D* polarization vs. R(D$^{(*)}$) anomalies in the leptoquark models (LQs)

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Based on
JHEP 1902 (2019) 194 w/ T. Kitahara, R. Watanabe, Y. Omura and K. Yamamoto
and **update after Moriond2019**
PhysRevD.99.075013 w/ Y. Omura(KMI), M. Takeuchi(IPMU),
(Nucl.Phys. B925 (2017) 560-606 w/ K. Tobe(KMI,Nagoya-U)).

D^* polarization vs. $R(D^{(*)})$ anomalies

One day Youtuber

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JHEP 1902 (2019) 194 w/ T. Kitahara, R. Watanabe,
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(**Nucl.Phys. B925 (2017) 560-606** w/ K. Tobe(KMI,Nagoya-U)).

menu

- D* polarization in $B \to D^{*}\tau\nu$ and R(D$^{(*)}$) anomalies.
- One operator analysis
- LQ analysis

  Leptoquark (LQ): a boson couples to a quark and lepton pair
- Summary

There are B anomalies in b ->c τ ν and b ->s μ μ transitions.

Good playground

O(700) > papers for $R(D^{(*)})$

Evidence for an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays
BaBar Collaboration (J.P. Lees (Annecy, LAPP) *et al.*). May 2012. 8 pp.
Published in **Phys.Rev.Lett. 109 (2012) 101802**
BABAR-PUB-12-012, SLAC-PUB-15028
DOI: 10.1103/PhysRevLett.109.101802
e-Print: **arXiv:1205.5442 [hep-ex] | PDF**

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server; Link to DISCOVERY; Link to Physics Synopsis; SLAC Document Server

レコードの詳細 - Cited by 695 records 500+

Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$
LHCb Collaboration (Roel Aaij (CERN) *et al.*). Jun 29, 2015. 10 pp.
Published in **Phys.Rev.Lett. 115 (2015) no.11, 111803,** Erratum: **Phys.Rev 115 (2015) no.15, 159901**
CERN-PH-EP-2015-150, LHCB-PAPER-2015-025
DOI: 10.1103/PhysRevLett.115.159901, 10.1103/PhysRevLett.115.111803
e-Print: **arXiv:1506.08614 [hep-ex] | PDF**

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; Link to livescience article; Link to Scientific American article

レコードの詳細 - Cited by 616 records 500+

Measurement of the branching ratio of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle
Belle Collaboration (M. Huschle (Karlsruhe U., EKP) *et al.*). Jul 12, 2015. 14 pp.
Published in **Phys.Rev. D92 (2015) no.7, 072014**
KEK-REPORT-2015-18
DOI: 10.1103/PhysRevD.92.072014
e-Print: **arXiv:1507.03233 [hep-ex] | PDF**

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server; Link to Scientific American article

レコードの詳細 - Cited by 507 records 500+

Our question.

Is there any model that explain
D* polarization in $B \to D^* \tau \nu$ and R(D$^{(*)}$) anomalies
at the same time?

$$F_L^{D^*} = \frac{\Gamma(B \to D_L^* \tau \nu)}{\Gamma(B \to D^* \tau \nu)}$$

1907.02257

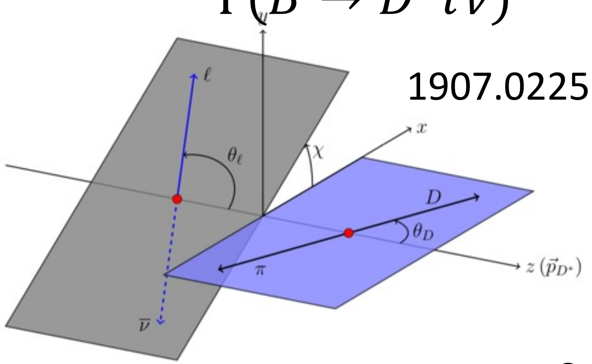


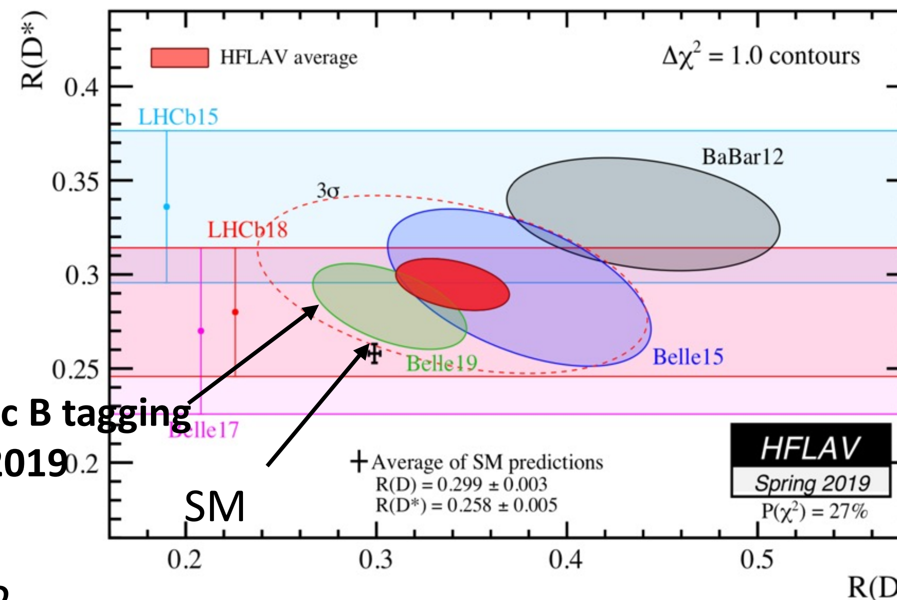
Figure 1: Kinematics of the $\overline{B} \to D^*(\to D\pi)\ell\overline{\nu}$ decay.

$$F_{L\,SM}^{D^*} = 0.453$$

$$F_L^{D^*} = 0.60 \pm 0.09$$ Belle: 1903.03102

1.7σ

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



New
Semileptonic B tagging @Moriond2019

SM

~~3.8σ~~ 3.1σ discrepancy↓

New result from the theoretical calculation

by Marzia Bordone et al. @EPS
1907.XXXXX

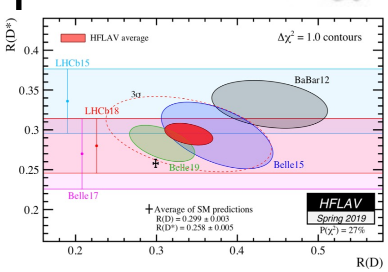
They calculated the higher order correction.

$$\frac{\alpha_s}{\pi} \sim \frac{\Lambda_{QCD}}{2m_b} \sim \frac{\Lambda_{QCD}^2}{4m_c^2}$$

	HFLAV	Our predictions
R_D	0.299 ± 0.003	0.299 ± 0.003
R_{D^*}	0.258 ± 0.005	0.252 ± 0.004
V_{cb}^{BD}	$(39.18 \pm 1.00) \times 10^{-3}$	$(41.8 \pm 1.1) \times 10^{-3}$
$V_{cb}^{BD^*}$	$(38.71 \pm 0.75) \times 10^{-3}$	$(40.1 \pm 1.1) \times 10^{-3}$

0.15σ and 1.5σ from incl. V_{cb}

$$V_{cb}^{incl.} = (42.00 \pm 0.64) \times 10^{-3}$$



menu

- D* polarization in $B \to D^{*}\tau\nu$ and R(D$^{(*)}$) anomalies.
- One operator analysis
- LQ analysis
- Summary

Effective Lagrangian for b ->c τ ν

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + C_{V1}) O_{V1} + C_{V2} O_{V2} + C_{S1} O_{S1} + C_{S2} O_{S2} + C_T O_T \right]$$

Operator basis

$$O_{S1} = (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau)$$
$$O_{S2} = (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau)$$

Scalar

$$O_{V1} = (\bar{c} \gamma^\mu P_L b)(\bar{\tau} \gamma^\mu P_L \nu_\tau)$$
$$O_{V2} = (\bar{c} \gamma^\mu P_R b)(\bar{\tau} \gamma^\mu P_L \nu_\tau)$$

Vector

$$O_T = (\bar{c} \sigma^{\mu\nu} P_L b)(\bar{\tau} \sigma_{\mu\nu} P_L \nu_\tau)$$

Tensor

Assumption: $\nu_{\tau L}$

$$(\bar{c} \sigma^{\mu\nu} P_R b)(\bar{\tau} \sigma_{\mu\nu} P_L \nu_\tau) = 0$$

Sterile ν scenarios are also considered.

X. G. He, et al. 1711.09525
Syuhei Iguro, Y. Omura 1802.01732
A. Greljo , et al. 1804.04642

Effective Lagrangian for b ->c τ ν

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + C_{V1}) O_{V1} + C_{V2} O_{V2} + C_{S1} O_{S1} + C_{S2} O_{S2} + C_T O_T \right]$$

Operator basis

$$O_{S1} = (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau)$$

$$O_{S2} = (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau)$$

Scalar H^-

$$O_{V1} = (\bar{c} \gamma^\mu P_L b)(\bar{\tau} \gamma^\mu P_L \nu_\tau)$$

$$O_{V2} = (\bar{c} \gamma^\mu P_R b)(\bar{\tau} \gamma^\mu P_L \nu_\tau)$$

Vector W'

$$O_T = (\bar{c} \sigma^{\mu\nu} P_L b)(\bar{\tau} \sigma_{\mu\nu} P_L \nu_\tau)$$

Tensor LQ

Calculation of RD Y.Sakaki et al.1309.0301

Generic formula

$$\frac{d\Gamma(\overline{B}\to D\tau\overline{\nu}_l)}{dq^2} = \frac{G_F^2|V_{cb}|^2}{192\pi^3 m_B^3} q^2\sqrt{\lambda_D(q^2)}\left(1-\frac{m_\tau^2}{q^2}\right)^2 \times \Bigg\{ |\delta_{l\tau}+C_{V_1}^l+C_{V_2}^l|^2\left[\left(1+\frac{m_\tau^2}{2q^2}\right)H_{V,0}^{s\,2}+\frac{3}{2}\frac{m_\tau^2}{q^2}H_{V,t}^{s\,2}\right] + \frac{3}{2}|C_{S_1}^l+C_{S_2}^l|^2 H_S^{s\,2} + 8|C_T^l|^2\left(1+\frac{2m_\tau^2}{q^2}\right)H_T^{s\,2} + 3\mathcal{R}e[(\delta_{l\tau}+C_{V_1}^l+C_{V_2}^l)(C_{S_1}^{l*}+C_{S_2}^{l*})]\frac{m_\tau}{\sqrt{q^2}}H_S^s H_{V,t}^s - 12\mathcal{R}e[(\delta_{l\tau}+C_{V_1}^l+C_{V_2}^l)C_T^{l*}]\frac{m_\tau}{\sqrt{q^2}}H_T^s H_{V,0}^s\Bigg\},$$

Input form factors

$$H_{V,0}^s(q^2)\equiv H_{V_1,0}^s(q^2)=H_{V_2,0}^s(q^2)=\sqrt{\frac{\lambda_D(q^2)}{q^2}}F_1(q^2),$$

$$H_{V,t}^s(q^2)\equiv H_{V_1,t}^s(q^2)=H_{V_2,t}^s(q^2)=\frac{m_B^2-m_D^2}{\sqrt{q^2}}F_0(q^2),$$

$$H_S^s(q^2)\equiv H_{S_1}^s(q^2)=H_{S_2}^s(q^2)\simeq\frac{m_B^2-m_D^2}{m_b-m_c}F_0(q^2),$$

$$H_T^s(q^2)\equiv H_{T,+-}^s(q^2)=H_{T,0t}^s(q^2)=-\frac{\sqrt{\lambda_D(q^2)}}{m_B+m_D}F_T(q^2),$$

$$\langle D(k)|\bar{c}\gamma_\mu b|\overline{B}(p)\rangle = \left[(p+k)_\mu-\frac{m_B^2-m_D^2}{q^2}q_\mu\right]F_1(q^2)+q_\mu\frac{m_B^2-m_D^2}{q^2}F_0(q^2)$$

$$F_1(q^2)=\frac{1}{2\sqrt{m_B m_D}}\left[(m_B+m_D)h_+(w(q^2))-(m_B-m_D)h_-(w(q^2))\right]$$

$$F_0(q^2)=\frac{1}{2\sqrt{m_B m_D}}\left[\frac{(m_B+m_D)^2-q^2}{m_B+m_D}h_+(w(q^2)) - \frac{(m_B-m_D)^2-q^2}{m_B-m_D}h_-(w(q^2))\right],$$

$$F_T(q^2)=\frac{m_B+m_D}{2\sqrt{m_B m_D}}h_T(w(q^2)).$$

Too complicated

We used Form Factors(FFs) of 1703.05330 to get the generic formula

$O(\Lambda_{QCD}/m_{b,c})$ and $O(\alpha_S)$

M. Tanaka and R. Watanabe 1212.1878.

We evaluate observables with μ=mb

$$\frac{R_D}{R_D^{\rm SM}} = |1 + C_{V_1} + C_{V_2}|^2 + 1.02|C_{S_1} + C_{S_2}|^2 + 0.90|C_T|^2$$

Vector Scalar Tensor

$$+ 1.49{\rm Re}[(1 + C_{V_1} + C_{V_2})(C_{S_1}^* + C_{S_2}^*)] + 1.14{\rm Re}[(1 + C_{V_1} + C_{V_2})C_T^*] \,,$$

$$\frac{R_{D^*}}{R_{D^*}^{\rm SM}} = |1 + C_{V_1}|^2 + |C_{V_2}|^2 + 0.04|C_{S_1} - C_{S_2}|^2 + 16.07|C_T|^2$$

$$- 1.81{\rm Re}[(1 + C_{V_1})C_{V_2}^*] + 0.11{\rm Re}[(1 + C_{V_1} - C_{V_2})(C_{S_1}^* - C_{S_2}^*)]$$

$$- 5.12{\rm Re}[(1 + C_{V_1})C_T^*] + 6.66{\rm Re}[C_{V_2}C_T^*] \,,$$

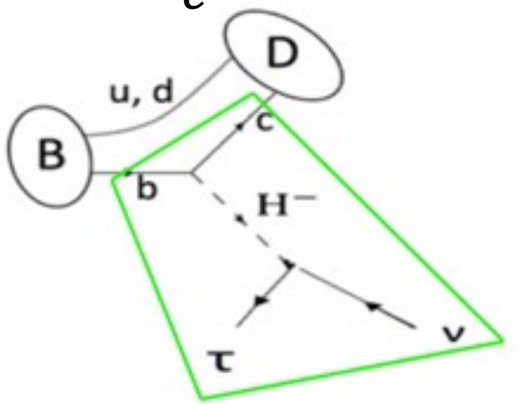
$$\frac{F_L^{D^*}}{F_{L,\,\rm SM}^{D^*}} = \left(\frac{R_{D^*}}{R_{D^*}^{\rm SM}}\right)^{-1} \times \Big(|1 + C_{V_1} - C_{V_2}|^2 + 0.08|C_{S_1} - C_{S_2}|^2 + 7.02|C_T|^2$$

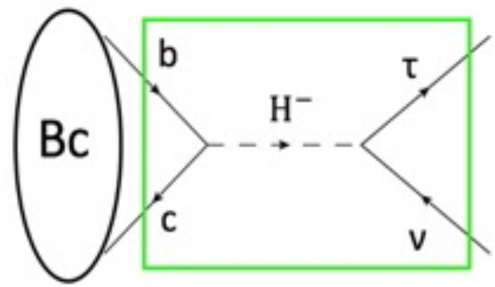
$$+ 0.24{\rm Re}[(1 + C_{V_1} - C_{V_2})(C_{S_1}^* - C_{S_2}^*)] - 4.37{\rm Re}[(1 + C_{V_1} - C_{V_2})C_T^*]\Big)$$

large scalar effect is need to enhance RD*

Constraint 1

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





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

$$\mathrm{BR}(\mathrm{B}_c^- \to \tau\bar{\nu})_{\mathrm{SM}} \times \left| 1 + C_{V1} - C_{V2} + \boxed{\frac{\mathrm{m}_{\mathrm{Bc}}^2}{\mathrm{m}_\tau(\mathrm{m}_\mathrm{b} + \mathrm{m}_\mathrm{c})}} (C_{S1} - C_{S2}) \right|^2$$

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

~ 4.2

Scalar operator drastically enhances $\mathrm{BR}(\mathrm{B}_c^- \to \tau\bar{\nu})$

Previous constraint

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

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

Current constraint

$< 60\%$ M.Blanke.et al. 1811.09603

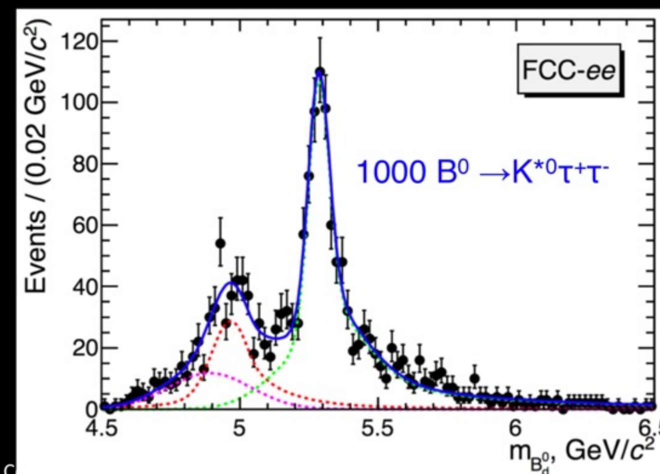
Good news for the (far) future.

B Physics

	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}

LEP data $\times 10^5$

- 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

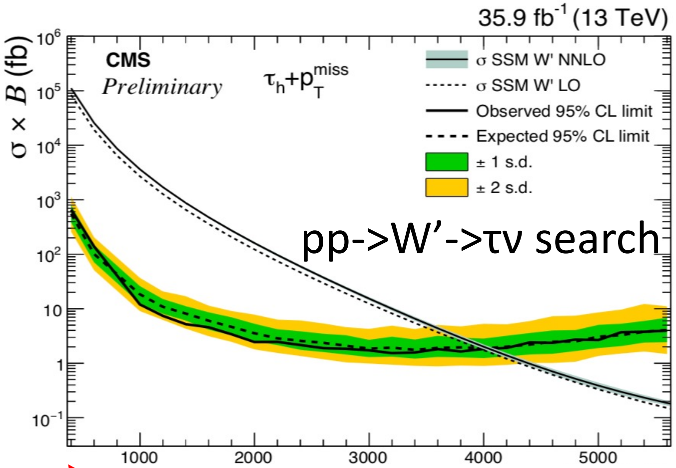
Slide by Daniela on the first day

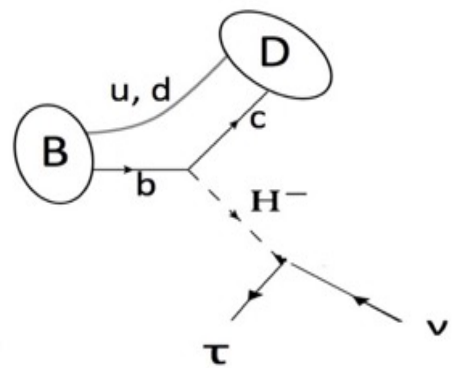
The upper limit on $B_c^- \to \tau\bar{\nu}$ from a future lepton collider can test the scenario!

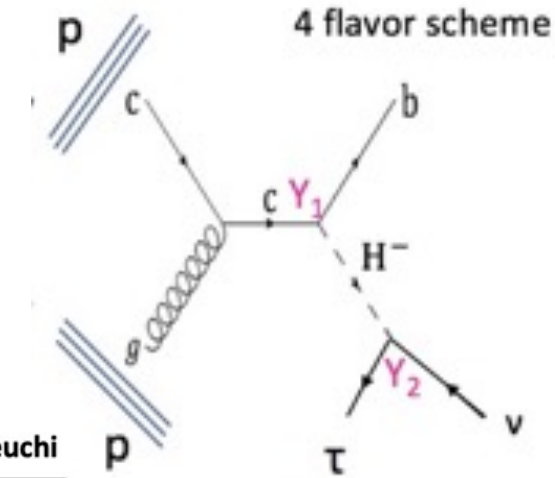
FCC-ee also

Constraint 2

Severe constraint for the charged Higgs $m_{H^-} > 400\text{GeV}$

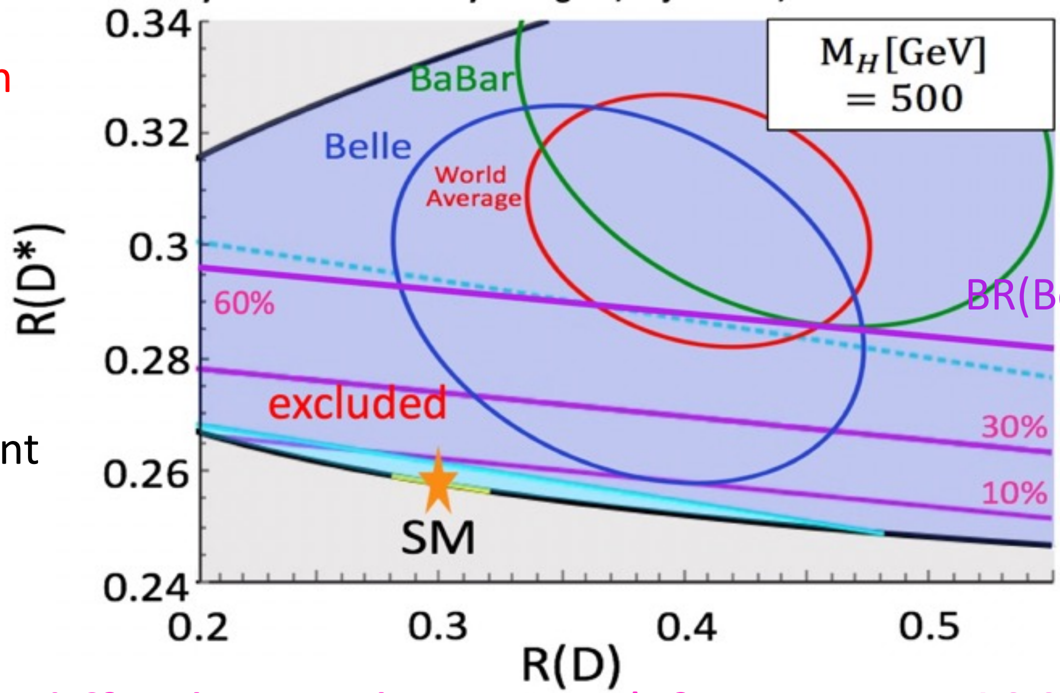






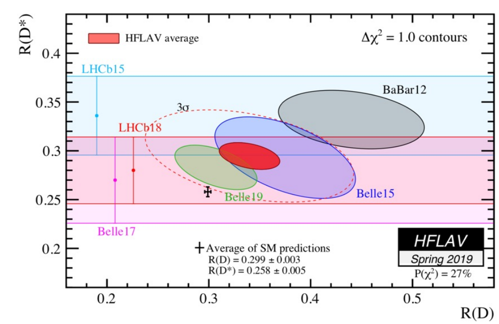
Heavier than 400GeV

PhysRevD.99.075013 Syuhei Iguro, Yuji Omura, Michihisa Takeuchi



BR(Bc->τν)

Scale dependent bound



seems difficult to enhance RD* for $m_{H^-} > 400\text{GeV}$

One operator analysis.

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \begin{bmatrix} (1 + C_{V1}) O_{V1} + C_{V2} O_{V2} \\ + C_{S1} O_{S1} + C_{S2} O_{S2} + C_T O_T \end{bmatrix}$$

Scalar

$$O_{S1} = (\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau)$$
$$O_{S2} = (\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau)$$

Vector

$$O_{V1} = (\bar{c} \gamma^\mu P_L b)(\bar{\tau} \gamma^\mu P_L \nu_\tau)$$
$$O_{V2} = (\bar{c} \gamma^\mu P_R b)(\bar{\tau} \gamma^\mu P_L \nu_\tau)$$

Tensor

$$O_T = (\bar{c} \sigma^{\mu\nu} P_L b)(\bar{\tau} \sigma_{\mu\nu} P_L \nu_\tau)$$

$$C_X = |C_X| e^{i\delta_X}$$

Absolute value

Phase

$$\frac{R_D}{R_D^{\rm SM}} = |1 + C_{V_1} + C_{V_2}|^2 + 1.02|C_{S_1} + C_{S_2}|^2 + 0.90|C_T|^2$$

Vector / Scalar / Tensor

$$+ 1.49 {\rm Re}[(1 + C_{V_1} + C_{V_2})(C_{S_1}^* + C_{S_2}^*)] + 1.14 {\rm Re}[(1 + C_{V_1} + C_{V_2}) C_T^*] \,,$$

$$\frac{R_{D^*}}{R_{D^*}^{\rm SM}} = |1 + C_{V_1}|^2 + |C_{V_2}|^2 + 0.04|C_{S_1} - C_{S_2}|^2 + 16.07|C_T|^2$$
$$- 1.81 {\rm Re}[(1 + C_{V_1}) C_{V_2}^*] + 0.11 {\rm Re}[(1 + C_{V_1} - C_{V_2})(C_{S_1}^* - C_{S_2}^*)]$$
$$- 5.12 {\rm Re}[(1 + C_{V_1}) C_T^*] + 6.66 {\rm Re}[C_{V_2} C_T^*] \,,$$

$$\frac{F_L^{D^*}}{F_{L,\,\rm SM}^{D^*}} = \left(\frac{R_{D^*}}{R_{D^*}^{\rm SM}} \right)^{-1} \times \Big(|1 + C_{V_1} - C_{V_2}|^2 + 0.08|C_{S_1} - C_{S_2}|^2 + 7.02|C_T|^2$$
$$+ 0.24 {\rm Re}[(1 + C_{V_1} - C_{V_2})(C_{S_1}^* - C_{S_2}^*)] - 4.37 {\rm Re}[(1 + C_{V_1} - C_{V_2}) C_T^*] \Big)$$

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$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \begin{bmatrix} (1 + C_{V1})O_{V1} + C_{V2}O_{V2} \\ +C_{S1}O_{S1} + C_{S2}O_{S2} + C_T O_T \end{bmatrix}$$

Scalar

$$O_{S1} = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau)$$
$$O_{S2} = (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau)$$

Vector

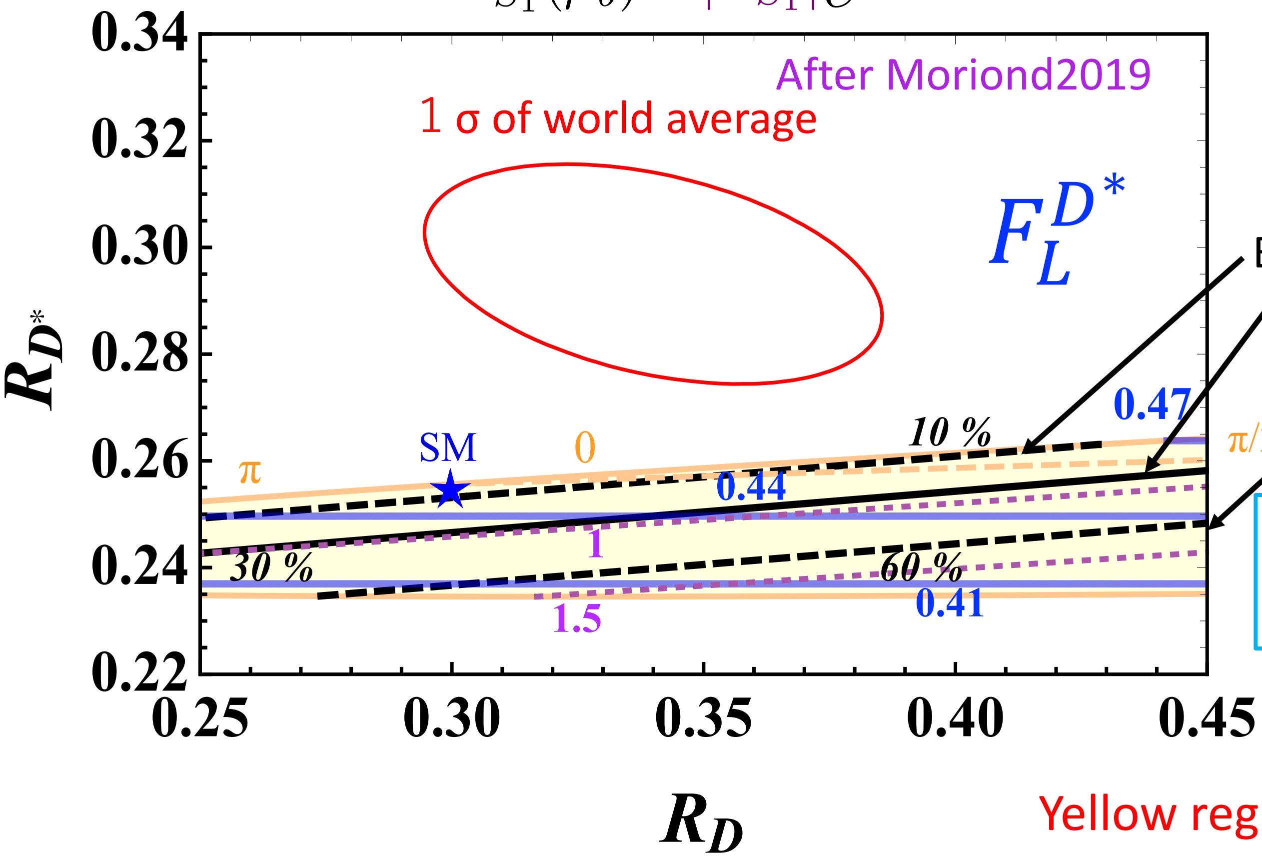
$$O_{V1} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$
$$O_{V2} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$

Tensor

$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$

O_{S1} operator

$$C_{S_1}(\mu_b) = |C_{S_1}| e^{i\delta_{S_1}}$$



$F_{L\,SM}^{D^*} = 0.453$,
$F_L^{D^*} = 0.60 \pm 0.09$

C_{S_1} can not enhance RD RD*😢
e.g. Type-II 2HDM 1303.0571 .

Yellow region is predicted

One operator analysis.

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \begin{bmatrix} (1 + C_{V1})O_{V1} + C_{V2}O_{V2} \\ +C_{S1}O_{S1} + C_{S2}O_{S2} + C_T O_T \end{bmatrix}$$

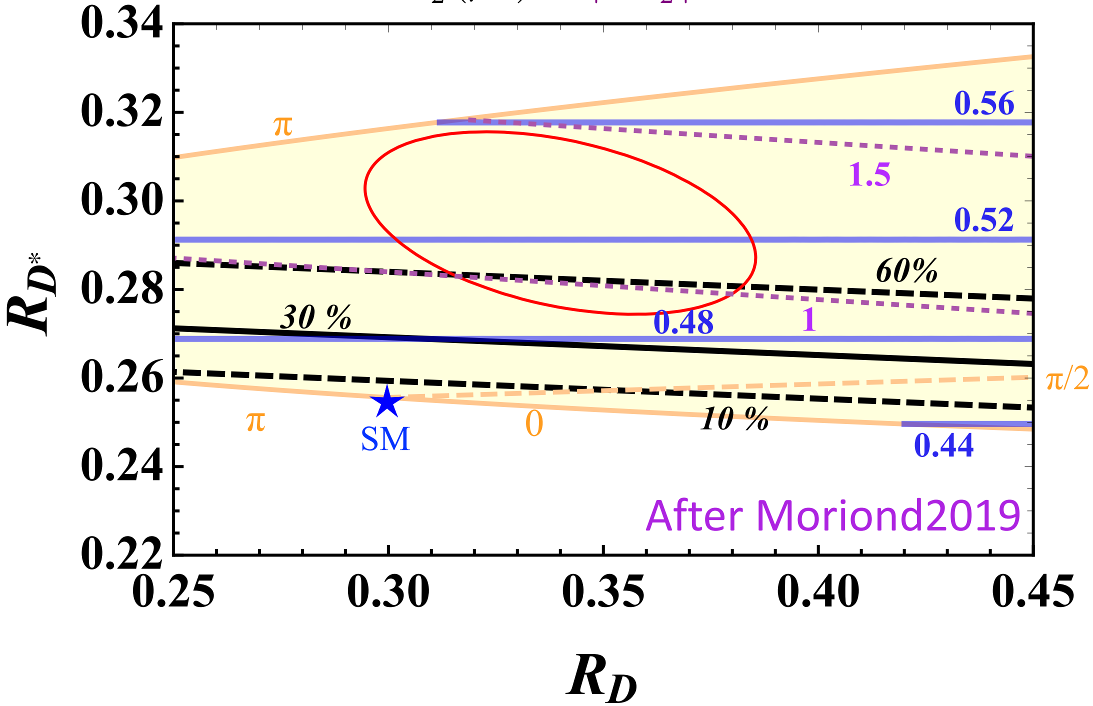
$$O_{S1} = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau)$$
$$O_{S2} = (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau)$$
Scalar

$$O_{V1} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$
$$O_{V2} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$
Vector

$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$
Tensor

O_{S2} operator

$$C_{S_2}(\mu_b) = |C_{S_2}| e^{i\delta_{S_2}}$$

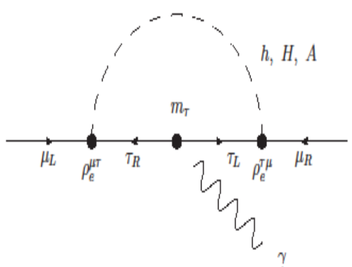


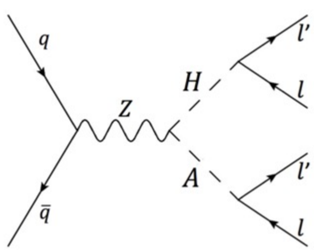
C_{S_2} can enhance RD RD*
e.g. generic 2HDM.

Enhances $F_L^{D^*}$ and BR($B_c^- \to \tau\bar{\nu}$).
Collider search is interesting.

G2HDM can accommodate δa_μ and RD
1802.01732 Syuhei Iguro, Y.Omura

$\mu\mu\bar{\tau}\bar{\tau}$ search is powerful!
1907.09845 Syuhei Iguro, Y.Omura, M.Takeuchi





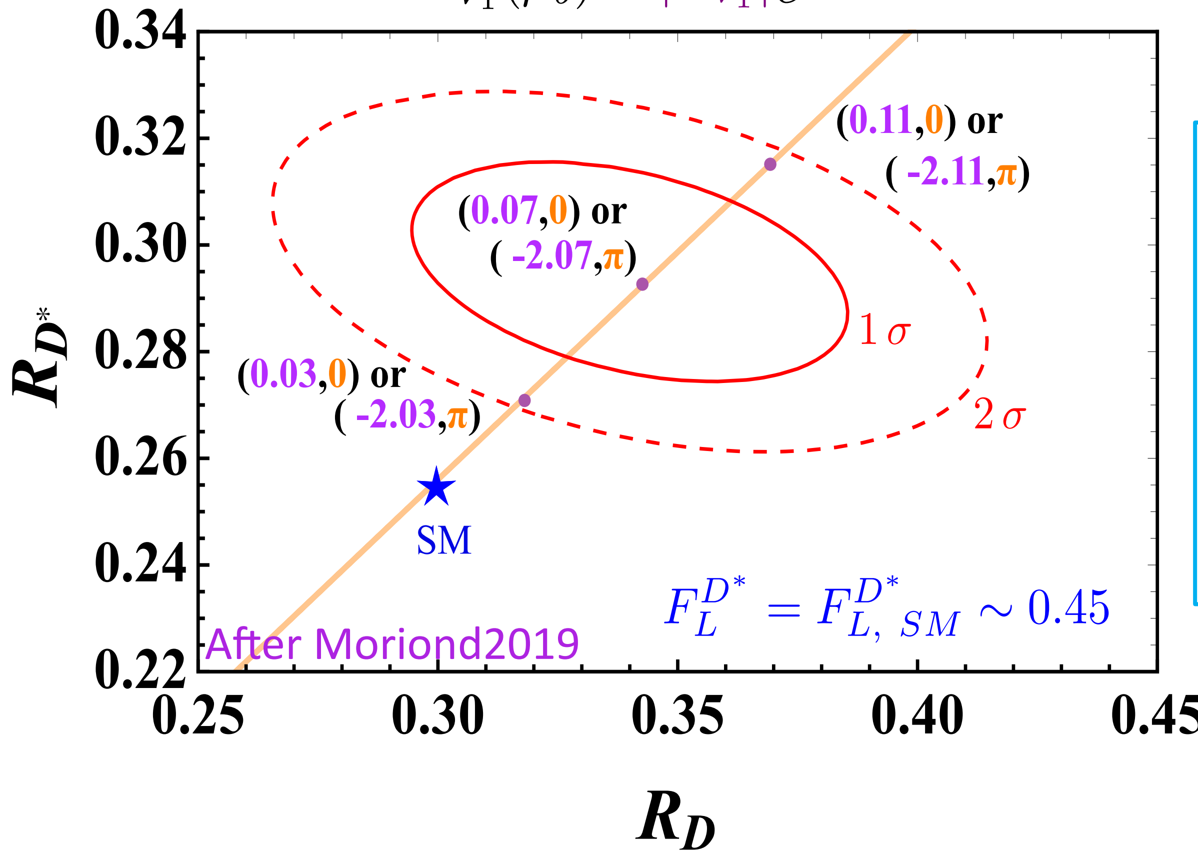
One operator analysis.

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \begin{bmatrix} (1 + C_{V1})O_{V1} + C_{V2}O_{V2} \\ +C_{S1}O_{S1} + C_{S2}O_{S2} + C_T O_T \end{bmatrix}$$

$$O_{S1} = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau)$$ Scalar
$$O_{S2} = (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau)$$
$$O_{V1} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$ Vector
$$O_{V2} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$
$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$ Tensor

O_{V1} operator

$$C_{V_1}(\mu_b) = |C_{V_1}| e^{i\delta_{V_1}}$$



$F_L^{D^*}$ does not change 😅

The required $|C_{V_1}|$ is much smaller than $|C_{S_2}|$.
Hard to search in LHC with O(100)fb^{-1}.

One operator analysis.

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \begin{bmatrix} (1 + C_{V1})O_{V1} + C_{V2}O_{V2} \\ +C_{S1}O_{S1} + C_{S2}O_{S2} + C_T O_T \end{bmatrix}$$

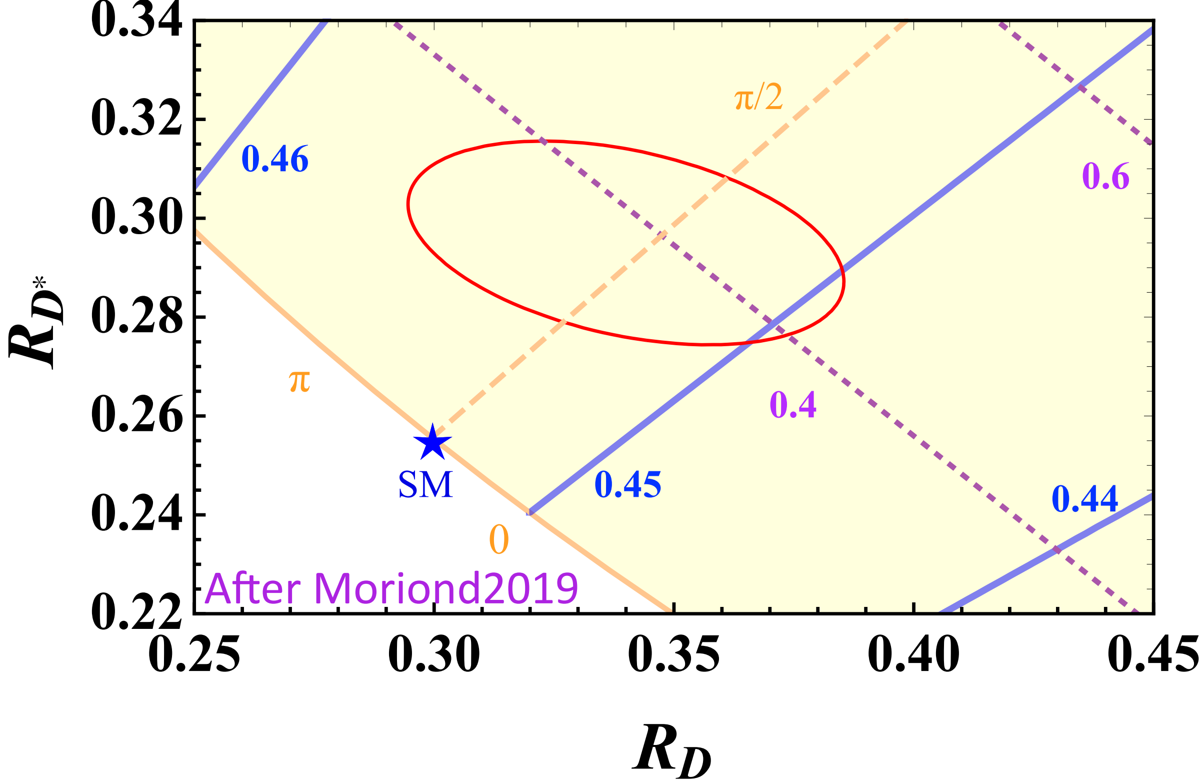
$$O_{S1} = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau)$$
$$O_{S2} = (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau)$$
Scalar

$$O_{V1} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$
$$O_{V2} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$
Vector

$$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$
Tensor

O_{V2} operator

$$C_{V_2}(\mu_b) = |C_{V_2}| e^{i\,\delta_{V_2}}$$



$F_L^{D^*}$ almost does not change😅

Not easy to search in LHC with O(100) fb^{-1}.
1b+τν resonance search is more sensitive!
A.Soni, et al. 1704.06659
Syuhei Iguro, K. Tobe 1708.08176
M. Abdullah, et al. 1805.01869

One operator analysis.

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \begin{bmatrix} (1 + C_{V1})O_{V1} + C_{V2}O_{V2} \\ + C_{S1}O_{S1} + C_{S2}O_{S2} + C_T O_T \end{bmatrix}$$

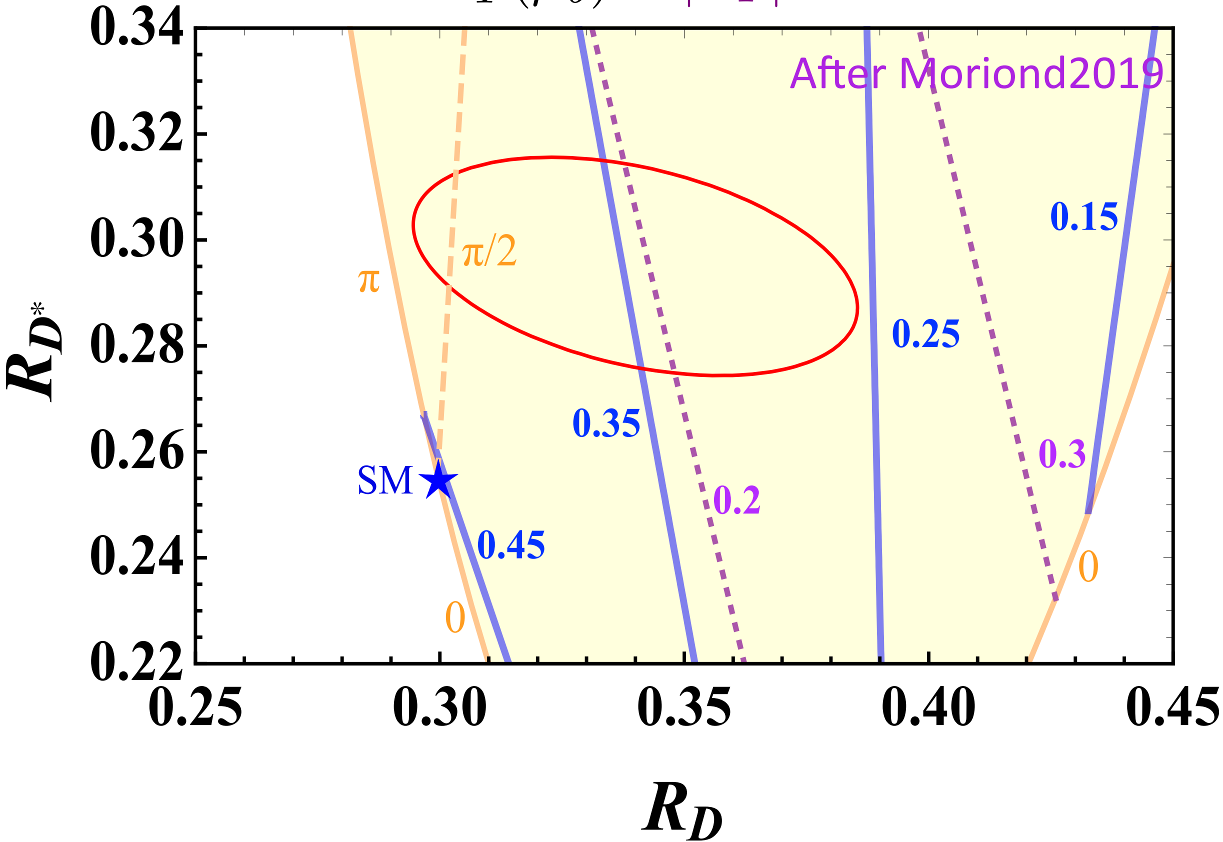
$O_{S1} = (\bar{c}P_R b)(\bar{\tau}P_L \nu_\tau)$ Scalar
$O_{S2} = (\bar{c}P_L b)(\bar{\tau}P_L \nu_\tau)$

$O_{V1} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$ Vector
$O_{V2} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$

$O_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$ Tensor

O_T operator

$C_T(\mu_b) = |C_T| e^{i\delta_T}$



Enhances RD,RD*
suppresses $F_L^{D^*}$ 😩.

Summary of one operator analysis

	RD	RD*	$F_L^{D^*}$
O_{S1}	○	×	→
O_{S2}	○	△	↗
O_{V1}	○	○	→
O_{V2}	○	○	→
O_T	○	○	↘

Scalar operator easily enhances $BR(B_c^- \to \tau\bar{\nu})$ and testable in LHC.

Vector operator can not enhance $F_L^{D^*}$.

Tensor operator suppresses $F_L^{D^*}$.

It seems not easy to enhance $F_L^{D^*}$

H^- and W' are covered so far.

Next we consider the LQ scenarios

Where beyond one operator analysis is needed

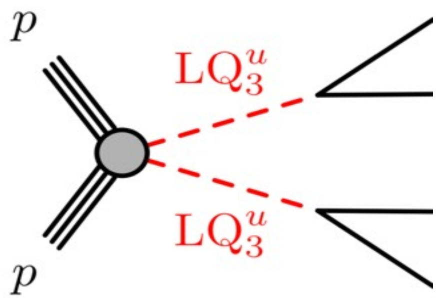
menu

- D* polarization in $B \to D^*\tau\nu$ and R(D$^{(*)}$) anomalies.
- One operator analysis
- LQ analysis

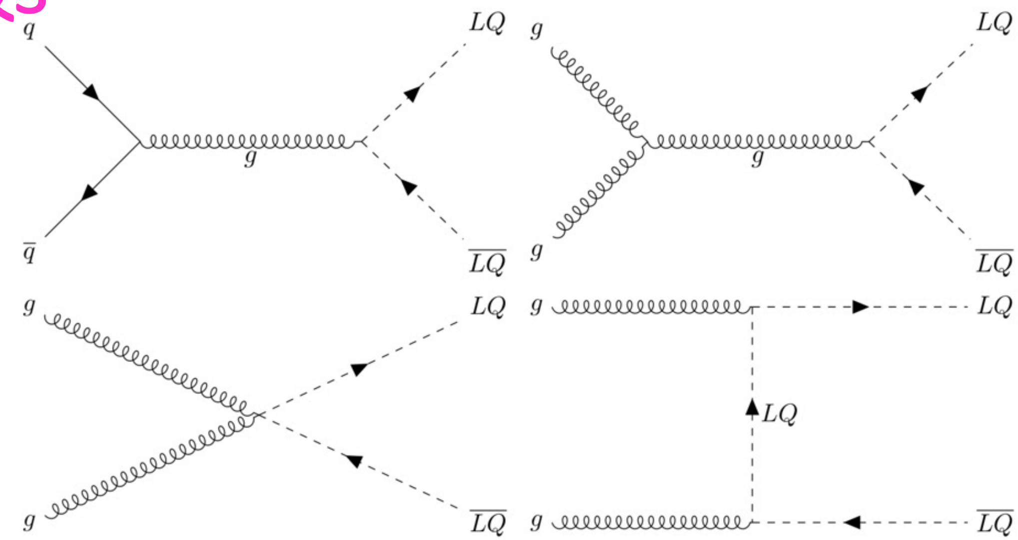
Leptoquark (LQ): a boson couples to a quark and lepton pair

- Summary

LHC bound for LQs



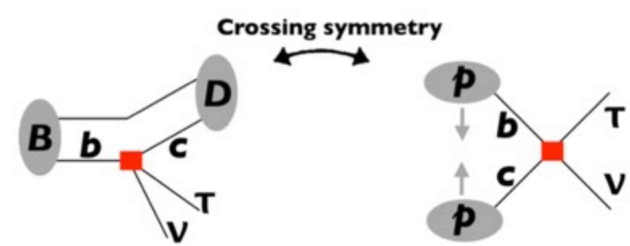
ATLAS 1902.08103



CMS 1811.00806

jjττ(ccνν) search:36fb^{-1} directly sets the lower bound on LQ mass ～1TeV

High P$_T$ mono-τ search also constrains the LQ scenario as



$$|C_{V1}| < 0.32, |C_{S1,S2}| < 0.57, |C_T| < 0.16$$

1811.07920 A.Greljo, J.M.Camalich and J.D.Ruiz-A΄lvarez
1905.08253 M. Blanke, et al.

3 types of LQs are known to explain RD, RD* anomalies

R_2, S_1 and U_1

1808.08179 A. Angelescu, et al.

$(SU(3), SU(2)_L, U(1)_Y)$

R_2 : $(3, 2, 7/6)$ scalar

$$C_{S_2}(\mu_{LQ}) = 4C_T(\mu_{LQ})$$

X. Q. Li, et al. 1605.09308.......

S_3 with $(\overline{3}, 3, 1)$ is needed for R(K)

I. Dorsner,et al. 1701.08322

S_1 : $(\overline{3}, 1, 1/3)$ scalar

$$C_{S_2}(\mu_{LQ}) = -4C_T(\mu_{LQ}), C_{V_1}(\mu_{LQ})$$

Y. Sakaki, et al. 1309.0301........

$S_1 - S_3$ combination is considered

A. Crivellin, et al. 1703.09226

U_1: $(3, 1, 2/3)$ vector

$$C_{S_1}(\mu_{LQ}), C_{V_1}(\mu_{LQ})$$

R(K) is also possible

UV completion is needed

J.Heeck, D.Teresi 1808.07492

B.Grinstein 1812.01603

Pati Salam

$$SU(4)_C \times SU(2)_L \times SU(2)_R$$

$$SU(4)_C \to SU(3)_C \times U(1)_{B-L}$$

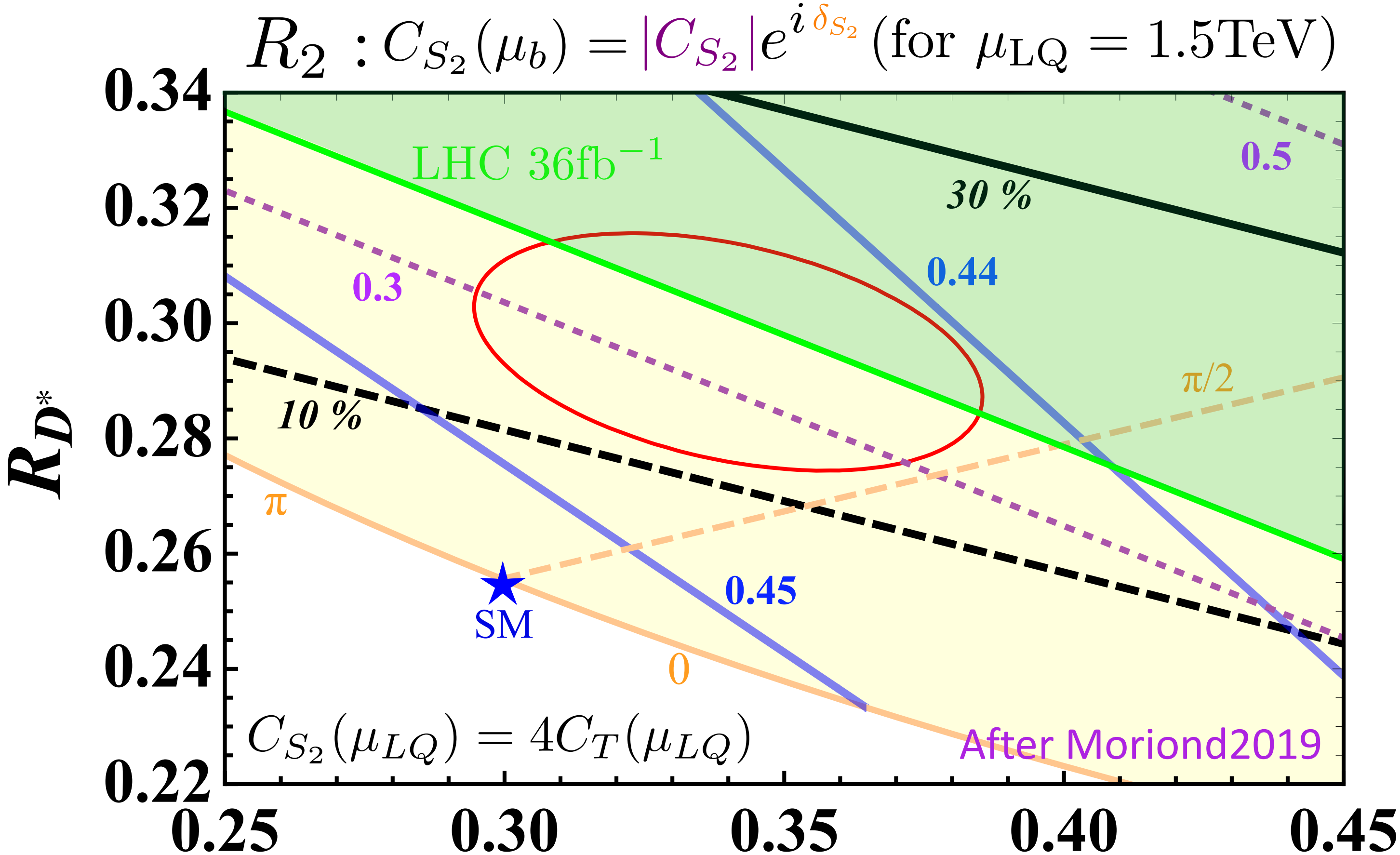
Massive vector LQ appear

We set $\mu_{LQ} = 1.5$ TeV : LHC bound

1-loop EW, 3-loop QCD, 1-loop QED RG running is considered.

Changing LQ scale into $\mu_{LQ} = 3$ TeV does not our following results more than 1%

R_2 : (3, 2, 7/6) scalar $C_{S_2}(\mu_{LQ}) = 4C_T(\mu_{LQ})$

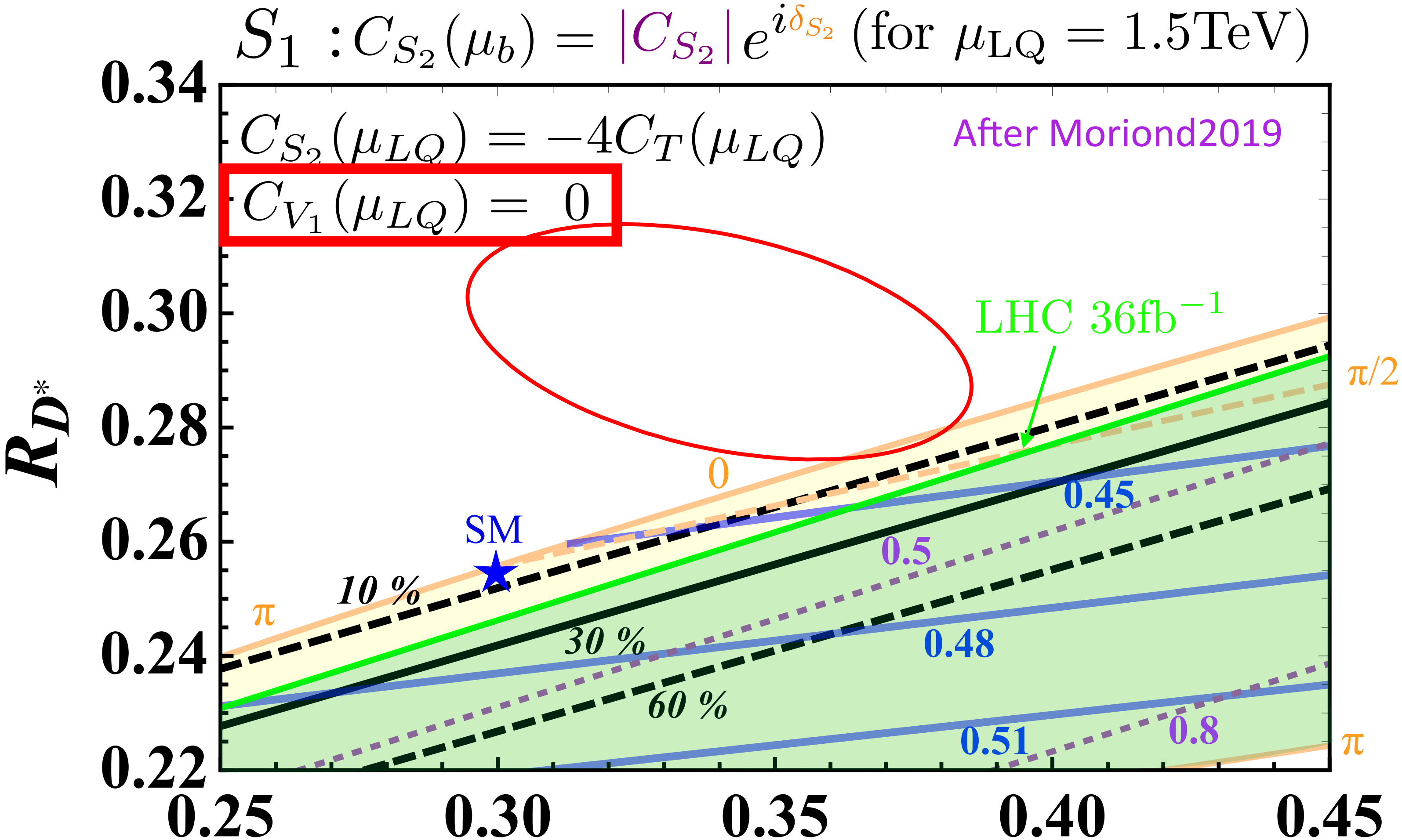


$|C_{S1,S2}| < 0.57$ or $|C_{V1}| < 0.32$ or $|C_T| < 0.16$
conservative bound from LHC

$F_L^{D^*}$ does not change a lot!

The enhancement by C_{S_2} is cancelled by the suppression by C_T

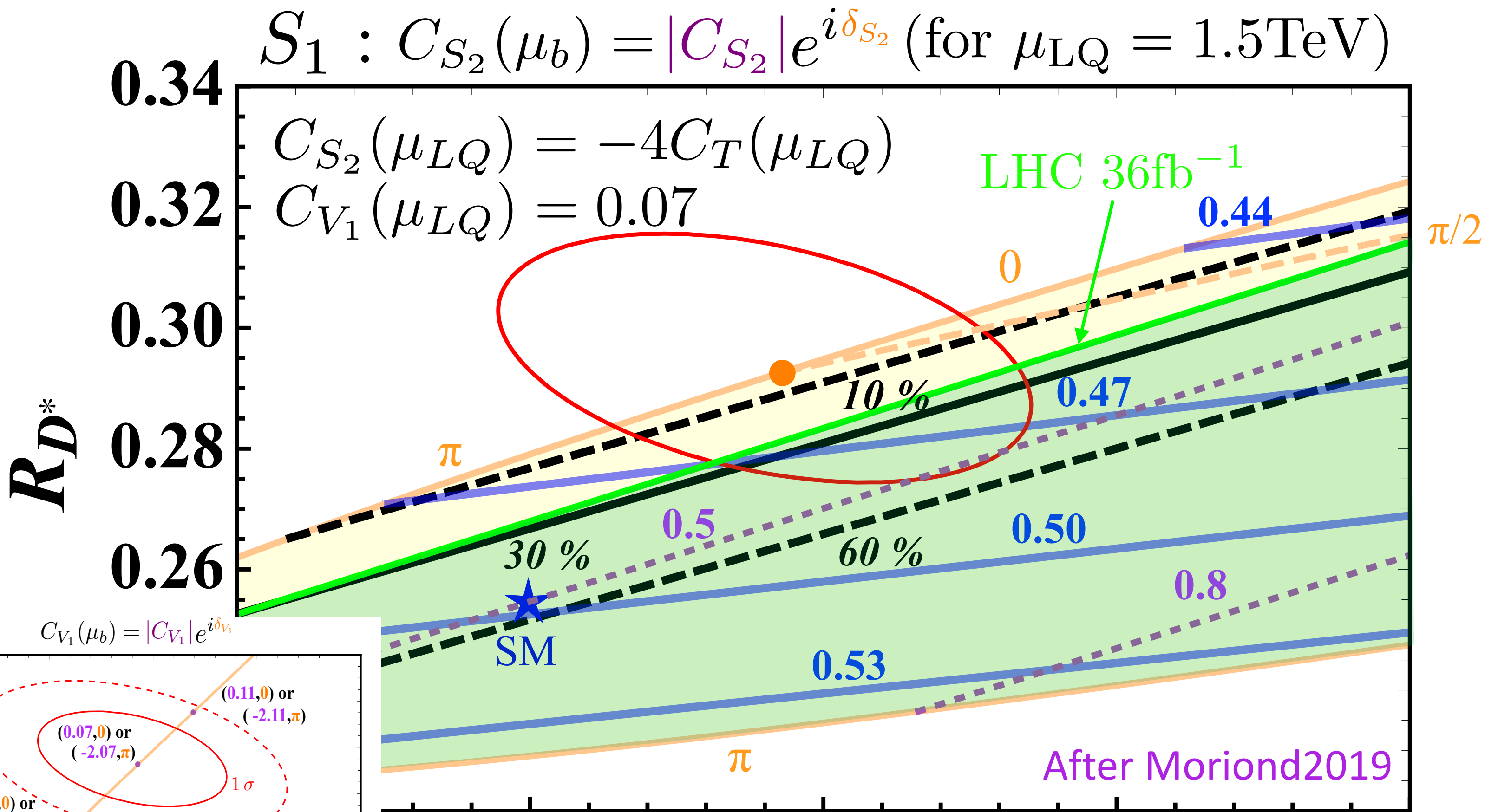
$S_1 : (\bar{3}, 1, 1/3)$ scalar $C_{S_2}(\mu_{LQ}) = -4C_T(\mu_{LQ})$, $C_{V_1}(\mu_{LQ})$

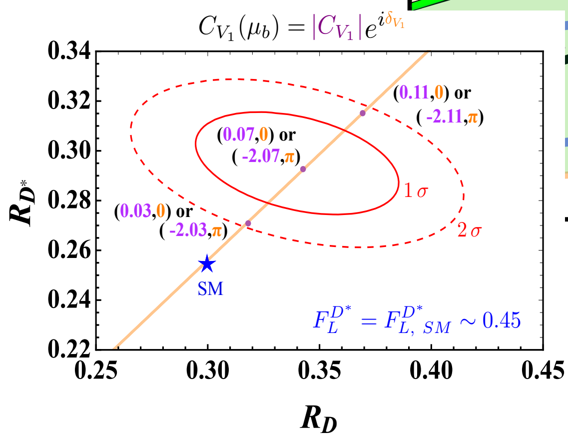


$F_L^{D^*}$ does not change a lot!

C_{V_1} does not change polarization observables.

$S_1 : (\bar{3}, 1, 1/3)$ scalar $C_{S_2}(\mu_{LQ}) = -4C_T(\mu_{LQ})$, $C_{V_1}(\mu_{LQ})$

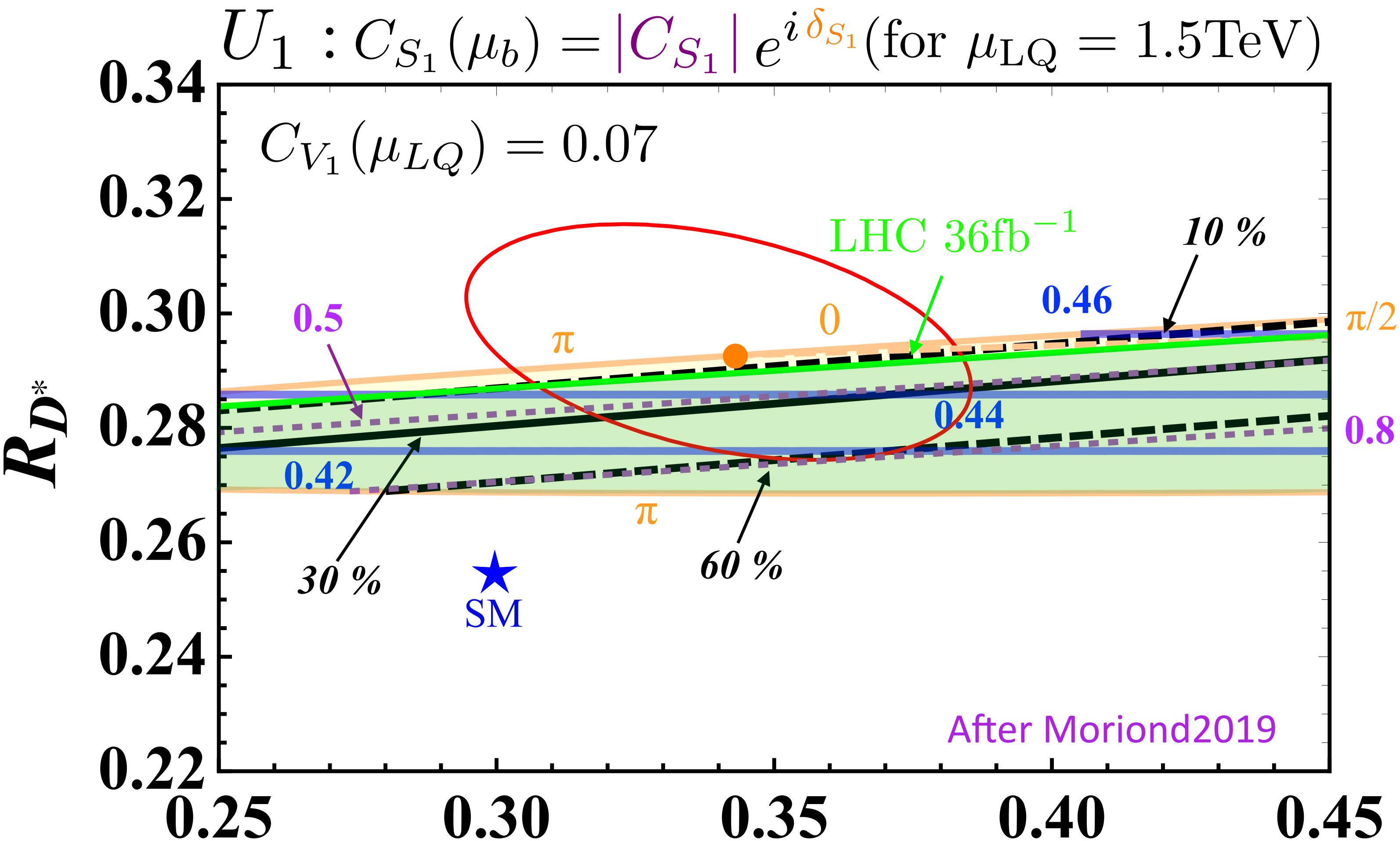




$F_L^{D^*}$ does not change a lot!

C_{V_1} does not change polarization observables.

U_1: (3, 1, 2/3) vector $C_{S_1}(\mu_{LQ}), C_{V_1}(\mu_{LQ})$



$F_L^{D^*}$ does not change a lot!

Summary for LQs after Moriond2019

	$F_L^{D^*}$	P_τ^D	$P_\tau^{D^*}$	R_D	R_{D^*}
R_2 LQ	[0.442, 0.447]	[0.336, 0.456]	[−0.464, −0.424]	1 σ data	1 σ data
S_1 LQ	[0.436, 0.481]	[−0.006, 0.489]	[−0.512, −0.450]	1 σ data	1 σ data
U_1 LQ	[0.440, 0.459]	[0.156, 0.422]	[−0.542, −0.488]	1 σ data	1 σ data
SM	0.46(4)	0.325(9)	−0.497(13)	0.299(3)	0.258(5)
data	0.60(9)	-	−0.38(55)	**0.340(30)**	**0.295(14)**
Belle II	0.04	3%	0.07	3%	2%

After Moriond2019

The amplified $F_L^{D^*}$, compared with the SM prediction $F_{L\,SM}^{D^*}$ is severely constrained from LHC and $Br(B_c \to \tau\nu)$ in R_2, S_1 and U_1 leptoquarks with the parameter set which explains R($D^{(*)}$) within 1σ of the world average.

Then, is there any good quantity to distinguish LQ model?

Summary for LQs after Moriond2019

	$F_L^{D^*}$	P_τ^D	$P_\tau^{D^*}$	R_D	R_{D^*}
R_2 LQ	[0.442, 0.447]	[0.336, 0.456]	[−0.464, −0.424]	1 σ data	1 σ data
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data	0.60(9)	-	−0.38(55)	**0.340(30)**	**0.295(14)**
Belle II	0.04	3%	0.07	3%	2%

After Moriond2019

P_τ^D is a good quantity to distinguish LQ models.
Statistical error is dominant in polarization observables.
Let's wait Belle II for the new data!

$$P_\tau^D = \frac{\Gamma\left(\lambda_\tau = \frac{1}{2}\right) - \Gamma\left(\lambda_\tau = -\frac{1}{2}\right)}{\Gamma\left(\lambda_\tau = \frac{1}{2}\right) + \Gamma\left(\lambda_\tau = -\frac{1}{2}\right)}$$

Back ups start from the next

Acknowledgement

My work (especially this year) is supported by Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Toyoaki scholarship foundation and the Japan Society for the Promotion of Science (JSPS) Research Fellowships for Young Scientists, No. 19J10980.

Many thanks for collaborators!

Other related observables.

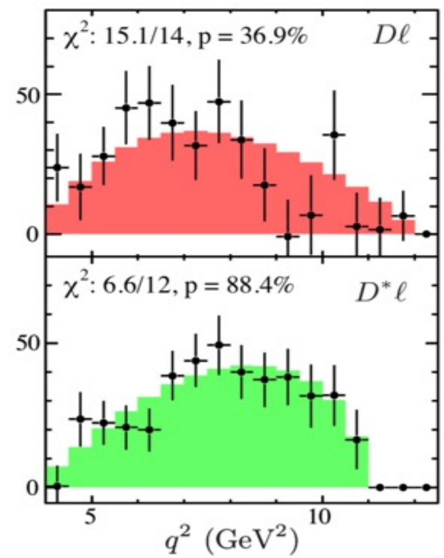
- **Tau polarization in $B \to D^{(*)}\tau\nu$ process.**

$P^{D}_{\tau,SM} = -0.32, P^{D^*}_{\tau,SM} = -0.51$ M. Tanaka. R. Watanabe 1005.4306

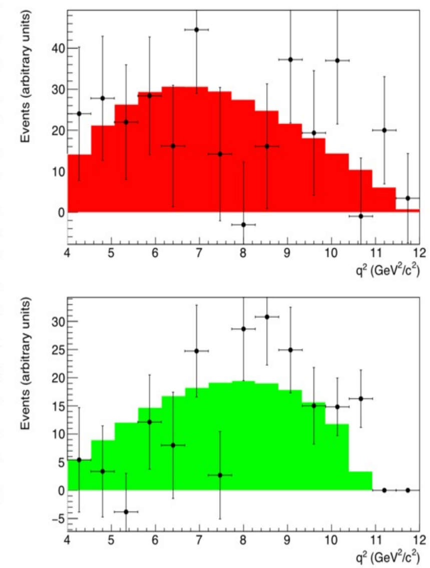
$P^{D}_{\tau,\exp}$ =×××, $P^{D^*}_{\tau,\,Belle}$ = −0.38 ± 0.51(stat.)+0.21(syst.) 1709.00129

- **q² distribution in $B \to D^{(*)}\tau\nu$**

BaBar 1303.0571



Belle 1507.03233



Currently not so accurate.

- $R(J/\psi) = \frac{BR(B_c \to J/\psi\tau\nu)}{BR(B_c \to J/\psi\mu\nu)}$

$R(J/\psi)_{\mathrm{LHCb}}$ = 0.71 ± 0.17 ± 0.18
$R(J/\psi)_{\mathrm{SM}}$ = 0.283 ± 0.048

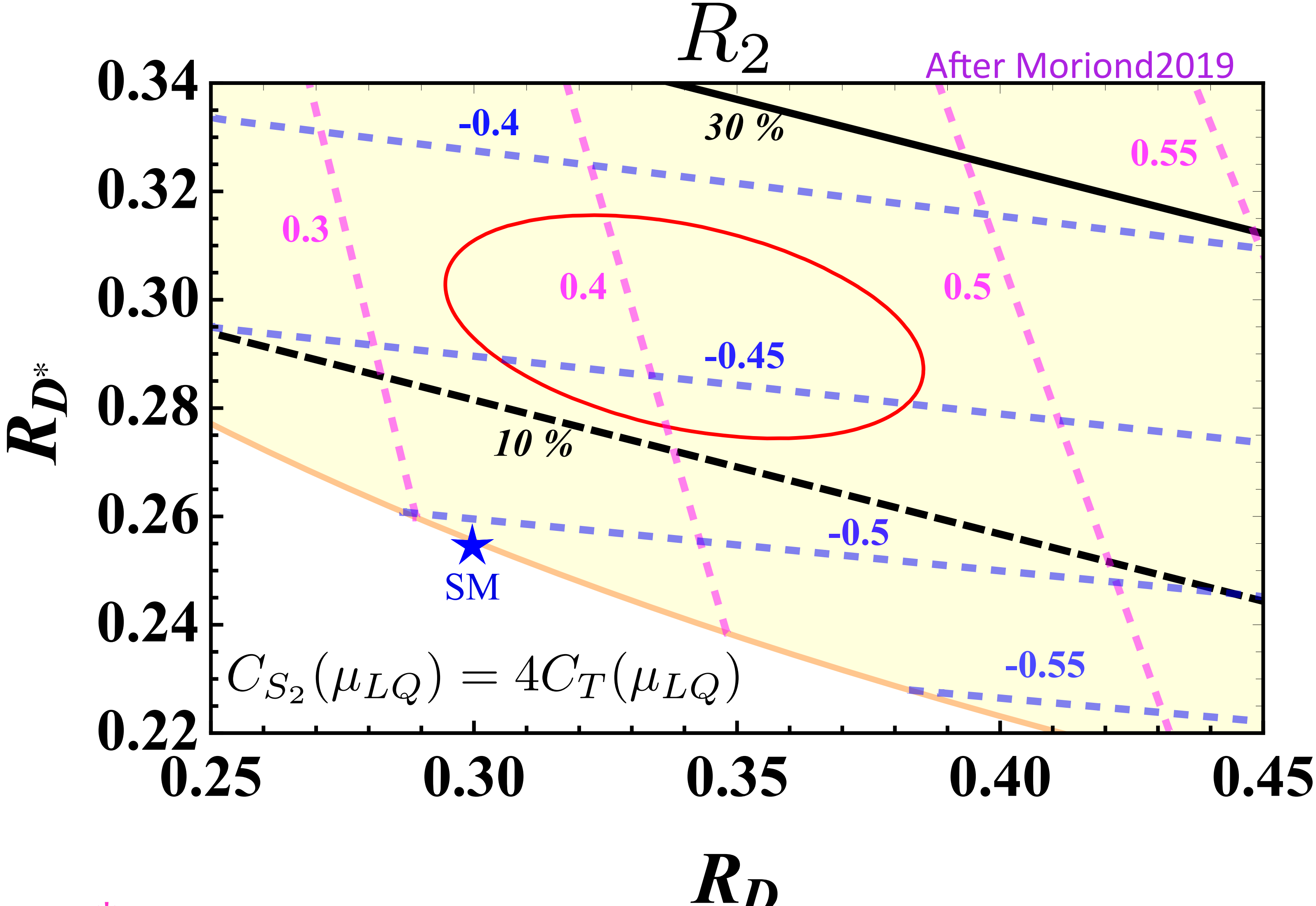
R. Watanabe 1709.08644

The generic formula for $P_\tau^{D^*}$ and P_τ^{D}

$$\frac{P_\tau^{D^*}}{P_{\tau,\mathrm{SM}}^{D^*}} = \left(\frac{R_{D^*}}{R_{D^*}^{\mathrm{SM}}}\right)^{-1} \times \Big(|1 + C_{V_1}|^2 + |C_{V_2}|^2 - 0.07|C_{S_1} - C_{S_2}|^2 - 1.86|C_T|^2$$
$$- 1.77\mathrm{Re}[(1 + C_{V_1})C_{V_2}^*] - 0.22\mathrm{Re}[(1 + C_{V_1} - C_{V_2})(C_{S_1}^* - C_{S_2}^*)]$$
$$- 3.37\mathrm{Re}[(1 + C_{V_1})C_T^*] + 4.37\mathrm{Re}[C_{V_2}C_T^*]\Big),$$

$$\frac{P_\tau^{D}}{P_{\tau,\mathrm{SM}}^{D}} = \left(\frac{R_{D}}{R_{D}^{\mathrm{SM}}}\right)^{-1} \times \Big(|1 + C_{V_1} + C_{V_2}|^2 + 3.18|C_{S_1} + C_{S_2}|^2 + 0.18|C_T|^2$$
$$+ 4.65\mathrm{Re}[(1 + C_{V_1} + C_{V_2})(C_{S_1}^* + C_{S_2}^*)] - 1.18\mathrm{Re}[(1 + C_{V_1} + C_{V_2})C_T^*]\Big),$$

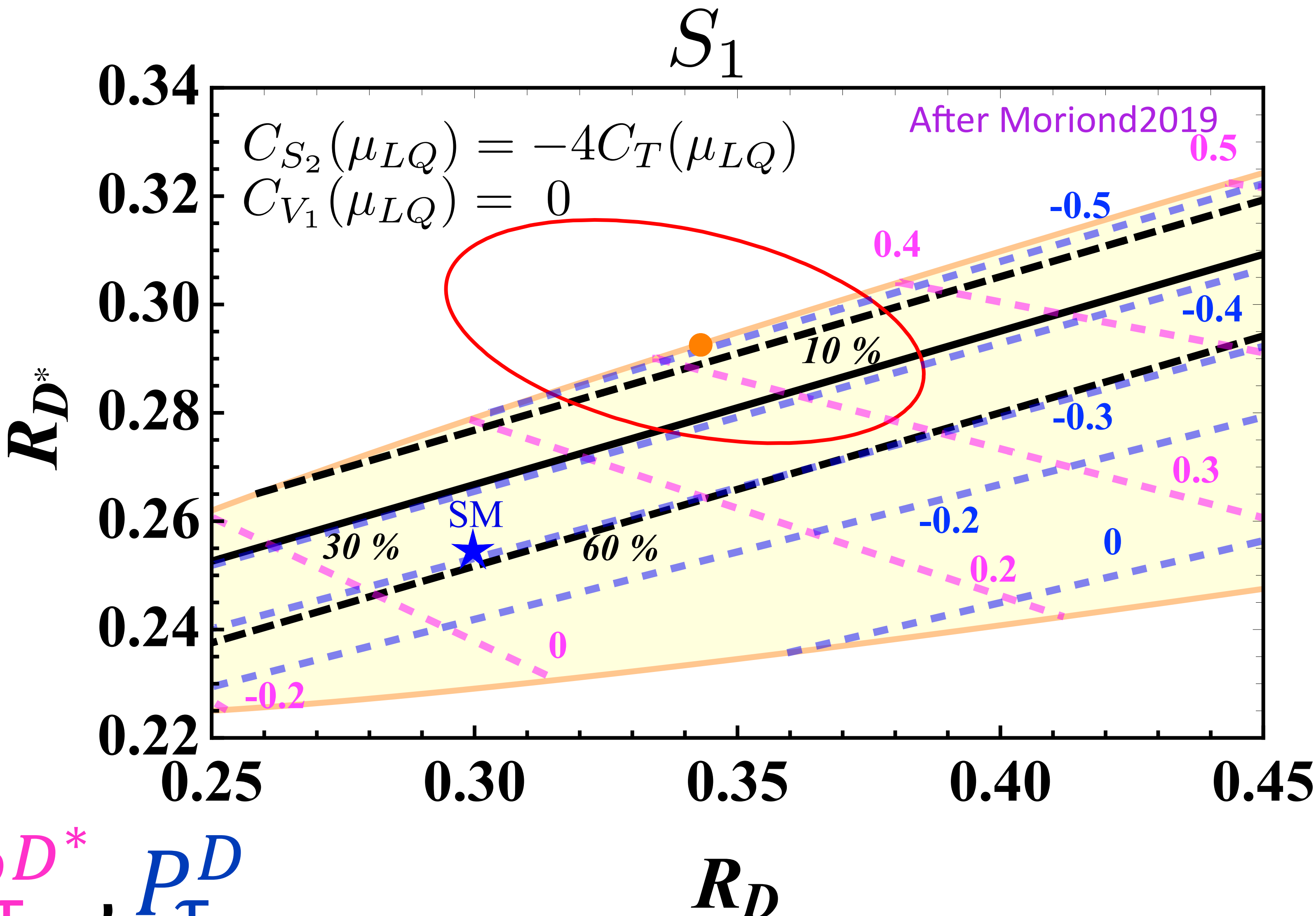
R_2 : (3, 2, 7/6) scalar $C_{S_2}(\mu_{LQ}) = 4C_T(\mu_{LQ})$



$P_\tau^{D^*}$, P_τ^D

enhances $P_\tau^{D^*}$ and P_τ^D

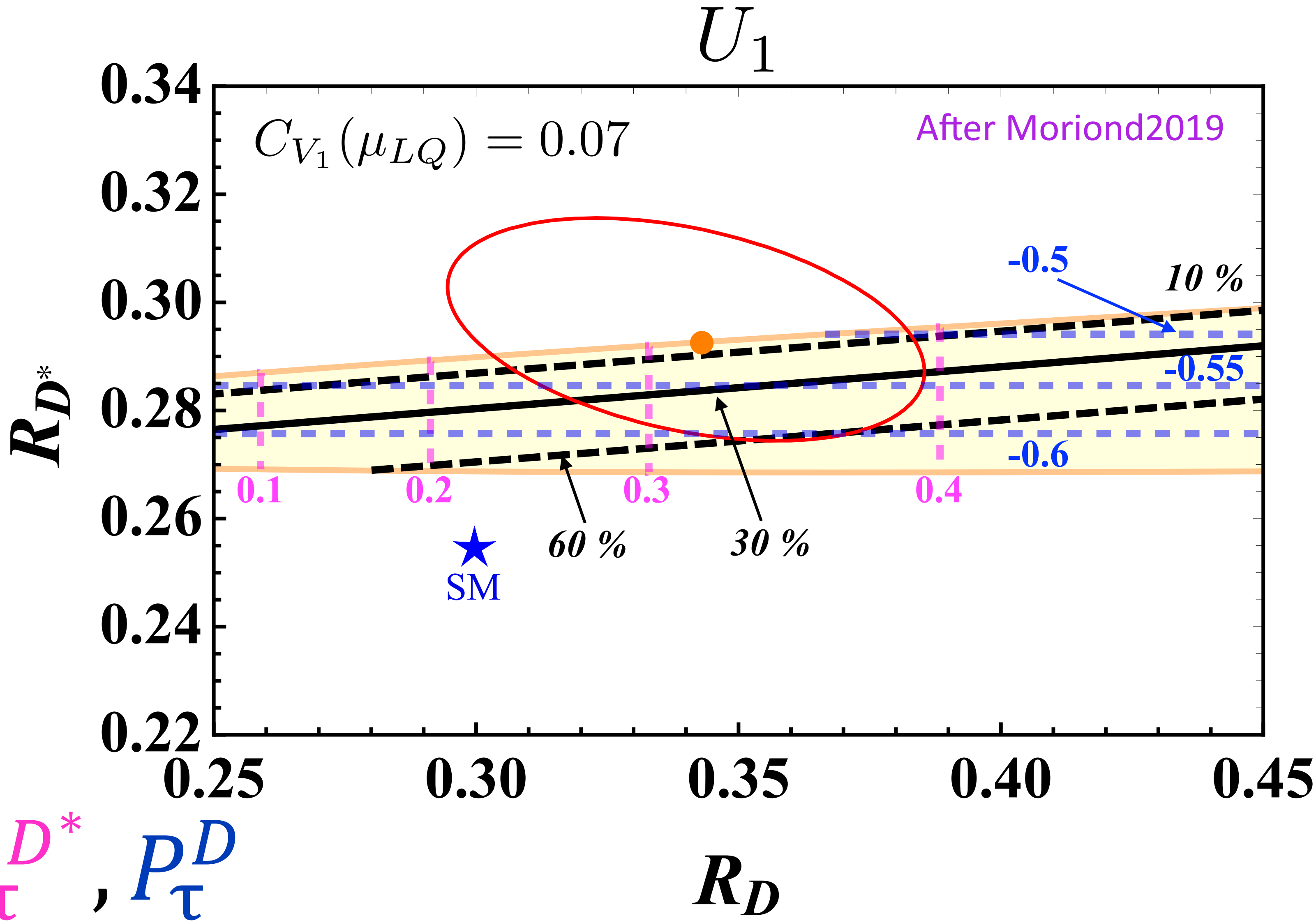
$S_1 : (\bar{3}, 1, 1/3)$ scalar $C_{S_2}(\mu_{LQ}) = -4C_T(\mu_{LQ})$, $C_{V_1}(\mu_{LQ})$



$P_\tau^{D^*}$, P_τ^D

enhances and suppresses $P_\tau^{D^*}$ and suppresses P_τ^D

U_1: (3, 1, 2/3) vector $C_{S_1}(\mu_{LQ}), C_{V_1}(\mu_{LQ})$

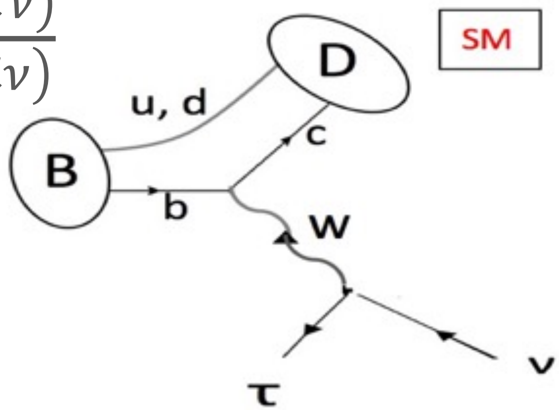


$P_\tau^{D^*}$, P_τ^{D}

enhances and suppresses $P_\tau^{D^*}$ and suppresses P_τ^{D}

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

Theoretical point



$B \to D\tau\nu$ is mediated by the W boson.

Dominant uncertainty from the hadronic matrix element is cancelled.
Vcb dependence is also canceled in the ratio.
-> theoretically clean!

Nice place to look for new physics and deviation there.

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

Non-trivial set up for the flavor structure is necessary.

Some hints for a new flavor structure?

Calculation of RD Y.Sakaki et al.1309.0301

Generic formula

$$\frac{d\Gamma(\overline{B}\to D\tau\overline{\nu}_l)}{dq^2} = \frac{G_F^2|V_{cb}|^2}{192\pi^3 m_B^3} q^2 \sqrt{\lambda_D(q^2)} \left(1-\frac{m_\tau^2}{q^2}\right)^2 \times \Bigg\{ |\delta_{l\tau}+C_{V_1}^l+C_{V_2}^l|^2 \left[\left(1+\frac{m_\tau^2}{2q^2}\right) H_{V,0}^{s\,2} + \frac{3}{2}\frac{m_\tau^2}{q^2} H_{V,t}^{s\,2}\right] + \frac{3}{2}|C_{S_1}^l+C_{S_2}^l|^2 H_S^{s\,2} + 8|C_T^l|^2\left(1+\frac{2m_\tau^2}{q^2}\right) H_T^{s\,2} + 3\mathcal{R}e[(\delta_{l\tau}+C_{V_1}^l+C_{V_2}^l)(C_{S_1}^{l*}+C_{S_2}^{l*})]\frac{m_\tau}{\sqrt{q^2}} H_S^s H_{V,t}^s - 12\mathcal{R}e[(\delta_{l\tau}+C_{V_1}^l+C_{V_2}^l)C_T^{l*}]\frac{m_\tau}{\sqrt{q^2}} H_T^s H_{V,0}^s \Bigg\},$$

Input form factors

$$H_{V,0}^s(q^2) \equiv H_{V_1,0}^s(q^2) = H_{V_2,0}^s(q^2) = \sqrt{\frac{\lambda_D(q^2)}{q^2}} F_1(q^2),$$

$$H_{V,t}^s(q^2) \equiv H_{V_1,t}^s(q^2) = H_{V_2,t}^s(q^2) = \frac{m_B^2-m_D^2}{\sqrt{q^2}} F_0(q^2),$$

$$H_S^s(q^2) \equiv H_{S_1}^s(q^2) = H_{S_2}^s(q^2) \simeq \frac{m_B^2-m_D^2}{m_b-m_c} F_0(q^2),$$

$$H_T^s(q^2) \equiv H_{T,+-}^s(q^2) = H_{T,0t}^s(q^2) = -\frac{\sqrt{\lambda_D(q^2)}}{m_B+m_D} F_T(q^2),$$

$$\langle D(k)|\bar{c}\gamma_\mu b|\overline{B}(p)\rangle = \left[(p+k)_\mu - \frac{m_B^2-m_D^2}{q^2}q_\mu\right] F_1(q^2) + q_\mu \frac{m_B^2-m_D^2}{q^2} F_0(q^2)$$

$$F_1(q^2) = \frac{1}{2\sqrt{m_B m_D}}\left[(m_B+m_D)h_+(w(q^2)) - (m_B-m_D)h_-(w(q^2))\right]$$

$$F_0(q^2) = \frac{1}{2\sqrt{m_B m_D}}\left[\frac{(m_B+m_D)^2-q^2}{m_B+m_D} h_+(w(q^2)) - \frac{(m_B-m_D)^2-q^2}{m_B-m_D} h_-(w(q^2))\right],$$

$$F_T(q^2) = \frac{m_B+m_D}{2\sqrt{m_B m_D}} h_T(w(q^2)).$$

Too complicated

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.

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

Charm mass uncertainty

Substituting a SM calculation

Combining LEP data with inputs obtained in LHCb

1708.04072

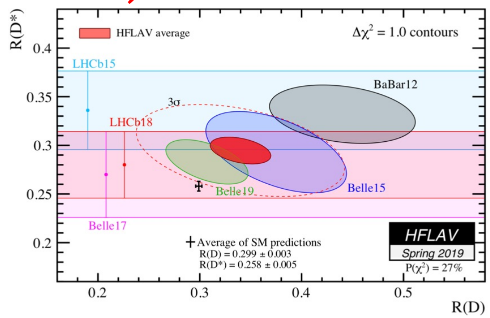
Scale dependence for the fragmentation

LEP has an u ... Cb, they got an
upper limit c

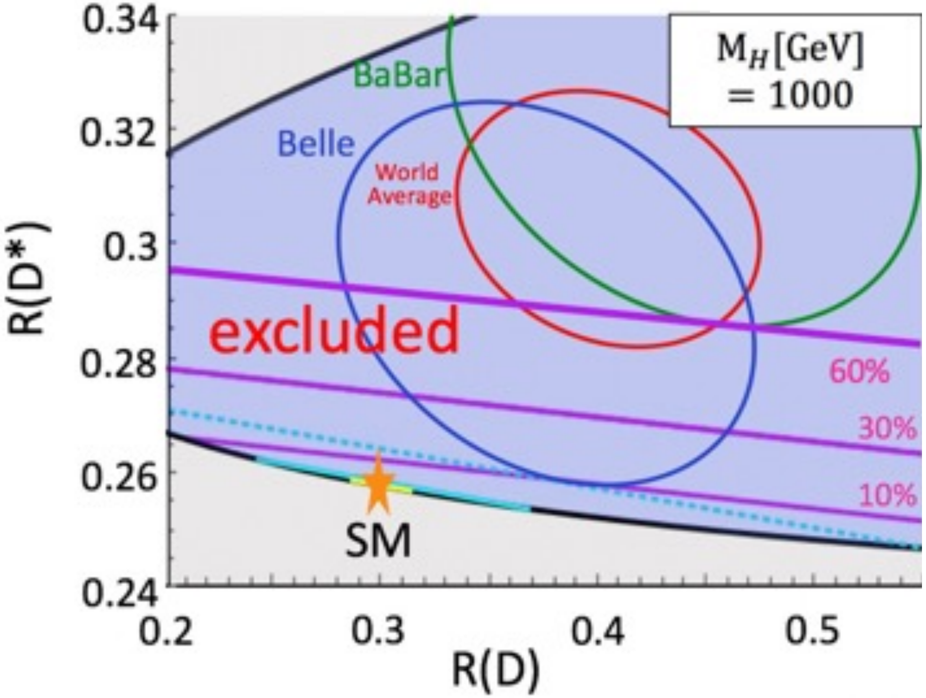
comment: they used $BR(B_c \to J/\psi l\nu)_{SM}$ as an input.

Result

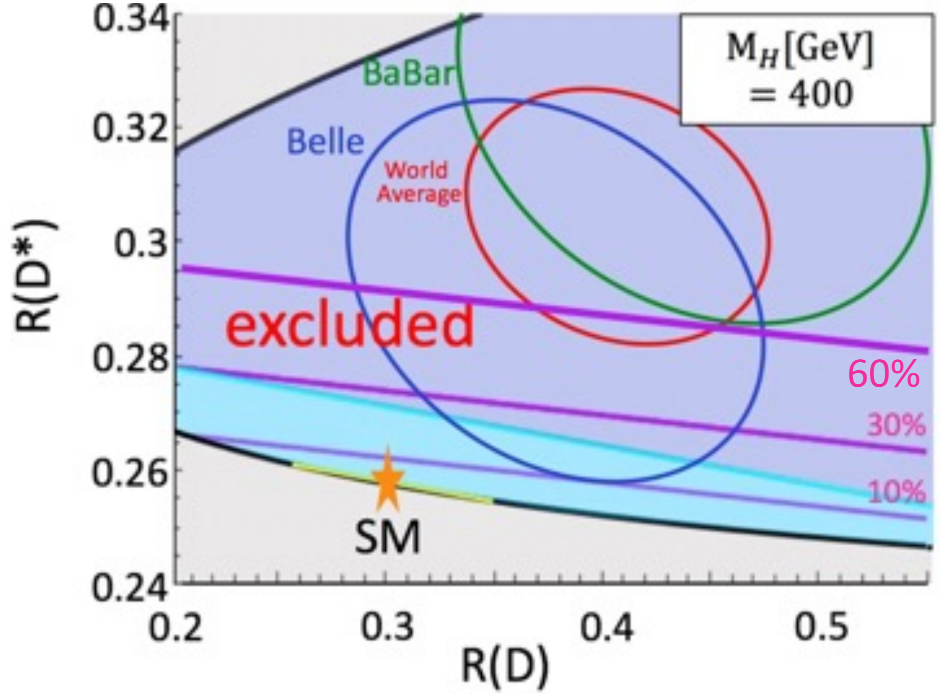
Heavier H^-, more severe constraint.



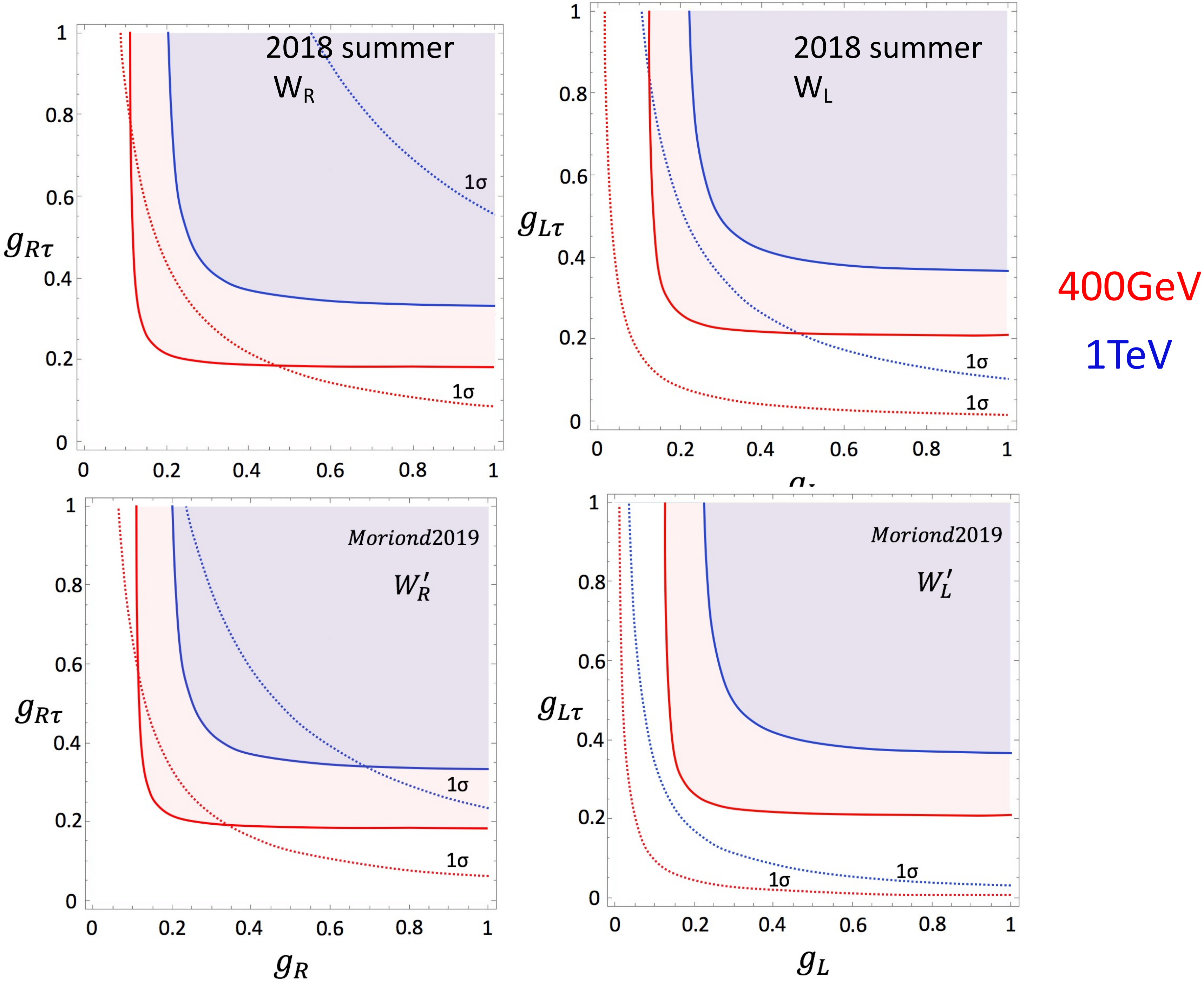
heavier



lighter

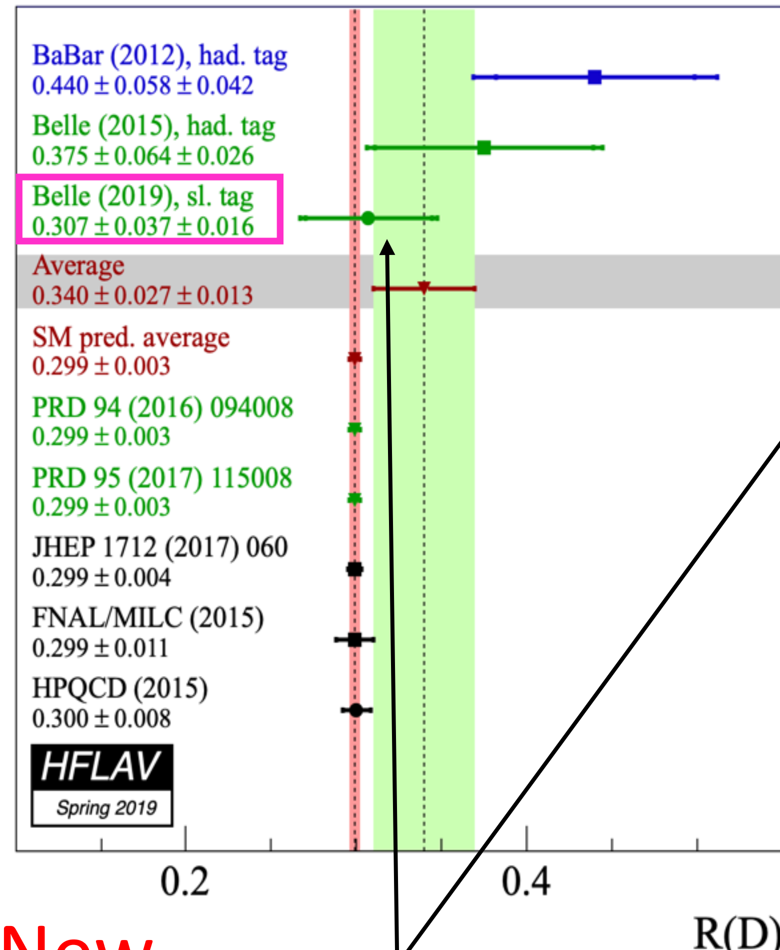


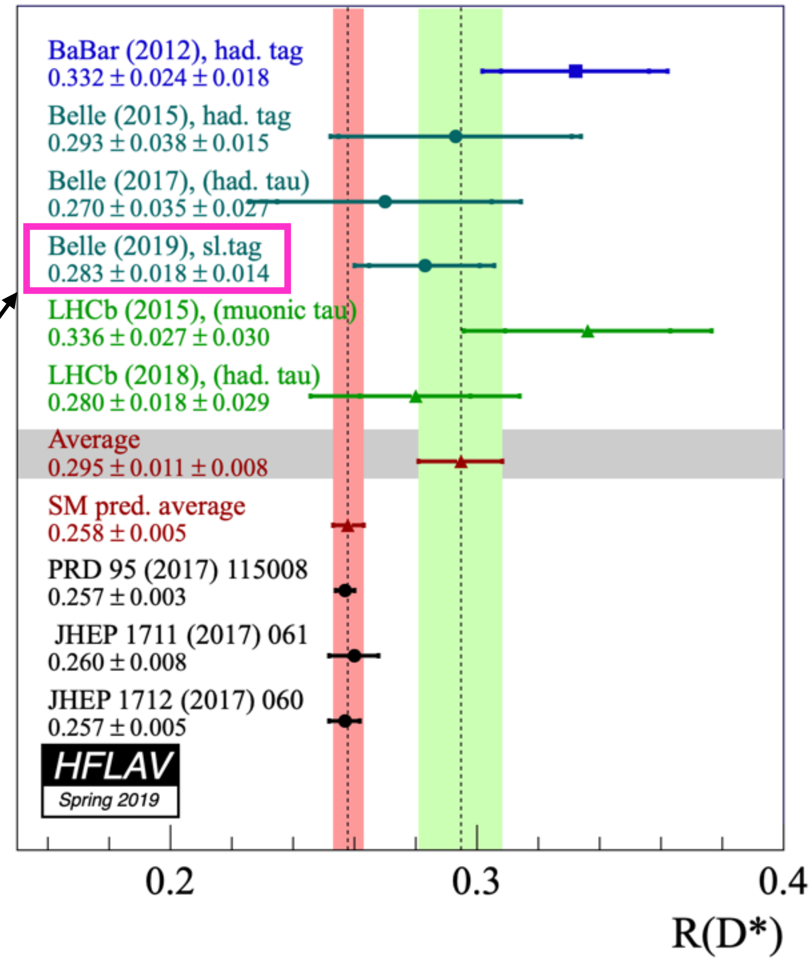
Better sensitivity for heavy $\tau\nu$ resonances: experimentally $\tau\nu$ resonance search for W' is more sensitive to a heavier resonance because of the low background from W→ $\tau\nu$.


2018 summer
W_R
1σ
1σ
$g_{R\tau}$
2018 summer
W_L
1σ
1σ
$g_{L\tau}$
400GeV
1TeV
Moriond2019
W'_R
1σ
1σ
$g_{R\tau}$
g_R
Moriond2019
W'_L
1σ
1σ
$g_{L\tau}$
g_L

Current status of RD,RD* anomalies

HFLAG 2019 spring





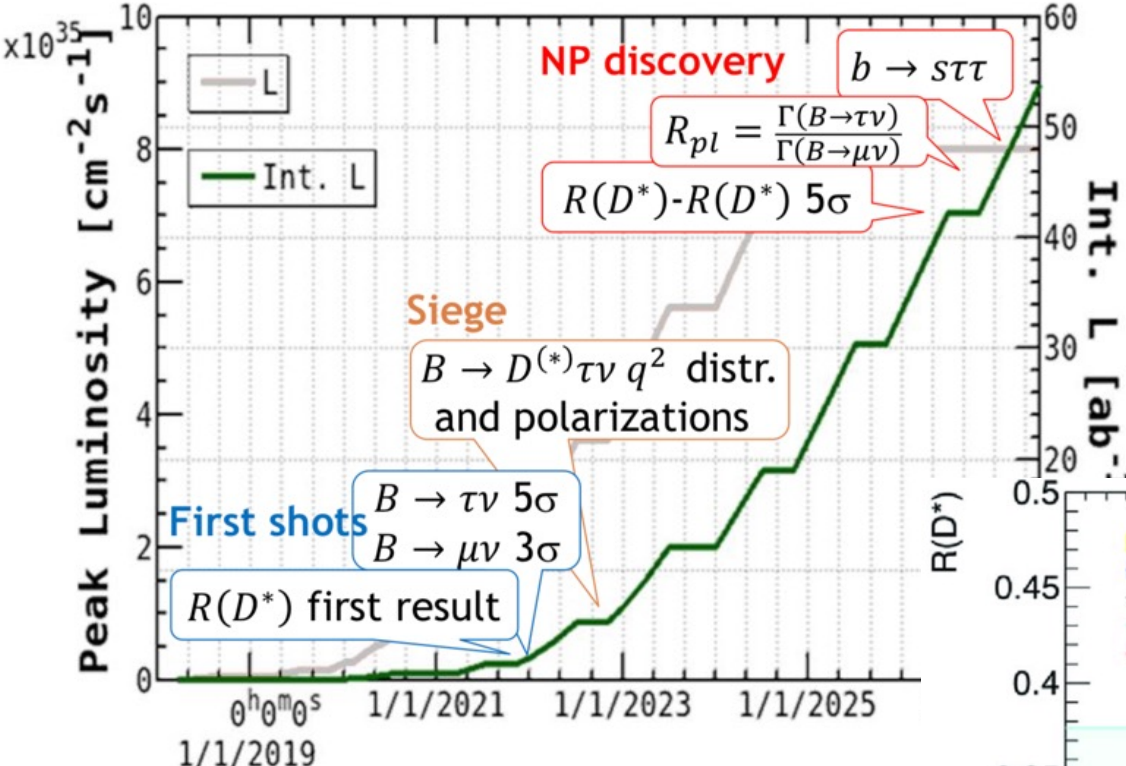
New

Semileptonic B tagging

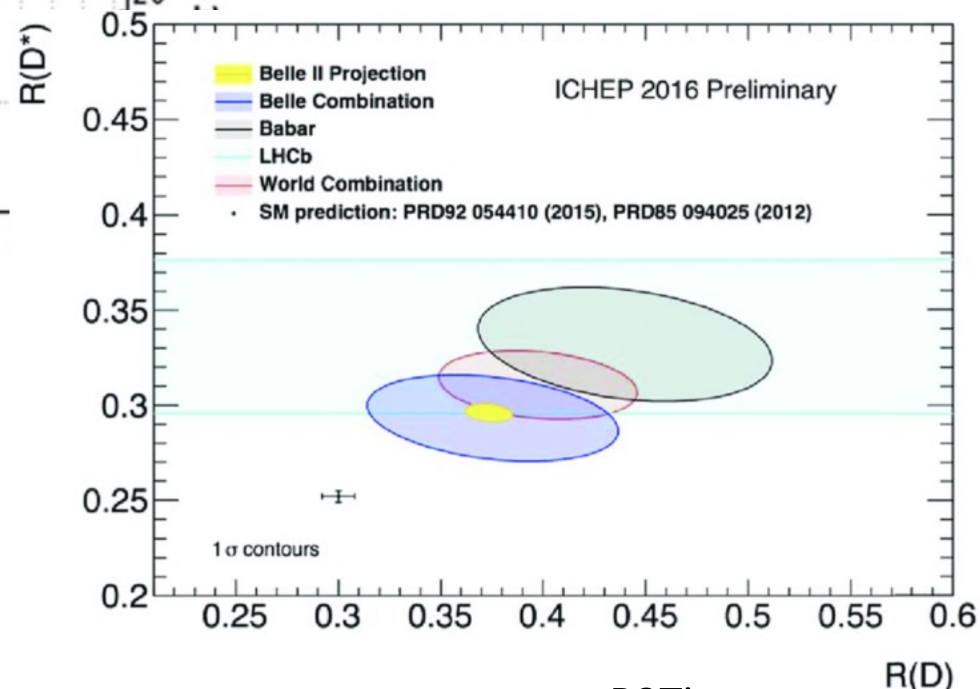
2.5σ

1.4σ

Prospects



Slide by Kodai Matsuoka(KMI)

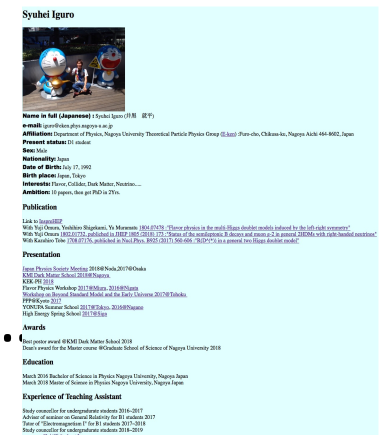


B2Tips

Let me introduce myself in 2min

去年、やった自己紹介

- 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 (5 from my idea).



残り3本(0本)

- I love football,
  most aggressive student in theoretical group (E-lab)

おかげさまで順調！

- For more info: http://www.eken.phys.nagoya-u.ac.jp/~iguro/IGURO.html

There are B anomalies.

https://tokyo2020.org

Our question.

Is there any model that explain

D* polarization in $B \to D^*\tau\nu$ and R(D$^{(*)}$) anomalies

at the same time?

$$F_L^{D^*} = \frac{\Gamma(B \to D_L^*\tau\nu)}{\Gamma(B \to D^*\tau\nu)}$$

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

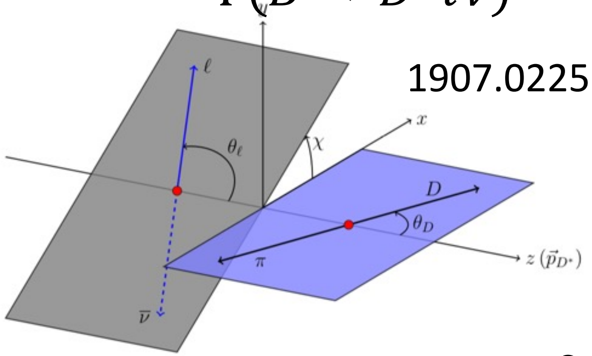


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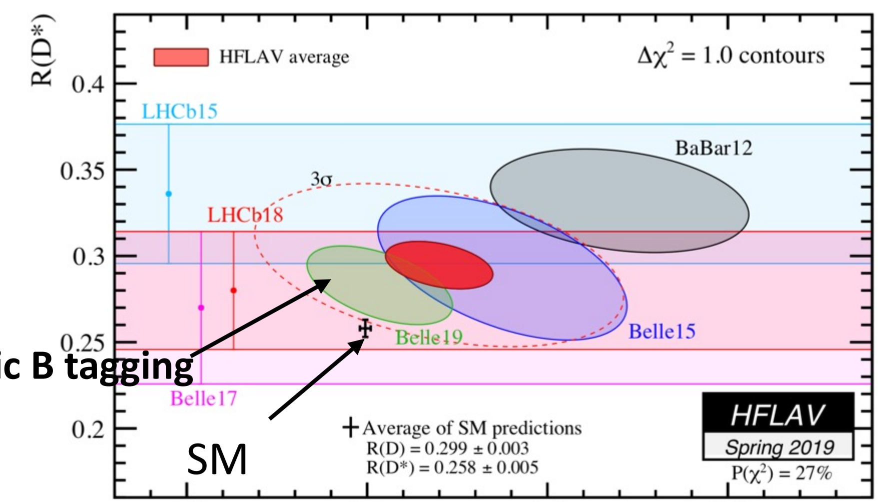
Figure 1: Kinematics of the $\overline{B} \to D^*(\to D\pi)\ell\overline{\nu}$ decay.

New

Semileptonic B tagging



SM

$$F_{L\,SM}^{D^*} = 0.453$$

1.7σ

$$F_L^{D^*} = 0.60 \pm 0.09$$ Belle: 1903.03102

~~3.8σ~~ 3.1σ discrepancy↓