Status of the semileptonic B decays and muon g-2 in general 2HDMs with right-handed neutrinos

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Based on

JHEP 1805 (2018) 173 S.I, Y. Omura(KMI),

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

What I do today

I summarize a compatibility of explaining anomalies in **B decays** and **muon g-2** within a General Two Higgs Doublet Model (G2HDM)

Introduction

Guiding principles for BSM

- Simplicity of the model.
- Electroweak precision test.

Why Higgs?

Extending Higgs sector keeps the gauge anomaly-free condition.
SM Higgs already exist!

General Two Higgs Doublet Model (G2HDM)

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

Rich flavor phenomenology

Introduction

Guiding princi

- Simplicity of
- Electroweak

may explain the discrepancies in flavor physics

- muon g-2
- $\mathrm{R}\left(\mathrm{D}^{(*)}\right)=\mathrm{BR}\left(\mathrm{B} \to \mathrm{D}^{(*)}\tau\nu\right)/\mathrm{BR}\left(\mathrm{B} \to \mathrm{D}^{(*)}\mathrm{l}\nu\right)$
- P'_5 : angular observable in $\mathrm{B} \to \mathrm{K}^{*}\mu\mu$
- $\mathrm{R}\left(\mathrm{K}^{(*)}\right)=\mathrm{BR}\left(\mathrm{B} \to \mathrm{K}^{(*)}\mu\mu\right)/\mathrm{BR}\left(\mathrm{B} \to \mathrm{K}^{(*)}ee\right)$

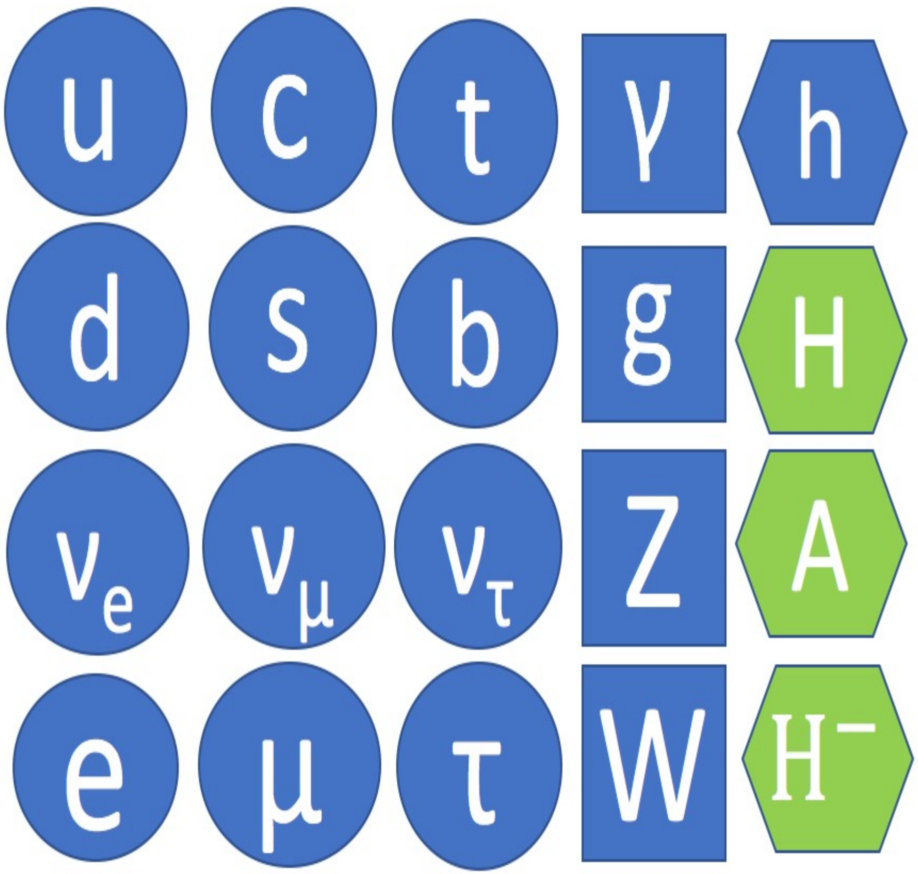
General Two Higgs Doublet Model (G2HDM)

- Simple extensi of scalar sector
- STU paramete s controllable
- Flavor violatin Yukawa could exist

Rich flavor phenomenology

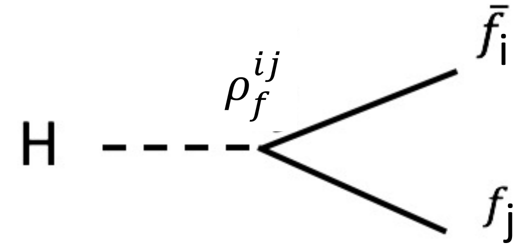
Our Model

Particle set in G2HDM



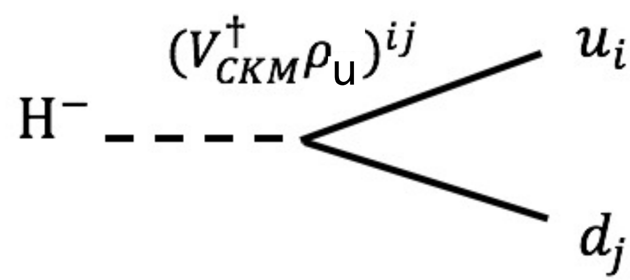
Neutral Scalar

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



Charged Scalar

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



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→sγ
- B→τν .....

$$\rho_d^{ij} << 1,$$

ρ_u^{ij} other than ρ_u^{tc}, ρ_u^{ct} , ρ_u^{tt} should be small

We turn them off for simplicity and clarify how this model can explain those anomalies

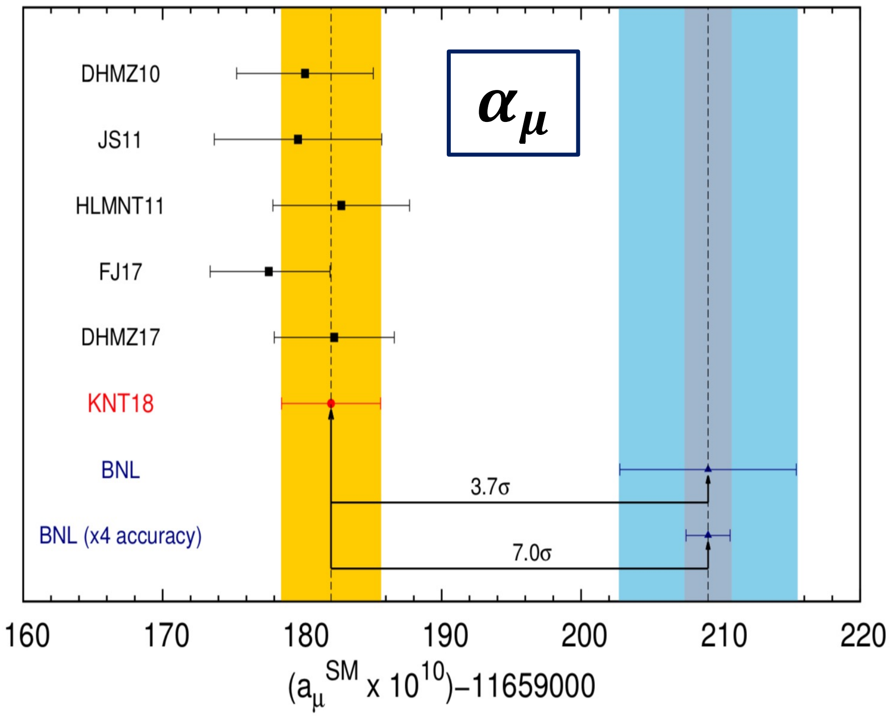
For the top-down approach of this model see e.g. Cheng et al. 1507.04354

S.I et al. 1804.07478 Poster T_14

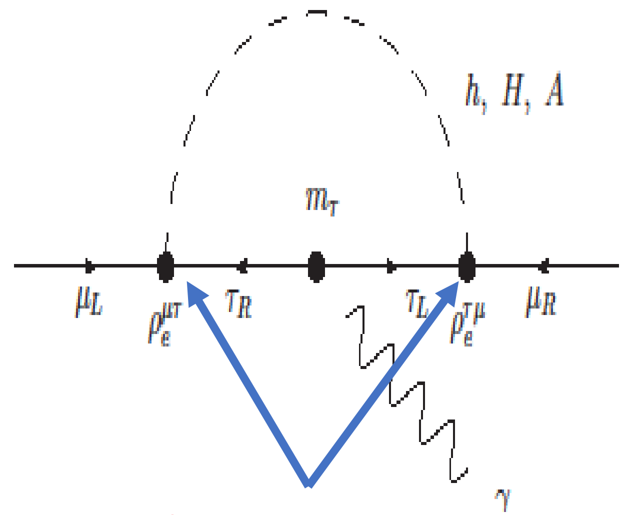
Anomalies to try to explain

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

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

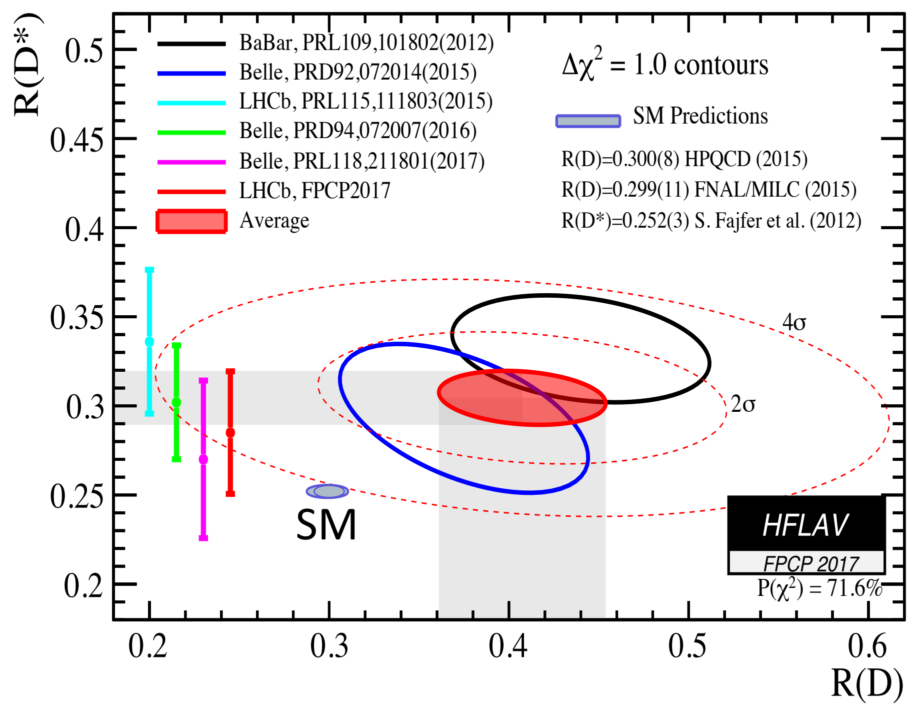
$$\approx 2.6 \left(\frac{\rho_e^{\mu\tau} \rho_e^{\tau\mu}}{-0.034}\right) \times 10^{-9} \text{ for } (m_A, m_H) = (200{,}250) \text{ GeV}$$

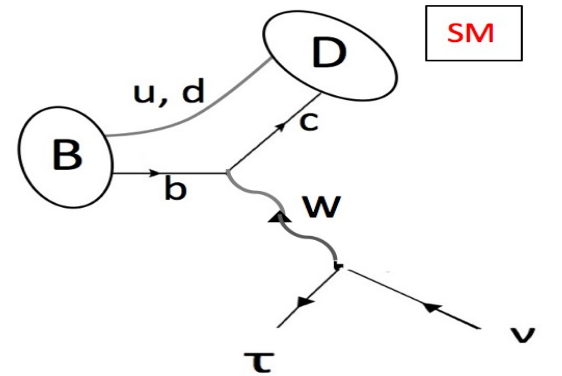
$m_A - m_H \neq 0$ is needed

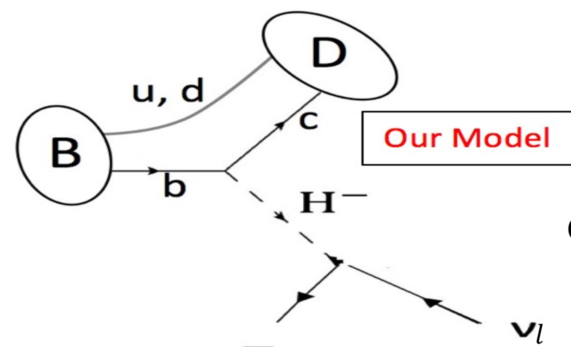
$\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ anomaly $\approx 4\sigma$ discrepancy

b-c transition

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







$$\propto \frac{\rho_u^{tc} \rho_\tau^{l\tau}}{m_{H^-}^2}$$

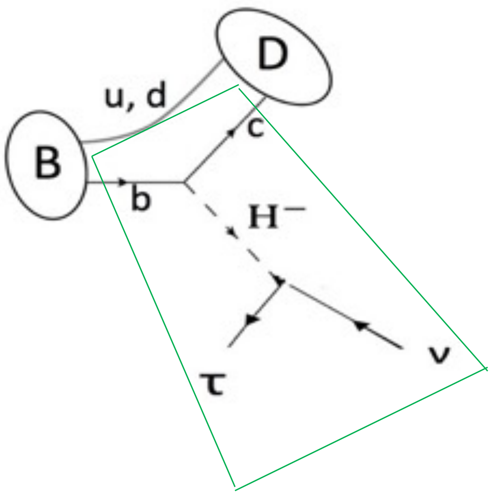
l; lepton flavor of a neutrino

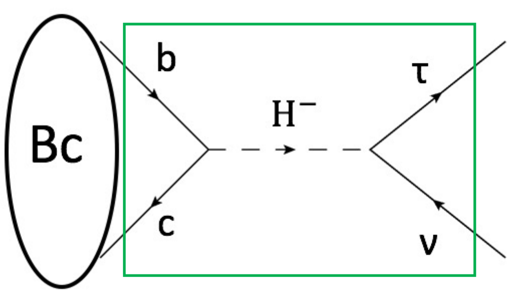
Phys.Rev. D86 (2012) 054014 A. Crivellin et al.
Nucl.Phys. B925 (2017) 560-606 w/ K. Tobe(KMI,Nagoya-U),,,,,

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

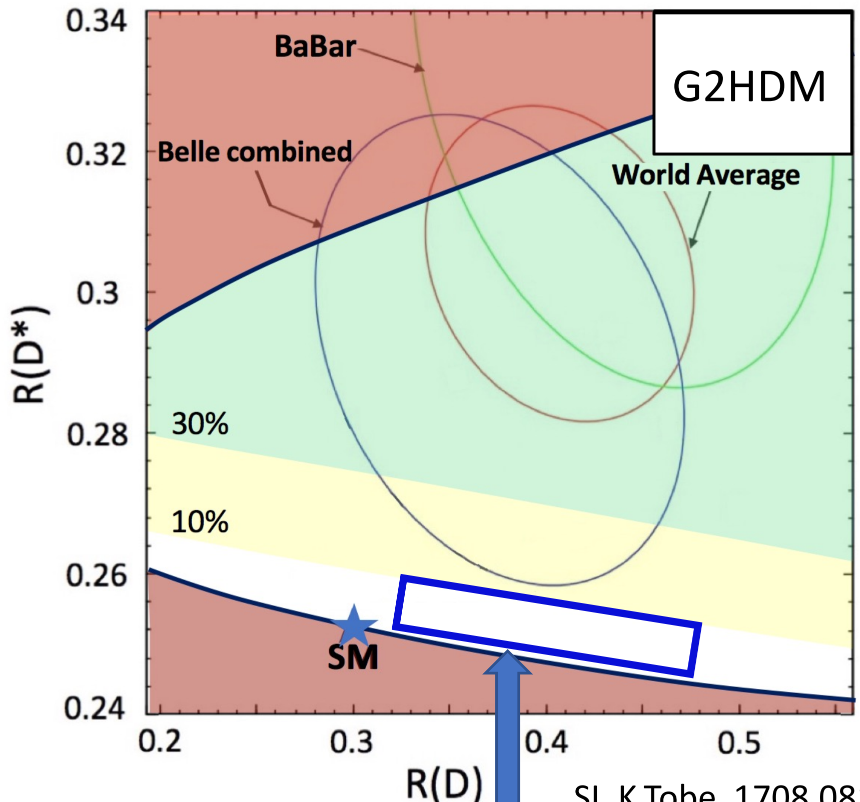
R.Alonso et al. 1611.06676, A.G.Akeroyd.et al. 1708.04072

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





G2HDM can not reach red region



SI, K.Tobe 1708.08176

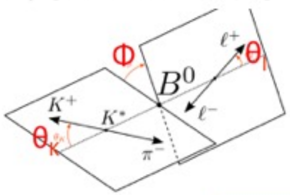
$$\frac{\rho_u^{tc}\rho_\tau^{l\tau}}{m_{H^-}^2} \approx \frac{0.03}{300^2}$$

Still explains only R(D).

$P'_5, R(K^{(*)})$ anomalies

b→s transition

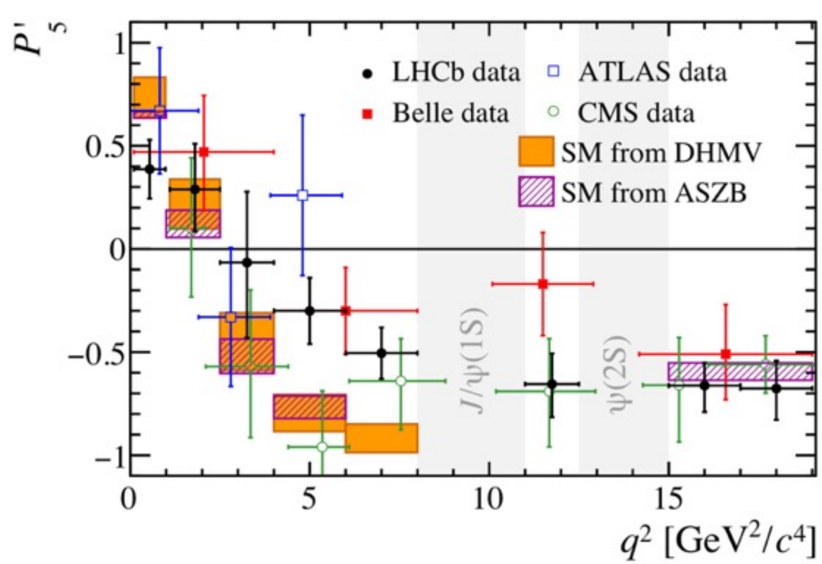
P'_5 : angular observable in $B \to K^*\mu\mu$



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

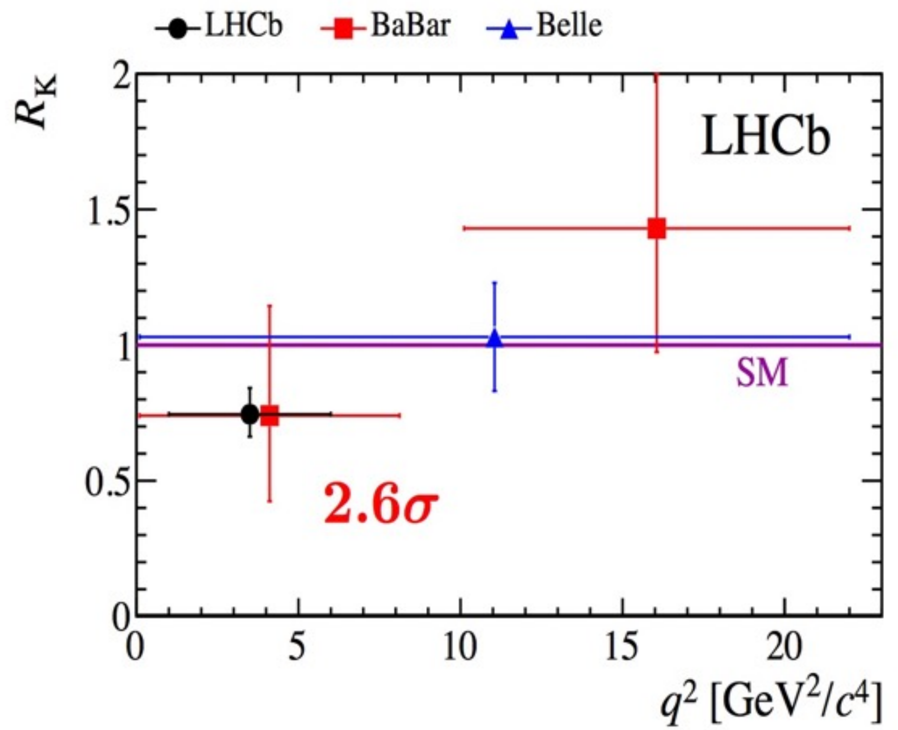
Optimized observable

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



Violation of Lepton Flavor Universality

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$



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

P'_5 anomalies

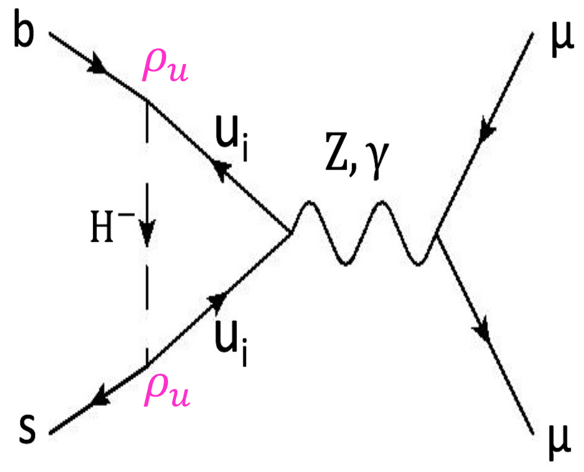
$$\mathcal{H}_{B_s} = -g_{\mathrm{SM}}\left\{C_9^l(\overline{s_L}\gamma_\mu b_L)(\bar{l}\gamma^\mu l) + C_{10}^l(\overline{s_L}\gamma_\mu b_L)(\bar{l}\gamma^\mu\gamma_5 l) + h.c.\right\},$$

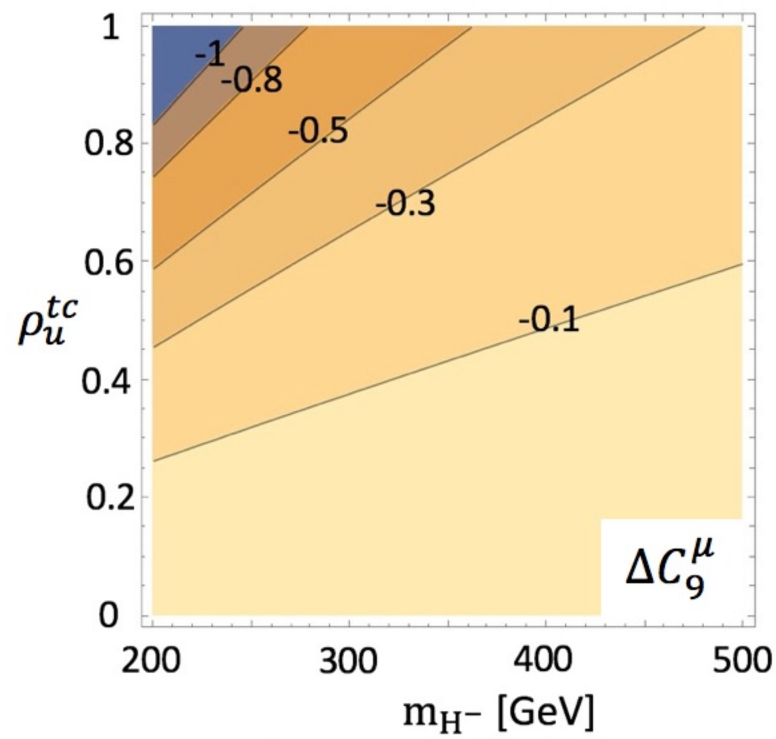
$$g_{\mathrm{SM}} = \frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{e^2}{16\pi^2}.$$

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





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

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

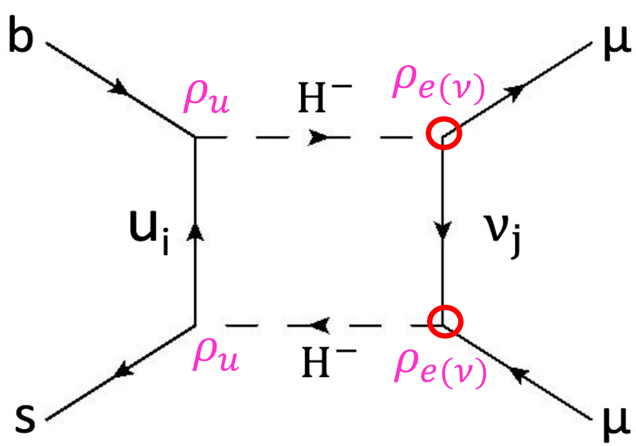
$$g_{\rm SM} = \frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{e^2}{16\pi^2}.$$

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

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 $\mathrm{R}(\mathrm{K}^{(*)})$.

$\boxed{\text{Constraint from } N_{eff}^\nu}$

PLANCK: 1303.5076

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

Result1

$$\rho_u^{ij}=\begin{pmatrix}\rho_u^{uu} & \rho_u^{uc} & \rho_u^{ut}\\ \rho_u^{cu} & \rho_u^{cc} & \rho_u^{ct}\\ \rho_u^{tu} & \rho_u^{tc} & \rho_u^{tt}\end{pmatrix},\rho_d^{ij}=\begin{pmatrix}\rho_d^{dd} & \rho_d^{ds} & \rho_d^{db}\\ \rho_d^{sd} & \rho_d^{ss} & \rho_d^{sb}\\ \rho_d^{bd} & \rho_d^{bs} & \rho_d^{bb}\end{pmatrix}$$

$$\rho_e^{ij}=\begin{pmatrix}\rho_e^{ee} & \rho_e^{e\mu} & \rho_e^{e\tau}\\ \rho_e^{\mu e} & \rho_e^{\mu\mu} & \rho_e^{\mu\tau}\\ \rho_e^{\tau e} & \rho_e^{\tau\mu} & \rho_e^{\tau\tau}\end{pmatrix},\rho_\nu^{ij}=\begin{pmatrix}\rho_\nu^{ee} & \rho_\nu^{e\mu} & \rho_\nu^{e\tau}\\ \rho_\nu^{\mu e} & \rho_\nu^{\mu\mu} & \rho_\nu^{\mu\tau}\\ \rho_\nu^{\tau e} & \rho_\nu^{\tau\mu} & \rho_\nu^{\tau\tau}\end{pmatrix}$$

Result1

Meson mixing, b→sγ,,,,,

$$\rho_u^{ij} = \begin{pmatrix} \rho_u^{uu} & \rho_u^{uc} & \rho_u^{ut} \\ \rho_u^{cu} & \rho_u^{cc} & \rho_u^{ct} \\ \rho_u^{tu} & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}, \rho_d^{ij} = \begin{pmatrix} \rho_d^{dd} & \rho_d^{ds} & \rho_d^{db} \\ \rho_d^{sd} & \rho_d^{ss} & \rho_d^{sb} \\ \rho_d^{bd} & \rho_d^{bs} & \rho_d^{bb} \end{pmatrix}$$

$$\rho_e^{ij} = \begin{pmatrix} \rho_e^{ee} & \rho_e^{e\mu} & \rho_e^{e\tau} \\ \rho_e^{\mu e} & \rho_e^{\mu\mu} & \rho_e^{\mu\tau} \\ \rho_e^{\tau e} & \rho_e^{\tau\mu} & \rho_e^{\tau\tau} \end{pmatrix}, \rho_\nu^{ij} = \begin{pmatrix} \rho_\nu^{ee} & \rho_\nu^{e\mu} & \rho_\nu^{e\tau} \\ \rho_\nu^{\mu e} & \rho_\nu^{\mu\mu} & \rho_\nu^{\mu\tau} \\ \rho_\nu^{\tau e} & \rho_\nu^{\tau\mu} & \rho_\nu^{\tau\tau} \end{pmatrix}$$

μ→eγ, μ-e conversion

Constraint from N_{eff}^{ν}

PLANCK: 1303.5076

Result1

$\mathrm{R}(D)$: $\rho_u^{tc}\rho_e^{\mu\tau}$ is large

$\mathrm{P'}_5$: ρ_u^{tc} is large

muon g-2: $\rho_e^{\tau\mu}\rho_e^{\mu\tau}$ is large

$$\rho_u^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_u^{ct} \\ 0 & \boxed{\boxed{\rho_u^{tc}}} & \rho_u^{tt} \end{pmatrix}, \quad \rho_e^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \boxed{\boxed{\rho_e^{\mu\tau}}} \\ 0 & \boxed{\rho_e^{\tau\mu}} & \boxed{\rho_e^{\tau\tau}} \end{pmatrix}$$

Can $\rho_u^{tc} \approx \rho_e^{\tau\mu} \approx \rho_e^{\mu\tau} \approx O(1)$ explain all of three?

Result1

R(D): $\rho_u^{tc}\rho_e^{\mu\tau}$ is large

P$'_5$: ρ_u^{tc} is large

muon g-2: $\rho_e^{\tau\mu}\rho_e^{\mu\tau}$ is large

$$\rho_u^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_u^{ct} \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}, \quad \rho_e^{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_e^{\mu\tau} \\ 0 & \rho_e^{\tau\mu} & \rho_e^{\tau\tau} \end{pmatrix}$$

Combination of $\rho_u^{tc}\rho_e^{\tau\mu}$ enhances Br($B \to D^{(*)}\mu\nu$) and breaks Lepton Flavor Universality in $B \to D^{(*)}e\nu$ and $B \to D^{(*)}\mu\nu$

$$R_{D^*l} \equiv \frac{Br(B \to D^* e\nu)}{Br(B \to D^* \mu\nu)} = 1.04 \pm 0.05$$ Belle 1702.01521

One can evade the constraint by taking $\rho_u^{tc} \ll 1$ or $\rho_e^{\tau\mu} \ll 1$.

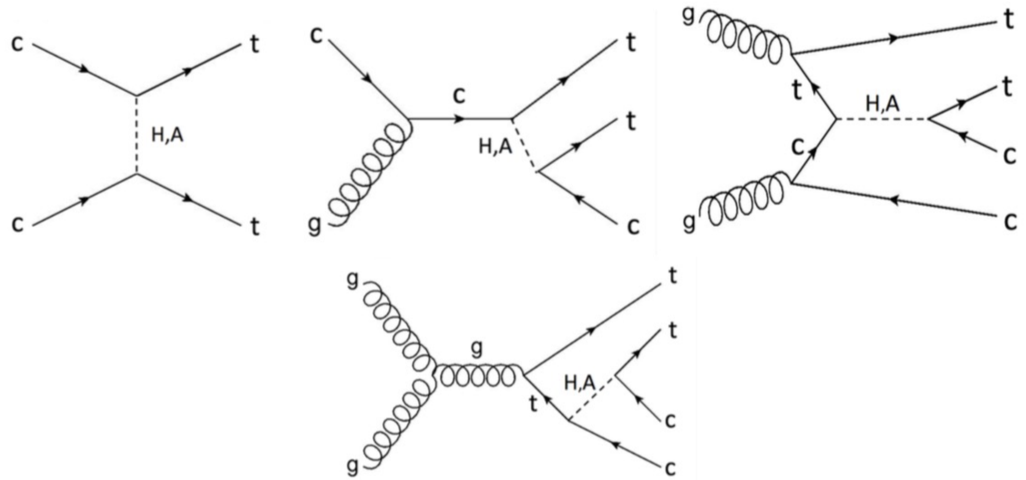
Result2 compatibiity

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

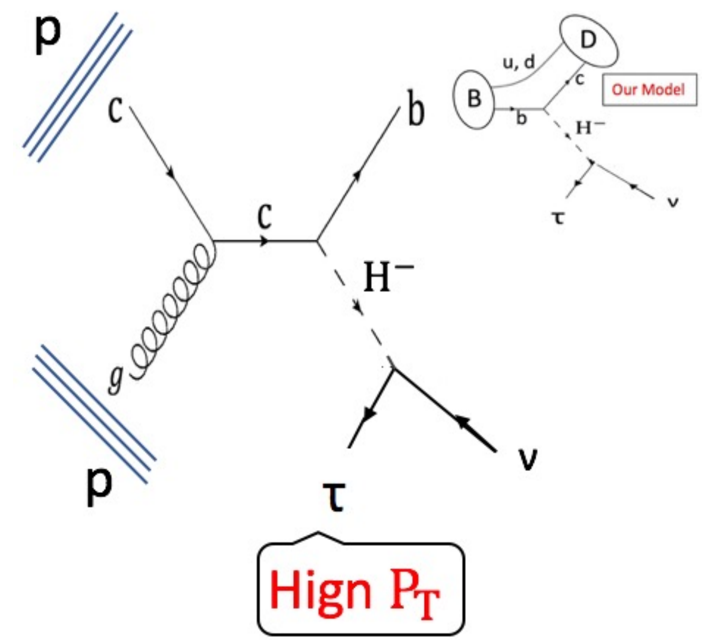
Collider signals



$$\sigma(pp \to tt + \overline{tt}) = 4.23 \times 10^{-3} |\rho_u^{tc}|^4 [\mathrm{pb}],$$
$$\sigma(pp \to tt\bar{c} + \overline{tt}c) = 4.13 \times 10^{-1} |\rho_u^{tc}|^4 [\mathrm{pb}],$$
$$\sigma(pp \to tt\bar{c}\bar{c} + \overline{tt}cc) = 1.14 \times 10^{-1} |\rho_u^{tc}|^4 [\mathrm{pb}].$$

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

An energetic tau lepton as a final state.
(A.Soni, et al. arXiv:1704.06659, SI K.Tobe 1708.06176)



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

○: within 1σ

	$R(K^{(*)})$	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}	×	×	×	×	○

or ××○×○

Summary

Several deviations from SM prediction are known in Flavor Physics.

We analyzed the possibility of a simultaneous explanation of $\mathrm{R}(\mathrm{D}^{(*)})$, a_μ , P'_5 , $\mathrm{R}(\mathrm{K}^{(*)})$ anomalies in G2HDM. Flavor violating couplings may play an important role.

We found some interesting scenarios.
they can be tested in LHC and Belle II in the near future.

Back up

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

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

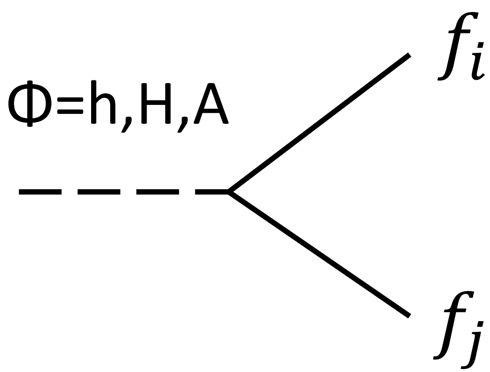
Yukawa terms

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

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

Model: G2HDM

Yukawa couplings between a neutral scalar and fermions



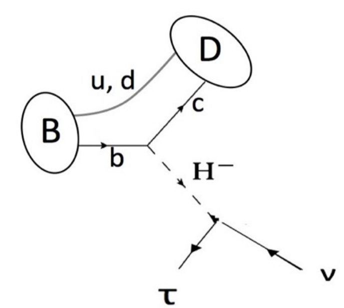
$$\approx i(y^f_{\Phi ij}\,P_R + y^{f*}_{\Phi ji}\,P_L)$$

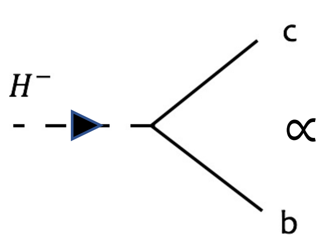
$$y^f_{hij} = \frac{m^i_f}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho^{ij}_f}{\sqrt{2}} c_{\beta\alpha},$$

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

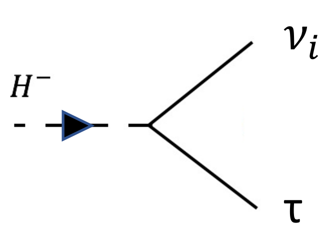
$$y^f_{Hij} = \frac{m^i_f}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho^{ij}_f}{\sqrt{2}} s_{\beta\alpha}$$

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





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



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

$\boxed{\text{Yukawa interactions relevant to } R(D^{(*)}) \quad (\rho_u^{tc}, \rho_d^{sb}) \times (\rho_e^{e\tau}, \rho_e^{\mu\tau}, \rho_e^{\tau\tau})}$

Flavor anomalies in G2HDM

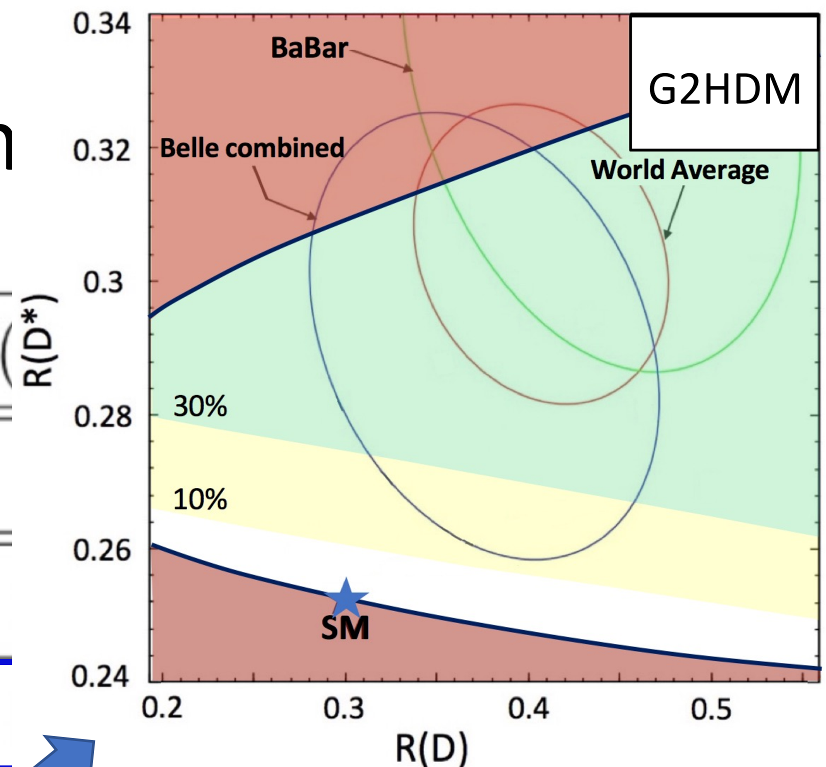
muon g-2	$\mathrm{R}\left(\mathrm{D}^{(*)}\right)$
$\rho_e^{\mu\tau}\rho_e^{\tau\mu} \neq 0,$ $m_A - m_H \neq 0$	$\dfrac{\rho_u^{tc}\rho_e^{l\tau}}{m_{H^-}^2} \neq 0$
$\mathrm{P'}_5$	$\cancel{\mathrm{R}\left(\mathrm{K}^{(*)}\right)}$
$\rho_u^{tc} \neq 0,$ light H^-	$\cancel{\rho_u^{tc} \times \rho_\nu \neq 0}$

G2HDM needs flavor violating couplings for those anomalies

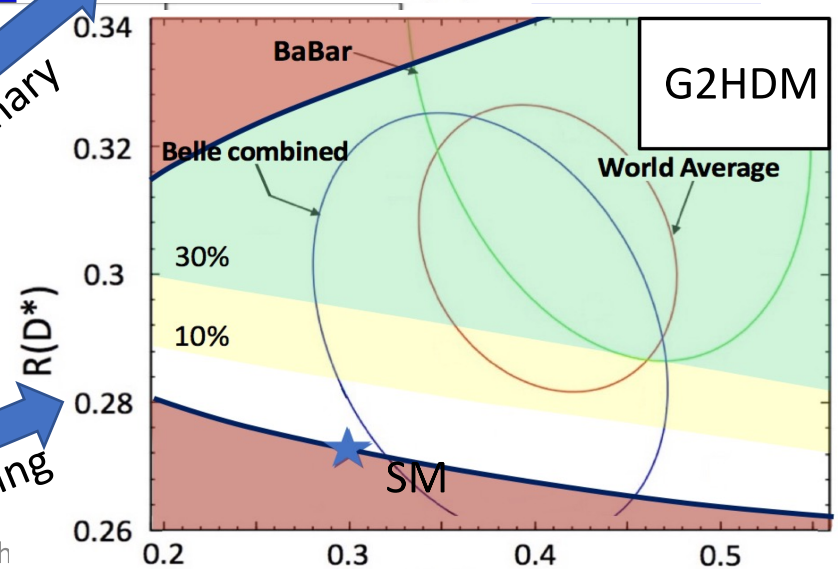
Result2

com

	$R(K^{(*)})$	P_5'	$R(D)$	$R($
(B) $\rho_e \neq 0,\ \rho_\nu = 0$				
ρ_u^{tt}	×	×	×	
ρ_u^{tc}	×	○	○	
ρ_u^{ct}	×	×	×	



ordinary

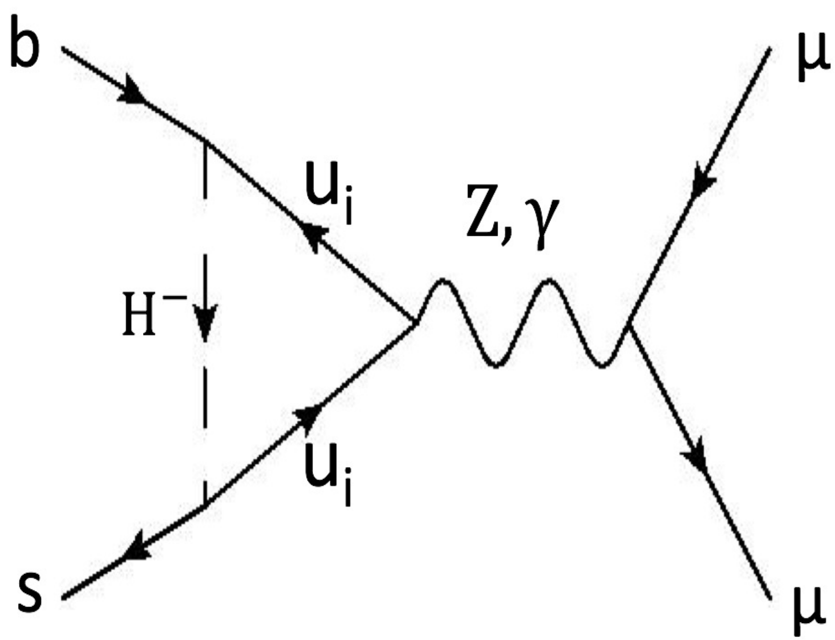


recasting

Recently by taking into account that D∗ → Dπ, the mode where the D∗ is observed, $\mathrm{R(D^*)}_{SM}$= 0.272. This is consistent with Belle and LHCb. J. E. Chavez-Saab et al. 1806.06997

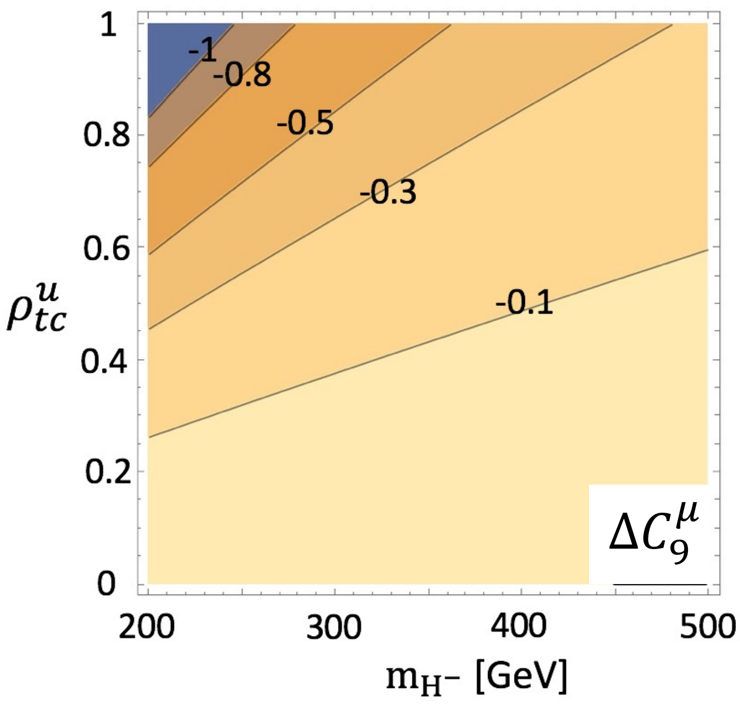
No need for explaining R(D∗)?

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



Key point

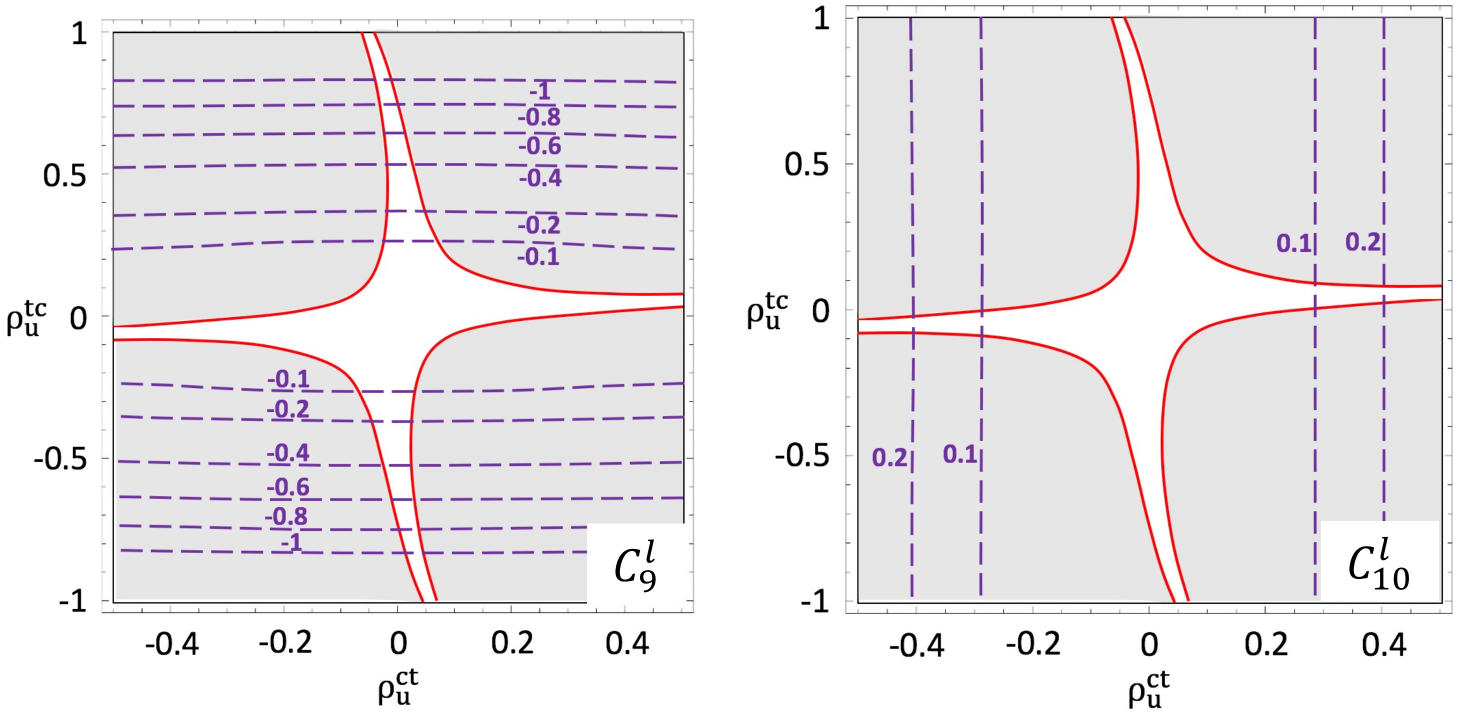
This γ penguin contribution has a dimensionless log $\frac{m_c}{m_{H^-}}$ enhancement



Other prediction

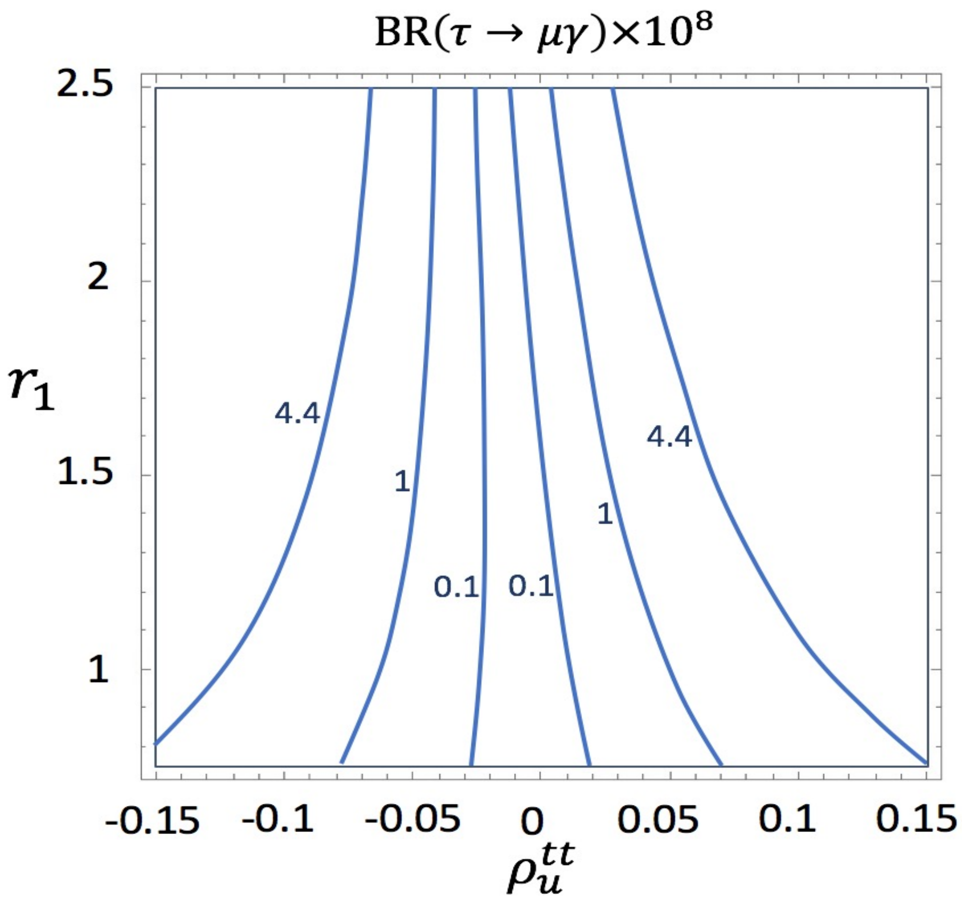
With ρ_u^{tc} which generates a large contribution to C_9^l via γ penguin diagram do not change $\mathrm{Br}(\mathrm{B_s} \to \mu\mu)$.

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



Belle Ⅱ

$\tau \to \mu\gamma$: 2-loop Bar-Zee diagram

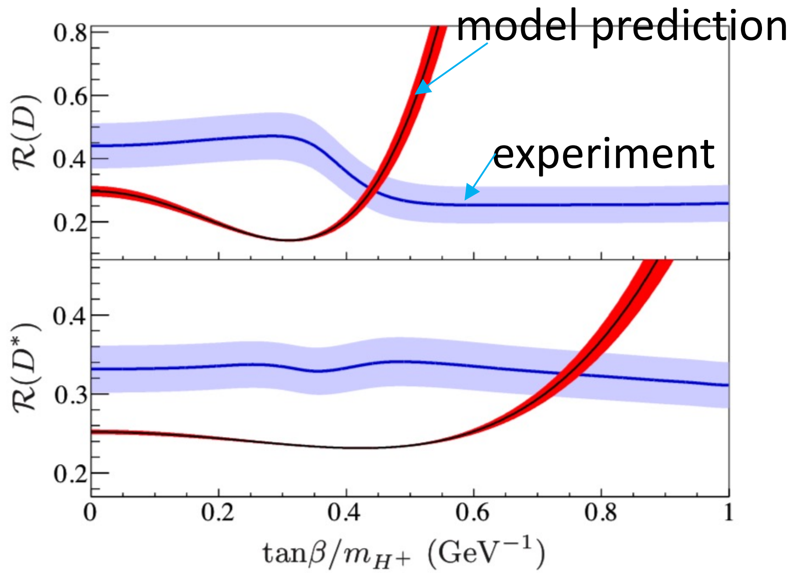


$$r_1 = \frac{\rho_e^{\mu\tau}}{-0.27} = \frac{\rho_e^{\tau\tau}}{-0.1}$$

However ρ_u^{tt} generates $\tau \to \mu\gamma$,
ρ_u^{tt} insensitive to $\mathrm{R}(\mathrm{D}^{(*)})$

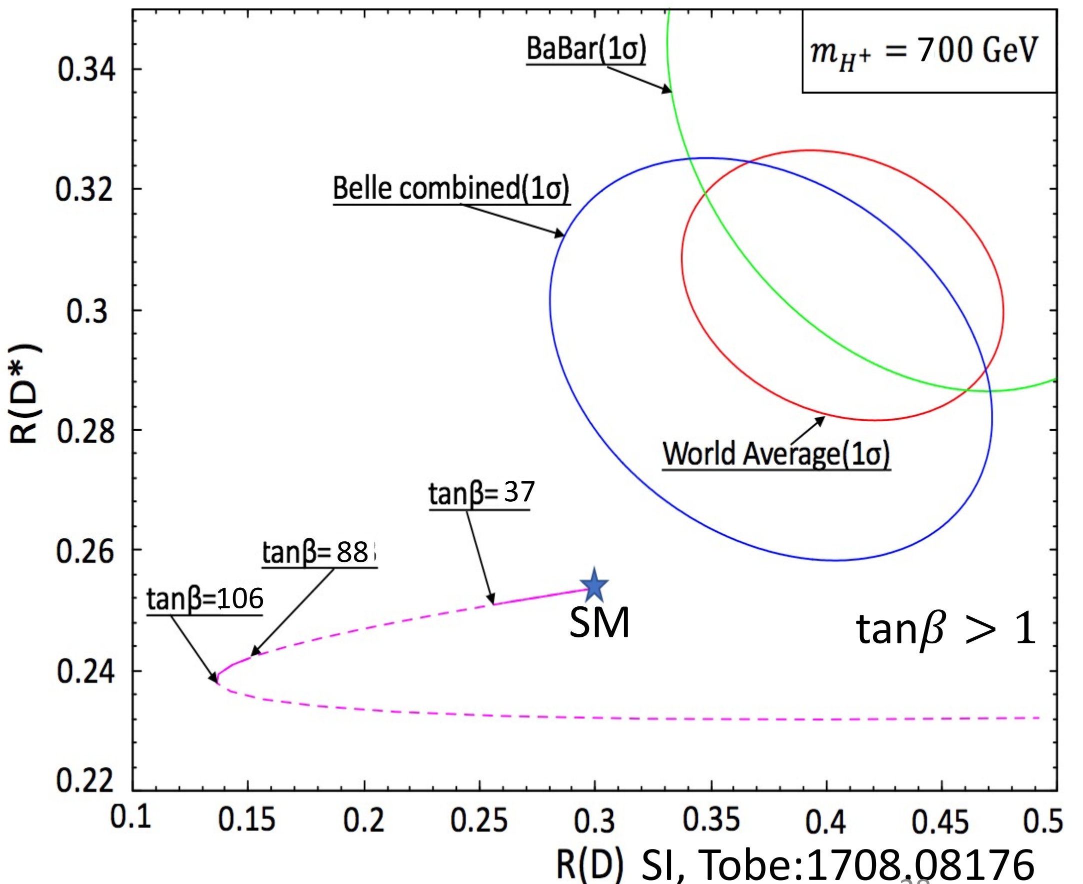
A contribution to $\frac{\mathrm{Br}(\tau\to\mu\nu\bar{\nu})/f(y_\mu)}{\mathrm{Br}(\tau\to e\nu\bar{\nu})/f(y_e)}$
is small enough.

$\mathrm{R}(\mathrm{D}^{(*)})$ Type II 2HDM can not explain this anomaly



BaBar :1303.0571

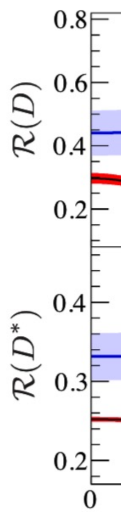
Extension of Higgs sector w/o flavor violation can not explain this anomaly

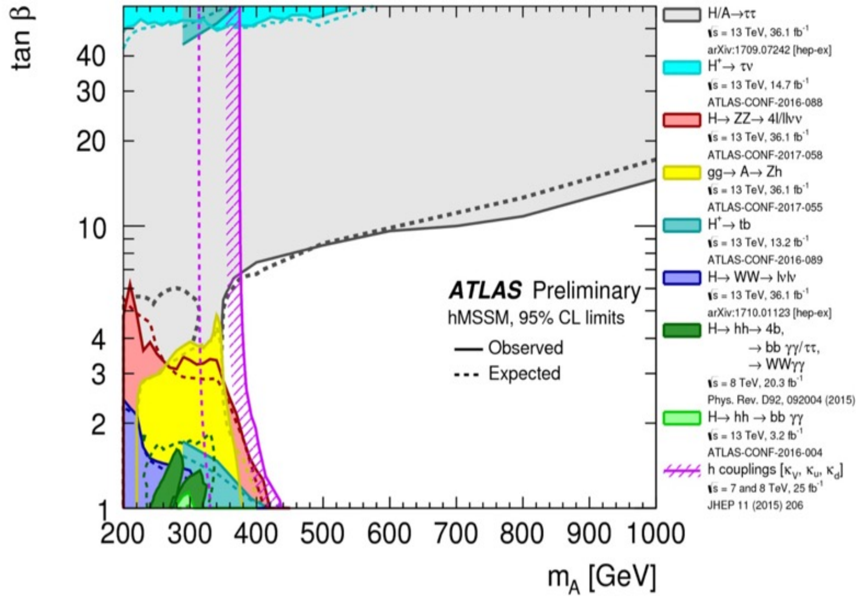


SI, Tobe:1708.08176

We need more parameters to fit the data

$R(D^{(*)})$ Type II 2HDM can not explain this anomaly

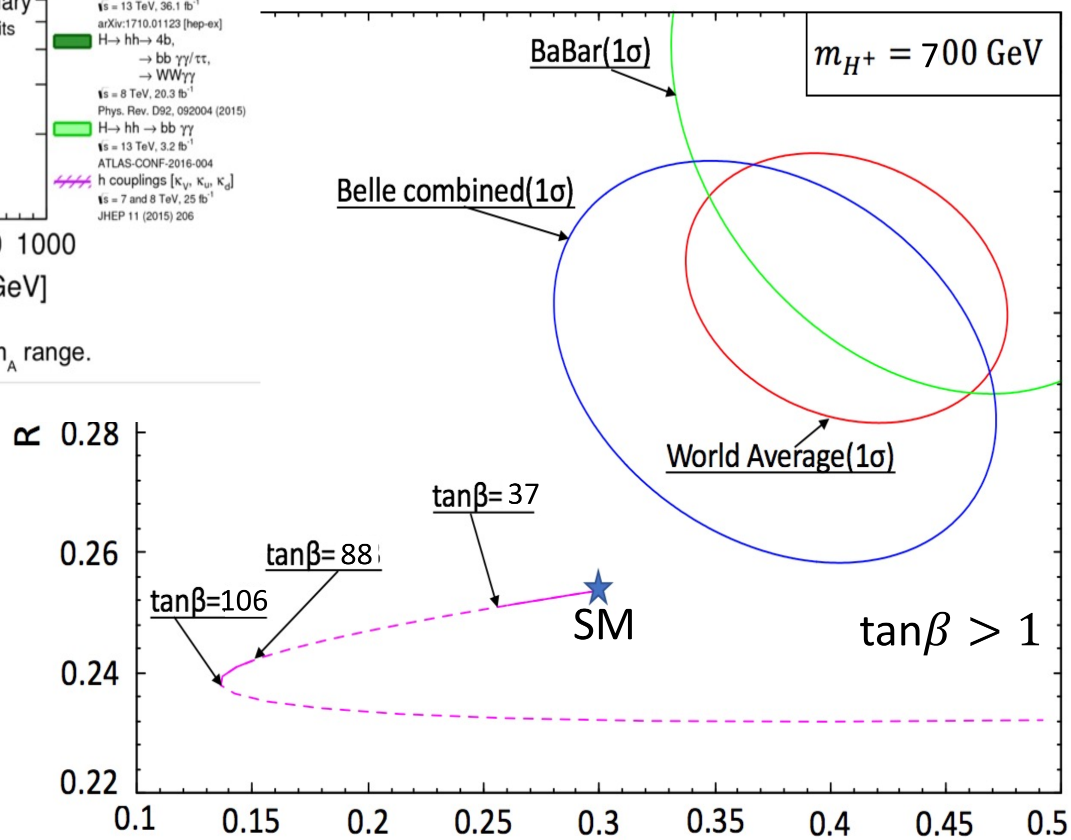




Same plot as on slide 11, but extended m_A range.

Jan Stark for the ATLAS collaboration Moriond EW -- March 10-17, 2018

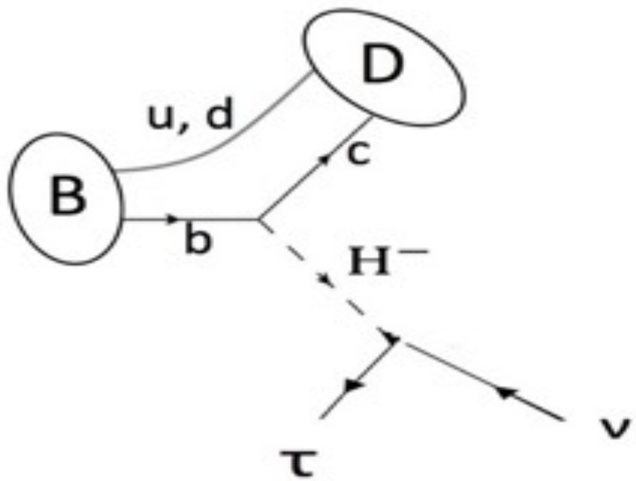
of Higgs sector w/o flavor violation
xplain this anomaly

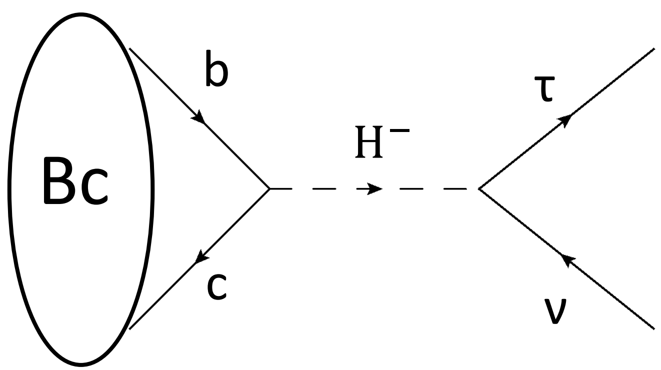


We need more parameters
to fit the data

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

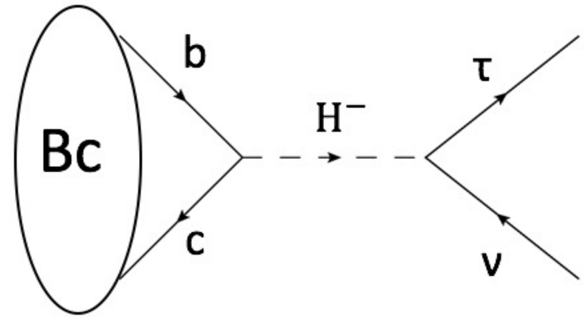
Diagram for $\mathrm{R}(\mathrm{D}^{(*)})$ automatically contributes to ($B_c^- \to \tau\bar{\nu}$)





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

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



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

Scalar operators have a large coefficient

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

$$\mathrm{BR}(B_c^- \to \tau\bar{\nu})_{SM} \times \left| 1 + \underbrace{\frac{m_{Bc}^2}{m_\tau(m_b + m_c)}}_{\approx 4} (S_R - S_L) \right|^2$$

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

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

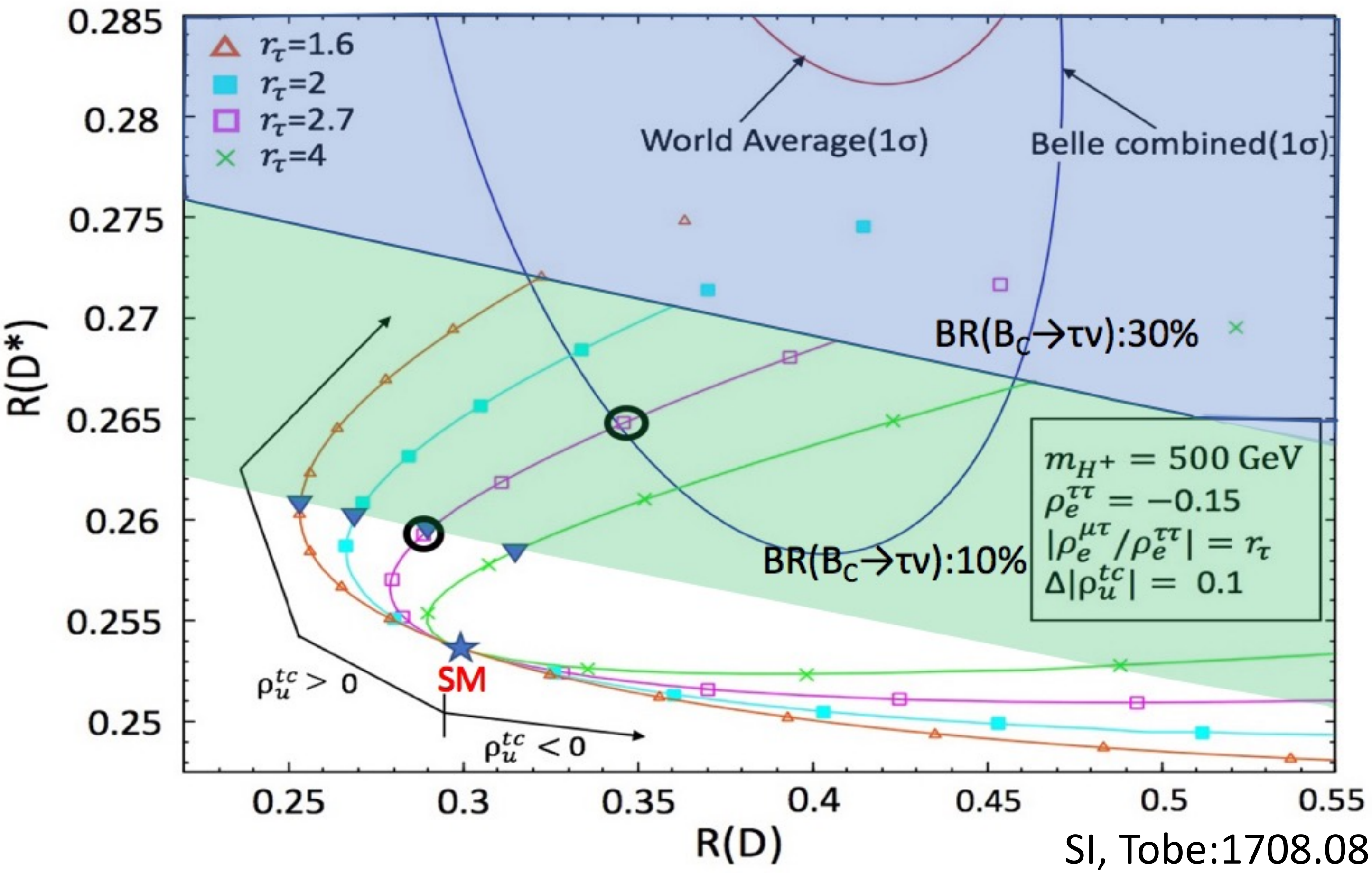
BR($B_c^- \to \tau\bar{\nu}$) =1-Br(Bc the other decay) $= 30\%$ R.Alonso et al. 1611.06676

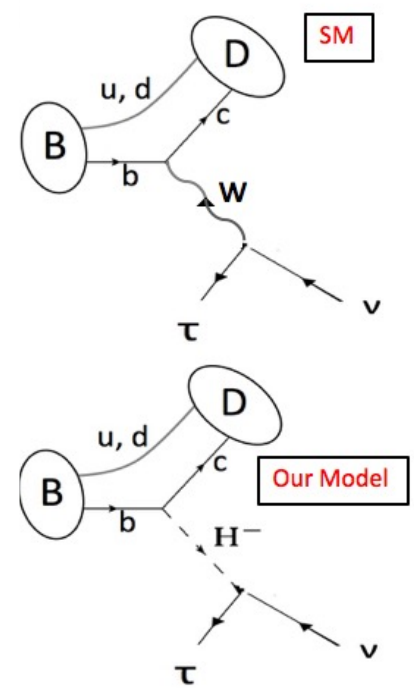
Combining LEP data with inputs obtained in LHCb 10% A.G.Akeroyd.et al. 1708.04072

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

However scalar model can not explain the current world average,

by allowing BR($B_c^- \to \tau\bar{\nu}$) < 30(10)%, G2HDM still can (not) explain $\mathrm{R}(\mathrm{D}^{(*)})$ in Belle experiment at 1σ

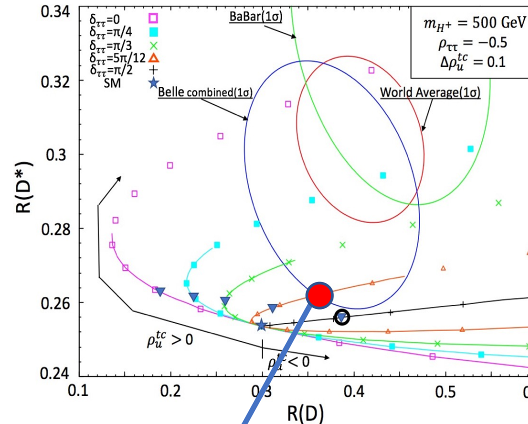


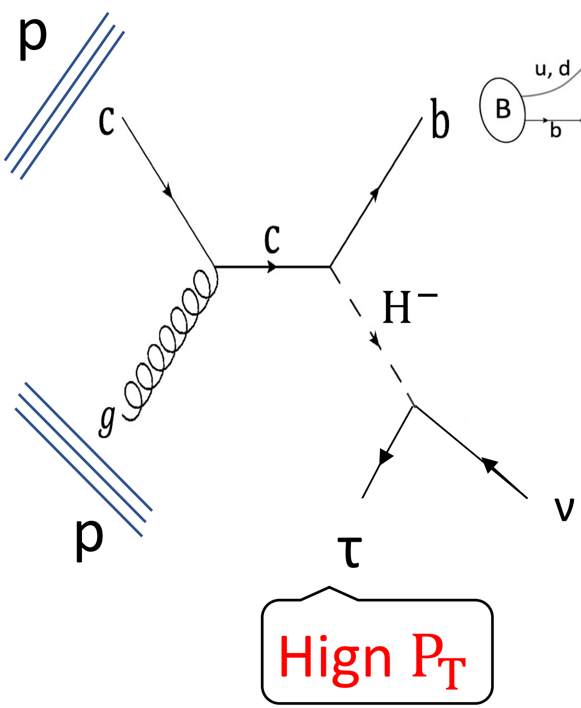


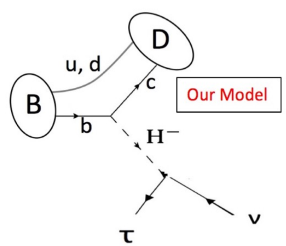
SI, Tobe:1708.08176

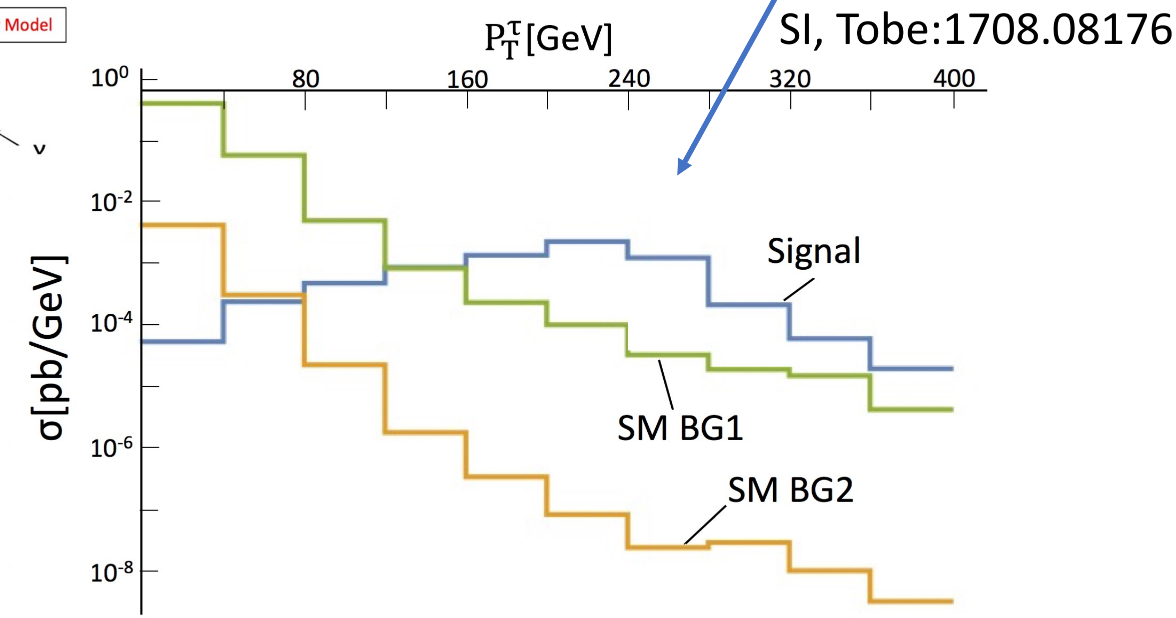
Implications for LHC

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)

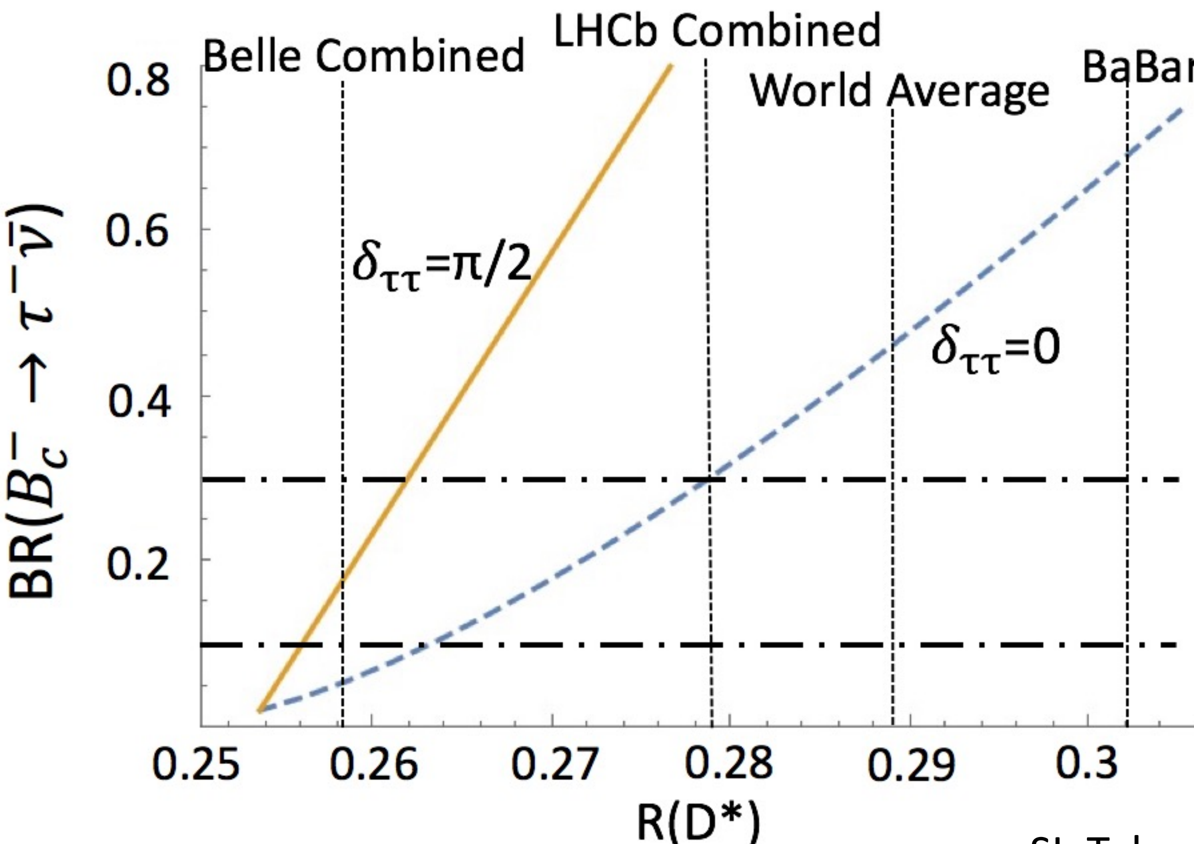








Even if we explain Belle result (smaller deviation), there are many implications in LHC



SI, Tobe:1708.08176