FPCP2022 at the University of Mississippi

23 May 2022

Anomalies in charged-current B decays

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Sezione di Pisa

INFN Sezione di Pisa

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MIUR
MINISTERO DELL' ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

PRIN "The consequences of flavor"

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)	$0.280 \pm 0.018 \pm 0.029$	–	–
Average	0.338 ± 0.030	0.297 ± 0.013	-0.39

Latest results:

Belle 2019 / LHCb run 1 2018 ➡ no update in 3 years

Waiting lists:

CMS with "B-parking" / Belle II / LHCb run2 ➡ afternoon talk(?)

RD(*): usual interpretations

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

— Solutions to the RD(*) anomaly

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

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

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

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

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'): $C^\tau_{\text{SM-like}}, C^\tau_{\mathrm{VRL}}$

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

Charged Higgs: C^τ_{SLL}

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

RD(*): usual interpretations

Leptoquarks (LQ): $\mathrm{S}_1,\ \mathrm{R}_2,\ \mathrm{U}_1$

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

- ➡ 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: $C_{\mathrm{VLL}},\ C_{\mathrm{SLL}}$ 1709.00692, 1808.07492, 1812.01603, 2103.11889

- ➡ VLL and SLL are independent apart from UV completion
- ➡ Famous Pati-Salam UV induces Z' that has to be managed (model dependent)
- ➡ Another UV from U(2) flavor symmetry gives $C_{\mathrm{SLL}} = -2\, e^{I\phi}\, C_{\mathrm{VLL}}$

This talk:
How are related observables to RD(*) & impacts on these solutions?

Content

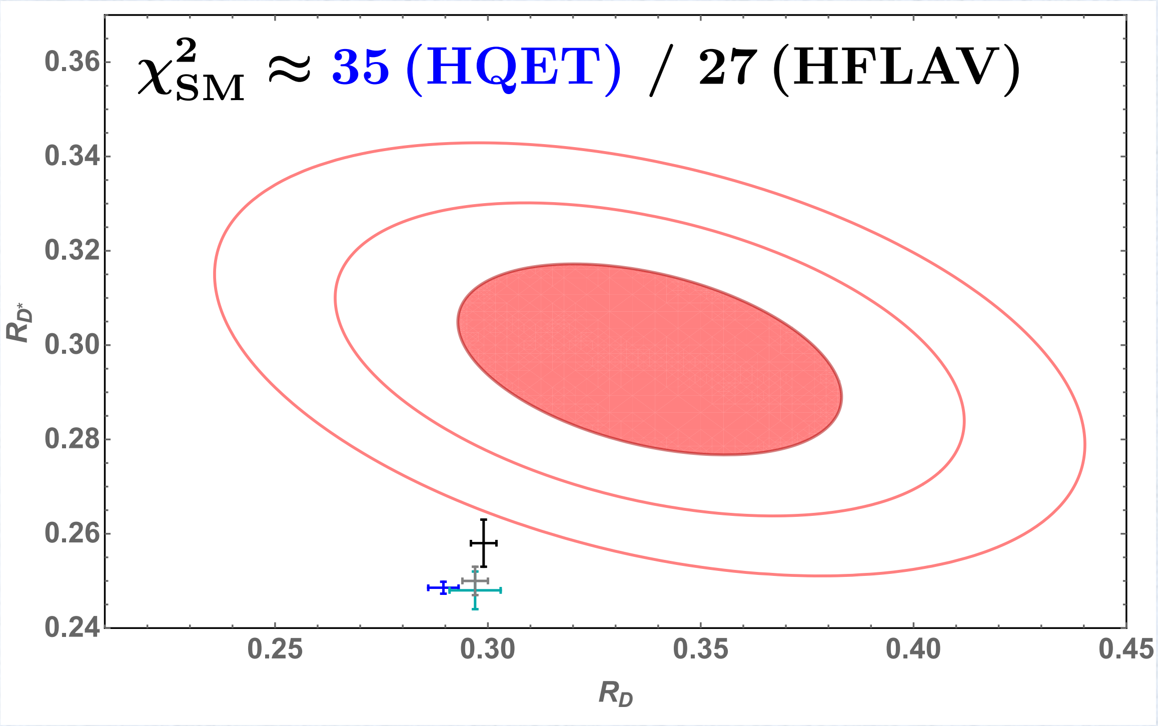
— SM predictions

— NP in the light lepton modes?

— Flavor signals: B_c, Λ_b, (Tau polarizations)

— Collider signals: Tau + missing

SM predictions (Form Factors)



BGL parameterization:

+ HFLAV (Spring2019)

General HQET parameterization:

+ EPJC80(2020)74 [3/2/1 model]

+ JHEP08(2020)006 [3/2/1 model]

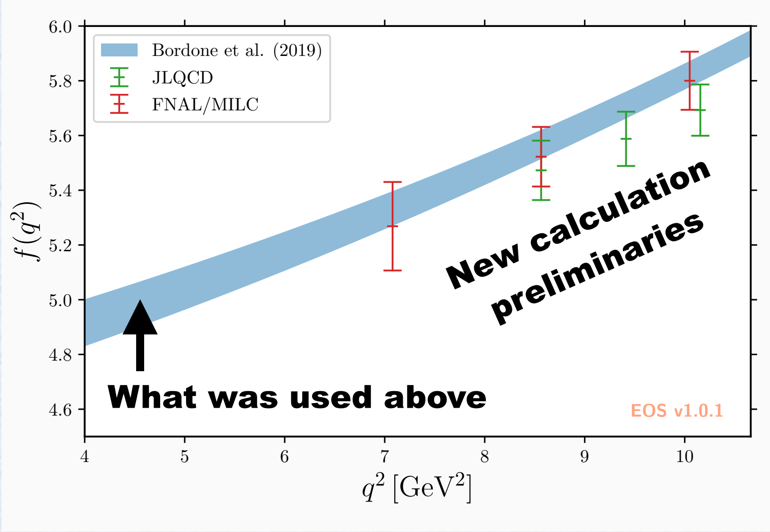
+ JHEP08(2020)006 [2/1/0 model]

Why different?:

— **FF shape fit is still unstable**

➡ **We need more theory calculation**

— **Lattice was available only for B → D**



New lattice calculations for B → D*:

Plot from Danny van Dyk

— **JLQCD, FNAL/MILC, HPQCD results will be available**

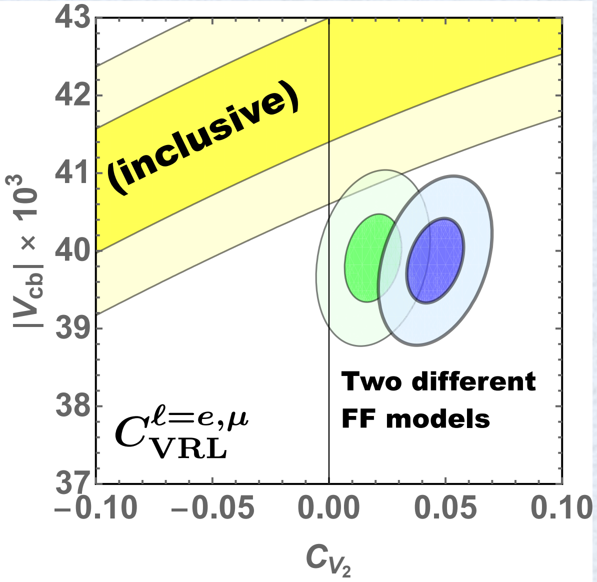
— **can be compared with the current FF fit of blue band**

— **This plot is good while others look inconsistent**

(Still preliminaries and so I don't show much)

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

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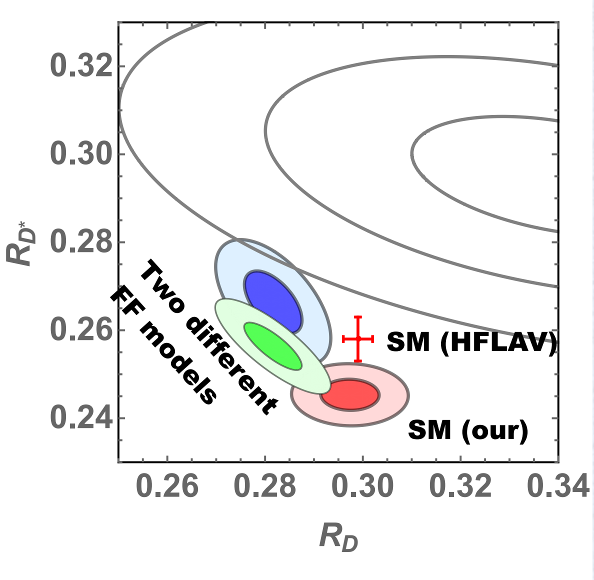

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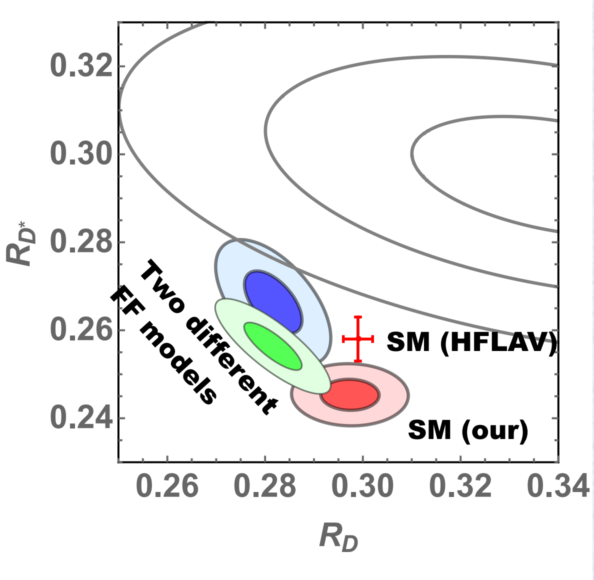

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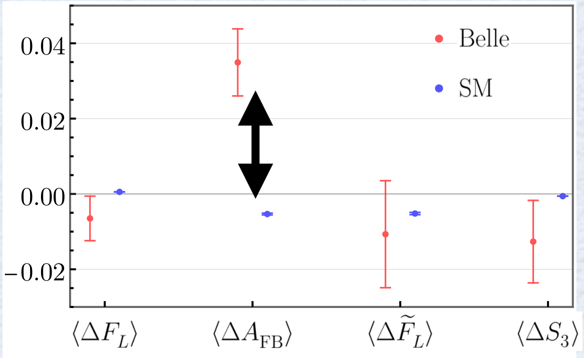
(2) New anomaly in angular obs. $\Delta A_{\rm FB} = A_{\rm FB}(D^*\mu\nu) - A_{\rm FB}(D^*e\nu)$



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

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

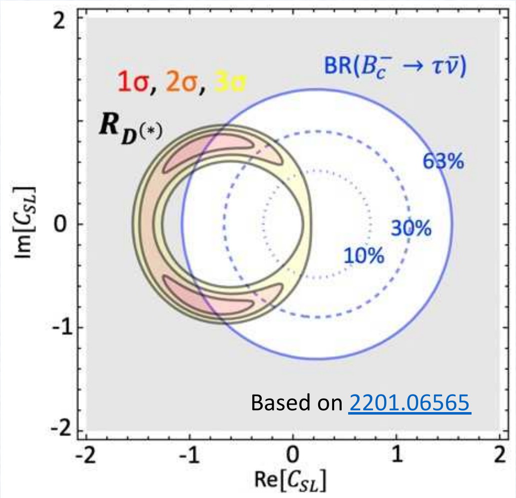
$$[\tau_{B_c}^{\rm exp} \approx 0.5{\rm ps}] \text{ vs. } [0.4{\rm ps} < \tau_{B_c}^{\rm th} < 0.7{\rm ps}] \quad \Rightarrow \quad {\rm Br}(B_c \to \text{induced by NP}) < 30\%$$

— **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 has to be revisited now!**

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

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

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

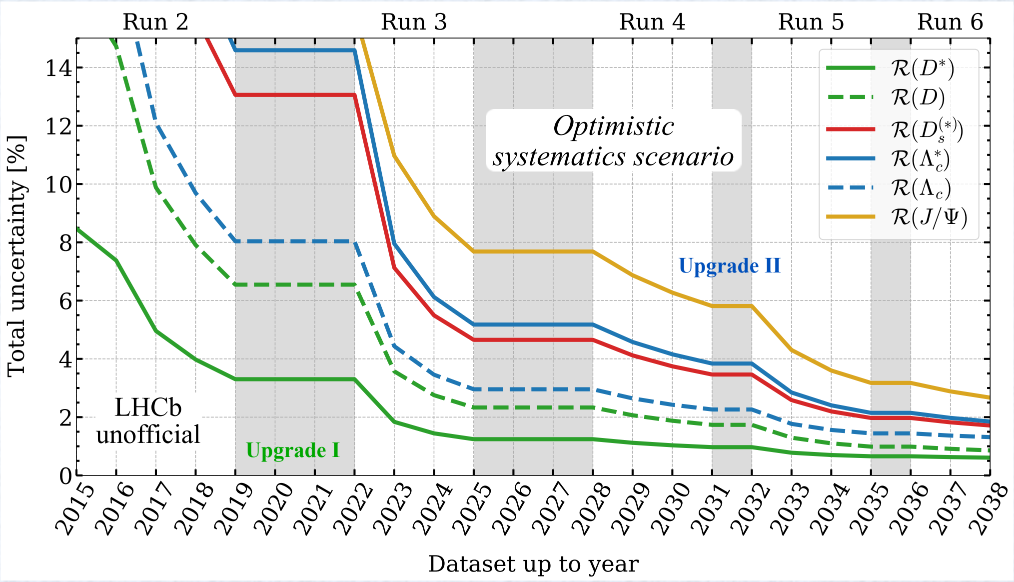
35%

— 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



Flavor signals

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1711.05623

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

$\text{SM (2017)}: 0.28 \pm 0.05$ — 1709.08644

$\text{SM (2019)}: 0.24 \pm 0.01$ — 1901.08368

$\text{SM (2022)}: 0.258 \pm 0.004$ — 2204.04357

— Update is planned in the LHCb roadmap

➡ error could go into 8% in 5 years

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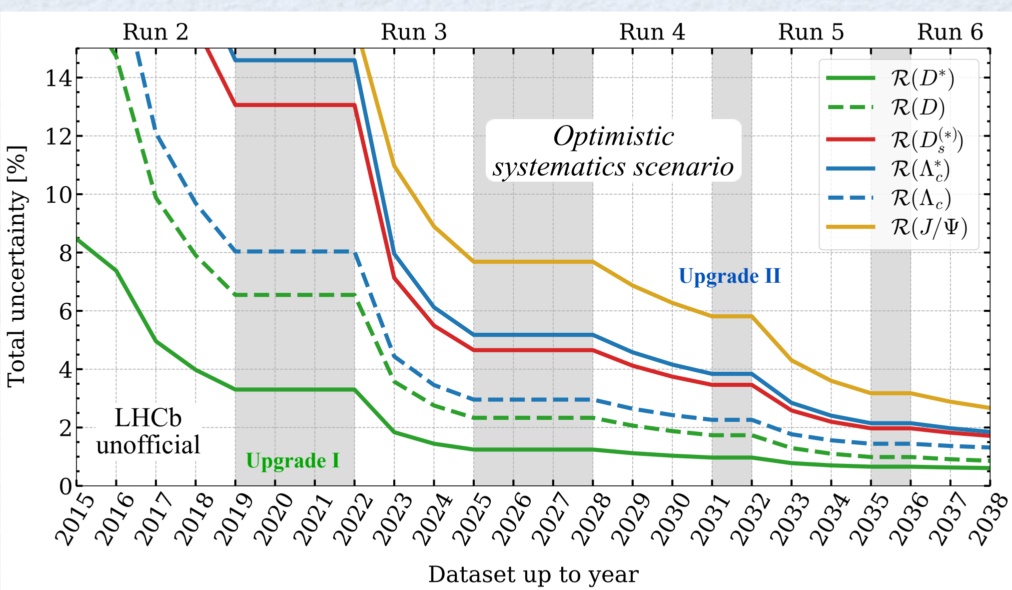
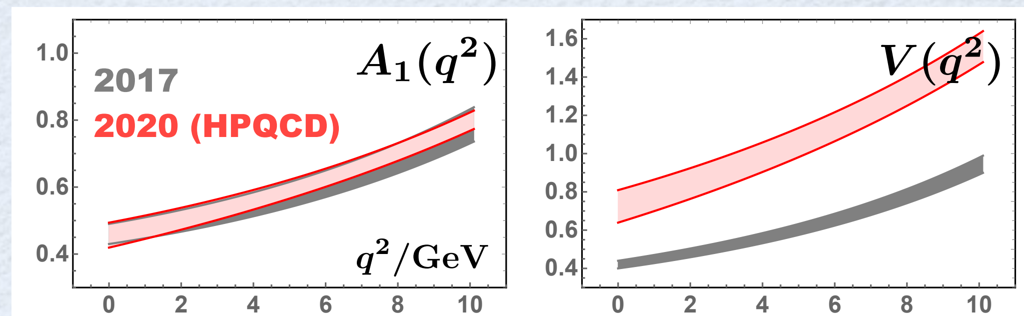


— FF updated: 2007.06957

➡ 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

Flavor signals

(3) 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

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

Flavor signals

(3) Λ_b decay

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

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

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

1811.09603, 1905.08253

— δ=0 holds 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: $R_{\Lambda_c}^{\rm fit} = 0.380 \pm 0.013 \pm 0.005$

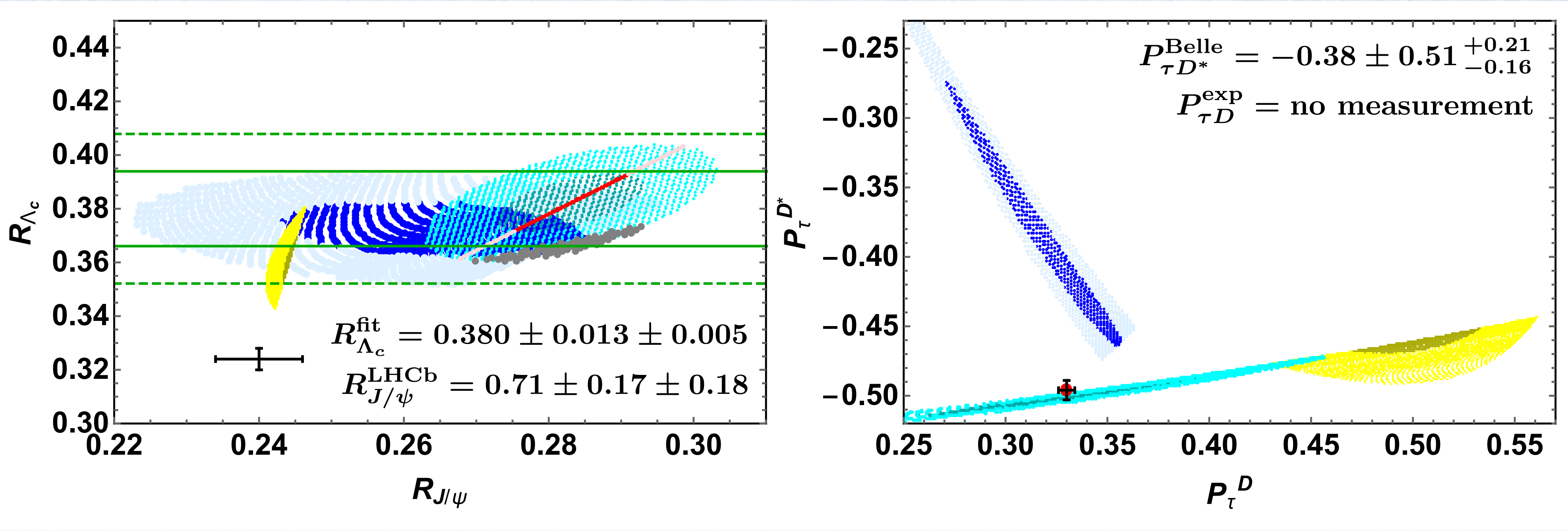
➡ **is another index to test the anomaly**

➡ **IOW, this R cannot distinguish NP types but is a unique value for every NP solution**

➡ **For now, the measured RΛc is not consistent with the RD(*) anomaly**

Flavor signals

NP prediction summary:



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

➡ **RΛc are in the same range as explained and has to be tested**

➡ **RJψ has a clear correlation with RΛc for the VLL/VRL solution (red/gray)**

➡ **Tau spin polarizations could identify T/SLL/LQ solution (blue/yellow/cyan)**

➡ **Current experimental measurements are out of range in this plot**

Collider signals

W boson resonance:

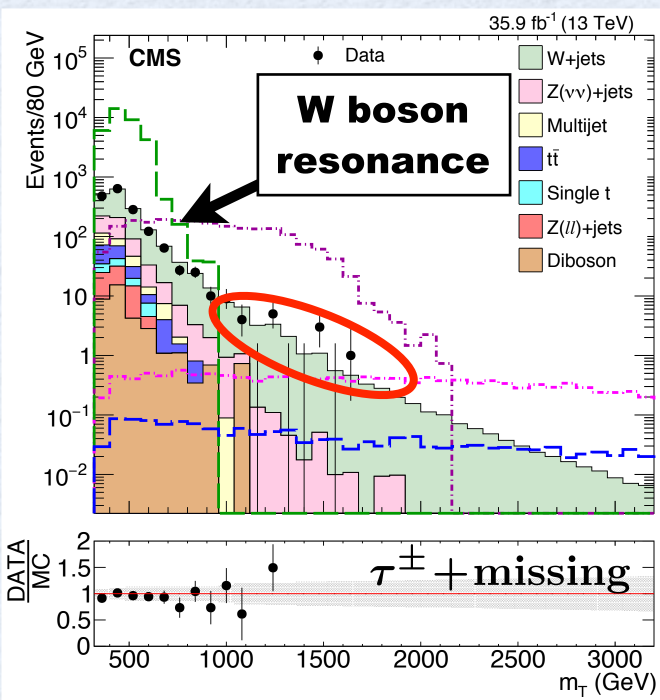
— has been observed with missing transverse mass

— 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:

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

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

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

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

— 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:

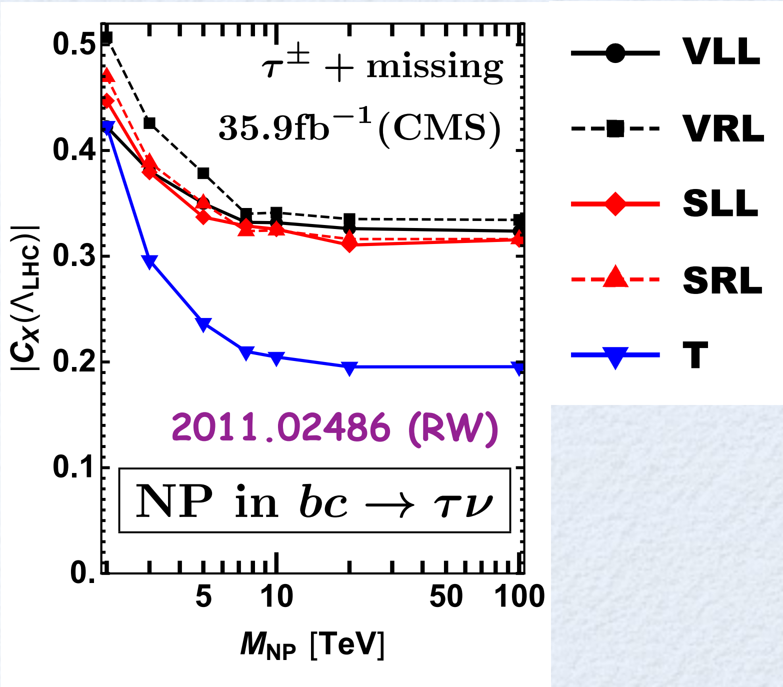
— EFT approximation is not good at high-mT

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

➡ In particular, it overestimates the signal for t-channel

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

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



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

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

Future capability:

➡ 3ab^-1 LHC reaches all the solutions except VLL

$$|C_{\mathrm{VLL}}^{\text{LHC 3ab}^{-1}}| < 0.15 \quad \Leftrightarrow \quad C_{\mathrm{VLL}}^{R_{D^{(*)}}} \approx 0.09$$

Collider signals

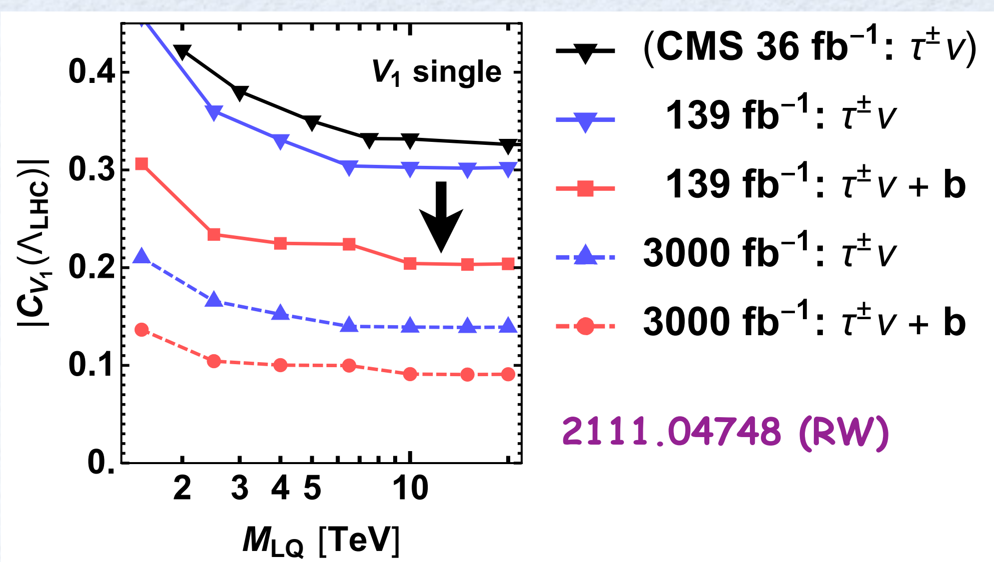
proposal of improvement:

— **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:** $|C_{\rm VLL}^{\rm 3ab^{-1}\,+\,b}| \lesssim 0.1$



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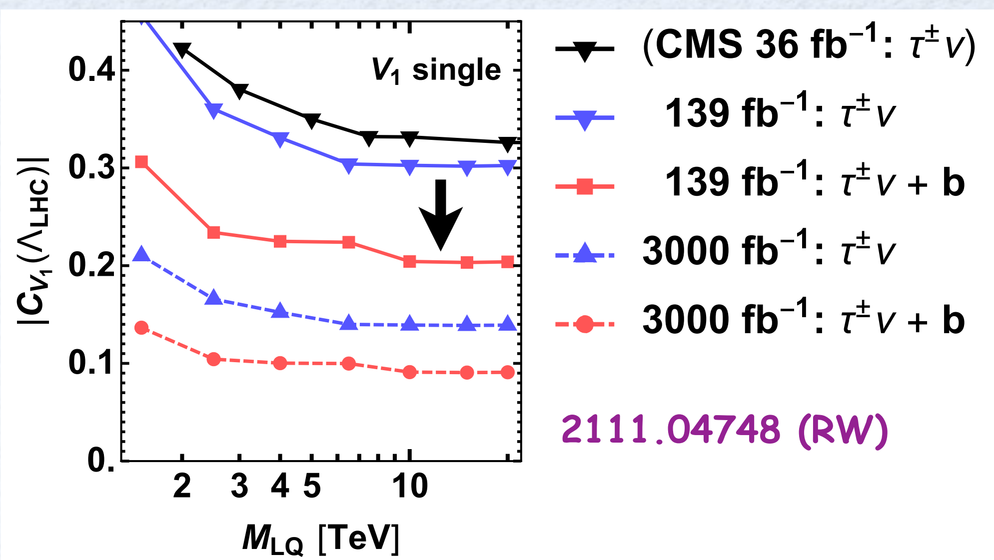
➡ **simulation shows +b search could improve the LHC bound by ~50%**

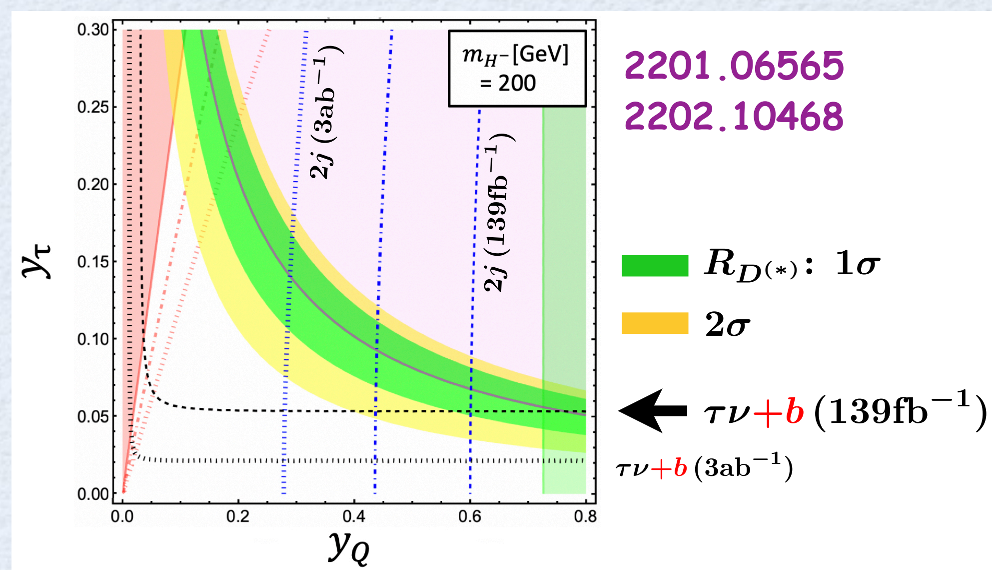
➡ **3ab^-1 LHC could reach the VLL solution:** $|C_{\mathrm{VLL}}^{3\mathrm{ab}^{-1}+b}| \lesssim 0.1$

— **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(*)**





Summary

— SM predictions

- ☑ Upcoming lattice form factor calculations will 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
- ☑ New anomaly in angular asymmetry for e/μ is found, but nothing to do with RD(*)

— Flavor signals: B_c, Λ_b, (Tau polarizations)

- ☑ $R_{\Lambda c}$ has model-independent sum rule with RD(*), and gives another index for the anomaly
- ☑ $R_{J\psi}$ will be updated both from th./exp., and has potential to identify the RD(*) solution

— Collider signals: Tau + missing

- ☑ 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

Missing in this talk

Right-handed neutrino scenarios

Model construction issues

Interplay with anomalies in neutral-current B decay

Interplay with LFV

...

Backup

(Leptoquark setup)

Prepare LQ interactions that generate 4 Fermi current:

$$\mathcal{L}_{[V_1]} = h^{ij}\left(\bar{q}_L^i \gamma^\mu \ell_L^j\right) U_\mu + \text{h.c.} \quad \Longrightarrow \quad C_{V_1}$$

$$\mathcal{L}_{[V_2]} = \left(h^{ij}\bar{u}_R^i \nu_L^j + h'^{ij}\bar{d}_R^i \ell_L^j\right) R_2^{2/3} + \text{h.c.} \quad \Longrightarrow \quad C_{V_2}$$

$$\mathcal{L}_{[S_1]} = \left(h^{ij}\bar{u}_L^i \gamma^\mu \nu_L^j + h'^{ij}\bar{d}_R^i \gamma^\mu \ell_R^j\right) U_\mu + \text{h.c.} \quad \Longrightarrow \quad C_{S_1}$$

⋮

— **Every given LQ mass, the coupling h is constrained from LHC data**

— **The result is represented as the WC bound:** $2\sqrt{2}G_F V_{cb} C_X = N_X \dfrac{h_1 h_2}{M_{\rm LQ}^2}$

(Amplitude)

$$|\mathcal{M}_{V_1}^{\rm LQ}|^2 = 4\,(h_{\rm LQ}^{21} h_{\rm LQ}^{31*})^2 E^4 \hat{C}_t^2 (1-\cos\theta)^2,$$
$$|\mathcal{M}_{V_2}^{\rm LQ}|^2 = (h_{\rm LQ_1}^{21} h_{\rm LQ_2}^{31*})^2 E^4 \hat{C}_t^2 (1+\cos\theta)^2,$$
$$|\mathcal{M}_{S_1}^{\rm LQ}|^2 = 16\,(h_{\rm LQ_1}^{21} h_{\rm LQ_2}^{31*})^2 E^4 \hat{C}_t^2,$$
$$|\mathcal{M}_{S_2/T}^{\rm LQ}|^2 = (\tilde{h}_{\rm LQ_2}^{12*} \tilde{h}_{\rm LQ_1}^{13})^2 E^4 \Big[\hat{C}_t^2 (1+\cos\theta)^2 + \hat{C}_u^2 (1-\cos\theta)^2 \pm 2\hat{C}_t \hat{C}_u (1-\cos^2\theta)\Big],$$

where $\hat{C}_t$ and $\hat{C}_u$ involve the LQ propagator written as

$$\hat{C}_t = \Big[2E^2(1+\cos\theta) + M_{\rm NP}^2\Big]^{-1},$$
$$\hat{C}_u = \Big[2E^2(1-\cos\theta) + M_{\rm NP}^2\Big]^{-1}.$$

EFT: $\hat{C}_t = \hat{C}_u = 1/M_{\rm NP}^2$

(Leptoquark setup)

Prepare LQ interactions that generate 4 Fermi current:

$$\mathcal{L}_{[V_1]} = h^{ij} \left(\bar{q}_L^i \gamma^\mu \ell_L^j \right) U_\mu + \text{h.c.} \quad \Longrightarrow \quad C_{V_1}$$

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$$\mathcal{L}_{[S_1]} = \left(h^{ij} \bar{u}_L^i \gamma^\mu \nu_L^j + h'^{ij} \bar{d}_R^i \gamma^\mu \ell_R^j \right) U_\mu + \text{h.c.} \quad \Longrightarrow \quad C_{S_1}$$

⋮

— Every given LQ mass, the coupling h is constrained from LHC data

— The result is represented as the WC bound: $2\sqrt{2} G_F V_{cb} C_X = N_X \dfrac{h_1 h_2}{M_{\text{LQ}}^2}$

(Numerical Analysis)

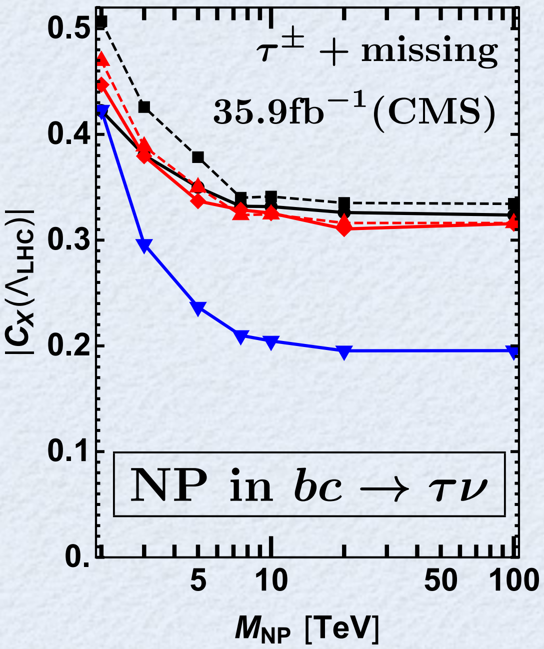
— Signal simulated as usual Madgraph5, PYTHIA8, DELPHES3

— Selection cuts following ATLAS (light lepton) / CMS (tau) ATLAS (2019), CMS (2019)

— Observed # in distribution of mT bin ~ 1TeV is analyzed to compute the bound

Result 2/2

The tau case:



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

↓

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

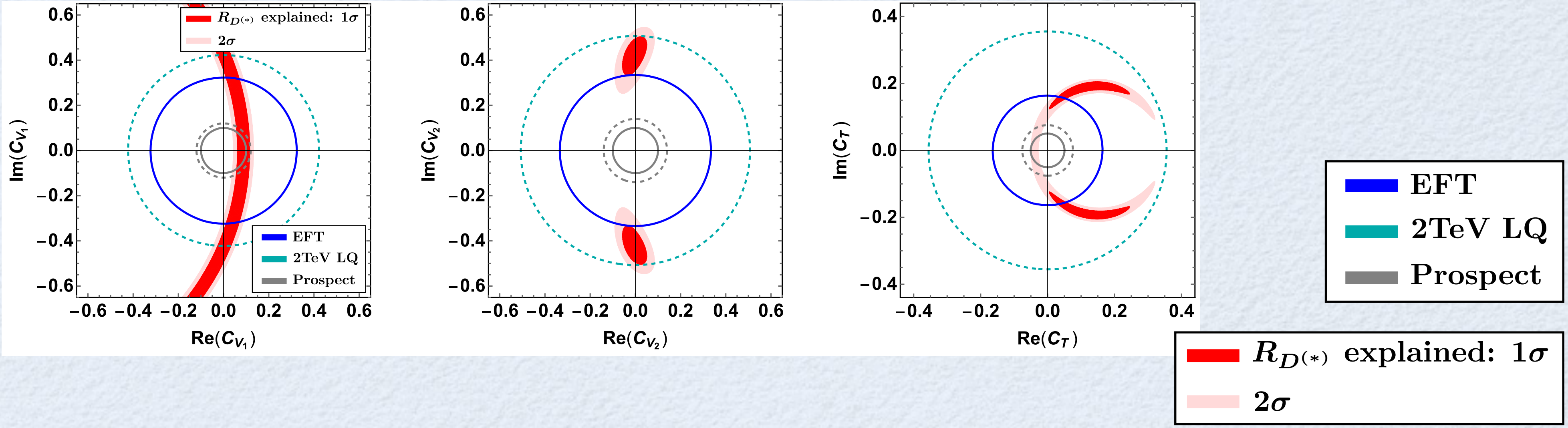
$\leftrightarrow \; |C_T|_{R_{D^{(*)}}} \approx |0.15 + i\,0.19| = 0.24$

(Summary)

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

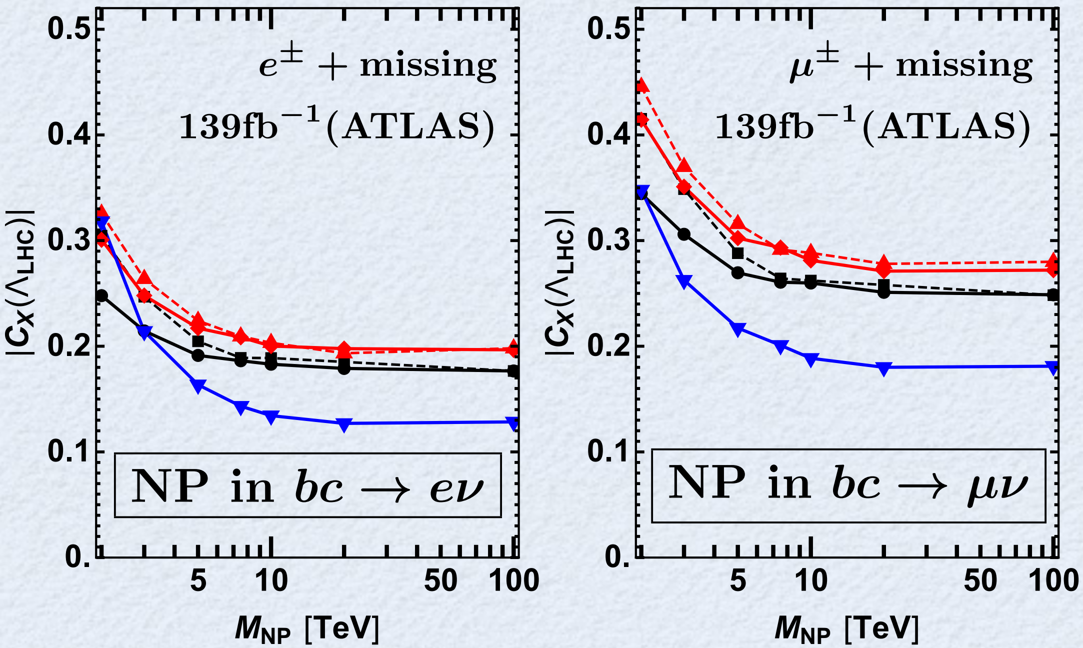
5TeV LQ: 10~20% overestimated

Impact on Flavor (RD(*) anomaly):



Result 1/2

Mediator (LQ) mass dependence:

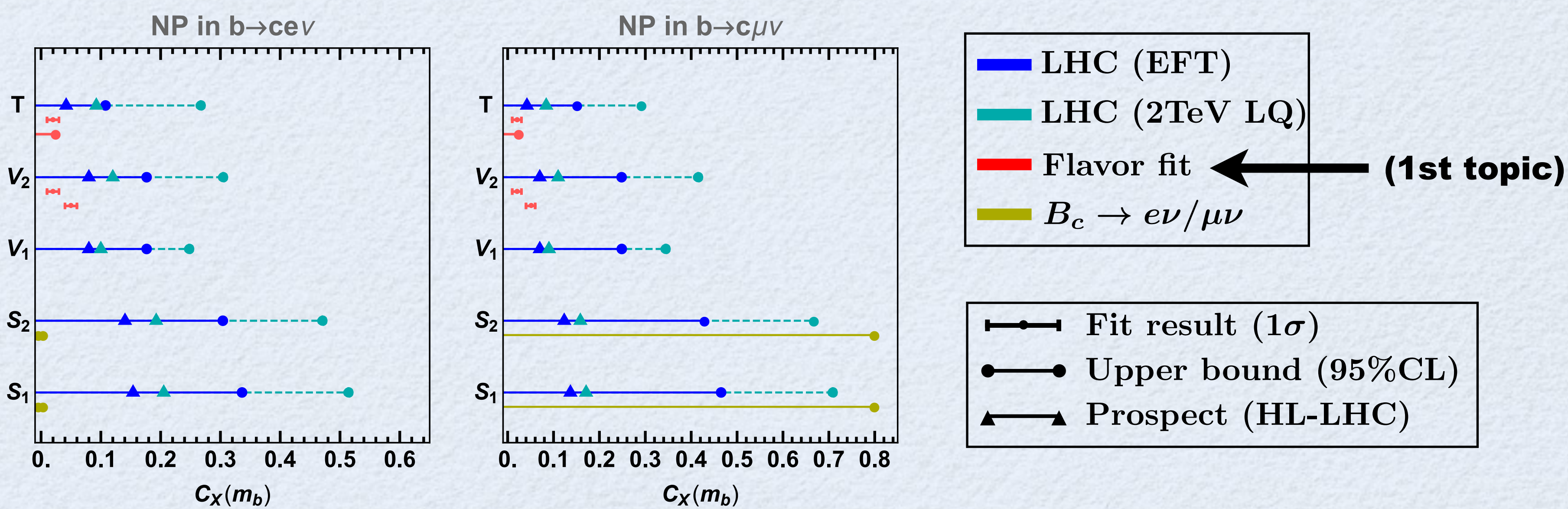


(WC definition)

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

- V1
- V2
- S1
- S2
- T

Impact on Flavor (Vcb+NP fit):



+ 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

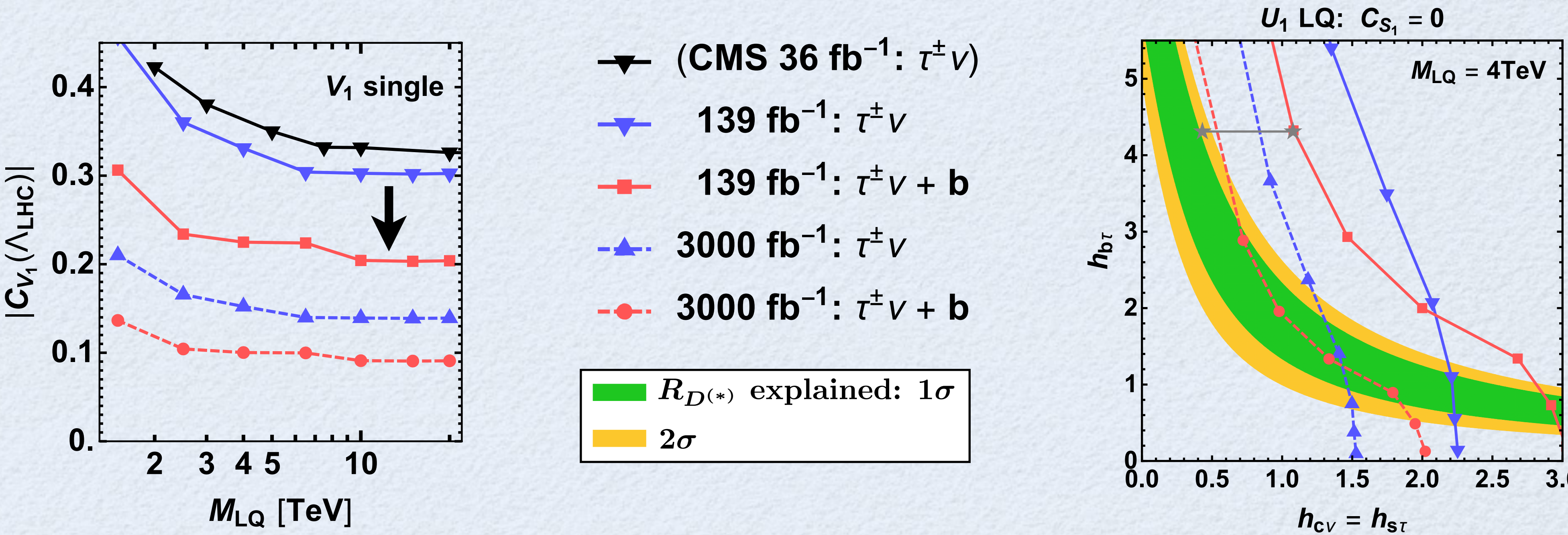
+ b-jet tag

2111.104748

(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 $(\Lambda/m_c)^2 \sim (\Lambda/m_b)^1$

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/-)

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

FF+Vcb+NP fit

To summarize:

— **Data points to be taken in our fit analysis**

- **FF constraints [7+33+8+UB] + Distribution data [10+40+80] + Br [2]**
- **Total: 180 data points**

— **Parameters to be fitted**

- **FF model [23 or 13] + Vcb [1] (+ Cx [1] for NP)**
- **Our fit: 14 ~ 25 parameters applying Bayesian MCMC**

Stan

SM result → Consistency check for our fit