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

Syuhei Iguro (Nagoya-U)

NAGOYA UNIVERSITY

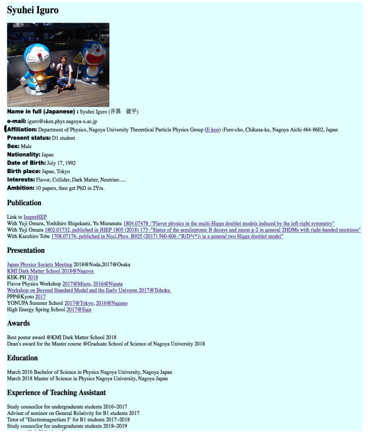
Based on

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

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

Let me introduce myself in 2 min

- Name: Syuhei Iguro (井黒　就平)
- Position: D1 student
- Birth place: Japan, Tokyo
- Interests: Flavor, Collider, Dark Matter, Neutrino…
- Ambition: 10 papers by 24/7/2020
- I love football,
  most aggressive student in theoretical group (E-lab)
- For more info: http://www.eken.phys.nagoya-u.ac.jp/~iguro/IGURO.html



Syuhei Iguro

Name in full (Japanese) : Syuhei Iguro (井黒　就平)
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Affiliation: Department of Physics, Nagoya University Theoretical Particle Physics Group (E-ken) :Furo-cho, Chikusa-ku, Nagoya Aichi 464-8602, Japan
Present status: D1 student
Sex: Male
Nationality: Japan
Date of Birth: July 17, 1992
Birth place: Japan, Tokyo
Interests: Flavor, Collider, Dark Matter, Neutrino.....
Ambition: 10 papers, then get PhD in 2Yrs.

Publication

Link to InspreHEP
With Yuji Omura, Yoshihiro Shigekami, Yu Muramatu 1804.07478 :"Flavor physics in the multi-Higgs doublet models induced by the left-right symmetry"
With Yuji Omura 1802.01732, publiched in JHEP 1805 (2018) 173 :"Status of the semileptonic B decays and muon g-2 in general 2HDMs with right-handed neutrinos"
With Kazuhiro Tobe 1708.07176, publiched in Nucl.Phys. B925 (2017) 560-606 :"R(D^(*)) in a general two Higgs doublet model"

Presentation

Japan Physics Society Meeting 2018@Noda,2017@Osaka
KMI Dark Matter School 2018@Nagoya
KEK-PH 2018
Flavor Physics Workshop 2017@Miura, 2016@Nigata
Workshop on Beyond Standard Model and the Early Universe 2017@Tohoku
PPP@Kyoto 2017
YONUPA Summer School 2017@Tokyo, 2016@Nagano
High Energy Spring School 2017@Siga

Awards

Best postor award @KMI Dark Matter School 2018
Dean's award for the Master course @Graduate School of Science of Nagoya University 2018

Education

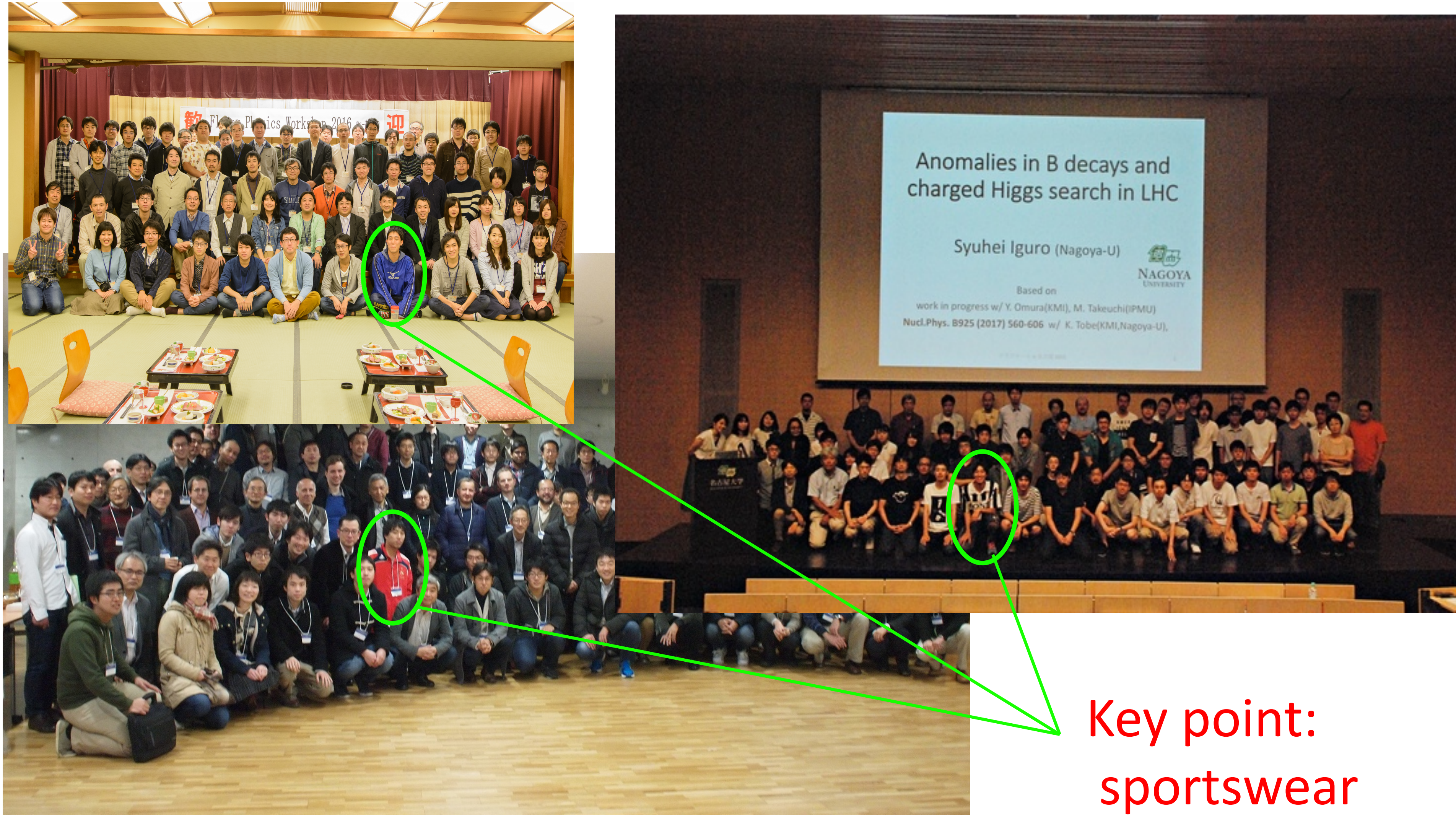
March 2016 Bachelor of Science in Physics Nagoya University, Nagoya Japan
March 2018 Master of Science in Physics Nagoya University, Nagoya Japan

Experience of Teaching Assistant

Study councellor for undergraduate students 2016~2017
Adviser of seminor on General Relativity for B1 students 2017
Tutor of "Electromagnetism I" for B1 students 2017~2018
Study councellor for undergraduate students 2018~2019

The easiest way to find me

The easiest way to find me



Key point:
sportswear
and vivid color

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)

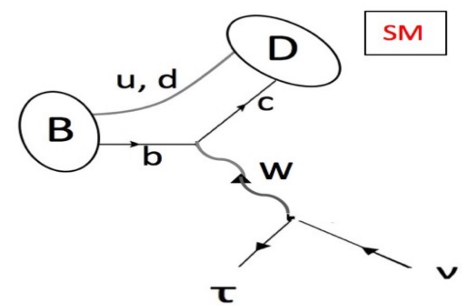
Menu

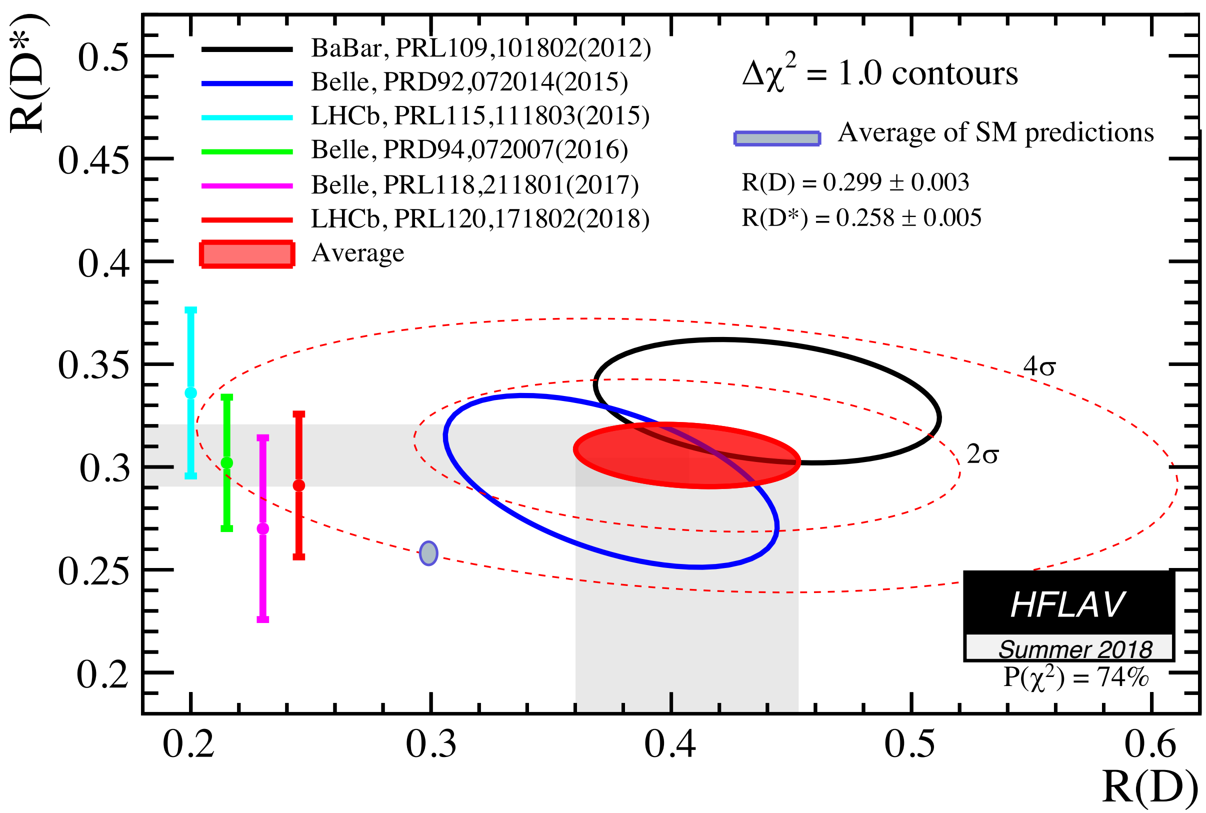
- $\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ anomaly
- Introduction of G2HDM
- Collider search
- Summary

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

3.9σ discrepancy

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





ICHEP 2018

No new result but minor change from last year

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

↓

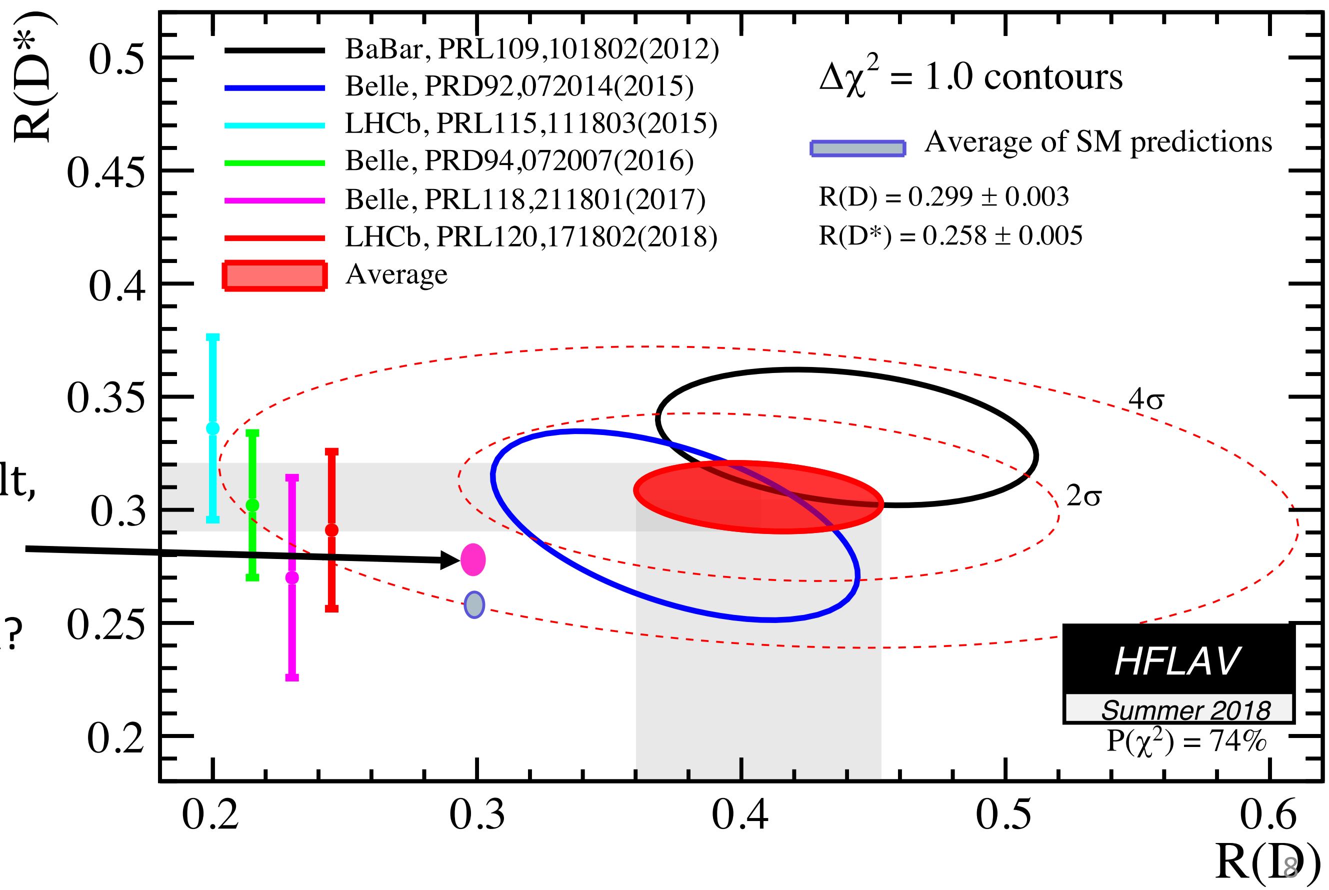
$$\mathrm{R}(\mathrm{D}^{*})_{SM} = 0.258$$

Recently by taking into account the phase space in $D^* \to D\pi$, the mode a D^* is observed, $R(D^*)_{SM} = 0.272$. This is consistent with Belle and LHCb. J. E. Chavez-Saab et al. 1806.06997

4 body decay

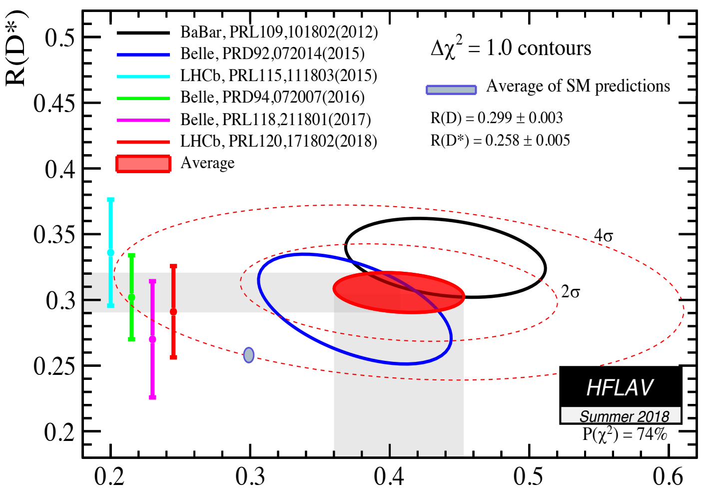
Updating their result, $R(D^*)_{SM} = 0.278$

$R(D^{(*)})$ is almost OK?

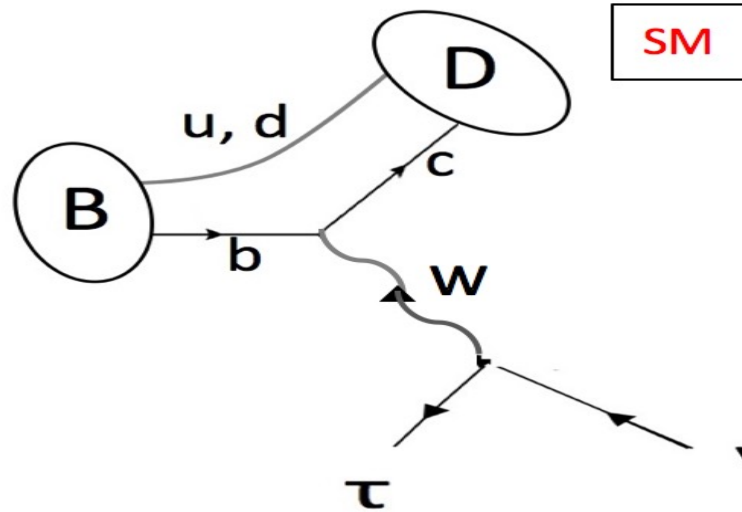


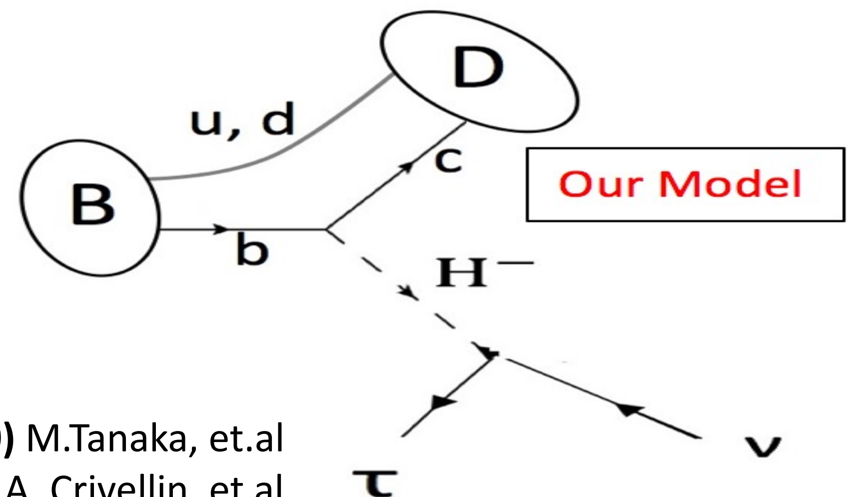
Naively, H^- is a good candidate.

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



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

Motivation

Guiding princi
- Simplicity of
- Electroweak
- Extending Hi
  condition

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 $B \to K^{*}\mu\mu$ If time allows
- $R(K^{(*)})=BR(B \to K^{(*)}\mu\mu)/BR(B \to K^{(*)}ee)$

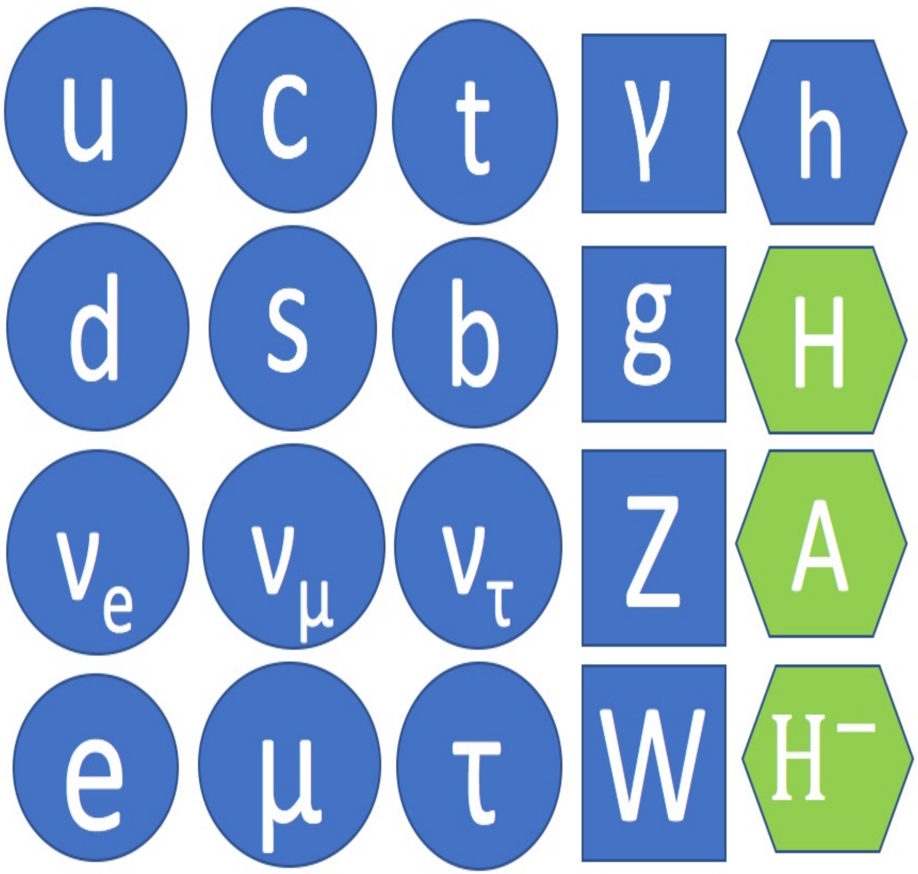
for a combination of them, see **JHEP 1805 (2018) 173** SI, Y. Omura

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

Rich flavor phenomenology

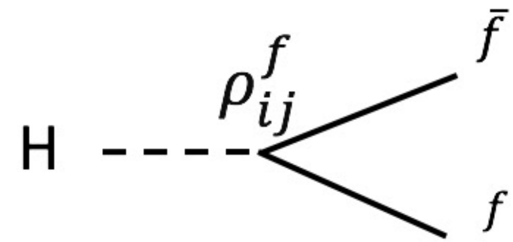
Our Model

Particle set in G2HDM



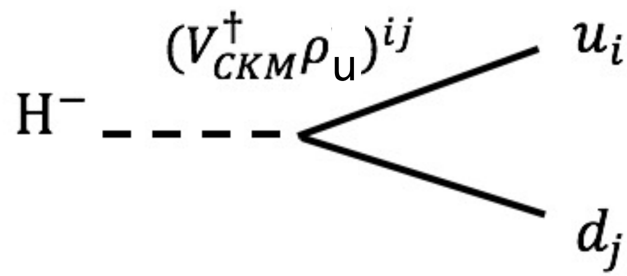
Neutral Scalar

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



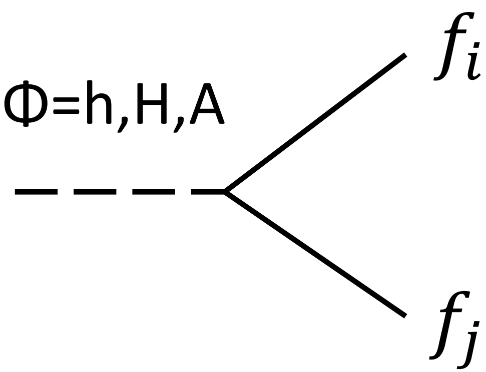
Charged Scalar

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



Model: G2HDM

Yukawa couplings between a neutral scalar and fermions



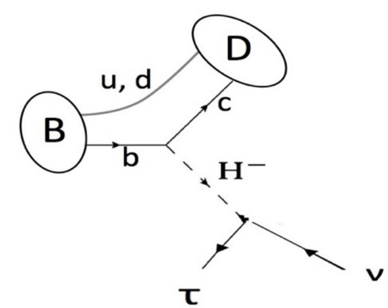
$$\approx i(y^{f}_{\Phi ij}\, P_R + y^{f*}_{\Phi ji}\, P_L)$$

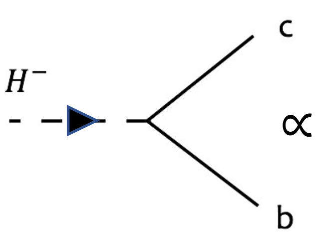
$$y^f_{hij} = \frac{m^i_f}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho^{ij}_f}{\sqrt{2}} c_{\beta\alpha},$$

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

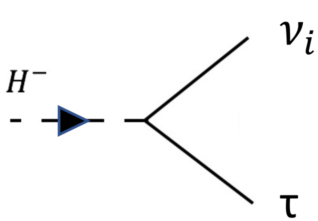
$$y^f_{Hij} = \frac{m^i_f}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho^{ij}_f}{\sqrt{2}} s_{\beta\alpha}$$

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





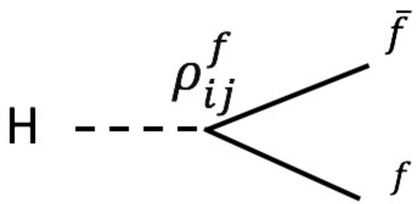
$$\propto (V_{CKM}\rho_d P_R - \rho_u^\dagger V_{CKM} P_L)^{cb} \approx \rho_d^{sb} P_R - \rho_u^{tc*} P_L$$



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

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

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
- $b \to s\gamma$
- $B \to \tau\nu$ .....

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

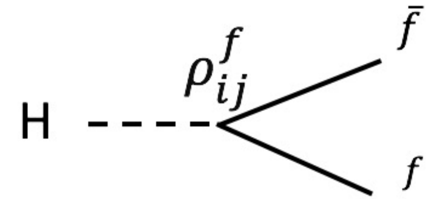
ρ_u^{tc} can be O(1)

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

Yukawa couplings



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- $B \to \tau\nu$ …..

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15:45～　重神さん

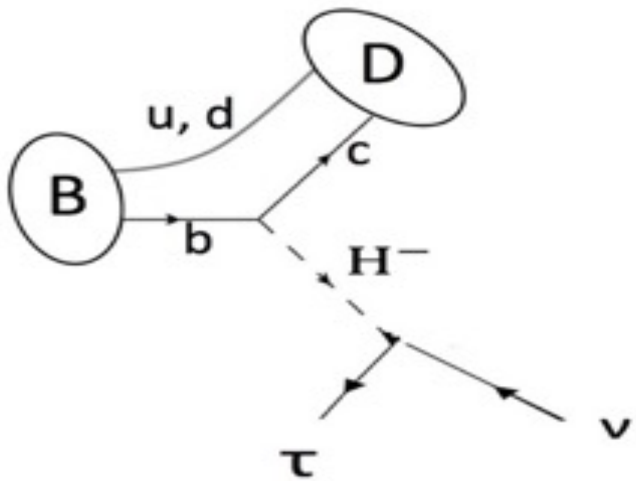
We turn others off for … nalies

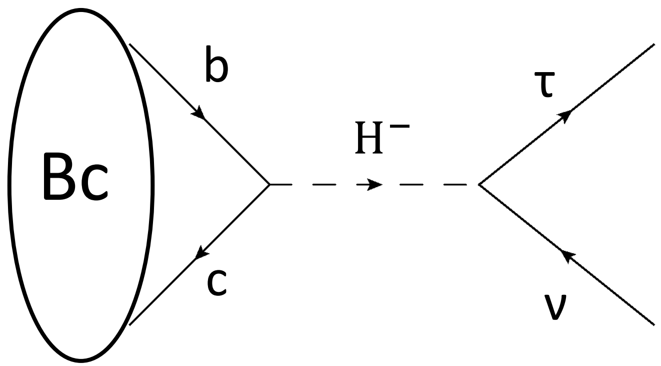
For the top down …

Iguro et al. 1804.07478

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

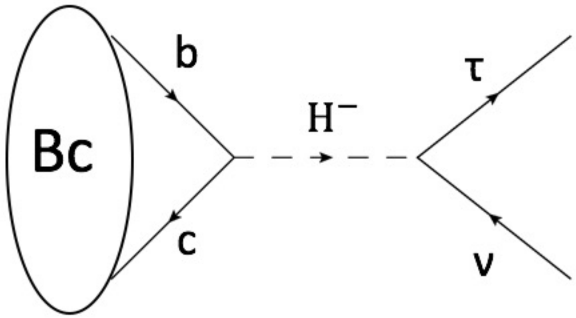
Diagram for $\mathrm{R}(\mathrm{D}^{(*)})$ automatically contributes to ($B_c^- \to \tau\bar{\nu}$)





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

≈ 4

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

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

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

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.

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

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

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

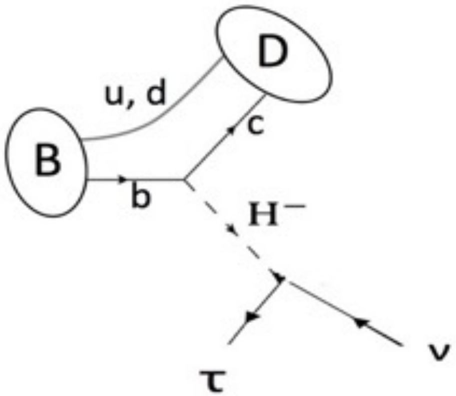
$\rho_d^{sb} << 1 \rightarrow \mathrm{C^S_L} << 1$

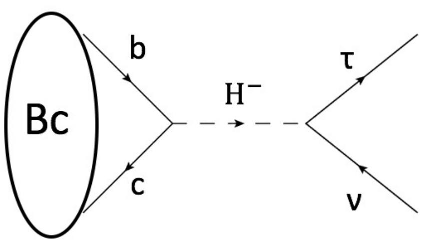
P. Asadi ,et at.1804.04135

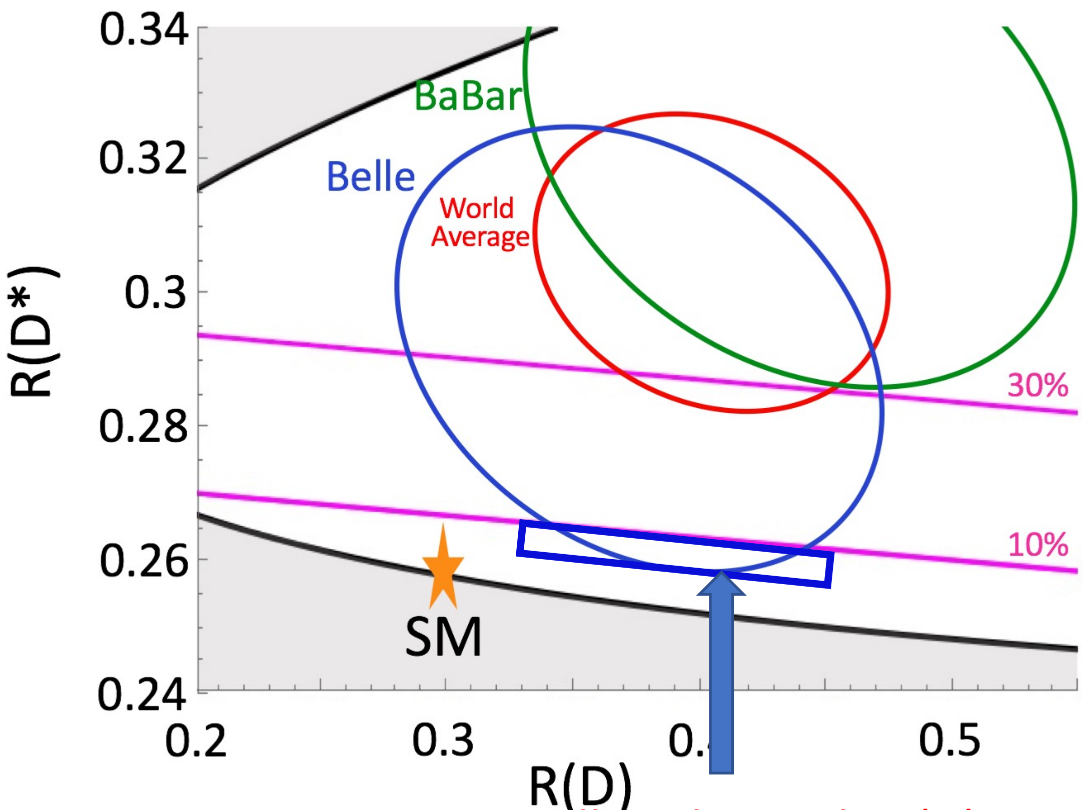
Stringent bound from BR($B_c^- \to \tau\bar{\nu}$)

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

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







Still explain only R(D).

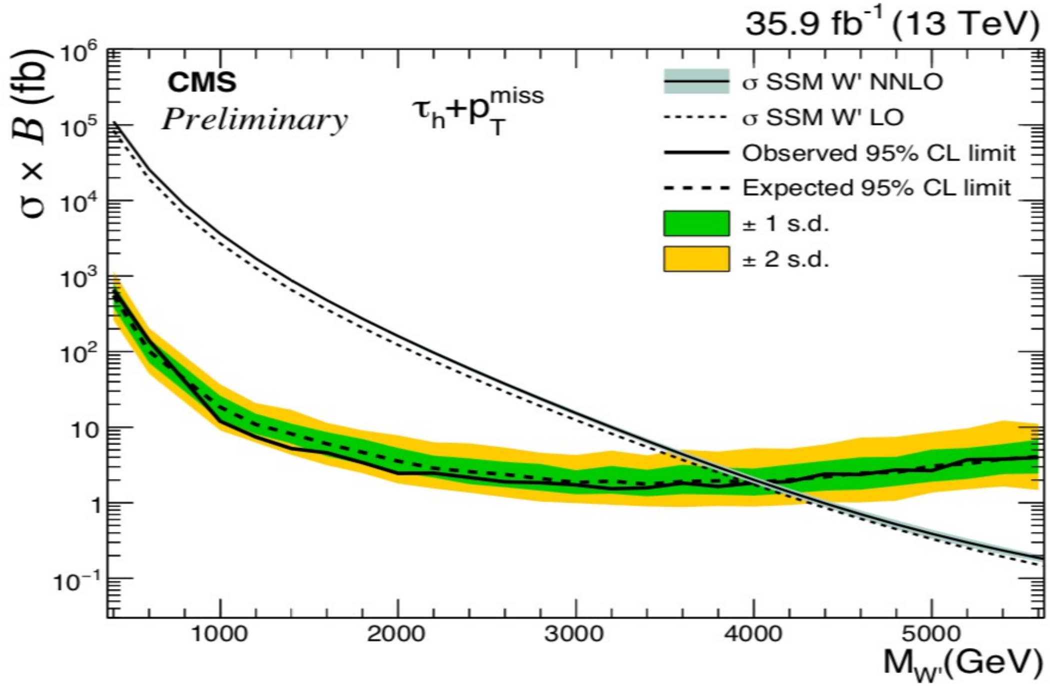
Collider study

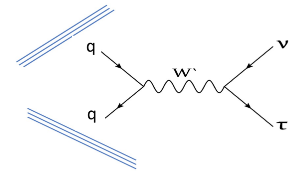
Any direct limit from collider experiment right now?

$\tau\nu$ 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

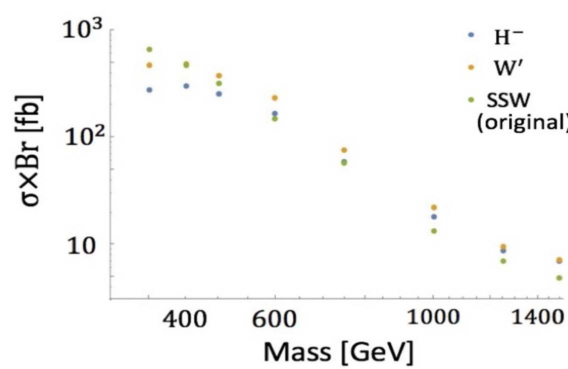




Need to reinterpret this limit for H^-.

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

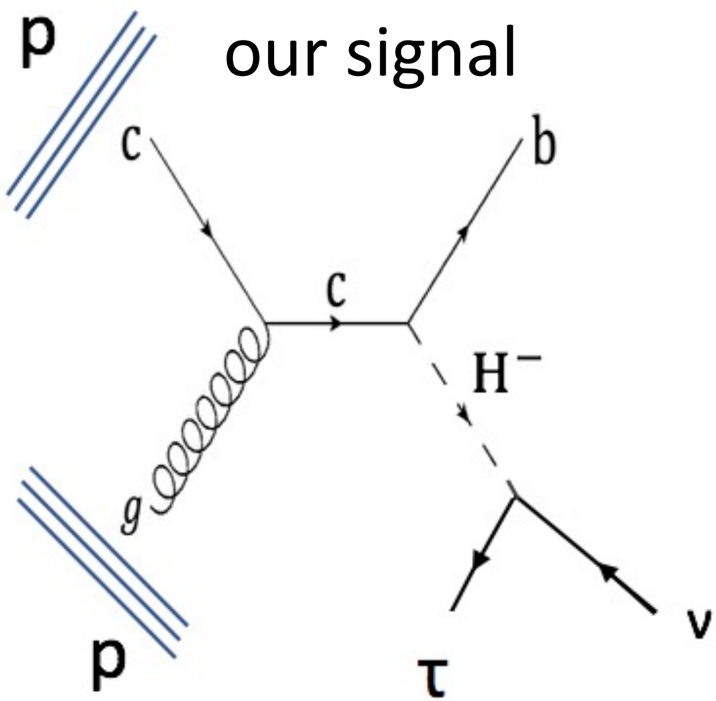
Upper bounds on $\sigma \times$ Br



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

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

Why no study so far?

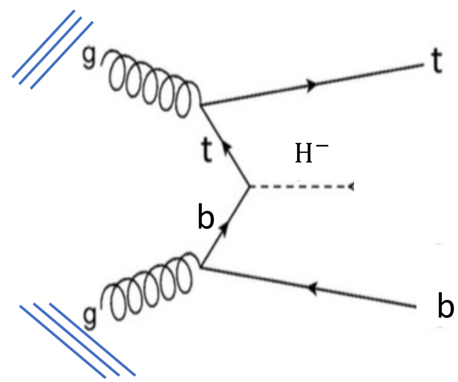


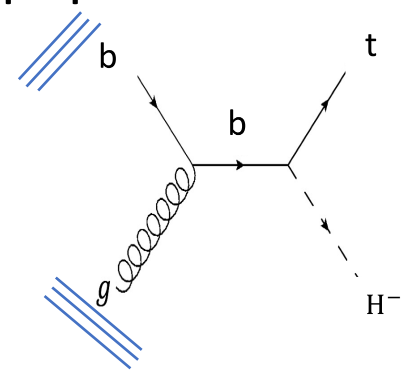
H^- in Type II 2HDM mainly couple to $bt, \tau\nu$.

No top quark in proton PDF.

↓

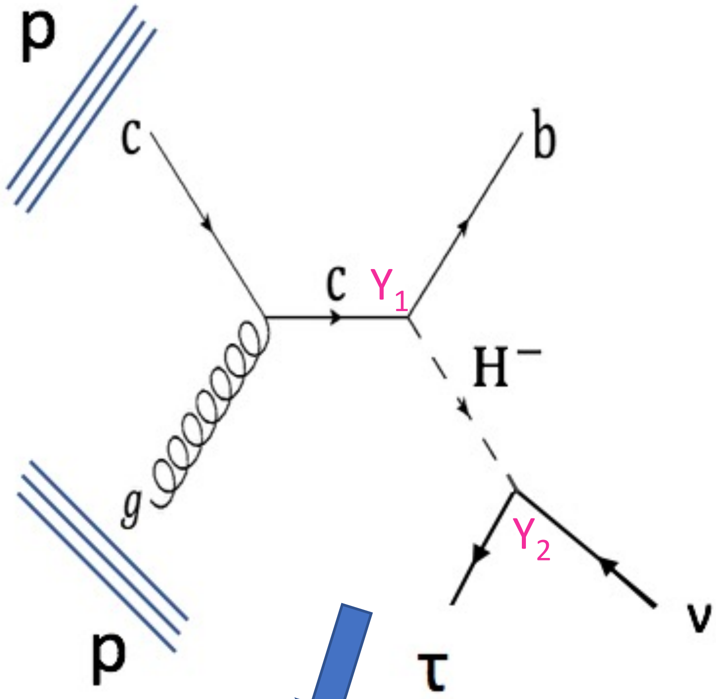
H^- is produced with top quark



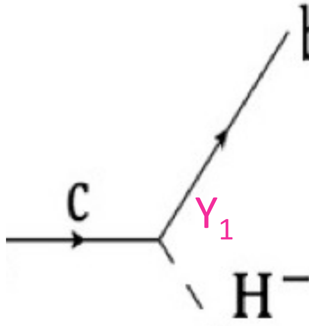


Exotic process for H^-

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



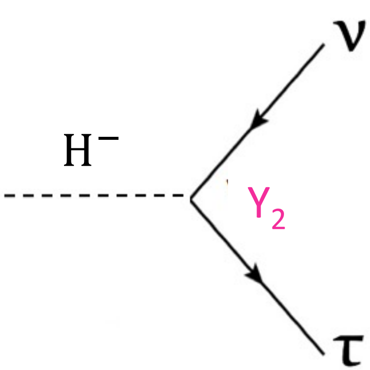
Production



depending on H^- mass

σ=$X_{H^-}|Y_1|^2$

Branching ratio



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

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

To fit $\mathrm{R(D^{(*)})}$ 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

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

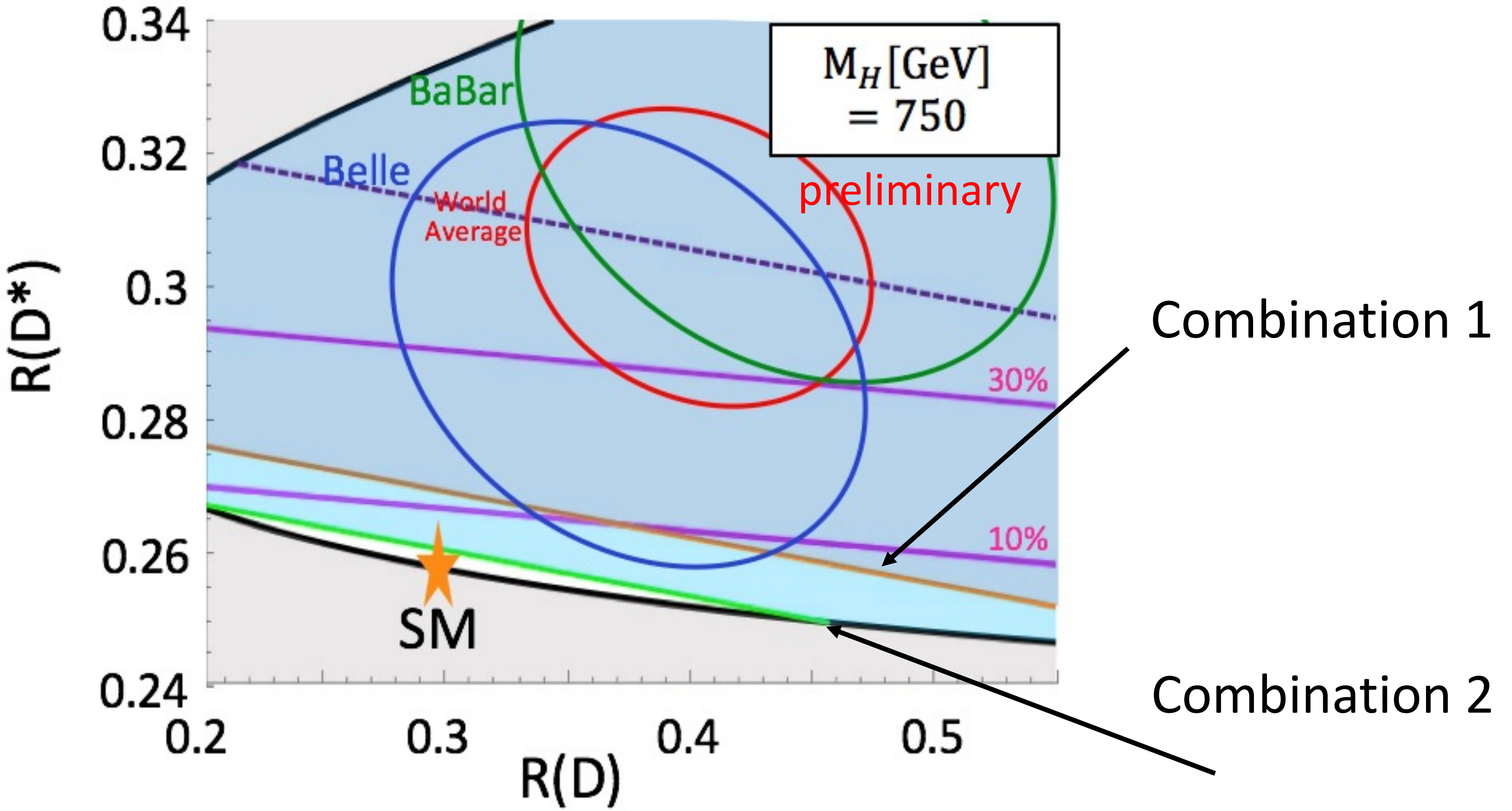
Combination 1 :$Y_1 = 1$, maximizing denominator.

weaker constraint.

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

severe constraint.

Result



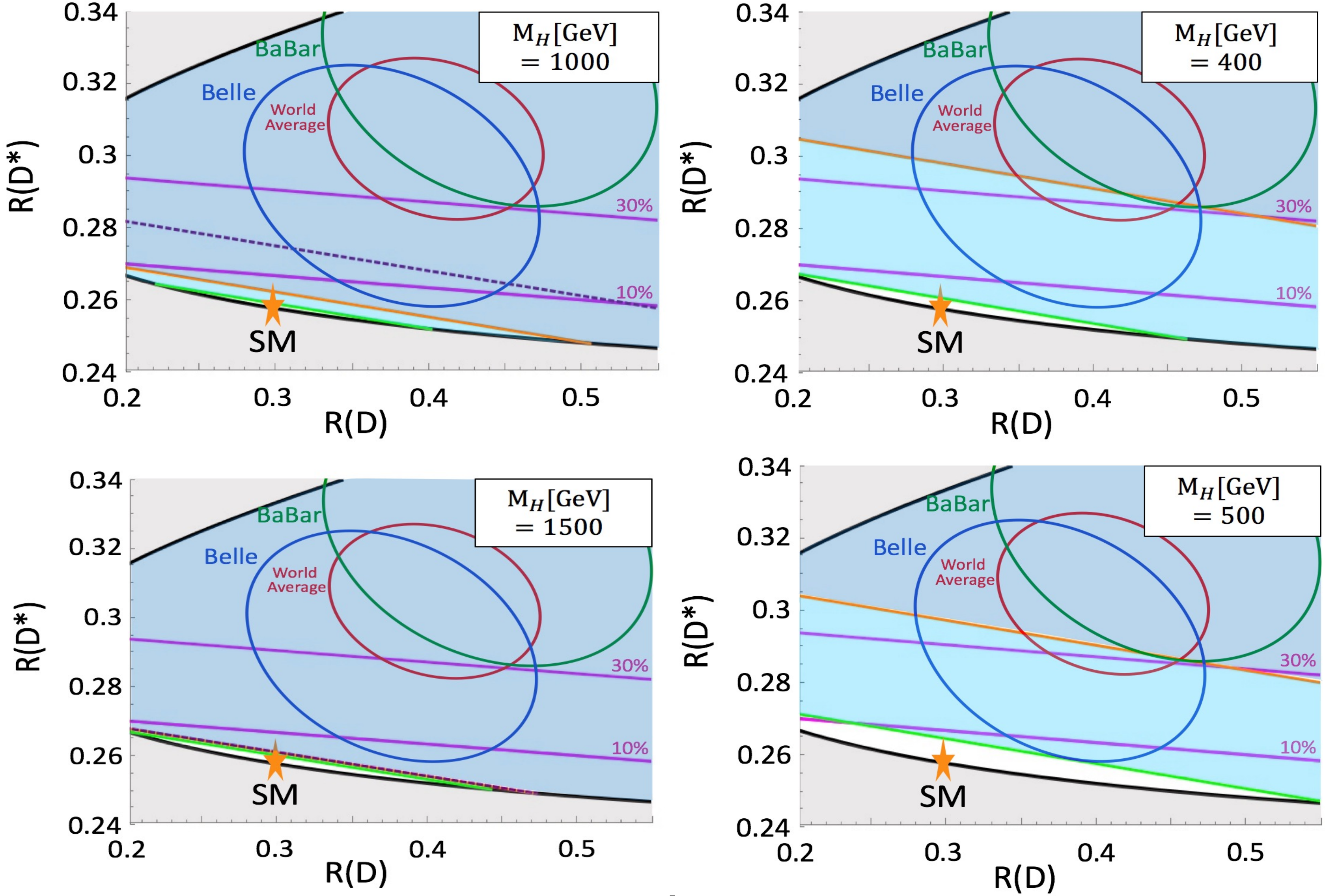
Comparable or more stringent constraint than $B_c^- \to \tau\bar{\nu}$

Result

Heavier H^-, more severe constraint.

preliminary heavier

lighter



Result

Heavier H^-, more severe constraint.

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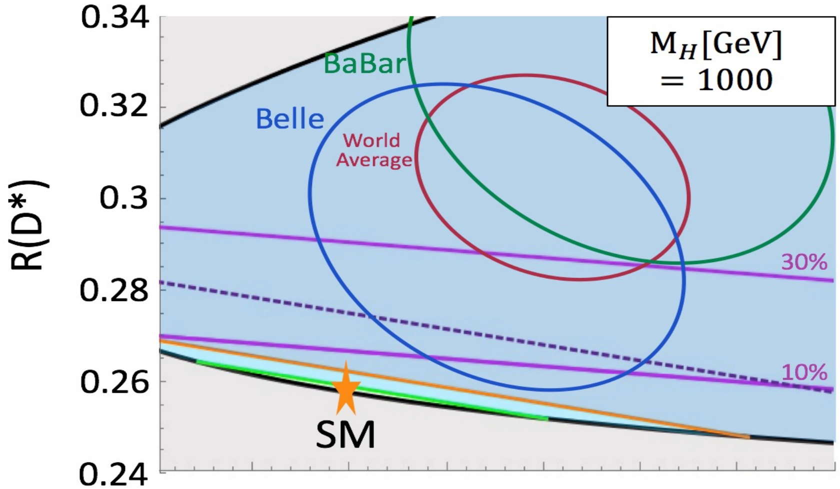
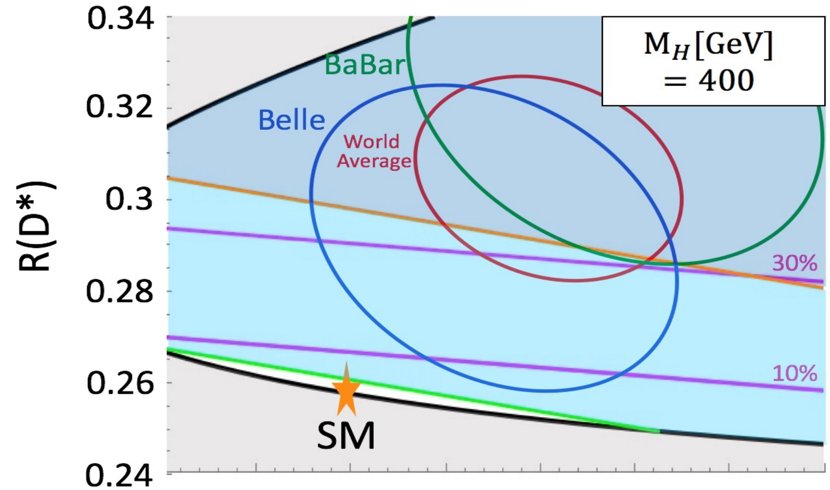
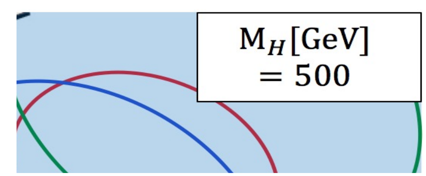
lighter

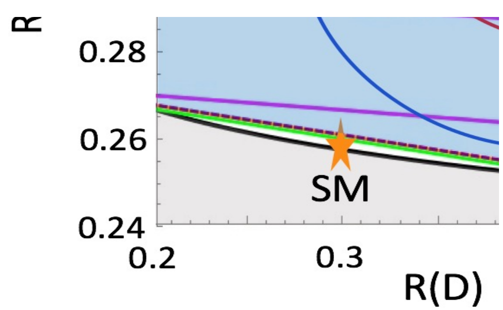




Better sensitivity for heavy $\tau\nu$ resonance:



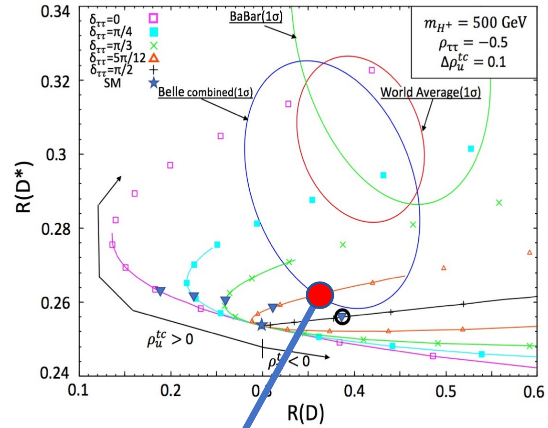
low background from W→ $\tau\nu$.

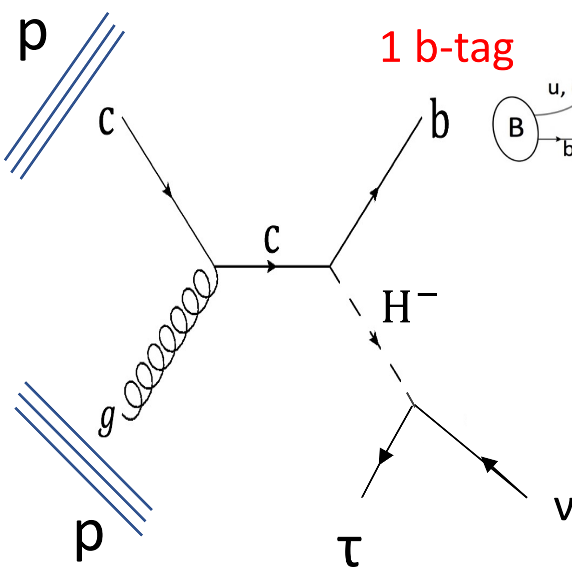


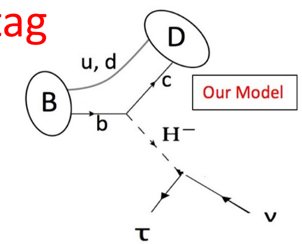
Experiment:arXiv	$\sqrt{s}$[TeV]	L[fb^{-1}]	Range $M_{W'}$[TeV]
CMS:1508.04308	7,8	19.7	0.3–4
CMS:CMS-PAS-EXO-16-006	13	2.3	1–5.8
ATLAS:1801.06992	13	36.1	0.5–5
CMS:CMS-PAS-EXO-17-008	13	35.9	0.4–4

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)

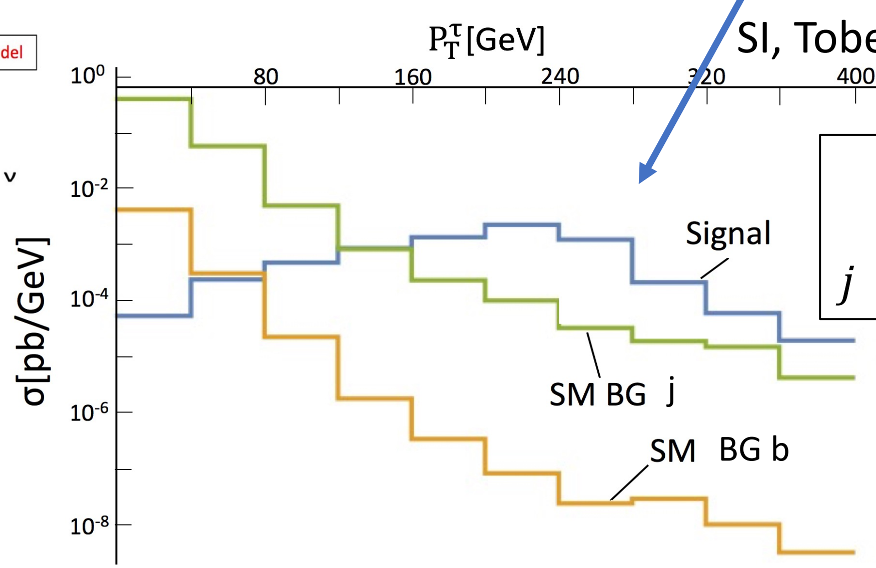






High P_T

SI, Tobe:1708.08176



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

This process looks promising, but not measured yet

Summary

G2HDM can still explain R(D).

τν resonance search can test it.

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

An interplay between flavor physics and collider physics is important.

Back up

Menu

- W' case
- P'_5 anomaly and H^-
- ……

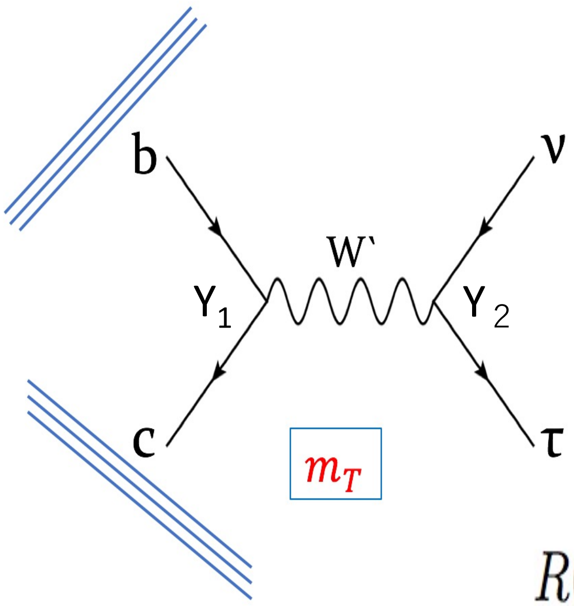
Constraint for W’

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....



$$L_{eff} = -2\sqrt{2}G_F V_{cb}\left((\delta_{l\tau} + C^l_{v1})O^l_{v1} + C^l_{v2}O^l_{v2}\right)$$

$$O^l_{V1} = (\bar{c}\gamma^\mu P_L b)(\bar{l}\gamma_\mu P_L \nu_\tau)$$

$$O^l_{V2} = (\bar{c}\gamma^\mu P_R b)(\bar{l}\gamma_\mu P_L \nu_\tau)$$

left handed case

$$\frac{R(D)}{R(D)_{SM}} = \frac{R(D^*)}{R(D^*)_{SM}} = 1 + 2Re\{C^\tau_{v1}\} + |C^\tau_{v1}|^2 + |C^\mu_{v1}|^2 + |C^e_{v1}|^2$$

Left handed vector charged current

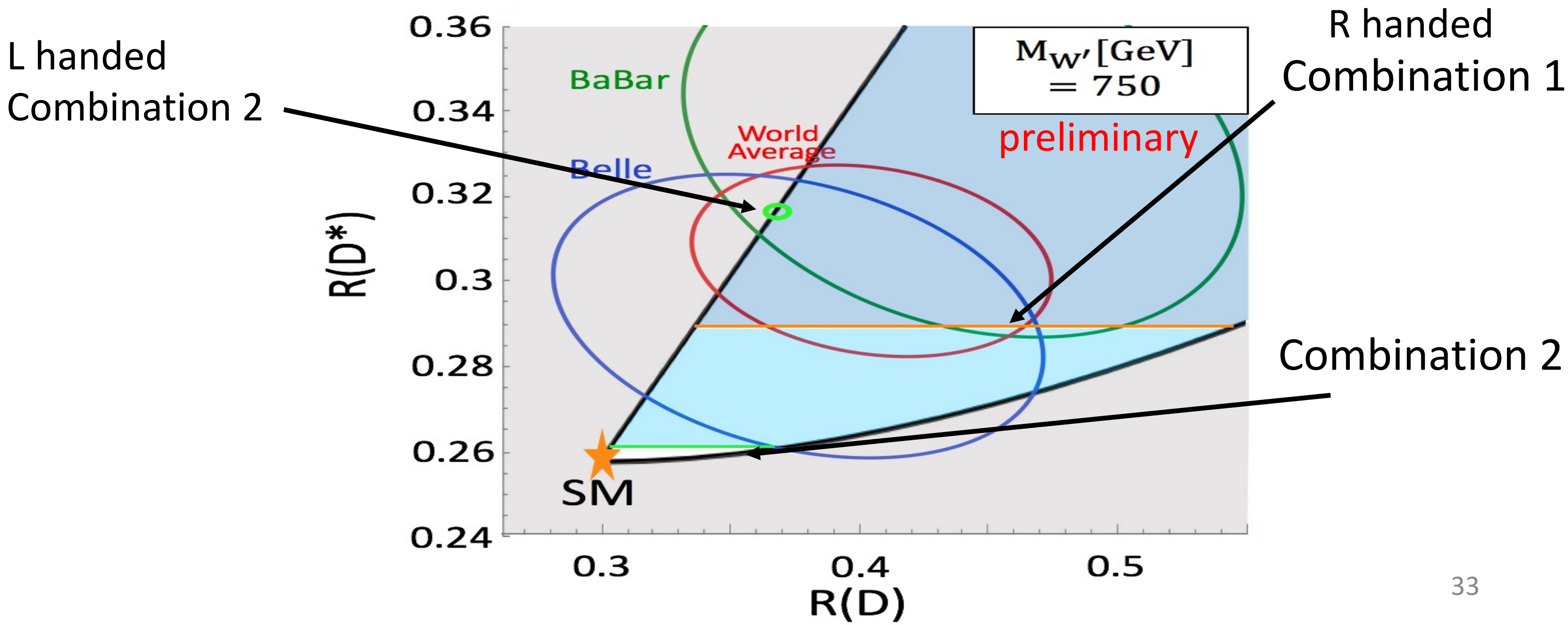
$$\frac{R(D)}{R(D)_{SM}} = \frac{R(D^*)}{R(D^*)_{SM}} = 1 + 2Re\{C_{v1}^{\tau}\} + |C_{v1}^{\tau}|^2 + |C_{v1}^{\mu}|^2 + |C_{v1}^{e}|^2$$

Right handed vector charged current

$$\frac{R(D)}{R(D)_{SM}} = 1 + 2Re\{C_{v1}^{\tau}\} + |C_{v1}^{\tau}|^2 + |C_{v1}^{\mu}|^2 + |C_{v1}^{e}|^2$$
$$\frac{R(D^*)}{R(D^*)_{SM}} = 1 + |C_{v1}^{\tau}|^2 + |C_{v1}^{\mu}|^2 + |C_{v1}^{e}|^2$$

This behavior comes from meson properties

D: pseudo scalar, D*:vector meson.

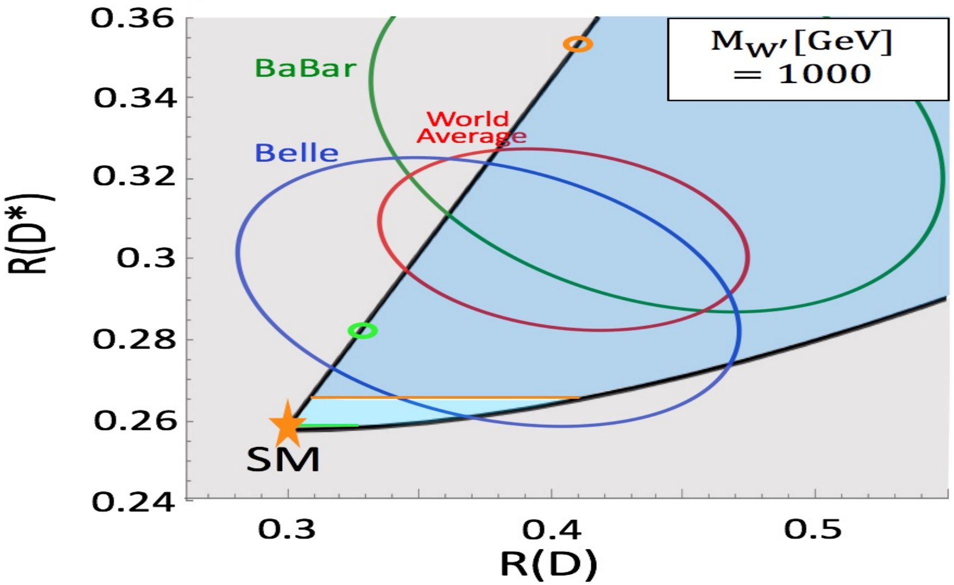


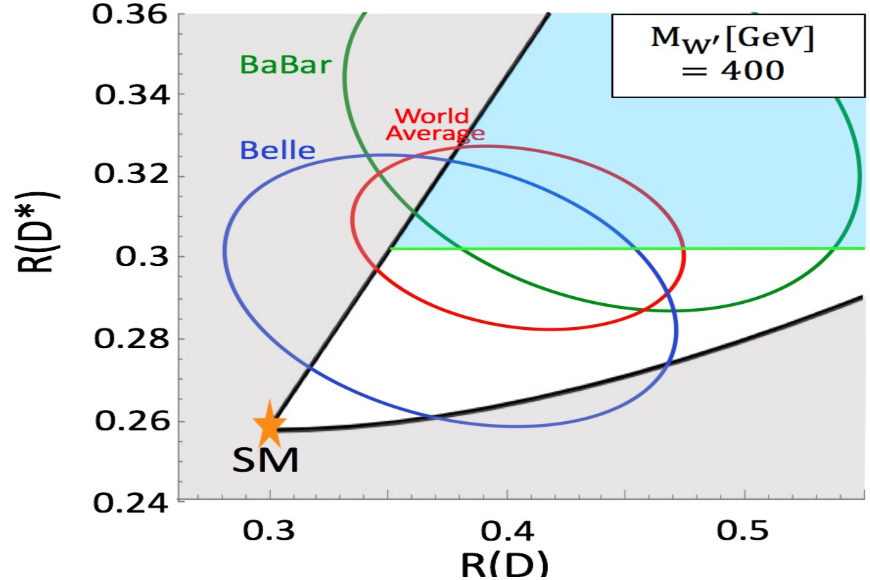
Result

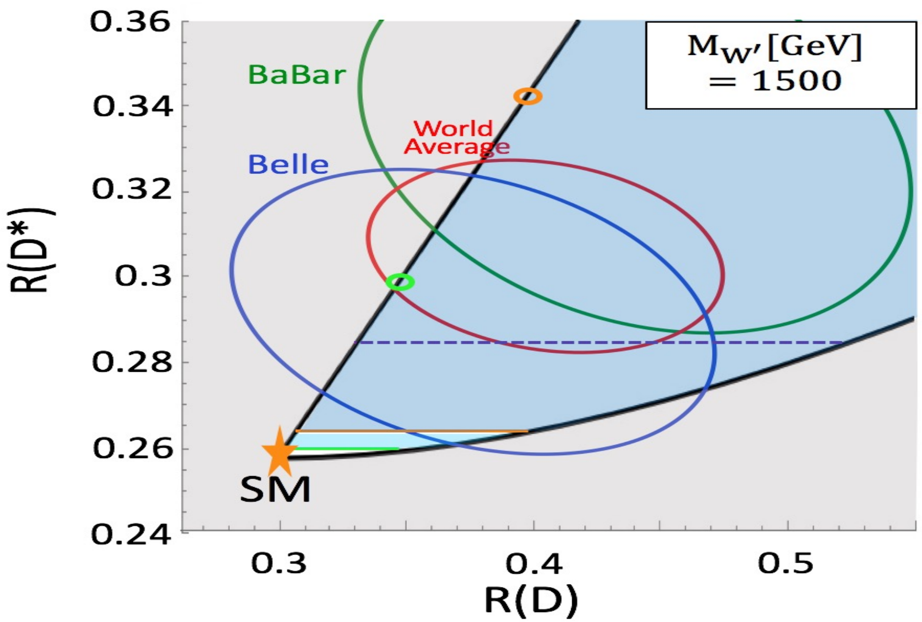
the heavier W’, the more severe constraint.

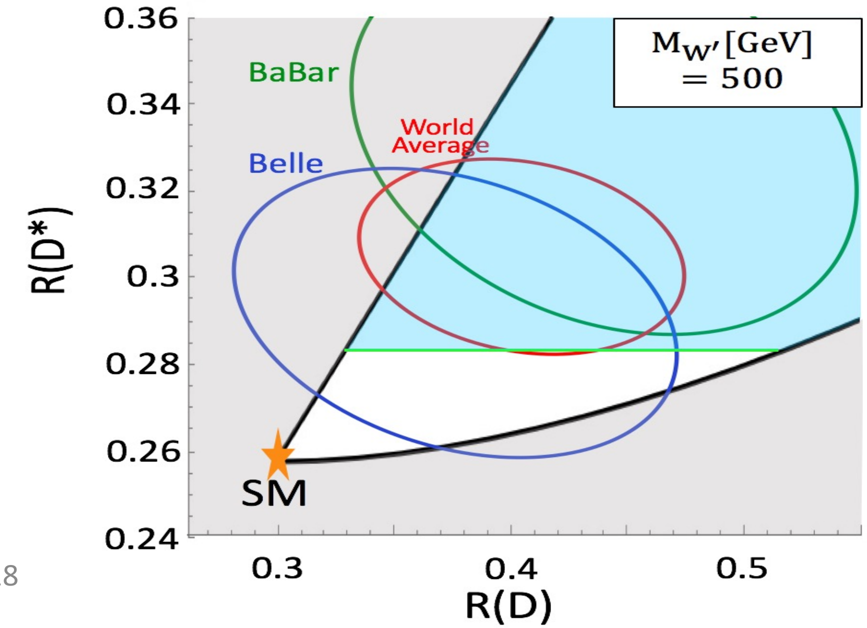
preliminary heavier

lighter



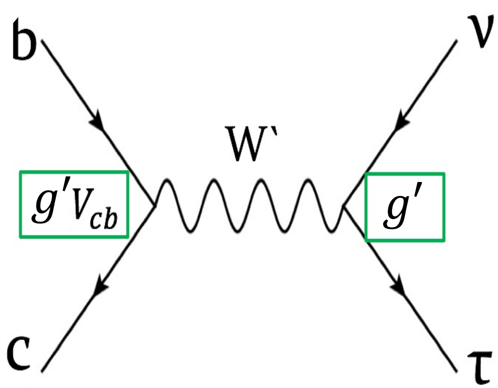






discussion

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

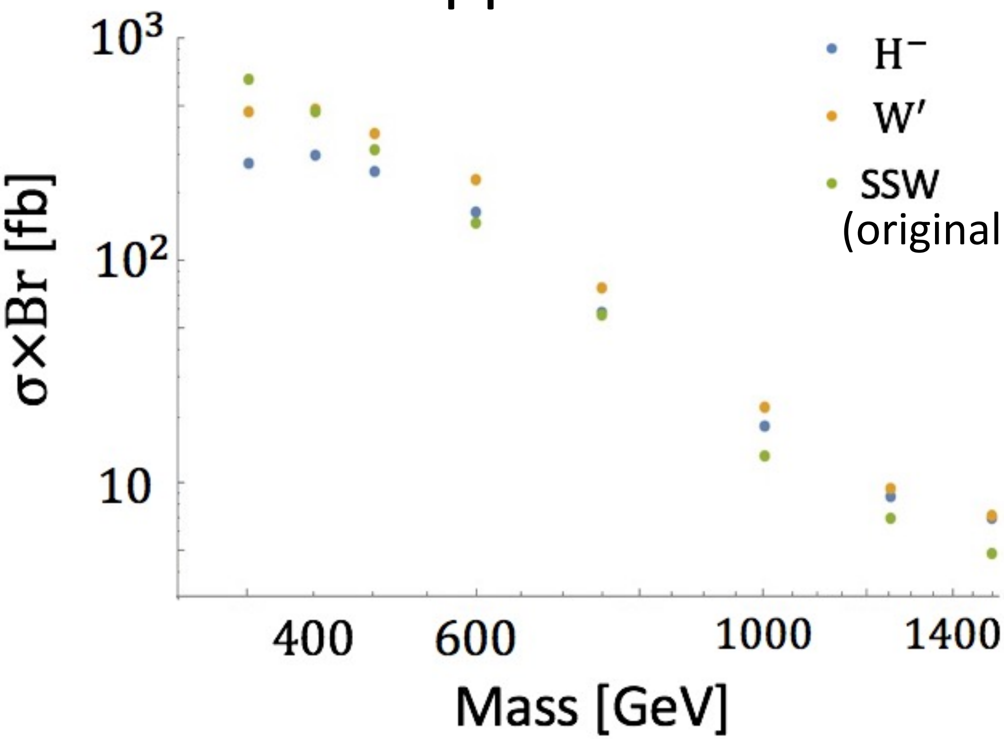
500GeV > $m_{W'}$ $\mathrm{R}(\mathrm{D}^{(*)})$ at that time.

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

reinterpretation

Comparing their efficiencies by generating events with SSW, H^- and W'.

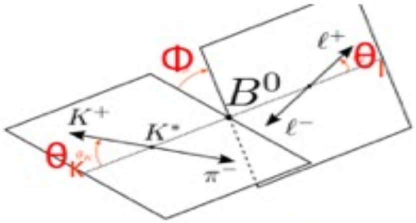
Upper limit



Cut $P_T^\tau \geq$80GeV $|\eta| \leq 2.4$. $E_{miss} \geq$200GeV. No e ($P_T^e \geq$ 20GeV, $|\eta| \leq 2.5$) nor μ ($P_T^\mu \geq$ 20GeV, $|\eta| \leq 2.4$). $0.7 \leq P_T^\tau/E_{miss} \leq 1.3$, azimuthal angle b/w τ and E_{miss}:$\Delta\phi \geq$2.4.

P'_5 anomaly in G2HDM

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



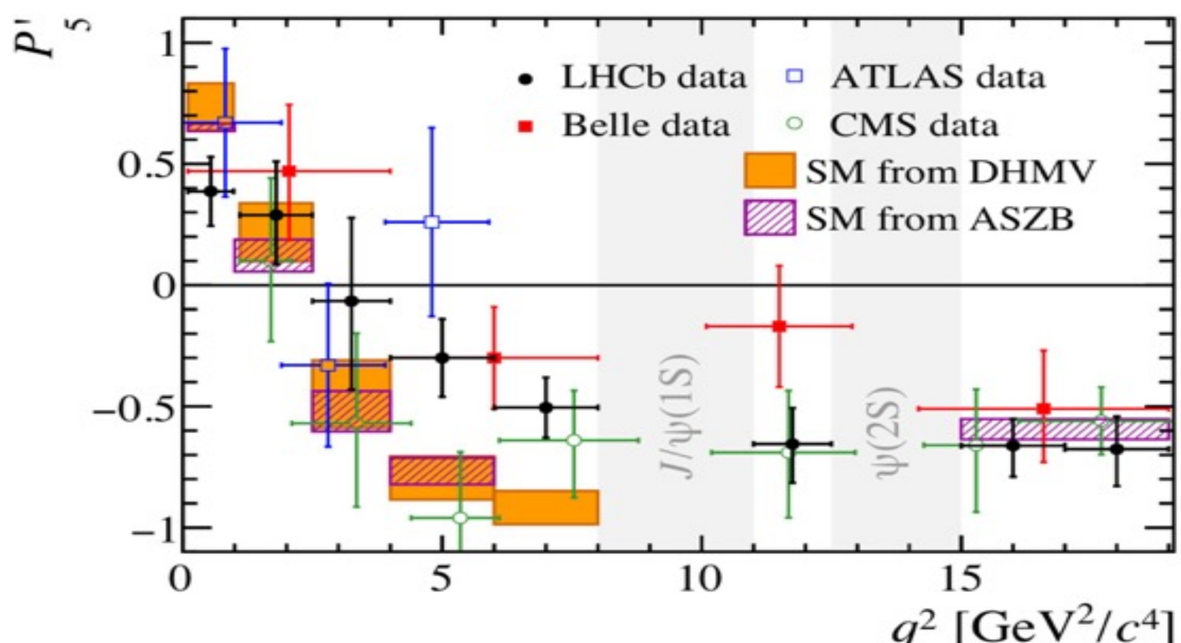
Optimized observable

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

b→s transition

P'_5 : angular observable

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



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

P'_5 anomalies

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

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

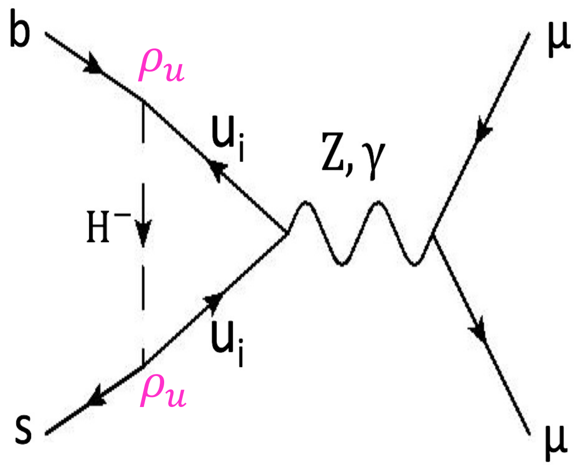
ρ_u^{tc} generates charm rotating diagrams : u_i =c

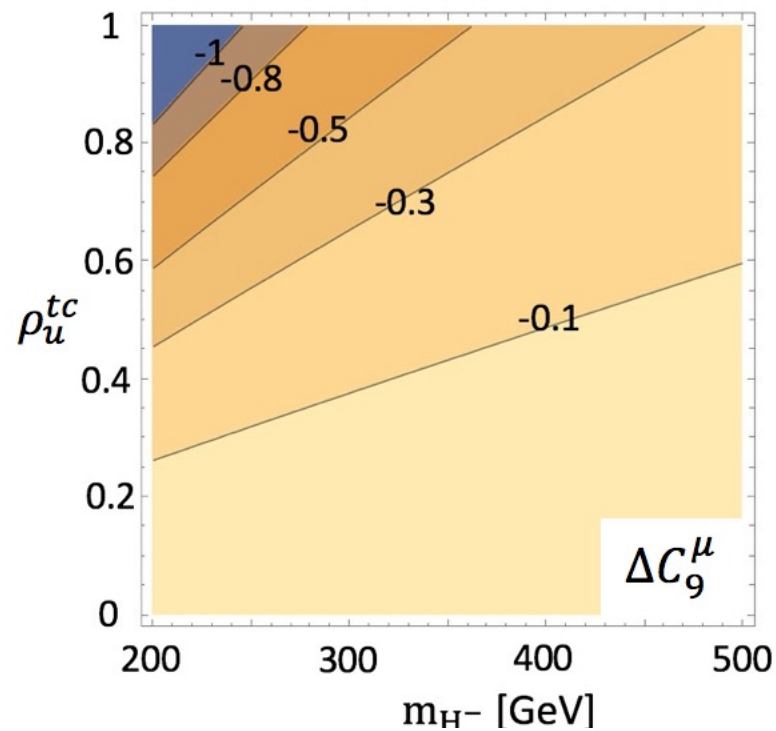
This γ penguin contribution has a dimensionless log $\frac{m_c}{m_{H^-}}$ enhancement

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

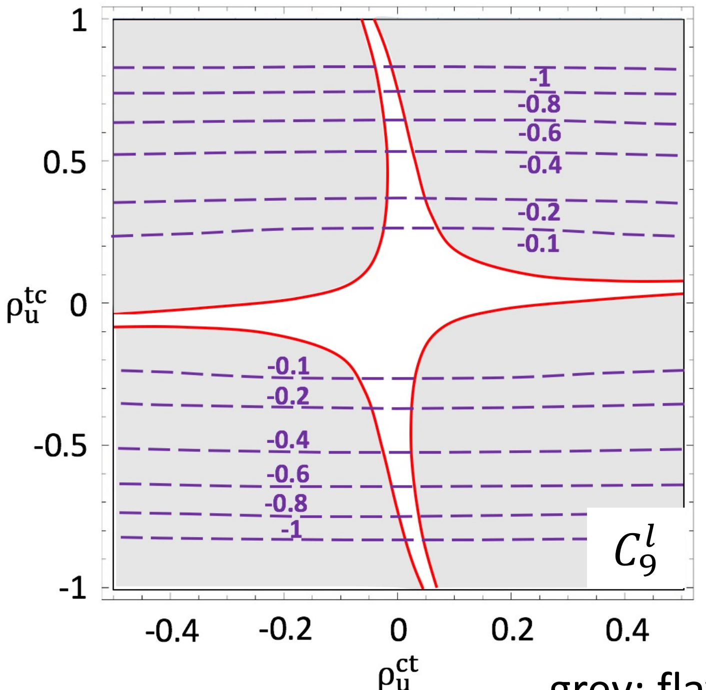


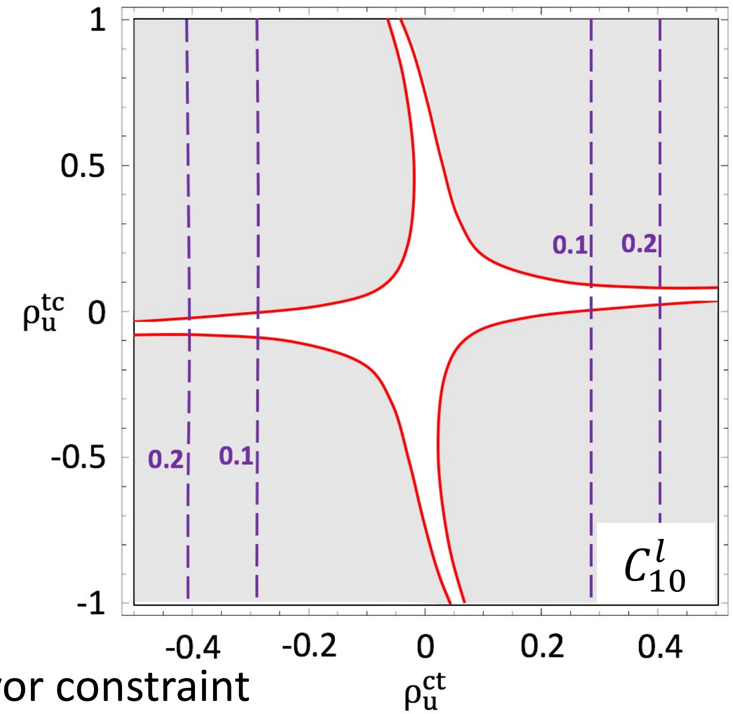


Other prediction

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

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

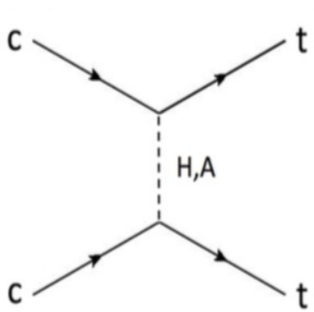


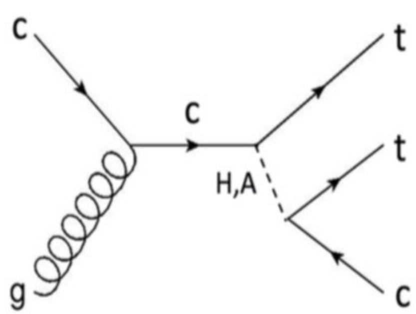


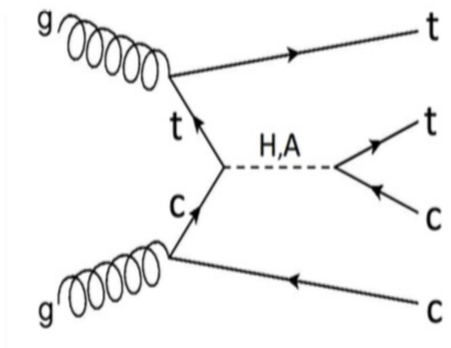
grey: flavor constraint

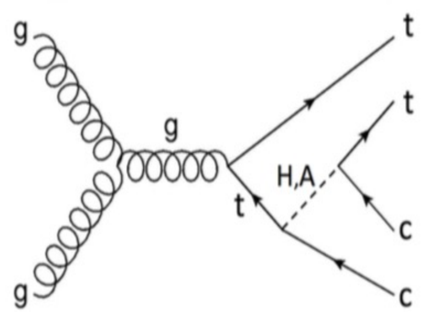
Collider signal

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.

G2HDM

We take so called Higgs base : a doublet acquires VEV

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

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

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

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

Result2 compatibility

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