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

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Based on

PhysRevD.99.075013 w/ Y. Omura(KMI), M. Takeuchi(IPMU),

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

Only one student from Japan.

Sorry for that!

This does not mean that the collider physics is unpopular among Japanese students!

What I do today

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

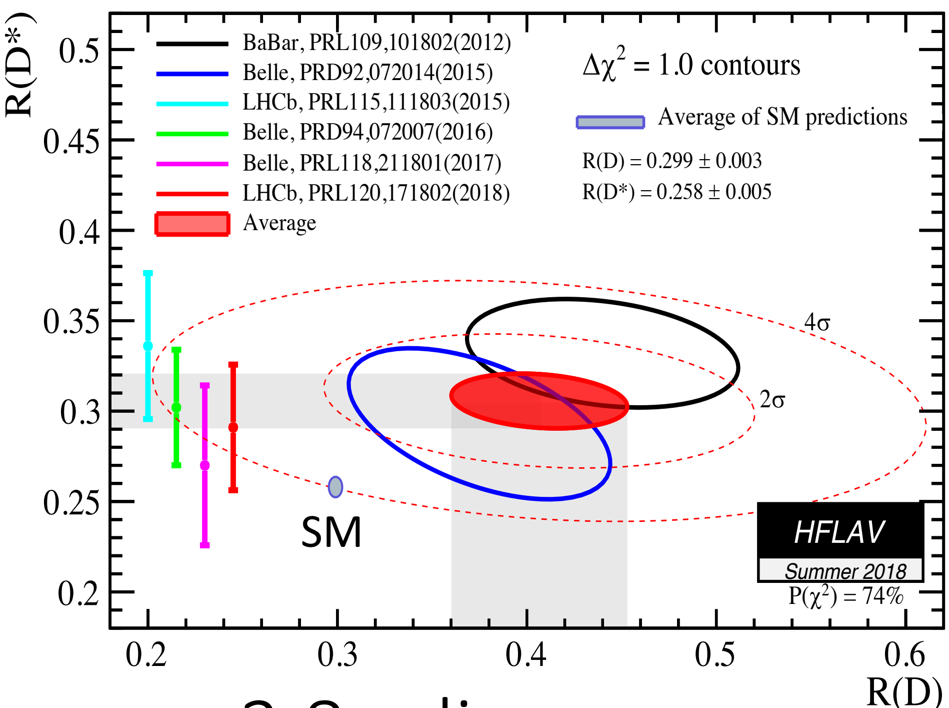
Result

We found the most stringent limit on the interpretation with this model!

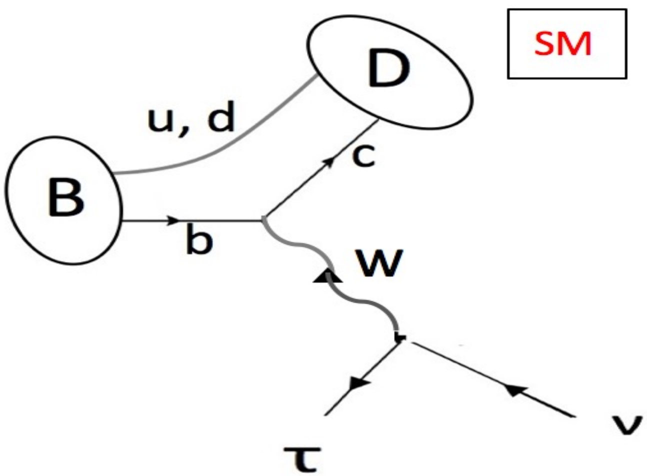
Current status of $R(D^{(*)})$ anomaly

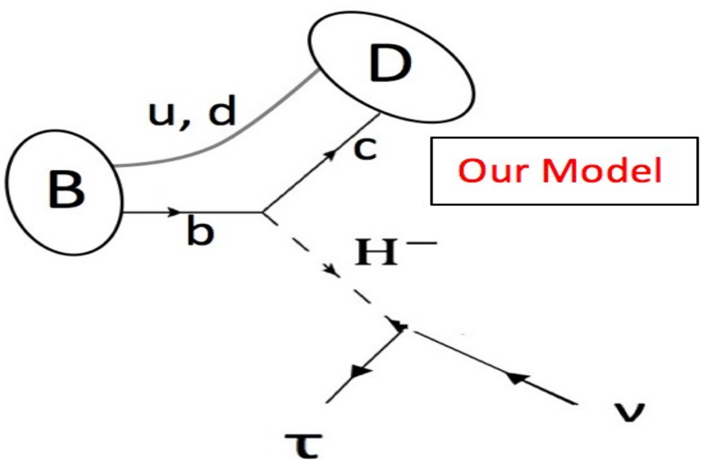
Naively, H^- is a good candidate.

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



3.8σ discrepancy





Phys. Rev. D 82, 034027 (2010) M.Tanaka, et.al
Phys.Rev. D86 (2012) 054014 A. Crivellin, et al.

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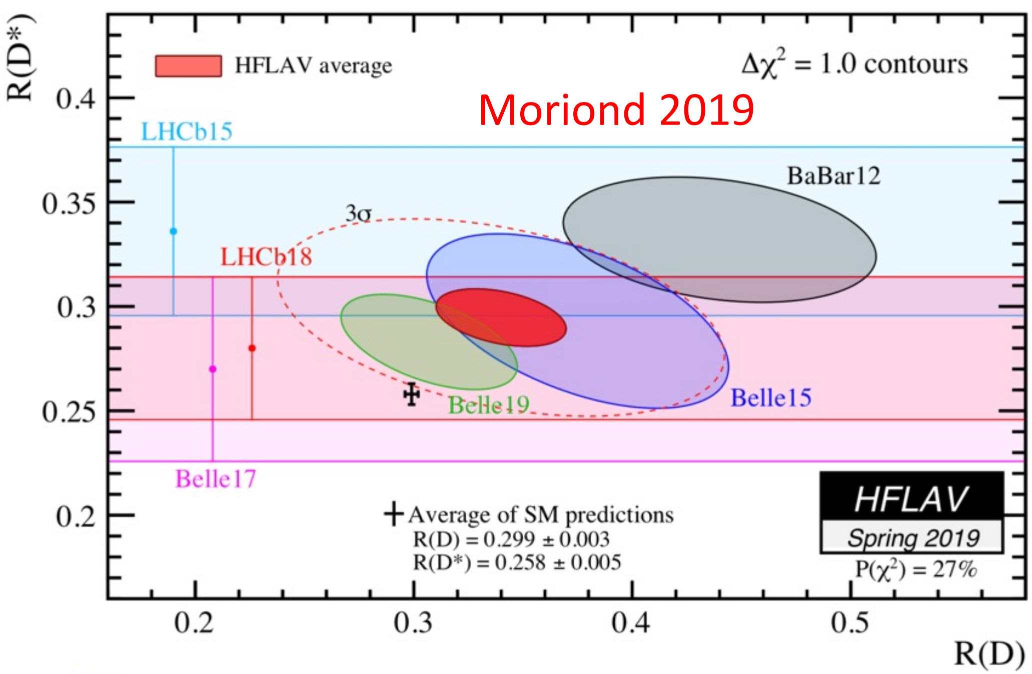
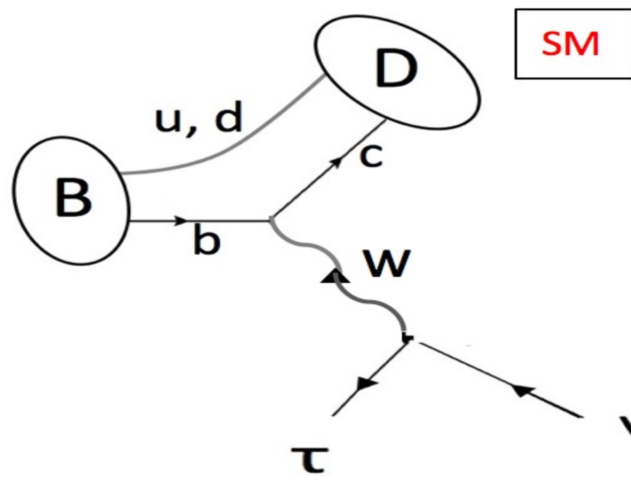
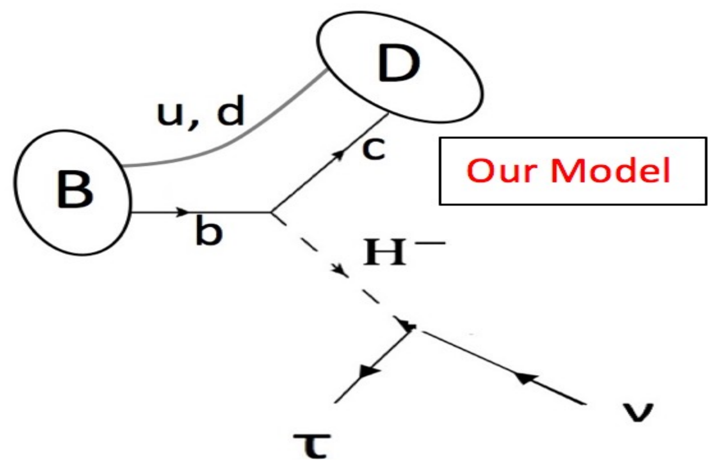
$$\mathrm{R}\left(\mathrm{D}^{(*)}\right) = \frac{BR\left(B\to D^{(*)}\tau\nu\right)}{BR\left(B\to D^{(*)}l\nu\right)}$$







~~3.8σ~~ 3.1σ discrepancy↓

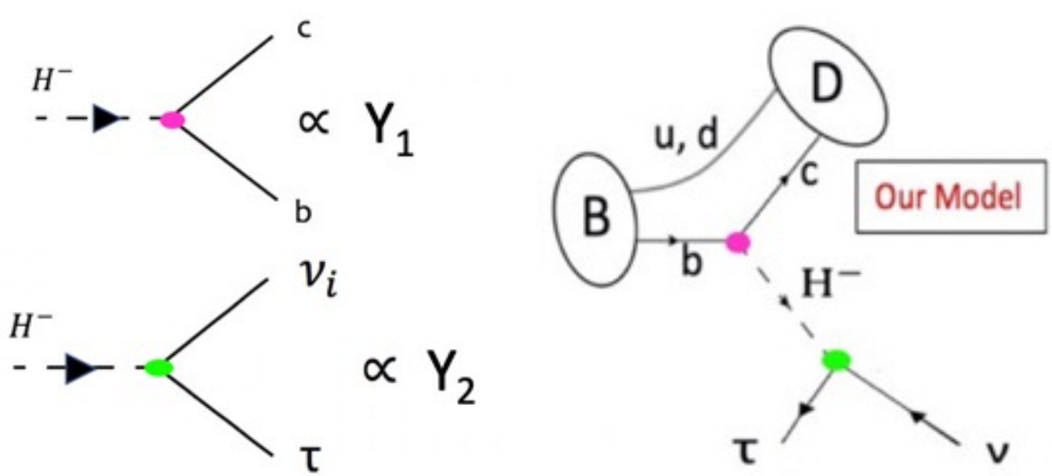
Phys. Rev. D 82, 034027 (2010) M.Tanaka, et.al
Phys.Rev. D86 (2012) 054014 A. Crivellin, et al.

Model

General Two Higgs Doublet Model (G2HDM)

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

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



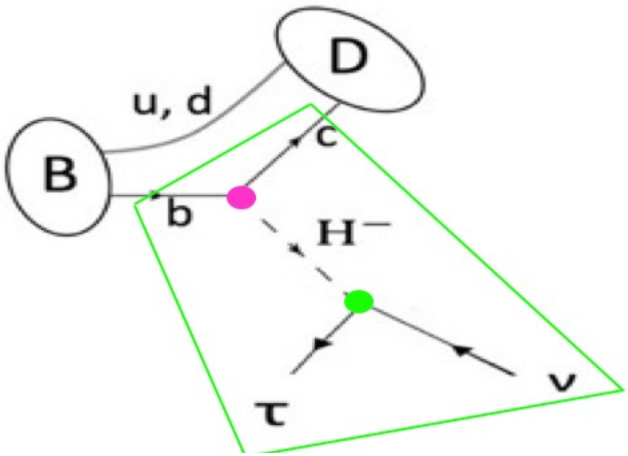
Additional particles in G2HDM

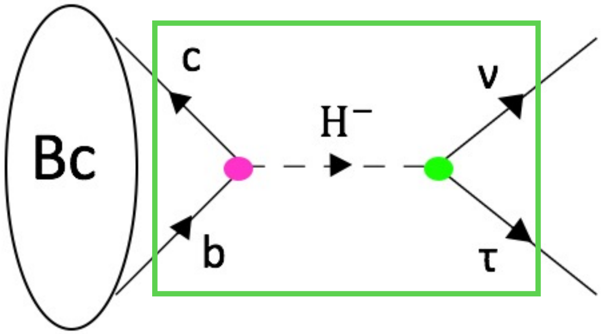
Main actor today

Yukawa interactions relevant to $R(D^{(*)})$ are Y_1, Y_2

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

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





$$C_R'^S \propto \frac{Y_1 Y_2}{m_{H^-}^2}$$

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

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

Scalar operators have a large coefficient

≈ 4

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

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

Conservative bound $<$ 60% 1811.09603

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

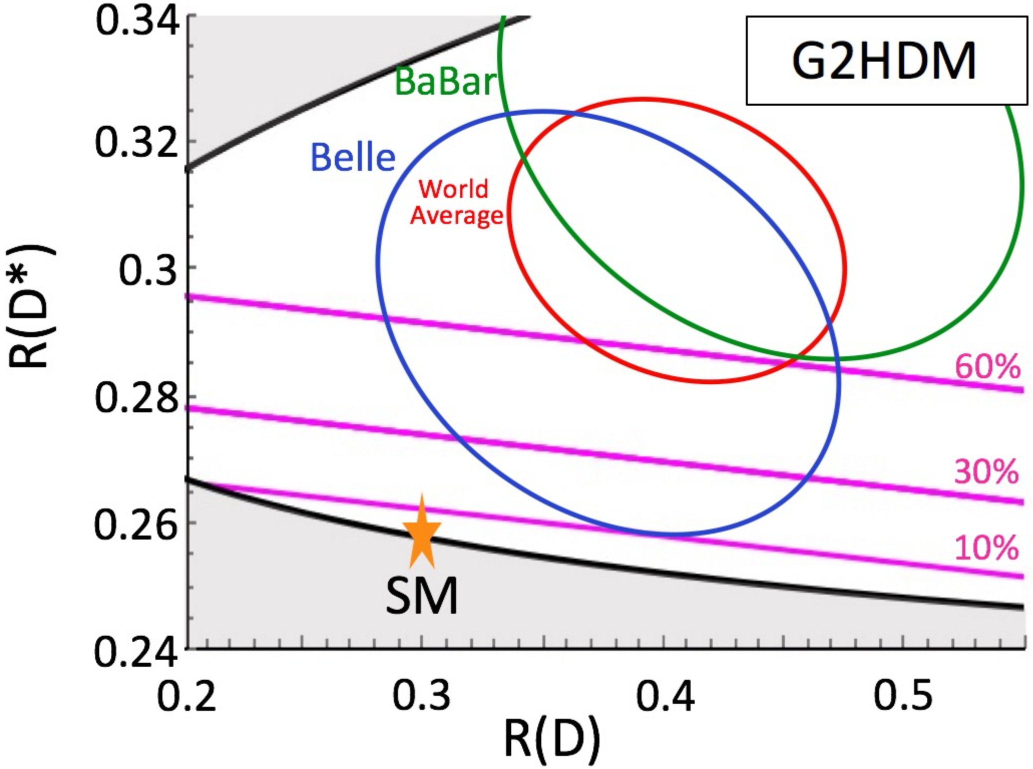
$$C_R'^S \sim \frac{Y_1 Y_2}{m_{H^-}^2}$$

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

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

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

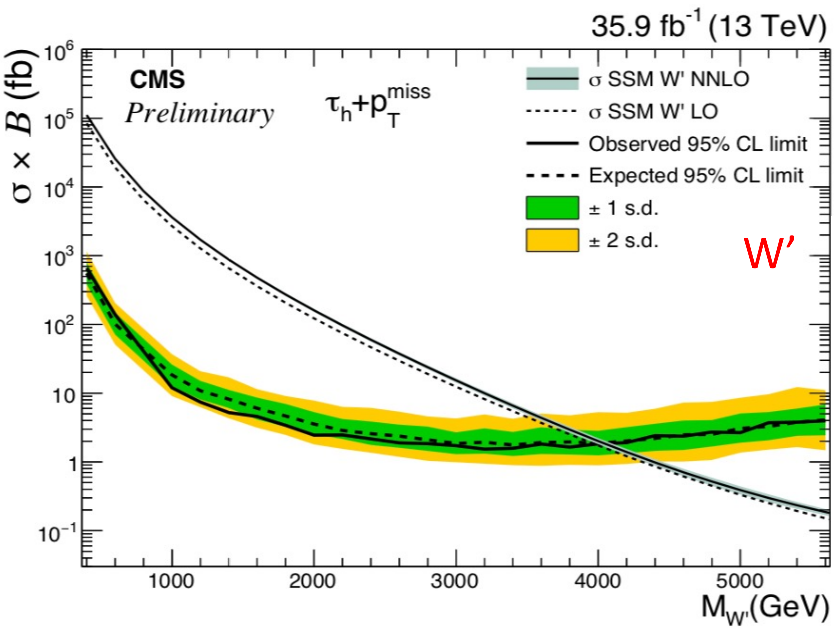
Large coefficient is necessary to enhance R(D*) in G2HDM.

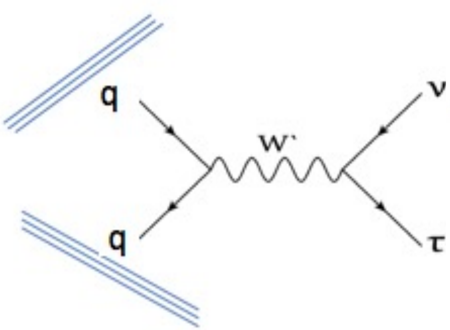


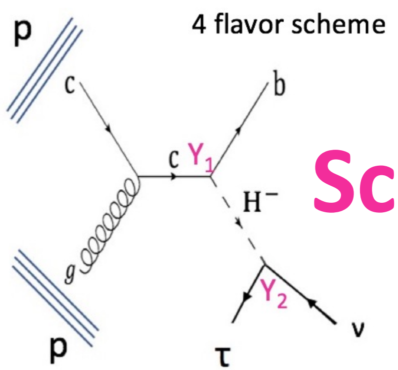
$\mathrm{BR}(B_c^- \to \tau\bar{\nu})$

Large coefficient (large coupling) allows the collider search!

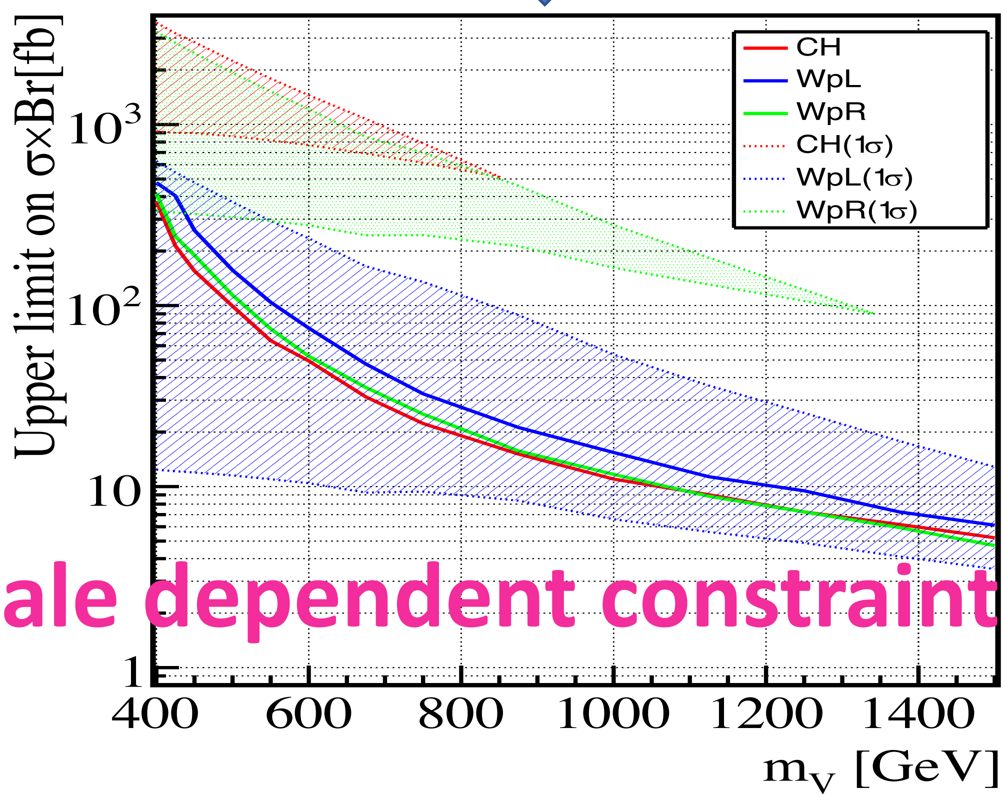
$\tau\nu$ resonance (+j) search in LHC can give a stringent limit.
But, the limit is for W’. CMS-PAS-EXO-17-008







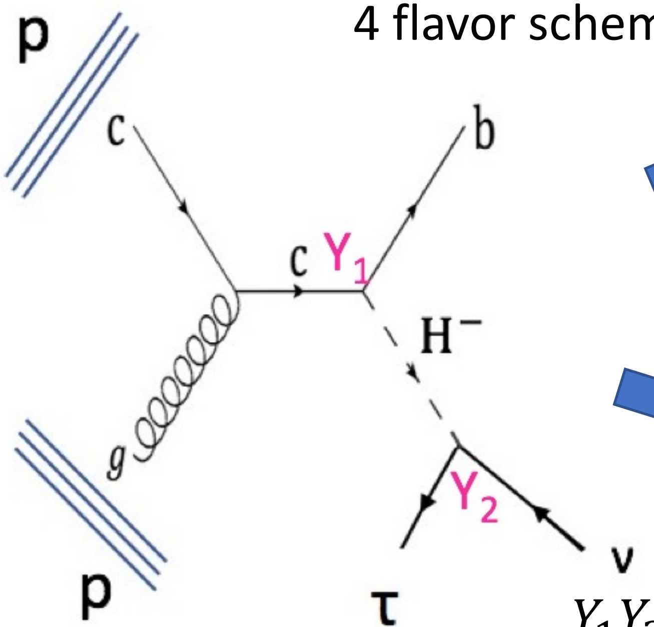
We reinterpreted this limit into H^- by the collider simulation.



Scale dependent constraint!

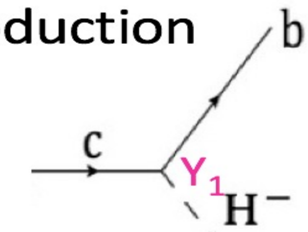
σ × Br in G2HDM

4 flavor scheme



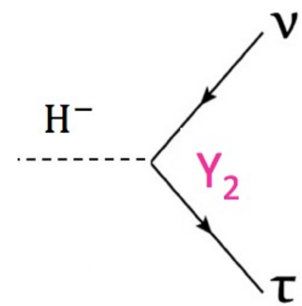
$C_R^{\prime S} \sim \frac{Y_1 Y_2}{m_{H^-}^2}$

Production



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

Branching ratio



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

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

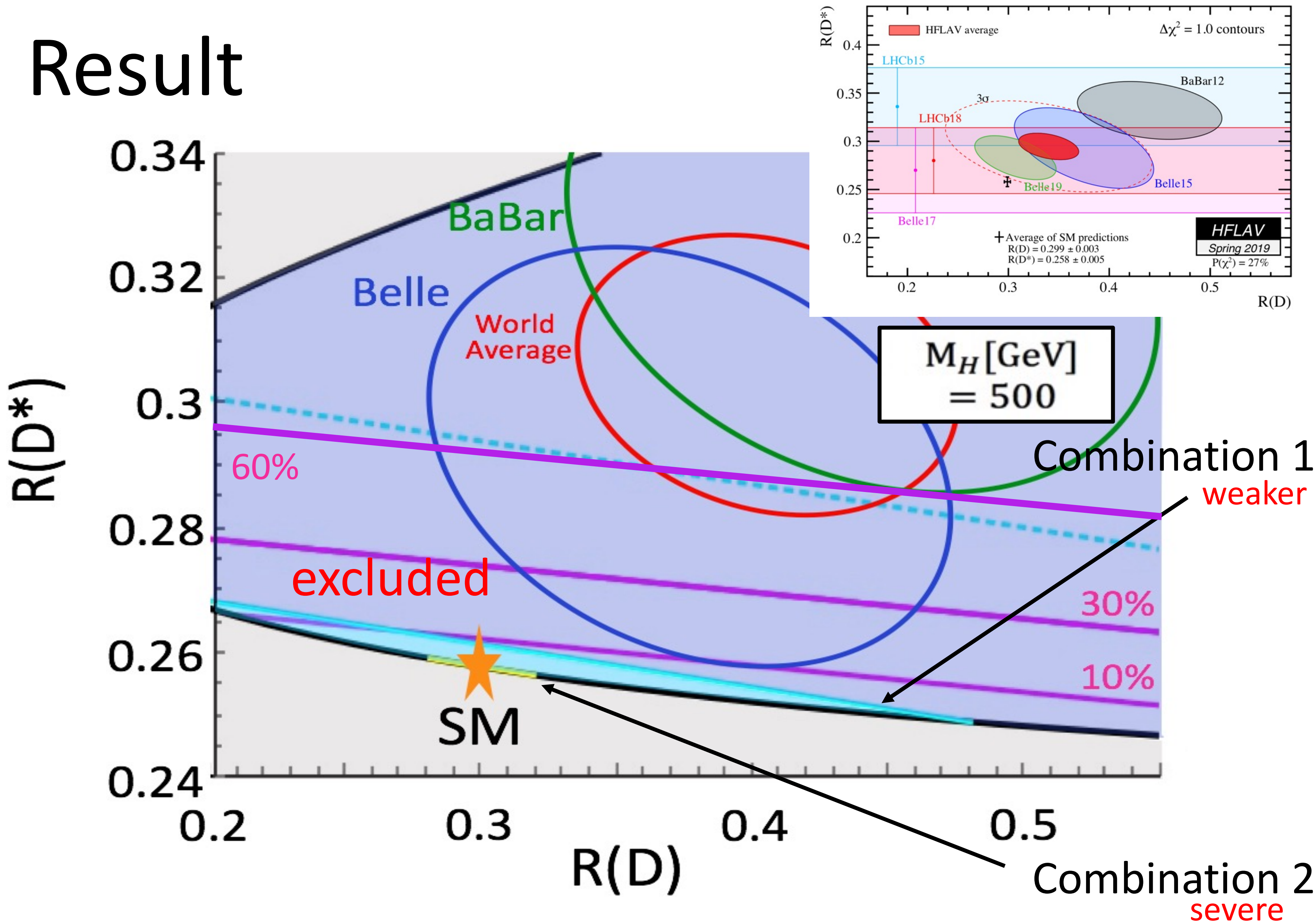
Combination 1 : $Y_1 = 1$, maximizing denominator.
less events, weaker constraint.

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

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

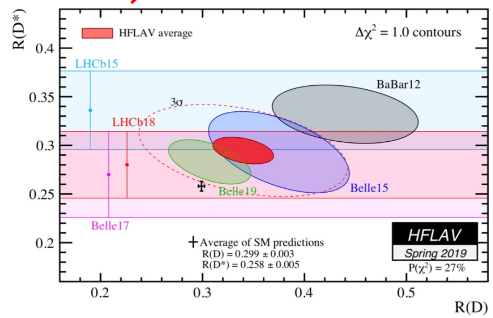
Result



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

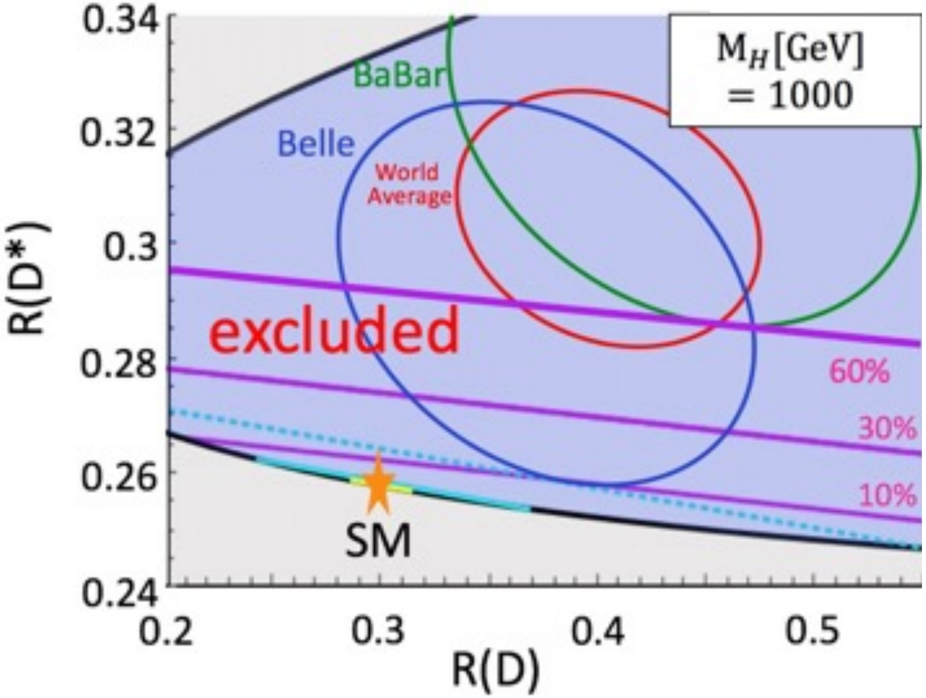
Result

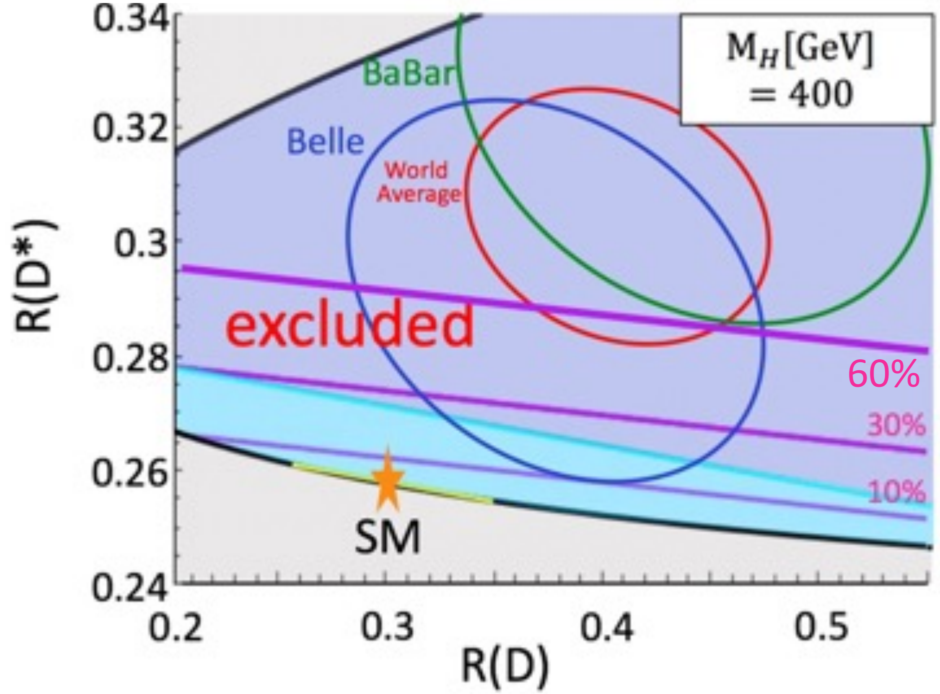
Heavier H^-, more severe constraint.



heavier

lighter





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

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

It is difficult to explain $\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ with a charged scalar

Heavier than 400GeV

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!

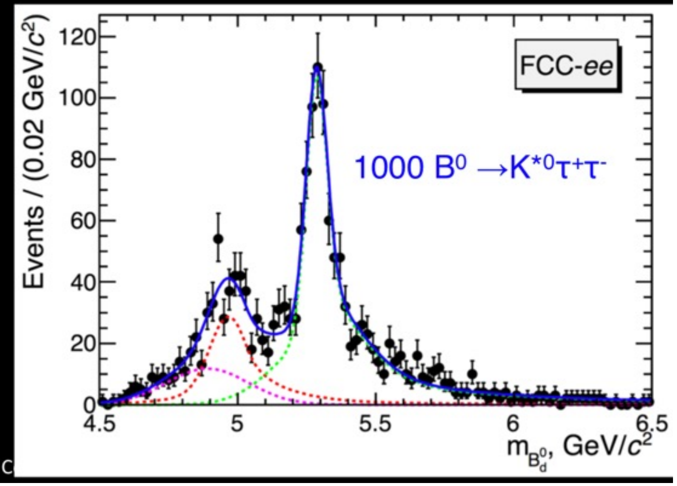
Good news

B Physics

UNIVERSITY OF OXFORD

	CEPC (10^{12} Z)	Belle II (50 ab^{-1} @$\Upsilon(4S)$ & 5 fb^{-1} @$\Upsilon(5S)$)	LHCb (50 fb^{-1})
$B^{\pm}/B^0$	6×10^{10}	3×10^{10}	3×10^{13}
B_s	2×10^{10}	3×10^{8}	8×10^{12}
B_c	10^{8}	-	6×10^{10}
b baryons	10^{10}	-	10^{13}

- Yield matches or exceeds Belle but is below LHCb
- Advantages:
  - B's are produced back to back and with predictable momenta
- Tau decay modes might be accessible
  - B→Kττ with 3-prong tau decays allows 4 vertex positions and thus full mass reconstruction
  - $B_c \to \tau\nu$



7/8/19

Daniela Bortoletto, KAIST-KAIX Workshop on Future C

Slide by Daniela on the first day

The upper limit on $B_c^- \to \tau\bar{\nu}$ from a future lepton collider can test the scenario!

감사합니다.

Thank you

Back up

- W' case
- Other tensions; 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.

Table 1. Predicted ranges of the polarizations for R_2, S_1 and U_1 LQ models ($\mu_{LQ} = 1.5\,\text{TeV}$), which satisfy the current $1\,\sigma$ 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 $50\,\text{ab}^{-1}$ 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]	$1\,\sigma$ data	$1\,\sigma$ data
S_1 LQ	[0.42, 0.48]	[0.11, 0.63]	[−0.51, −0.41]	$1\,\sigma$ data	$1\,\sigma$ data
U_1 LQ	[0.43, 0.47]	[0.23, 0.52]	[−0.57, −0.47]	$1\,\sigma$ data	$1\,\sigma$ 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 Syuhei Iguro, 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....

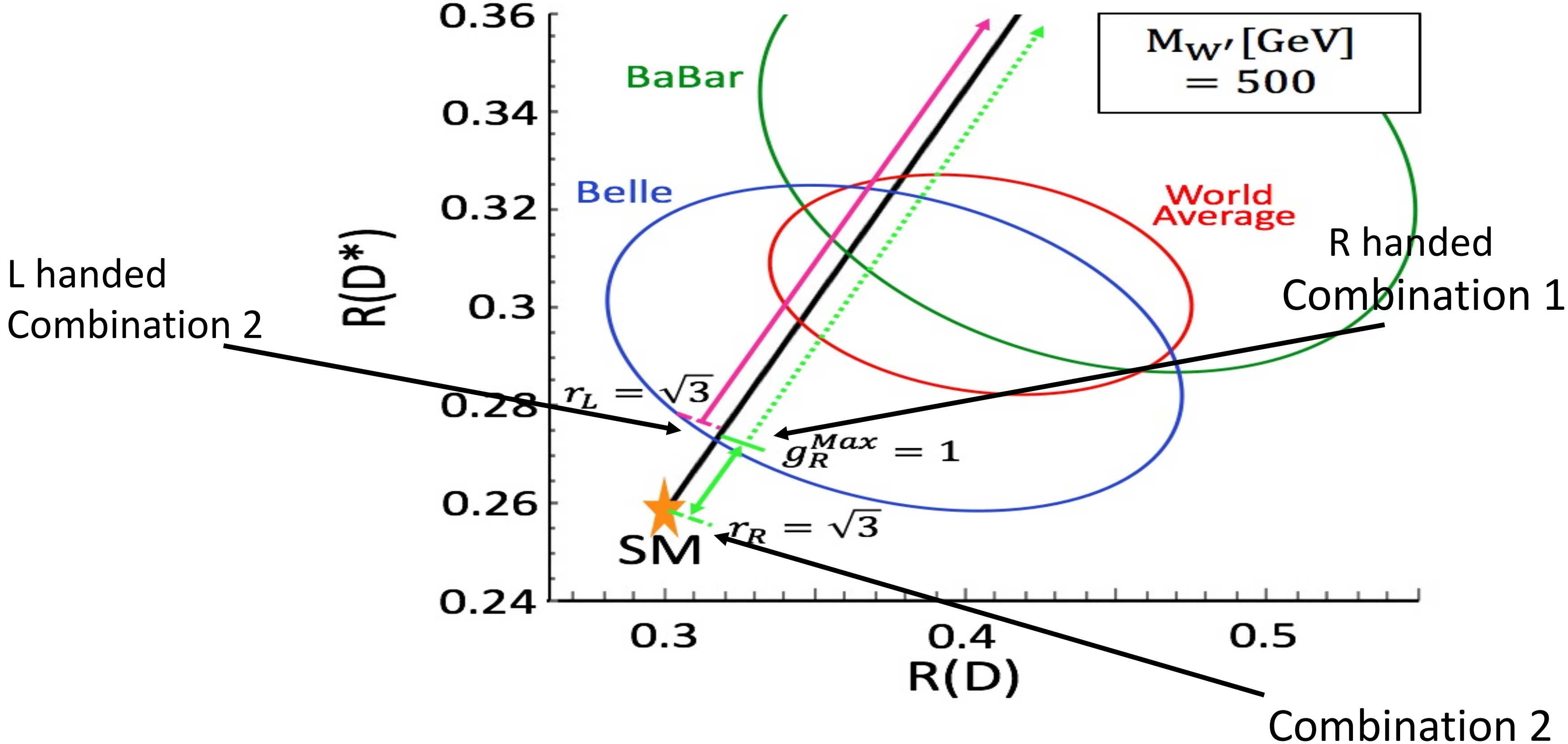
$$L_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb}\left[\left(1 + C_L'^{V}\right)\left(\bar{\tau}\gamma_\mu P_L \nu\right)\left(\bar{c}\gamma^\mu P_L b\right)\right] + C_R'^{V}\left(\bar{\tau}\gamma_\mu P_R \nu\right)\left(\bar{c}\gamma^\mu P_R b\right) + \text{h.c.}$$

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

Left handed vector charged current

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

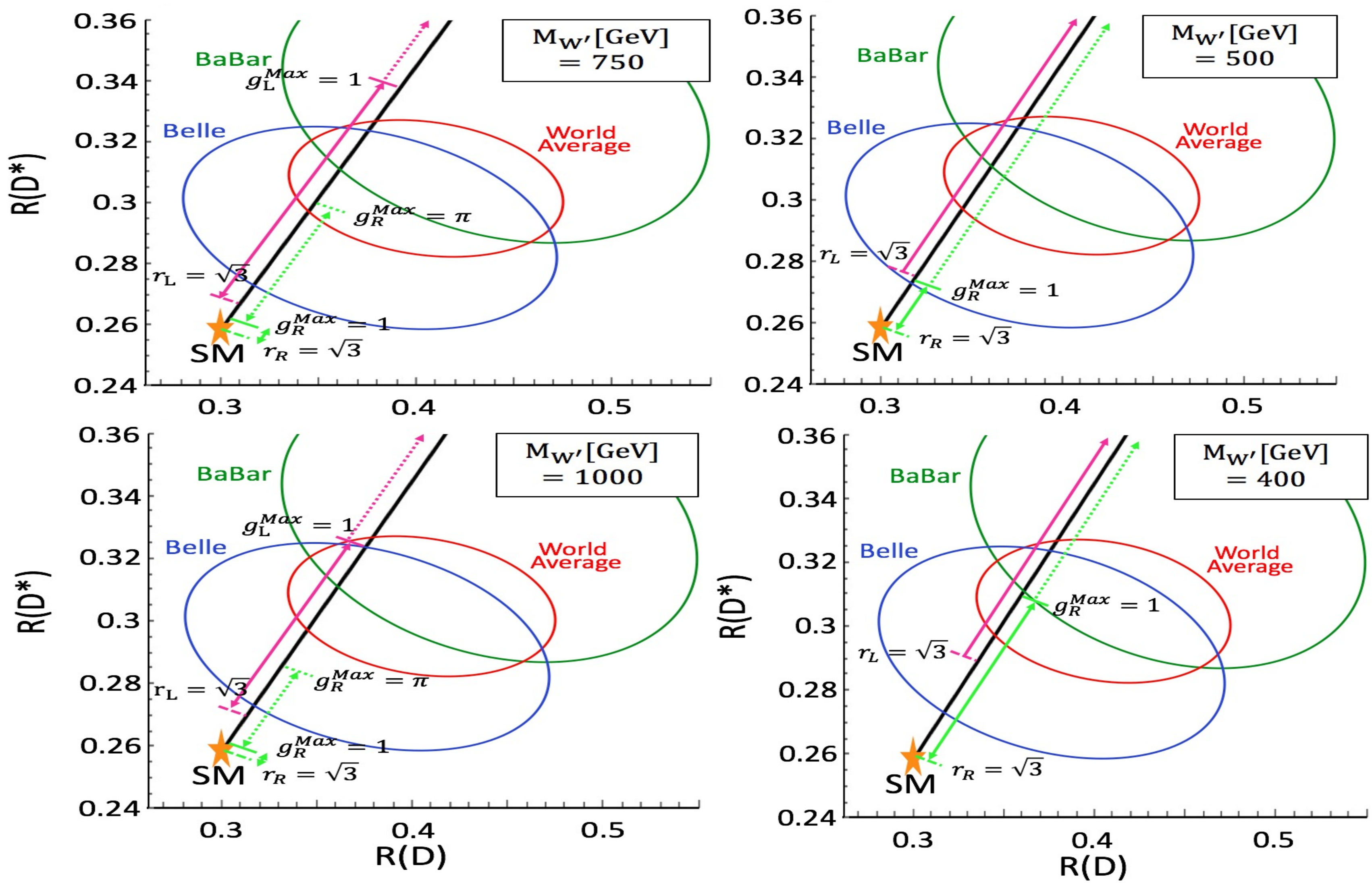
$$\sigma(pp \to V^{\pm}) \times Br(V^{\pm} \to \tau\nu) = \sigma_0(m_V) \times \frac{|g|^2|g_\tau|^2}{3|g|^2 + |g_\tau|^2} = \sigma_0(m_V) \times \bar{g}^2 \frac{r}{3 + r^2}.$$



Result

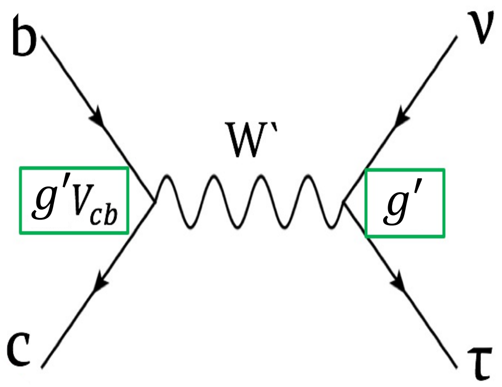
the heavier W', the more severe constraint.

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→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: $\delta\alpha_\mu$ Omura, Senaha, Tobe: **JHEP 1505 (2015) 028**
- P'_5 : angular observable in $B \to K^*\mu\mu$
- $R(K^{(*)}) = BR(B \to K^{(*)}\mu\mu)/BR(B \to K^{(*)}ee)$

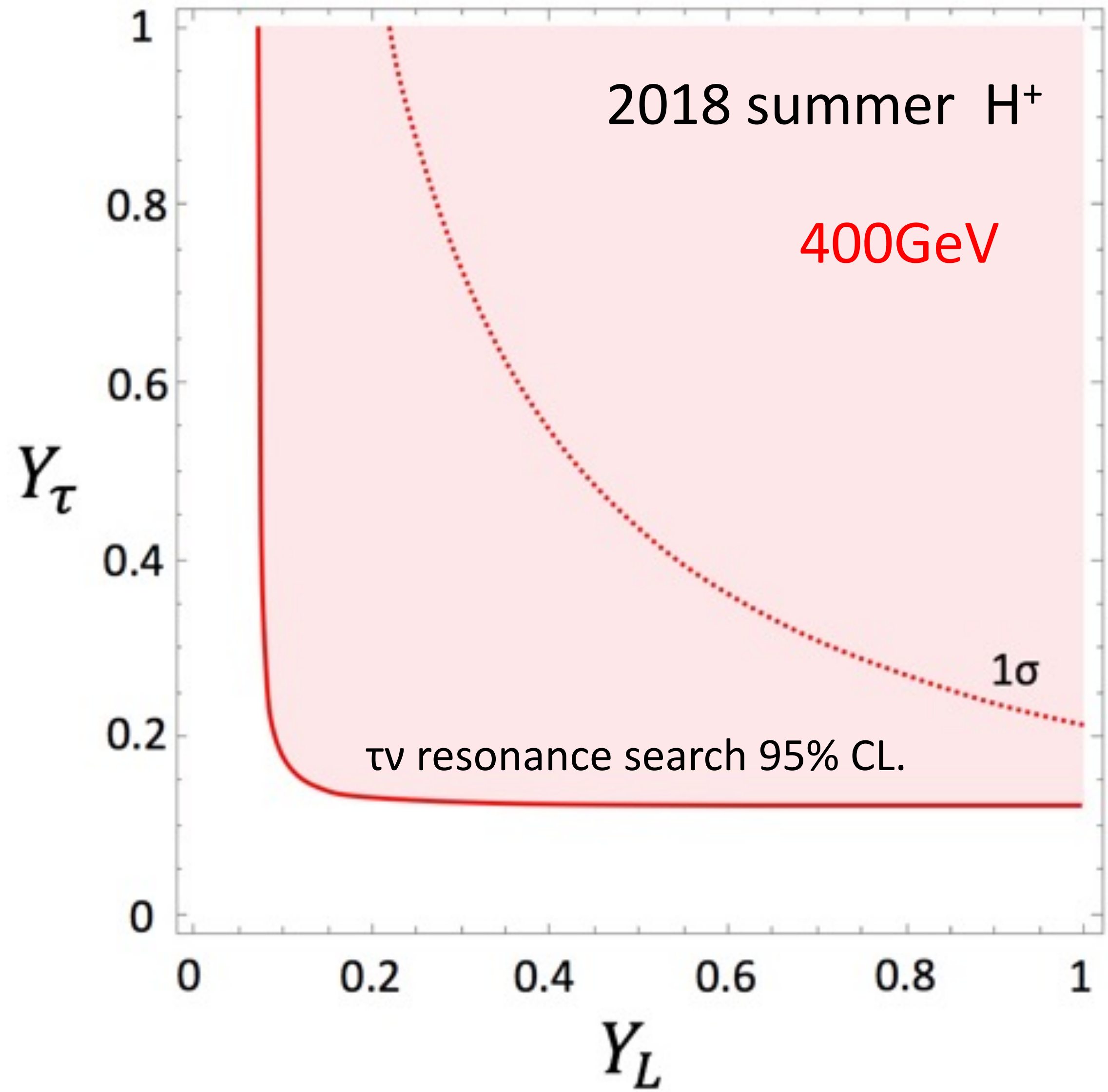
	$R(K^{(*)})$	P'_5	$R(D)$	$R(D^*)$	$\delta\alpha_\mu$
(B) $\rho_e \neq 0,\ \rho_\nu = 0$					
ρ_u^{tt}	×	×	×	×	○
ρ_u^{tc}	×	○	○	×	×
ρ_u^{ct}	×	×	×	×	○

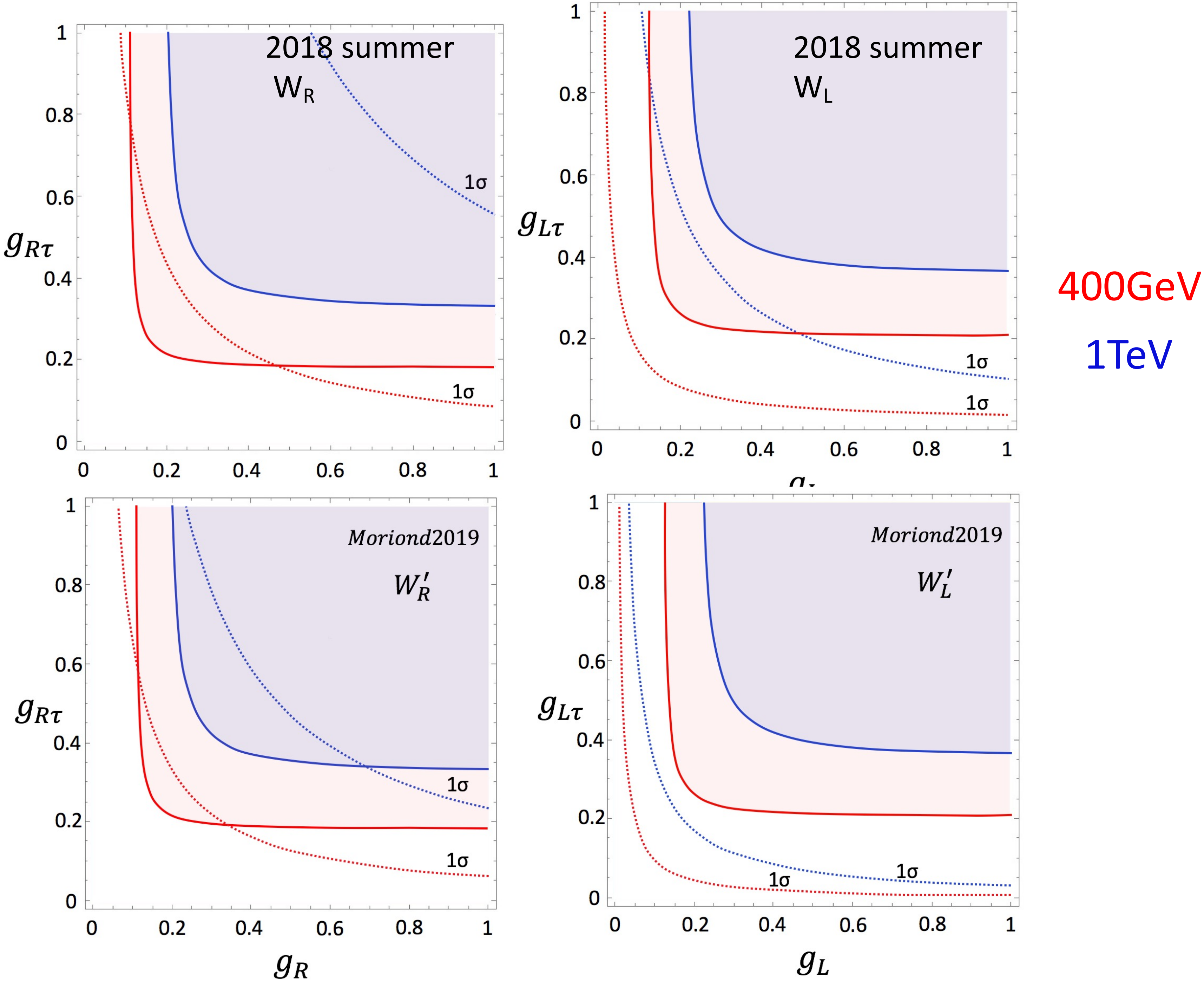
○: within 1σ

or X X O X O

JHEP 1805 (2018) 173 SI, Y. Omura

Constraint on the coupling plane



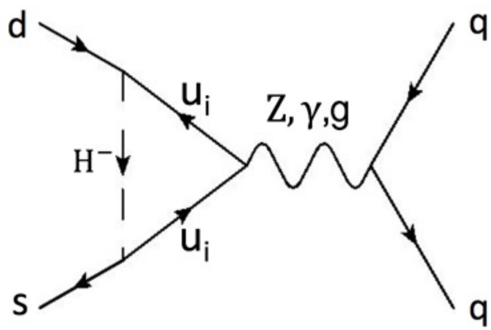

2018 summer
W_R
1σ
1σ
g_Rτ
0
0.2
0.4
0.6
0.8
1
2018 summer
W_L
1σ
1σ
g_Lτ
400GeV
1TeV
Moriond2019
W'_R
1σ
1σ
g_Rτ
g_R
Moriond2019
W'_L
1σ
1σ
g_Lτ
g_L

The latest paper of us

We found that G2HDM can not explain the deviation in ε'/ ε.

$$(\epsilon'/\epsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$$

$$(\epsilon'/\epsilon)_{SM} = ((1-2) \pm 5) \times 10^{-4}.$$

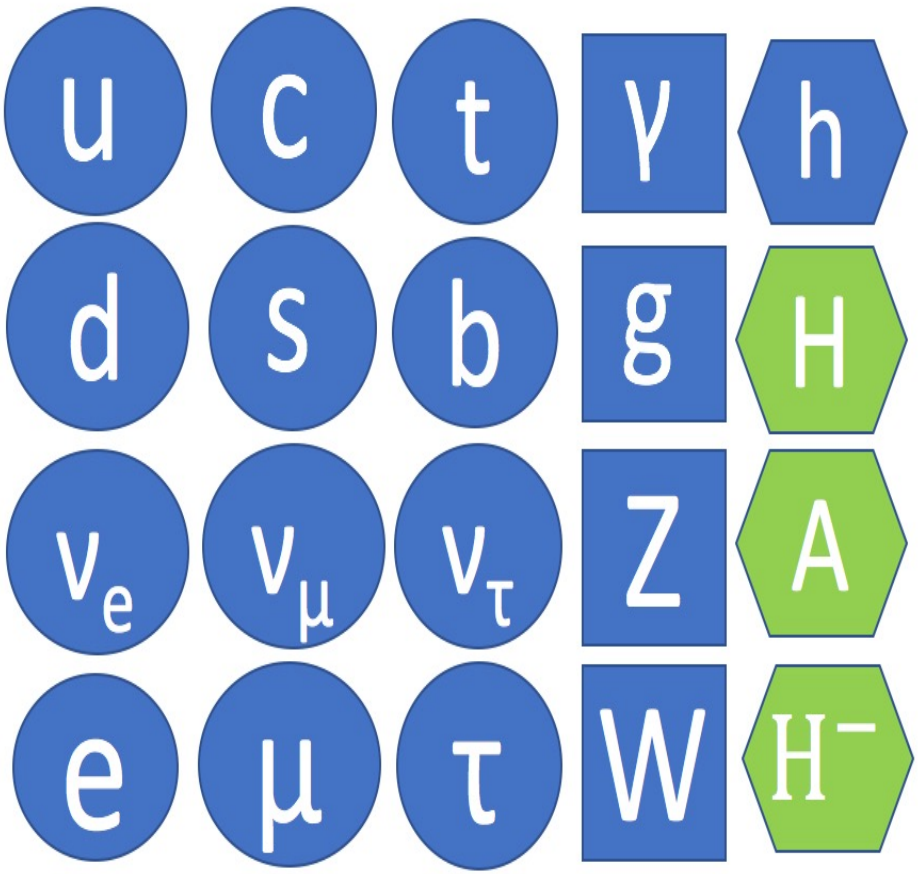


See our paper or ask me for more detail!

1. **The direct CP violation in a general two Higgs doublet model**
Syuhei Iguro (Nagoya U.), Yuji Omura (Kinki U., Osaka). May 28, 2019. 20 pp.
e-Print: arXiv:1905.11778 [hep-ph] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

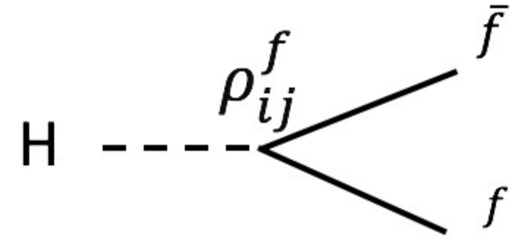
Our Model

Particle set in G2HDM



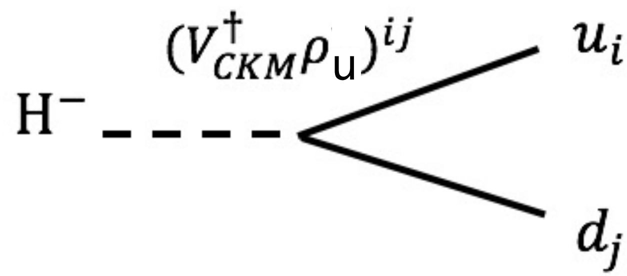
Neutral Scalar

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



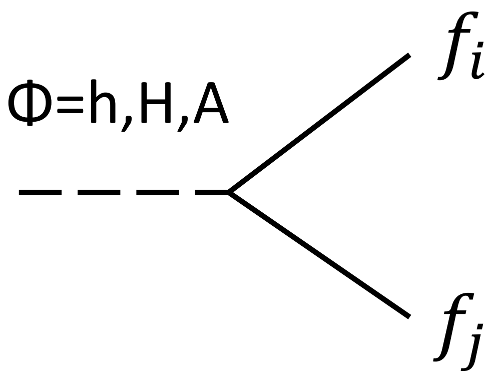
Charged Scalar

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



Model: G2HDM

Yukawa couplings between a neutral scalar and fermions



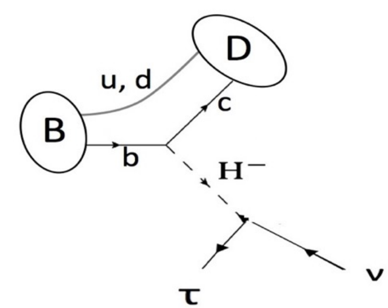
$$\approx i(y^{f}_{\Phi ij}\, P_R + y^{f*}_{\Phi ji}\, P_L)$$

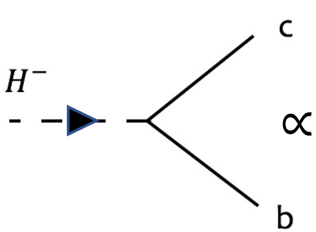
$$y^f_{hij} = \frac{m^i_f}{v} s_{\beta\alpha}\delta_{ij} + \frac{\rho^{ij}_f}{\sqrt{2}} c_{\beta\alpha},$$

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

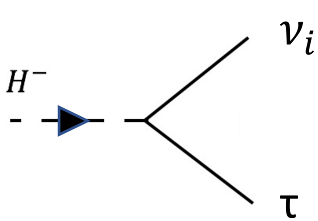
$$y^f_{Hij} = \frac{m^i_f}{v} c_{\beta\alpha}\delta_{ij} - \frac{\rho^{ij}_f}{\sqrt{2}} s_{\beta\alpha}$$

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



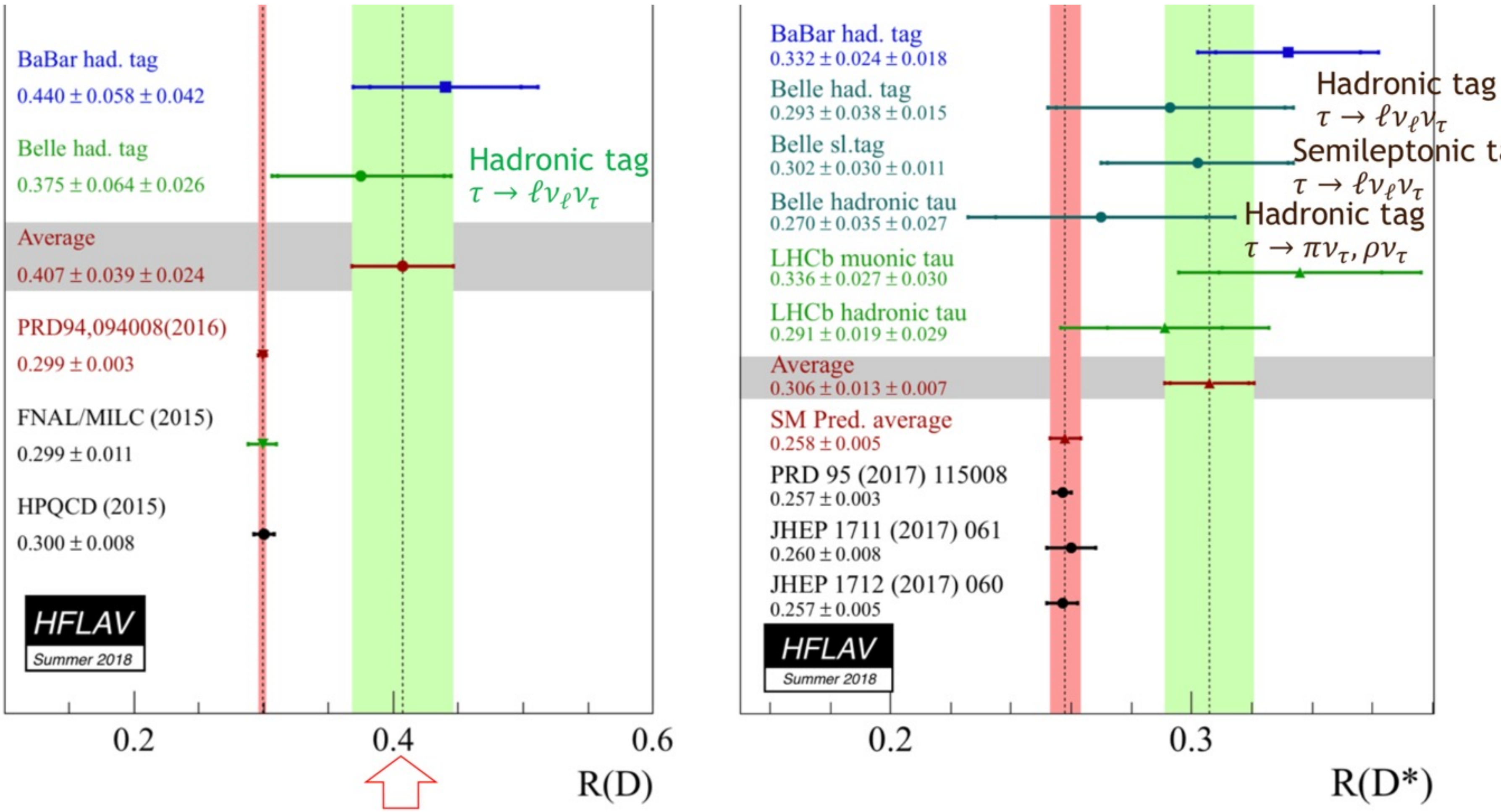


$$\propto (V_{CKM}\rho_d P_R - \rho_u^\dagger V_{CKM} P_L)^{cb} \approx \rho_d^{sb} P_R - \rho_u^{tc*} P_L$$



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

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



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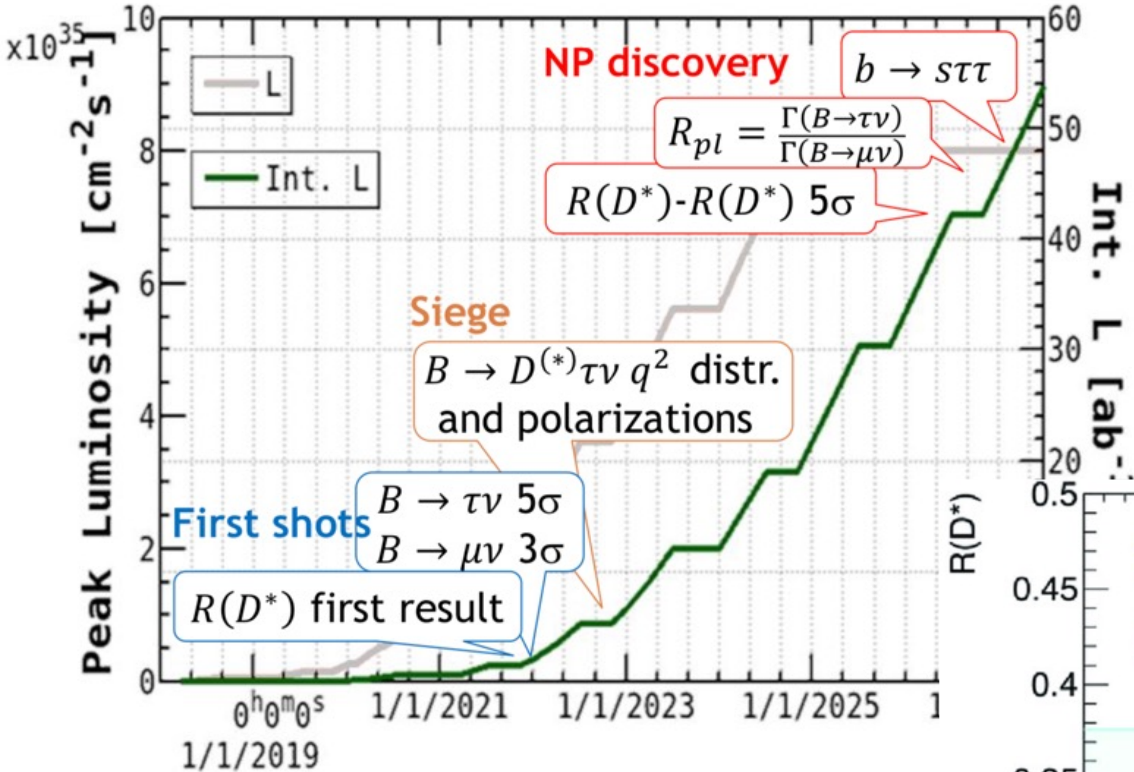
Prospects



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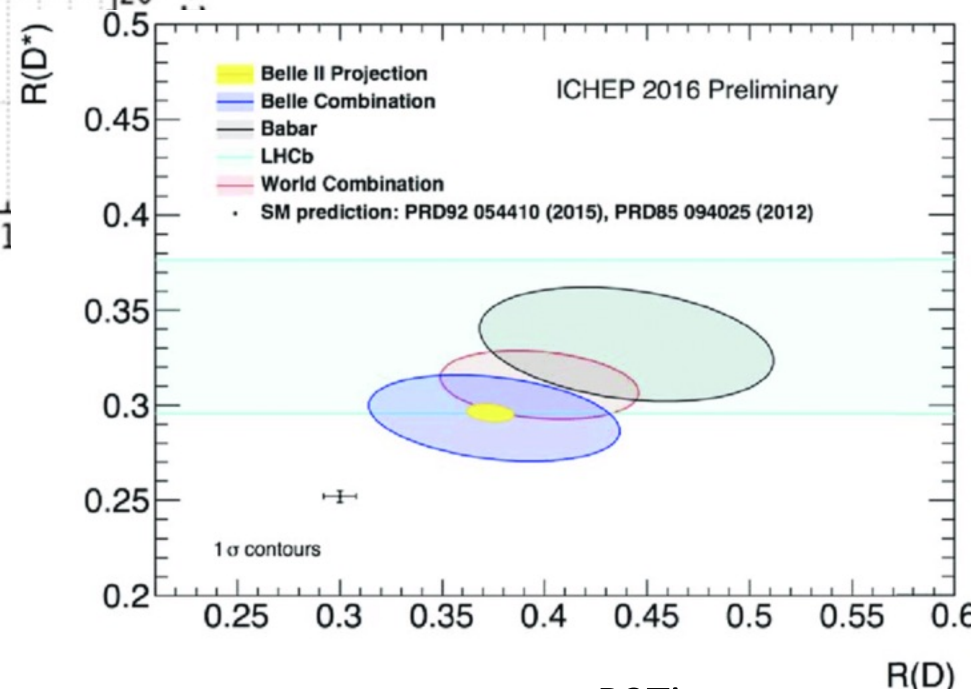

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