# New Physics in b->sll and b->cτν (and 95GeV?)

ALPS 2023 27/03/2023

## Syuhei Iguro

Karlsruher Institut für Technologie

Theoretical Particle Physics

Mainly based on

2302.08935, 2211.14172, 2211.00011, 2210.10751, 2205.03187, 2202.10468 and more

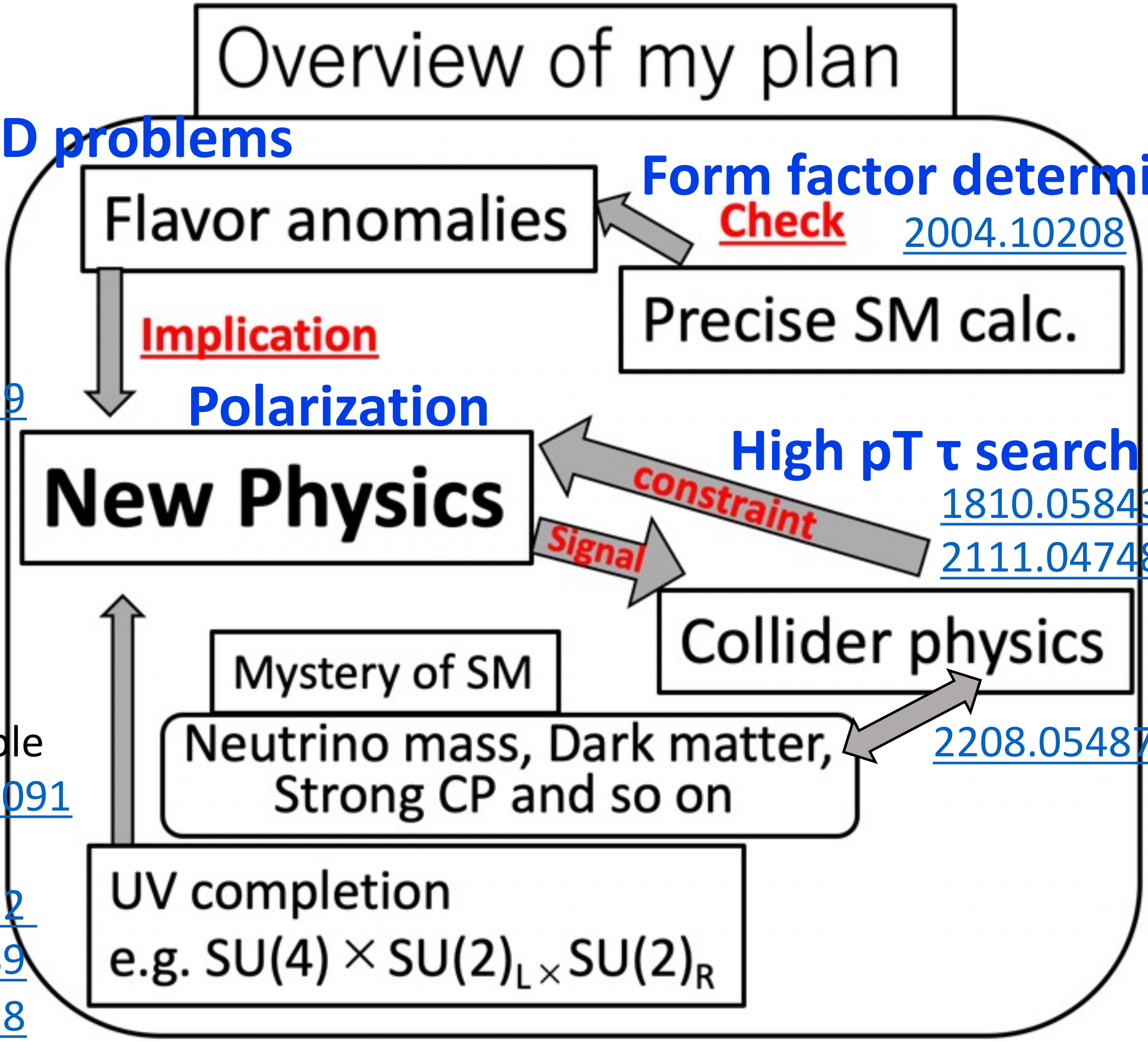
With Motoi Endo(KEK), Michihisa Takeuchi(Sun Yat Sen), Teppei Kitahara (KMI)
Yuji Omura(Kindai), Ryoutaro Watanabe(Pisa!?), Hantian Zhang(KIT), Monika Blanke(KIT)
Marco Fedele(KIT), Andreas Crivellin(PSI), Nierste Urlich(KIT)

# Anomaly workshop

Just as Kobayashi-Maskawa proposed more than 3 generation model motivated by the Kaon CP result, experimental results are strong drivers of particle phenomenology

- **$V_{cb}$ puzzle**
- **$b \to c\bar{u}q$ puzzle**
- **b->cτν**
- **b->sll**
- **Hint for 95 GeV scalar?**

# Summary of the my physics view



Overview of my plan

**Vcb, RD problems**

Flavor anomalies

**Form factor determination**

**Check**

2004.10208

Precise SM calc.

**Implication**

1811.08899
2211.14172

**Polarization**

**New Physics**

**High pT τ search**

**constraint**

**Signal**

1810.05843 2011.02486
2111.04748 2202.10468

Collider physics

Mystery of SM

Neutrino mass, Dark matter,
Strong CP and so on

2208.05487

Monopole
2111.12091

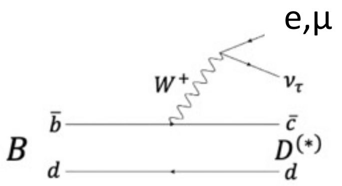
2103.12712
2103.11889
2201.04638

UV completion
e.g. $SU(4) \times SU(2)_L \times SU(2)_R$

**Task for NP theorists is building a model and proposing a smoking gun**

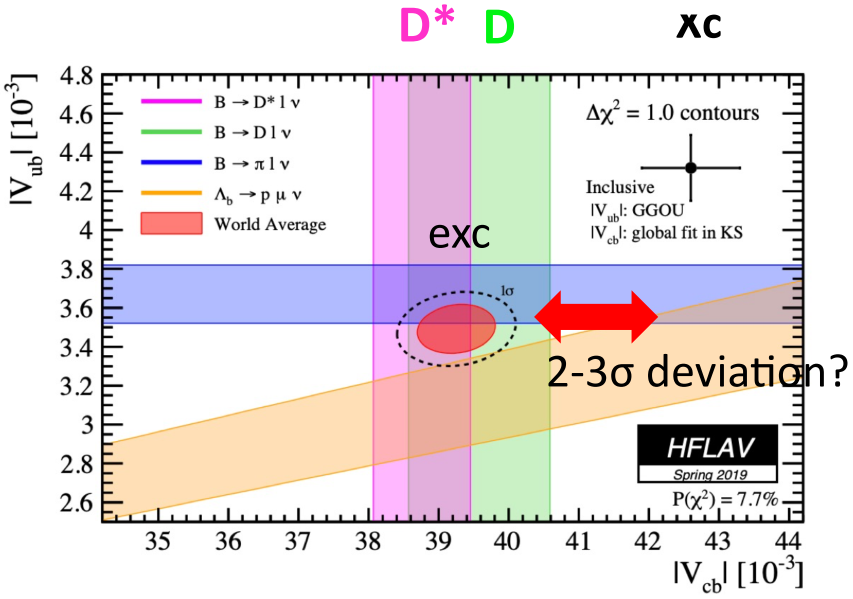
# Current status of B anomalies

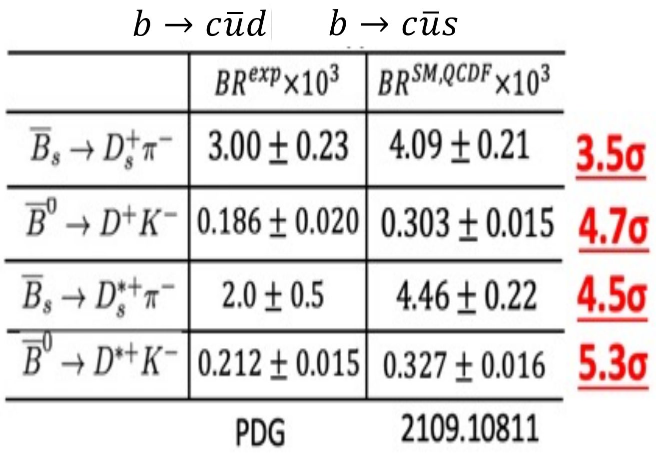
$V_{cb}$ puzzle



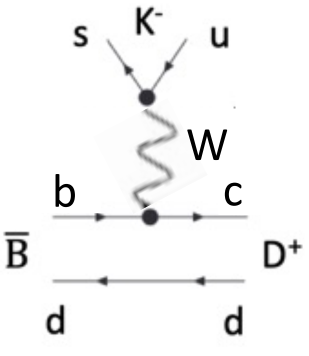
$b \to c\bar{u}q$ puzzle

**New**





| | $b \to c\bar{u}d$ | $b \to c\bar{u}s$ | |
|---|---|---|---|
| | $BR^{exp}\times10^3$ | $BR^{SM,QCDF}\times10^3$ | |
| $\bar{B}_s \to D_s^+\pi^-$ | $3.00 \pm 0.23$ | $4.09 \pm 0.21$ | **3.5σ** |
| $\bar{B}^0 \to D^+K^-$ | $0.186 \pm 0.020$ | $0.303 \pm 0.015$ | **4.7σ** |
| $\bar{B}_s \to D_s^{*+}\pi^-$ | $2.0 \pm 0.5$ | $4.46 \pm 0.22$ | **4.5σ** |
| $\bar{B}^0 \to D^{*+}K^-$ | $0.212 \pm 0.015$ | $0.327 \pm 0.016$ | **5.3σ** |
| | PDG | 2109.10811 | |



Tree level W

inclusive Vcb: determined from B->Xc lν mode

Xc: all hadronic state containing a charmed hadron.

exclusive Vcb: determined from B->$D^{(*)}$ l ν mode

l=e, μ

Amplitude ∝ B->D Form Factor

SM prediction updated in 2007.10338.

**20% amplitude suppression**

Recent workshop on this topic

https://indico.scc.kit.edu/event/2352/overview

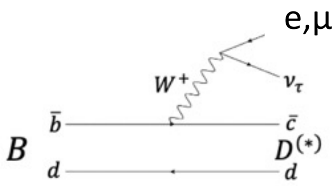
**It is difficult to explain with NP**

2008.01086

See also Bordone et al 2103.10332, Cai et al 2103.04138

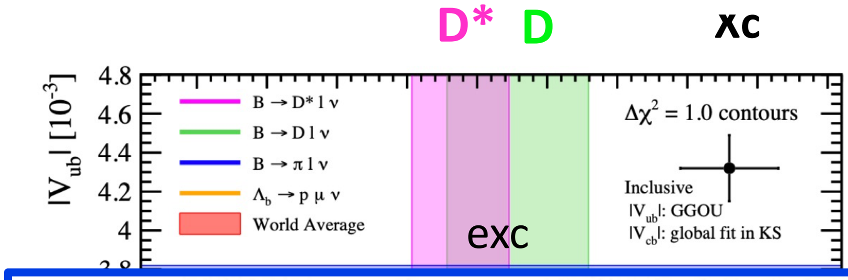
# Current status of B anomalies

$V_{cb}$ puzzle



$b \to c\bar{u}q$ puzzle

**New**

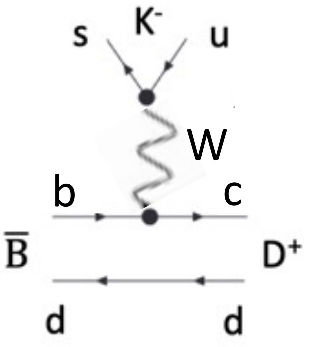


WA values [HFLAV 2021]

$$|V_{cb}|_{\mathrm{excl}} = (39.10 \pm 0.50) \times 10^{-3}$$

$b \to c\bar{u}d$ $b \to c\bar{u}s$

| | $BR^{exp} \times 10^3$ | $BR^{SM,QCDF} \times 10^3$ | |
|---|---|---|---|
| $\bar{B}_s \to D_s^+ \pi^-$ | $3.00 \pm 0.23$ | $4.09 \pm 0.21$ | **3.5σ** |
| $\bar{B}^0 \to D^+ K^-$ | $0.186 \pm 0.020$ | $0.303 \pm 0.015$ | **4.7σ** |
| | $\pm 0.5$ | $4.46 \pm 0.22$ | **4.5σ** |
| | $2 \pm 0.015$ | $0.327 \pm 0.016$ | **5.3σ** |
| | DG | 2109.10811 | |



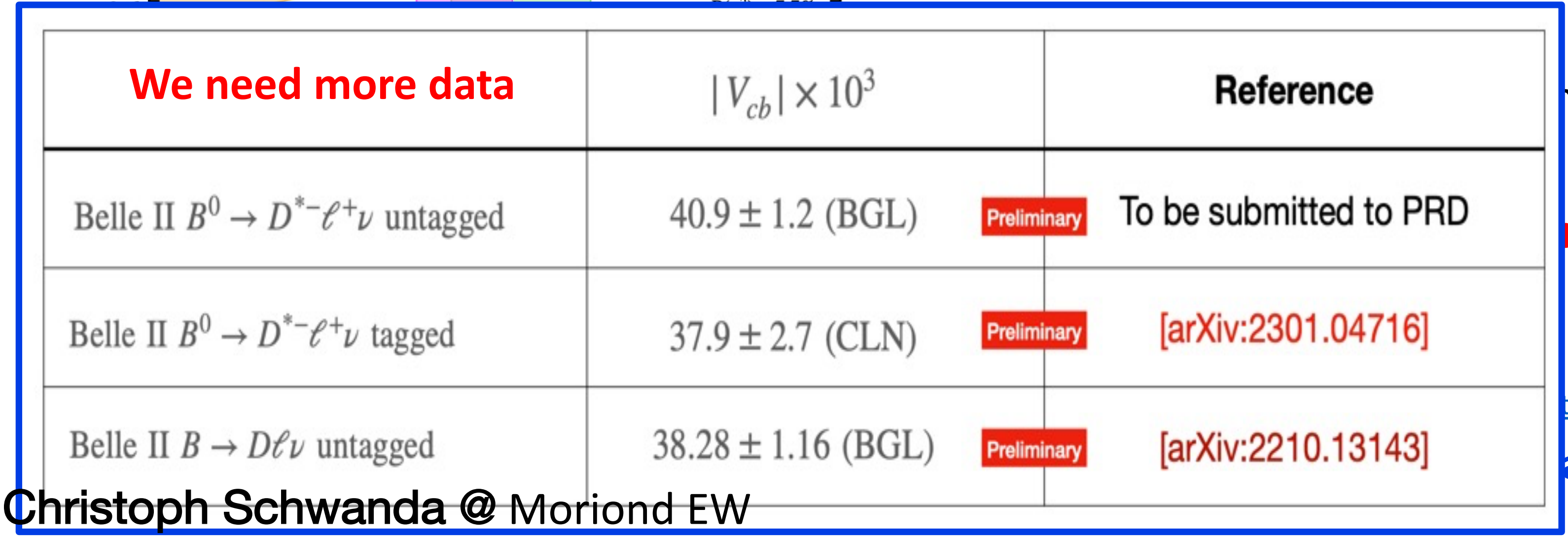
Tree level W

n Factor
in 2007.10338.

**ppression**

this topic
t/2352/overview

**ain with NP**

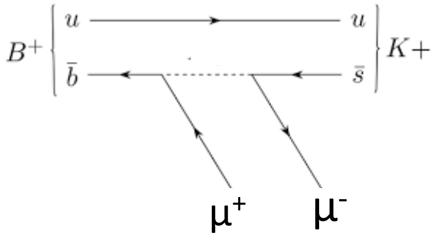


| **We need more data** | $\lvert V_{cb}\rvert \times 10^3$ | **Reference** |
|---|---|---|
| Belle II $B^0 \to D^{*-}\ell^+\nu$ untagged | $40.9 \pm 1.2$ (BGL) | Preliminary To be submitted to PRD |
| Belle II $B^0 \to D^{*-}\ell^+\nu$ tagged | $37.9 \pm 2.7$ (CLN) | Preliminary [arXiv:2301.04716] |
| Belle II $B \to D\ell\nu$ untagged | $38.28 \pm 1.16$ (BGL) | Preliminary [arXiv:2210.13143] |

**Christoph Schwanda @** Moriond EW

# $R_{K^{(*)}}$ anomaly $\quad b \to s\mu\bar{\mu}$

Leptoquark(LQ)

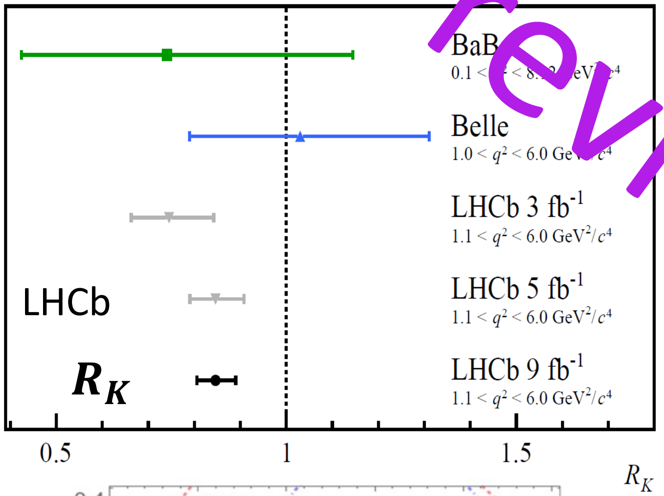


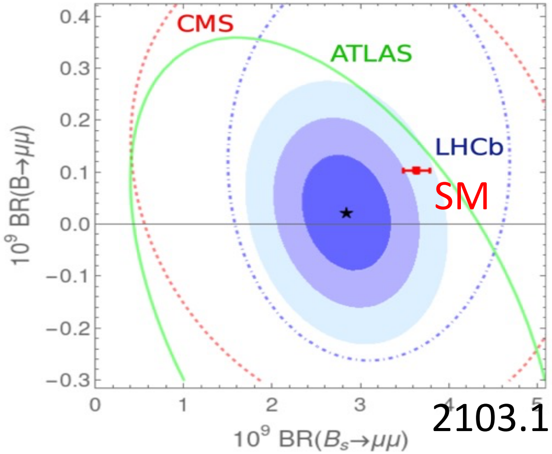
**Lepton flavor universality is a key prediction of the SM**

$$R_{K^{(*)}} = \frac{BR(B\to K^{(*)}\mu\bar{\mu})}{BR(B\to K^{(*)}e\bar{e})}$$

Taking ratio greatly cancels uncertainty in the hadronic matrix element

Previous situation



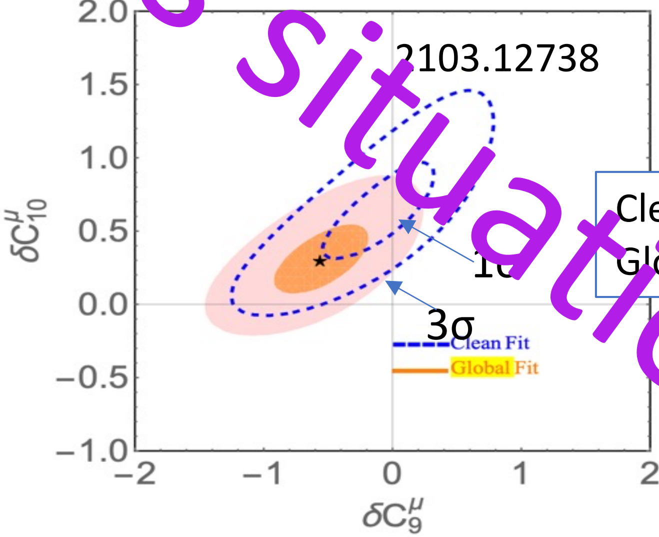


2103.12738

Global fit

$$\mathcal{H}_{\rm eff}^{\rm SM} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_{ps} \left( C_1 O_1^p + C_2 O_2^p + \sum_{i=3}^{10} C_i O_i \right) \qquad \lambda_{ps} = V_{pb} V_{ps}^*$$

$$O_9^\ell = \frac{e^2}{16\pi^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell), \quad O_{10}^\ell = \frac{e^2}{16\pi^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell).$$



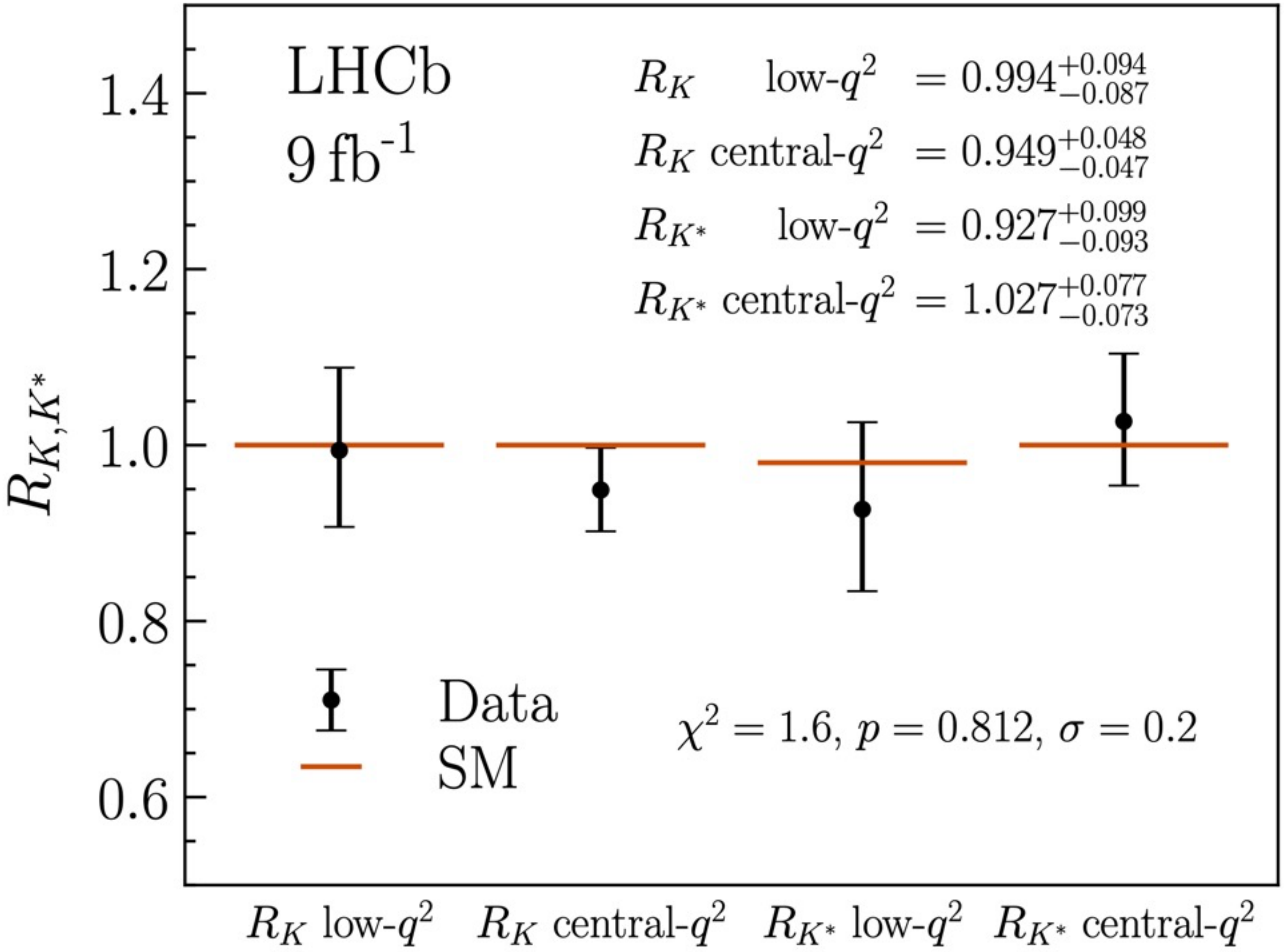
Clean obs. : $R_K, R_{K^*}, B_s \to \mu\bar{\mu}$.
Global obs.: Clean+ angular

Currently there is sizable deviation!

**Current status**

# $R_{K^{(*)}}$ *anomaly has gone!*

2212.09153
Electron tagging



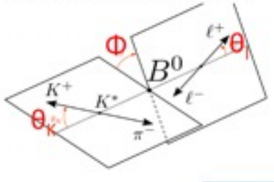
Furthermore $B_s \to$ μμ is SM like (CMS)

# Flavor universal C9 ?

The tensions in BR(Bs → ϕμμ), BR(Λb → Λμμ), BR(B → K(∗)μμ) and angular observable $P_5'$ in B → K(∗)μμ

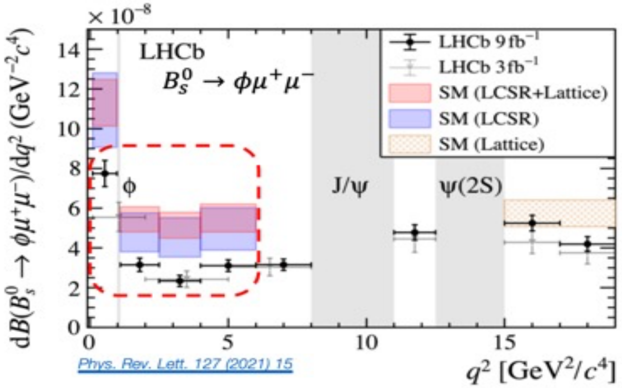
Matias 11

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos2\theta_\ell - F_L\cos^2\theta_K\cos2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_K\sin2\theta_\ell\cos\phi + S_5\sin2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin2\theta_K\sin\theta_\ell\sin\phi + S_8\sin2\theta_K\sin2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big]$$



***Optimized observable***

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}},$$



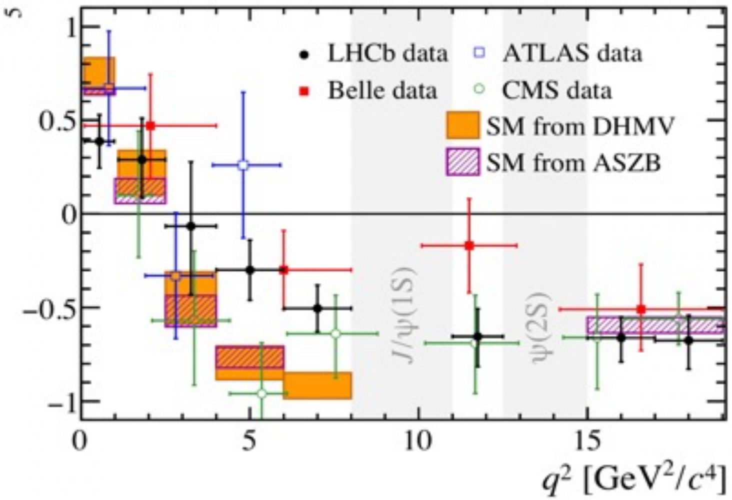
Phys. Rev. Lett. 127 (2021) 15

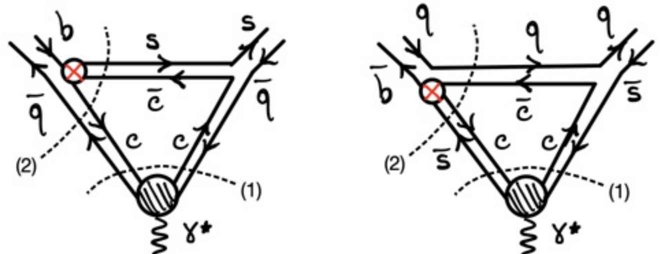
Global fit

Hurth, et al 2210.07221

$$C_9^l(\mu_b) = -0.95 \pm 0.13$$

Similar result is obtained (2212.10516)
if charm rescattering contribution is small.



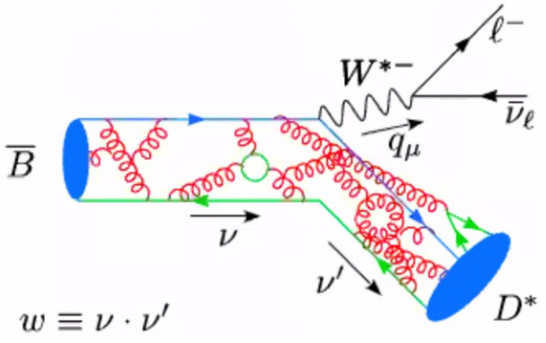


See talk by Bernat this moring

$$\mathcal{L} = \frac{\alpha G_F V_{td_i} V^*_{td_k}}{\sqrt{2}\pi}\Big[m_b C_7(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu} + m_b C_8(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{a,\mu\nu} + C_9^\ell(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu \ell) + C_{10}^\ell(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu\gamma_5\ell)\Big],$$

**2022 Mid-Auturm**

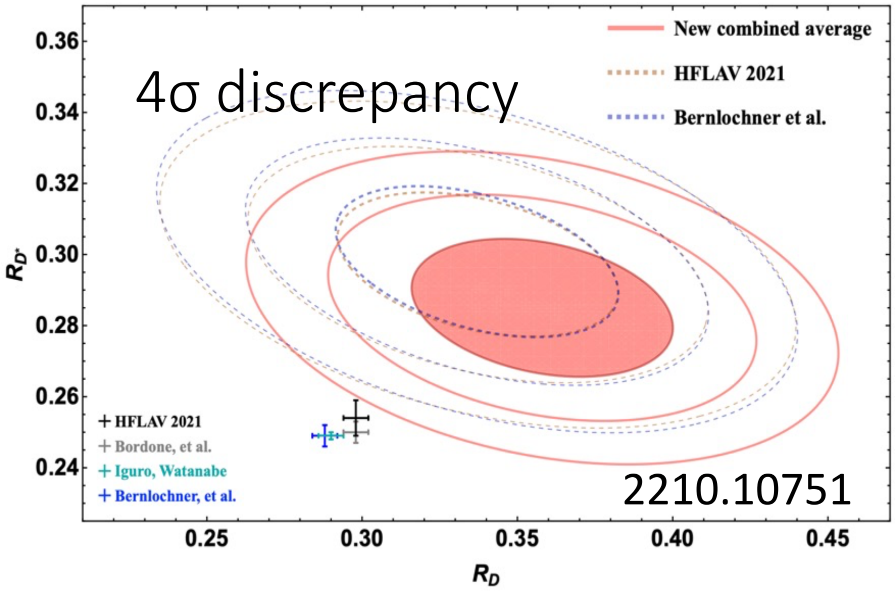
# $R_{D^{(*)}}$ anomaly



**Lepton flavor universality is a key prediction of the SM**

$$R_{D^{(*)}} = \frac{BR(B\to D^{(*)}\tau\nu)}{BR(B\to D^{(*)}l\nu)}\ , \quad l = \mu, e$$

Taking ratio greatly cancels uncertainty in the hadronic matrix element



4σ discrepancy

2210.10751

**Several deviations**

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

$F_{L\,SM}^{D^*} = 0.46 \pm 0.01$ 1.7σ

$F_{L\,exp}^{D^*} = 0.60 \pm 0.09$ Belle: 1903.03102

$$R_{J/\psi} = \frac{BR(B_c\to J/\psi\tau\nu)}{BR(B_c\to J/\psi\mu\nu)}$$

$R_{J/\psi}^{SM} = 0.24 \pm 0.01$ 1.8σ

$R_{J/\psi}^{exp} = 0.71 \pm 0.25$ LHCb: 1711.05623

LHCb 2201.03497

$R(\Lambda_c) = \mathcal{B}(\Lambda_b \to \Lambda_c\tau\bar{\nu})/\mathcal{B}(\Lambda_b \to \Lambda_c\mu\bar{\nu})$ Smaller than the SM

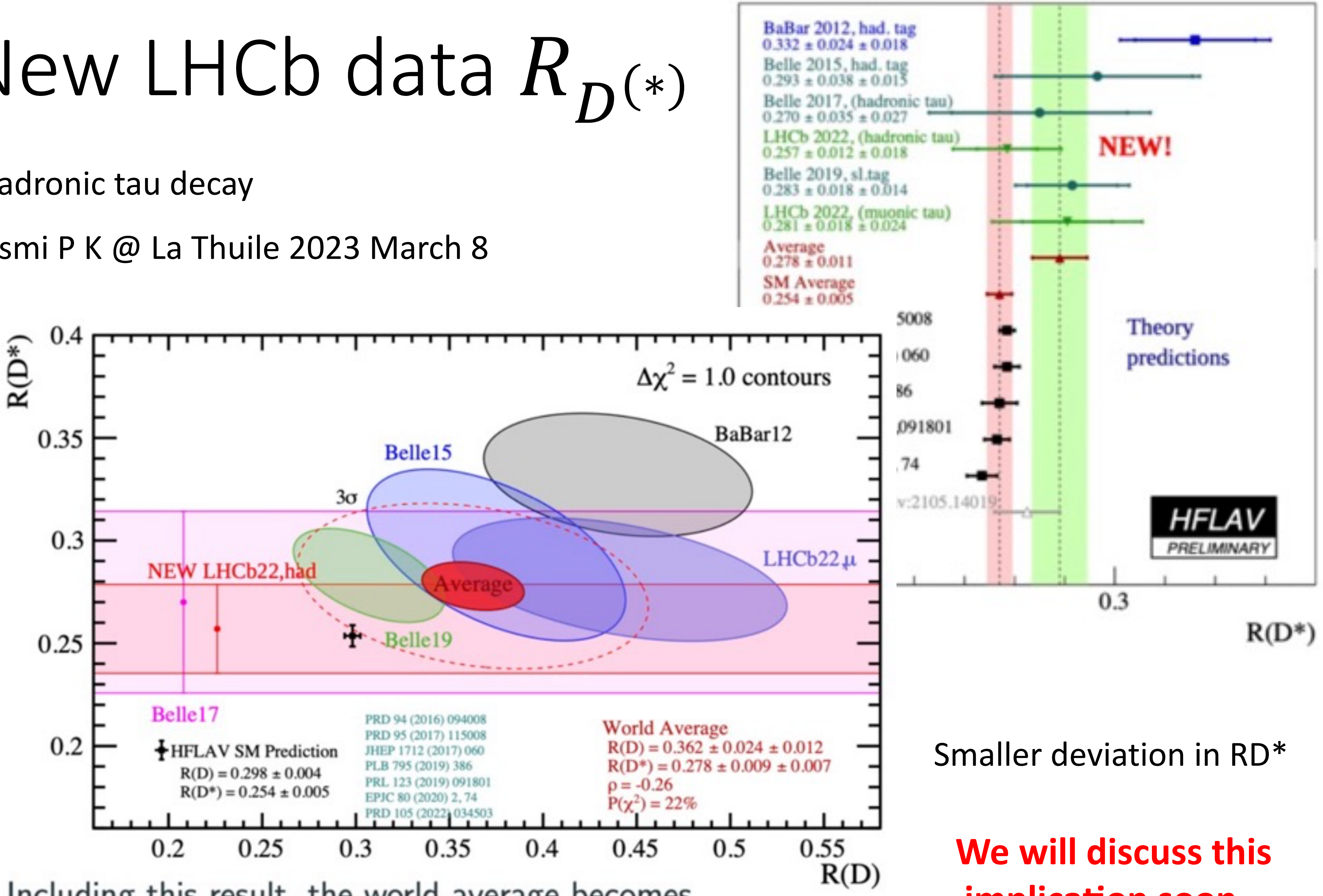
$R_{\Lambda c}^{LHCb} = 0.24 \pm 0.08$, $R_{\Lambda c}^{SM} = 0.324 \pm 0.004$

$R_{\Lambda c}^{Ligeti} = 0.285 \pm 0.073$ However, systematic uncertainty is still large to say something

# New LHCb data $R_{D^{(*)}}$

Hadronic tau decay

Resmi P K @ La Thuile 2023 March 8



- Including this result, the world average becomes $R(D^*) = 0.278 \pm 0.011; \quad R(D) = 0.362 \pm 0.027$

Smaller deviation in RD*

**We will discuss this implication soon**

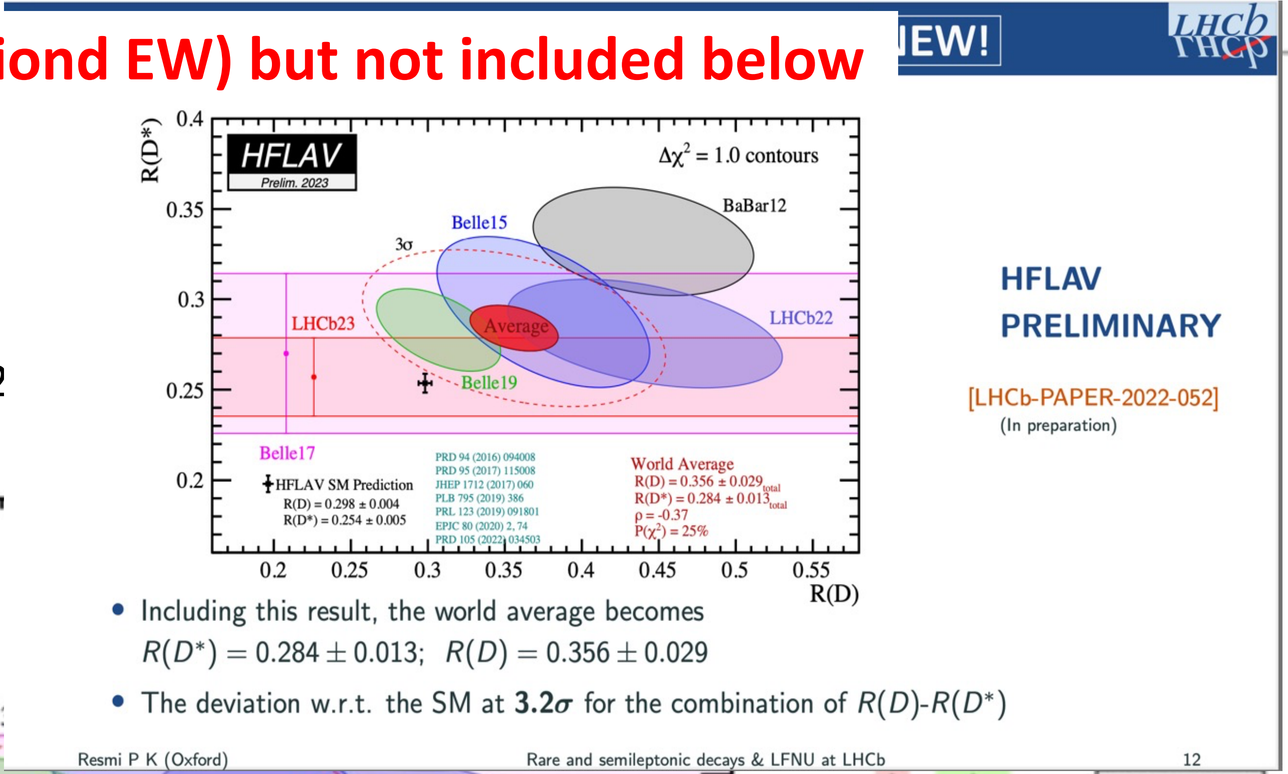
Still 3.9σ based on Iguro-Watanabe form factor (FF)

**Further update (Moriond EW) but not included below**

# New LHCb

Hadronic tau decay

Resmi P K @ La Thuile 202

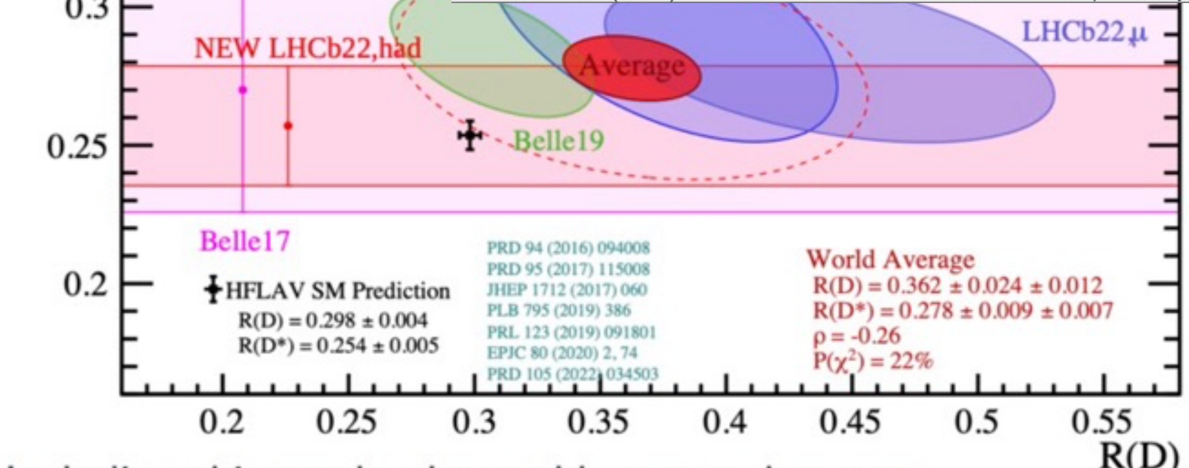


- Including this result, the world average becomes $R(D^*) = 0.284 \pm 0.013$; $R(D) = 0.356 \pm 0.029$
- The deviation w.r.t. the SM at **3.2$\sigma$** for the combination of $R(D)$-$R(D^*)$

**HFLAV PRELIMINARY**

[LHCb-PAPER-2022-052]
(In preparation)

Resmi P K (Oxford) Rare and semileptonic decays & LFNU at LHCb 12



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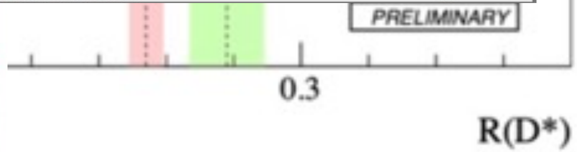


Smaller deviation in RD*

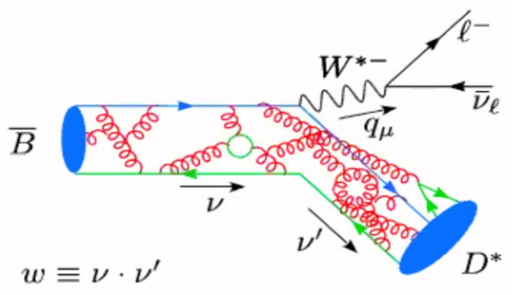
**We will discuss this implication soon**

Still 3.9σ based on Iguro-Watanabe form factor (FF)

# B decays involve hadron physics

## Importance of $\mathrm{B} \rightarrow \mathrm{D}^{(*)}$ form factor (FF)

Non-perturbative information extracted from
Lattice, experiments, QCDSR,,,,



- $V_{cb}$ puzzle **BR($B \rightarrow \mathrm{D}^{(*)}$lν)∝|Vcb × FFs|$^2$**
- $b \rightarrow c\bar{u}q$ anomaly **BR($B \rightarrow DK$) ∝ | FFs |$^2$**
- $R_{K^{(*)}}$ anomaly
- $R_{D^{(*)}}$ anomaly **BR($B \rightarrow \mathrm{D}^{(*)}$lν)∝|Vcb × FFs|$^2$**

B->D form factor is very important

,,,,,,,,

We have updated FF (HQET) using experimental input from Belle
***Iguro, Watanabe JHEP*** **08 (2020) 08, 006**

**Several Lattice group are working!**

# Effective Lagrangian for b ->c τ ν

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[ (1 + C_{VL}) O_{VL} + C_{VR} O_{VR} + C_{SR} O_{SR} + C_{SL} O_{SL} + C_T O_T \right]$$

Operator basis

$$O_{SR} = (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau)$$

$$O_{SL} = (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau)$$

$$O_{VL} = (\bar{c} \gamma^\mu P_L b)(\bar{\tau} \gamma^\mu P_L \nu_\tau)$$

$$O_{VR} = (\bar{c} \gamma^\mu P_R b)(\bar{\tau} \gamma^\mu P_L \nu_\tau)$$

$$O_T = (\bar{c} \sigma^{\mu\nu} P_L b)(\bar{\tau} \sigma_{\mu\nu} P_L \nu_\tau)$$

**Possible candidate**

Scalar H⁻ $B_c^- \to \tau\bar{\nu}$

Vector ~~W'~~ Bs mixing & bb > ττ

Tensor LQ

**Progress in BR($B_c^- \to \tau\bar{\nu}$)**

Previous constraint

~~< 30%~~ R.Alonso et al 1611.06676

~~< 10%~~ A.G.Akeroyd et al 1708.04072

$\Gamma_{Bc} \propto m_Q^5$ + large error in charm mass

-> large error for $\Gamma_{Bc}$

**Current constraint**

< 63% B.Grinstein et al 2105.02988

M.Blanke et al 1811.09603

# Sum rule

Based on the our FF we updated the sum rule proposed in 1905.08253 (KIT group).

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} = \left|1 + C^{\tau}_{V_L}\right|^2 + 0.50\,{\rm Re}\left[\left(1 + C^{\tau}_{V_L}\right) C^{\tau *}_{S_R}\right] + 0.33\,{\rm Re}\left[\left(1 + C^{\tau}_{V_L}\right) C^{\tau *}_{S_L}\right] + 0.52\,{\rm Re}\left(C^{\tau}_{S_L} C^{\tau *}_{S_R}\right) \\ + 0.32\,\left(|C^{\tau}_{S_L}|^2 + |C^{\tau}_{S_R}|^2\right) - 3.11\,{\rm Re}\left[\left(1 + C^{\tau}_{V_L}\right) C^{\tau *}_{T}\right] + 10.4\,|C^{\tau}_{T}|^2\,,$$

$$\frac{R_D}{R_D^{\rm SM}} = |1 + C_{V_L} + C_{V_R}|^2 + 1.01|C_{S_L} + C_{S_R}|^2 + 0.84|C_T|^2 \\ + 1.49{\rm Re}[(1 + C_{V_L} + C_{V_R})(C^*_{S_L} + C^*_{S_R})] + 1.08{\rm Re}[(1 + C_{V_L} + C_{V_R})C^*_T]\,,$$

$$\frac{R_{D^*}}{R_{D^*}^{\rm SM}} = |1 + C_{V_L}|^2 + |C_{V_R}|^2 + 0.04|C_{S_L} - C_{S_R}|^2 + 16.0|C_T|^2 \\ - 1.83{\rm Re}[(1 + C_{V_L})C^*_{V_R}] - 0.11{\rm Re}[(1 + C_{V_L} - C_{V_R})(C^*_{S_L} - C^*_{S_R})] \\ - 5.17{\rm Re}[(1 + C_{V_L})C^*_T] + 6.60{\rm Re}[C_{V_R} C^*_T]\,,$$

Eliminating interference terms

2211.14172

Small correction

$$\boxed{\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} = 0.280\,\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.720\,\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)} + \delta_{\Lambda_c}\,,}$$

$$\delta_{\Lambda_c} = {\rm Re}\left[\left(1 + C^{\tau}_{V_L}\right)\left(0.314\,C^{\tau *}_{T} - 0.003\,C^{\tau *}_{S_R}\right)\right] \\ + 0.014\,\left(|C^{\tau}_{S_L}|^2 + |C^{\tau}_{S_R}|^2\right) \\ + 0.004\,{\rm Re}\left(C^{\tau}_{S_L} C^{\tau *}_{S_R}\right) - 1.30\,|C^{\tau}_{T}|^2\,.$$

$\mathcal{R}(\Lambda_c)$ =0.367±0.013

$R_{\Lambda c}^{LHCb}$ = 0.24 ± 0.08,

$R_{\Lambda c}^{Ligeti}$ = 0.285 ± 0.073

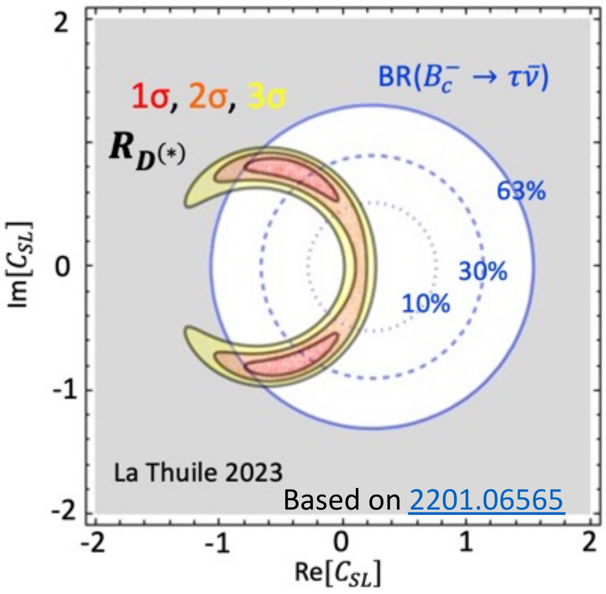
**Solid correlation**

Small RD* is more consistent but we need more data to conclude

**Even if we include the NP in light lepton mode, we can not explain all.**

# Scalar operator revived

$O_{SL} = (\bar{c}P_L b)(\bar{\tau}P_L\nu_\tau)$



Based on 2201.06565

Thanks to the relaxed upper bound from $B_c^- \to \tau\bar{\nu}$ scalar scenario is still viable!

Only scalar can enhance $F_L^{D^*}$

$$F_{L\,exp}^{D^*} = 0.60 \pm 0.09, \quad F_{L\,SM}^{D^*} = 0.46 \pm 0.01$$

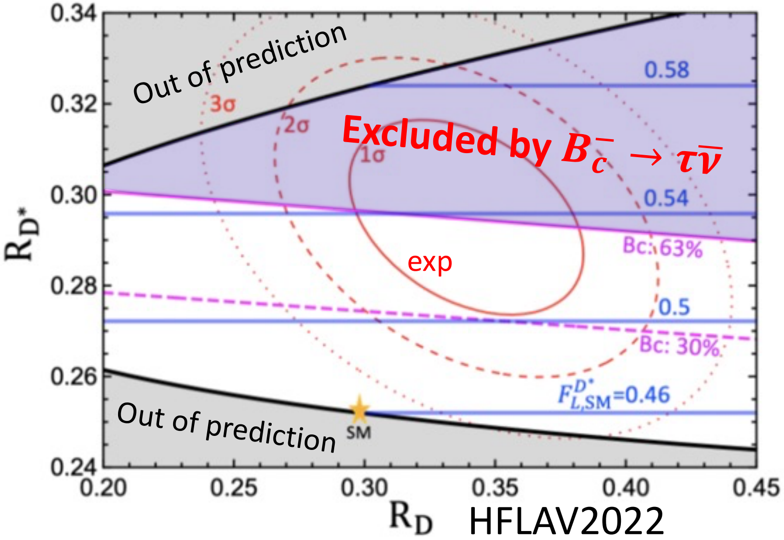
We need complex WC

=> Complex Yukawa in type III (General) 2HDM

Scenario 1 in Iguro-Tobe 1708.06176

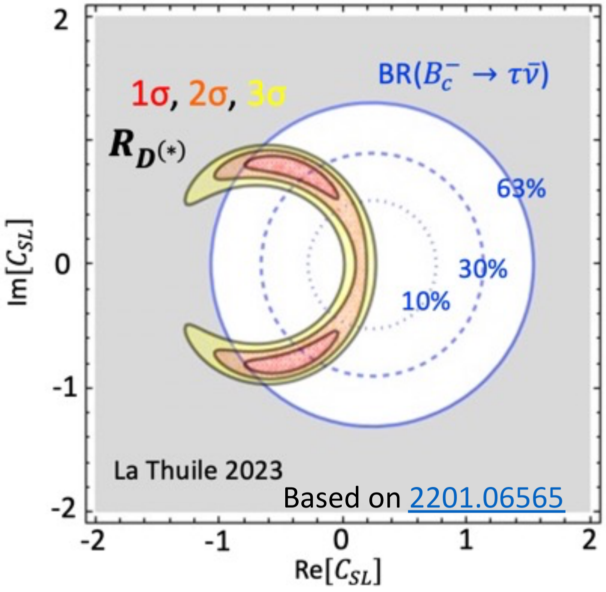
Only top-charm flavor violating Yukawa coupling can provide sizable $C_{SL}$ without violating LHC, flavor, EDM constraints see also Nierste et al 2019, George-Hou 2018

**bb →ττ is less relevant to this model**



HFLAV2022

# Scalar operator revived



Based on 2201.06565

Thanks to the relaxed upper bound from $B_c^- \to \tau\bar{\nu}$ scalar scenario is still viable!

Only scalar can enhance $F_L^{D^*}$

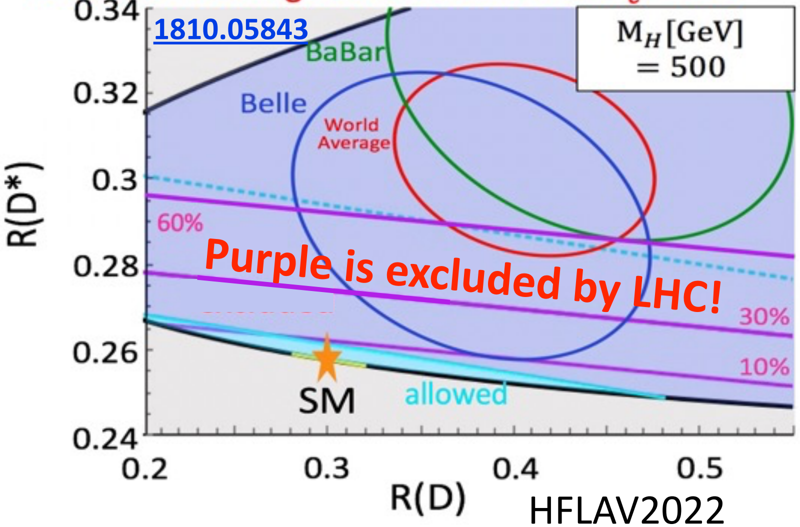
$$F_{L\,exp}^{D^*} = 0.60 \pm 0.09, \quad F_{L\,SM}^{D^*} = 0.46 \pm 0.01$$

We need complex WC

=> Complex Yukawa in type III (General) 2HDM

Reinterpreting **τν resonance search** from the CMS(36fb$^{-1}$) excludes the scenario with $m_{H^+} > 400$GeV

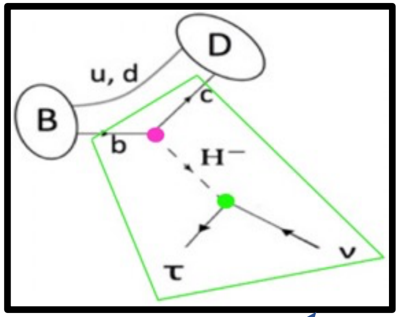
Much more stringent constraint than $B_c^- \to \tau\bar{\nu}$



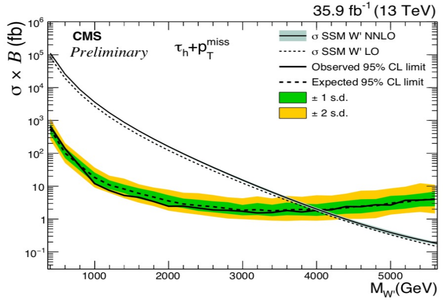
1810.05843

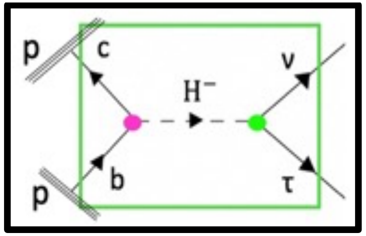
Purple is excluded by LHC!

HFLAV2022



correlation





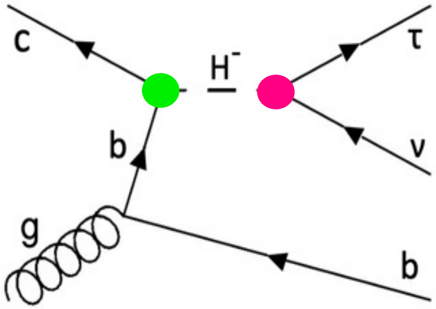
There is no data available for $m_{H^+} < 400$GeV

Additional b-jet would suppress the trigger rate

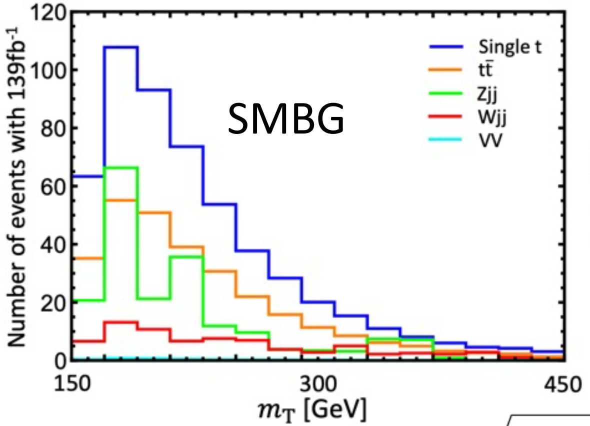
# Closing the low mass window with τν+b search! $180\text{GeV} < m_{H^+} < 400\text{GeV}$

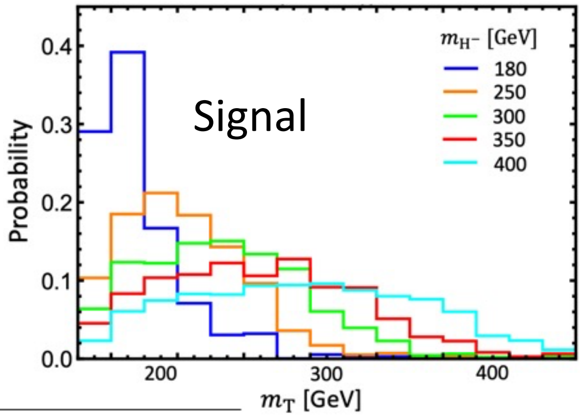
**Syuhei Iguro 2201.06565** **Syuhei Iguro, Hantian Zhang, Monika Blanke 2202.10468**

⑩



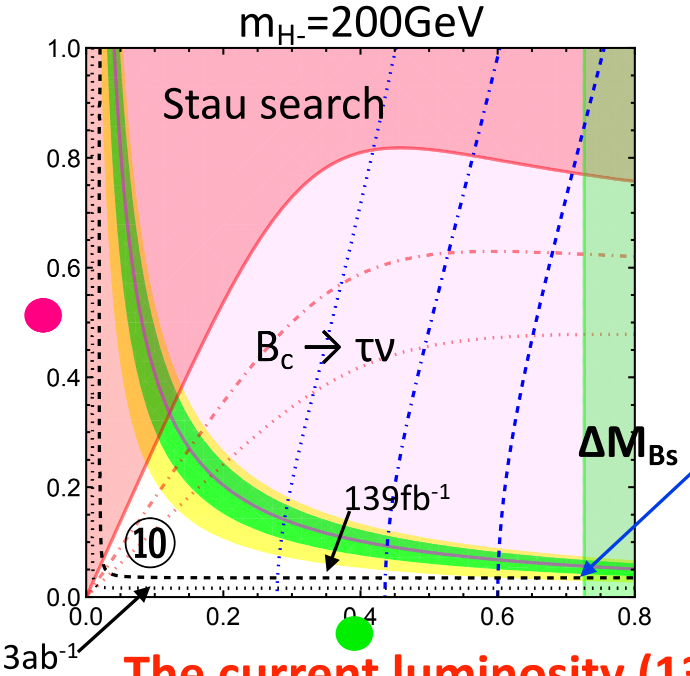
b-tagging suppress the SMBG

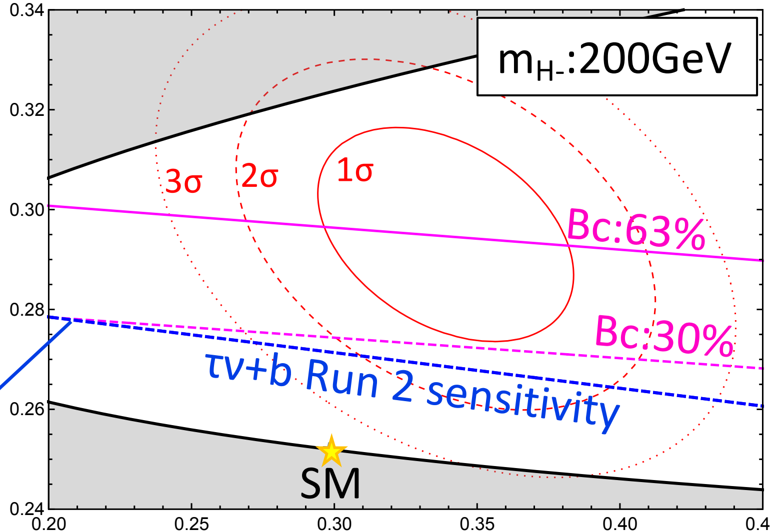




$$m_T = \sqrt{2p_T^\ell E_T^{\rm miss}(1-\cos\theta_{\ell\nu})}$$

NP signal event number (with parameters to explain the anomaly) is comparable with SMBG!





Very conservative syst. error is assigned

**Heavier scenario is more easy due to smaller BG!**

**The current luminosity (139fb$^{-1}$) is already enough to judge the model!**

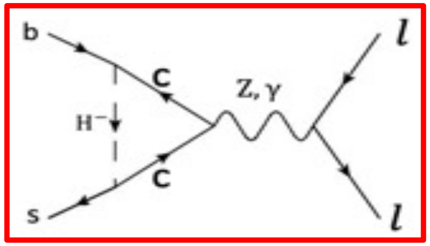
# Flavor universal $C_9$ ?

**Syuhei Iguro** 2302.08935

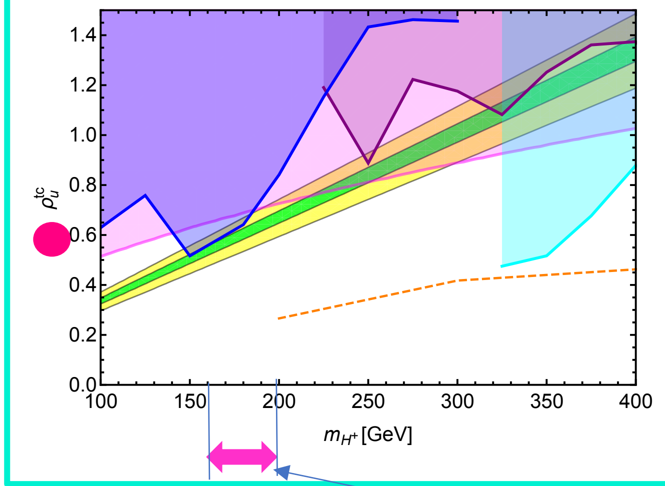
See also 1802.01732

SU(2)$_L$ doublet

$$\begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H+iA) \end{pmatrix} \qquad \begin{aligned} \mathcal{L}_{int} = {} & \rho_u^{tc}\frac{H+iA}{\sqrt{2}}(\bar{t}P_R c) + \rho_e^{\tau\tau}\frac{H-iA}{\sqrt{2}}(\bar{\tau}P_R\tau) \\ & + V^*_{td_i}\rho_u^{tc}H^-(\bar{d}_i P_R c) - \rho_e^{\tau\tau}H^-(\bar{\tau}P_L\nu_\tau) + \text{h.c.}, \end{aligned}$$



## Parameter space



Green and yellow are interesting parameter region

Bs mixing and di-jet also put interesting constraints

Stringent upper bound from same sign top (SST) search
ATLAS-CONF-2022-039

**Although this can be avoided by taking $m_A=m_H$ at O(1) GeV**

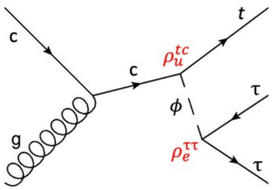
$m_{A,H}<m_t$ is also excluded by multi tau lepton search

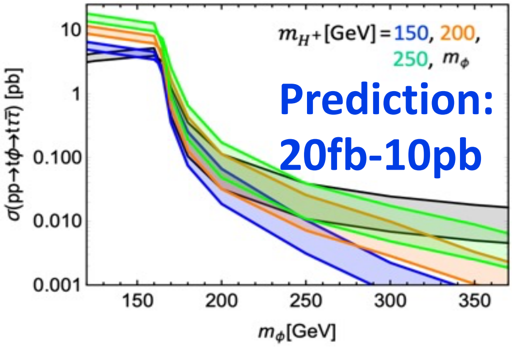
➡ O(1) GeV turning or $m_t < m_{A,H} < 200$ GeV

mass window

How to test the remaining mass window?

**A. FCNC top production**
**(cg→ t+ττ)**

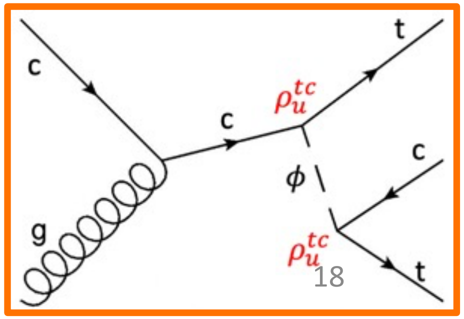




**Prediction:**
**20fb-10pb**

Naïve Run 2 sensitivity:
100fb for $m_{\tau\tau}$ =125 GeV, 2011.03652 (CMS)
but we have heavier resonance -> small BG

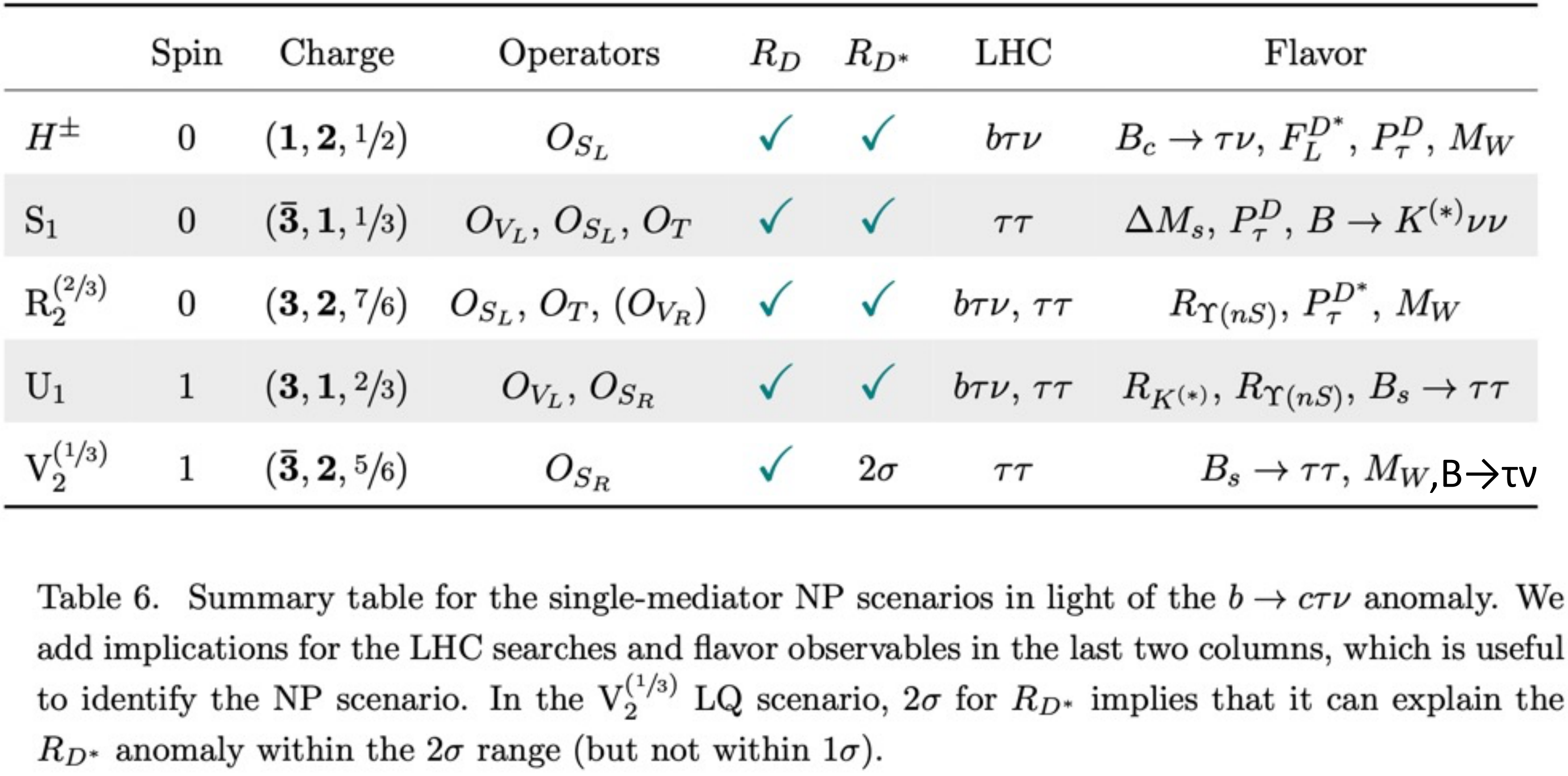
Diagram for SST



LQ possibility?

# Model prediction: correlation

2210.10751



| | Spin | Charge | Operators | $R_D$ | $R_{D^*}$ | LHC | Flavor |
|---|---|---|---|---|---|---|---|
| $H^\pm$ | 0 | $(\mathbf{1},\mathbf{2},{}^1\!/_2)$ | $O_{S_L}$ | ✓ | ✓ | $b\tau\nu$ | $B_c\to\tau\nu$, $F_L^{D^*}$, $P_\tau^D$, $M_W$ |
| $\mathrm{S}_1$ | 0 | $(\bar{\mathbf{3}},\mathbf{1},{}^1\!/_3)$ | $O_{V_L}$, $O_{S_L}$, $O_T$ | ✓ | ✓ | $\tau\tau$ | $\Delta M_s$, $P_\tau^D$, $B\to K^{(*)}\nu\nu$ |
| $\mathrm{R}_2^{(2/3)}$ | 0 | $(\mathbf{3},\mathbf{2},{}^7\!/_6)$ | $O_{S_L}$, $O_T$, $(O_{V_R})$ | ✓ | ✓ | $b\tau\nu$, $\tau\tau$ | $R_{\Upsilon(nS)}$, $P_\tau^{D^*}$, $M_W$ |
| $\mathrm{U}_1$ | 1 | $(\mathbf{3},\mathbf{1},{}^2\!/_3)$ | $O_{V_L}$, $O_{S_R}$ | ✓ | ✓ | $b\tau\nu$, $\tau\tau$ | $R_{K^{(*)}}$, $R_{\Upsilon(nS)}$, $B_s\to\tau\tau$ |
| $\mathrm{V}_2^{(1/3)}$ | 1 | $(\bar{\mathbf{3}},\mathbf{2},{}^5\!/_6)$ | $O_{S_R}$ | ✓ | $2\sigma$ | $\tau\tau$ | $B_s\to\tau\tau$, $M_W$,B→τν |

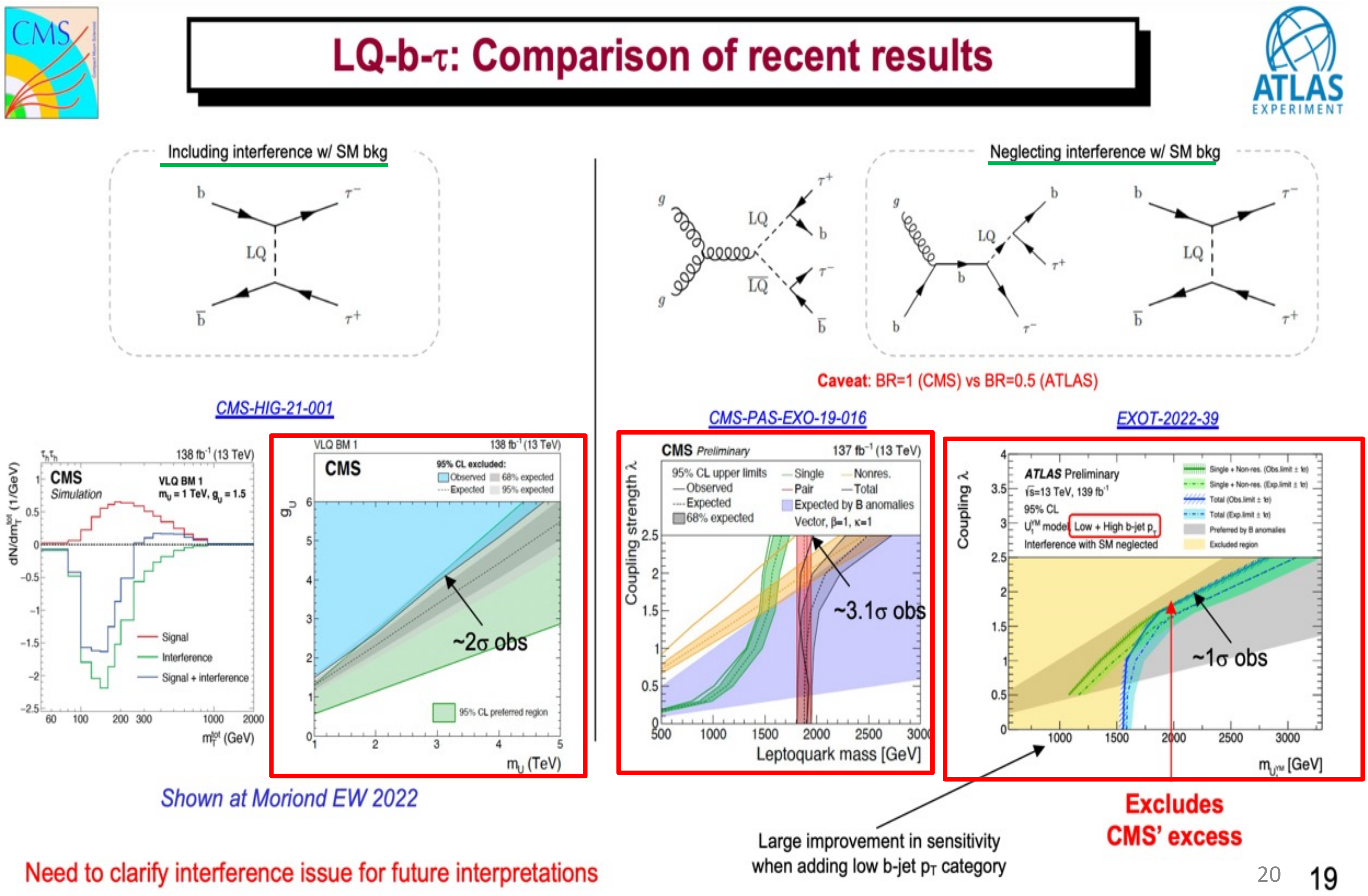
Table 6. Summary table for the single-mediator NP scenarios in light of the $b\to c\tau\nu$ anomaly. We add implications for the LHC searches and flavor observables in the last two columns, which is useful to identify the NP scenario. In the $\mathrm{V}_2^{(1/3)}$ LQ scenario, $2\sigma$ for $R_{D^*}$ implies that it can explain the $R_{D^*}$ anomaly within the $2\sigma$ range (but not within $1\sigma$).

See also Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, 2103.12504; Athron, Balazs , Jacob , Kotlarski, Stockinger , Stockinger-Kim, 2104.03691 for the previous version.

**Recent news!**

# Aurelio Juste @Morind EW

CMS excess is officially in danger



## LQ-b-τ: Comparison of recent results

Including interference w/ SM bkg

Neglecting interference w/ SM bkg

**Caveat:** BR=1 (CMS) vs BR=0.5 (ATLAS)

CMS-HIG-21-001

CMS-PAS-EXO-19-016

EXOT-2022-39

~2σ obs

~3.1σ obs

~1σ obs

*Shown at Moriond EW 2022*

Large improvement in sensitivity when adding low b-jet $p_T$ category

**Excludes CMS' excess**

Need to clarify interference issue for future interpretations

# $V_2$ LQ solution for b→cτν

2304.0XXXX

**Syuhei Iguro**, Yuji Omura

Preliminary

$V_2$ $(\bar{3}, 2, 5/6)$ contributes to $(\bar{c}P_R b)(\bar{\tau}P_L\nu)$: this solution revived recently!

Assigning approximate τ number to this doublet the fermion interaction is given as

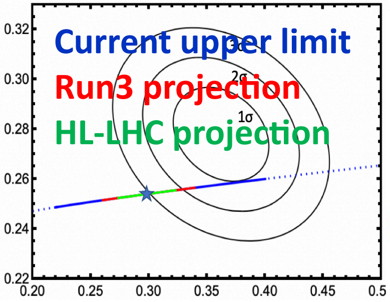
$$L = h_1^{ij}(\overline{d_i^C}\gamma_\mu P_L L_j^b)\epsilon^{ab}V_2^{\mu,a} + h_2^{ij}(\overline{Q_i^{C,a}}\gamma_\mu P_R e_j)\epsilon^{ab}V_2^{\mu,b} + h_3^{ij}(\overline{Q_i^C}\gamma_\mu P_R u_j)V_2^{\mu *} + \mathrm{h.c.}$$ 2204.05942

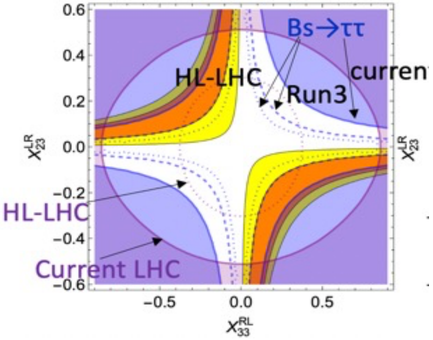
$$h_1^{ij} = \begin{pmatrix} \times & \times & h_1^{13} \\ \times & \times & h_1^{23} \\ \times & \times & \underline{h_1^{33}} \end{pmatrix}, \quad h_2^{ij} = \begin{pmatrix} \times & \times & \underline{h_2^{13}} \\ \times & \times & \underline{h_2^{23}} \\ \times & \times & h_2^{33} \end{pmatrix}, \quad h_3 = 0.$$

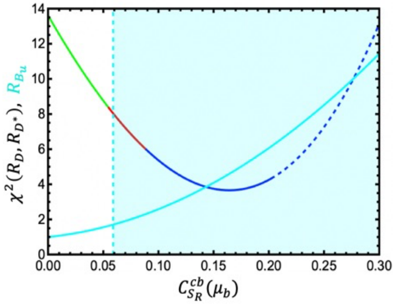
proton decay, $K_L$→eμ does not occur!

EFT like approach

## Minimal scenario: $h_1^{33}, h_2^{23}$ is excluded by $B_u$→τν







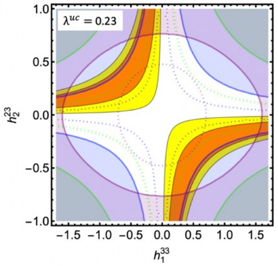
Bs→ττ vs. $R_D$, $R_{D^*}$

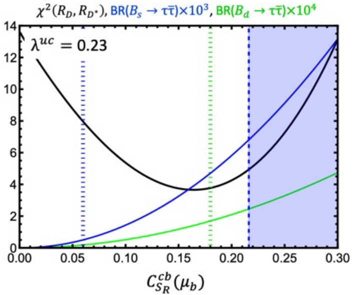
## Next to minimal scenario: $h_1^{33}, h_2^{23}, h_2^{13}$ can explain $R_{D^{(*)}}$

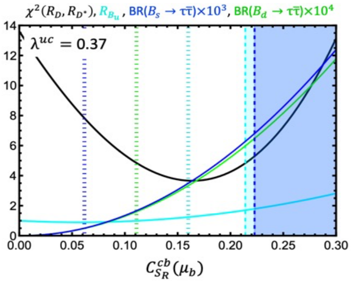
$$h_2^{23} = -\lambda_{uc} h_2^{13}$$

$\lambda_{uc} = 0.23$ cancels $B_u$→τν

$0.16 < \lambda_{uc} < 0.37$ is allowed







### Relevant flavor processes

| Coupling product | $V^{4/3}$ | $V^{1/3}$ |
|---|---|---|
| $h_1^{33} \times h_2^{23}$ | $b \to s\tau\bar{\tau}$<br>$B_s \to \tau\bar{\tau}, B \to K\tau\bar{\tau}$ | $b \to c\tau\bar{\nu}_\tau$<br>$B \to D^{(*)}\tau\bar{\nu}_\tau$<br>$B_c \to \tau\nu_\tau, B \to \tau\bar{\nu}$ |
| $h_1^{33} \times h_2^{13}$ | $b \to d\tau\bar{\tau}$<br>$B \to \tau\bar{\tau}, B \to \pi\tau\bar{\tau}$ | $b \to u\tau\bar{\nu}_\tau$<br>$B \to D^{(*)}\tau\bar{\nu}_\tau$<br>$B \to \tau\nu_\tau, B \to \pi\tau\bar{\nu}_\tau$ |
| $h_1^{33} \times h_2^{33}$ | $b\bar{b} \to \tau\bar{\tau}$<br>~~$\Upsilon(nS) \to \tau\bar{\tau}$~~ | $t \to b\tau\bar{\nu}_\tau$<br>— |
| $h_1^{33} \times h_1^{13}$ | $b \to d\tau\bar{\tau}$<br>$B \to \tau\bar{\tau}, B \to \pi\tau\bar{\tau}$ | $b \to d\nu\bar{\nu}$<br>~~$B \to \nu\bar{\nu}$~~, $B \to \pi\nu\bar{\nu}$ |
| $h_1^{33} \times h_1^{23}$ | $b \to s\tau\bar{\tau}$<br>$B_s \to \tau\bar{\tau}, B \to K\tau\bar{\tau}$ | $b \to s\nu\bar{\nu}$<br>~~$B_s \to \nu\bar{\nu}$~~, $B \to K\nu\bar{\nu}$ |
| $h_1^{13} \times h_2^{23}$ | $s \to d\tau\bar{\tau}$<br>— | $c \to d\tau\bar{\nu}$<br>$D \to \tau\bar{\nu}$ |
| $h_1^{23} \times h_2^{23}$ | $s\bar{s} \to \tau\bar{\tau}$<br>— | $c \to s\tau\bar{\nu}$<br>$D_s \to \tau\bar{\nu}$ |
| $h_2^{13} \times h_2^{23}$ | $s \to d\tau\bar{\tau}$<br>— | $c \to u\tau\bar{\tau}$<br>— |
| $h_2^{33} \times h_2^{23}$ | $b \to s\tau\bar{\tau}$<br>$B_s \to \tau\bar{\tau}, B \to K\tau\bar{\tau}$ | $t \to c\tau\bar{\tau}$<br>— |

**Next step: UV completion w.i.p**

# Other conventional LQ scenarios

- U(2) flavored U1 LQ (see 2210.13422 for the update)
- For the others please check 2210.10751

Version 2 is pretty better

# Other conventional LQ scenarios

- U(2) flavored U1 LQ (see 2210.13422 for the update)
- For the others please check 2210.10751

**Recent finding** Preliminary

Iguro, Kitahara 2304.0XXXX

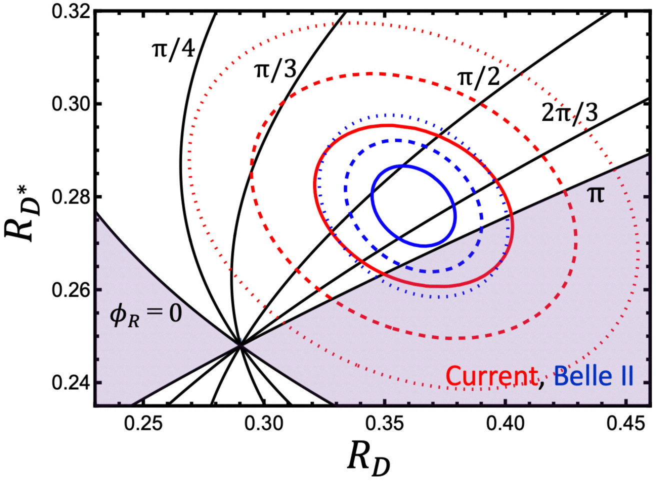
See also 2002.01400
1809.09114

$$\mathcal{L} \supset \left(\beta_L^{ij} \overline{Q}_i \gamma_\mu P_L L_j + \beta_R^{ij} \overline{d}_i \gamma_\mu P_R e_j\right) U_1^\mu . \quad \beta_L^{ij} \simeq \begin{pmatrix} 0 & 0 & -|V_{td}/V_{ts}| c_d s_{q_2} s_\chi \\ 0 & 0 & c_d s_{q_2} s_\chi \\ 0 & 0 & c_\chi \end{pmatrix}, \beta_R^{ij} \simeq e^{i\phi_R} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

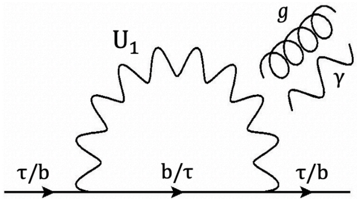
$$r_L^{23} \equiv \beta_L^{23} / \beta_L^{33}$$

Javier Claudia Gino 1903.11517, 1909.02519,,,,

$$C_{S_R}(\mu_b) \simeq -3.7 e^{-i\phi_R} C_{V_L}(\mu_b).$$



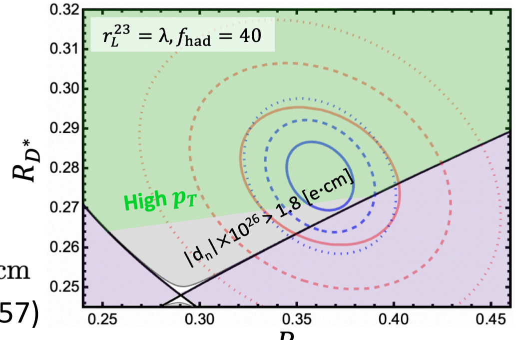
ϕ$_R$=0 is not good => CPV

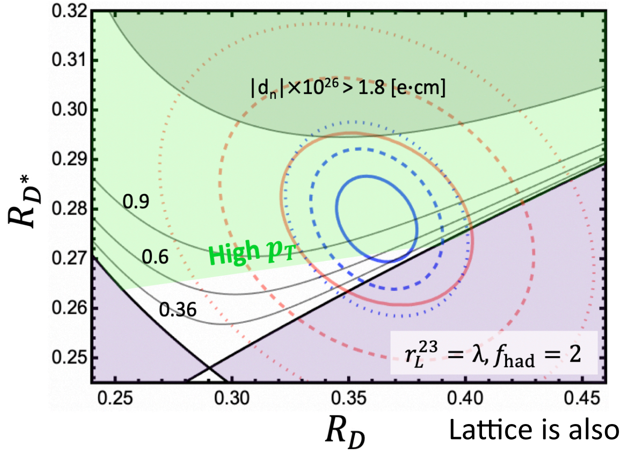


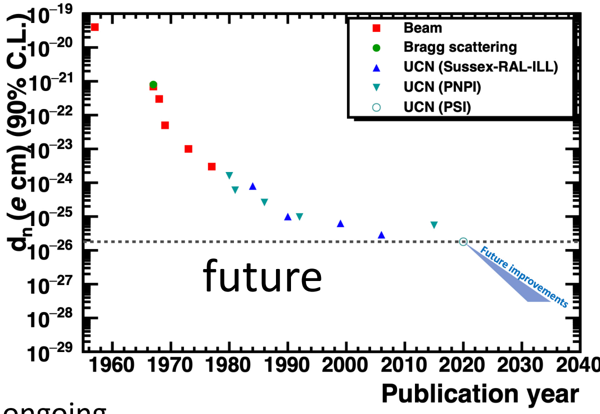
f$_{\rm had}$

$$d_n = \frac{g_s^2 v^2}{32\pi^2 m_Q} \beta_n^{\hat{G}} \hat{d}_Q \qquad \beta_n^{\hat{G}} = [2,\ 40] \times 10^{-20}\ \mathrm{e{\cdot}cm}$$

QCDSR (Pospelov 0208257)







Lattice is also ongoing

# Improving LHC search potential

$\Lambda_{NP}$=O(1) TeV for RD, RD*

Direct searches are powerful!

# Improvement of LHC search in τν mode

## An additional b-tagging

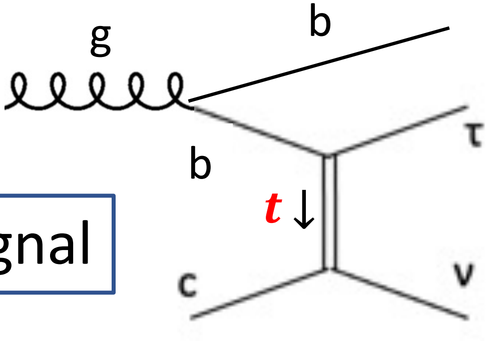
A. Soni et al [1704.06659](1704.06659), Iguro-Tobe [1708.06176](1708.06176)

Importance of b-tagging

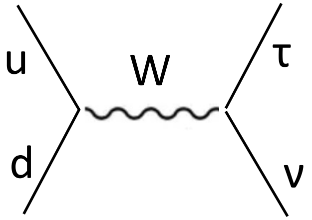
1. smaller BG, 2. different BG → semi-independent cross check

3. specifying interaction one of quarks in 4-fermi is b

**Signal**

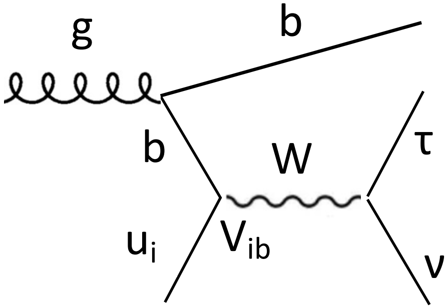


See also Greljo et al. 1811.07920

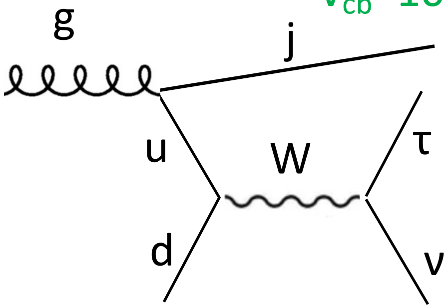


No b-jet previous

**BG**



$V_{cb}$~$10^{-2}$, $V_{ub}$~$10^{-3}$



j->b mis tag less than 1%

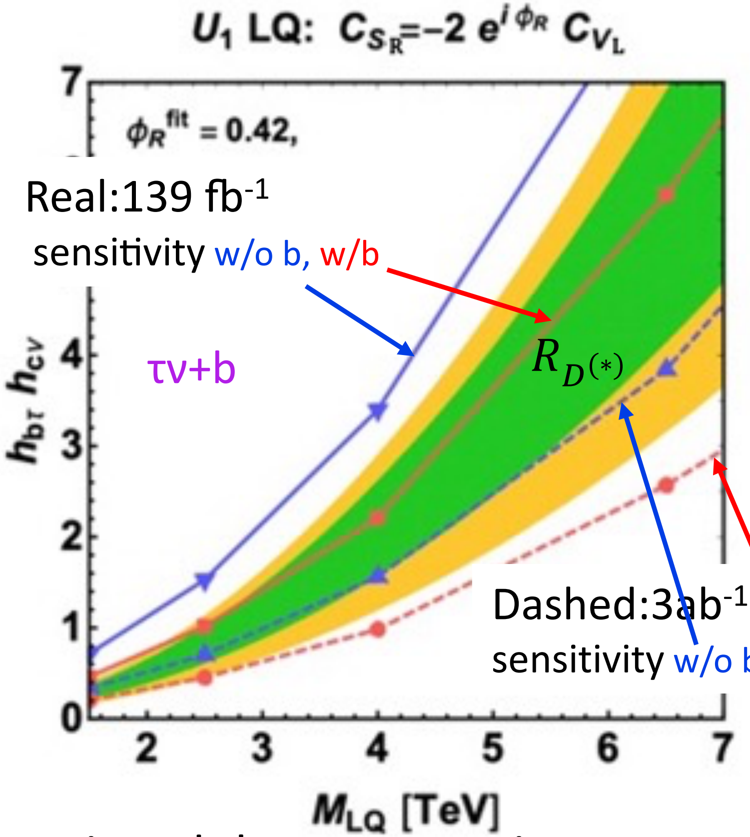
Within the EFT framework,
an additional b-jet tagging improve WC sensitivity
by 30-40% Minho et al [2008.07541](2008.07541)

We keep mediator mass dependence
even with b-jet tagging Iguro et al [2111.04748](2111.04748)

WZ, single t ,,, are
also important

# Other scenarios: $U_1$ LQ with U(2) flavor symmetry

2111.04748



Real:139 $\text{fb}^{-1}$

sensitivity w/o b, w/b

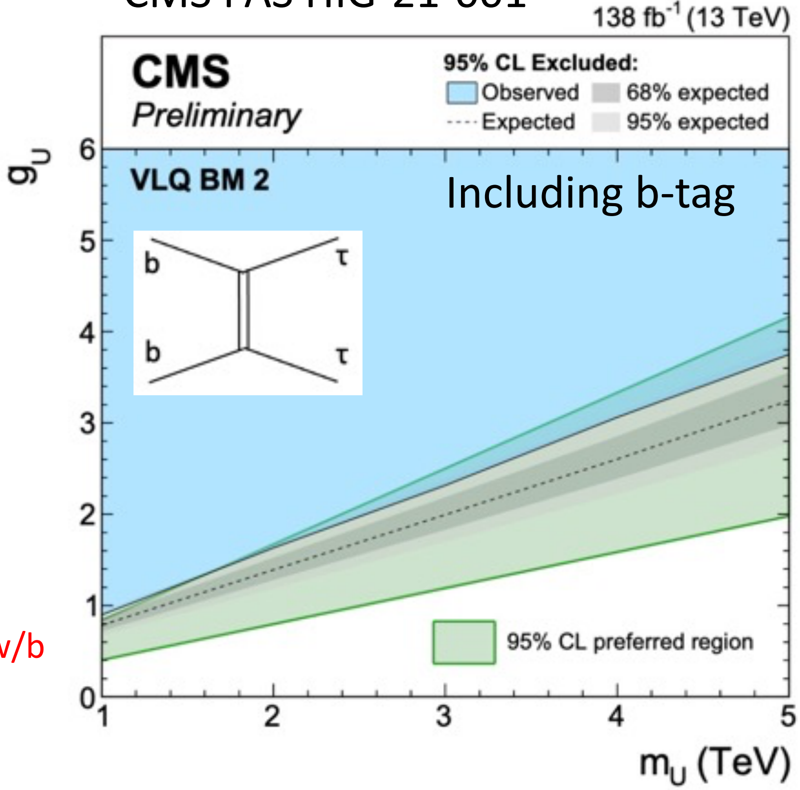
τν+b

$R_{D^{(*)}}$

Dashed:3$\text{ab}^{-1}$

sensitivity w/o b, w/b

CMS PAS HIG-21-001



Including b-tag

We assigned the conservative uncertainty corresponding to the one with 36 $\text{fb}^{-1}$ to estimate the sensitivity with 139 $\text{fb}^{-1}$ → our sensitivity is conservative.

We can touch the interesting region with the LHC.

An additional b-tagging is important but not performed yet

# τ ν +b with mass dependence

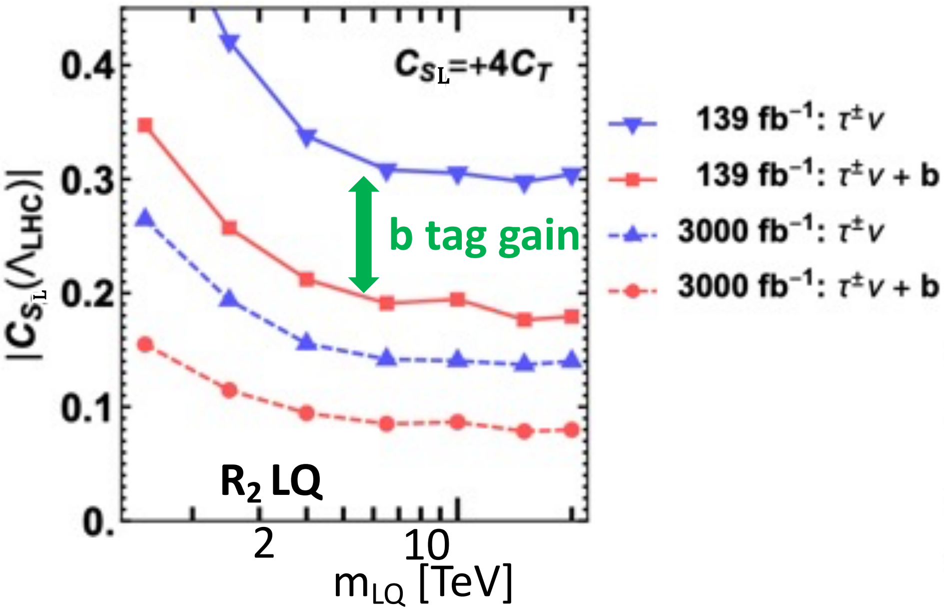
2111.04748

We observed the significant mass dependence

↓

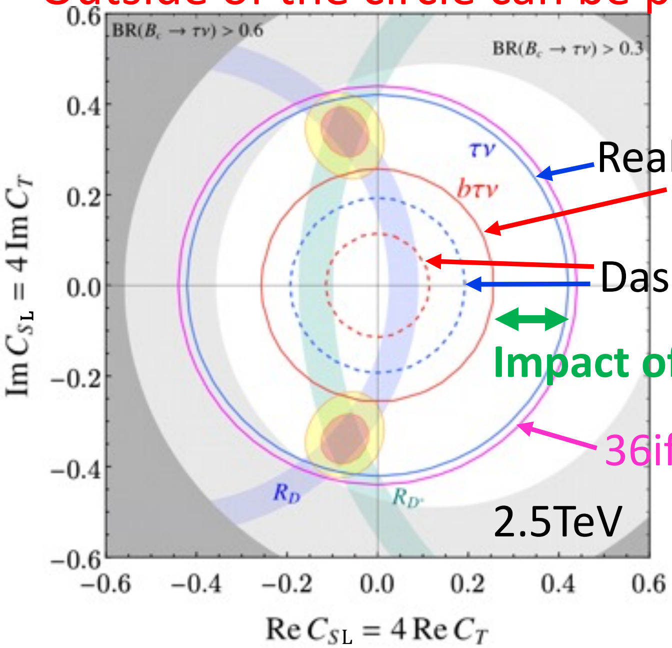
*t* parameter dependence is large in small mass region

Sensitivity to WC



b tag gain

Outside of the circle can be probed!



Real:139 $\mathrm{fb}^{-1}$

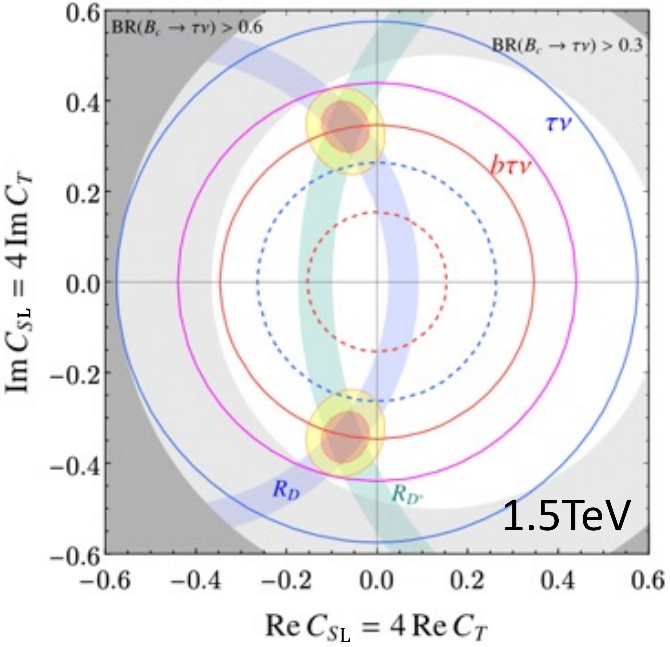
Dashed:3 $\mathrm{ab}^{-1}$

Impact of b tagging

36ifb CMS

2.5TeV

**$R_2$ LQ**



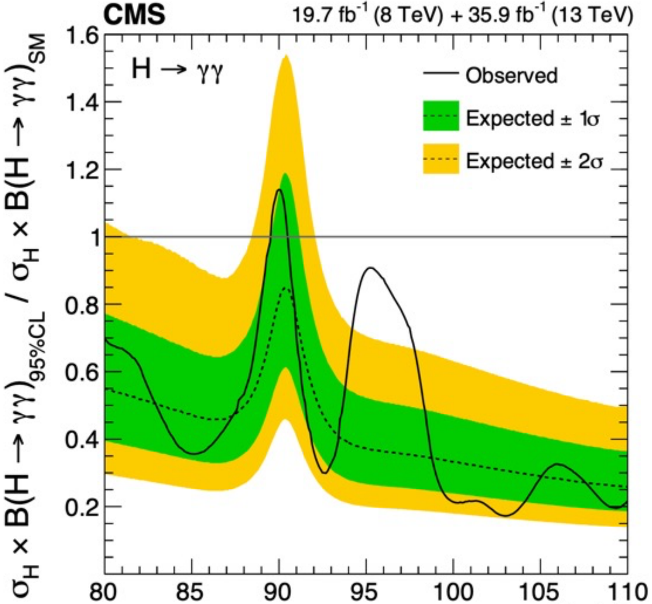
1.5TeV

Charge ID of b-jet would improve the sensitivity since the main BG does not come from the genuine b+τν event.

We can test the scenario soon!

# 95 GeV?

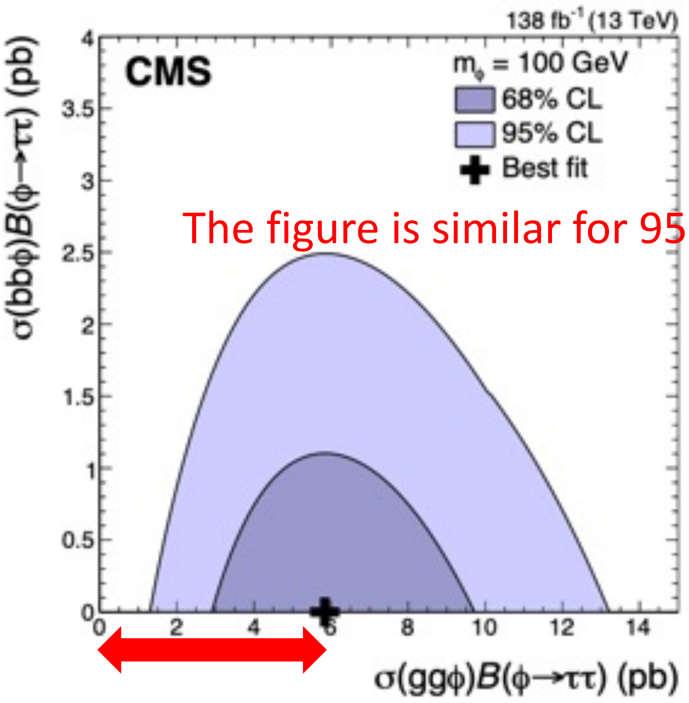
**CMS-HIG-17-013**



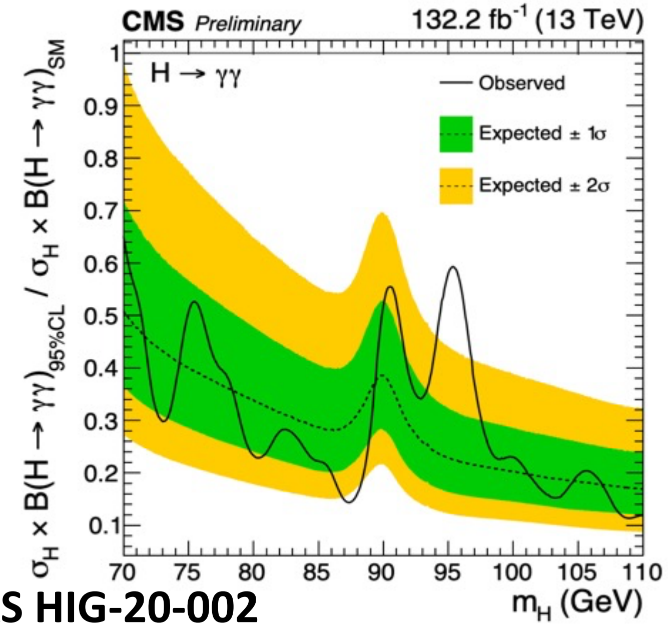
**There are several 3 sigma excesses around 95GeV. CMS γγ and $\tau\tau$, LEP $e^+e^-$ -> Z X -> Z bb,**

ATLAS is not sensitive enough.

**CMS-HIG-21-001**



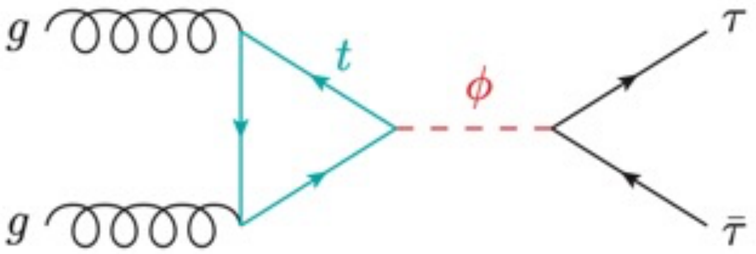
The figure is similar for 95GeV



**CMS PAS HIG-20-002**

ATLAS result is not sensitive enough

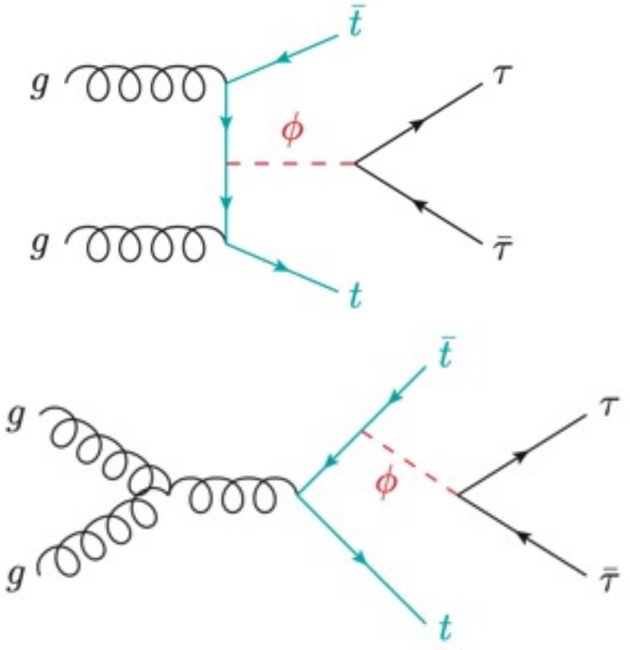
# 95 GeV?

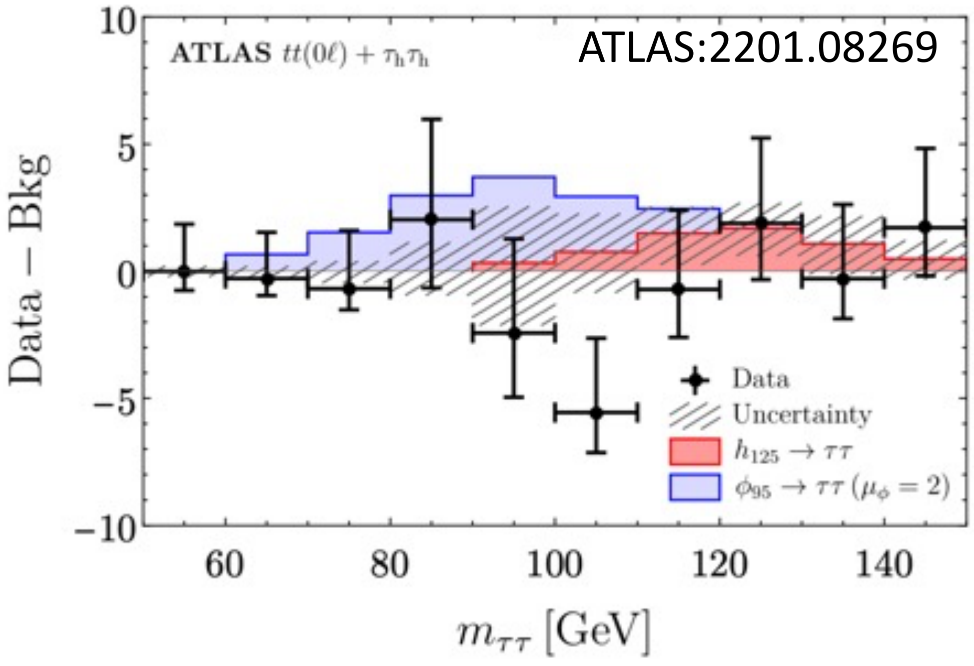


Let's consider a cross check.
Suppose we have a scalar with

$$-\mathcal{L}_{\text{eff}} = \frac{\rho^H_{tt}}{\sqrt{2}}\,\bar{t}Ht + \frac{\rho^H_{\tau\tau}}{\sqrt{2}}\,\bar{\tau}H\tau \pm i\frac{\rho^A_{tt}}{\sqrt{2}}\,\bar{t}A\gamma_5 t + i\frac{\rho^A_{\tau\tau}}{\sqrt{2}}\,\bar{\tau}A\gamma_5\tau$$

**Indirect constraint!**

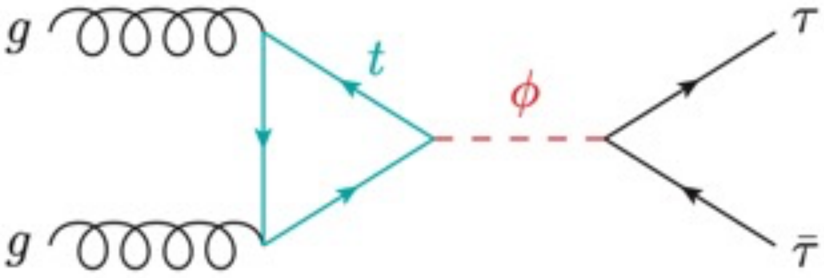




ATLAS:2201.08269

# 95 GeV?

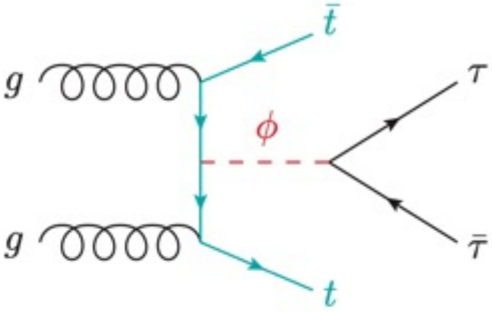
Let’s consider a cross check.

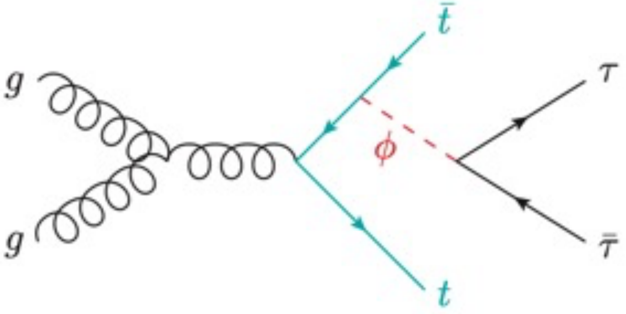


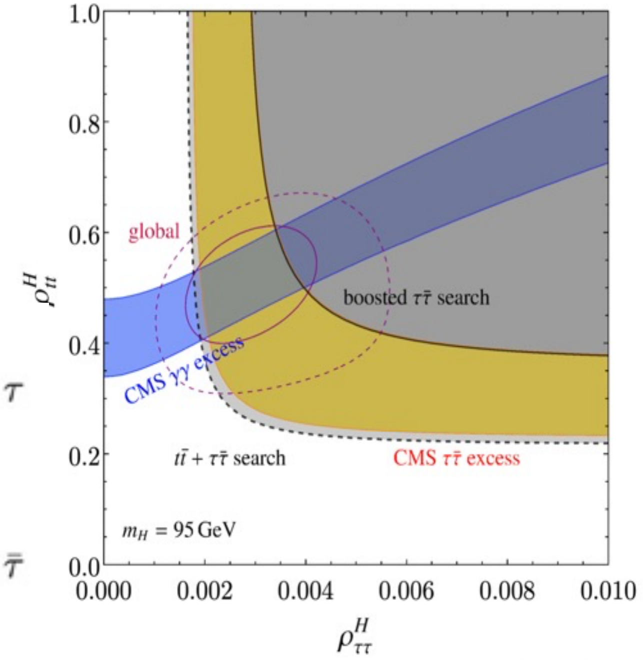
Loop function is different

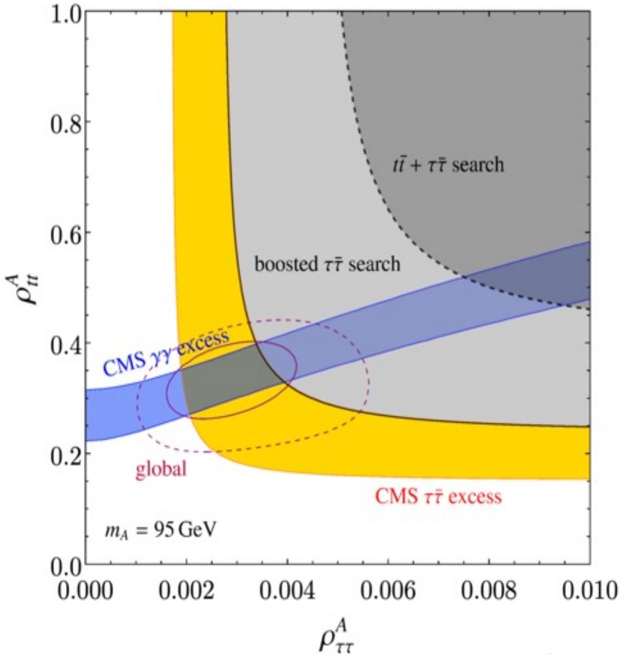
**Indirect constraint!**

Iguro et al 2205.03187









ttϕ, ϕ=A: destructive, ϕ=H: constructive **Scalar** 😅😩 **Pseudo-Scalar** 😄

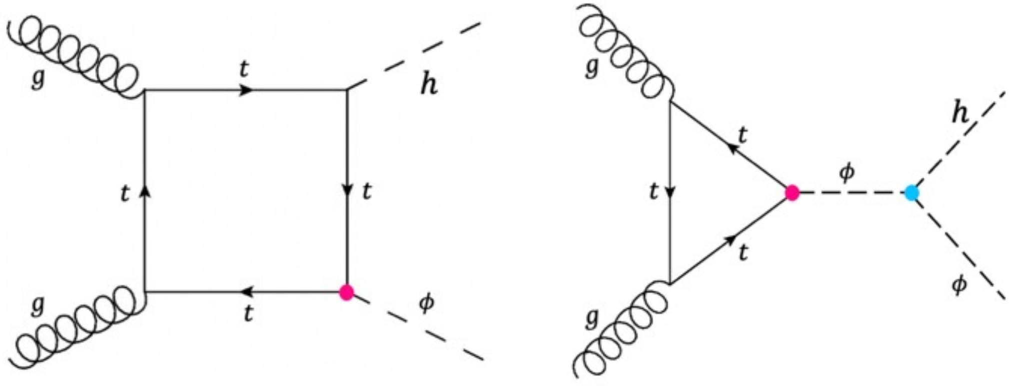
**We need detailed experimental analysis for the conclusion**

# 95 GeV?

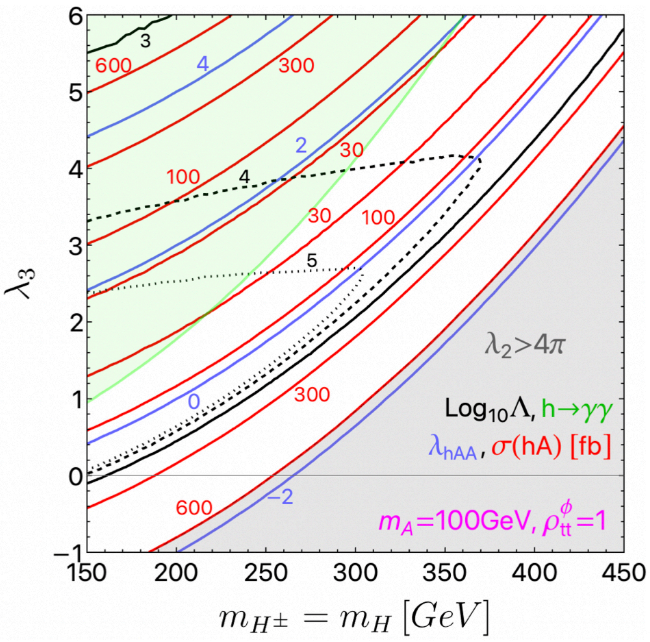
Q: How we can test pseudo-scalar solution?

A: Di-Higgs production!

Iguro et al  2211.00011



Something for TTP



We calculated at the leading order.
There is no relevant search as this 95GeV region.
If the K-factor is 2 (this is good approximation for heavy top limit),
σ(hϕ) > upper limit for σ(hh -> bb ττ).

**Di-Higgs is very interesting!**

Di-SM higgs production is one of the main targets of HL-LHC, but NSM search is also interesting.

# Last message

**Fact** No concrete NP signal at the LHC

Although there are many flavor anomalies on the market,
statistically and historically saying, most of them would not be true.

I started particle physics in 2016 and have seen disappearance,,,

$h \to \mu\tau$

2017

$\delta a_e$

2020

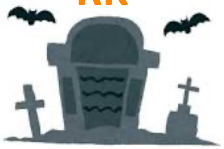
$\varepsilon'/\varepsilon$

2020

$W \to \tau\nu$

2021

RK



2022

Additional data Lattice New data

**At the same time many new discrepancies appeared!**

$b \to cuq$

CAA

$B_c \to J/\psi\tau\nu$

Charm $\Delta A_{CP}$

Many excesses in LHC

e.g. di-tau, di-γ (95GeV), di-di jets(1TeV), $h \to \mu\tau$, $h \to e\tau$.

**Keep testing the SM ->**
**Refining the SM or finding the New Physics.**
**Both are great don't be discouraged!**

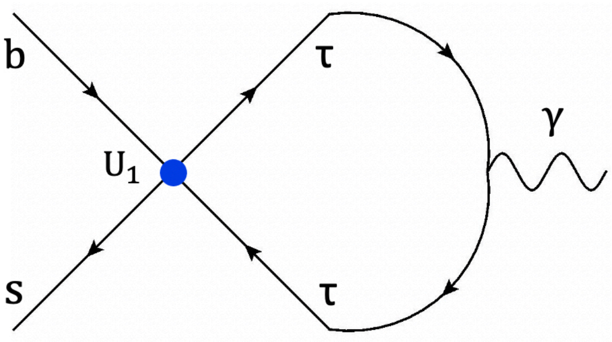
# Where we are?

## Let’s keep trying

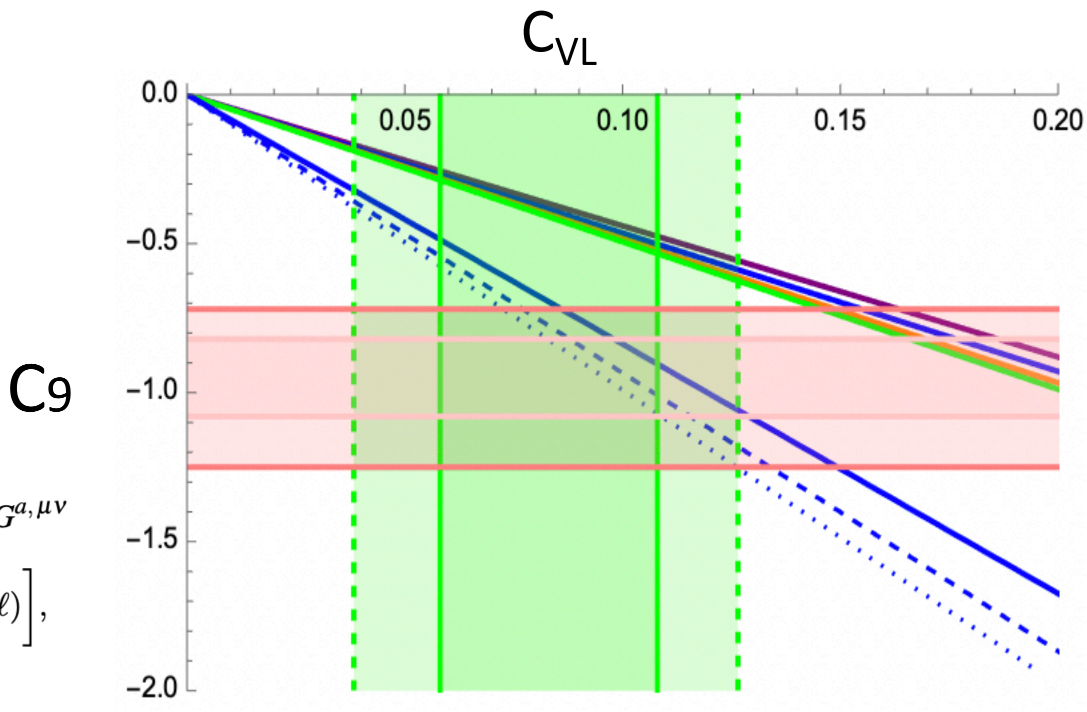
# Extra contents

# τ-loop induced $C_9$ universal

Crivellin et al 1807.02068, Greljo et at 1808.00942



Leading lox approximation Inclusion of heavy lepton



$$\mathcal{L} = \frac{\alpha G_F V_{td_i} V^*_{td_k}}{\sqrt{2}\pi}\Big[m_b C_7(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu} + m_b C_8(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{a,\mu\nu} + C_9^\ell(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu \ell) + C_{10}^\ell(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu\gamma_5\ell)\Big],$$

Finite part is missing for heavy lepton!

Balance with Bs mixing

# Summary of one operator analysis

|  | RD | RD* | $F_L^{D^*}$ |
|---|---|---|---|
| $O_{S1}$ | ○ | △ | → |
| $O_{S2}$ | ○ | △ | ↗ |
| $O_{V1}$ | ○ | ○ | → |
| $O_{V2}$ | ○ | ○ | → |
| $O_T$ | ○ | ○ | ↘ |

Scalar operator easily enhances $BR(B_c^- \to \tau\bar{\nu})$ and testable in LHC.

Vector operator can not enhance $F_L^{D^*}$.

Tensor operator suppresses $F_L^{D^*}$.

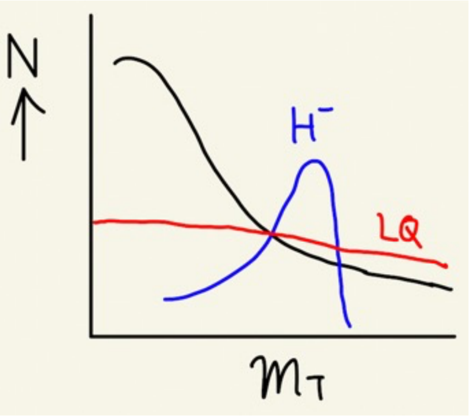
It seems not easy to enhance $F_L^{D^*}$

$\mathrm{H}^-$ and $\mathrm{W}'$ are covered so far.

Now, the primary candidate is LQ

Where beyond one operator analysis is needed

# Check list at the LHC



## $\tau\nu$ category

| Signal \ channel | | $\tau\nu$ | $\tau\nu$ +b |
|---|---|---|---|
| $H^+$ | S | Iguro et al<br>1810.05843<br>**Done** | Iguro et al<br>2202.10468<br>**Done** |
| LQ | t | Greljo et al<br>1811.07920<br>**Done** | Minho et al<br>2008.07541<br>**Done** |

**Mass dependence**

| $\tau\nu$ | $\tau\nu$ +b |
|---|---|
| Iguro et al<br>2011.02486<br>**Done** | Iguro et al<br>2111.04748<br>**Done** |

**Finally completed the table!**

**+b category is always more sensitive**

# Other related observables.

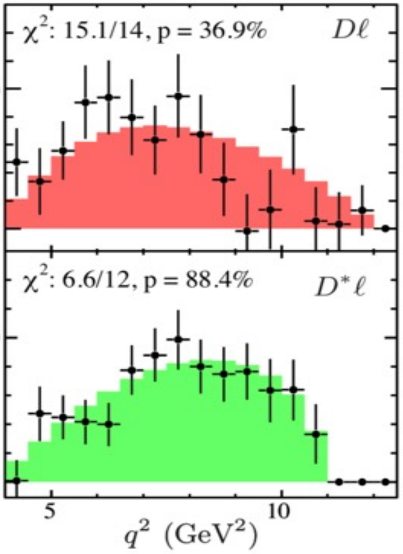
- **Tau polarization in $\boldsymbol{B \to D^{(*)}\tau\nu}$ process.**

$P^{D}_{\tau,SM} = -0.32, P^{D^*}_{\tau,SM} = -0.51$ M. Tanaka. R. Watanabe 1005.4306

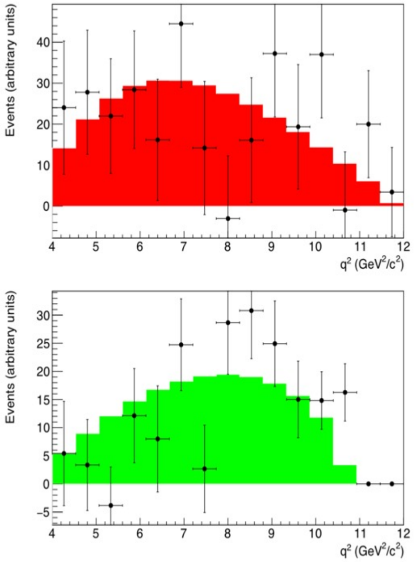
$P^{D}_{\tau,\exp}$ =×××, $P^{D^*}_{\tau,\,Belle}$ = −0.38 ± 0.51(stat.)+0.21(syst.) 1709.00129

- **$\mathbf{q^2}$ distribution in $\boldsymbol{B \to D^{(*)}\tau\nu}$**

BaBar 1303.0571



Belle 1507.03233



- $\boldsymbol{R(J/\psi) = \dfrac{BR(B_c \to J/\psi\tau\nu)}{BR(B_c \to J/\psi\mu\nu)}}$

$\boldsymbol{R(J/\psi)}_{\mathrm{LHCb}}$ = 0.71 ± 0.17 ± 0.18
$\boldsymbol{R(J/\psi)}_{\mathrm{SM}}$ = 0.283 ± 0.048

R. Watanabe 1709.08644

Currently not so accurate.

- Bin correlation is not available
- D* mode affects D mode

# Nice to meet you!

# I am a Postdoc at KIT for three years!

Oct. 2021 – September 2024

- Name: Syuhei Iguro
- Position: Postdoc
- Birth place: Japan, Tokyo
- Interests: Flavor, Collider, Dark Matter,
  Neutrino…..

**Especially for interplay between flavor physics and collider physics**

Syuhei Iguro

Basics

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**e-mail: iguro@eken.phys.nagoya-u.ac.jp**
**Affiliation: Department of Physics, Nagoya University, Theoretical Particle Physics Group E-Lab: Furo-cho, Chikusa-ku, Nagoya Aichi 464-8602, Japan**
**Present status: D2 student**
**Sex: Male**
**Nationality: Japan**
**Date of Birth: July 17, 1992**
**Birth place: Japan, Tokyo**
**Interests: Flavor, Collider, Dark Matter, Neutrino…..**
**Ambition: 10 papers before the Tokyo Olympic(more than half of them is originated from my idea), and get many grants**
**What's I like: Playing Football, travel cycling**

Publication -papers-

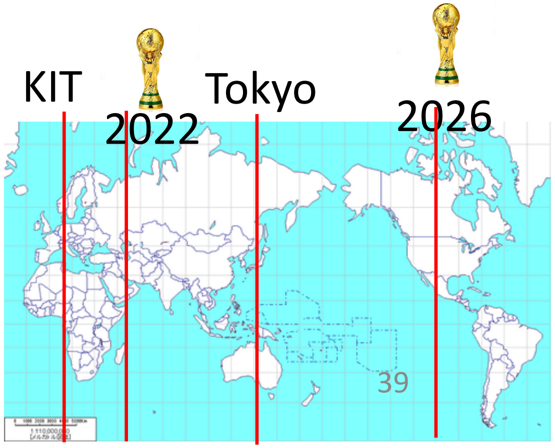
Link to my InspireHEP

7, With Michihisa Takeuchi and Yuji Omura
1907.09845 : "Testing the 2HDM explanation of the muon g-2 anomaly at the LHC"

6, With Yuji Omura
1905.11778 : "The direct CP violation in a general two Higgs doublet model"

5, With Teppei Kitahara, Ryotaro Watanabe, Yuji Omura and Kei Yamamoto
1811.08899, published inJHEP 1902 (2019) 194 :"$D^*$ polarization vs. $R(D^{(*)})$ anomalies in the leptoquark models"

- I love football! I came to EU since
  time gap is smaller between here and Qatar 2022 W cup.
  I will go to U.S. since we have the next one in U.S.
- For more info: https://igurosyuhei.wixsite.com/mysite



# Our SM is a very good theory to describe almost all measurements

,,,,

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However large part of theorists is not satisfied with the SM.

Mysteries of the SM

Dark Matter, matter vs antimatter asymmetry, strong CP problem, fine turning of Higgs mass, Yukawa hierarchy, Neutrino masses,,,,

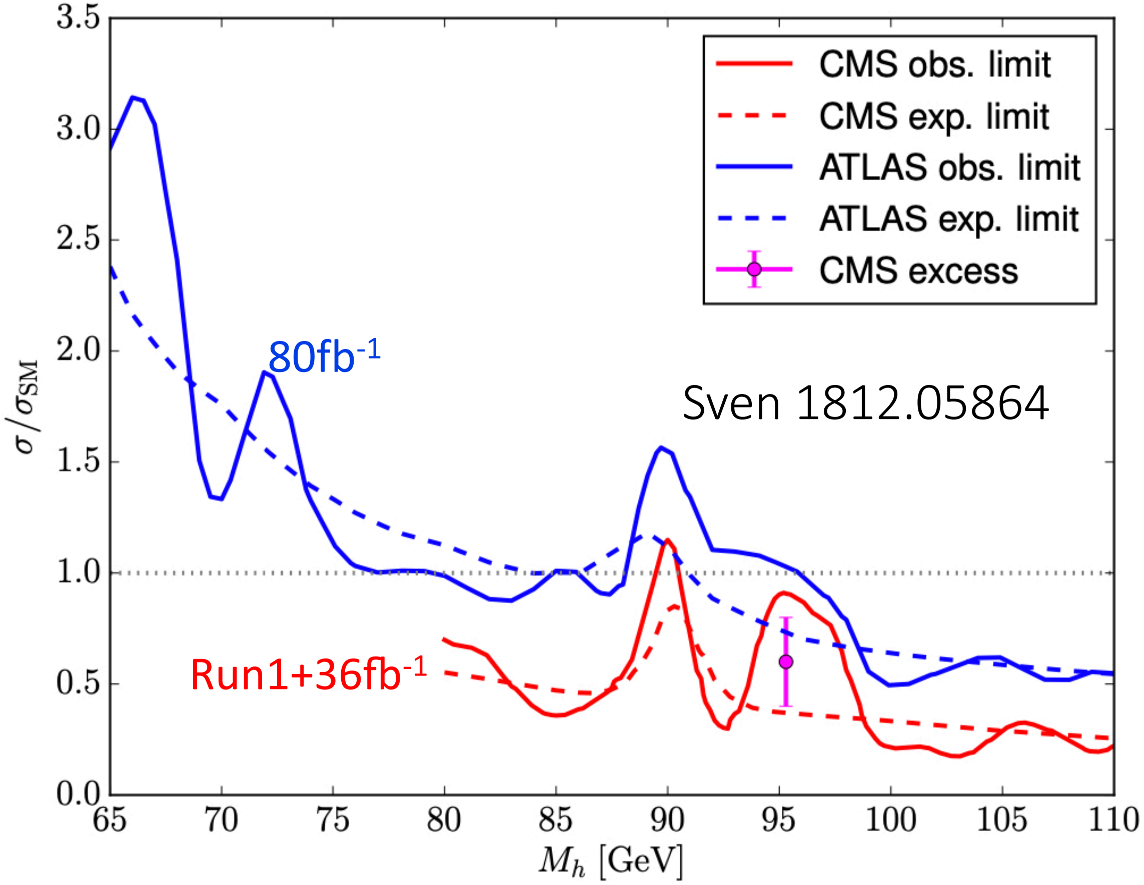
Each problem has several New Physics(NP) solutions and we need further hints to specify the scenario!

Deviations in flavor physics may be a hint for NP?

# How about ATLAS?

95GeV

They has the result with 80fb$^{-1}$



80fb$^{-1}$

Sven 1812.05864

Run1+36fb$^{-1}$

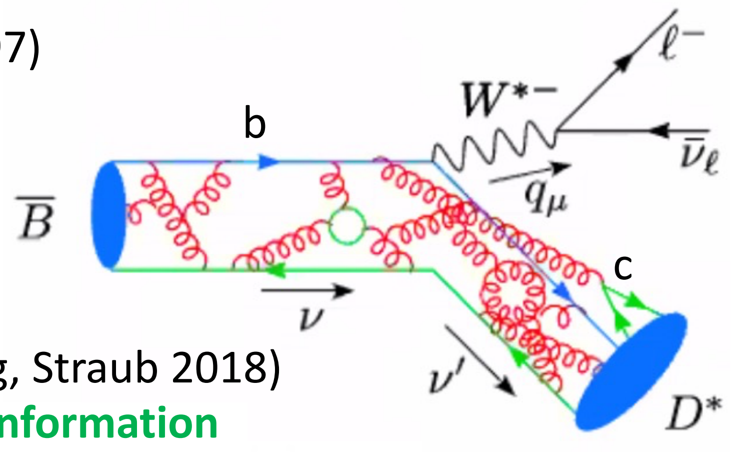
They do not show relevant
di-tau result

ATLAS result is not sensitive enough

# Form Factors in B->D,D* transition

**Conventional parametrization**

- CNL parametrization (Caprini, Lellouch, Neubert 1997)
  -> too much simplified
- BGL parametrization (Boyd, Grinstein, Lebed 1997)
  -> too general to use for the NP analysis



**Our approach**

- General Heavy Quark Effective Theory(GHQET) (Jung, Straub 2018)

**QCD information**

$$\langle D|\bar c\gamma^\mu b|B\rangle_{\rm HQET} = \sqrt{m_B m_D}\left[h_+(v+v')^\mu + h_-(v-v')^\mu\right],$$

**SM**

$$\langle D^*|\bar c\gamma^\mu\gamma^5 b|B\rangle_{\rm HQET} = \sqrt{m_B m_{D^*}}\left[h_{A_1}(w+1)\epsilon^{*\mu} - (\epsilon^*\cdot v)\left(h_{A_2}v^\mu + h_{A_3}v'^\mu\right)\right],$$

$$v^\mu = p_B^\mu/m_B,\ v'^\mu = p^\mu_{D^{(*)}}/m_{D^{(*)}},\ w = v\cdot v' = (m_B^2 + m_{D^{(*)}}^2 - q^2)/(2m_B m_{D^{(*)}}),$$

**Main difference: $h_+$, $h_-$, $h_{A1}$… are described by common parameters**

We want to determine $h_x$ precisely.

**Recent progress**

L. Zoltan et al 2017

$$\hat h_X = \hat h_{X,0} + \underset{0.1}{\frac{\alpha_s}{\pi}}\delta\hat h_{X,\alpha_s} + \underset{0.05}{\frac{\bar\Lambda}{2m_b}}\delta\hat h_{X,m_b} + \underset{0.2}{\frac{\bar\Lambda}{2m_c}}\delta\hat h_{X,m_c} + \underset{0.04}{\left(\frac{\bar\Lambda}{2m_c}\right)^2}\delta\hat h_{X,m_c^2},$$

M. Bordone et al.
EPJC 2020

# Three kinds of constraints (input of the fit)

- Lattice (6)

- prediction for large $q^2$
- unstable particles (D*) are problematic

-> hard to predict FF for B->D*

- Theory (45)

e.g. QCDSR
LCSR
Unitarity bound

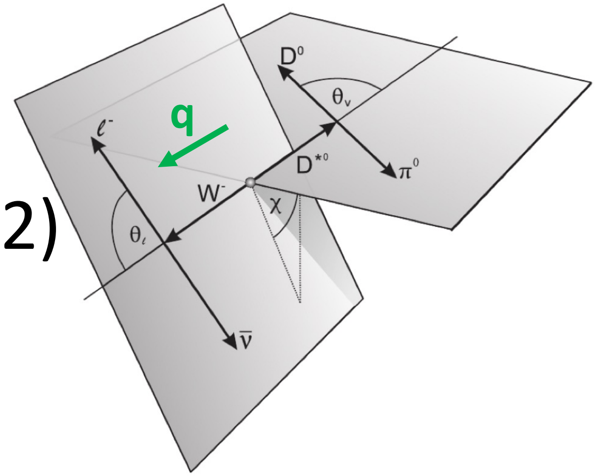
- prediction for small $q^2$

we newly included QCDSR constraints on higher derivative terms

- Experiment (132)

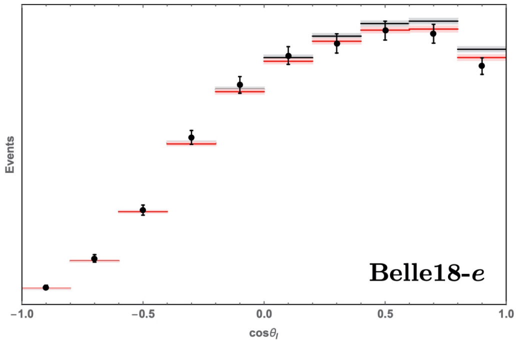
Belle 17,18

～180 constraints



Experimental data from Belle

we also newly included data of angular distribution in 1809.03290



full kinetic ($q^2$, $\theta_l$, $\theta_V$ , $\chi$) distributions of $B \to D^* l \nu$

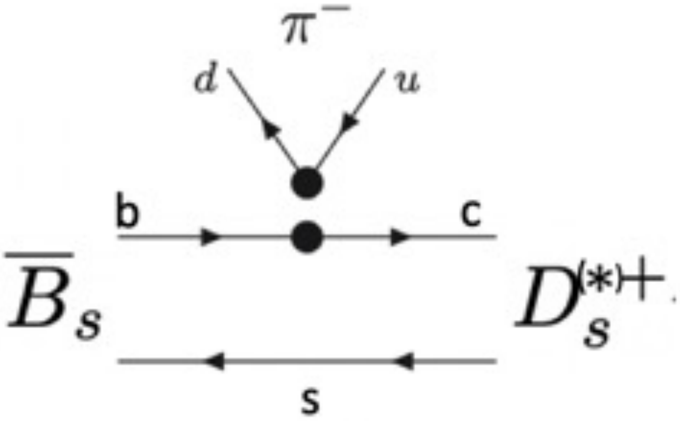
# Color allowed $B \to D^{(*)}M$ within the SM

The decays are described by

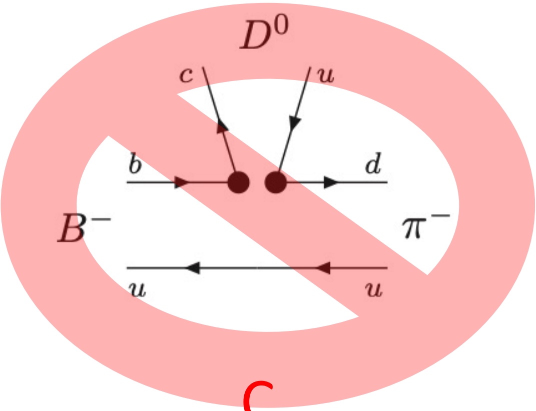
$$\mathcal{H}_W = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s} V_{cb}V_{uq}^{*}(C_1\mathcal{O}_1^q + C_2\mathcal{O}_2^q) + \text{h.c.},$$

$$\mathcal{O}_1^q = \left(\bar{c}\gamma^{\mu}T^{a}P_L b\right)\left(\bar{q}\gamma_{\mu}T^{a}P_L u\right),$$
$$\mathcal{O}_2^q = \left(\bar{c}\gamma^{\mu}P_L b\right)\left(\bar{q}\gamma_{\mu}P_L u\right),$$

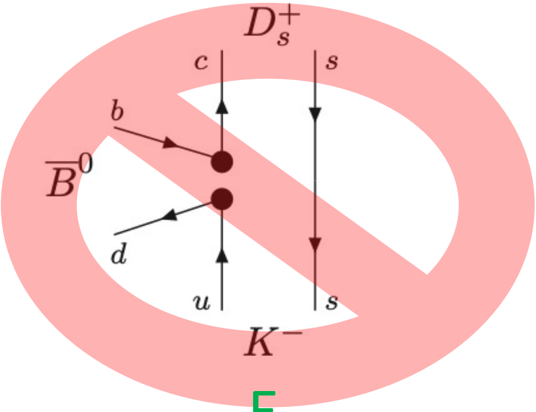
with $C_1(m_b)\sim -0.3, C_2(m_b)\sim 1$



Penguin, Color- suppressed and Exchange diagrams does not contribute since the involving quarks are all different.



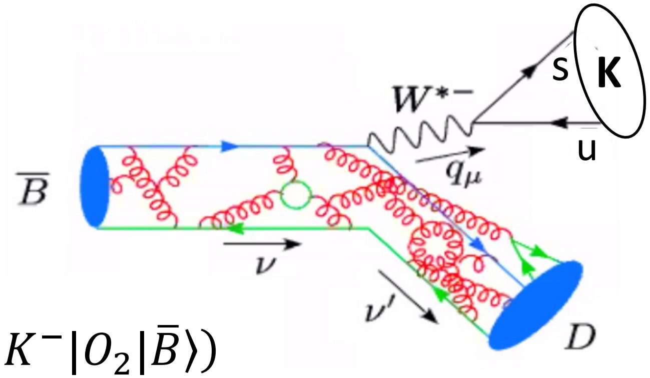
C



E

**Theoretically clean**

# Factorization amplitude



$$A(\bar{B} \to D^+K^-) = \frac{G_F V_{us}^* V_{cb}}{\sqrt{2}} \left(C_1 \langle D^+K^- | O_1 | \bar{B} \rangle + C_2 \langle D^+K^- | O_2 | \bar{B} \rangle\right)$$

The non factorizable soft gluon exchange contribution between BD system and K is suppressed. *Bjorken (89)*

Soft collinear effective theory shows the contribution is absent at leading order

Bauer et al. 0107002

$$= \frac{i\, G_F V_{us}^* V_{cb}}{\sqrt{2}} (m_B^2 - m_D^2) a_1(D^+K^-)\, f_K\, F_0^{B\to D}(m_K^2)$$

$a_1(D^+K^-)$ is calculated in pQCD at NNLO. See also Beneke et al 2107.03819 for QED correction

$$a_1(D^+K^-) = (1.069^{+0.009}_{-0.012}) + \left(0.046^{+0.023}_{-0.015}\right) i$$ *Huber et al, 1606.02888*

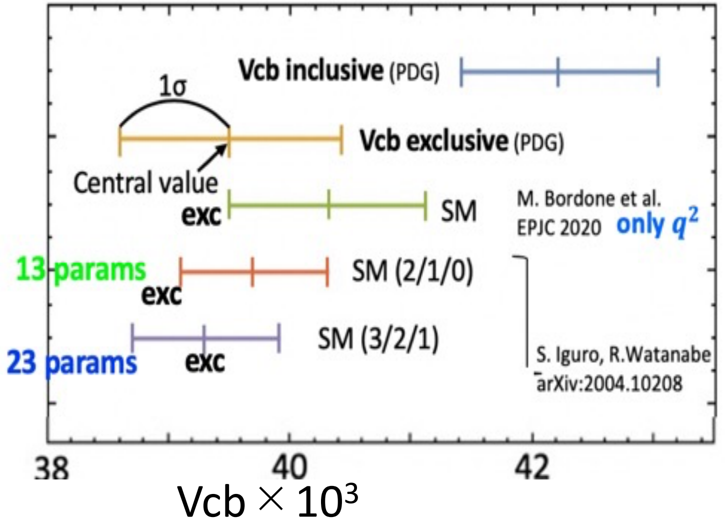
$V_{cb} \times F_0^{B\to D}(m_K^2)$: LCSR, Belle data, QCDSR, Lattice Iguro Watanabe 2004.10208.

LCSR dominance at $q^2 = m_K^2$

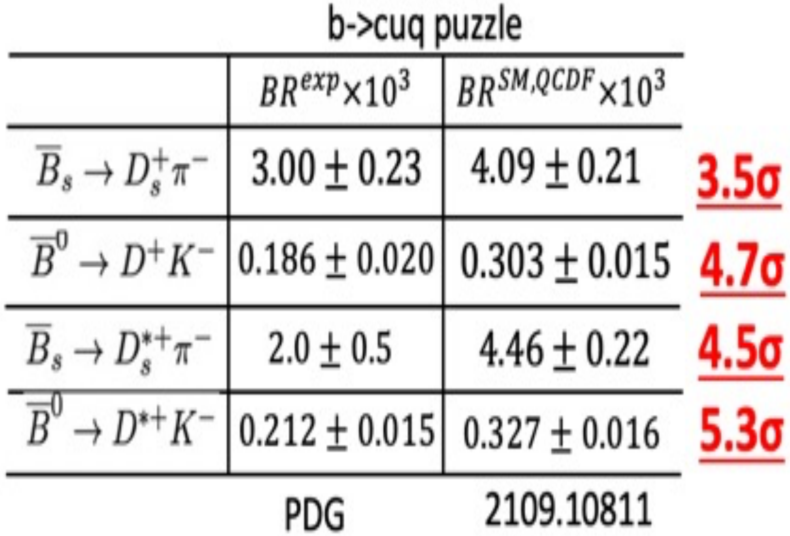
Uncertainty in $f_K$ and $V_{us}$ is negligible

# Latest status with our form factor

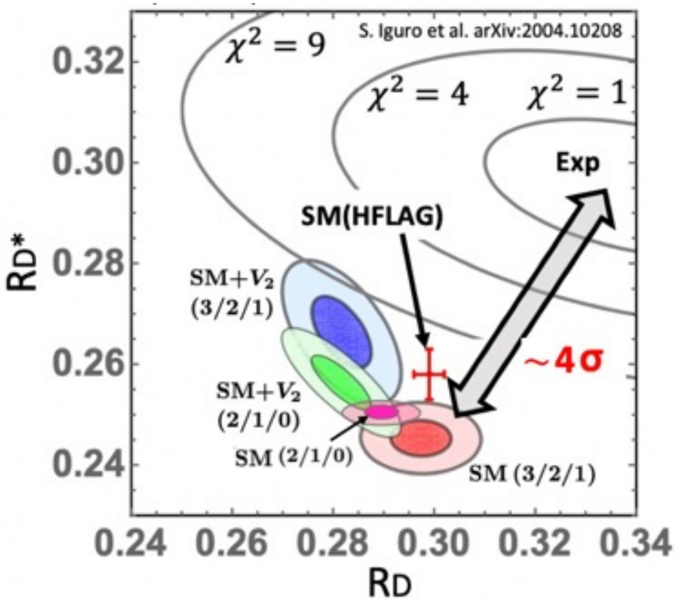
Vcb puzzle remains



b->cuq puzzle



| | $BR^{exp}\times10^3$ | $BR^{SM,QCDF}\times10^3$ | |
|---|---|---|---|
| $\overline{B}_s \to D_s^+\pi^-$ | $3.00 \pm 0.23$ | $4.09 \pm 0.21$ | 3.5σ |
| $\overline{B}^0 \to D^+K^-$ | $0.186 \pm 0.020$ | $0.303 \pm 0.015$ | 4.7σ |
| $\overline{B}_s \to D_s^{*+}\pi^-$ | $2.0 \pm 0.5$ | $4.46 \pm 0.22$ | 4.5σ |
| $\overline{B}^0 \to D^{*+}K^-$ | $0.212 \pm 0.015$ | $0.327 \pm 0.016$ | 5.3σ |
| | PDG | 2109.10811 | |



We got the smaller RD* value.

-> Now ~~3~~ 4σ discrepancy again.

Even if we have new physics in b->clν transition, the anomaly remains.

$$R_{D^{(*)}} = \frac{BR\left(B \to D^{(*)}\tau\nu\right)}{BR\left(B \to D^{(*)}l\nu\right)}\ ,\ \ l = \mu, \mathrm{e}$$

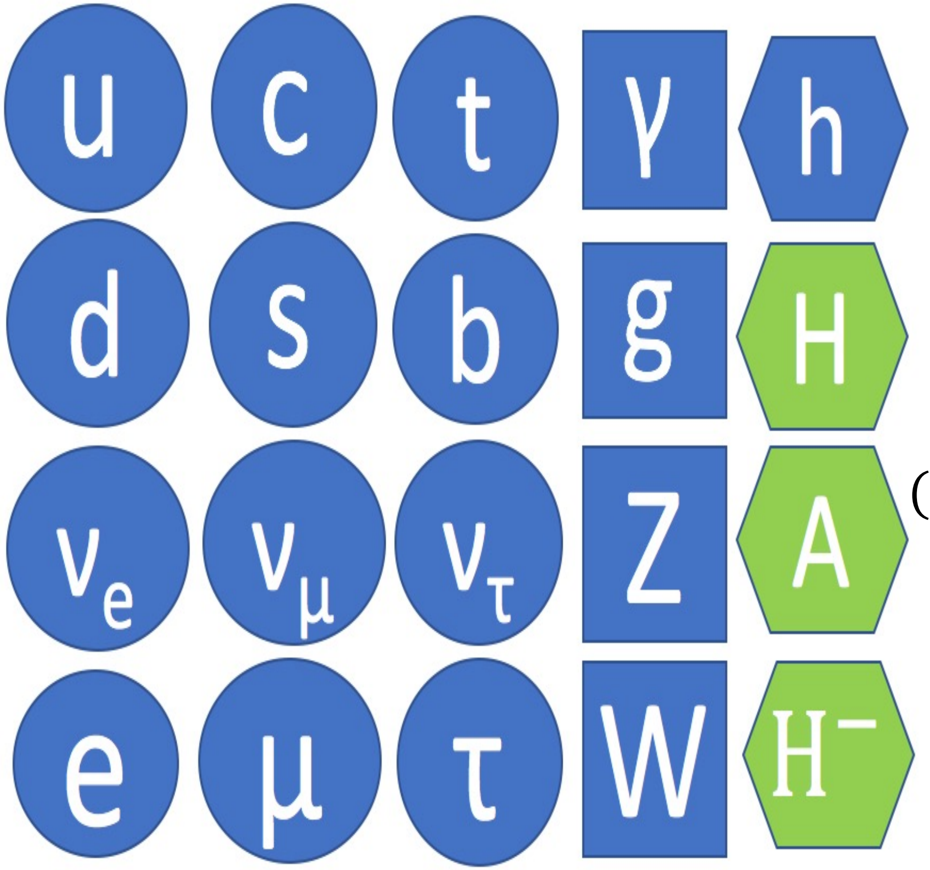
NP in τ mode is necessary.

# Additional contents for $H^-$ part

# Our Model

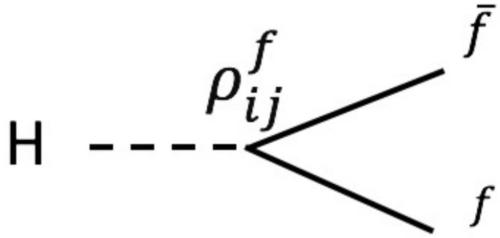
Iguro-Tobe 1708.06176

## Particle set in G2HDM



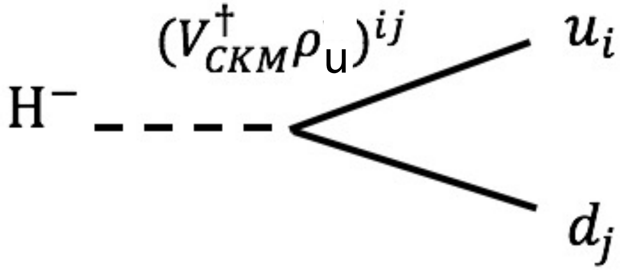
## Neutral Scalar

$$\frac{1}{\sqrt{2}}\rho_f^{ij}\mathrm{H}\overline{f_L^i}f_R^j \quad (f = u, d, e, \nu)$$



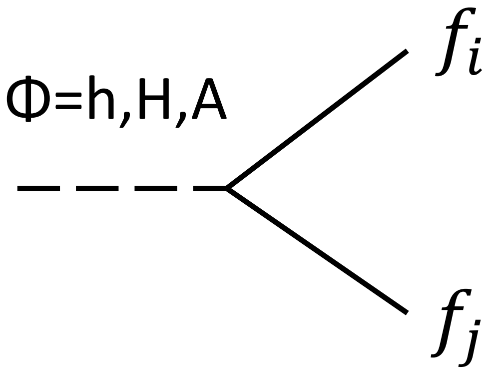
## Charged Scalar

$$(\mathrm{V}_{\mathrm{CKM}}\rho_d)^{ij}\mathrm{H}^-\overline{u_L^i}d_R^j + (V_{CKM}^\dagger\rho_u)^{ij}\mathrm{H}^-\overline{d_L^i}u_R^j$$



# Model: G2HDM

## Yukawa couplings between a neutral scalar and fermions



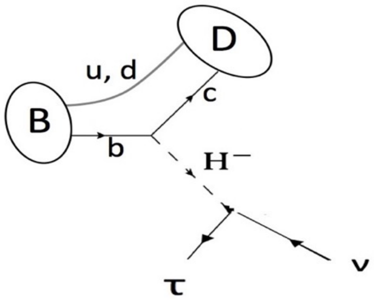
$$\approx i(y^{f}_{\Phi ij}\,\mathrm{P_R} + y^{f*}_{\Phi ji}\,\mathrm{P_L})$$

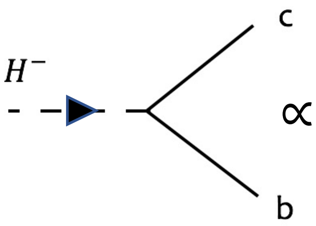
$$\mathrm{y^f_{hij} = \frac{m^i_f}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho^{ij}_f}{\sqrt{2}} c_{\beta\alpha},}$$

$$\mathrm{y^f_{Aij}} = \begin{cases} -\frac{\mathrm{i}\rho^{ij}_f}{\sqrt{2}} & \mathrm{for\ f = u} \\ +\frac{\mathrm{i}\rho^{ij}_f}{\sqrt{2}} & \mathrm{for\ f = d, e,} \end{cases}$$

$$\mathrm{y^f_{Hij} = \frac{m^i_f}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho^{ij}_f}{\sqrt{2}} s_{\beta\alpha}}$$

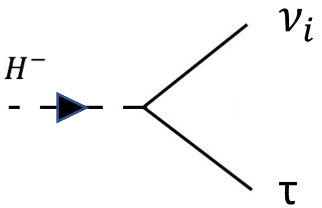
## Yukawa interactions relevant to $\mathrm{R\left(D^{(*)}\right)}$





$$\propto \mathrm{(V_{CKM}\rho_d P_R - \rho_u^\dagger V_{CKM} P_L)^{cb} \approx \rho_d^{sb} P_R - \rho_u^{tc*} P_L}$$

$\mathrm{\rho_d^{sb}}$<<1:Bs Mixing



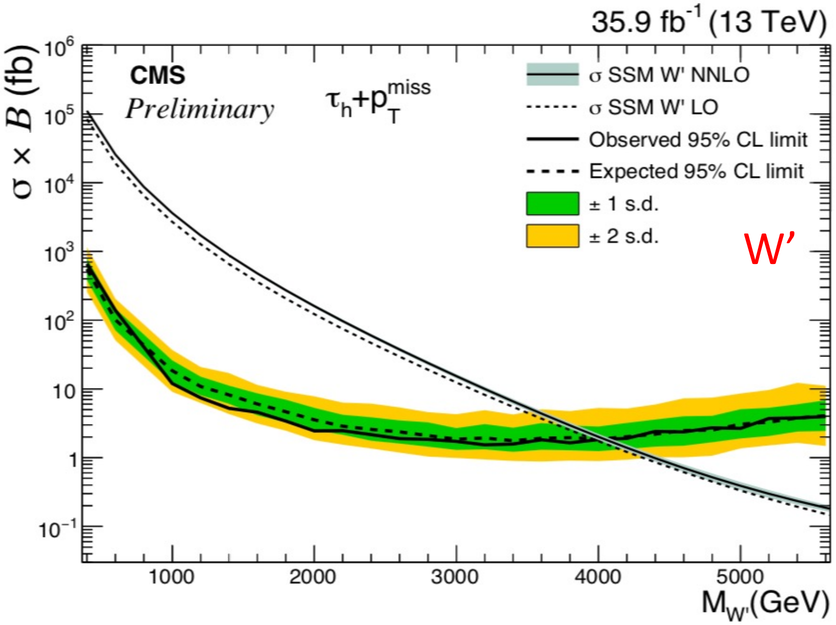
$$\propto \mathrm{\rho_e^{\tau\tau}}$$

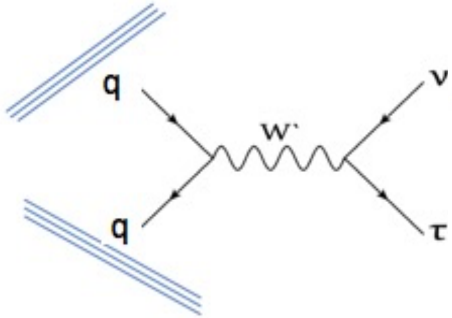
Yukawa interactions relevant to $\mathrm{R\left(D^{(*)}\right)}$
$\rho_u^{tc} \times \rho_e^{\tau\tau}$

$\rho_u^{tc}$ can be O(1) Nierste et al 2019, George-Hou 2018

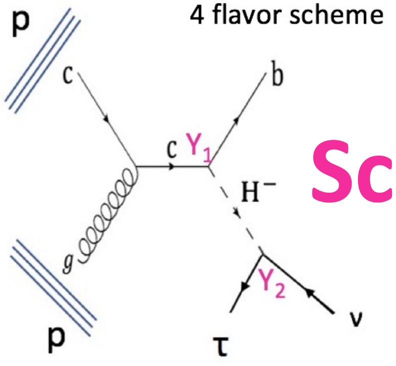
Large coefficient (large coupling) allows the collider search!

$\tau\nu$ resonance (+j) search in LHC can give a stringent limit.
But, the limit is for W’. CMS-PAS-EXO-17-008

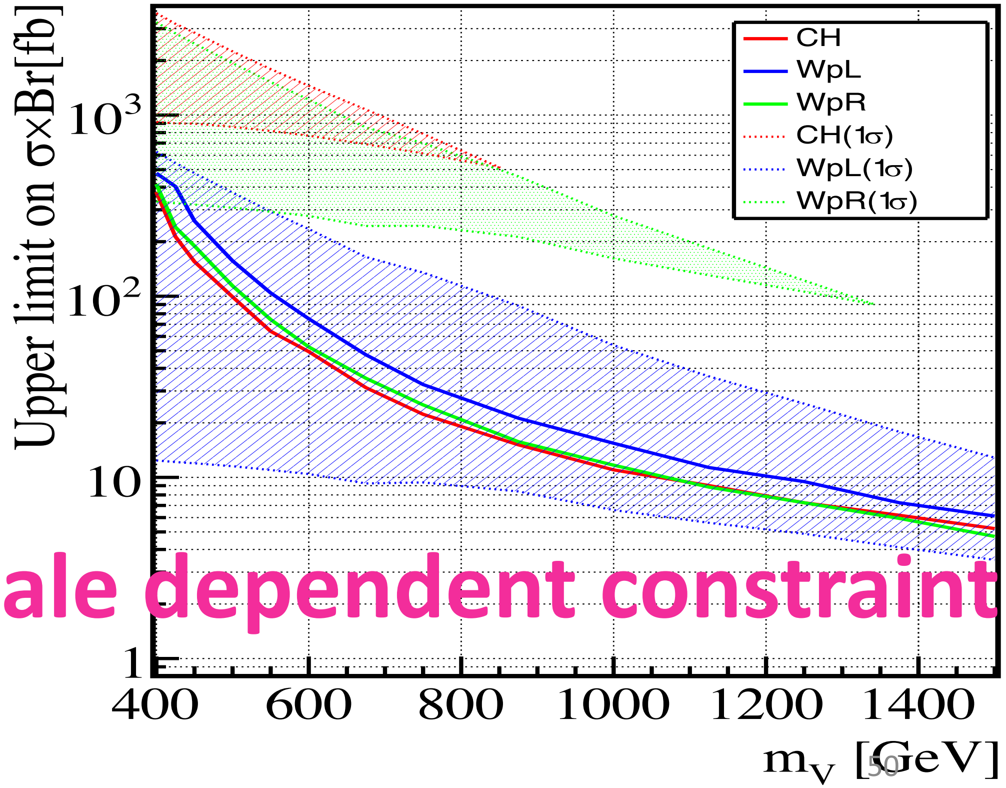




4 flavor scheme



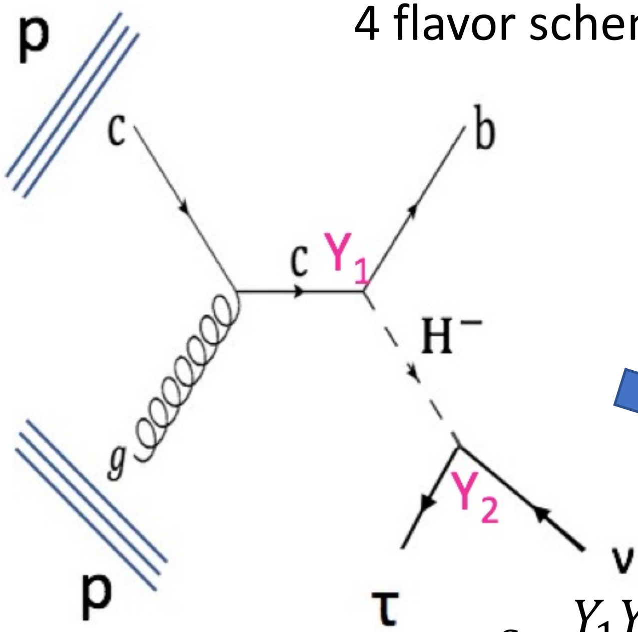
We reinterpreted this limit into $\mathrm{H}^-$ by the collider simulation.



Scale dependent constraint!

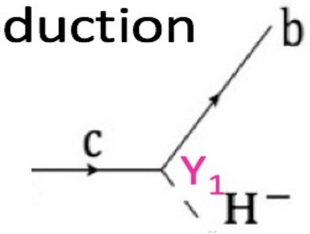
# σ × Br in G2HDM

4 flavor scheme



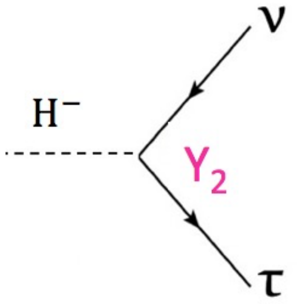
$$C_R'^S \sim \frac{Y_1 Y_2}{m_{H^-}^2}$$

**Production**



depending on $H^-$ mass
$\sigma = X_{H^-} |Y_1|^2$

**Branching ratio**



$$\mathrm{BR}(H^- \to \tau\nu) \approx \frac{|Y_2|^2}{3|Y_1|^2 + |Y_2|^2}$$

$$\boxed{\sigma \times \mathrm{BR} = \frac{X_{H^-} |Y_1|^2 \; |Y_2|^2}{3|Y_1|^2 + |Y_2|^2}}$$

Combination 1 : $Y_1 = 1$, maximizing denominator.
less events, weaker constraint.

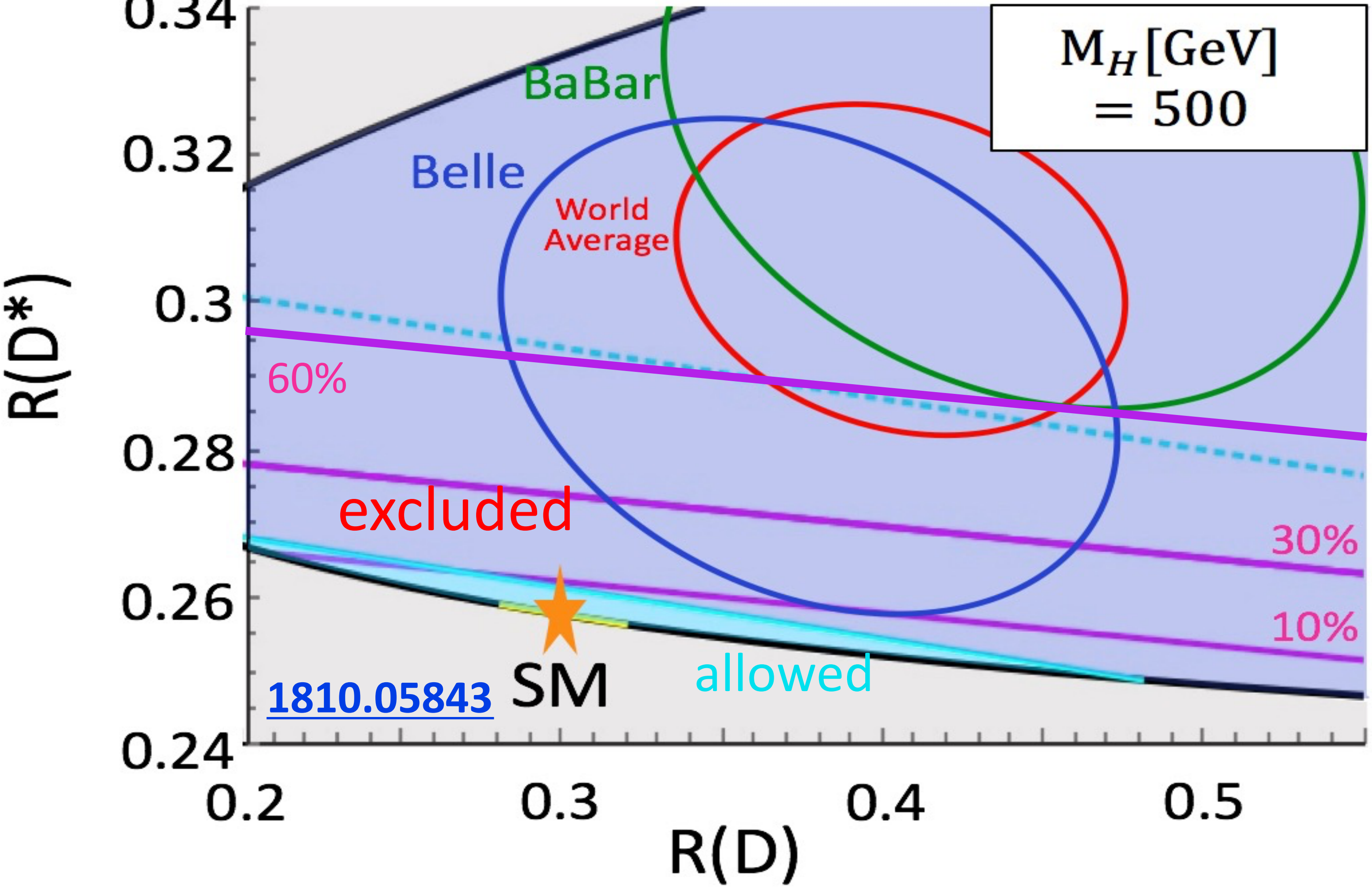
Combination 2 : $Y_2 = \sqrt{3} Y_1$, minimizing denominator.
more events, severe

**We set $|Y_1|, |Y_2| < 1$ : narrow resonance $\tau\nu$ search.**

$\Gamma(H^- \to bc) \sim 0.06 |Y_1|^2 m_{H^-}$, $\Gamma(H^- \to \tau\nu) \sim 0.02 |Y_2|^2 m_{H^-}$, then $\Gamma / m_{H^-} < 0.1$

# Result

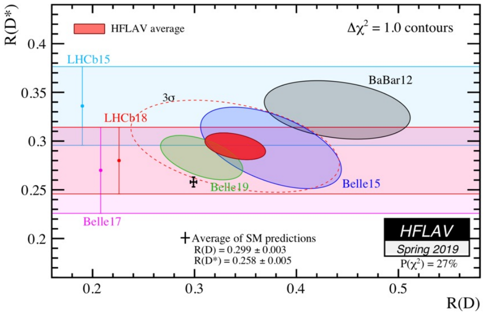
Much more stringent constraint than $B_c^- \to \tau\bar{\nu}$



# Result

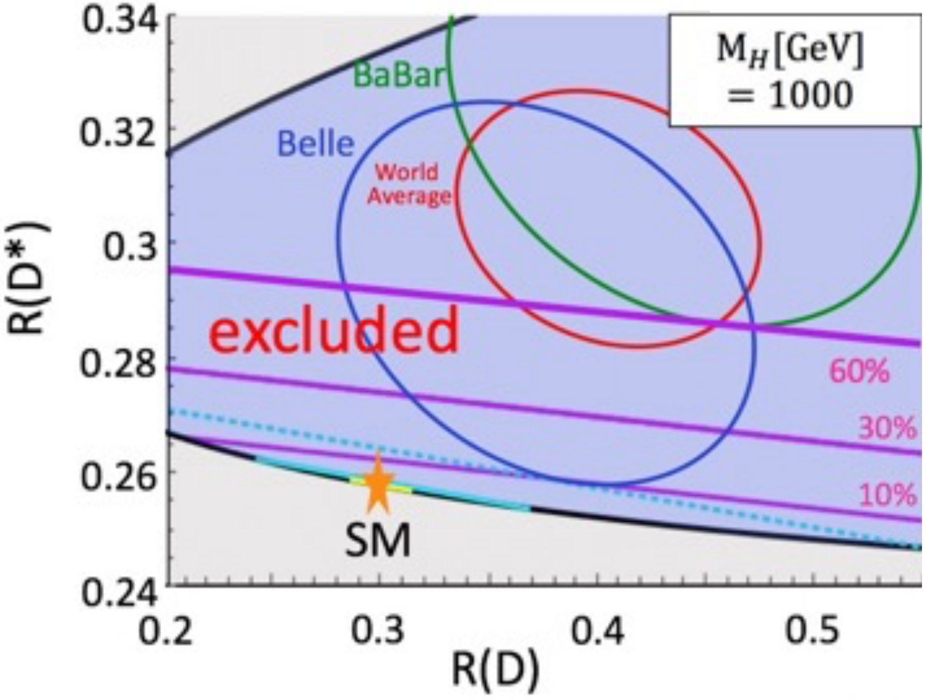
**Heavier $H^-$, more severe constraint.**

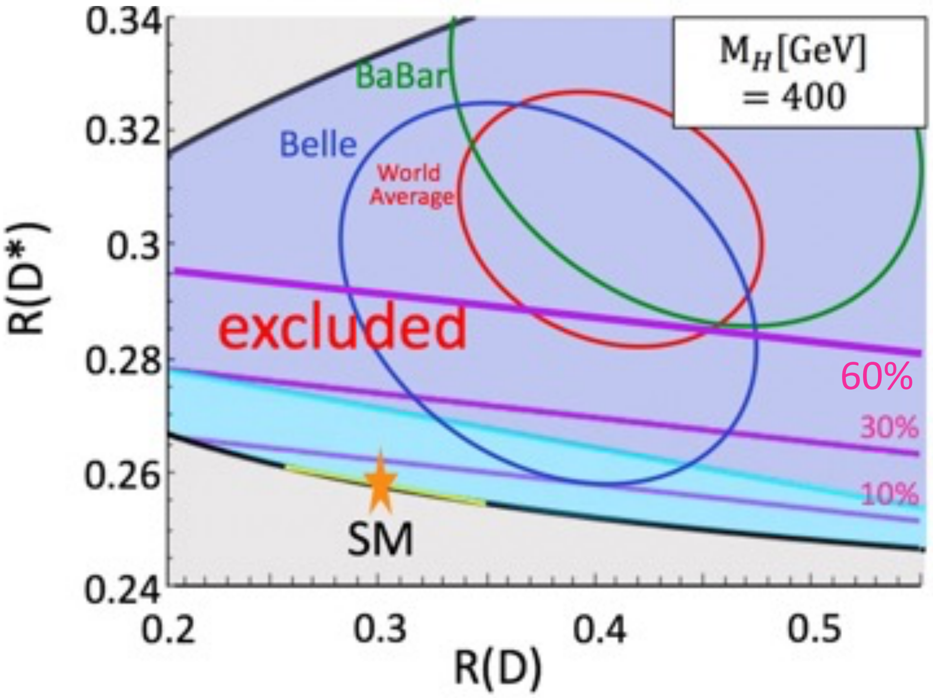
1810.05843



heavier

lighter

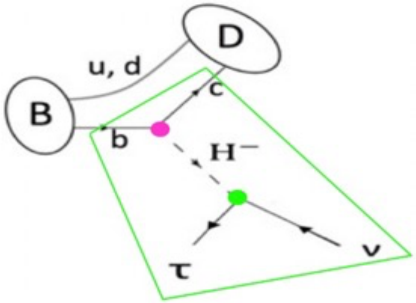


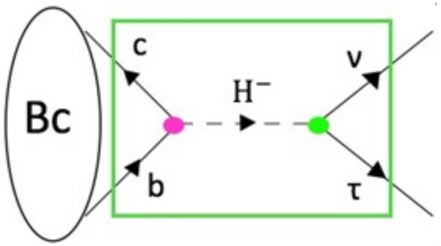


Better sensitivity for heavy $\tau\nu$ resonances: experimentally $\tau\nu$ resonance search for W' is more sensitive to a heavier resonance because of the low background from W→ $\tau\nu$.

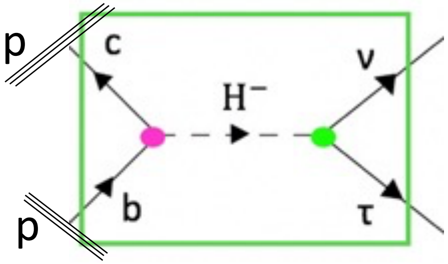
# $H^-$ interpretation of $R_D$ , $R_{D*}$ anomalies silently revived

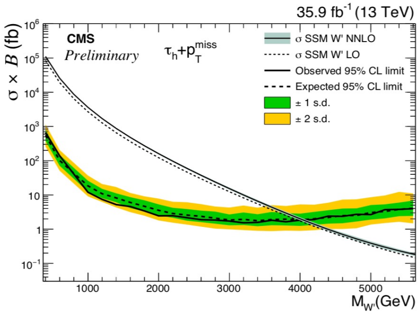
**Summary of the status and prospect are discussed** Syuhei Iguro, **2201.06565**



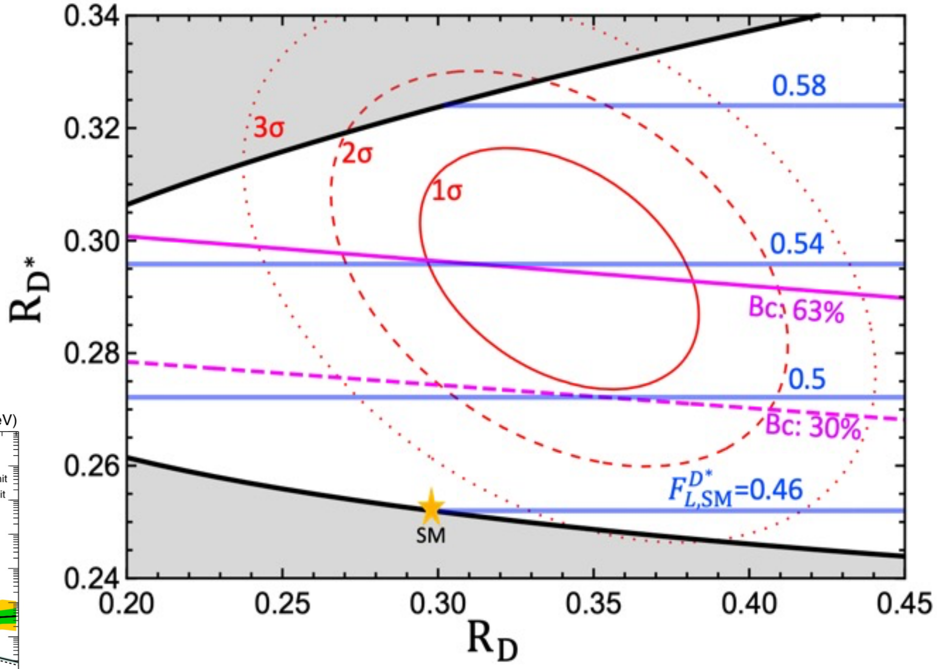


Due to the charm mass scheme dependence,
The bound is relaxed BR(Bc→τν)<63% Grinstein 2021





τν resonance search at LHC gives more stringent constraint for $m_{H-}$ > 400GeV Iguro 2018



$F_{L,SM}^{D^*}$=0.46, $F_{L,Belle}^{D^*}$=0.60 ± 0.09

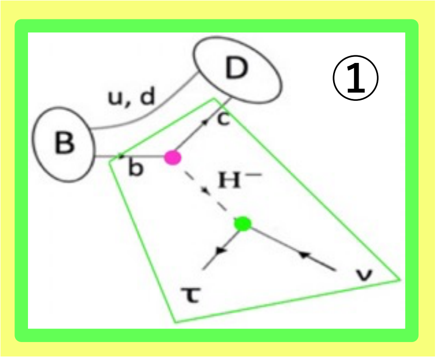
Only scalar can enhance $F_L^{D^*}$

τν resonance search result for $m_{H-}$ < 400GeV is not available at $\sqrt{s}$=13TeV probably because

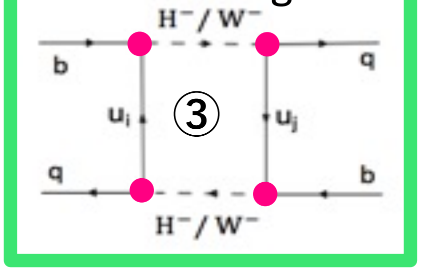
- they originally search for W' in SSM and wanted to push up the lower bound on $m_{W'}$
- SMBG (W-> τν tail ) is huge at low mT

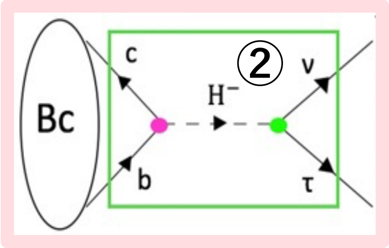
**How is the situation and prospect for $m_{H-}$ < 400GeV ?**

# Various bounds are very complementary
HL-LHC can probe large parameter space!

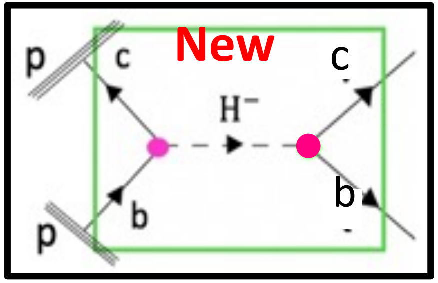


B mixings





Single production



3 categories of bounds

**1. right to left e.g. ③, ④, ⑤**

**2. above to bellow ⑦**

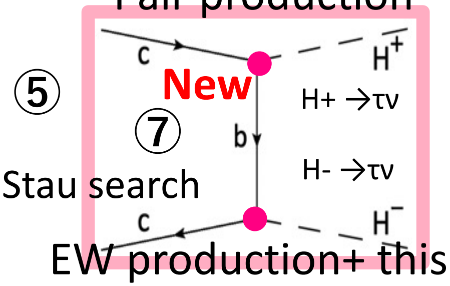
**3. constrain ↙ e.g. ②**

bb resonance search
$\sqrt{s}$=8TeV ④

bb + photon search
$\sqrt{s}$=13TeV ⑤

Flavor inclusive di-jet
$\sqrt{s}$=13TeV ⑥

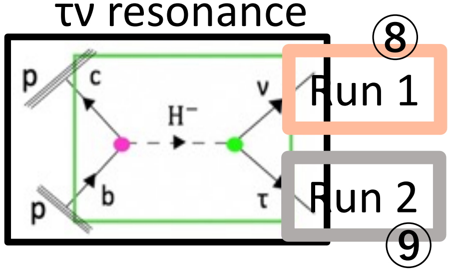
Pair production



Stau search

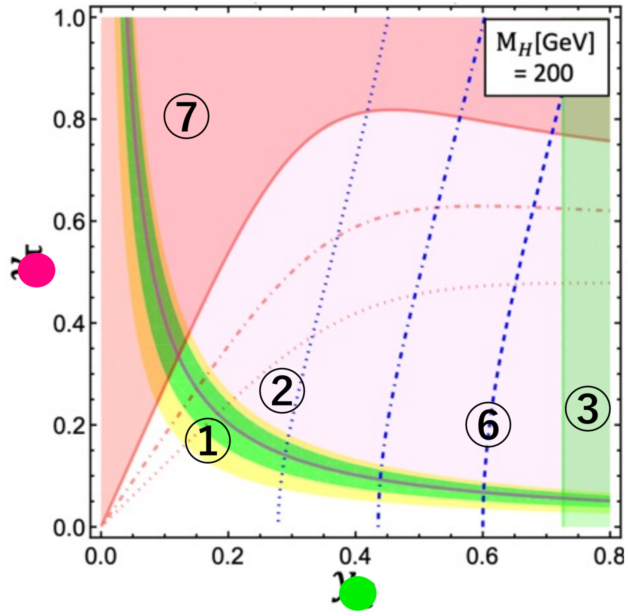
EW production+ this

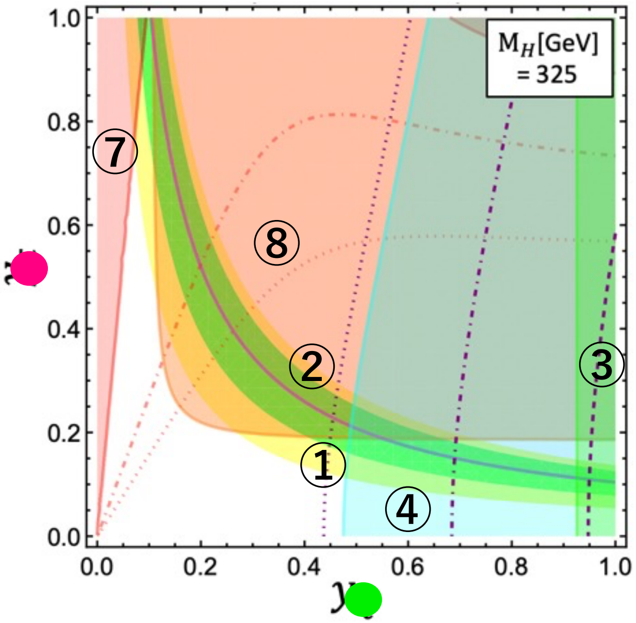
τν resonance

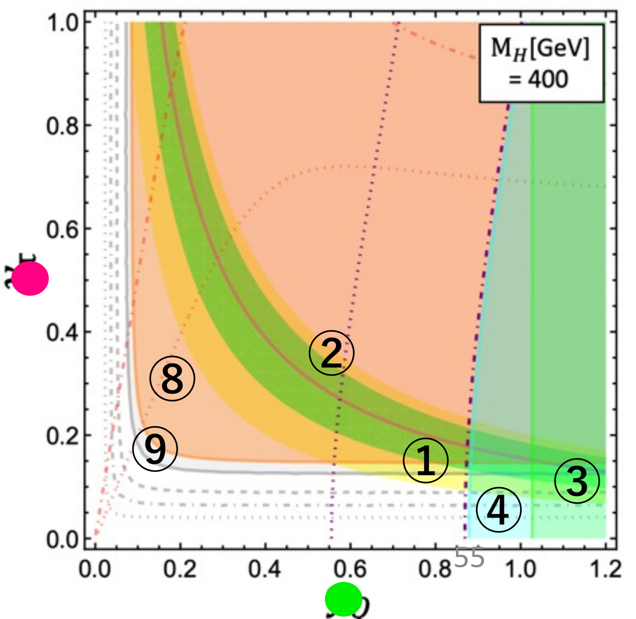


**Luminosity**

—— Current
— · · 500fb$^{-1}$
– – · 139fb$^{-1}$
········· 3ab$^{-1}$

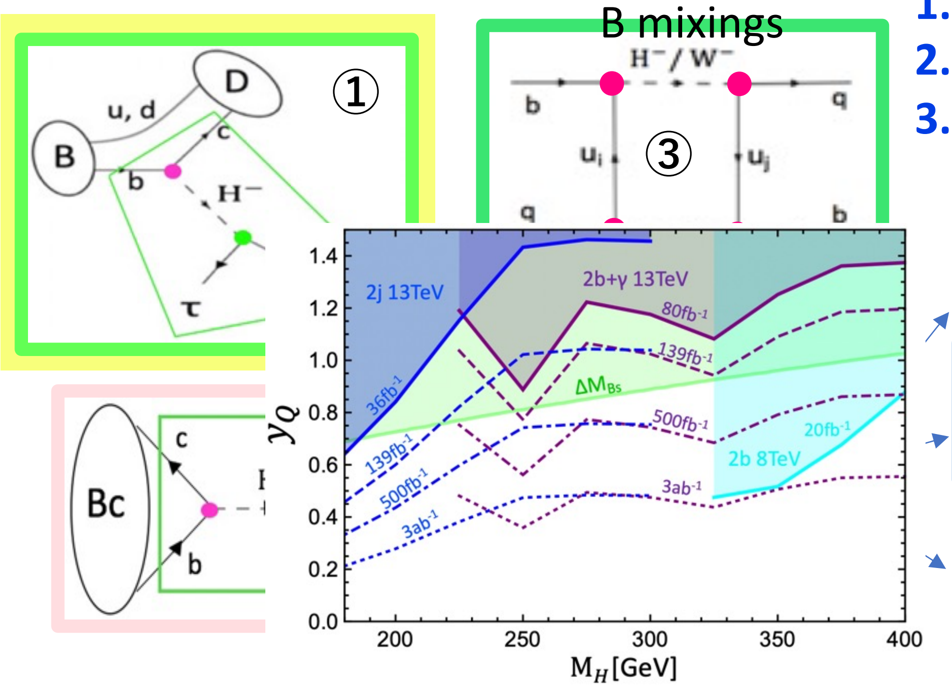






# Various bounds are very complementary

HL-LHC can probe large parameter space!

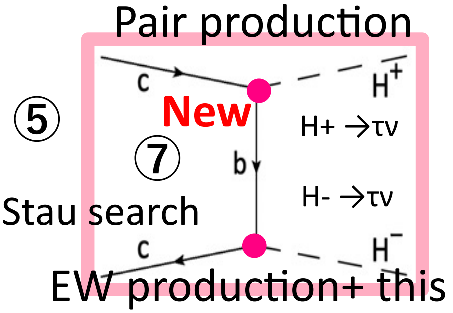


3 categories of bounds

**1. right to left e.g. ③, ④, ⑤**

**2. above to bellow ⑦**

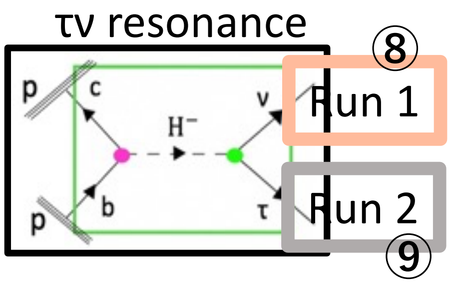
**3. constrain ↙ e.g. ②**



bb resonance search
$\sqrt{s}$=8TeV ④

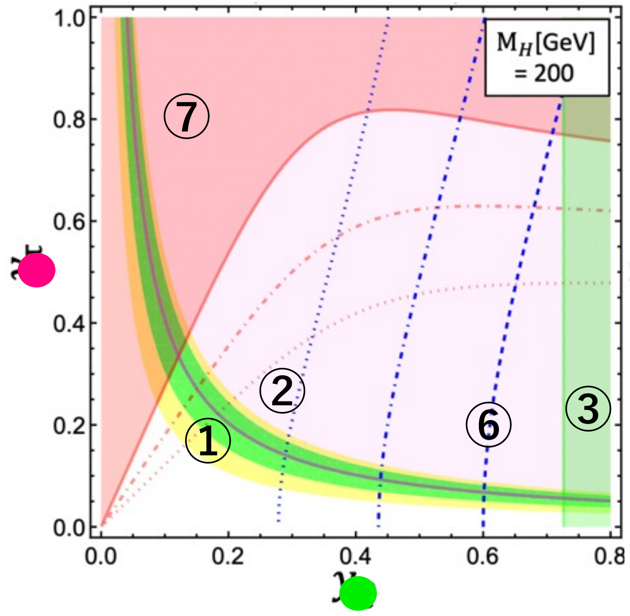
bb + photon search
$\sqrt{s}$=13TeV ⑤

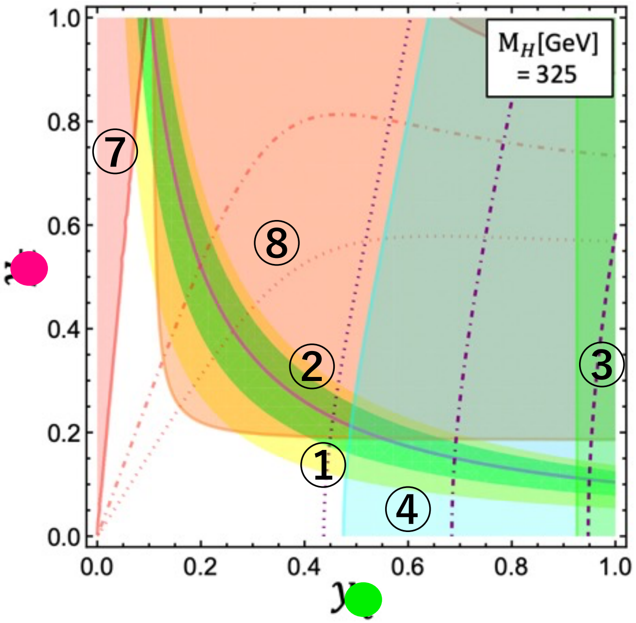
Flavor inclusive di-jet
$\sqrt{s}$=13TeV ⑥

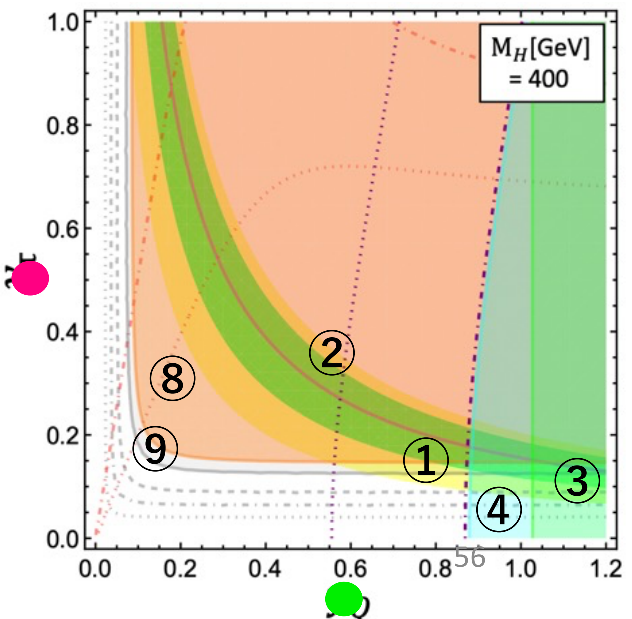


**Luminosity**

—— Current
— · - 500fb⁻¹
- - · 139fb⁻¹
········ 3ab⁻¹





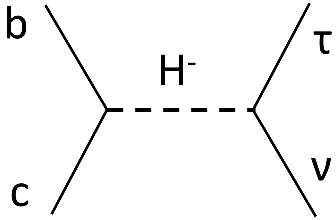


# Additional contents for LQ part

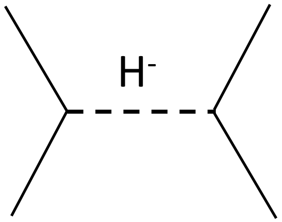
# Three NP categories for $R_{D^{(*)}}$ anomaly

$R_{D^{(*)}}$ LHC comment

- Charged Higgs



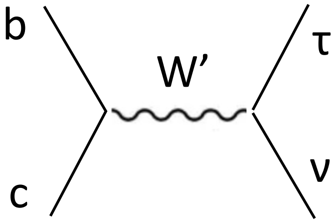
s-channel



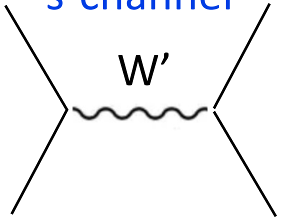
Next page!

τν resonance

- W' ( ,Z')

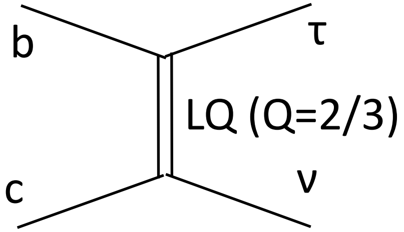


s-channel

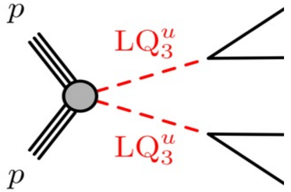


Excluded by ττ search (Z') and Bs meson mixing.

- Leptoquarks



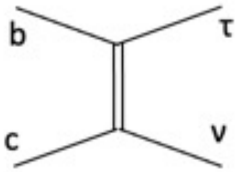
Various channels



Pair production

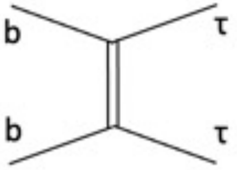
τb τb search

t-channel



Mono tau search

t-channel

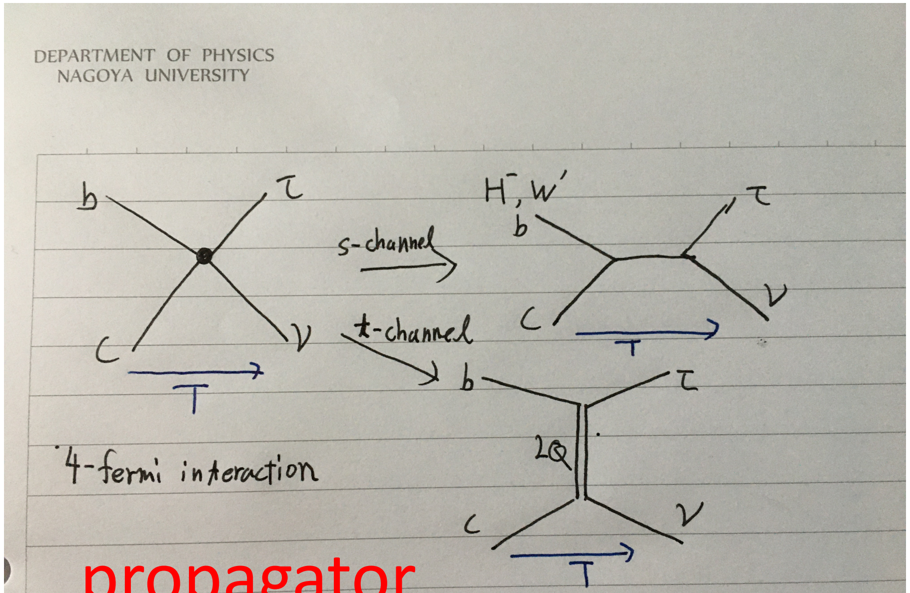


di-τ search

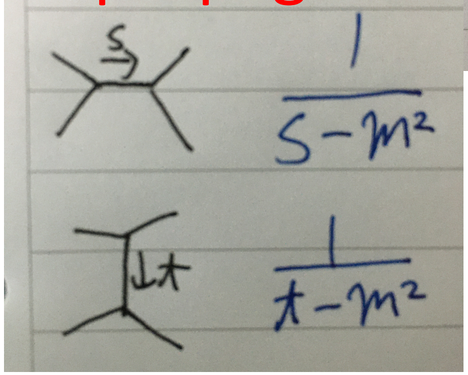
High pT

# Key feature of the NP signal at the LHC

The leading order process is pp-> bc-> τν

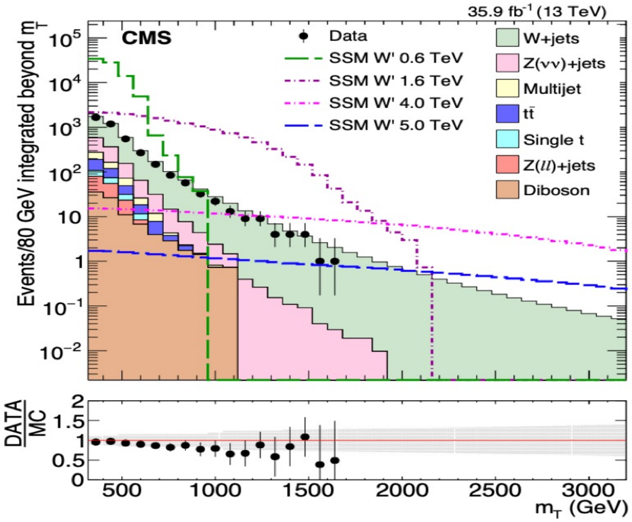


propagator



$$\frac{1}{s-m^2}$$

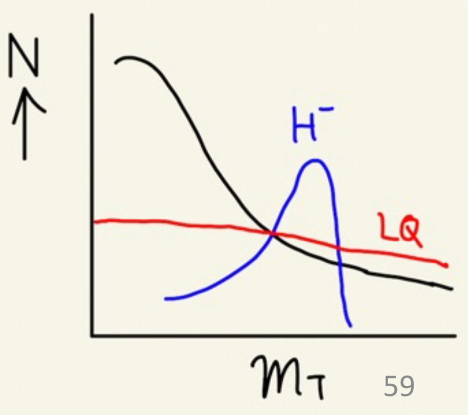
$$\frac{1}{t-m^2}$$



$$m_T = \sqrt{2p_T^{\ell} E_T^{\rm miss}(1-\cos\theta_{\ell\nu})}$$

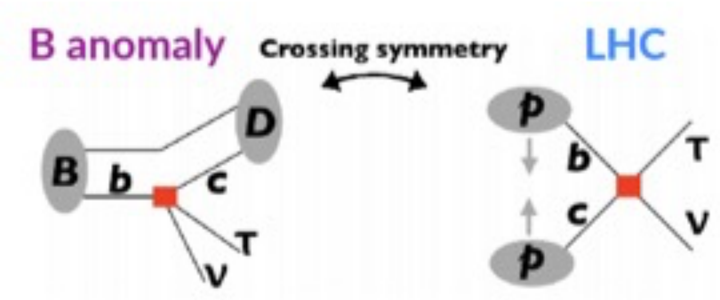
Main SM BG: pp -> qq->W->lν

signal shape on the mT plane
s-channel : cliff
t-channel : plateau (t<0)

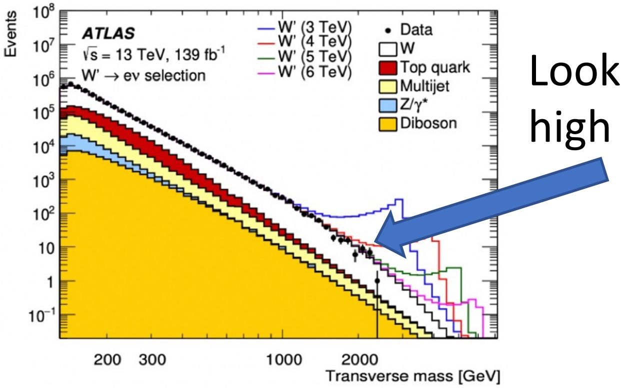


# Several works in the literature

## t-channel mediator: Leptoquark (LQ)



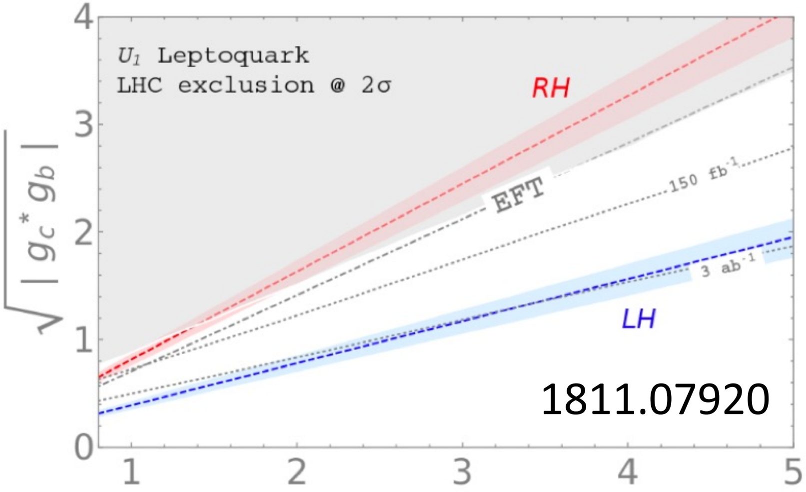
signal shape on the MT plane
t-channel : plateau



Look into the high pT region

$$m_T = \sqrt{2p_{\rm T}^{\ell} E_{\rm T}^{\rm miss}(1-\cos\theta_{\ell\nu})}$$

HL LHC can test LH scenario!



1811.07920

$$\mathcal{L}_{\rm eff}^{\rm LE} \supset -\frac{4G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^{\tau})(\bar{\tau}\gamma_\mu P_L \nu_\tau)(\bar{c}\gamma^\mu P_L b)$$ LH

# Authors of 1811.07920 also worked within EFT and set the limit on WCs

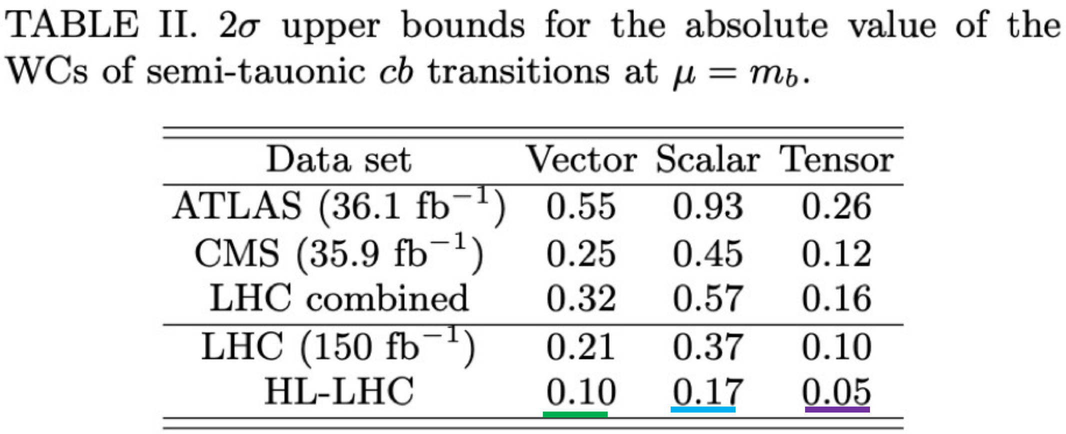
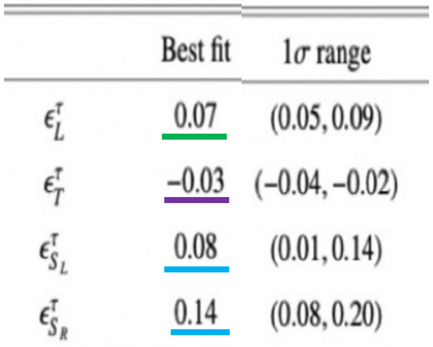


TABLE II. $2\sigma$ upper bounds for the absolute value of the WCs of semi-tauonic $cb$ transitions at $\mu = m_b$.

| Data set | Vector | Scalar | Tensor |
|---|---|---|---|
| ATLAS (36.1 $\mathrm{fb}^{-1}$) | 0.55 | 0.93 | 0.26 |
| CMS (35.9 $\mathrm{fb}^{-1}$) | 0.25 | 0.45 | 0.12 |
| LHC combined | 0.32 | 0.57 | 0.16 |
| LHC (150 $\mathrm{fb}^{-1}$) | 0.21 | 0.37 | 0.10 |
| HL-LHC | 0.10 | 0.17 | 0.05 |



| | Best fit | $1\sigma$ range |
|---|---|---|
| $\epsilon_L^\tau$ | 0.07 | (0.05, 0.09) |
| $\epsilon_T^\tau$ | −0.03 | (−0.04, −0.02) |
| $\epsilon_{S_L}^\tau$ | 0.08 | (0.01, 0.14) |
| $\epsilon_{S_R}^\tau$ | 0.14 | (0.08, 0.20) |

HL LHC is sensitive to the currently favored NP.

**According to them, we can apply the EFT limit for $m_{LQ}$ > 2-3 TeV.**

**However, this is not good approximation.**

The difference is crucial to judge the model

# Significant mass dependence

**Effective Lagrangian for b ->c τ ν**

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + C_{V1})O_{V1} + C_{V2}O_{V2} + C_{S1}O_{S1} + C_{S2}O_{S2} + C_T O_T\right]$$

At mb=4GeV

Operator basis 5 operators

$$O_{S1} = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau)$$
$$O_{S2} = (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau)$$

Scalar

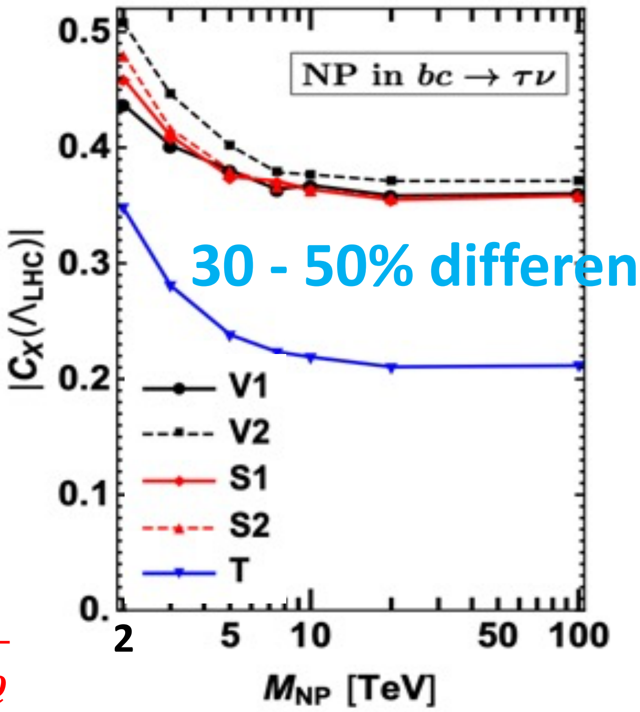
$$O_{V1} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$
$$O_{V2} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$

Vector

$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$

Tensor

Upper limit on WC



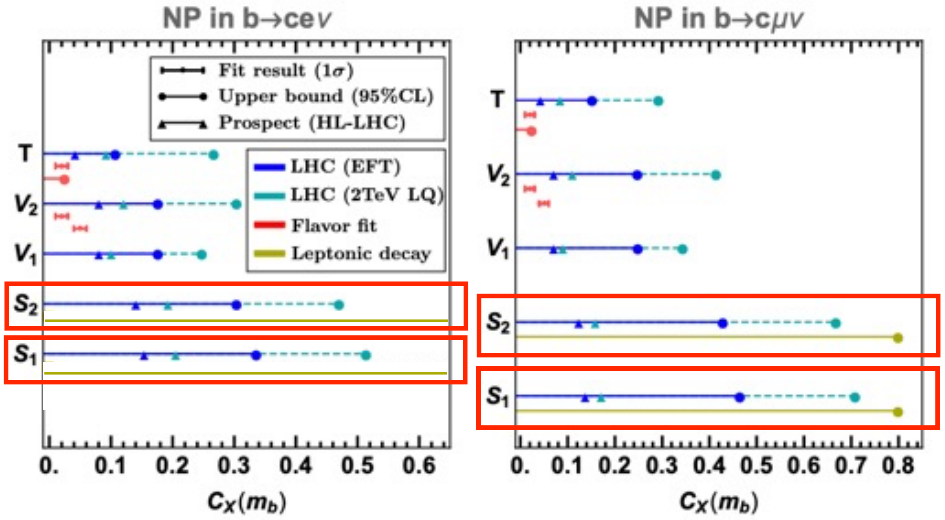
**30 - 50% difference**

$$\frac{1}{t - m_{LQ}^2}$$

***t*** **can not be neglected for the high pT mono tau region.**

# High pT collider physics is also sensitive to $b \to c\, l\, \nu$ and $b \to u\, l\, \nu$.

Iguro, et al. 2011.02486



$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{u_i b} \begin{bmatrix} (1 + C_{VL})O_{VL} + C_{VR}O_{VR} \\ +C_{SR}O_{SR} + C_{SL}O_{SL} + C_T O_T \end{bmatrix}$$

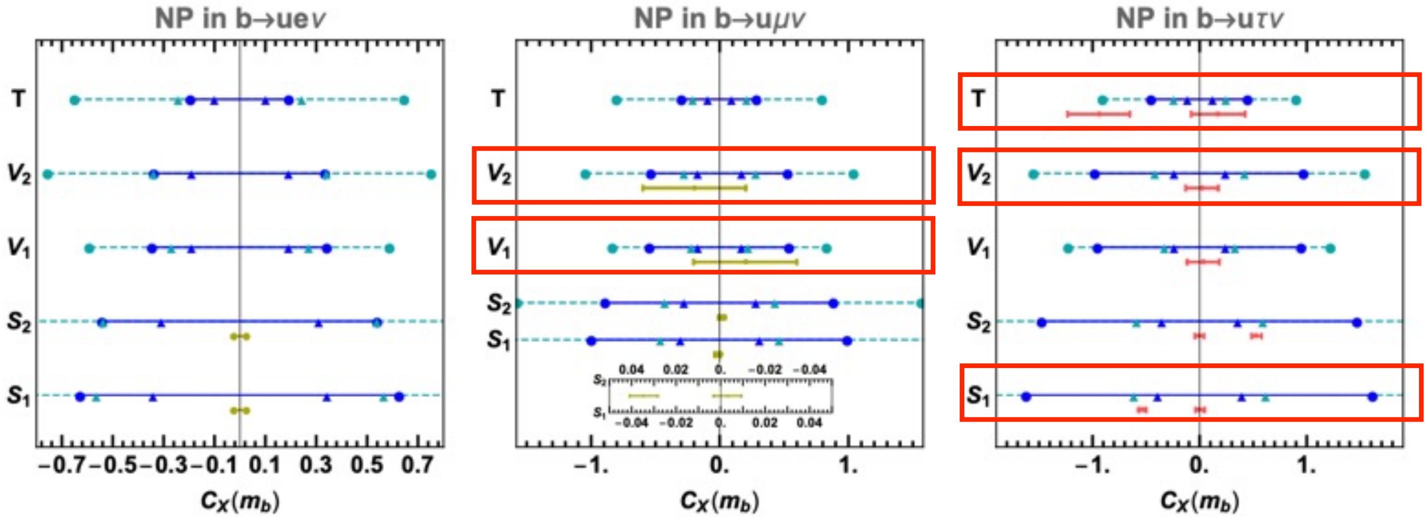
$$O_{SR(1)} = (\bar{u}_i P_R b)(\bar{l} P_L \nu_l)$$

$$O_{SL(2)} = (\bar{u}_i P_L b)(\bar{l} P_L \nu_l)$$

$$O_{VL(1)} = (\bar{u}_i \gamma^\mu P_L b)\big(\bar{l} \gamma^\mu P_L \nu_l\big)$$

$$O_{VR(2)} = (\bar{u}_i \gamma^\mu P_R b)(\bar{l} \gamma^\mu P_L \nu_l)$$

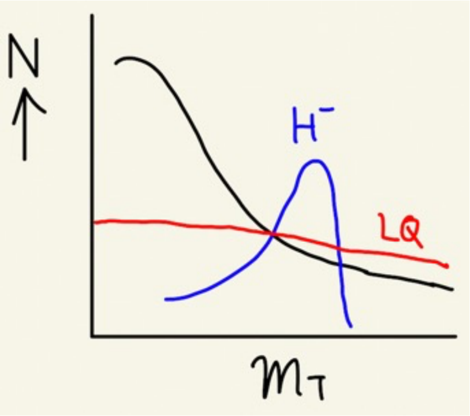
$$O_T = (\bar{u}_i \sigma^{\mu\nu} P_L b)(\bar{l} \sigma_{\mu\nu} P_L \nu_l)$$



**LHC is comparable with flavor sensitivity**

# Check list at the LHC

## $b\to c\tau\nu$ interaction



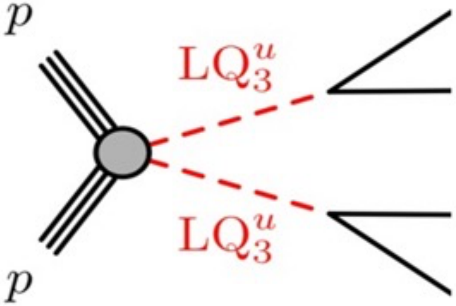
| Signal<br>channel | | $\tau\nu$ | $\tau\nu$ +b | **Mass dependence** | |
|---|---|---|---|---|---|
| | | | | $\tau\nu$ | $\tau\nu$ +b |
| $H^+$ | S | Iguro et al<br>1810.05843<br>Done | Iguro et al<br>2202.10468<br>Done | | |
| LQ | t | Greljo et al<br>1811.07920<br>Done | Minho et al<br>2008.07541<br>Done | Iguro et al<br>2011.02486<br>Done | Iguro et al<br>2111.04748<br>Done |

**Finally completed the table!**

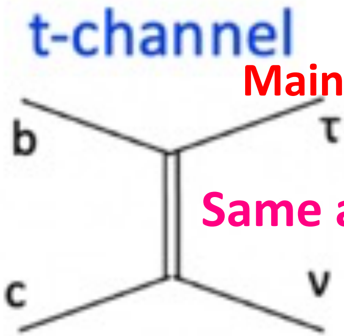
**+b category is always more sensitive**

# LHC implication in LQ cases

①



②

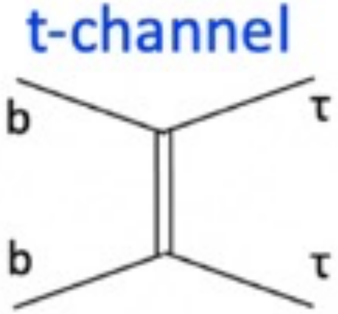


**Main focus**

**Same as $R_D$**

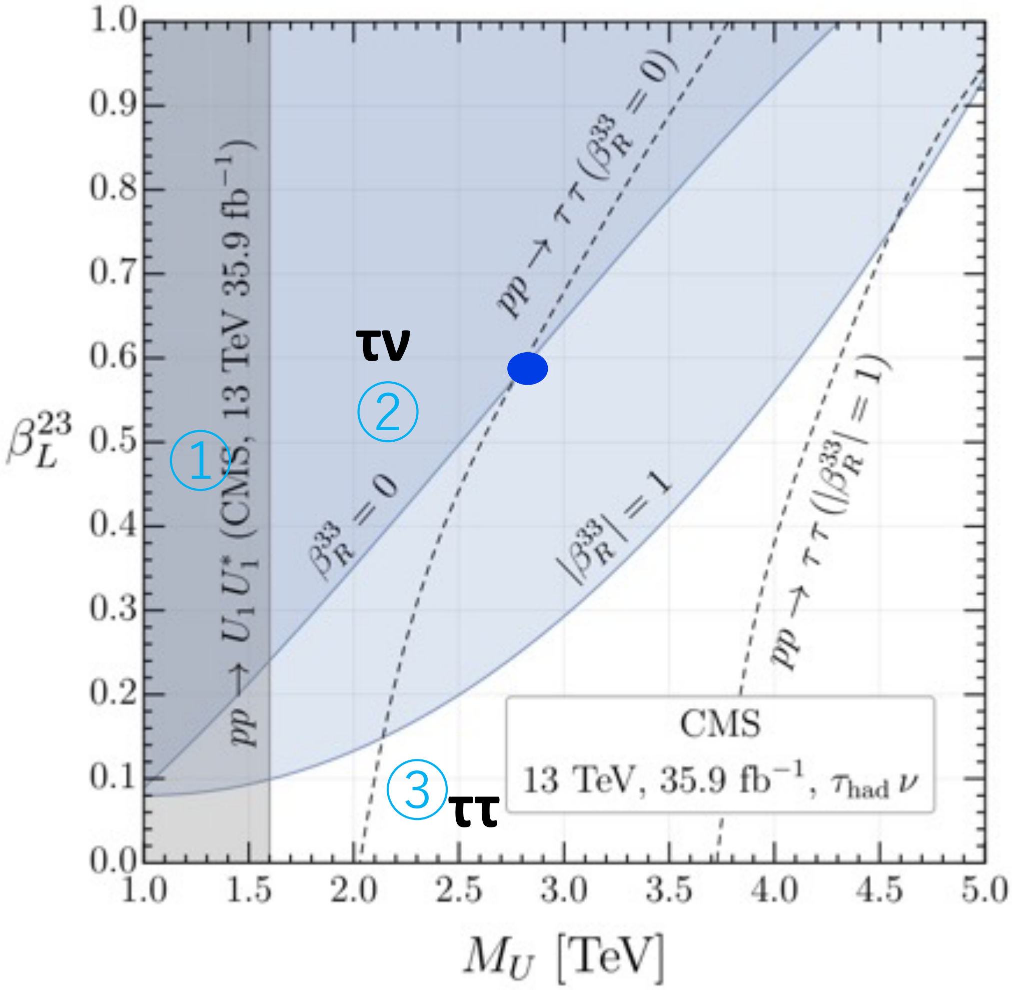
Model independent

③



Single production is also important

Gino et al [1901.10480](https://arxiv.org/abs/1901.10480)



**τν**

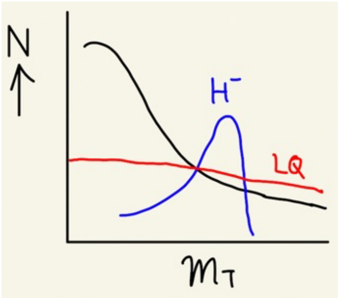
②

①

③ **ττ**

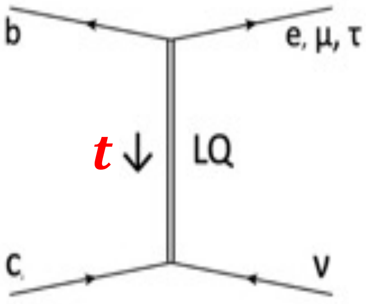
$\beta_R$: additional parameter

# LHC implication in LQ cases



## High $p_T$ τ events are sensitive to the scenarios

In some papers EFT limit is taken.

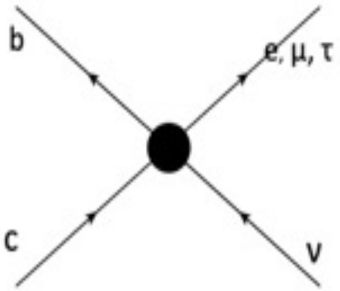


propagator

EFT limit

$$\frac{1}{t-m_{LQ}^2} \Rightarrow \frac{1}{m_{LQ}^2}$$

<



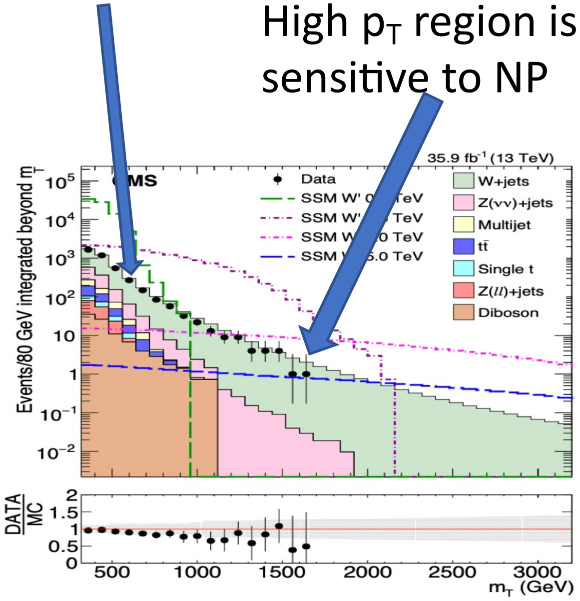
$$t = (p_b - p_c)^2 \sim -2p_b \cdot p_c < 0$$

Large $t$ is the source of the large transverse momentum.

We found up to 50% sensitivity mass dependence in terms of WC Iguro et al 2011.02486

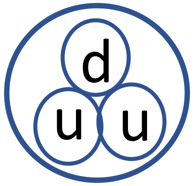
Huge BG from W

High $p_T$ region is sensitive to NP



## EFT limit is always aggressive for LQ models since t<0.

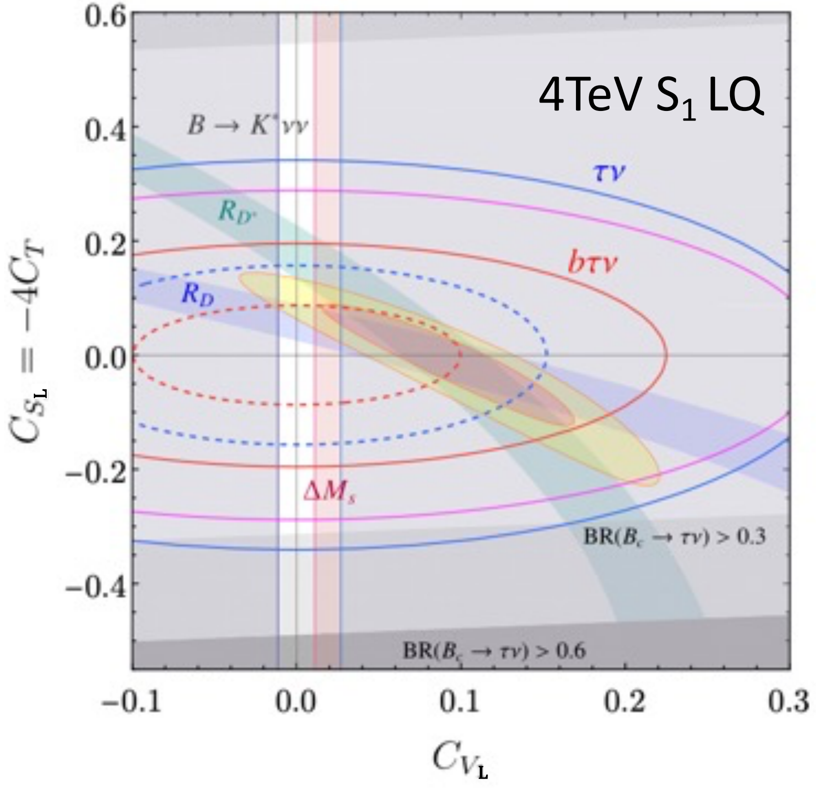
Main BG : pp→W→τν. N($W^+$) > N($W^-$) means collecting $\tau^-$ event improves the sensitivity



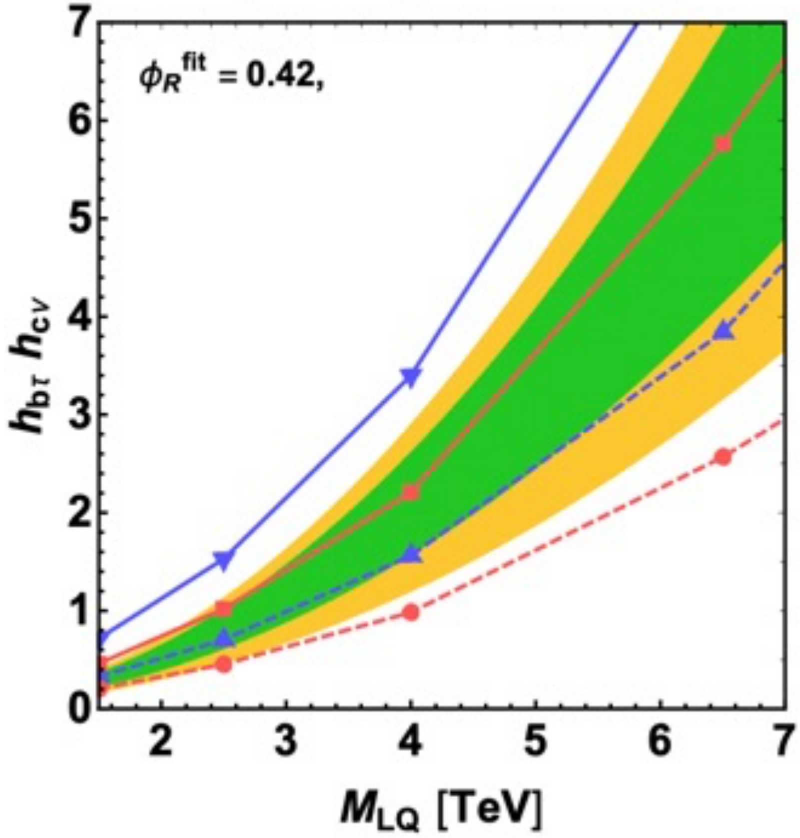
proton

# Other LQ scenarios

2111.04748



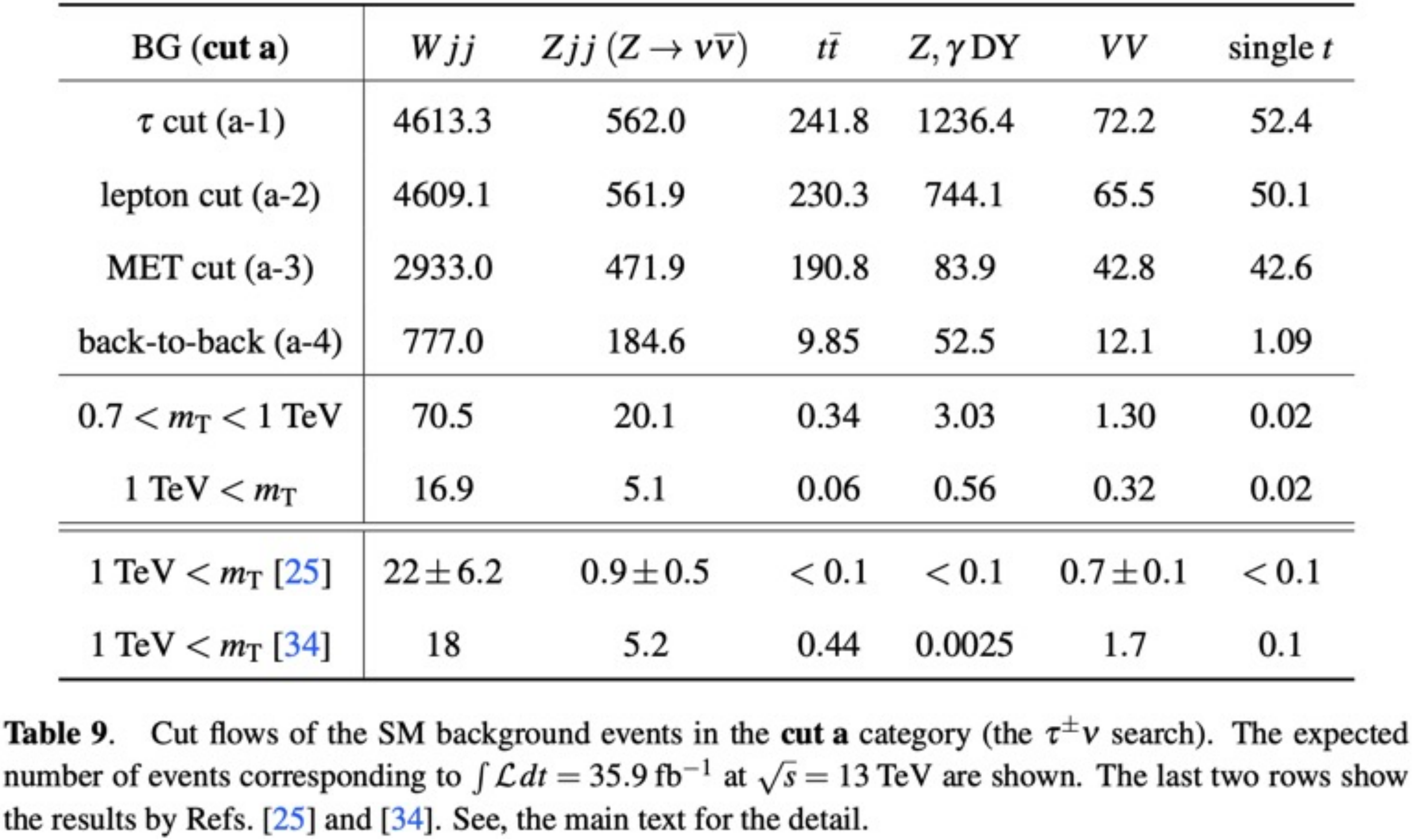
$U_1$ LQ: $C_{S_R} = -2\, e^{i\phi_R}\, C_{V_L}$



We can touch the interesting region with the LHC.

The angular correlation between b, τ, missing is also discussed

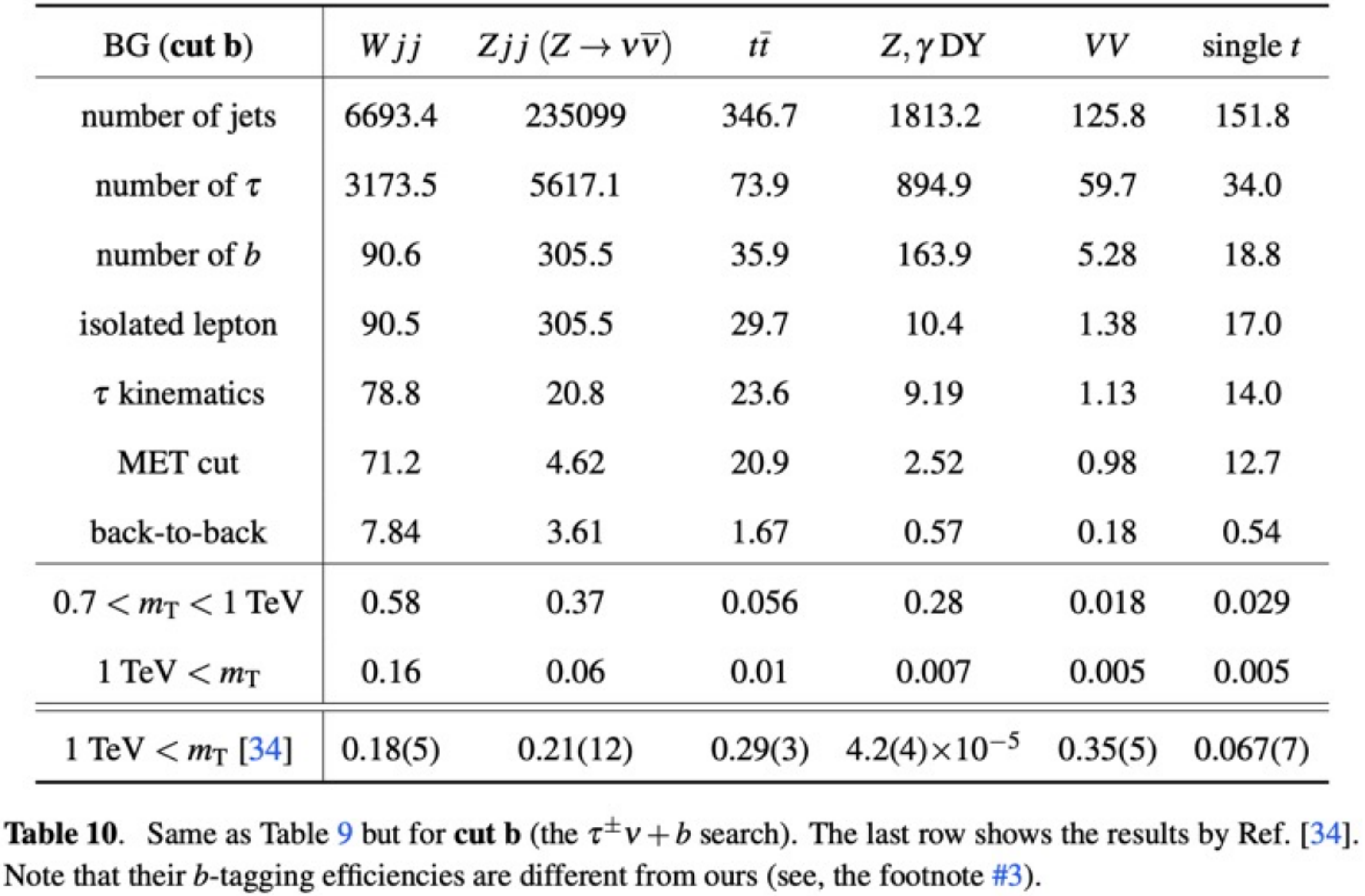
# BG cut flow



| BG (**cut a**) | $Wjj$ | $Zjj\,(Z \to \nu\bar{\nu})$ | $t\bar{t}$ | $Z,\gamma$ DY | $VV$ | single $t$ |
|---|---|---|---|---|---|---|
| $\tau$ cut (a-1) | 4613.3 | 562.0 | 241.8 | 1236.4 | 72.2 | 52.4 |
| lepton cut (a-2) | 4609.1 | 561.9 | 230.3 | 744.1 | 65.5 | 50.1 |
| MET cut (a-3) | 2933.0 | 471.9 | 190.8 | 83.9 | 42.8 | 42.6 |
| back-to-back (a-4) | 777.0 | 184.6 | 9.85 | 52.5 | 12.1 | 1.09 |
| $0.7 < m_T < 1$ TeV | 70.5 | 20.1 | 0.34 | 3.03 | 1.30 | 0.02 |
| 1 TeV $< m_T$ | 16.9 | 5.1 | 0.06 | 0.56 | 0.32 | 0.02 |
| 1 TeV $< m_T$ [25] | $22 \pm 6.2$ | $0.9 \pm 0.5$ | $< 0.1$ | $< 0.1$ | $0.7 \pm 0.1$ | $< 0.1$ |
| 1 TeV $< m_T$ [34] | 18 | 5.2 | 0.44 | 0.0025 | 1.7 | 0.1 |

**Table 9**. Cut flows of the SM background events in the **cut a** category (the $\tau^{\pm}\nu$ search). The expected number of events corresponding to $\int \mathcal{L} dt = 35.9\,\text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV are shown. The last two rows show the results by Refs. [25] and [34]. See, the main text for the detail.

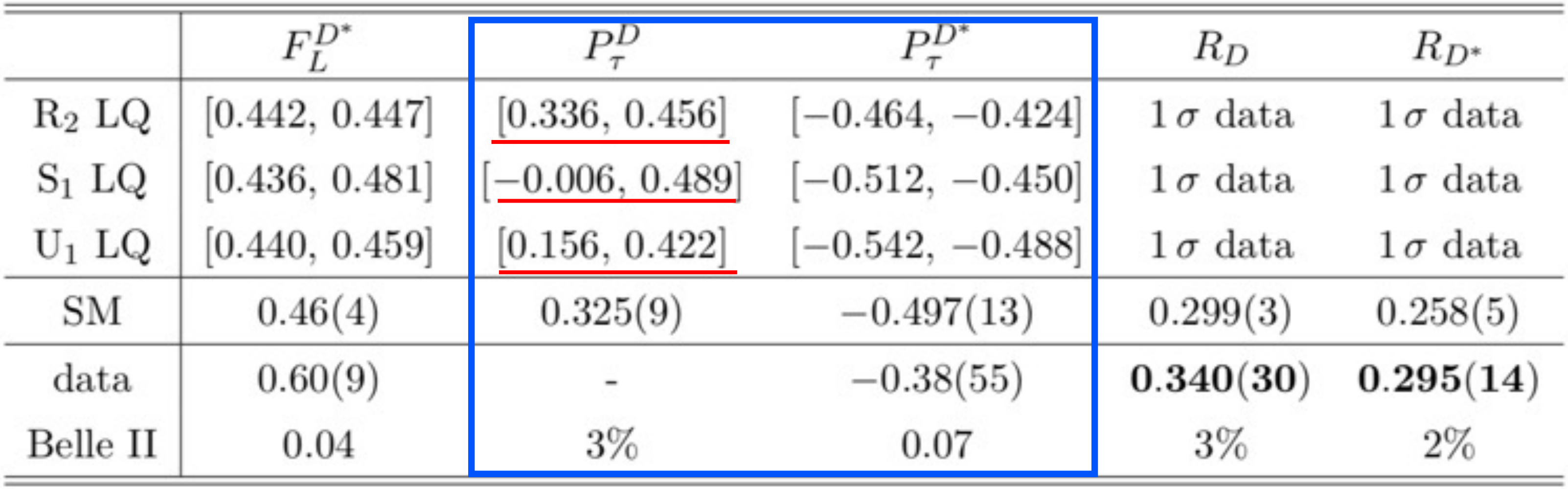
# BG cut flow



| BG (**cut b**) | $Wjj$ | $Zjj\,(Z \to \nu\bar{\nu})$ | $t\bar{t}$ | $Z,\gamma$ DY | $VV$ | single $t$ |
|---|---|---|---|---|---|---|
| number of jets | 6693.4 | 235099 | 346.7 | 1813.2 | 125.8 | 151.8 |
| number of $\tau$ | 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 |
| $\tau$ 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) |

**Table 10**. Same as Table 9 but for **cut b** (the $\tau^{\pm}\nu + b$ search). The last row shows the results by Ref. [34]. Note that their $b$-tagging efficiencies are different from ours (see, the footnote #3).

# Key observable for Belle II



| | $F_L^{D^*}$ | $P_\tau^D$ | $P_\tau^{D^*}$ | $R_D$ | $R_{D^*}$ |
|---|---|---|---|---|---|
| $R_2$ LQ | [0.442, 0.447] | [0.336, 0.456] | [−0.464, −0.424] | 1 $\sigma$ data | 1 $\sigma$ data |
| $S_1$ LQ | [0.436, 0.481] | [−0.006, 0.489] | [−0.512, −0.450] | 1 $\sigma$ data | 1 $\sigma$ data |
| $U_1$ LQ | [0.440, 0.459] | [0.156, 0.422] | [−0.542, −0.488] | 1 $\sigma$ data | 1 $\sigma$ 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)** |
| Belle II | 0.04 | 3% | 0.07 | 3% | 2% |

After Moriond2019

$\lambda_\tau$: Spin of τ

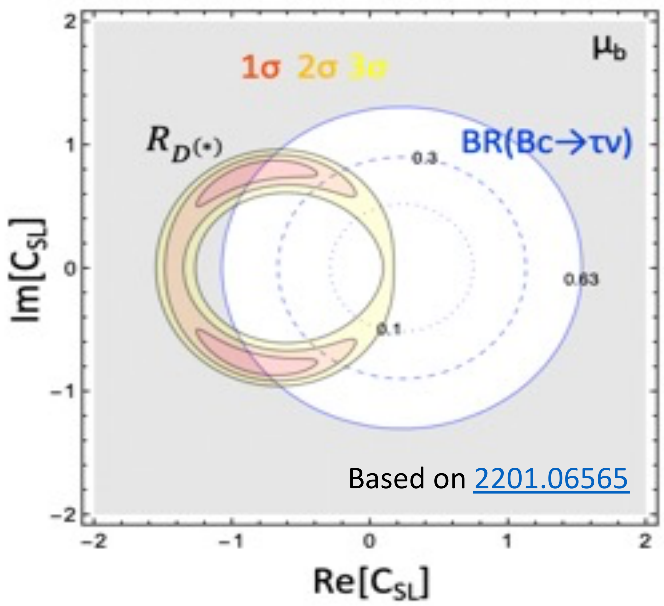
$$P_\tau^D = \frac{\Gamma\left(\lambda_\tau = \frac{1}{2}\right) - \Gamma\left(\lambda_\tau = -\frac{1}{2}\right)}{\Gamma\left(\lambda_\tau = \frac{1}{2}\right) + \Gamma\left(\lambda_\tau = -\frac{1}{2}\right)}$$

$P_\tau^D$ **is a good quantity to distinguish LQ models.**

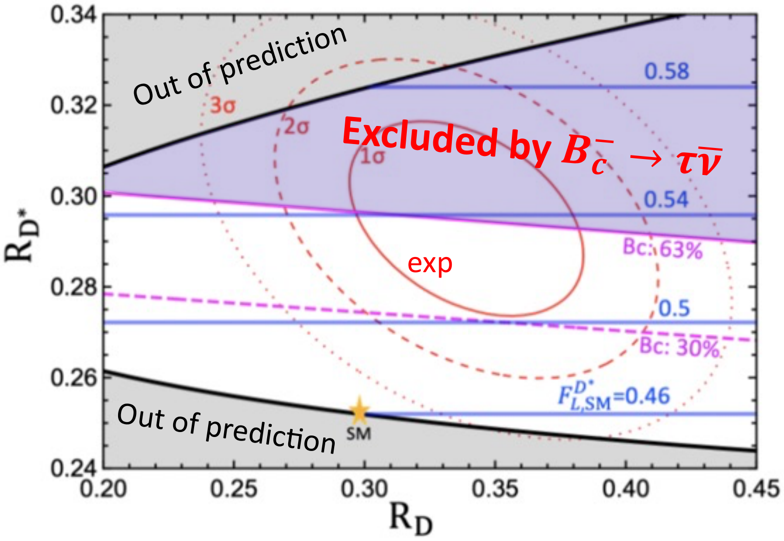
Statistical error is dominant in polarization observables.

Let's wait Belle II for the new data!

# Scalar operator revived



Based on 2201.06565



Thanks to the relaxed upper bound from $B_c^- \to \tau\bar{\nu}$ scalar scenario is still viable!

Only scalar can enhance $F_L^{D^*}$

$$F_{L\,exp}^{D^*} = 0.60 \pm 0.09, \quad F_{L\,SM}^{D^*} = 0.46 \pm 0.01$$

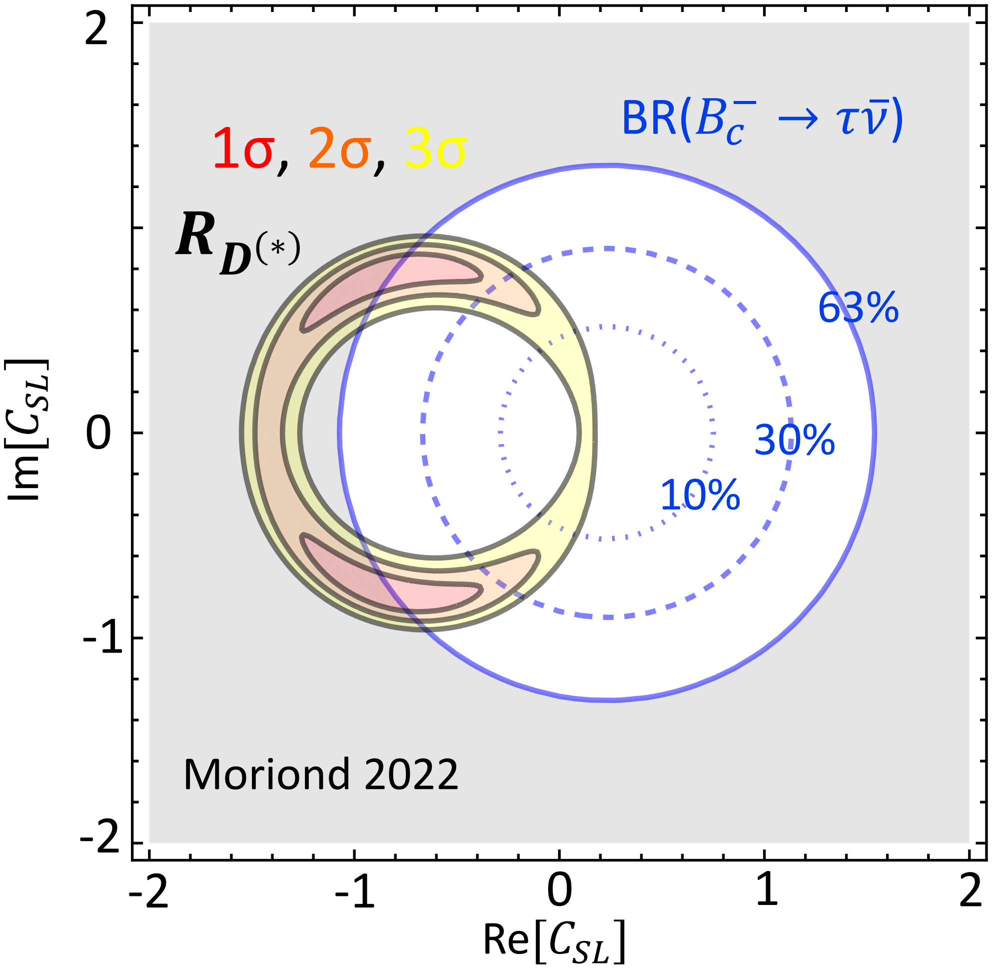
We need complex WC

=> Complex Yukawa in type III (General) 2HDM

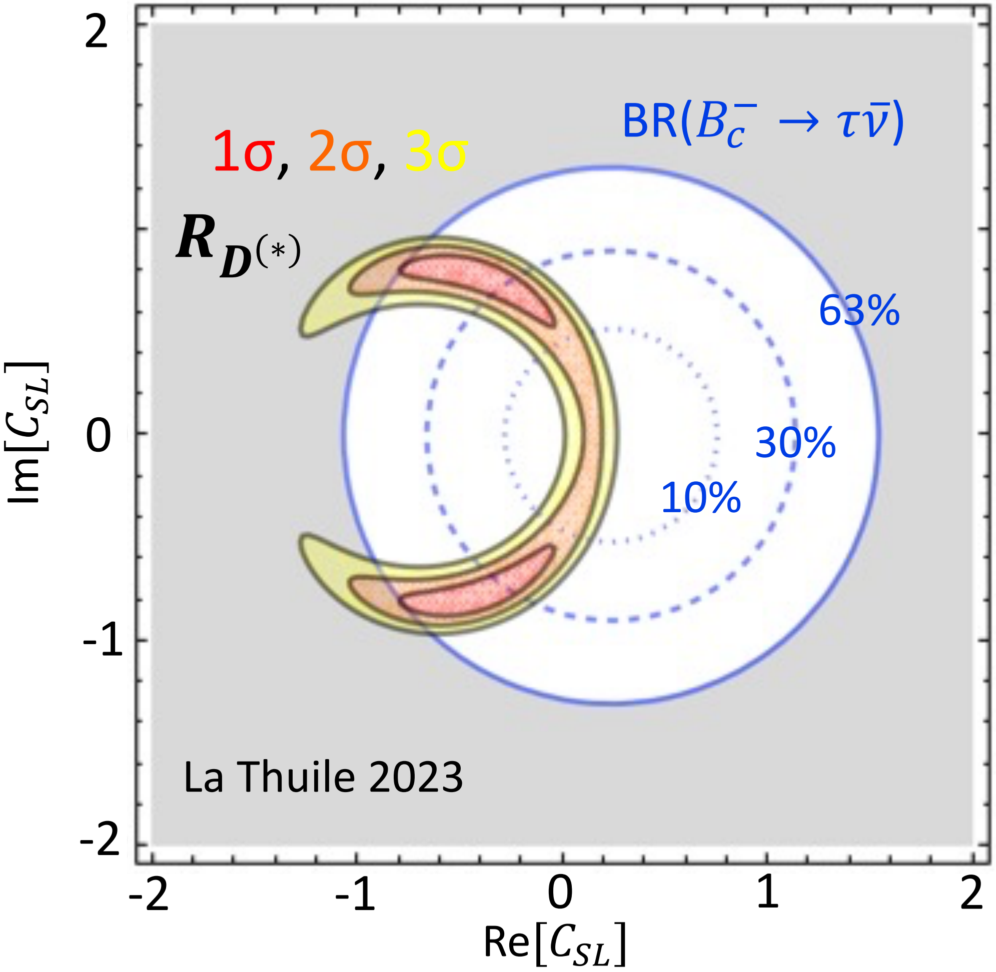
Scenario 1 in Iguro-Tobe 1708.06176

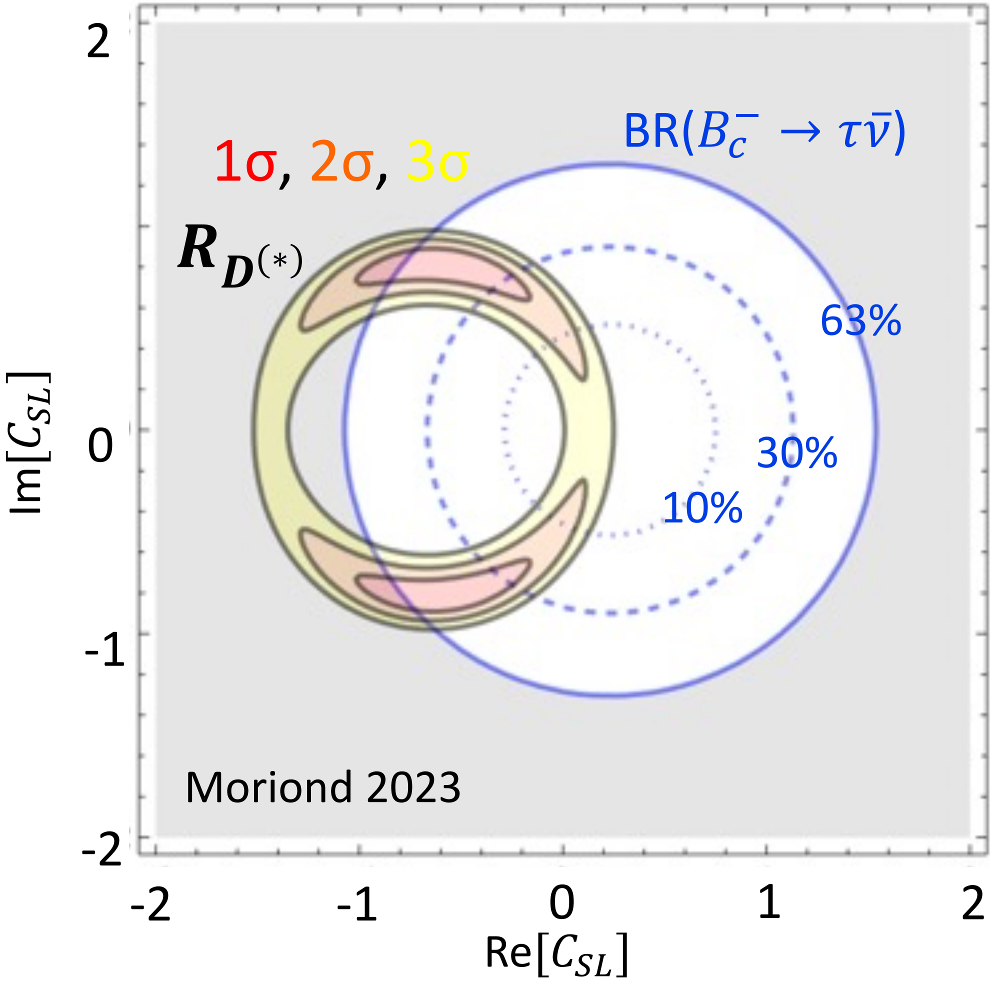
Only top-charm flavor violating Yukawa coupling can provide sizable $C_{SL}$ without violating LHC, flavor, EDM constraints see also Nierste et al 2019, George-Hou 2018

**bb →ττ is less relevant to this model**



2
0
-1
-2
-2
-1
0
1
2
$\mathrm{Re}[C_{SL}]$
$\mathrm{Im}[C_{SL}]$
1σ, 2σ, 3σ
$\boldsymbol{R_{D^{(*)}}}$
$\mathrm{BR}(B_c^- \to \tau\bar{\nu})$
63%
30%
10%
Moriond 2022


1σ, 2σ, 3σ
$R_{D^{(*)}}$
BR($B_c^- \to \tau\bar{\nu}$)
63%
30%
10%
La Thuile 2023
2
0
-1
-2
-2
-1
0
1
2
Im[$C_{SL}$]
Re[$C_{SL}$]



I can not update all of the previous result