Test of the $\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ anomaly in the LHC experiment

Syuhei Iguro (Nagoya-U)

NAGOYA UNIVERSITY

Based on

w/ Y. Omura(KMI), M. Takeuchi(IPMU)

1810.05843

What I do today

I interplay $\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ anomaly and $\tau\nu$ resonance search in LHC within a General Two Higgs Doublet Model (G2HDM)

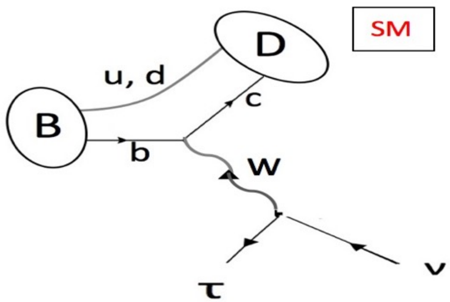
Menu

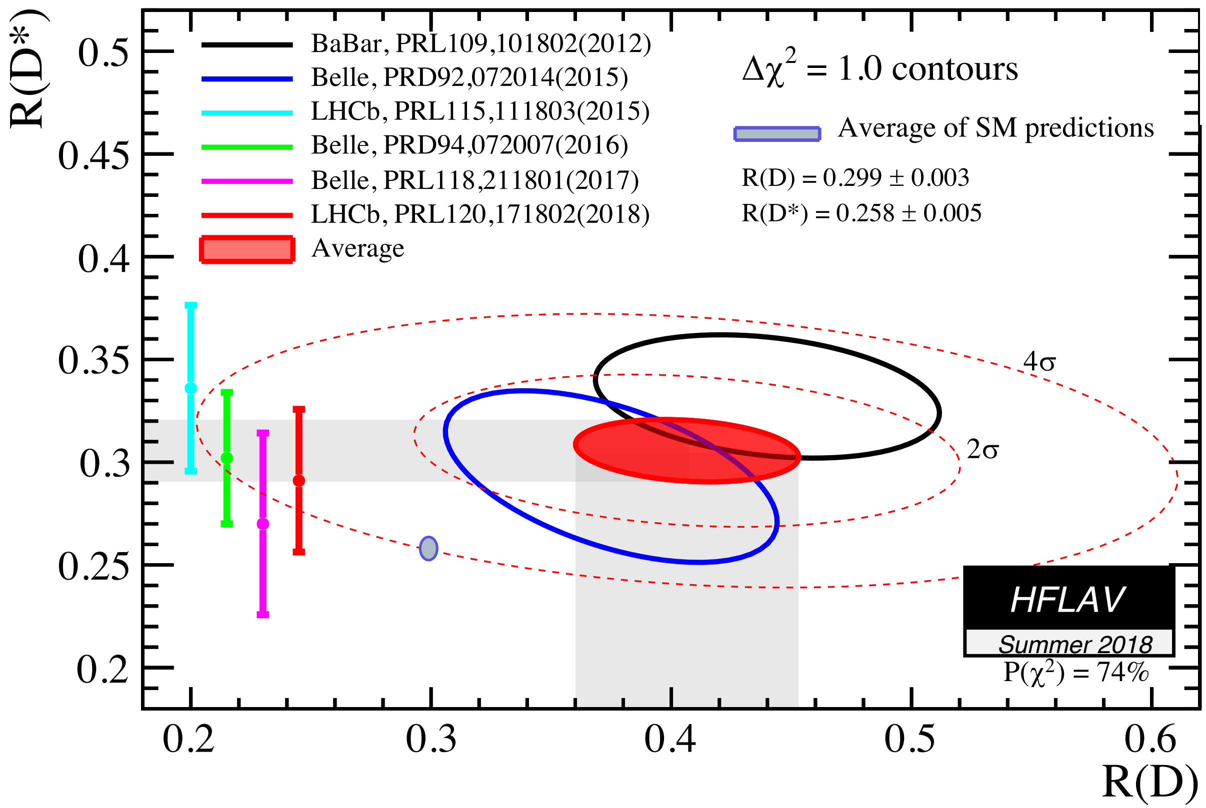
- $\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ anomaly
- Introduction of G2HDM
- Collider search
- Summary

Current status of $\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ anomaly

3.8σ discrepancy

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





ICHEP 2018

No new result but minor change from last year

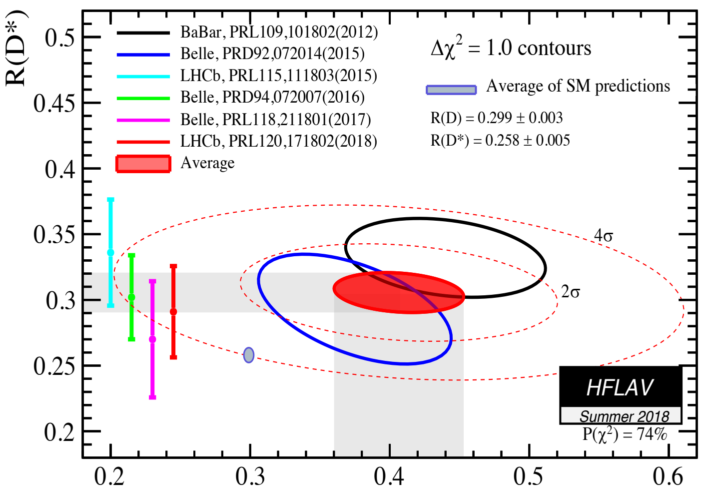
$\mathrm{R}(\mathrm{D}^*)_{SM} = 0.252$

↓

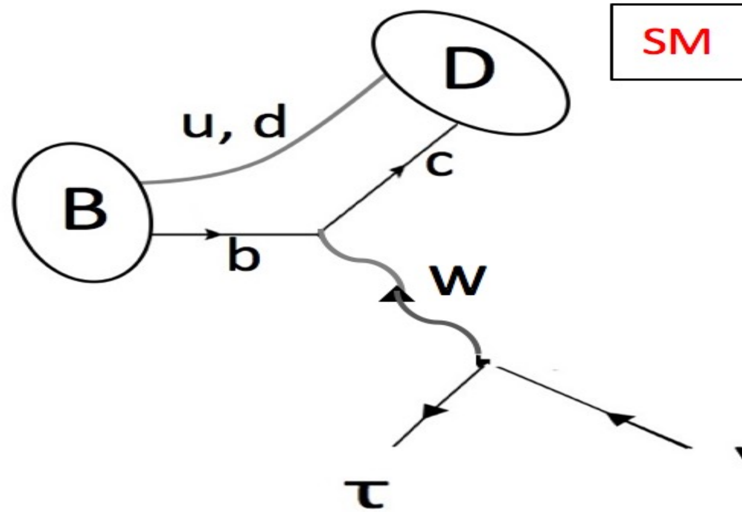
$\mathrm{R}(\mathrm{D}^*)_{SM} = 0.258$

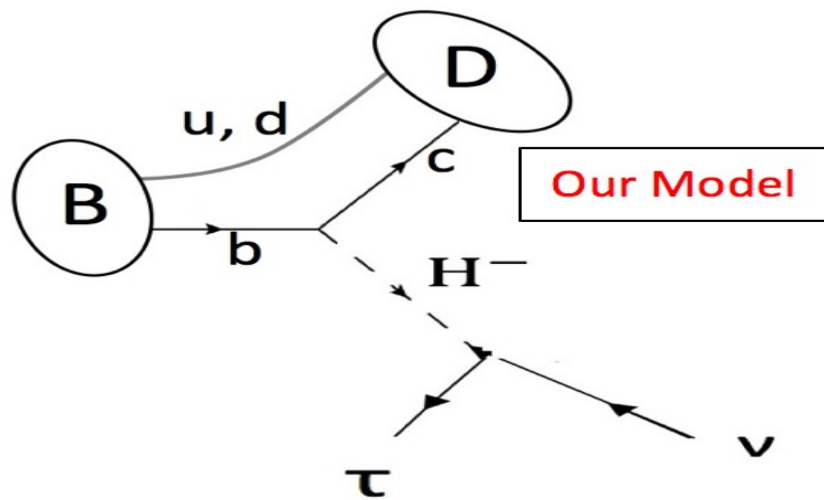
Naively, H^{-} is a good candidate.

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)} \tau \nu)}{BR(B \to D^{(*)} l \nu)}$$



SM





Phys. Rev. D 82, 034027 (2010) M.Tanaka, et.al
Phys.Rev. D86 (2012) 054014 A. Crivellin, et al.
Nucl.Phys. B925 (2017) 560-606 SI, K. Tobe

Motivation

Why I work on Higgs physics?

Guiding principles

- Simplicity of the model.
- Electroweak precision test
- Extending Higgs sector keeps the gauge anomaly-free condition

General Two Higgs Doublet Model (G2HDM)

- SM Higgs exist!
- Simple extension of scalar sector
- STU parameter is controllable
- Flavor violating Yukawa could exist

Rich flavor phenomenology

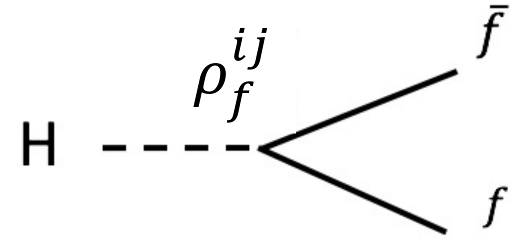
Our Model

New particles in G2HDM

- H CP even scalar
- A CP odd scalar
- H^- Charged scalar

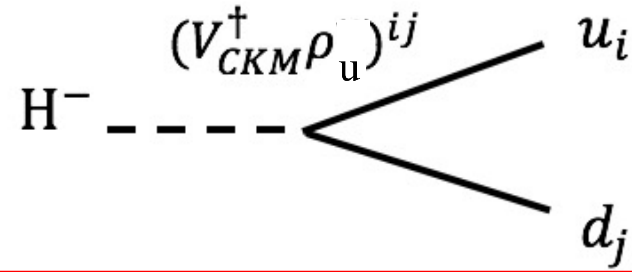
Neutral Scalar

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



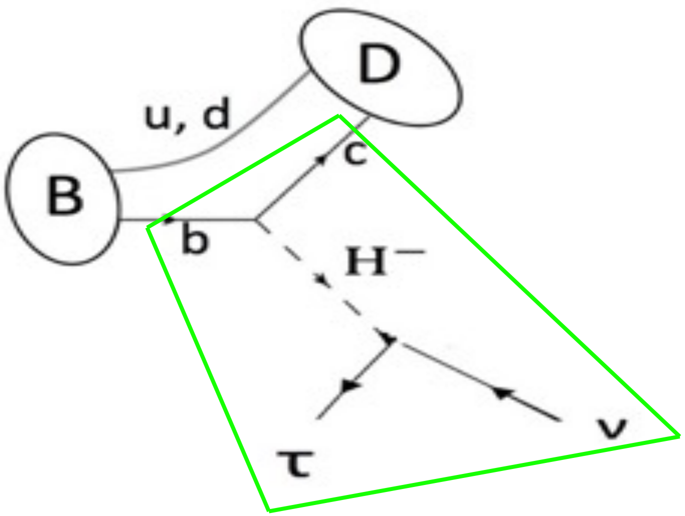
Charged Scalar

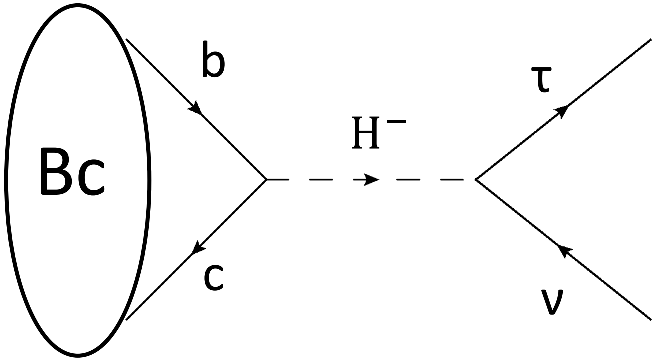
$$(\mathrm{V_{CKM}}\rho_d)^{ij}\mathrm{H}^-\overline{u_L^i}d_R^j + (V_{CKM}^\dagger\rho_u)^{ij}\mathrm{H}^-\overline{d_L^i}u_R^j$$



Stringent bound from BR($B_c^- \to \tau\bar{\nu}$)

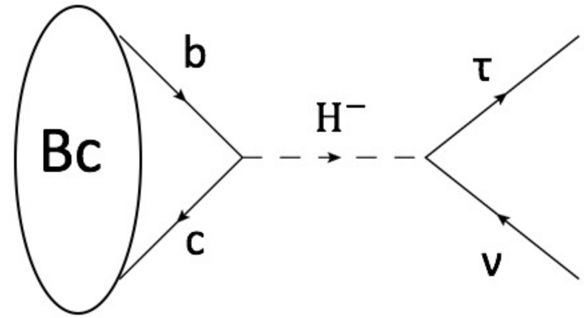
Diagram for $\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ automatically contributes to ($B_c^- \to \tau\bar{\nu}$)





$$L_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb}[(\bar{\tau}\gamma_\mu P_L \nu)(\bar{c}\gamma^\mu P_L b) + C_L^{\prime S}(\bar{\tau}P_L\nu)(\bar{c}P_L b) + C_R^{\prime S}(\bar{\tau}P_L\nu)(\bar{c}P_R b)] + \text{h.c.}$$

Stringent bound from $\mathrm{BR}(B_c^- \to \tau\bar{\nu})$



$$L_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb}[(\bar{\tau}\gamma_\mu P_L \nu)(\bar{c}\gamma^\mu P_L b) + C_L'^S(\bar{\tau}P_L\nu)(\bar{c}P_L b) + C_R'^S(\bar{\tau}P_L\nu)(\bar{c}P_R b)] + \text{h.c.}$$

$\mathrm{BR}(\mathrm{B_c^-} \to \tau\bar{\nu})_{\mathrm{SM}} = 2\%$

Scalar operators have a large coefficient

≈ 4

$\mathrm{BR}(\mathrm{B_c^-} \to \tau\bar{\nu})=$

$$\mathrm{BR}(\mathrm{B_c^-} \to \tau\bar{\nu})_{\mathrm{SM}} \times \left| 1 + \frac{\mathrm{m_{Bc}^2}}{\mathrm{m_\tau(m_b + m_c)}} (C_L'^S - C_R'^S) \right|^2$$

Conservative bound $< 30\%$ R.Alonso et al. 1611.06676

$< 10\%$ A.G.Akeroyd.et al. 1708.04072

$R\left(D^{(*)}\right)$ in G2HDM

$$L_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb}[(\bar{\tau}\gamma_\mu P_L \nu)(\bar{c}\gamma^\mu P_L b) + C_L^{\prime S}(\bar{\tau} P_L \nu)(\bar{c} P_L b) + C_R^{\prime S}(\bar{\tau} P_L \nu)(\bar{c} P_R b)] + \text{h.c.}$$

Phys.Rev. D86 (2012) 054014 A. Crivellin, et al.

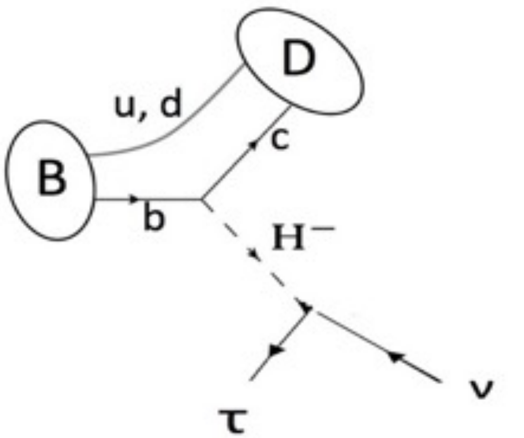
$$R(D) \simeq R(D)_{SM}\left\{1 + 1.5\mathrm{Re}\left[C_L^{\prime S} + C_R^{\prime S}\right] + |C_L^{\prime S} + C_R^{\prime S}|^2\right\},$$

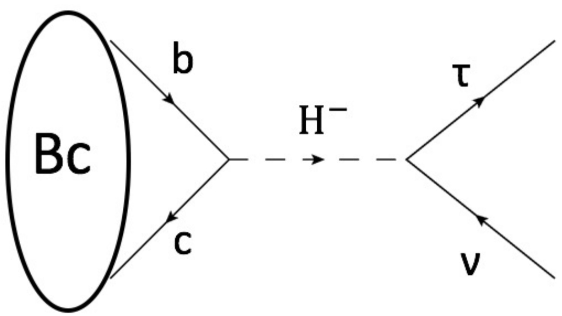
$$R(D^*) \simeq R(D^*)_{SM}\left\{1 + \underline{0.12}\mathrm{Re}\left[C_L^{\prime S} - C_R^{\prime S}\right] + \underline{0.05}|C_L^{\prime S} - C_R^{\prime S}|^2\right\}$$

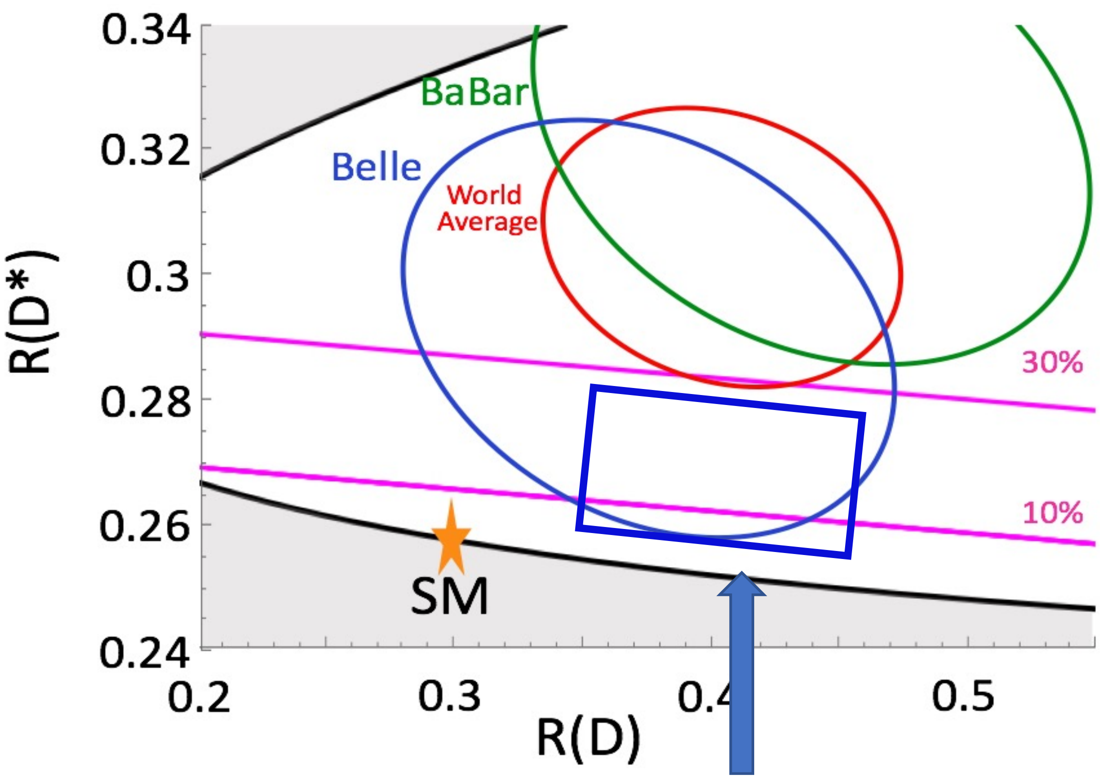
Large coupling is necessary to enhance R(D*)in our model.

$\mathrm{R}(\mathrm{D}^{(*)})$ anomaly in G2HDM

Diagram for $\mathrm{R}(\mathrm{D}^{(*)})$ automatically contributes to $\mathrm{Br}(B_c^- \to \tau\bar{\nu})$







Still explain only R(D).

Why collider study?

$$L_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb}[(\bar{\tau}\gamma_\mu P_L \nu)(\bar{c}\gamma^\mu P_L b) + C_L^{\prime S}(\bar{\tau}P_L\nu)(\bar{c}P_L b) + C_R^{\prime S}(\bar{\tau}P_L\nu)(\bar{c}P_R b)] + \text{h.c.}$$

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Large coupling is necessary to enhance R(D*)in our model.

↓

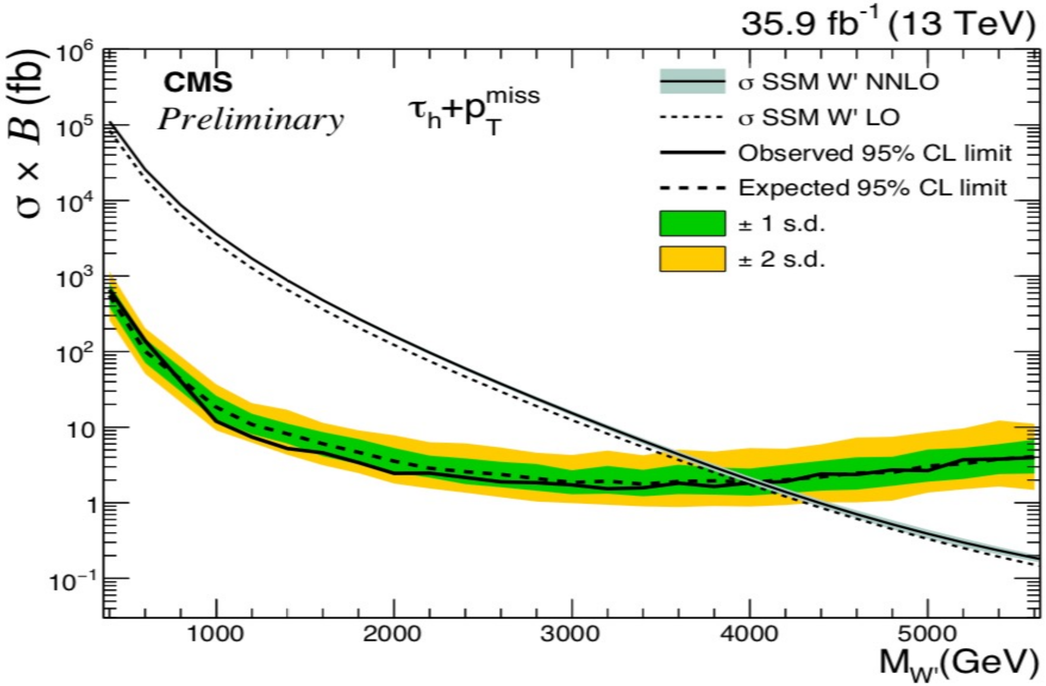
LHC can test it

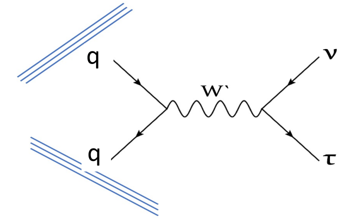
Any direct limit from collider experiment right now?

$\tau\nu$ resonance search

$\tau\nu$ resonance (+j) search in CMS can give a stringent limit.

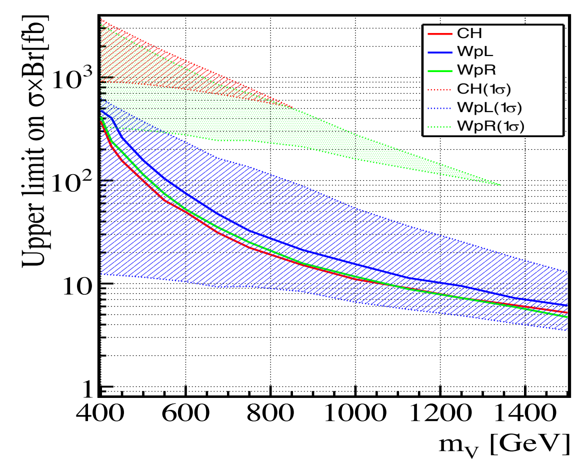
But, the limit is for W'. CMS-PAS-EXO-17-008





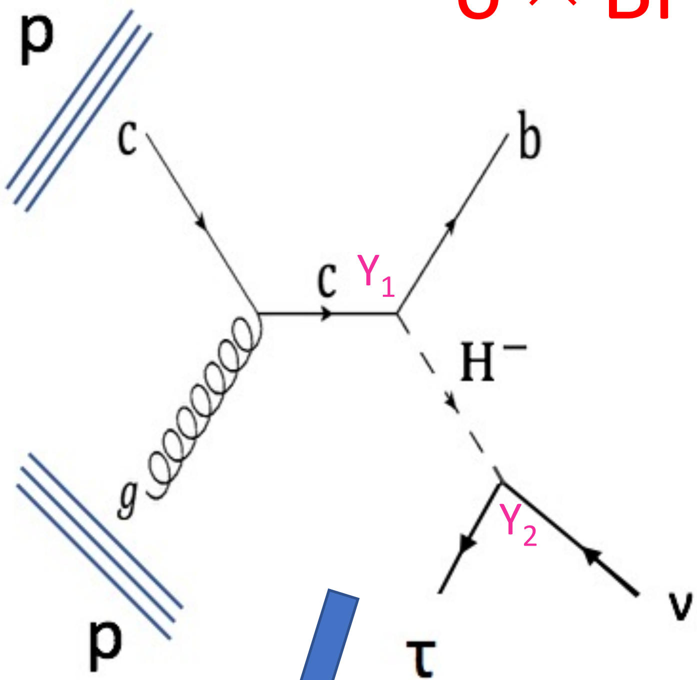
Need to reinterpret this limit for H^-.

We calculated an efficiency for H^- and obtained the limit.

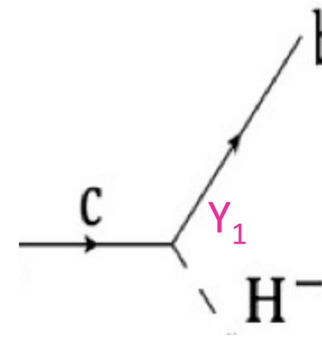


Experiment:arXiv	$\sqrt{s}$[TeV]	L[fb^{-1}]	Range $M_{W'}$[TeV]
CMS:1508.04308	7,8	19.7	0.3–4
CMS:CMS-PAS-EXO-16-006	13	2.3	1–5.8
ATLAS:1801.06992	13	36.1	0.5–5
CMS:CMS-PAS-EXO-17-008	13	35.9	0.4–4

σ × Br in G2HDM



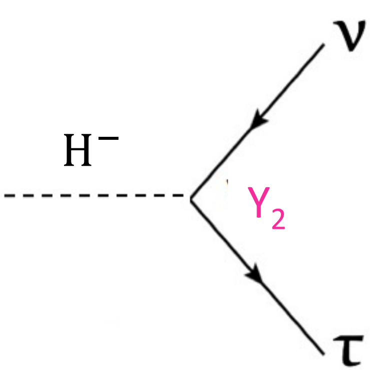
Production



depending on H$^-$ mass

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

Branching ratio



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

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

To fit $R(D^{(*)})$ data,
$Y_1 Y_2 \equiv \alpha$ is sizable.

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

Γ/m_{H^-}<0.1

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

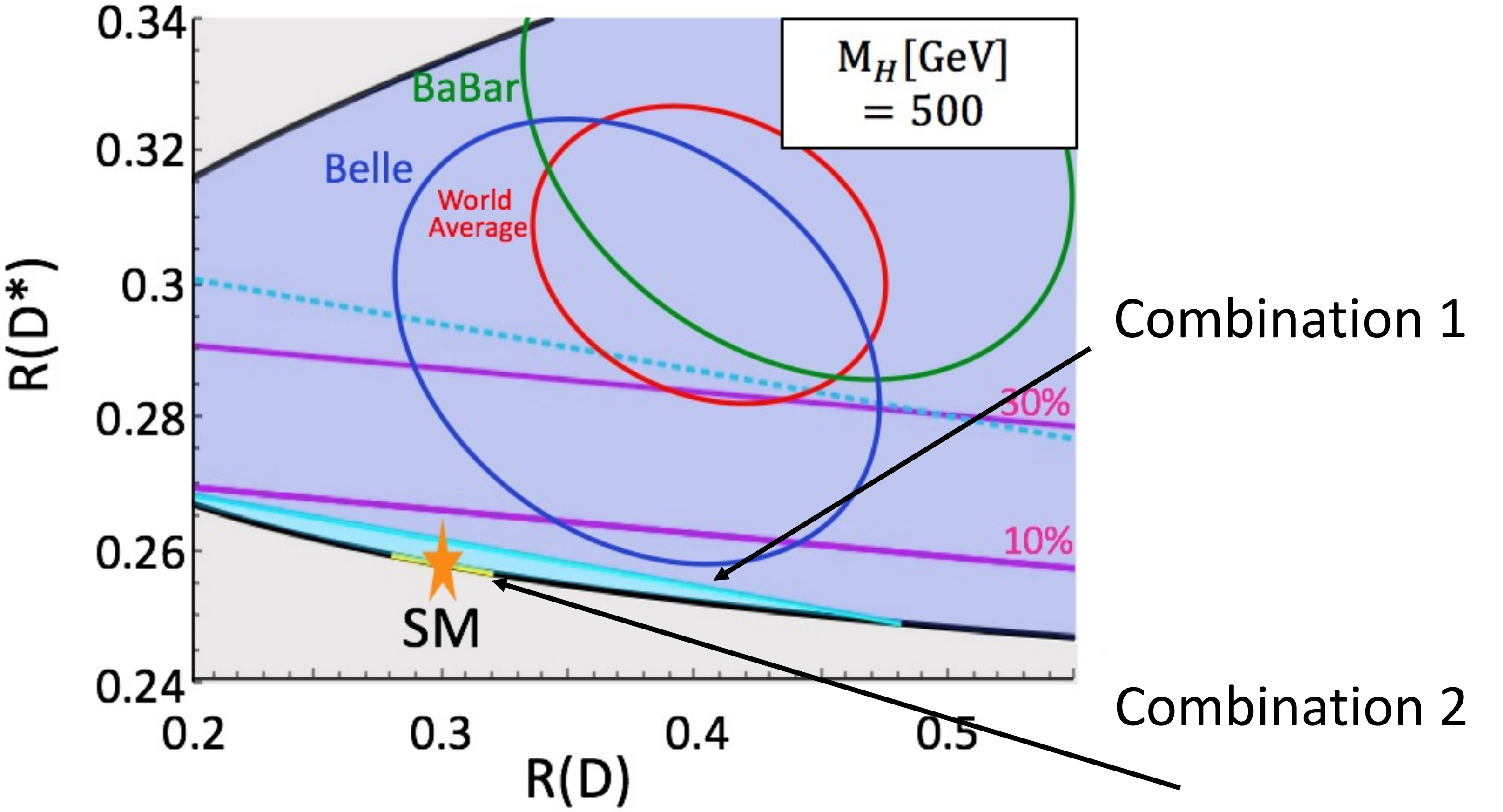
Combination 1 : $Y_1 = 1$, maximizing denominator.

weaker constraint.

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

severe constraint.

Result

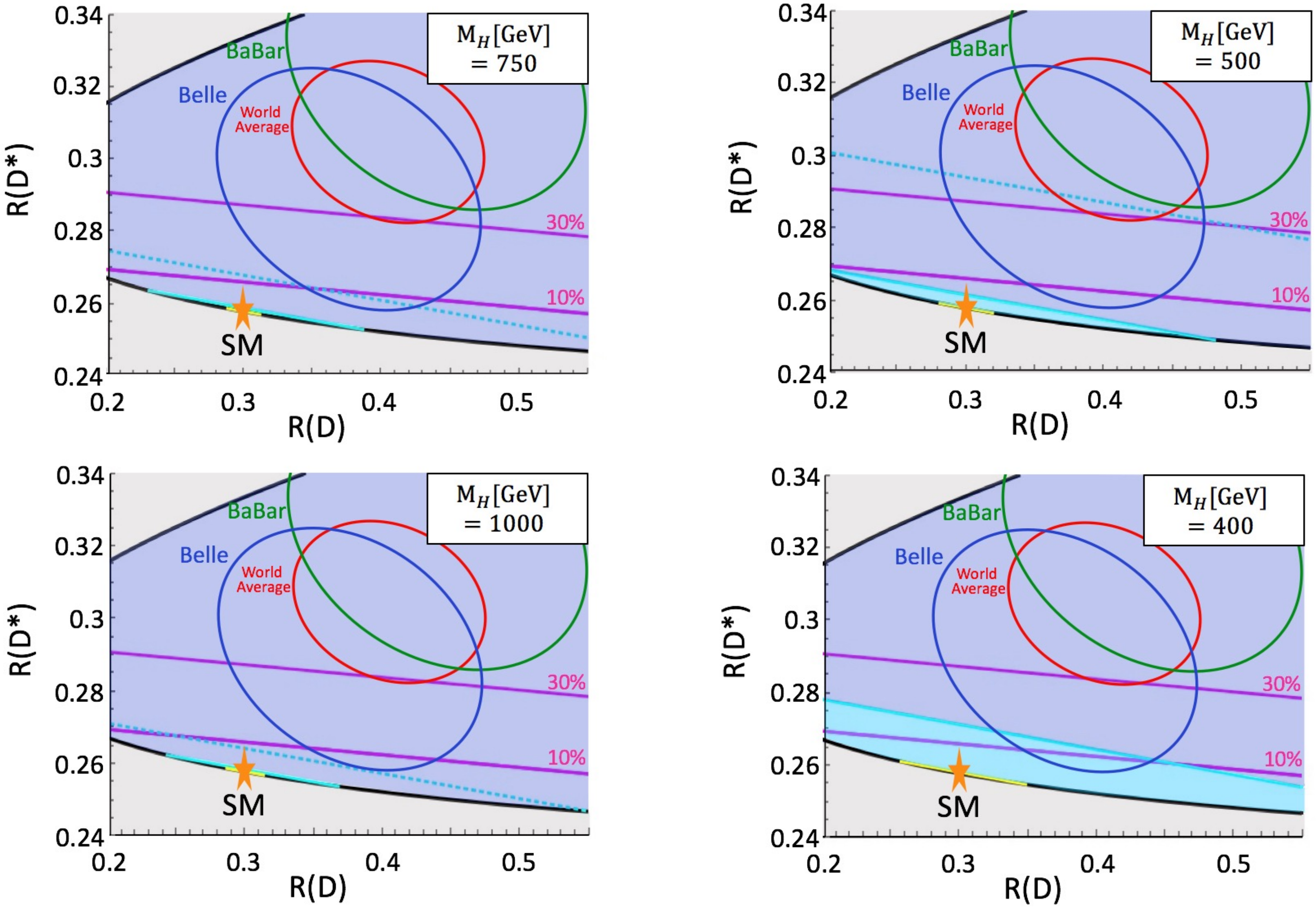


The more stringent constraint than $B_c^- \to \tau\bar{\nu}$

Result

Heavier H^{-}, more severe constraint.

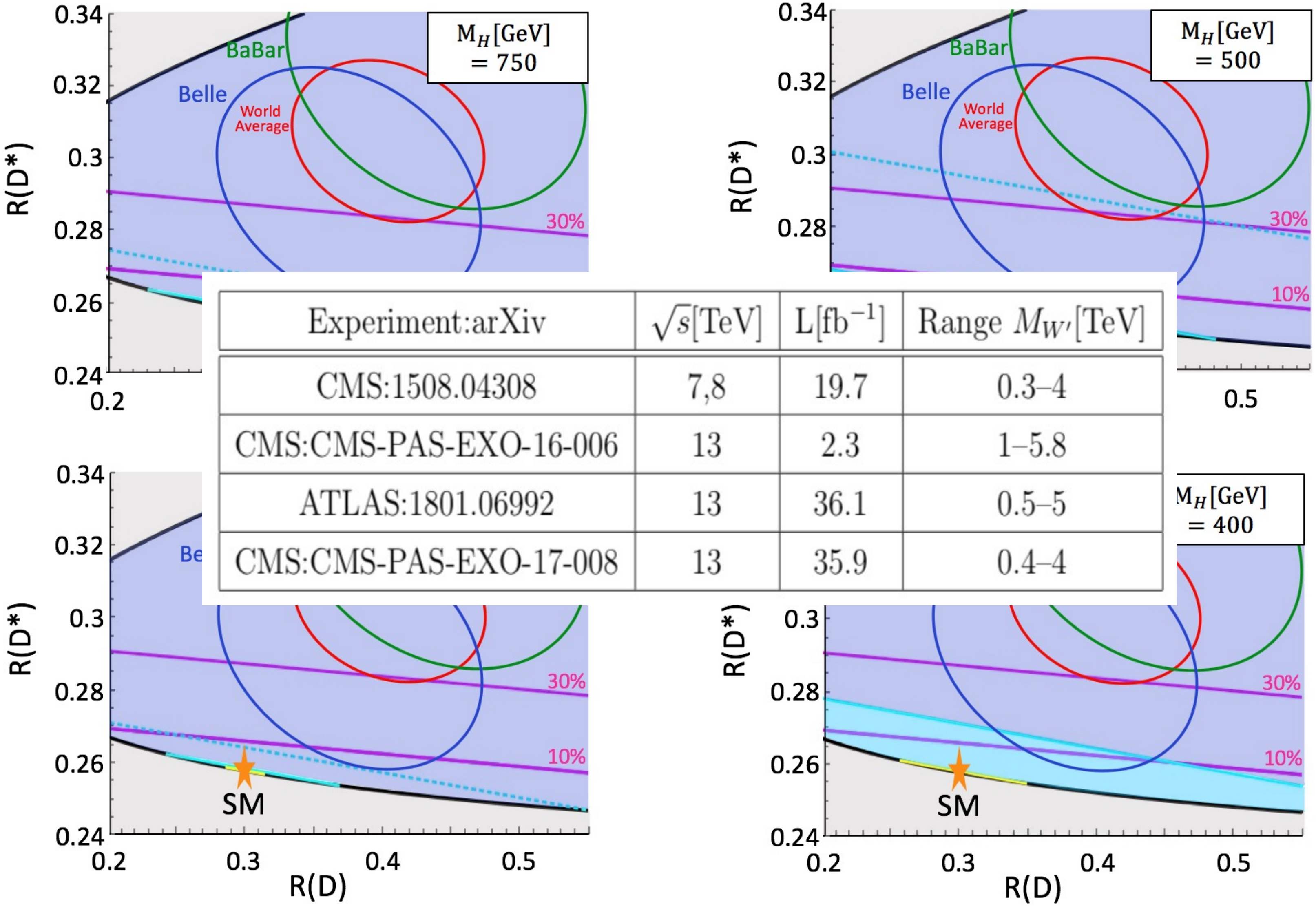
heavier lighter



Result

Heavier H^-, more severe constraint.

preliminary heavier lighter



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Summary

G2HDM can still explain R(D).

τν resonance search can test it.

τν resonance gives more stringent constraints than Br($B_c^- \to \tau\bar{\nu}$).

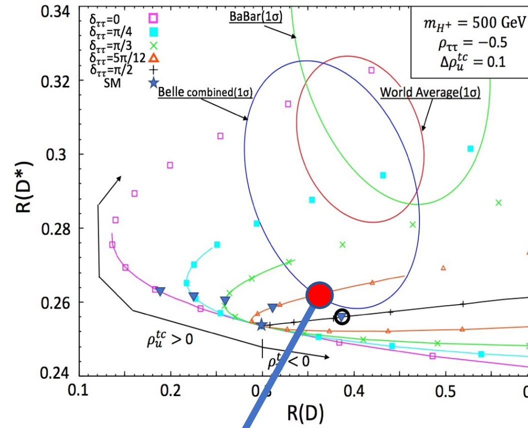
An interplay between flavor physics and collider physics is important.

Back up

- W' case
- P'_5 anomaly and H^-
- ……

Implications for LHC

Enhancing $\mathrm{R}(\mathrm{D}^{(*)})$ needs a large effective coupling $\bar{c}b\bar{\tau}\nu$ meditated by charged Higgs and generates an energetic tau lepton as a final state in LHC. (A.Soni, et al. arXiv:1704.06659)



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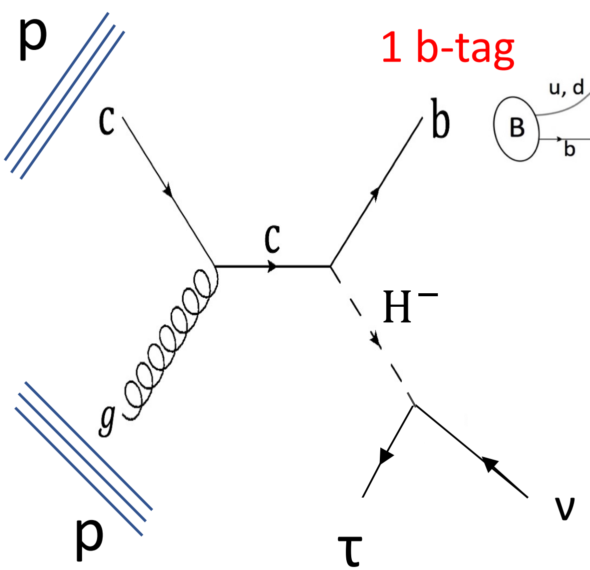
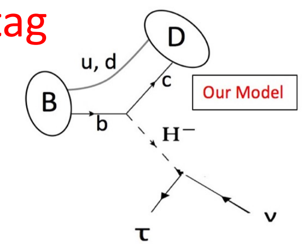
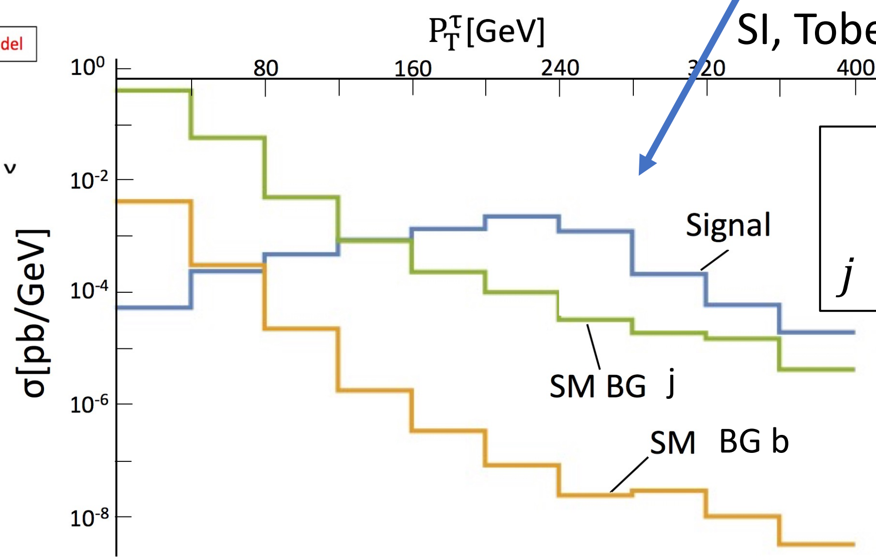




High P_T

SI, Tobe:1708.08176



main SM BG:
$\tau\nu + j$
j misID as b

This process looks promising, but not measured yet

Constraint for W'

See also M. Abdullah, et al.1805.01869

Vector (couple to left handed or right handed quarks)

We assume following operators.

A. Celis,et al. 1604.03088
G. Isidori,et al. 1506.01705....

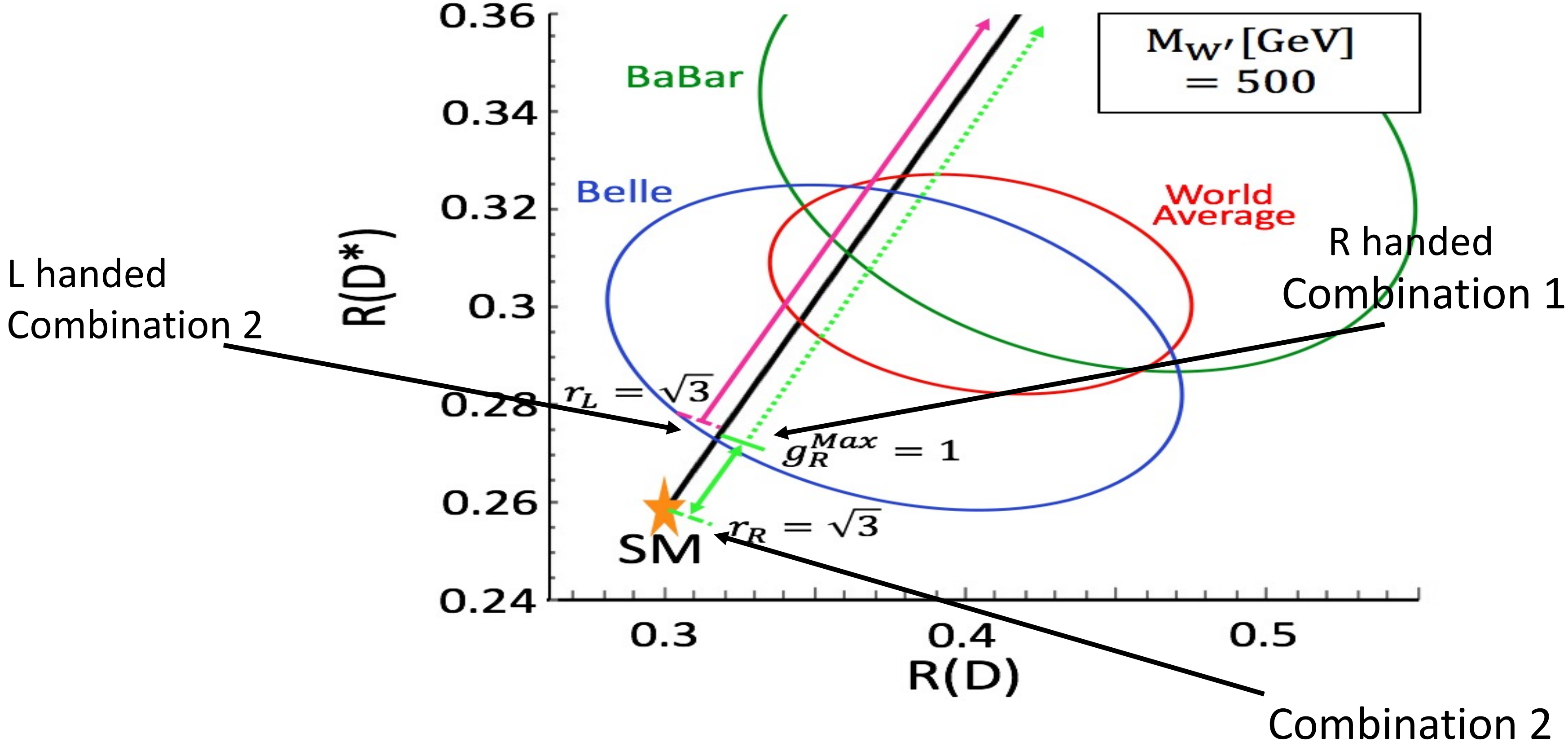
$$L_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb}\left[\left(1 + C_L'^{\,V}\right)\left(\bar{\tau}\gamma_\mu P_L \nu\right)\left(\bar{c}\gamma^\mu P_L b\right)\right] + C_R'^{\,V}\left(\bar{\tau}\gamma_\mu P_R \nu\right)\left(\bar{c}\gamma^\mu P_R b\right) + \text{h.c.}$$

↓

$$R(D^{(*)}) \simeq R(D^{(*)})_{SM}\left\{|1 + C_L'^{V}|^2 + |C_R'^{V}|^2\right\}$$

Left handed vector charged current

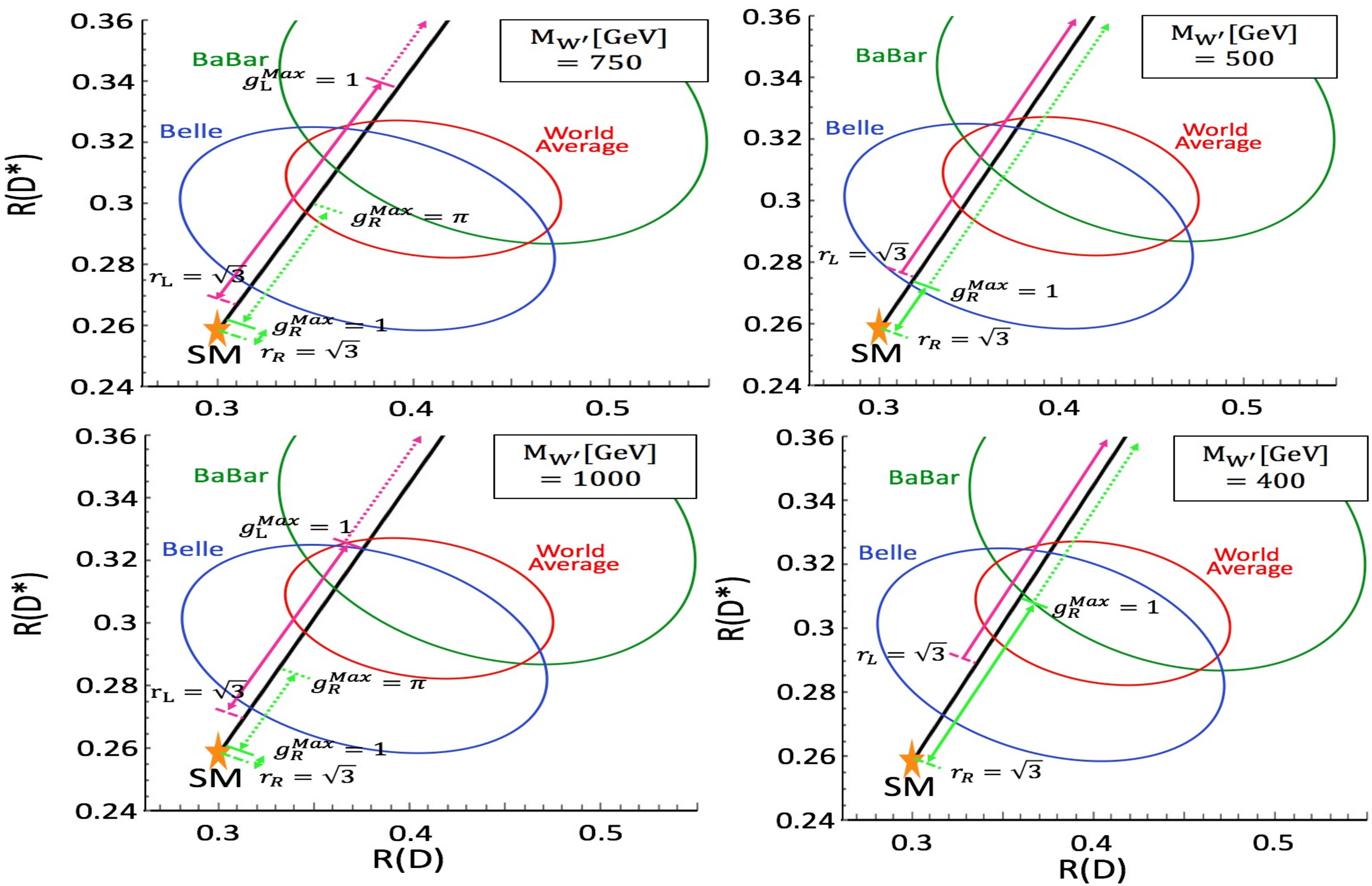
$$R(D^{(*)}) \simeq R(D^{(*)})_{SM}\left\{|1+C_L^{\prime V}|^2+|C_R^{\prime V}|^2\right\}$$



Result

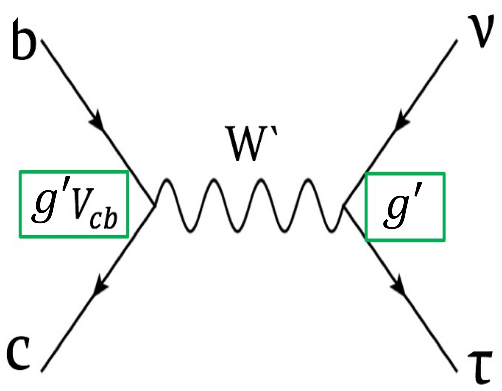
the heavier W', the more severe constraint.

heavier lighter



discussion

W’: difficulty for building models



SM like flavor structure is not favored. See left fig.

V_{cb}=0.04 suppression exists and requires large g'

T-parameter requires Z’ with $m_{W'} \approx m_{Z'}$.

Then, there should be V_{cb} unsuppressed
pp→bb→Z’ →ττ A.Greljo,et al:1609.07138

500GeV > $m_{W'}$ $\mathrm{R(D^{(*)})}$ at that time.

We need extended gauge bosons with
an exotic flavor structure and lighter mass.

Indirect upper bounds on BR($B_c^- \to \tau\bar{\nu}$)

BR($B_c^- \to \tau\bar{\nu}$) =1-Br(Bc the other decay) < 30% R.Alonso et al. 1611.06676

Substituting a SM calculation

Combining LEP data with inputs obtained in LHCb

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

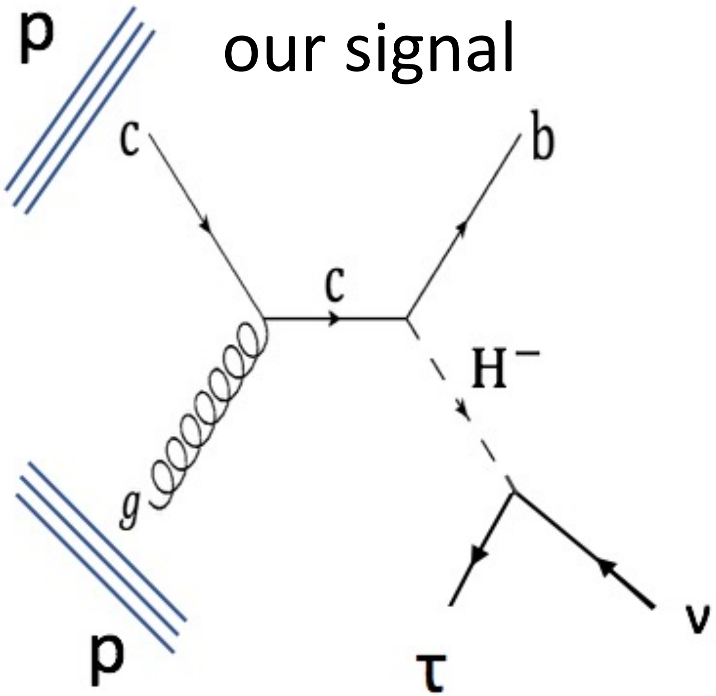
LEP has an upper limit on $\mathrm{B_c} \to \tau\bar{\nu} + \mathrm{B} \to \tau\bar{\nu}$. Combining recent result of LHCb, they got an upper limit on BR($B_c^- \to \tau\bar{\nu}$).

comment: they used BR($B_c \to J/\psi l \nu$)$_{SM}$ as an input.

$\tau\nu$ resonance search on H^-

Why no study so far?

our signal

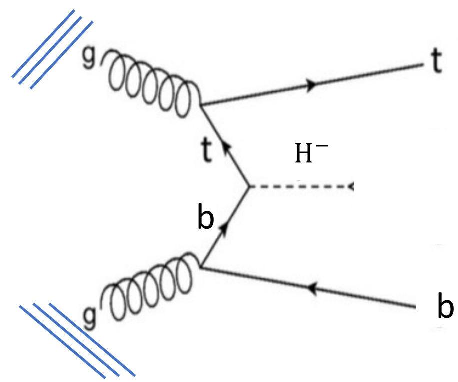


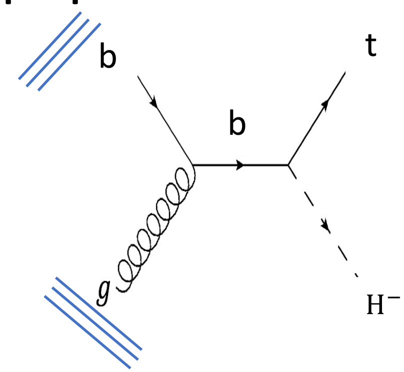
H^- in Type II 2HDM mainly couple to $bt, \tau\nu$.

No top quark in proton PDF.

↓

H^- is produced with top quark





Exotic process for H^-

We assume our H^- interacts only with bc or τν for simplicity.

G2HDM

We take so called Higgs base : a doublet acquires VEV

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+\Phi_1+iG}{\sqrt{2}} \end{pmatrix},\ H_2 = \begin{pmatrix} H^+ \\ \frac{\Phi_2+iA}{\sqrt{2}} \end{pmatrix}$$

G^+,G: N-G boson, H^+ :charged Higgs, A : CP odd Higgs

Linear transformation to mass base of CP even scalars

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\beta\alpha} & \sin\theta_{\beta\alpha} \\ -\sin\theta_{\beta\alpha} & \cos\theta_{\beta\alpha} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

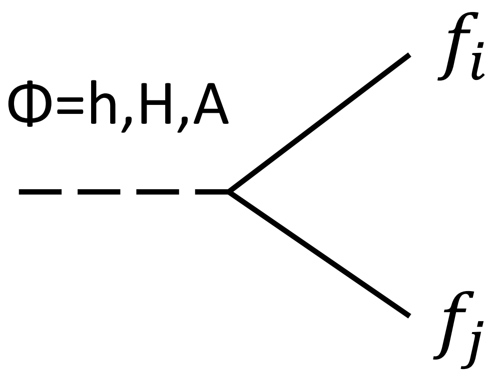
Yukawa terms

$$\begin{aligned} L_{CC} = & -\sum_{f=u,d,e}\sum_{\Phi=h,H,A} y^f_{\Phi ij}\overline{f_{Li}}\,\Phi f_{Rj} + \text{h.c.} \\ & -\ \overline{\nu_{Li}}(V^\dagger_{MNS}\rho_e)^{ij}H^+ e_{Rj} + \text{h.c.} \\ & -\bar{u}_i(V_{CKM}\rho_d P_R - \rho_u^\dagger V_{CKM} P_L)^{ij} H^+ d_j + \text{h.c.}, \end{aligned}$$

$$y^f_{hij} = \frac{m^i_f}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho^{ij}_f}{\sqrt{2}} c_{\beta\alpha},\quad y^f_{Aij} = \begin{cases} -\frac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = u \\ +\frac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = d, e, \end{cases}\quad y^f_{Hij} = \frac{m^i_f}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho^{ij}_f}{\sqrt{2}} s_{\beta\alpha}$$

Model: G2HDM

Yukawa couplings between a neutral scalar and fermions



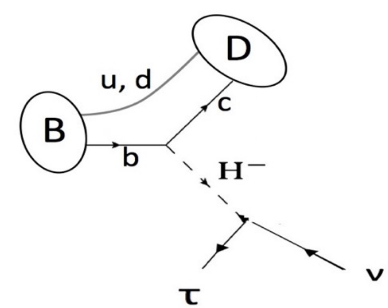
$$\approx i(y^f_{\Phi ij}\, P_R + y^{f*}_{\Phi ji}\, P_L)$$

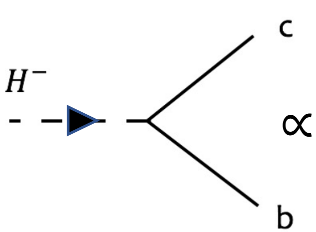
$$y^f_{hij} = \frac{m^i_f}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho^{ij}_f}{\sqrt{2}} c_{\beta\alpha},$$

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

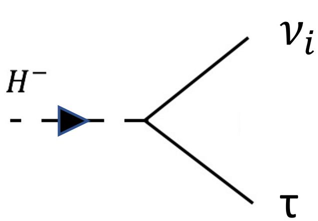
$$y^f_{Hij} = \frac{m^i_f}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho^{ij}_f}{\sqrt{2}} s_{\beta\alpha}$$

Yukawa interactions relevant to $R(D^{(*)})$





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



$$\propto (V^{ki*}_{MNS}\rho^{k\tau}_e)$$

Yukawa interactions relevant to $R(D^{(*)})$

$(\rho_u^{tc}, \rho_d^{sb}) \times (\rho_e^{e\tau}, \rho_e^{\mu\tau}, \rho_e^{\tau\tau})$

Motivation

Guiding princi

- Simplicity of
- Electroweak
- Extending Hi

  condition

may explain the discrepancies in flavor physics

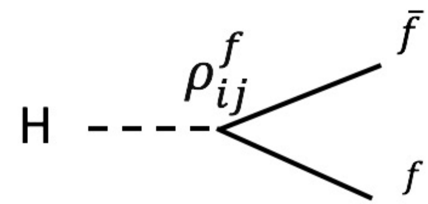
- $\mathrm{R}(\mathrm{D}^{(*)})$=$\mathrm{BR}(\mathrm{B} \to \mathrm{D}^{(*)}\tau\nu)/\mathrm{BR}(\mathrm{B} \to \mathrm{D}^{(*)}\mathrm{l}\nu)$ today
- muon g-2 Omura, Senaha, Tobe: **JHEP 1505 (2015) 028**
- P'_5 : angular observable in $\mathrm{B} \to \mathrm{K}^{*}\mu\mu$ If time allows
- $\mathrm{R}(\mathrm{K}^{(*)})$=$\mathrm{BR}(\mathrm{B} \to \mathrm{K}^{(*)}\mu\mu)/\mathrm{BR}(\mathrm{B} \to \mathrm{K}^{(*)}ee)$

for a combination of them, see **JHEP 1805 (2018) 173** SI, Y. Omura

- SM Higgs exist!
- Simple extension of scalar sector
- STU parameter is controllable
- Flavor violating Yukawa could exist

Rich flavor phenomenology

Yukawa couplings



Without discrete symmetry like Z_2 symmetry,
G2HDM has flavor violating interactions at tree level.

Experimentally, Yukawa couplings to use are limited

e.g. Stringent bounds come from
- meson mixing
- $b \rightarrow s\gamma$
- $B \rightarrow \tau\nu$ .....

$\rho_d^{sb} << 1$, but

ρ_u^{tc} can be O(1)

We turn others off for simplicity and clarify how G2HDM can explain $\mathrm{R}(\mathrm{D}^{(*)})$ anomalies

For the top down approach of this model e.g. Cheng et al. 1507.04354
Iguro et al. 1804.07478

$$\mathcal{H}_{eff} = C^V_{LL}(\overline{b_L}\gamma_\mu c_L)(\overline{\nu_L}\gamma^\mu \tau_L) + C^V_{RL}(\overline{b_R}\gamma_\mu c_R)(\overline{\nu_L}\gamma^\mu \tau_L)$$
$$+C^V_{LR}(\overline{b_L}\gamma_\mu c_L)(\overline{\nu_R}\gamma^\mu \tau_R) + C^V_{RR}(\overline{b_R}\gamma_\mu c_R)(\overline{\nu_R}\gamma^\mu \tau_R)$$
$$+C^S_L(\overline{b_R}c_L)(\overline{\nu_L}\tau_R) + C^S_R(\overline{b_L}c_R)(\overline{\nu_L}\tau_R) + h.c..$$

$$R(D) \simeq R(D)_{SM}\Big\{|1 + C^V_{LL} + C^V_{RL}|^2 + |C^V_{RR} + C^V_{LR}|^2 + 0.99|C^S_L + C^S_R|^2$$
$$+ 1.47\mathrm{Re}\Big[(1 + \mathrm{C^V_{LL}} + \mathrm{C^V_{RL}})(\mathrm{C^{S*}_L} + \mathrm{C^{S*}_R})\Big]\Big\},$$

$$R(D^*) \simeq R(D^*)_{SM}\Big\{|1 + C^V_{LL}|^2 + |C^V_{RL}|^2 + |C^V_{RR}|^2 + |C^V_{LR}|^2 + 0.02|C^S_L - C^S_R|^2$$
$$-1.77\mathrm{Re}\Big[(1 + C^V_{LL})(C^{V*}_{RL}) + (C^V_{RR})(C^{V*}_{LR})\Big] + 0.09\mathrm{Re}\Big[(1 + \mathrm{C^V_{LL}} - \mathrm{C^V_{RL}})(\mathrm{C^{S*}_L} - \mathrm{C^{S*}_R})\Big]\Big\}$$

$\rho_d^{sb} << 1 \rightarrow \mathrm{C^S_L}<<1$

P. Asadi ,et at.1804.04135