Test of the $\mathrm{R}(\mathrm{D}^{(*)})$ 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)

Our result

- G2HDM can still explain R(D).

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

2018 WPI-next mini-workshop "Hints for New Physics in Heavy Flavors"

15-17 November 2018
Nagoya University
Japan timezone

- Overview
- Scientific Programme
- Timetable
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- Registration
  - Registration Form

The World Research Unit for Heavy Flavor Particle Physics, Nagoya University, will host a mini-workshop entitled as "Hints for New Physics in Heavy Flavor Physics", at Nagoya, Japan on November 15 through 17, 2018. The primary purpose of the workshop is to review the most recent experimental and theoretical works on particle physics phenomena involving heavy quarks and leptons and related topics, which may hint the New Physics beyond the Standard Model. We will also discuss the QCD aspects with heavy flavors. Topics will include;

- New Physics in B and Charm Physics
- New Physics in Top and high Pt physics
- New Physics in Tau and related topics (such as muon g-2)
- New Physics in QCD (XYZ hadrons, penta-quarks etc.)
- Interplay between LHC and flavor experiments
- New idea for future experiments, analysis techniques, etc.

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5/6

My talk is suitable for this workshop

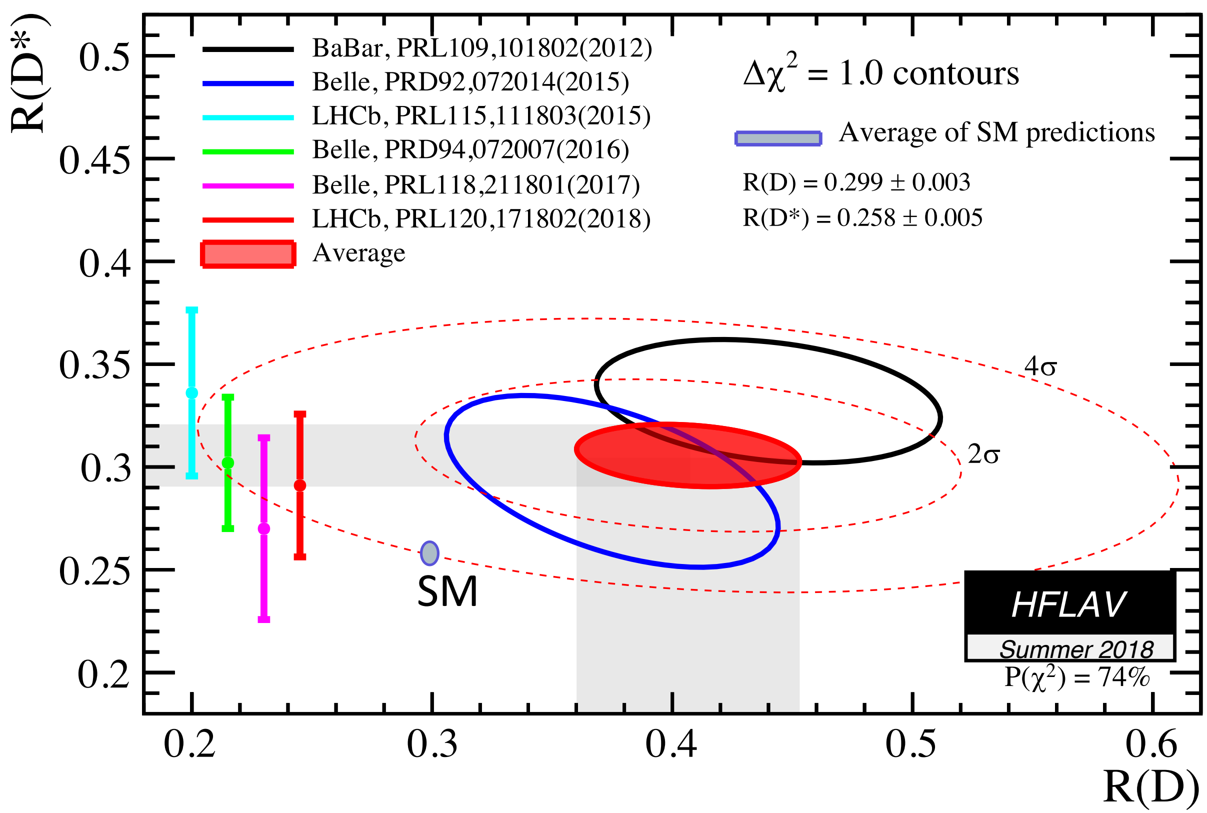
Menu

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

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

3.8σ discrepancy

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



ICHEP 2018

No new experimental result but minor change from last year in SM prediction

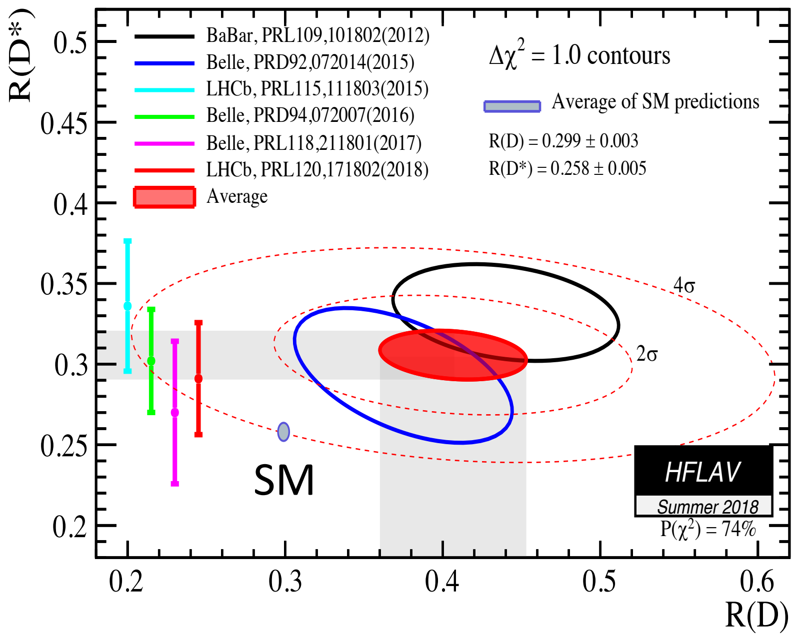
$R(D^*)_{SM} = 0.252$

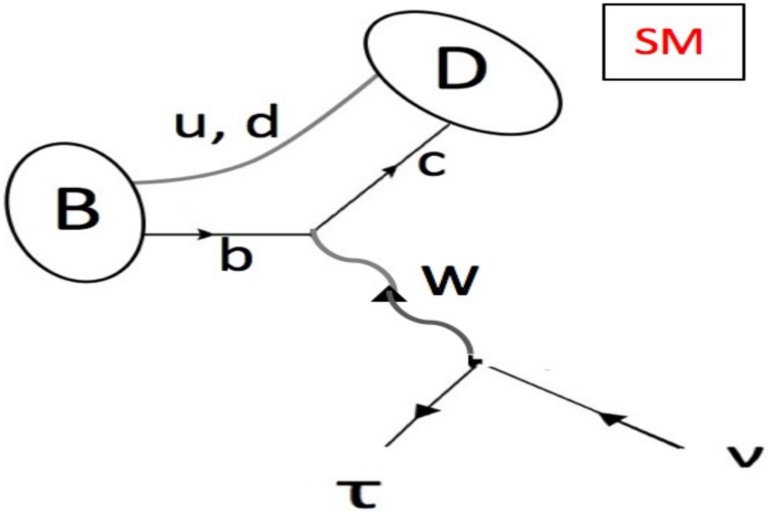
↓

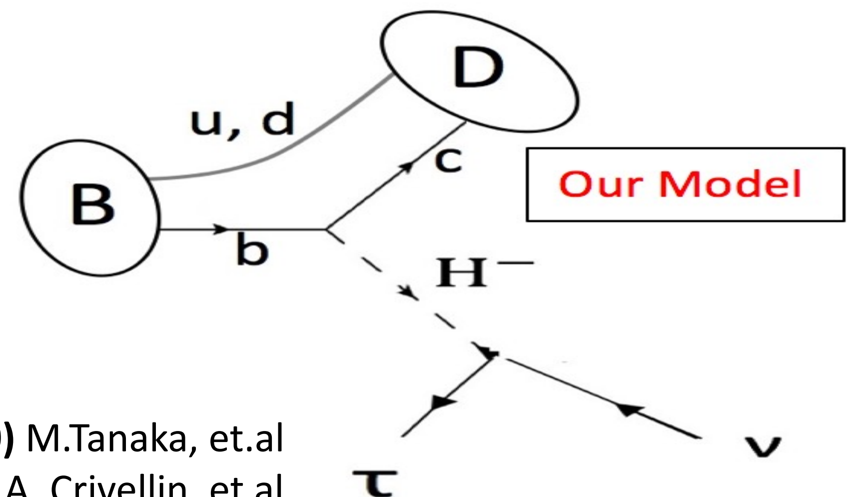
$R(D^*)_{SM} = 0.258$

Naively, H^- is a good candidate.

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







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
- SM Higgs exist!
- Flavor violating Yukawa could exist

Rich flavor phenomenology

Extending Higgs sector keeps the gauge anomaly-free condition automatically

Motivation

Guiding princi

- Simplicity of
- Electroweak

Ge

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- STU parameter is co rollable
- SM Higgs exist!
- Flavor violating Yukaw could exist

may explain the discrepancies in flavor physics

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

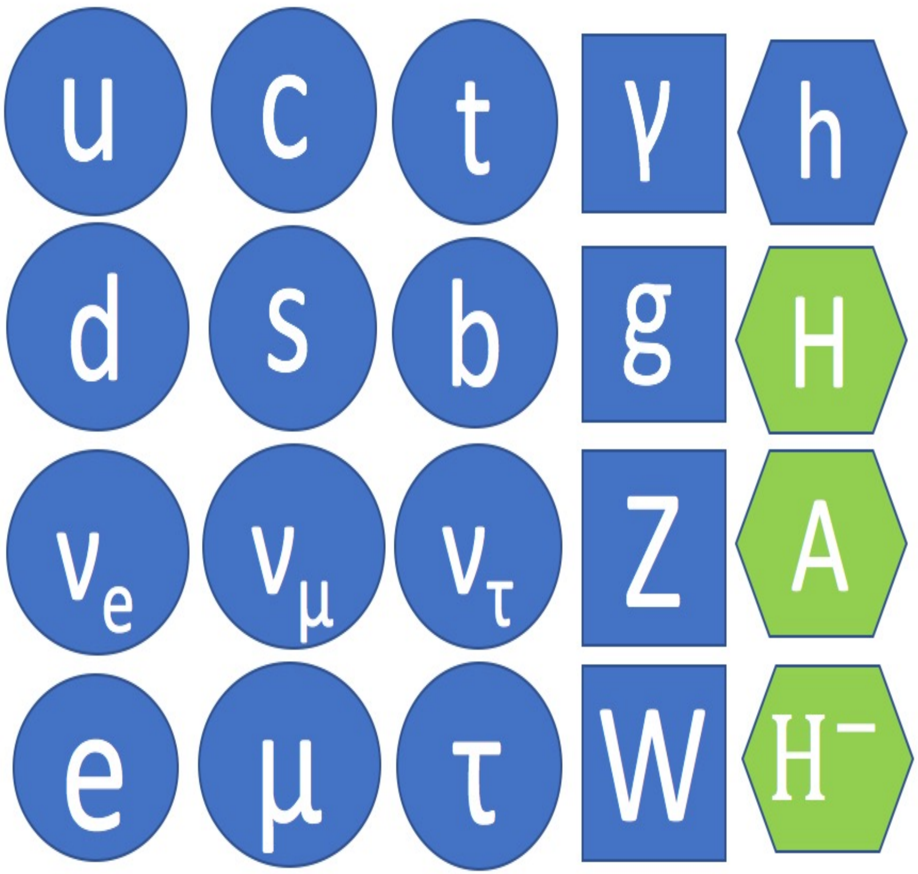
for a combination of them, see **JHEP 1805 (2018) 173** SI, Y. Omura

Rich flavor phenomenology

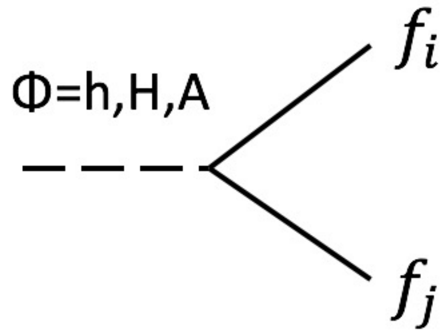
Extending Higgs sector keeps the gauge anomaly-free condition automatically

Our Model

Particle set in G2HDM



Yukawa with neutral scalar



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

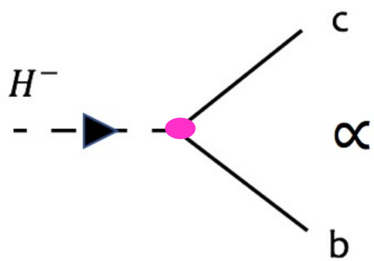
$$y^f_{hij} = \frac{m^i_f}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho^{ij}_f}{\sqrt{2}} c_{\beta\alpha},$$

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

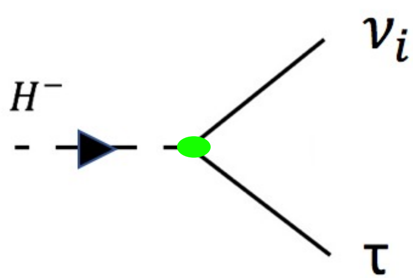
$$y^f_{Hij} = \frac{m^i_f}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho^{ij}_f}{\sqrt{2}} s_{\beta\alpha}$$

Model: G2HDM

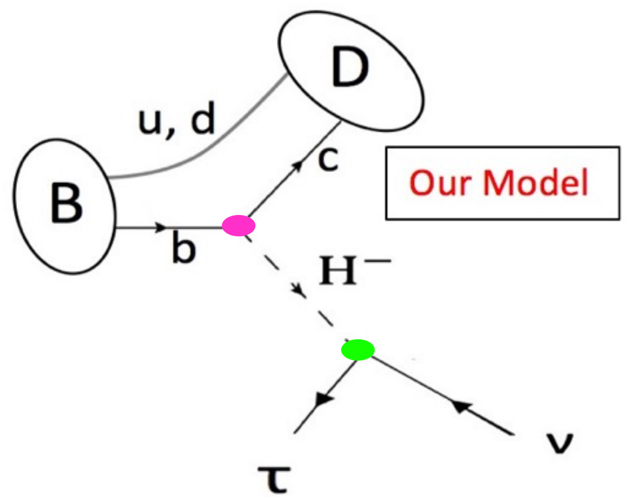
Yukawa interactions relevant to $\mathrm{R}(\mathrm{D}^{(*)})$



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



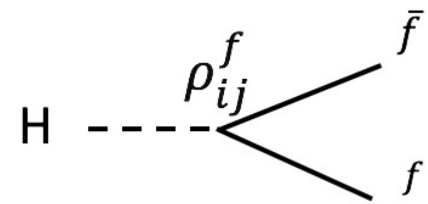
$$\propto (V_{MNS}^{ki*} \rho_e^{k\tau})$$



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

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

Yukawa couplings



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

Experimentally, Yukawa couplings are constrained

e.g. Stringent bounds come from

- meson mixing
- b→sγ
- B→τν .....

$\rho_d^{sb} << 1$, but
ρ_u^{tc} can be O(1)

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

We drop other Yukawas by hand

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

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

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

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

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

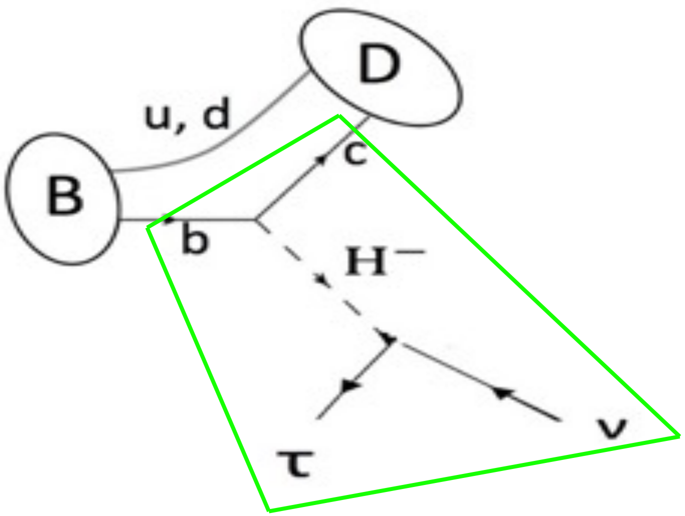
$$R(D) \simeq R(D)_{SM}\left\{1 + 1.5\mathrm{Re}\left[C_R^{\prime S}\right] + |C_R^{\prime S}|^2\right\},$$

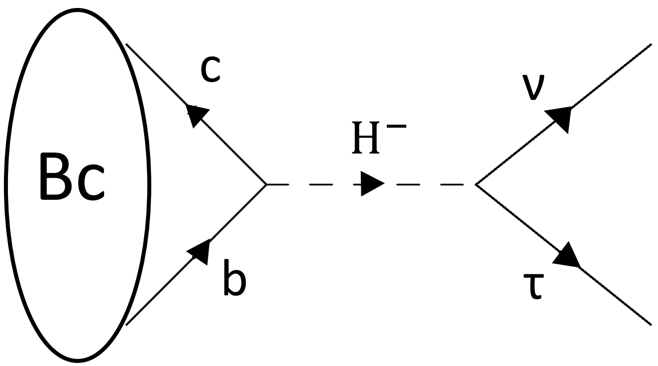
$$R(D^*) \simeq R(D^*)_{SM}\left\{1 - \underline{0.12}\mathrm{Re}\left[C_R^{\prime S}\right] + \underline{0.05}|C_R^{\prime S}|^2\right\}$$

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

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

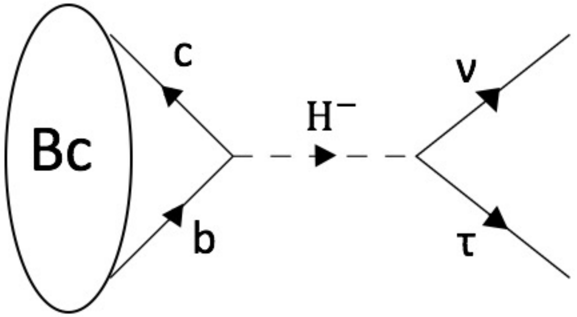
Diagram for $\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ automatically contributes to ($B_c^- \to \tau\bar{\nu}$)





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

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



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

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

Scalar operators have a large coefficient

≈ 4

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

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

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

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

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

Conservative bound

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

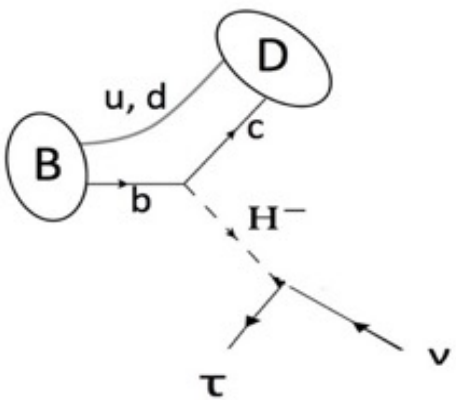
$< 10\%$ A.G.Akeroyd.et al. 1708.04072

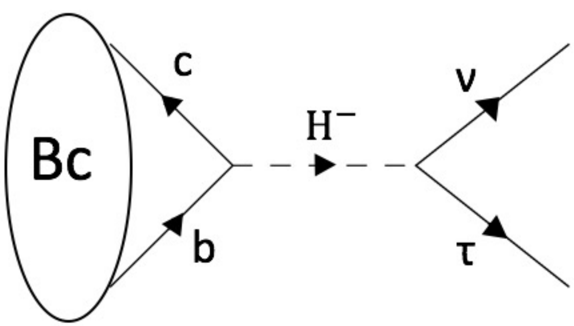
LEP has an upper limit on $\mathrm{B_c} \to \tau\bar{\nu} + \mathrm{B} \to \tau\bar{\nu}$. Combining recent result of LHCb, they got an upper limit on BR($B_c^- \to \tau\bar{\nu}$).

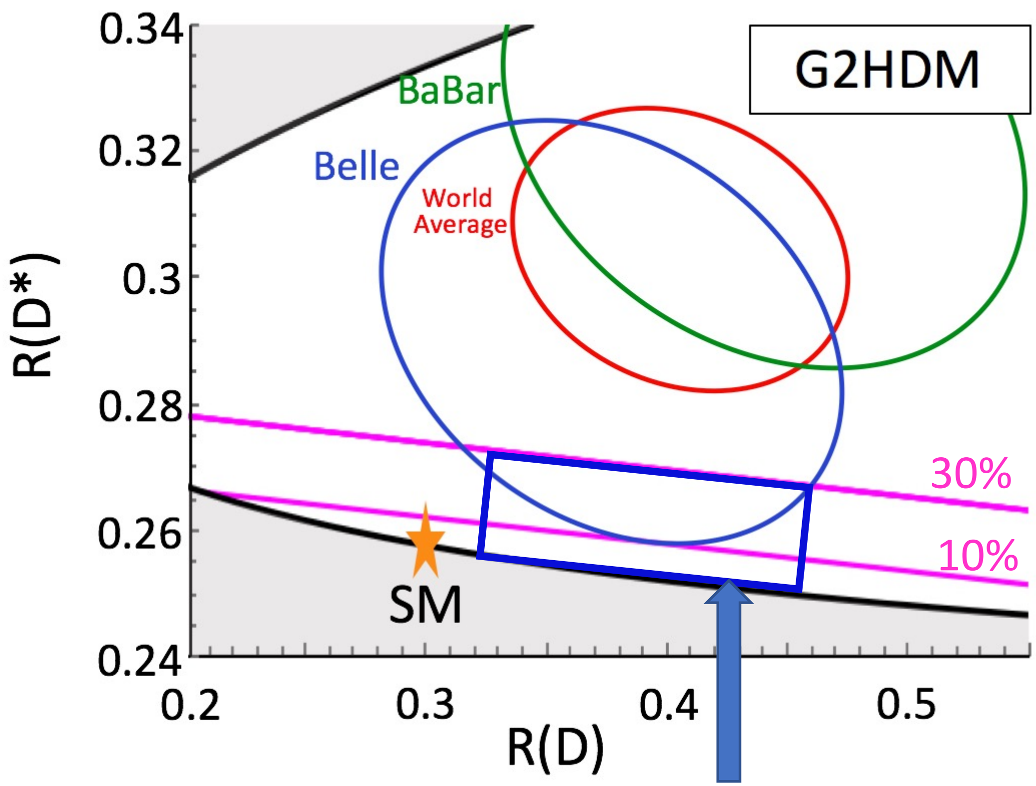
comment: they used BR($B_c \to J/\psi l\nu)_{SM}$ as an input.

Current status of $\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ in G2HDM

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







Still explain only R(D).

Collider study

Why collider study?

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

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

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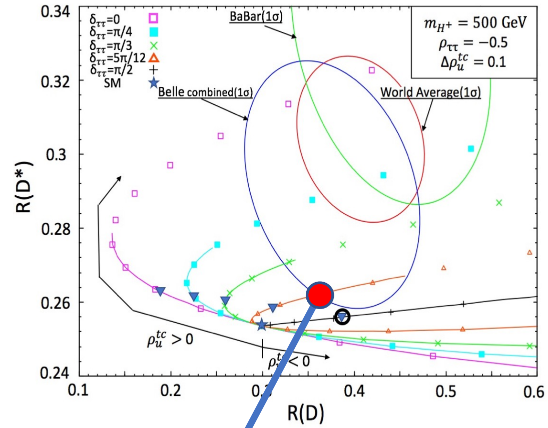
Large coefficient is necessary to enhance R(D*) in our model.

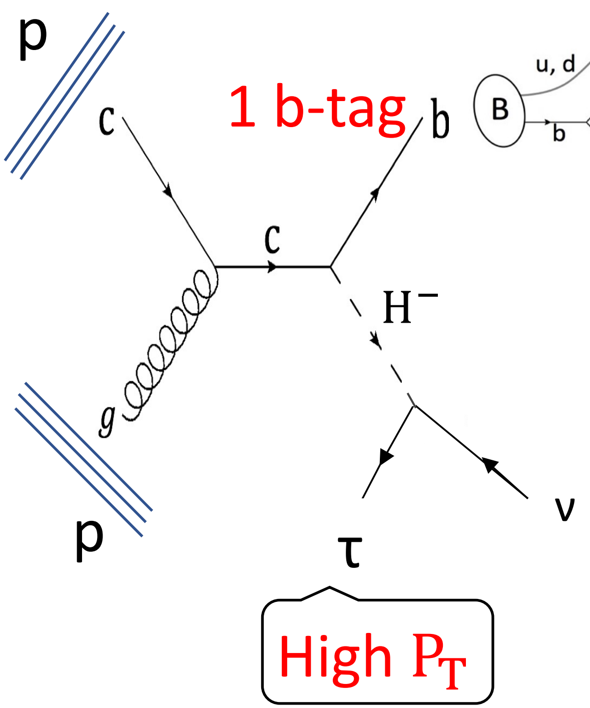
↓

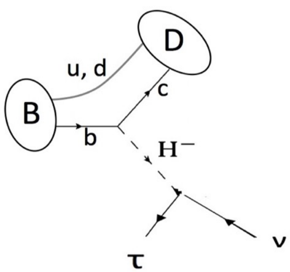
Large couplings, light mass → LHC can test it

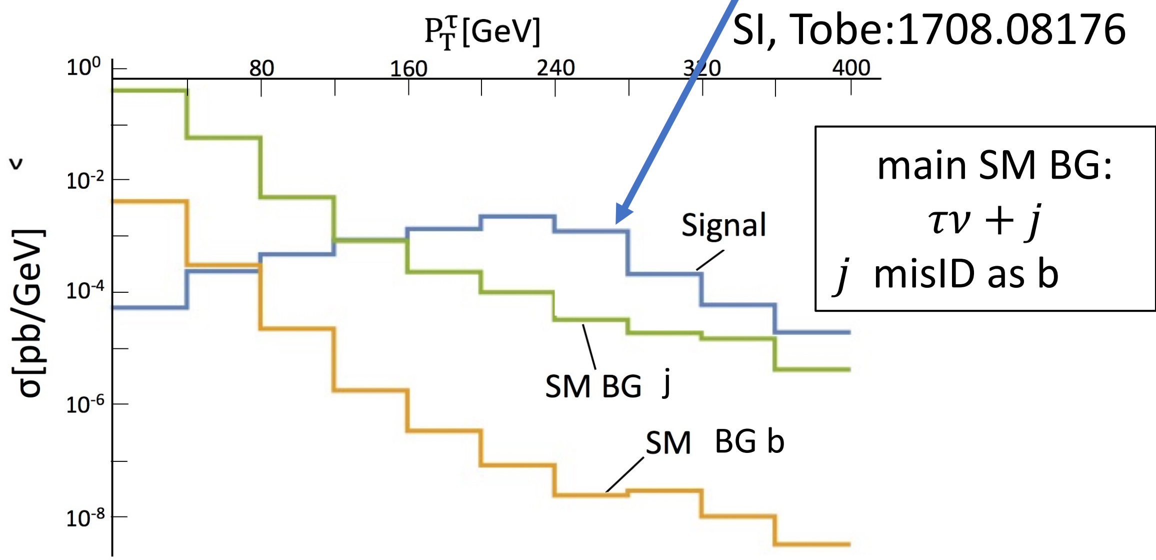
Implications for LHC

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









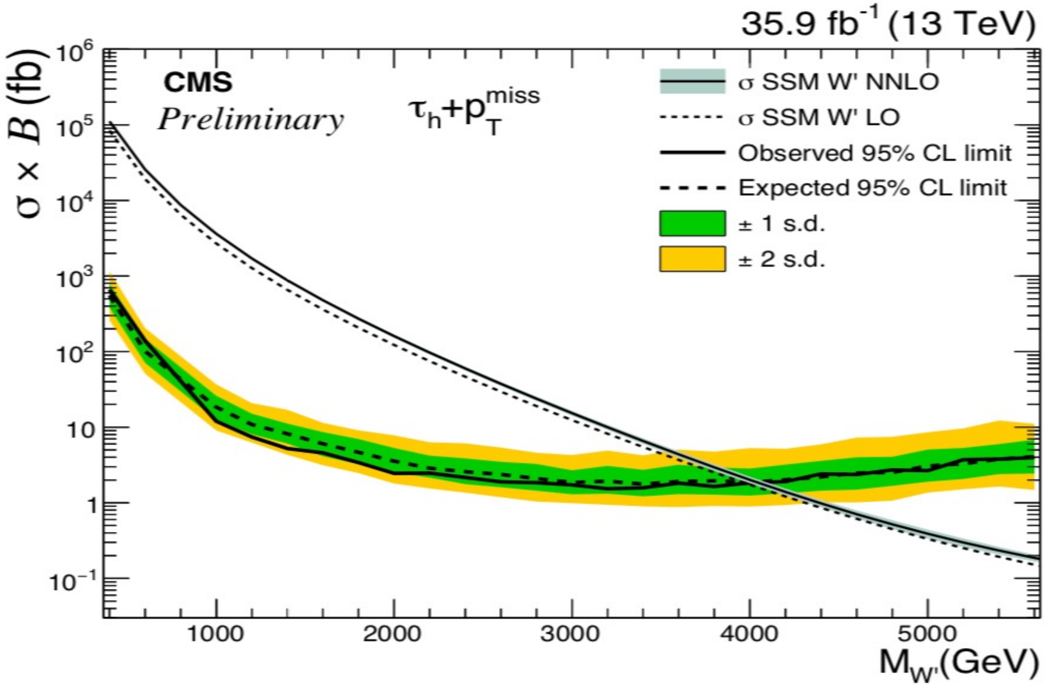
This process looks promising, but not measured yet

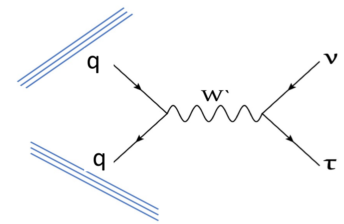
Any direct limit from collider experiment right now?

$\tau\nu$ resonance search

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

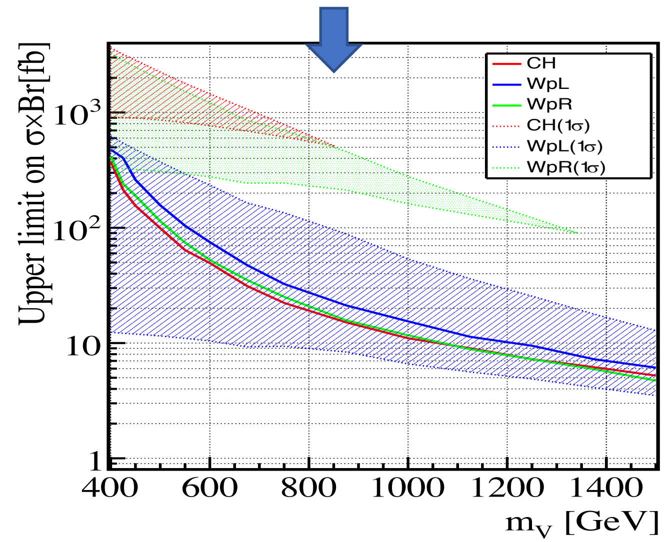
But, the limit is for W'. CMS-PAS-EXO-17-008





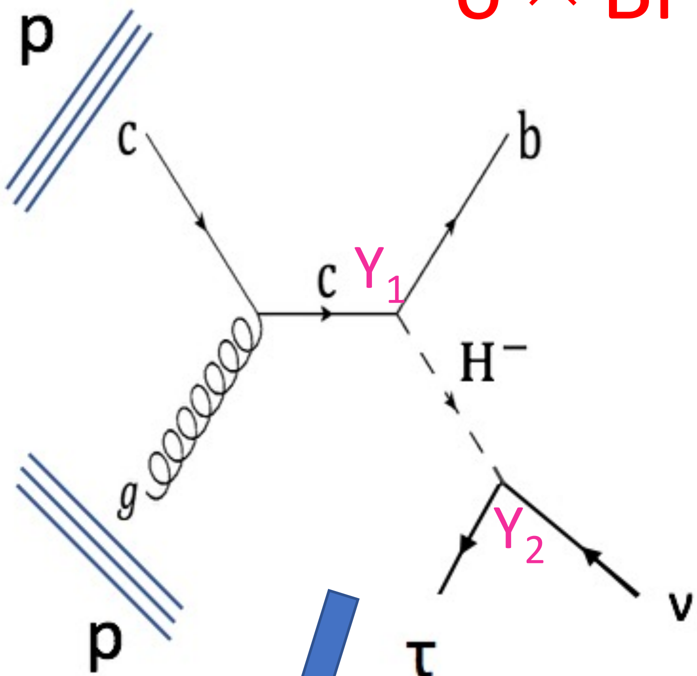
Need to reinterpret this limit for H^-.

We compared efficiencies for H^- and W', then obtained the limit.

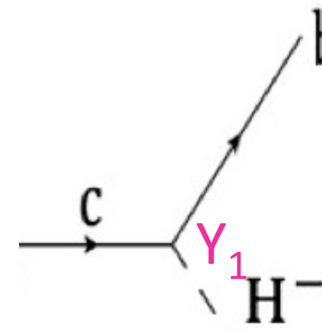


Experiment:arXiv	$\sqrt{s}$[TeV]	L[fb^{-1}]	Range $M_{W'}$[TeV]
CMS:1508.04308	7,8	19.7	0.3–4
CMS:CMS-PAS-EXO-16-006	13	2.3	1–5.8
ATLAS:1801.06992	13	36.1	0.5–5
CMS:CMS-PAS-EXO-17-008	13	35.9	0.4–4

$\sigma \times$ Br in G2HDM



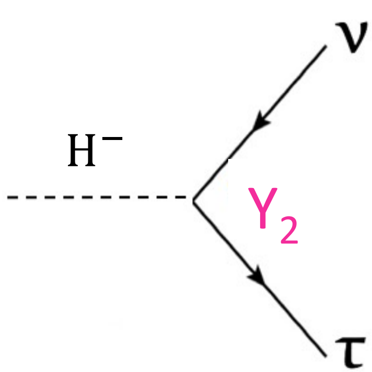
Production



depending on H^- mass

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

Branching ratio



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

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

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

$\Gamma(\mathrm{H}^- \to \mathrm{bc}) \sim 0.06|Y_1|^2 m_{H^-}$ $\quad$ $\Gamma(\mathrm{H}^- \to \tau\nu) \sim 0.02|Y_2|^2 m_{H^-}$

$\Gamma/m_{H^-} < 0.1$

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

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

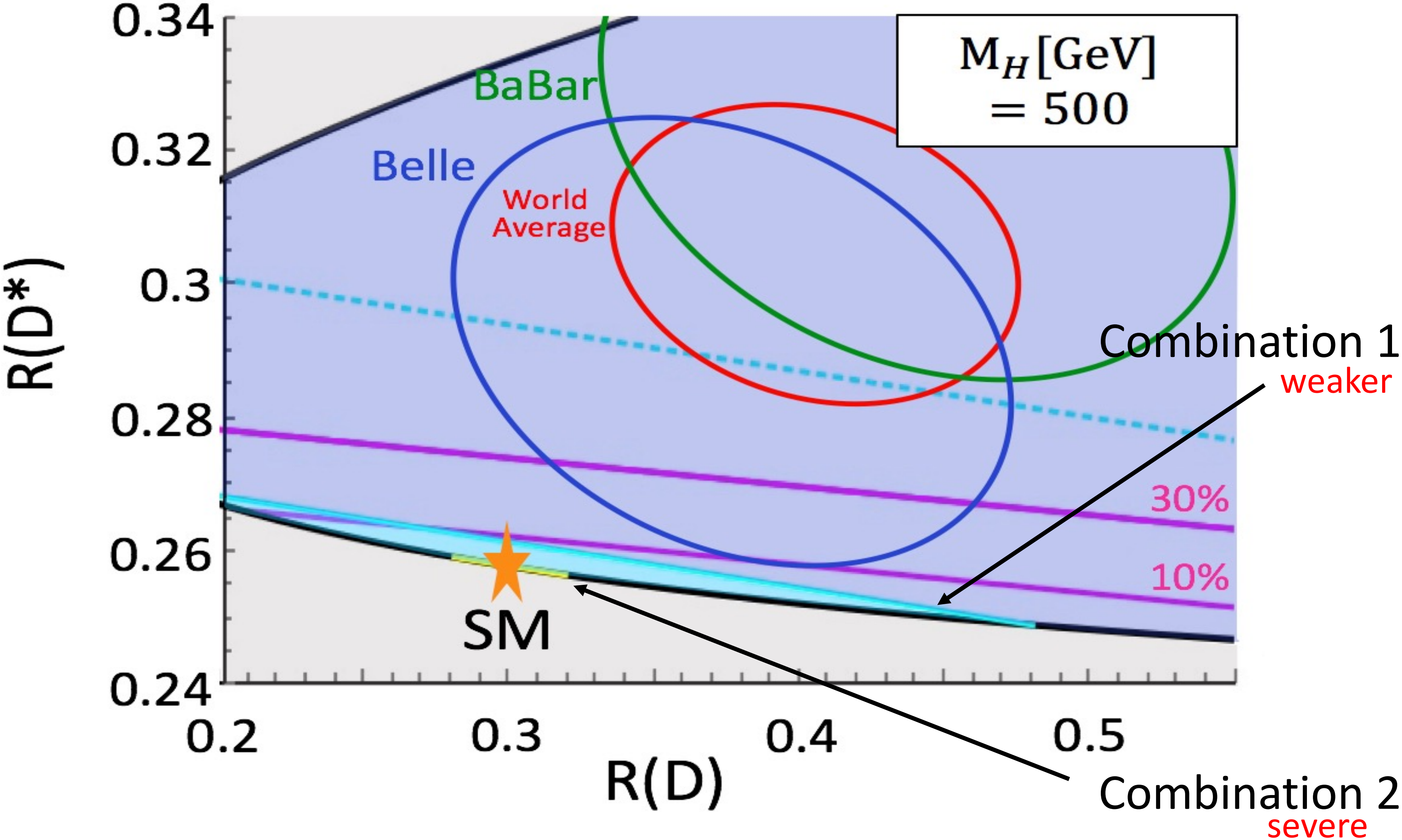
Combination 1 : $Y_1 = 1$, maximizing denominator.

weaker constraint.

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

severe constraint.

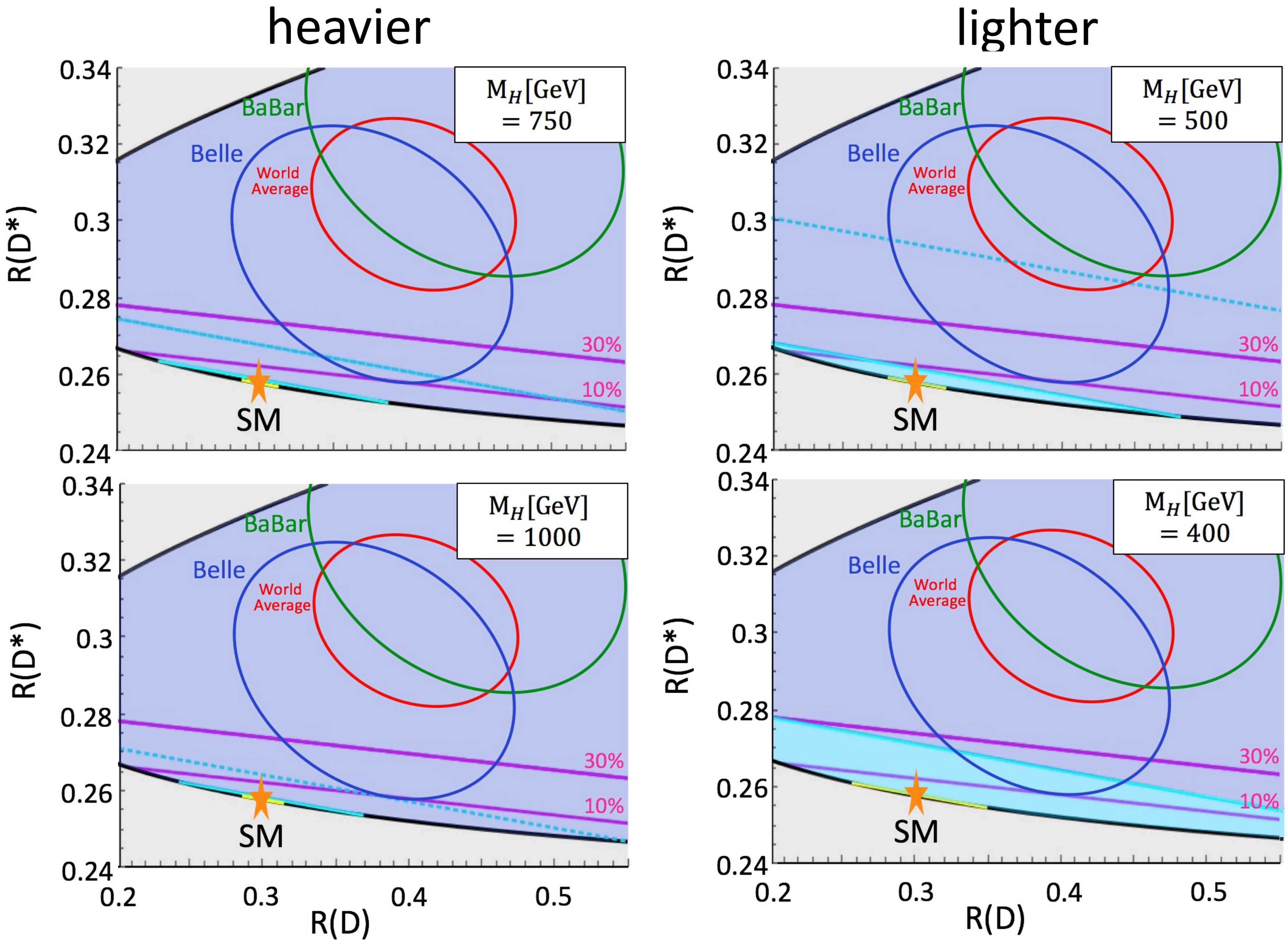
Result



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

Result

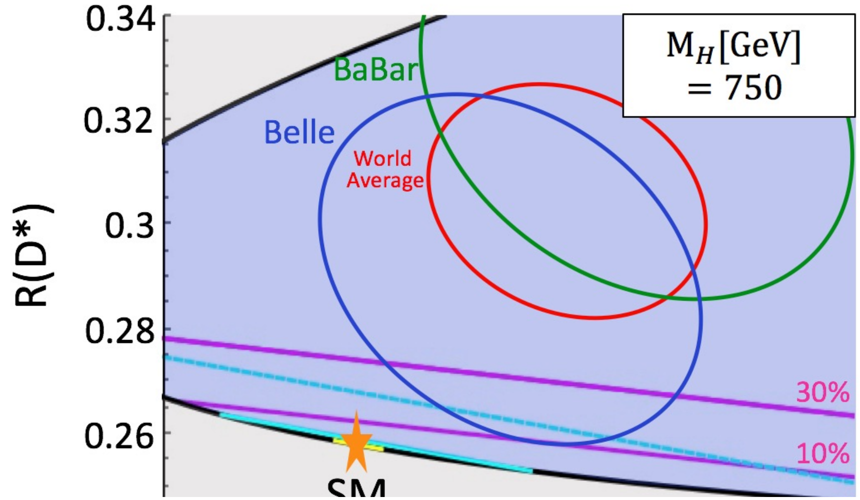
Heavier H^{-}, more severe constraint.



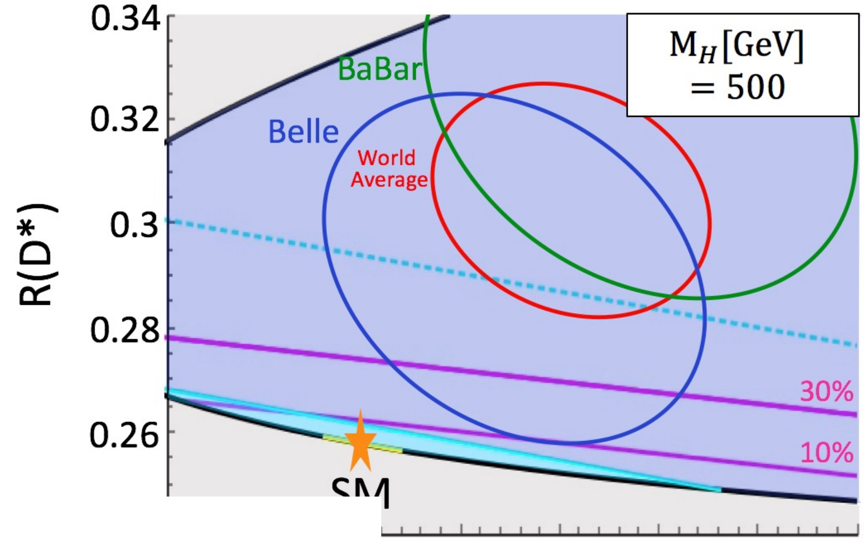
Result

Heavier H^-, more severe constraint.

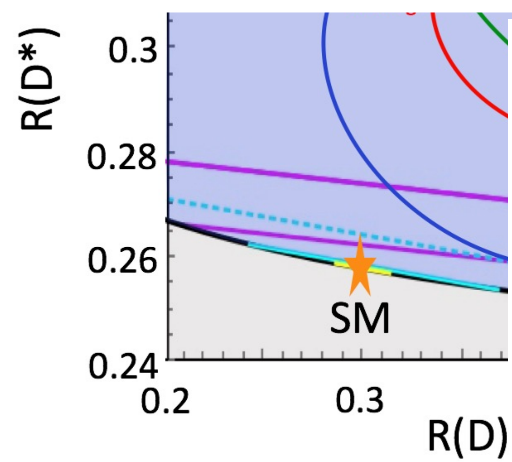
heavier

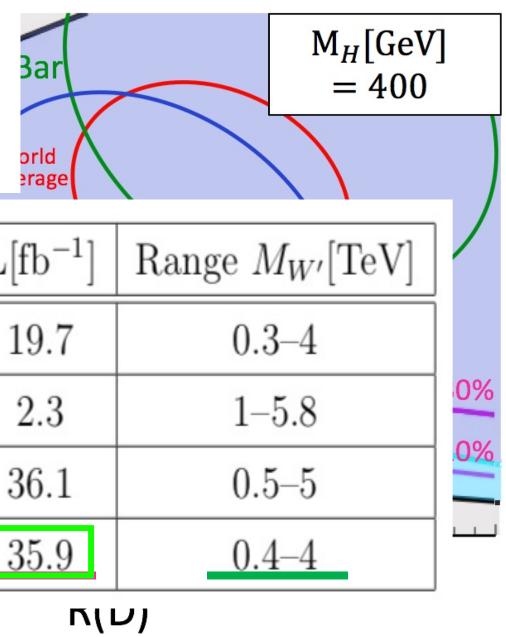


lighter



Better sensitivity for heavy $\tau\nu$ resonance:
low background from W→ $\tau\nu$.





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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

- 140 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

Menu

- 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.

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....

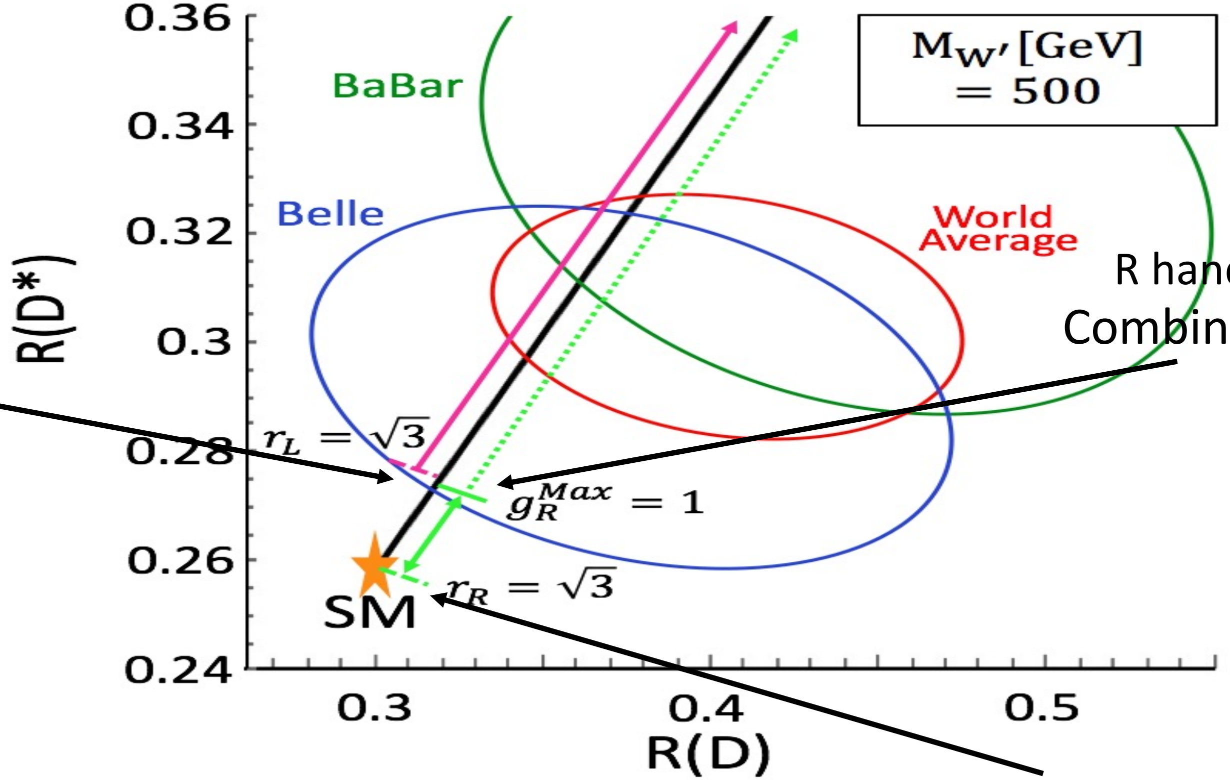
$$L_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb}\left[\left(1 + C_L'^{\,V}\right)\left(\bar{\tau}\gamma_\mu P_L \nu\right)\left(\bar{c}\gamma^\mu P_L b\right)\right] + C_R'^{\,V}\left(\bar{\tau}\gamma_\mu P_R \nu\right)\left(\bar{c}\gamma^\mu P_R b\right) + \text{h.c.}$$

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

Left handed vector charged current

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

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



L handed Combination 2

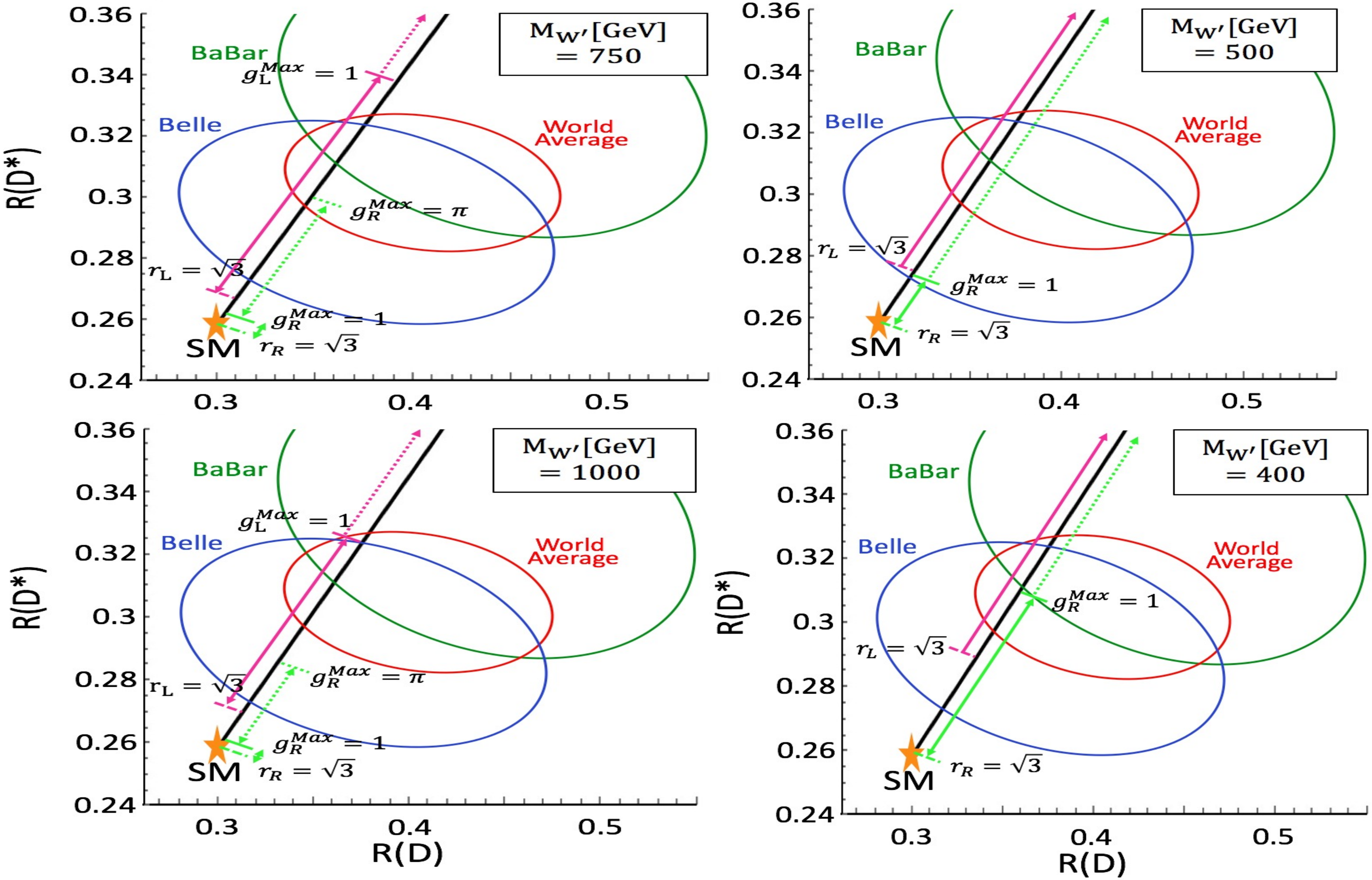
R handed Combination 1

Combination 2

Result

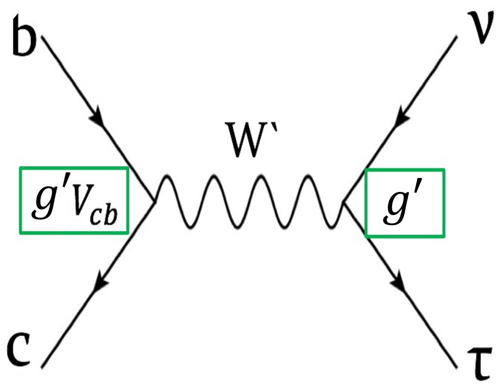
the heavier W', the more severe constraint.

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→bb→Z' →ττ A.Greljo,et al:1609.07138

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

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

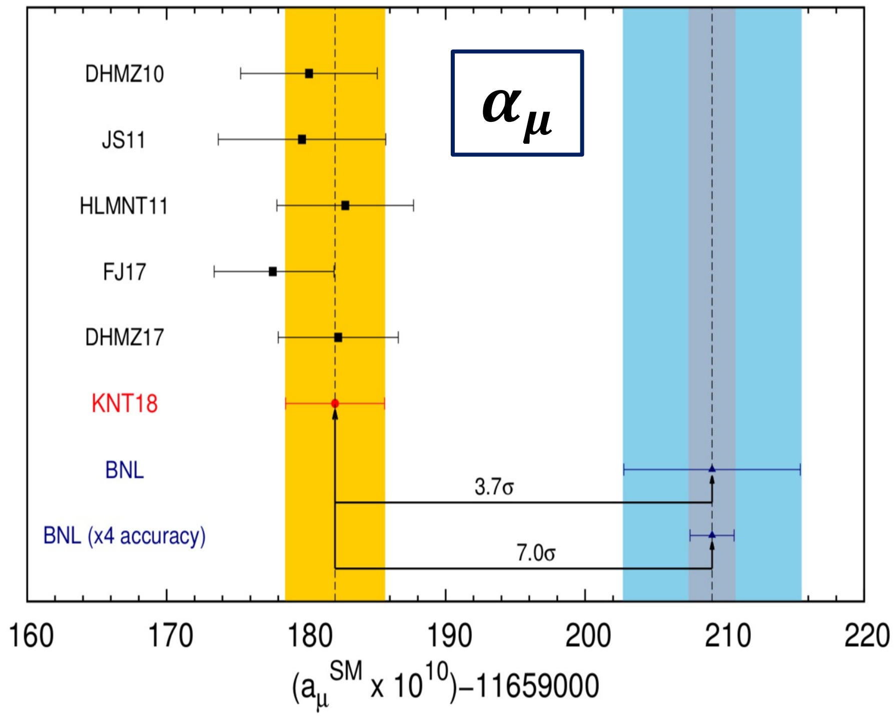
or X X O X O

JHEP 1805 (2018) 173 SI, Y. Omura

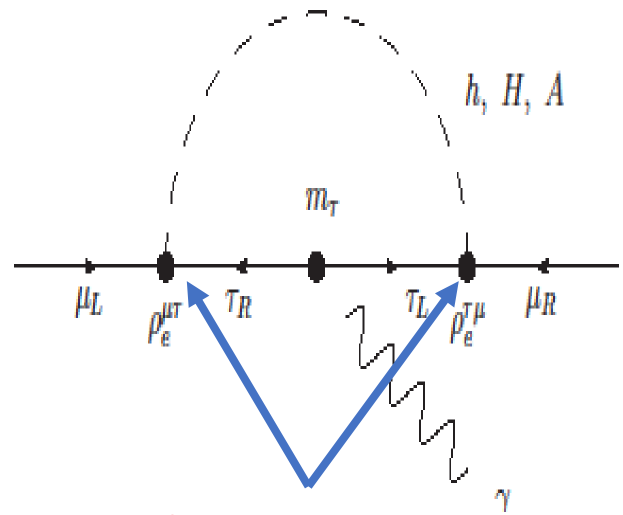
Anomalies to try to explain

muon g-2 anomaly >3σ discrepancy

can be explained in G2HDM Omura, Senaha, Tobe: **JHEP 1505 (2015) 028**



Alexander,et al:1802.02996



μ-τ Lepton flavor violating coupling generates τ mass enhancement

Chirality flip by τ ~~(μ)~~ mass

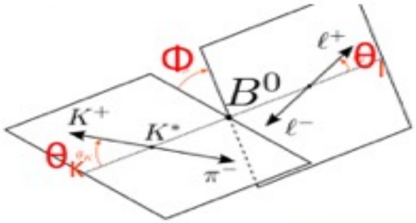
$$\alpha_\mu \approx \frac{m_\mu m_\tau \rho_e^{\mu\tau}\rho_e^{\tau\mu}}{16\pi^2}\left(\frac{log\frac{m_H^2}{m_\tau^2}-\frac{3}{2}}{m_H^2}-\frac{log\frac{m_A^2}{m_\tau^2}-\frac{3}{2}}{m_A^2}\right)$$

$$\approx 2.6\left(\frac{\rho_e^{\mu\tau}\rho_e^{\tau\mu}}{-0.034}\right)\times 10^{-9} \text{ for } (m_A, m_H) = (200{,}250) \text{ GeV}$$

$m_A - m_H \neq 0$ is needed

P'_5 anomaly in G2HDM

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



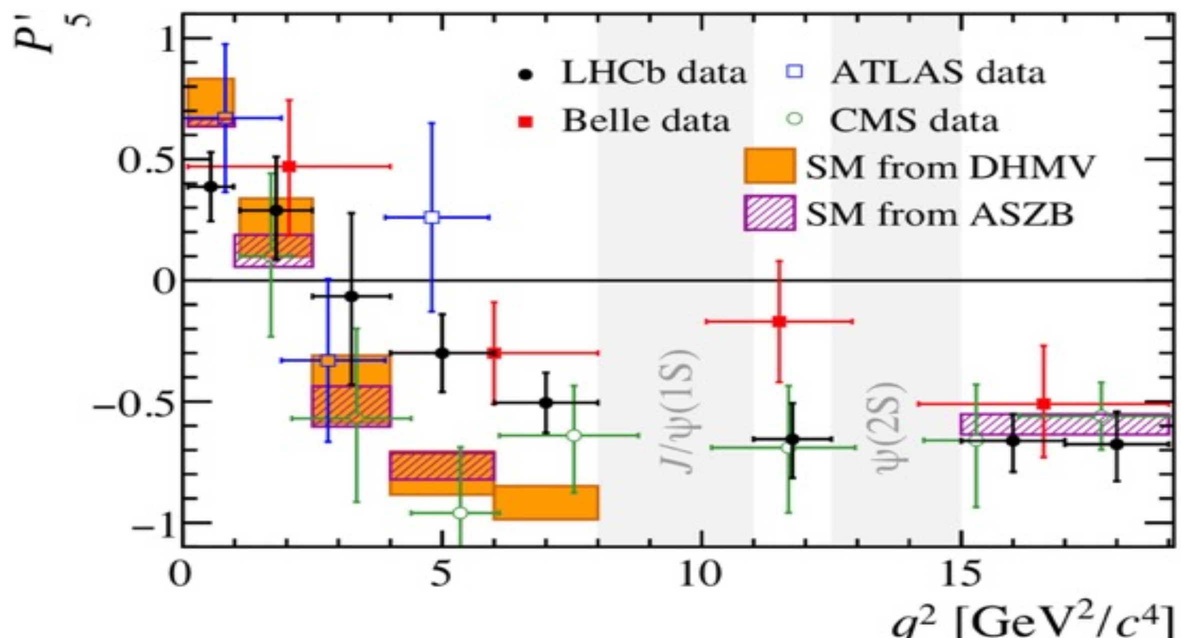
b→s transition

Optimized observable

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

P'_5 : angular observable

in $B\to K^*\mu\mu$



Talk by C. Langenbruch (RWTH)@ Moriond EW 2018

P'_5 anomalies

$$\mathcal{H}_{B_s} = -g_{\rm SM}\left\{C_9^l(\overline{s_L}\gamma_\mu b_L)(\bar{l}\gamma^\mu l) + C_{10}^l(\overline{s_L}\gamma_\mu b_L)(\bar{l}\gamma^\mu\gamma_5 l) + h.c.\right\},$$

$$g_{\rm SM} = \frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{e^2}{16\pi^2}.$$

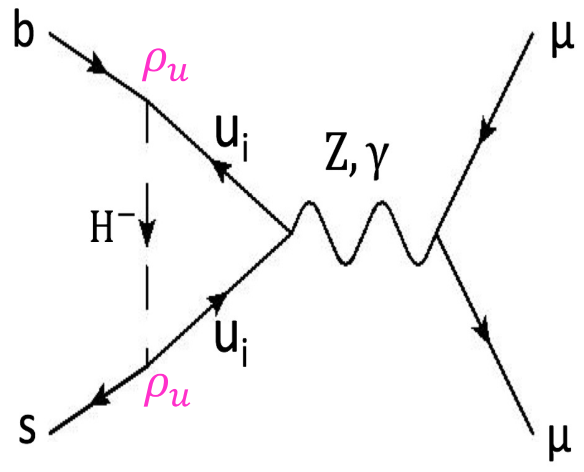
ρ_u^{tc} generates charm rotating diagrams : u_i =c

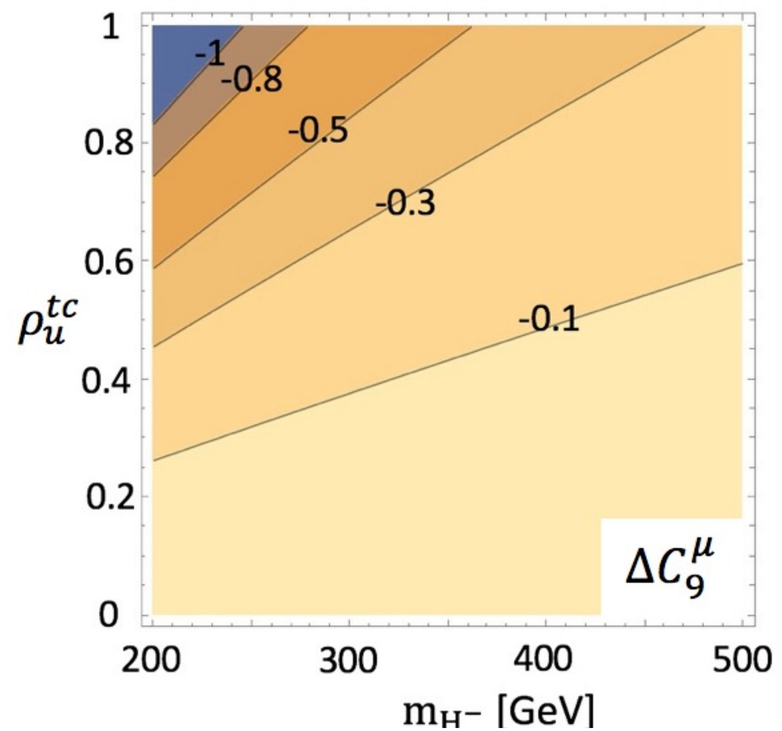
This γ penguin contribution has a dimensionless $\log\frac{m_c}{m_{H^-}}$ enhancement

P'_5

$\Delta C_9^\mu \approx -1$ or $\Delta C_9^\mu = -\Delta C_{10}^\mu \approx -0.5$

is favored G. D' Amico et al. 1704.05438





$R(K^{(*)})$ anomalies

$$\mathcal{H}_{B_s} = -g_{\rm SM}\left\{C_9^l(\overline{s_L}\gamma_\mu b_L)(\bar{l}\gamma^\mu l) + C_{10}^l(\overline{s_L}\gamma_\mu b_L)(\bar{l}\gamma^\mu\gamma_5 l) + h.c.\right\},$$

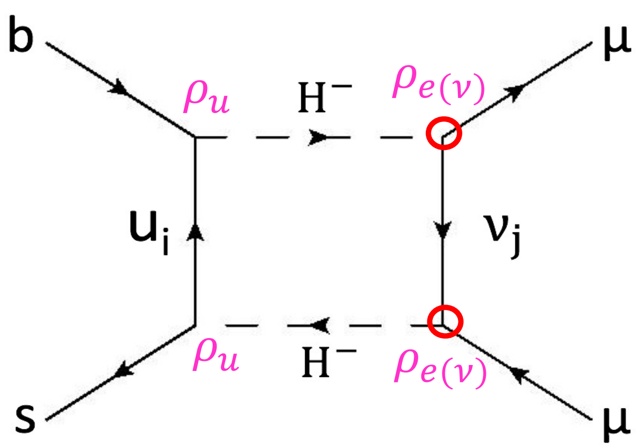
$$g_{\rm SM} = \frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{e^2}{16\pi^2}.$$

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

Lepton flavor dependent coupling is needed

$\Delta C_9^\mu \approx -1$ or $\Delta C_9^\mu = -\Delta C_{10}^\mu \approx -0.5$

with $\Delta C_9^e = \Delta C_{10}^e = 0$ is favored



$\rho_u \times \rho_e$ generates $\Delta C_9^\mu = \Delta C_{10}^\mu$

opposite sign

$\rho_u \times \rho_\nu$ generates $\Delta C_9^\mu = -\Delta C_{10}^\mu$

We can not have ρ_ν enough large to explain $R(K^{(*)})$.

Constraint from N_{eff}^ν

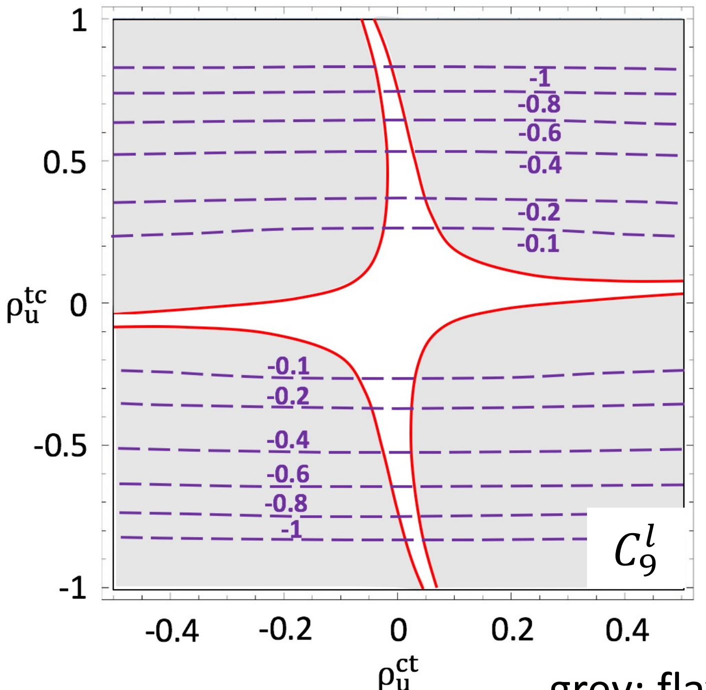
PLANCK: 1303.5076

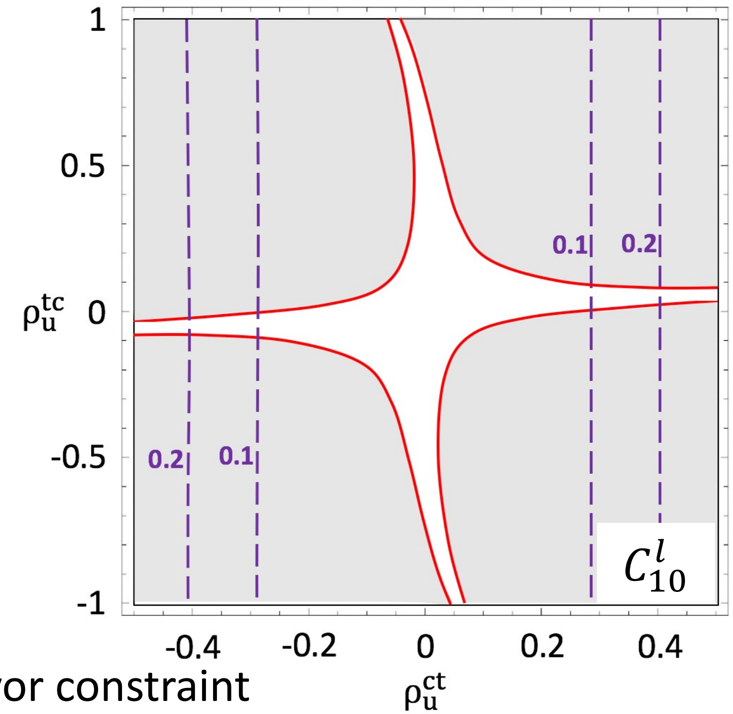
G2HDM can not explain $R(K^{(*)})$.

Other prediction

ρ_u^{tc} which generates a large contribution to C_9^l via γ penguin diagram, do not change $\mathrm{Br}(\mathrm{B_s} \to \mu\mu)$.

$$\frac{\mathrm{Br}(\mathrm{B_s} \to \mu\mu)}{\mathrm{Br}(\mathrm{B_s} \to \mu\mu)_{\mathrm{SM}}} = |1 - 0.24 C_{10}^{\mu}|^2$$

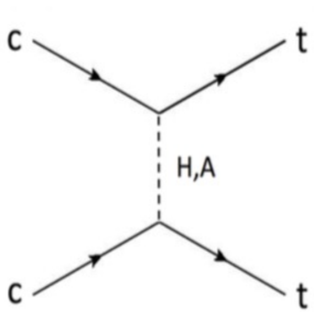


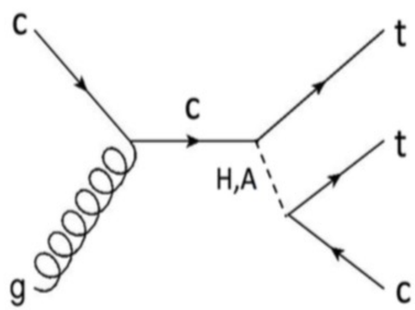


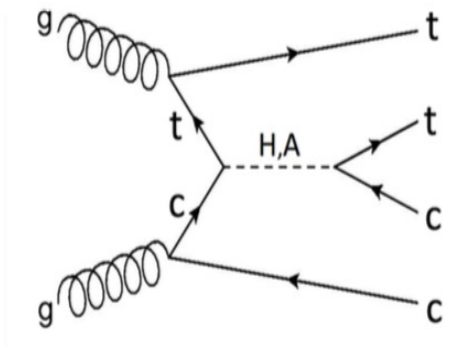
grey: flavor constraint

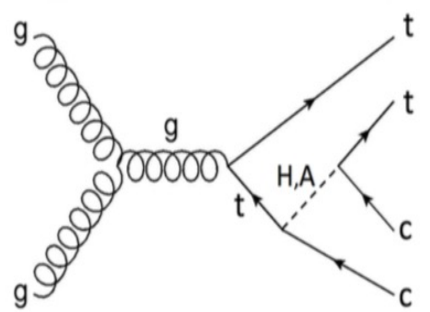
Collider signal

Same sign top is most striking









$$\sigma(pp \to tt + \bar{t}\bar{t}) = 4.23 \times 10^{-3} |\rho_u^{tc}|^4$$
$$\sigma(pp \to tt\bar{c} + \bar{t}\bar{t}c) = 4.13 \times 10^{-1} |\rho_u^{tc}|^4$$
$$\sigma(pp \to tt\bar{c}\bar{c} + \bar{t}\bar{t}cc) = 1.14 \times 10^{-1} |\rho_u^{tc}|^4$$

for $(m_A, m_H) = (200{,}250)$ GeV

$m_A = m_H$ suppresses the signal.

Upper bound on σ(same sign top)=1.2 [Pb] CMS:1704.07323 is still weak

For recent progress see 1808.00333.