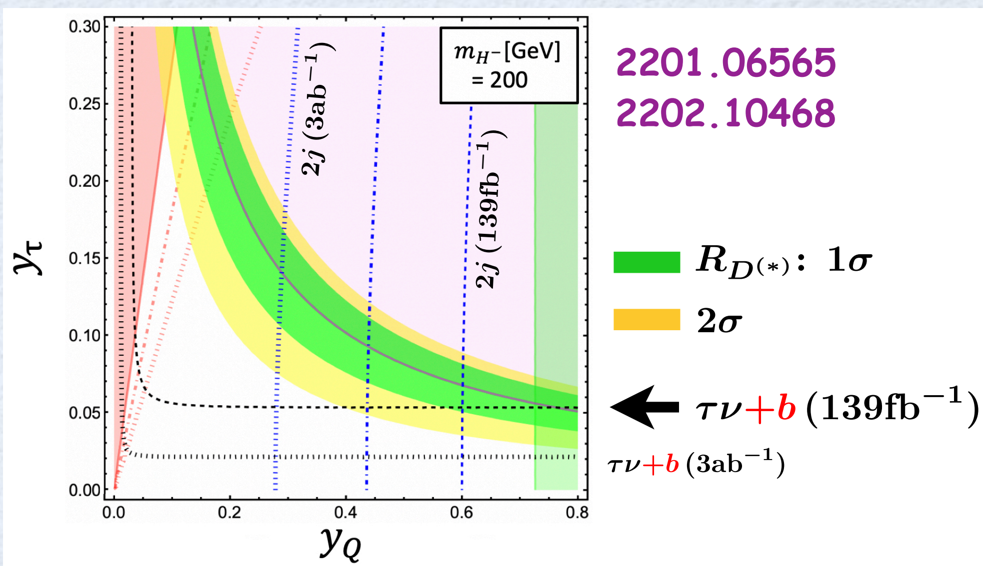
— **τν+b search can also access mH < 400GeV (out of range for τν search)**

➡ **suppressing trigger rate could reach up to 180GeV**

➡ **simulation shows 139fb^-1 data is sufficient to test the SLL solution for RD(*)**



2111.04748 (RW)



2201.06565
2202.10468

Summary

— SM predictions

- ☑ New lattice form factor calculations bring impacts on the SM values

— NP in the light lepton modes?

- ☑ NP hidden in the Vcb measurement is possible (< 5%), but impact on RD(*) is limited

— Flavor signals: B_c, Λ_b, Tau polarizations

- ☑ Bc → τν has great potential to pin down the RD(*) solution ➡️ CEPC has a crucial role!
- ☑ RΛc has model-independent sum rule with RD(*), and gives another index for the anomaly

— Collider signals: Tau + missing (+ b jet)

- ☑ High-pT (>500GeV) tail is sensitive to NP responsible for RD(*), and already competitive
- ☑ EFT bounds already excluded some RD(*) solutions, while t-channel bounds more milder
- ☑ Additional b-jet tag will improve the collider bound and reach 10% precision

Backup

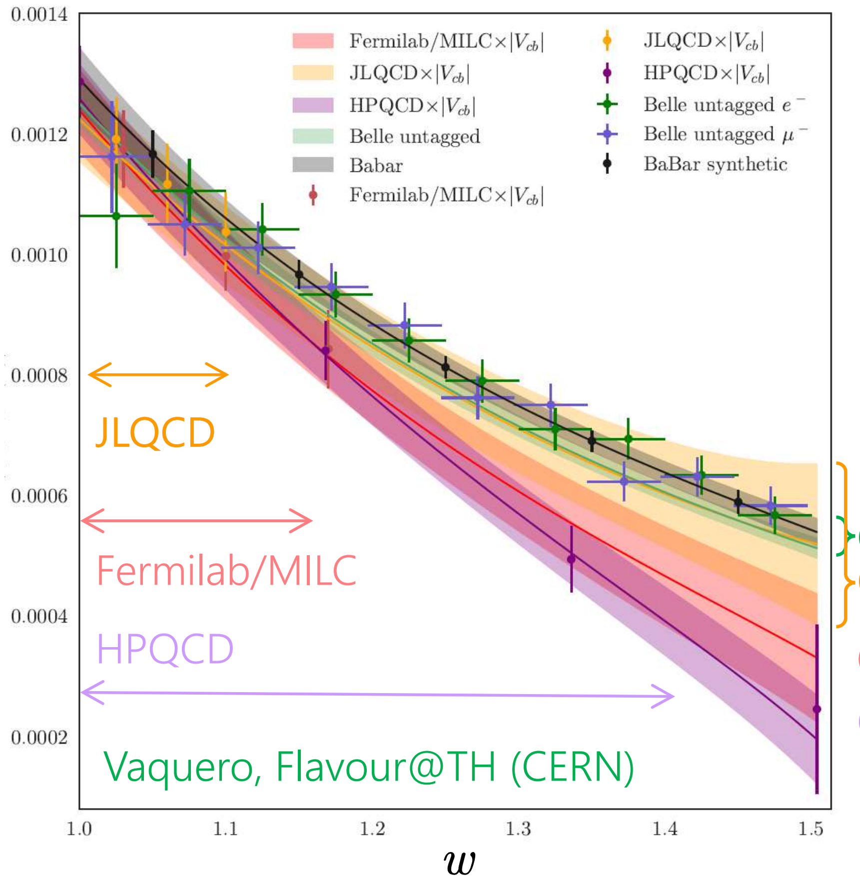
Lattice results competition

tension on $B \to D^* \ell \nu$

Vaquero [WG1+2] Tue 18:03

Colquhoun [WG2+3] Thu 18:50

$$|\eta_{EW} V_{cb} \mathcal{F}|^2 \qquad \mathcal{F}^2 \propto \left[2\frac{1-2wr+r^2}{(1-r)^2} \left\{ 1 + \frac{w-1}{w+1} R_1^2 \right\} + \left\{ 1 + \frac{w-1}{1-r}(1-R_2) \right\}^2 \right] h_{A_1}^2 \quad R_1 = \frac{h_V}{h_{A_1}}, \quad R_2 = \frac{h_{A_3} + r h_{A_2}}{h_{A_1}}$$



⓪ Belle and BaBar data

① Fermilab/MILC : steeper slope ?

+ χ^2/dof ~ 1.5 to fit w/ exp data

② HPQCD : even steeper slope !

+ siginifcant tension with exp (ℓ=e, μ) at medium/large w

+ $|V_{cb}|$ = 44.2(1.8) × 10^{-3} from total Γ

③ JLQCD : good consistency w/ exp

} ⓪ ③

① – tension on R_2 (?) [Belle 2301.07529, Jung Flavour@TH]

② – small recoils [JLQCD, Fermilab/MILC] ⇔ larger ap [HPQCD]

⇒ "safe" extension to large w: JLQCD; Fermilab/MILC a^{-1}~6.6GeV

Flavor signals

(2) B_c decay

The "R" observable for Bc: $R_{J/\psi} = \mathcal{B}(B_c \to J/\psi\, \tau\, \nu) \big/ \mathcal{B}(B_c \to J/\psi\, \mu\, \nu)$

1711.05623

$\text{LHCb (2017)}: 0.71 \pm 0.17 \pm 0.18$ (35%) $\Leftrightarrow$

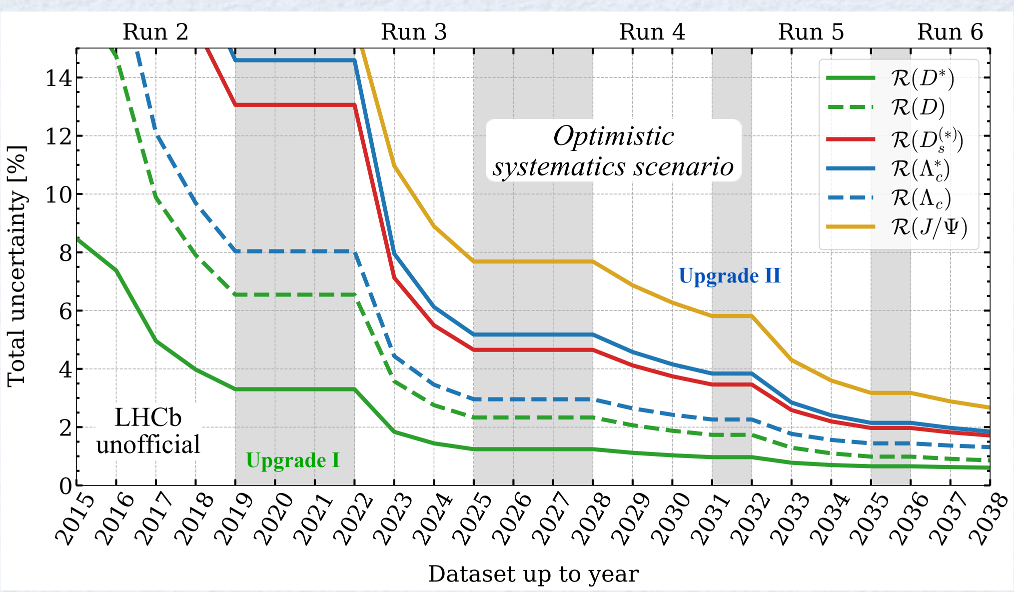
- SM (2017): 0.28 ± 0.05 — 1709.08644
- SM (2019): 0.24 ± 0.01 — 1901.08368
- SM (2022): 0.258 ± 0.004 — 2204.04357

— Update is planned in the LHCb roadmap

➡ error could go into 8% in 5 years

— Sufficiently crucial for the RD(*) anomaly

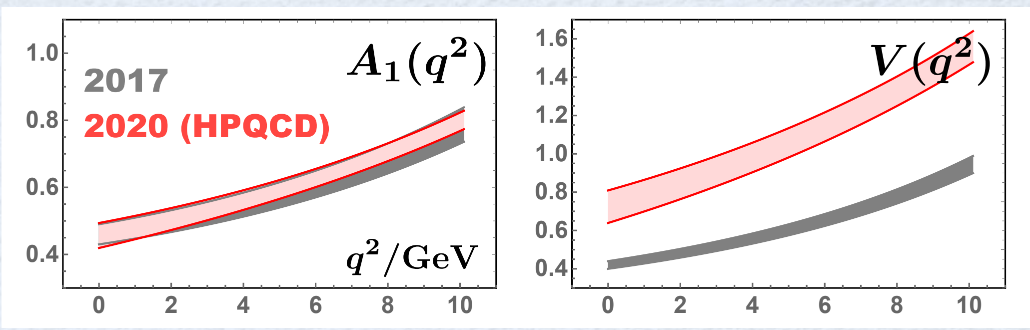
➡ NP prediction on RJψ can be tested



— FF updated: 2007.06957

➡ QCD (2017)/ SR (2019) / lattice (2020)

➡ deviations affected the SM value



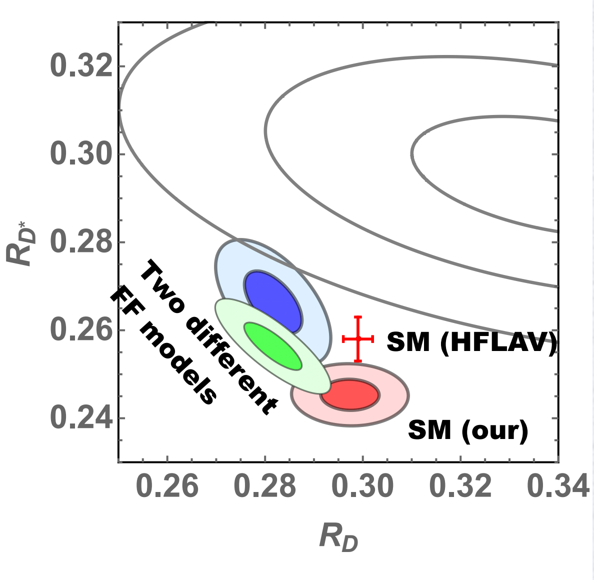
— NP prediction from the RD(*) solution:

➡ ex) VLL solution predicts 0.28-0.29

➡ Summary given later

NP in the light lepton modes?

(1) Simultaneous fit of FF + Vcb + NP in $B \to D^{(*)}\mu\nu\,,\ D^{(*)}e\nu$



2004.10208 (RW)

— assuming LFU type NP in e/μ $C_X^e = C_X^\mu$

— taking Belle full angular data (2017,2018) & all available theory

➡ processes usually used to measure Vcb

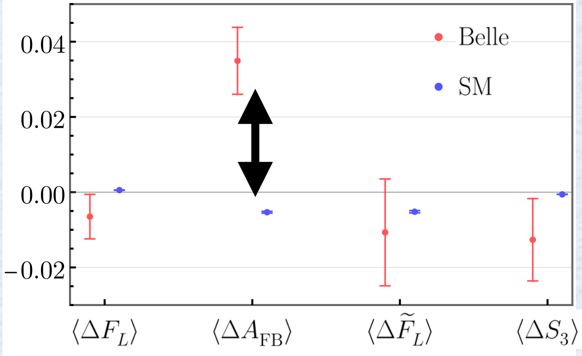
— NP can be hidden behind the Vcb measurement

➡ possible size is < 5% of the "SM size" $\equiv 2\sqrt{2}G_F V_{cb}$

— Impact on RD(*), NP in denominator, is mild

➡ RD* increases while RD decreases in case of VRL type NP

(2) New anomaly in angular obs. $\Delta A_{\rm FB} = A_{\rm FB}(D^*\mu\nu) - A_{\rm FB}(D^*e\nu)$



2104.02094, 2203.07189

— using Belle 2018 data, angular asymmetries can be constructed

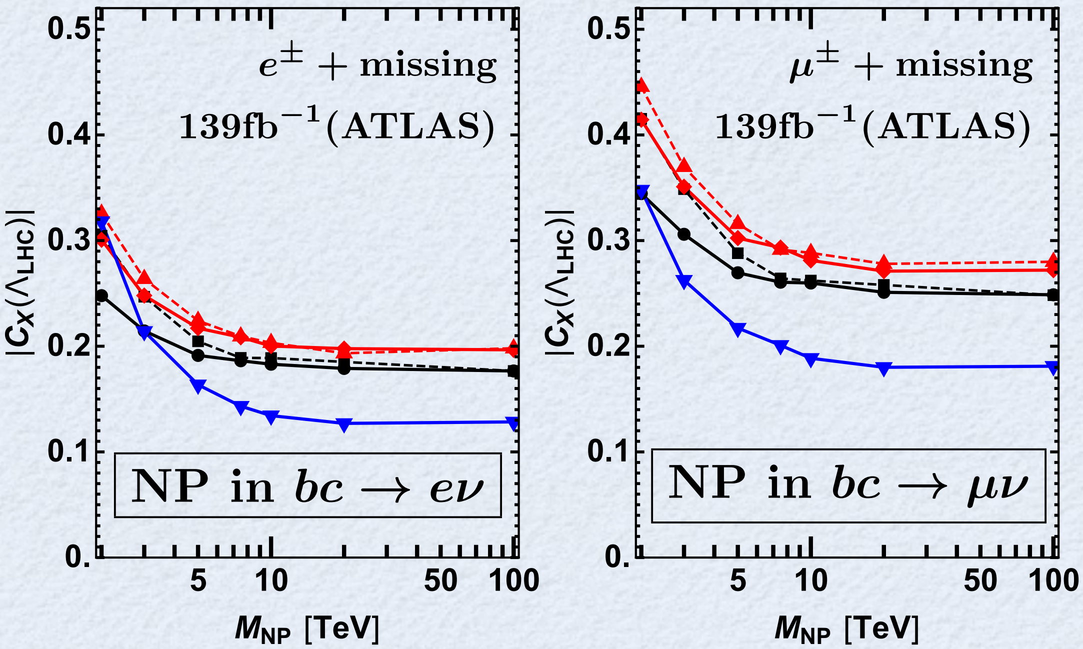
— "anomaly" was observed in the FB asymmetry between e/μ

➡ Single NP operators difficult / Tuned NP couplings needed

➡ Impact on RD(*) is very limited since Br(e/μ) = 1 ± 0.01

Result 1/2

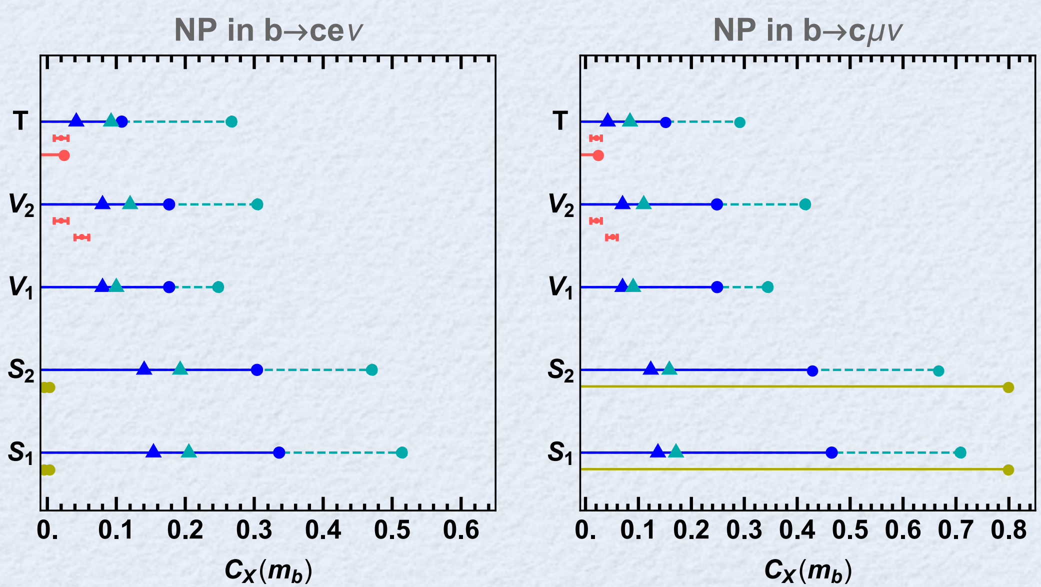
Mediator (LQ) mass dependence:



(WC definition)

- **V1** $2\sqrt{2}G_F V_{cb}\Big[C_{V_1}(\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu)$
- **V2** $+C_{V_2}(\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu)$
- **S1** $+C_{S_1}(\bar{c}P_R b)(\bar{\ell}P_L \nu)$
- **S2** $+C_{S_2}(\bar{c}P_L b)(\bar{\ell}P_L \nu)$
- **T** $+C_T(\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\ell}\sigma_{\mu\nu}P_L \nu)\Big]$

Impact on Flavor (Vcb+NP fit):

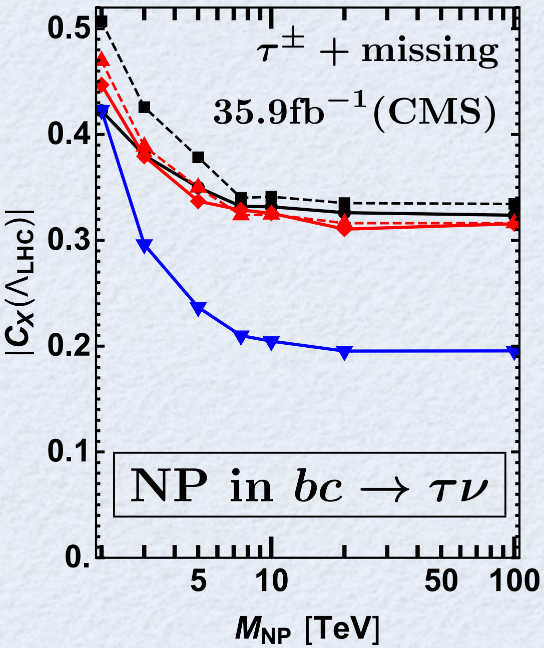


- LHC (EFT)
- LHC (2TeV LQ)
- Flavor fit ← **(1st topic)**
- $B_c \to e\nu/\mu\nu$

- Fit result (1σ)
- Upper bound (95%CL)
- Prospect (HL-LHC)

Result 2/2

The tau case:



EFT) $|C_T|_{\rm LHC} < 0.20$ (95%CL)

↓

LQ) $|C_T|_{\rm LHC} < 0.42$ (95%CL)

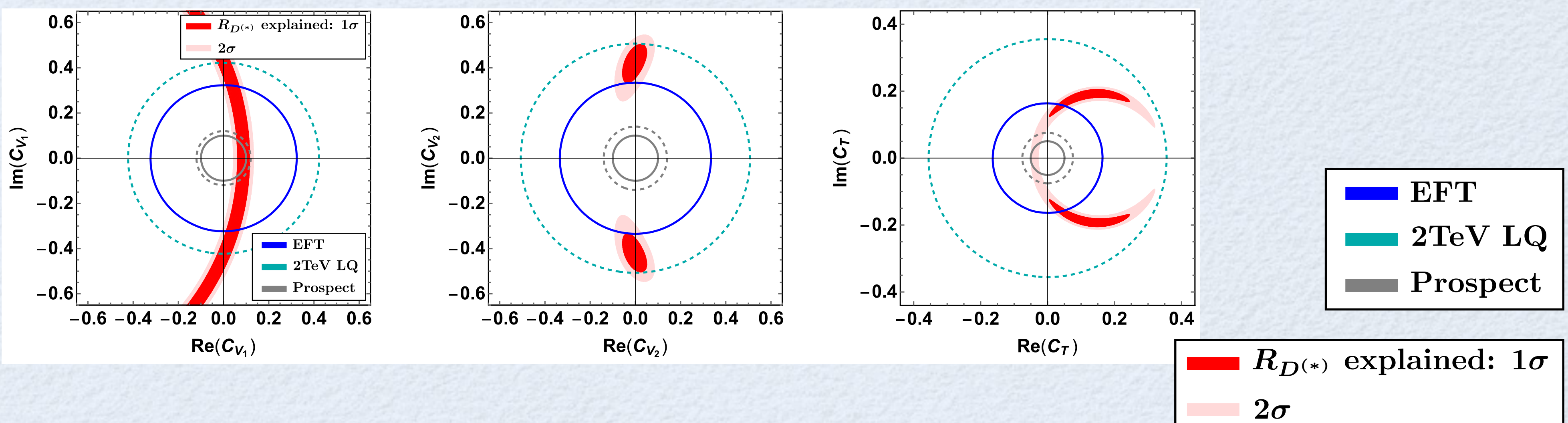
$\leftrightarrow\ |C_T|_{R_{D^{(*)}}} \approx |0.15 + i\,0.19| = 0.24$

(Summary)

2TeV LQ: EFT bound is 40~100% overestimated

5TeV LQ: 10~20% overestimated

Impact on Flavor (RD(*) anomaly):



+ b-jet tag

2111.104748

— Requiring **additional b-jet** greatly reduces the SM background

$$\ell^{\pm}\nu + b\Big|_{\rm SM} \quad \Rightarrow \quad gq \to b\ell\nu \quad (q = u, c) \quad \Rightarrow \quad |V_{ub,cb}|^2 \text{ suppression}$$

Improvement ①: stronger bound is simply expected

— can look into detail of the **U1-LQ** model = SM-like vector operator

$$\mathcal{L}_U = h_U^{ij} \left(\bar{q}_L^i \gamma^\mu \ell_L^j\right) U_\mu + \text{h.c.} \qquad C_{V_1} \equiv -\frac{h_U^{b\tau} \cdot h_U^{c\nu}}{m_{\rm LQ}^2}, \quad \text{but indeed } h_U^{c\nu} = h_U^{s\ell}$$

$$\ell^{\pm}\nu\Big|_{U_1\text{-LQ}} \quad \Rightarrow \quad cb, cs \to \ell\nu \quad \Rightarrow \quad \text{The } C_{V_1} \text{ bound is valid only if } h_U^{b\tau} \gg h_U^{c\nu} \text{ for } U_1\text{-LQ}$$

$$\ell^{\pm}\nu + b\Big|_{U_1\text{-LQ}} \quad \Rightarrow \quad cg \to b\ell\nu \quad \Rightarrow \quad \text{no } s \text{ quark, (but could be mis-tagged)}$$

Improvement ②: complementary bound on the two couplings

+ b-jet tag

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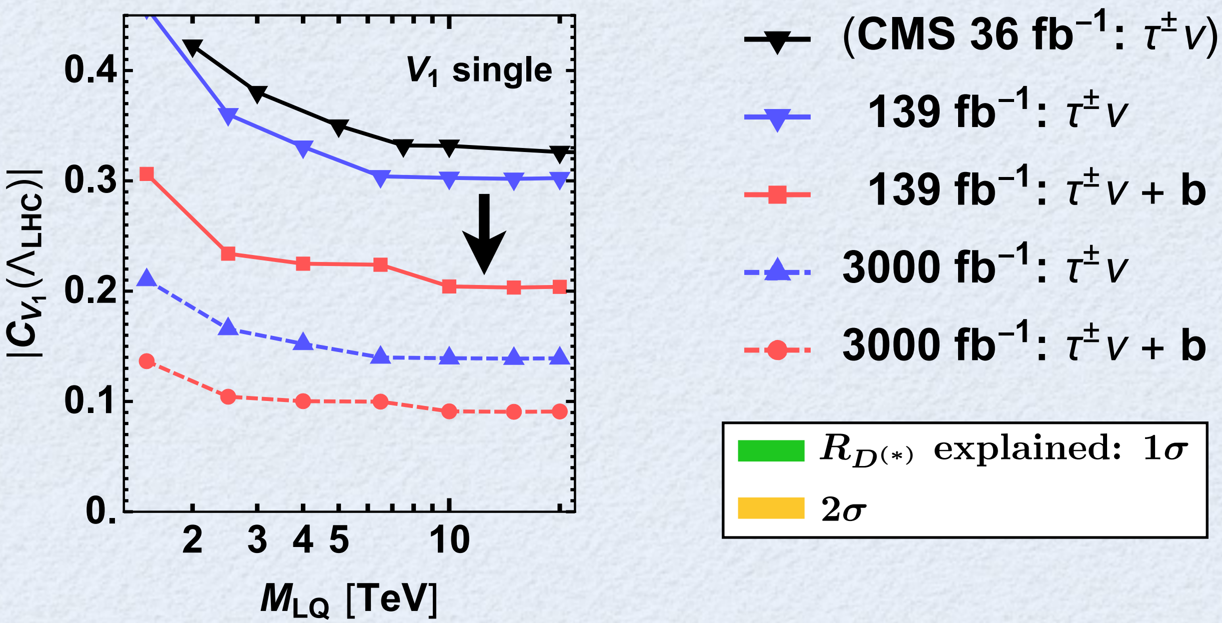
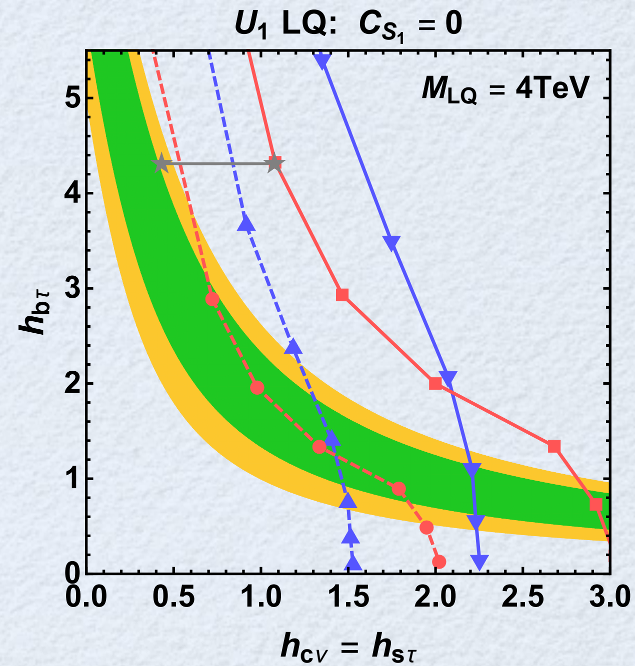
(BG/Signal events generated & simulated: details skipped)

Improvement ①:



Improvement ②:



Observations:

- +b search improves the bound by ~50%
- +b search at HL_LHC can achieve Cx~0.1, i.e. 10% NP effect
- Given the LQ mass, the two couplings (not combination) are constrained

FF parameterization

CLN

Caprini, Lellouch, Neubert (1997)

— "Traditional" parameterization based on HQET
— Form Factors are approximated and related with each other

Cons: parameterization is valid only up to $1/m_Q$ correction

↳ Comparison: inclusive decay has no $(1/m_Q)^1$ but starts from $(1/m_Q)^2$

BGL

Boyd, Grinstein, Lebed (1997)

— "General" parameterization with minimum requirement
— Each Form Factor involves independent parameters

Cons: FFs in New Physics involve new unknown parameters

FF parameterization

✓ "general HQET"   Jung, Straub (2018), Bordone, Jung, Dyk (2019)

— **general HQET based parameterization**

— **includes higher order corrections at the cost of larger parameter set**

Pros: NNLO could be competitive to NLO because $(\Lambda/m_c)^{\mathbf{2}} \sim (\Lambda/m_b)^1$

Pros: Including NNLO is also a fair comparison with inclusive mode

✓ Modeling

HQET property: one LO / three NLO / six NNLO Isgur-Wise functions

Parameterization: ex) $\xi(w) \equiv \sum_{n=0}^{N_{\rm LO}} a_\xi^{(n)} z^n$ **Truncation order: arbitrary**

Two proposed modelings for the truncation orders: * CLN is naively (3/0/-)

$$(N_{\rm LO}/N_{\rm NLO}/N_{\rm NNLO}) = \begin{cases} (3/2/1) & \to \textbf{23 parameters!} \\ (2/1/0) & \to \textbf{13 parameters!} \end{cases}$$

Tau Polarization in LQ