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

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Based on

arXiv:1810.05348 w/ Y. Omura(KMI), M. Takeuchi(IPMU),

Nucl.Phys. B925 (2017) 560-606 w/ K. Tobe(KMI,Nagoya-U).

What I do today

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

We found that τν resonance search can give more stringent constraints than Br($B_c^- \to \tau\bar{\nu}$).

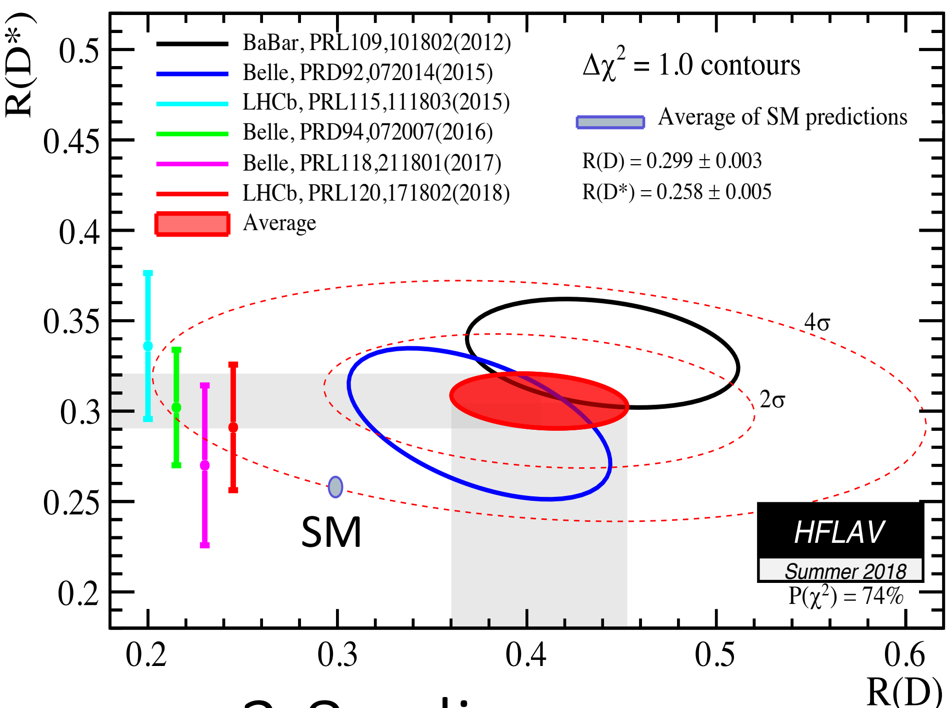
Contents

- $\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ anomaly
- G2HDM
- τν resonance search
- Summary

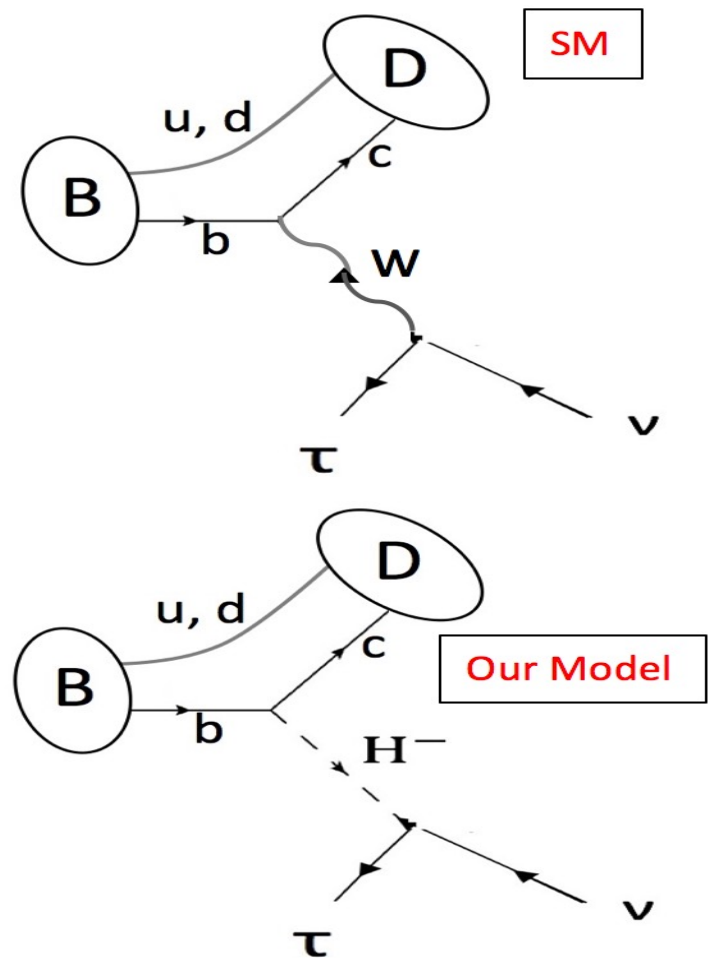
Current status of $R(D^{(*)})$ anomaly

Naively, H^- is a good candidate.

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



3.8σ discrepancy



Phys. Rev. D 82, 034027 (2010) M.Tanaka, et.al

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

Motivation

～Why I work on Higgs physics?～

Guiding principles for me

- Simplicity of the model
- Electroweak precision test

General Two Higgs Doublet Model (G2HDM)

- Simple extension of the scalar sector
- STU parameter is controllable
- Flavor violating Yukawa could exist

Rich flavor phenomenology

Extending Higgs sector keeps the gauge anomaly-free condition automatically

Motivation

Guiding princi

- Simplicity of
- Electroweak

may explain the discrepancies in flavor physics

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

for a compatibility, see **JHEP 1805 (2018) 173** SI, Y. Omura

Ge

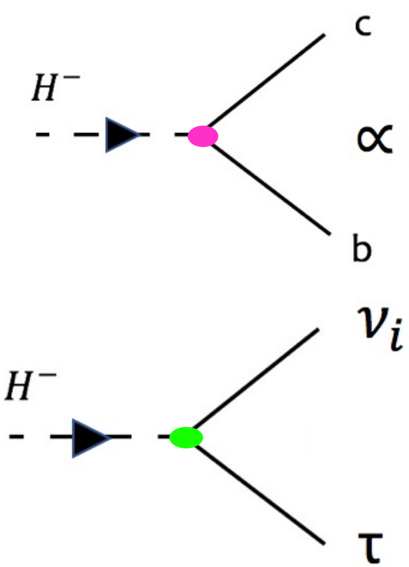
-
- STU parameter is co rollable
- Flavor violating Yuka a could exist

Rich flavor phenomenology

Extending Higgs sector keeps the gauge anomaly-free condition automatically

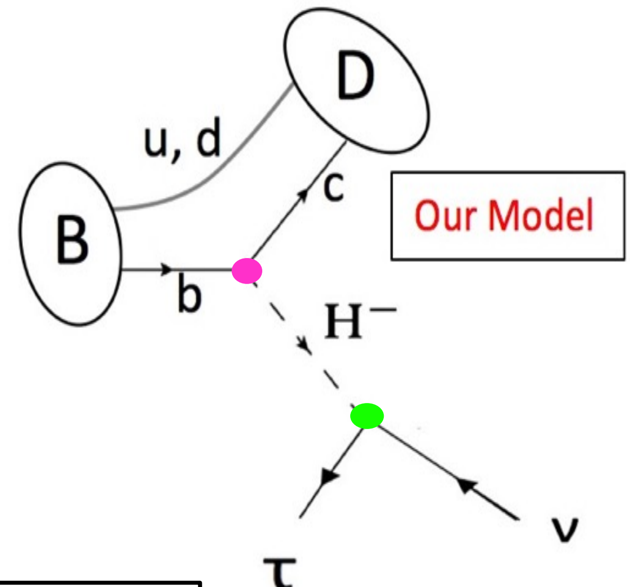
Model: G2HDM have a charged Higgs

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



$\propto -\rho_u^{tc}$

$\propto (V_{MNS}^{ki*}\rho_e^{k\tau})$



Yukawa interactions relevant to $R(D^{(*)})$
we consider $\rho_u^{tc}, \rho_e^{\tau\tau}$

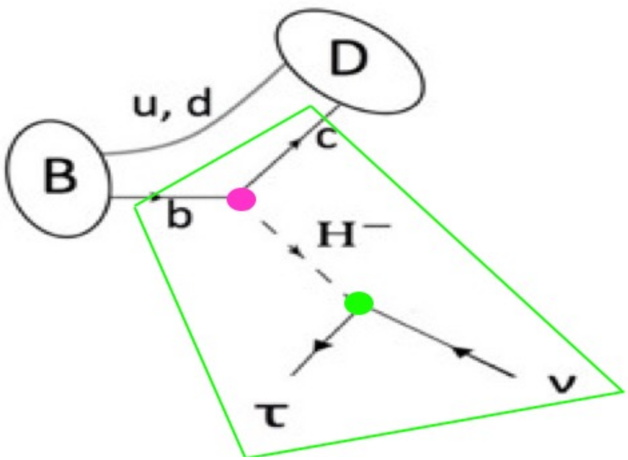
Other couplings are small e.g. meson mixing, b→sγ, B→τν, ττ resonance search.

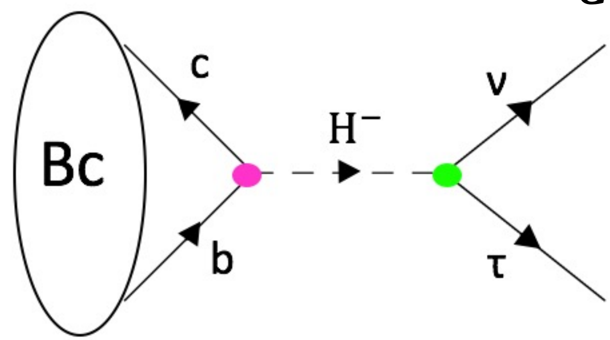
Nucl.Phys. B925 (2017) 560-606 SI, K. Tobe.

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

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

$$C_R'^S \propto \frac{\rho_u^{tc}\rho_e^{\tau\tau}}{m_{H^-}^2}$$





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

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

Scalar operators have a large coefficient

≈ 4

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

$$\mathrm{BR}(\mathrm{B}_c^- \to \tau\bar{\nu})_{\mathrm{SM}} \times \left|1 - \frac{\mathrm{m}_{\mathrm{Bc}}^2}{\mathrm{m}_\tau(\mathrm{m}_b + \mathrm{m}_c)} C_R'^S\right|^2$$

60%? 1811.09603 last week

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

$R(D^{(*)})$ in G2HDM

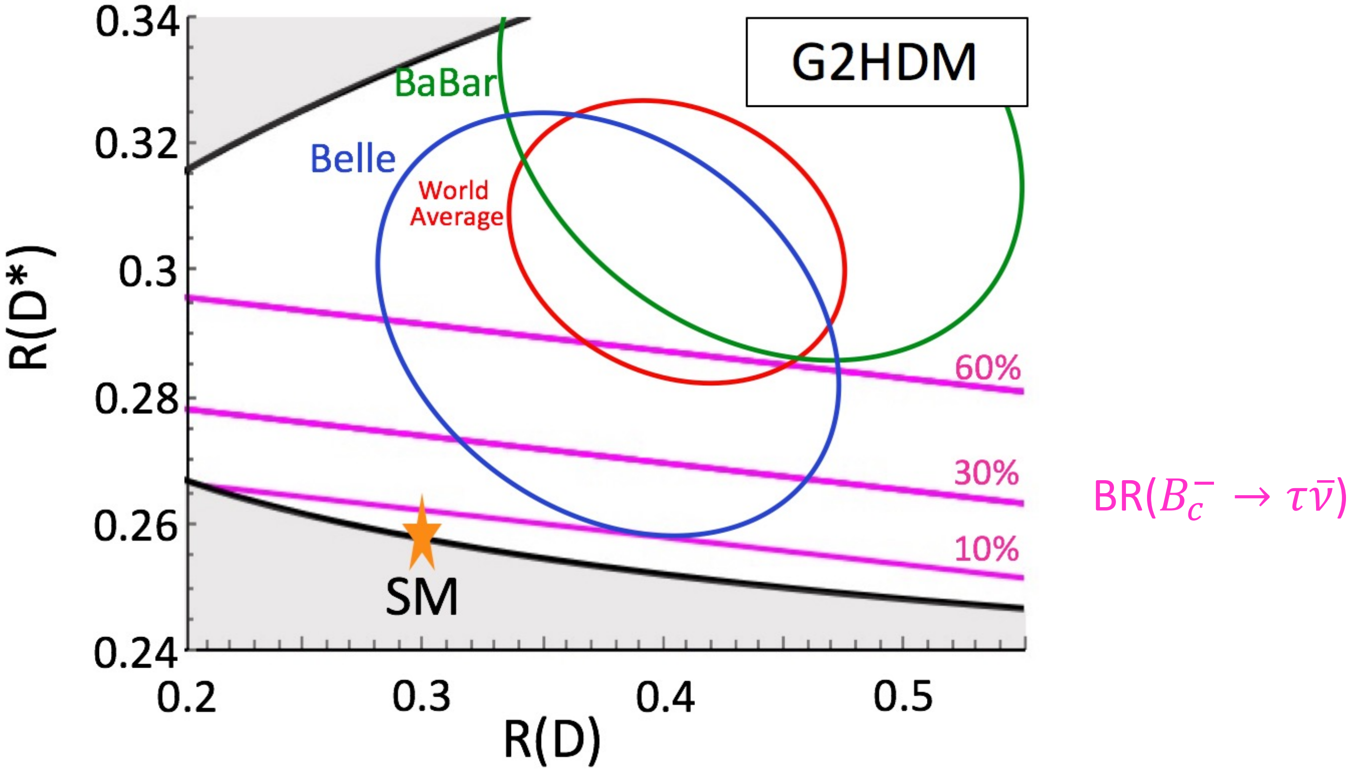
$$C_R'^S \sim \frac{\rho_u^{tc}\rho_e^{\tau\tau}}{m_{H^-}^2}$$

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

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

$$R(D) \simeq R(D)_{SM}\left\{1 + 1.5\mathrm{Re}[C_R'^S] + |C_R'^S|^2\right\}, \qquad R(D^*) \simeq R(D^*)_{SM}\left\{1 - \underline{0.12}\mathrm{Re}[C_R'^S] + \underline{0.05}|C_R'^S|^2\right\}$$

Large coefficient is necessary to enhance R(D*) in G2HDM.



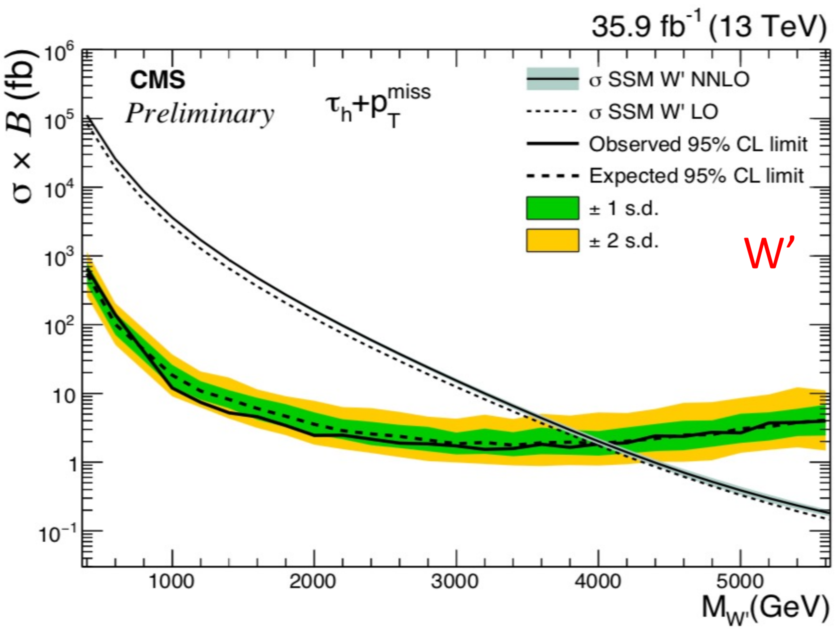
Collider study

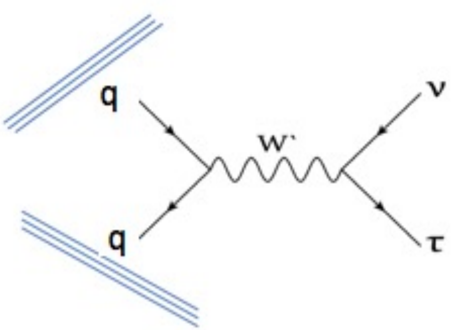
Q. Any direct limit from the collider experiment?

A. $\tau\nu$ resonance search

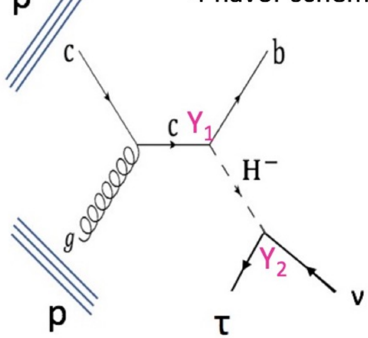
$\tau\nu$ resonance (+j) search in CMS can give a stringent limit.

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

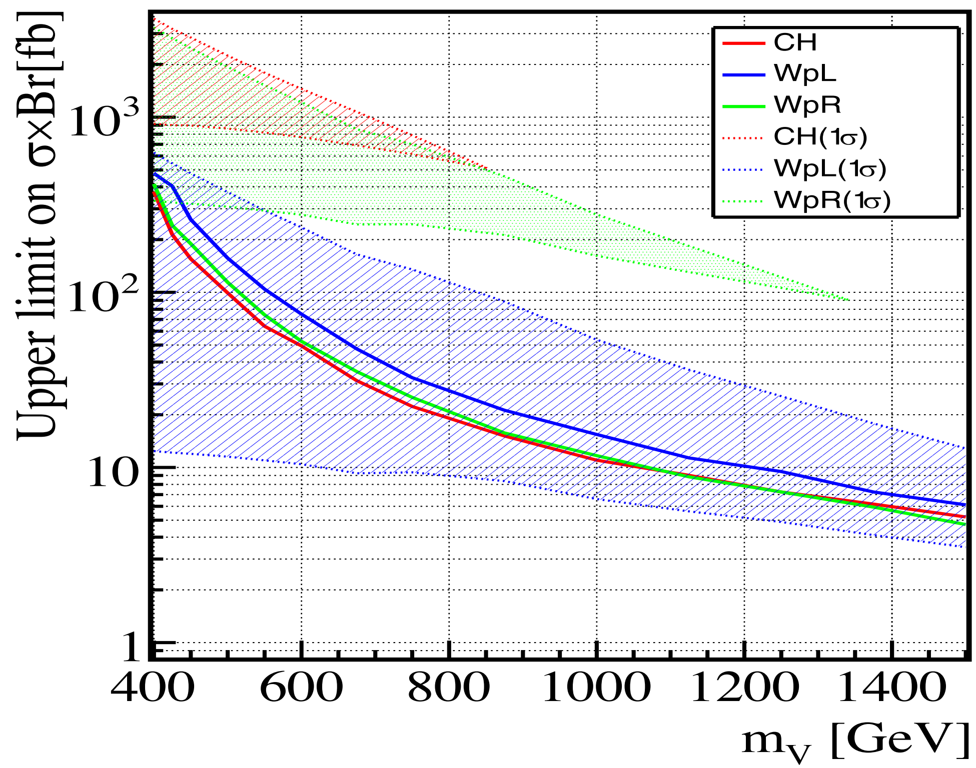




4 flavor scheme

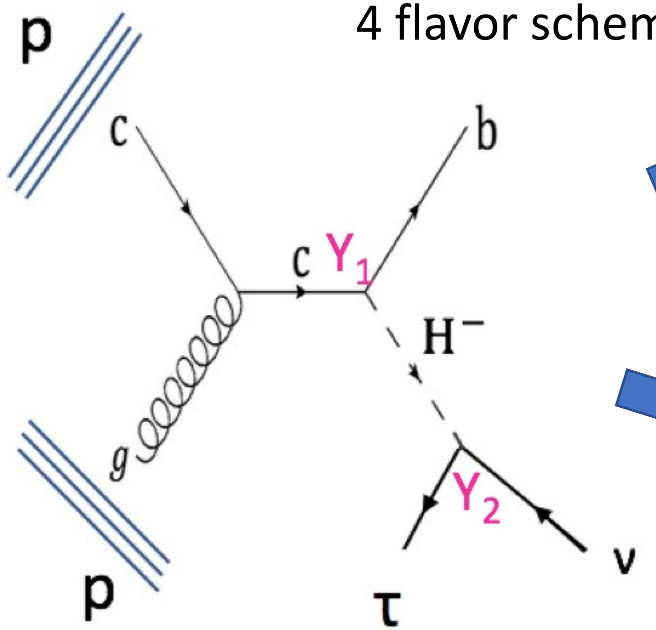


We reinterpreted this limit into H^- by the collider simulation.



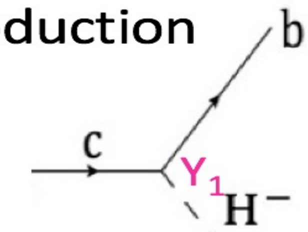
σ × Br in G2HDM

4 flavor scheme



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

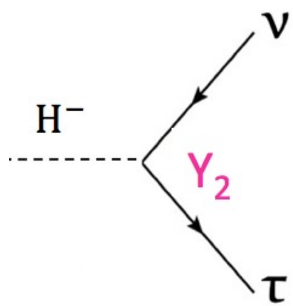
Production



depending on H⁻ mass

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

Branching ratio



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

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

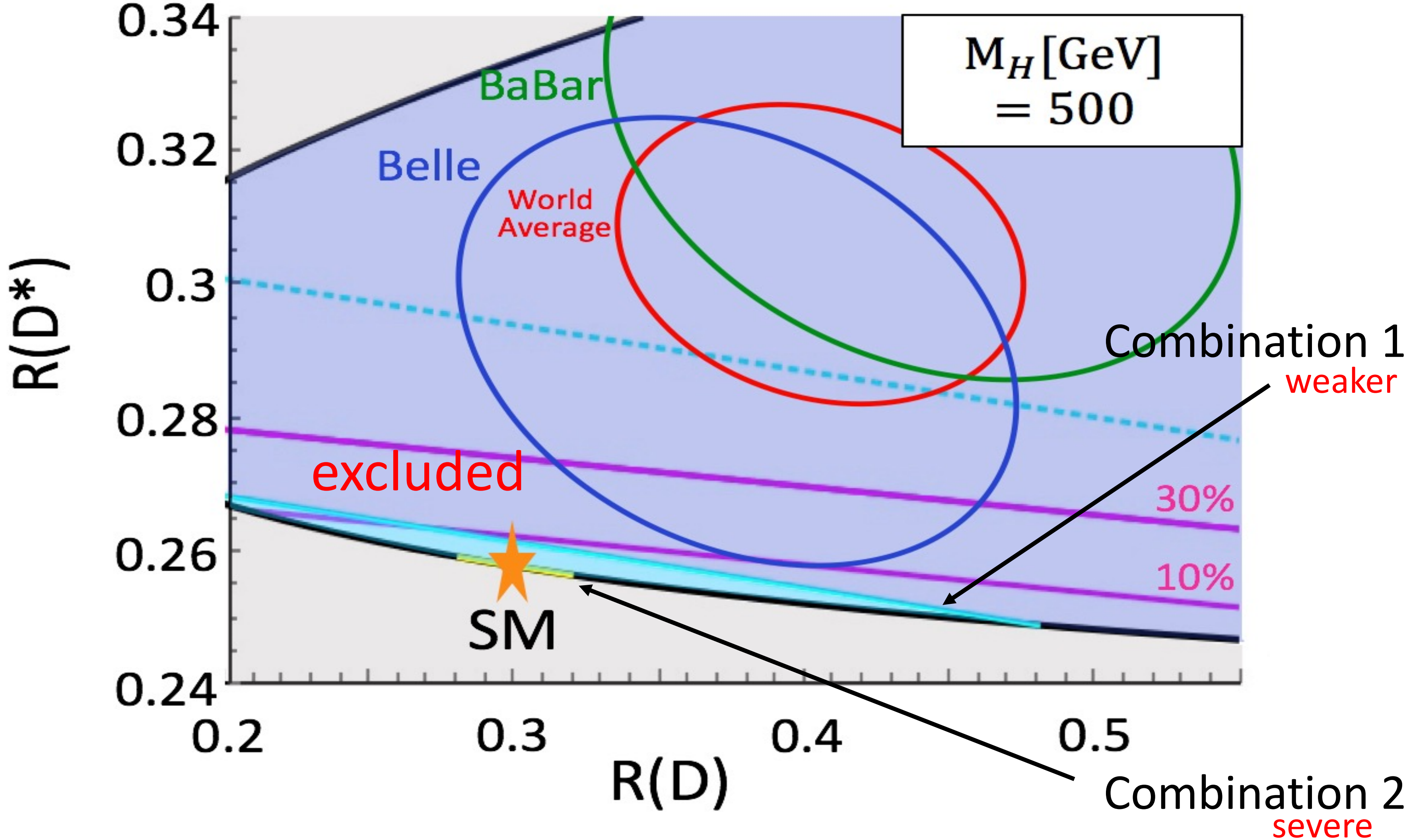
Combination 1 : $Y_1 = 1$, maximizing denominator.
weaker constraint.

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

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

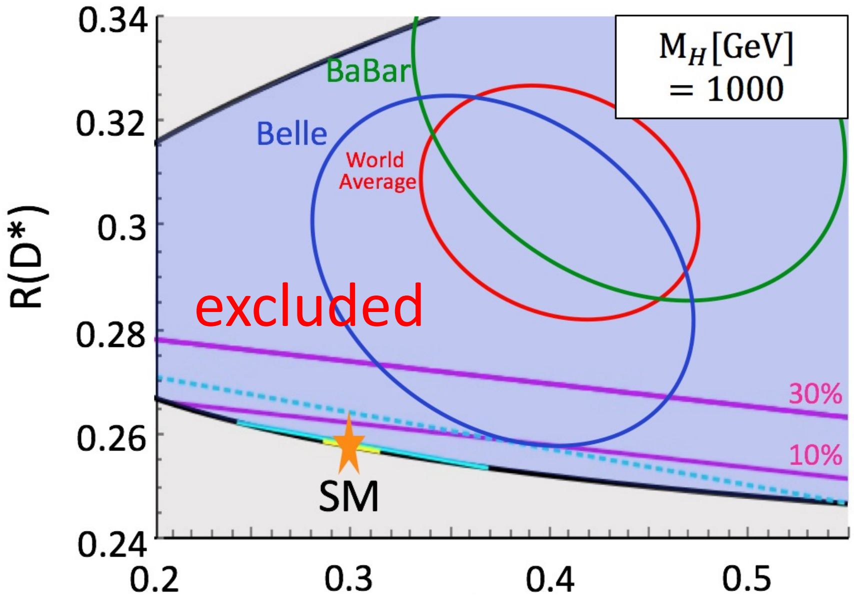


more stringent constraint than $B_c^- \to \tau\bar{\nu}$

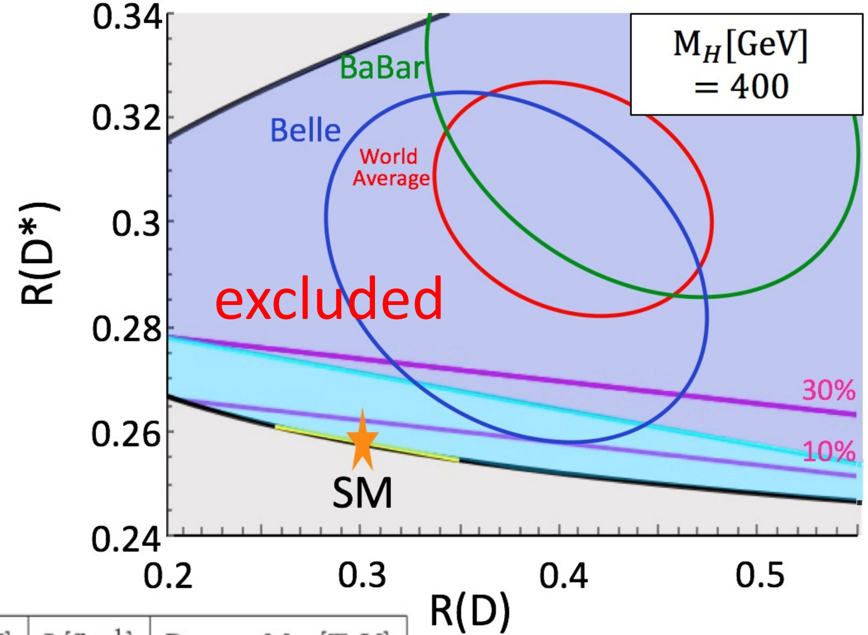
Result

Heavier H^{-}, more severe constraint.

heavier



lighter



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

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→ $\tau\nu$.

Summary

G2HDM can still explain R(D).

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

An interplay between flavor physics and collider physics is important.

We also analyzed bounds for $W'_{L(R)}$ see back ups!

Now LHC Run 2 (pp) finished

- 150 fb^{-1} data. 4 times larger than 36 fb^{-1}

Our bound can be improved soon.

- The bound for a lighter resonance (less than 400GeV) is helpful!

Back up

- W’ case
- P'_5 anomaly and H^-
- ……

Selection cut

- exactly one τ-tagged jet, satisfying $p_{T,\tau} \geq 80\text{GeV}$ and $|\eta_\tau| \leq 2.4$,
- no isolated electrons nor muons ($p_{T,e}, p_{T,\mu} \geq 20\text{GeV}$, $|\eta_e| \leq 2.5$, $|\eta_\mu| \leq 2.4$),
- large missing momentum $\not{E}_T \geq 200$ GeV,
- and it is balanced to the τ-tagged jet: $\Delta\phi(\not{E}_T, \tau) \geq 2.4$ and $0.7 \leq p_{T,\tau}/\not{E}_T \leq 1.3$, where $\Delta\phi(\not{E}_T, \tau)$ is the azimuthal angle between the missing momentum and the τ-jet.

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

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

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

Table 1. Predicted ranges of the polarizations for R_2, S_1 and U_1 LQ models ($\mu_{LQ} = 1.5$ TeV), which satisfy the current 1σ data of $R_{D^{(*)}}$ and the bound of $\mathcal{B}(B_c^+ \to \tau^+\nu) < 0.3$. The SM predictions, the current data, and the expected sensitivity at Belle II with 50 ab^{-1} data [59, 65] are also shown. The sensitivity for $P_\tau^{D^*}$ is absolute uncertainty while the others are relative.

	$F_L^{D^*}$	P_τ^D	$P_\tau^{D^*}$	R_D	R_{D^*}
R_2 LQ	[0.43, 0.44]	[0.42, 0.57]	[−0.44, −0.39]	1σ data	1σ data
S_1 LQ	[0.42, 0.48]	[0.11, 0.63]	[−0.51, −0.41]	1σ data	1σ data
U_1 LQ	[0.43, 0.47]	[0.23, 0.52]	[−0.57,−0.47]	1σ data	1σ data
SM	0.46(4)	0.325(9)	−0.497(13)	0.299(3)	0.258(5)
data	0.60(9)	-	−0.38(55)	0.407(46)	0.306(15)
Belle II	-	3%	0.07	3%	2%

1811.08899 SI, T. Kitahara, R. Watanabe, Y. Omura, K. Yamamoto.

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....

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

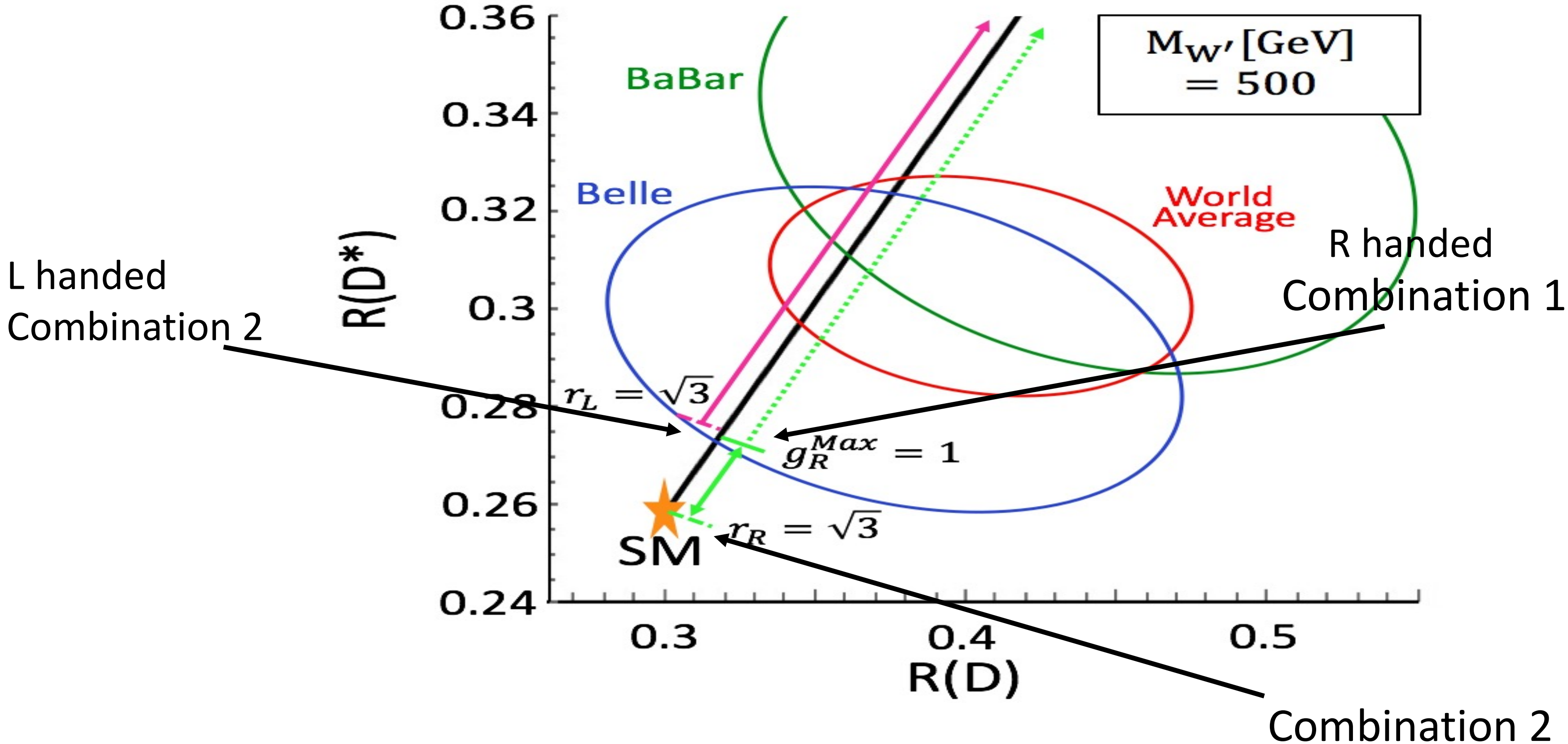
⇓

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

Left handed vector charged current

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

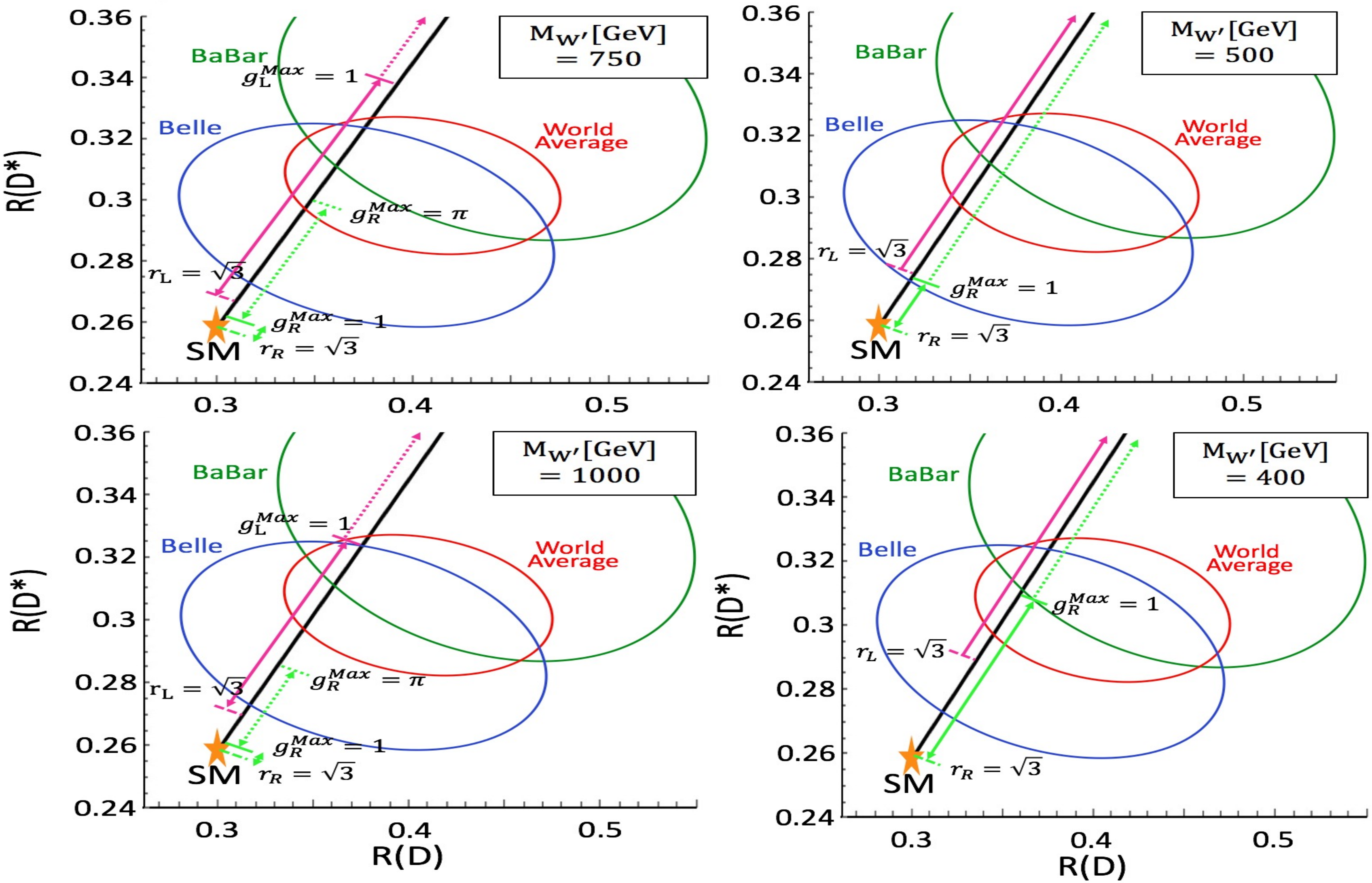
$$\sigma(pp\to V^\pm)\times Br(V^\pm\to\tau\nu)=\sigma_0(m_V)\times\frac{|g|^2|g_\tau|^2}{3|g|^2+|g_\tau|^2}=\sigma_0(m_V)\times\bar{g}^2\frac{r}{3+r^2}.$$



Result

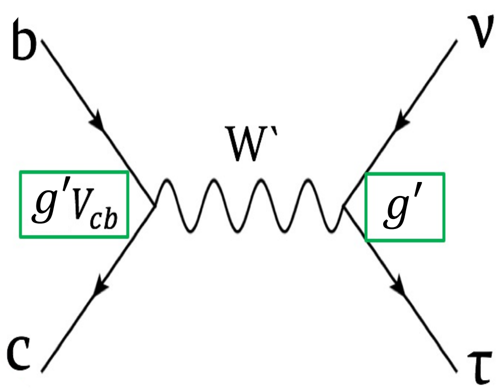
the heavier W', the more severe constraint.

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'

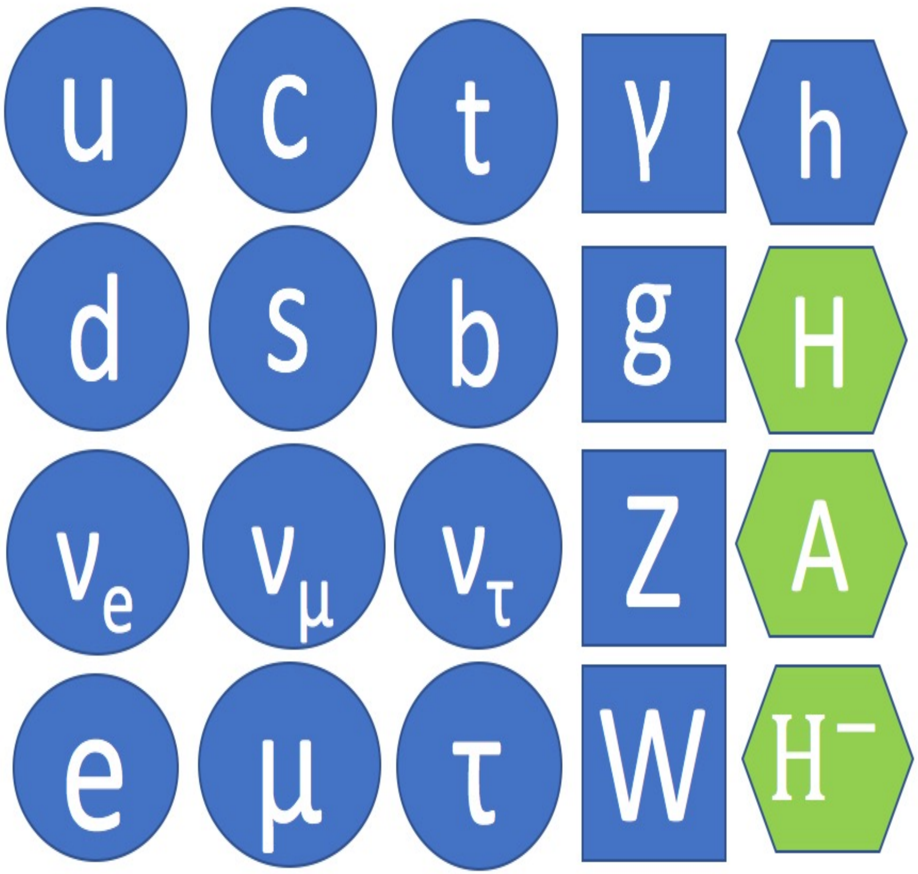
T-parameter requires Z' with $m_{W'} \approx m_{Z'}$.

Then, there should be V_{cb} unsuppressed
$pp \to bb \to Z' \to \tau\tau$ A.Greljo,et al:1609.07138

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

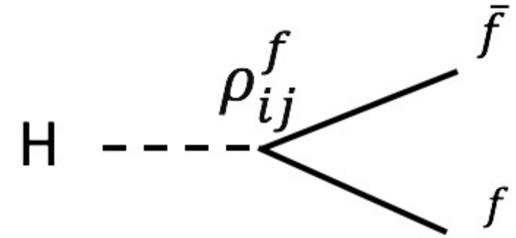
Our Model

Particle set in G2HDM



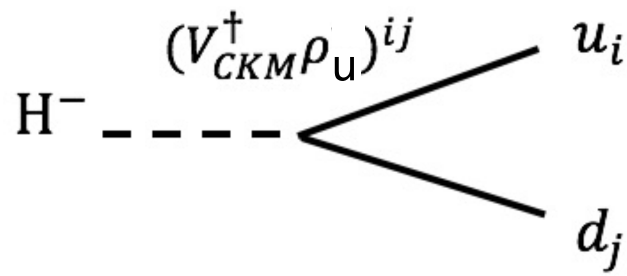
Neutral Scalar

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



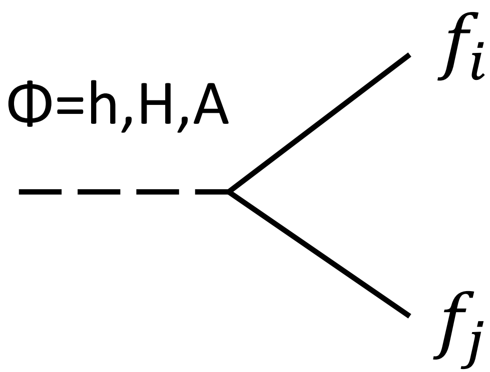
Charged Scalar

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



Model: G2HDM

Yukawa couplings between a neutral scalar and fermions



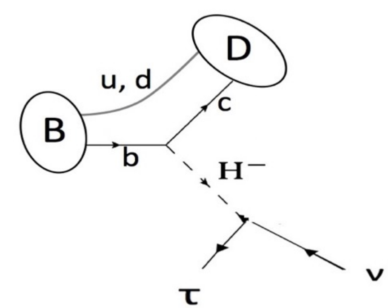
$$\approx i(y^f_{\Phi ij}\, P_R + y^{f*}_{\Phi ji}\, P_L)$$

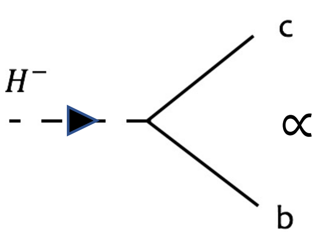
$$y^f_{hij} = \frac{m^i_f}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho^{ij}_f}{\sqrt{2}} c_{\beta\alpha},$$

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

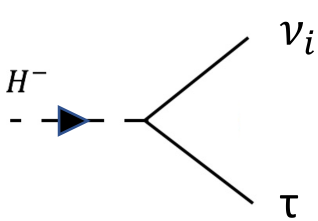
$$y^f_{Hij} = \frac{m^i_f}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho^{ij}_f}{\sqrt{2}} s_{\beta\alpha}$$

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

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

Simultaneous explanation can be ?

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

	$R(K^{(*)})$	P'_5	$R(D)$	$R(D^*)$	δa_μ
(B) $\rho_e \neq 0,\ \rho_\nu = 0$					
ρ_u^{tt}	×	×	×	×	○
ρ_u^{tc}	×	○	○	×	×
ρ_u^{ct}	×	×	×	×	○

○: within 1σ

or X X O X O

JHEP 1805 (2018) 173 SI, Y. Omura