

$B \rightarrow D^{(*)}\tau\bar{\nu}$ in various new physics models

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Physics at LHC and beyond

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Outline

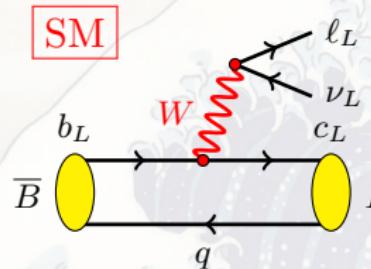
1 Introduction and motivation

2 Test of some New Physics models

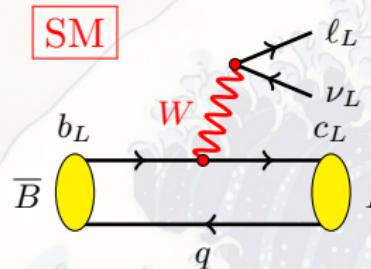
- 2HDM of type III
- Leptoquark models
- MSSM with R -parity violation

3 Conclusions

Introduction

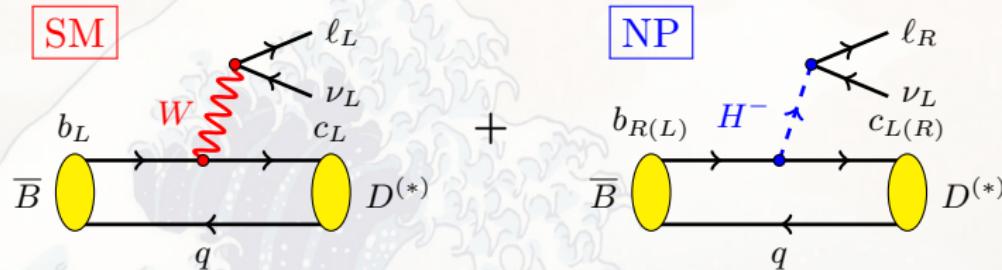


- Tree-level (TL) process. Large $\mathcal{B}^{(\text{SM})} \sim (1 - 2)\%$.

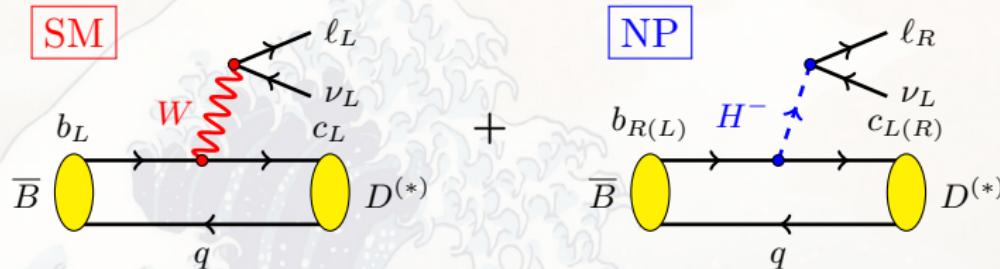


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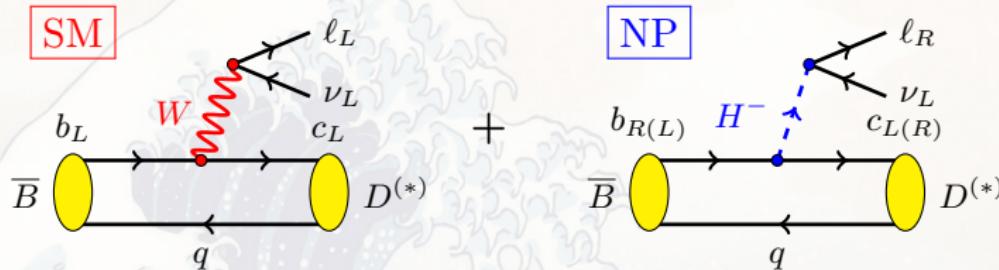
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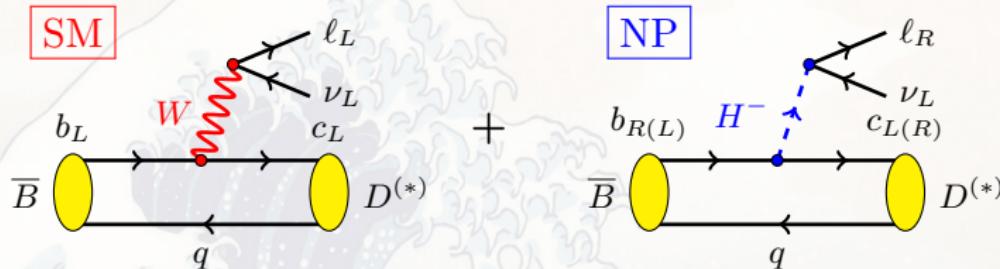
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- Hadronic uncertainties better controlled (or can be!).
- Popular NP test via

$$R(D) = \frac{\mathcal{B}(B \rightarrow D \tau \bar{\nu}_\tau)}{\mathcal{B}(B \rightarrow D \ell \bar{\nu}_\ell)}, \quad R(D^*) = \frac{\mathcal{B}(B \rightarrow D^* \tau \bar{\nu}_\tau)}{\mathcal{B}(B \rightarrow D^* \ell \bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

in order to cancel/reduce theoretical uncertainties in V_{cb} /FFs.

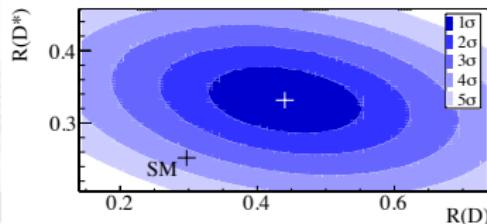
Motivation

The *BABAR* results [arXiv:1205.5442],

$$R(D)^{\text{exp}} = 0.440 \pm 0.058 \pm 0.042, \quad R(D)^{\text{SM}} = 0.297 \pm 0.017,$$

$$R(D^*)^{\text{exp}} = 0.332 \pm 0.024 \pm 0.018, \quad R(D^*)^{\text{SM}} = 0.252 \pm 0.003,$$

disagree with the SM at the 3.4σ level (combining with Belle result, we obtain 3.5σ).



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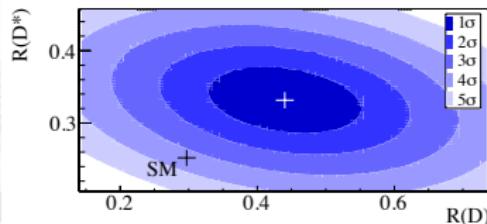
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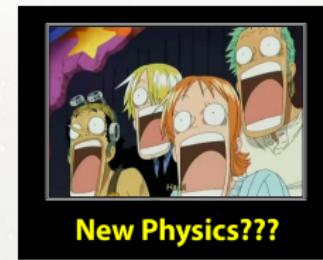
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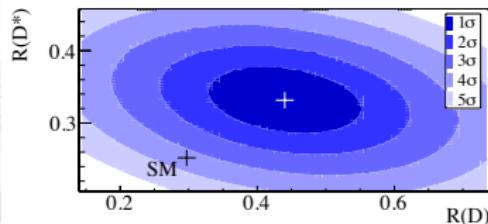
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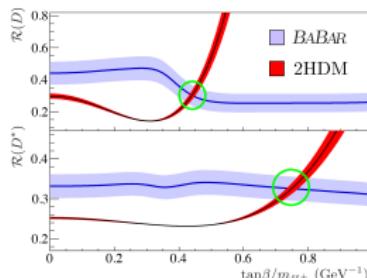
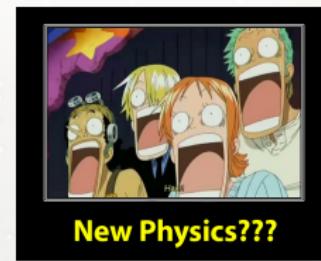
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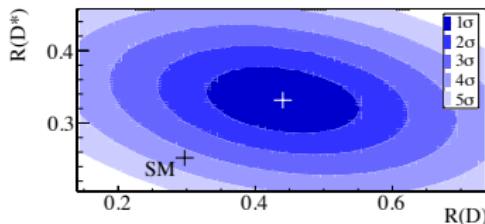
2HDM-II
EXCLUDED at 99.8% C.L.
© BABAR

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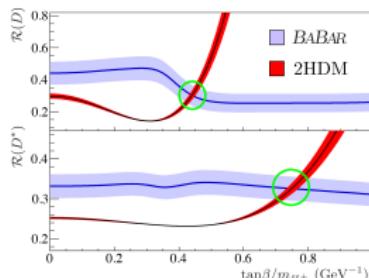
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New Physics???

EXCLUDED at 99.8% C.L.
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2HDM-II

2HDM-III ?

Leptoquarks ?

R MSSM ?

smth else ?

“Model independent” approach

- We assume that there is NO right-handed neutrino.

\mathcal{H}_{eff} describing the $b \rightarrow c\tau\bar{\nu}$ process

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[\underbrace{\left(1 + C_{V_1} \right) \mathcal{O}_{V_1} + C_{V_2} \mathcal{O}_{V_2} + C_{S_1} \mathcal{O}_{S_1} + C_{S_2} \mathcal{O}_{S_2} + C_T \mathcal{O}_T}_{\text{NP}} \right]$$

$$\begin{aligned}\mathcal{O}_{V_1} &= (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L), & \mathcal{O}_{V_2} &= (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L), \\ \mathcal{O}_{S_1} &= (\bar{c}_L b_R)(\bar{\tau}_R \nu_L), & \mathcal{O}_{S_2} &= (\bar{c}_R b_L)(\bar{\tau}_R \nu_L), \\ \mathcal{O}_T &= (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_L).\end{aligned}$$

- E.g. in the 2HDM-II

$$C_{S_1} = -\frac{m_b m_\tau}{m_{H^\pm}^2} \tan^2 \beta$$

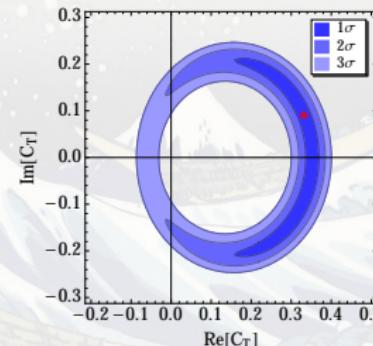
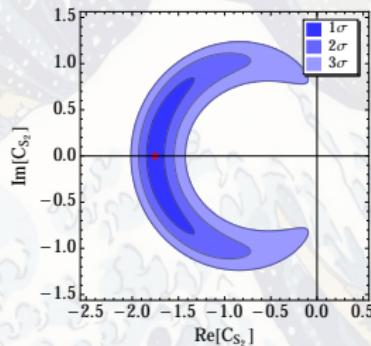
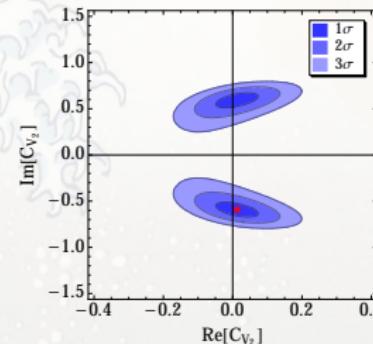
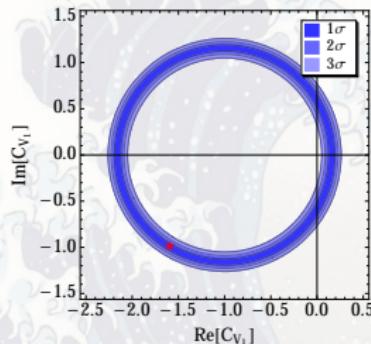
which is excluded by *BABAR* $\forall \tan \beta / m_{H^\pm} \Rightarrow$ the S_1 scenario is discarded!

NB: the pseudotensor operator is not independent of \mathcal{O}_T due to the relation

$$\bar{c} \sigma_{\mu\nu} \gamma_5 b = -\frac{i}{2} \epsilon_{\mu\nu\alpha\beta} \bar{c} \sigma^{\alpha\beta} b.$$

Constraints on NP from $R(D)$ & $R(D^*)$

Assuming the presence of only one NP type, we do χ^2 fit of the combined $BABAR+Belle$ result on $R(D)$ & $R(D^*)$ and obtain the constraints on the NP Wilson coefficients:



2HDM of type III with non-minimal flavour violation

- 2HDM III with MFV cannot explain $R(D)$ and $R(D^*)$ simultaneously.
- Both Higgs doublets couple simultaneously to up and down quarks (in the 2HDM-II one doublet couples to down quarks and charged leptons, while the other one gives masses to the up quarks).

$$\mathcal{L}_{\text{Yukawa}} = \overline{Q}_{fL}^a [Y_{fi}^d \epsilon_{ab} H_d^{b*} - \varepsilon_{fi}^d H_u^a] d_{iR} - \overline{Q}_{fL}^a [Y_{fi}^u \epsilon_{ab} H_u^{b*} + \varepsilon_{fi}^u H_u^a] u_{iR} + \text{h.c.}$$



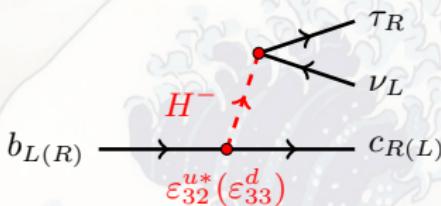
$$m_{ij}^d = v_d Y_{ij}^d + \textcolor{red}{v_u \varepsilon_{ij}^d}$$

$$m_{ij}^u = v_u Y_{ij}^u + \textcolor{red}{v_d \varepsilon_{ij}^u}$$

- $\varepsilon_{13,31}^d, \varepsilon_{23,32}^d, \varepsilon_{12,21}^d$ are stringently constrained from FCNC processes $B_{(s)} \rightarrow \mu^+ \mu^-$, $K_L \rightarrow \mu^+ \mu^-$ ($|\varepsilon| \lesssim \#10^{-5}$).
- $\varepsilon_{12,21}^u$ and $\varepsilon_{23,13}^u$ are constrained from $D \rightarrow \mu^+ \mu^-$ and $b \rightarrow (s, d)\gamma$ ($|\varepsilon| \lesssim \#10^{-2}$). **BUT $\varepsilon_{31,32}^u$ are still unconstrained!**
- Lepton-Higgs couplings are assumed to be like in the 2HDM-II.

[Crivellin et al. ('12), arXiv:1206.2634], [Crivellin @Moriond 2014, arXiv:1405.3701]

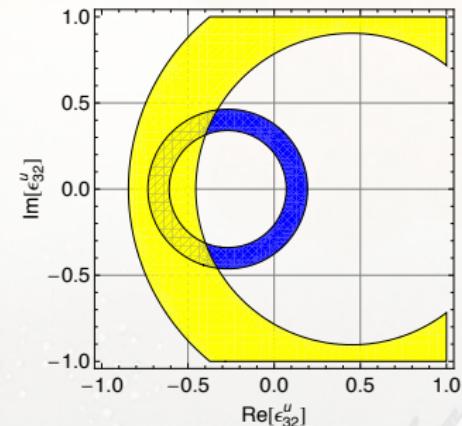
Constraining 2HDM-III



$$C_{S_1} \simeq \frac{1}{2\sqrt{2}G_F} \frac{m_\tau}{v} \epsilon_{33}^d \frac{\sin \beta \tan^2 \beta}{M_{H^\pm}^2}$$

-disfavoured by *BABAR*!

$$C_{S_2} \simeq \frac{1}{2\sqrt{2}G_F V_{cb}} \frac{m_\tau}{v} \epsilon_{32}^{u*} \frac{\sin \beta \tan \beta}{M_{H^\pm}^2}$$



Allowed 1σ regions from $R(D)$ (blue) and $R(D^*)$ (yellow) for $\tan \beta = 50$ and $M_H = 500$ GeV

[Crivellin et al. ('12), arXiv:1206.2634]

- 2HDM-III can explain $R(D)$ and $R(D^*)$ simultaneously using a single free parameter ϵ_{32}^u .
- Search for $A^0, H^0 \rightarrow \bar{t}c$ and $t \rightarrow h^0 c$ at the LHC to test the model.

Leptoquark models

\mathcal{L}_{eff} with generic dimensionless $SU(3) \times SU(2) \times U(1)$ invariant *non-diagonal* couplings of scalar and vector LQs (6 models)

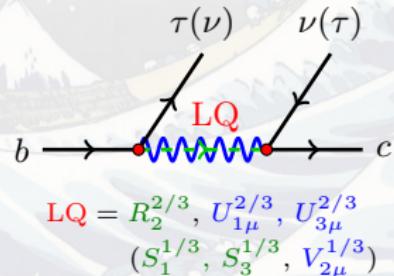
$$\begin{aligned}\mathcal{L}_{F=0}^{\text{LQ}} = & \left(h_{1L}^{ij} \overline{Q}_{iL} \gamma^\mu L_{jL} + h_{1R}^{ij} \overline{d}_{iR} \gamma^\mu \ell_{jR} \right) \mathbf{U}_{1\mu} + h_{3L}^{ij} \overline{Q}_{iL} \boldsymbol{\sigma} \gamma^\mu L_{jL} \mathbf{U}_{3\mu} \\ & + \left(h_{2L}^{ij} \overline{u}_{iR} L_{jL} + h_{2R}^{ij} \overline{Q}_{iL} i\sigma_2 \ell_{jR} \right) \mathbf{R}_2\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{F=-2}^{\text{LQ}} = & \left(g_{1L}^{ij} \overline{Q}_{iL}^c i\sigma_2 L_{jL} + g_{1R}^{ij} \overline{u}_{iR}^c \ell_{jR} \right) \mathbf{S}_1 + g_{3L}^{ij} \overline{Q}_{iL}^c i\sigma_2 \boldsymbol{\sigma} L_{jL} \mathbf{S}_3 \\ & + \left(g_{2L}^{ij} \overline{d}_{iR}^c \gamma^\mu L_{jL} + g_{2R}^{ij} \overline{Q}_{iL}^c \gamma^\mu \ell_{jR} \right) \mathbf{V}_{2\mu}\end{aligned}$$

[Buchmüller et al. ('87), Phys.Lett.B191]

Quantum numbers

| | S_1 | S_3 | V_2 | R_2 | U_1 | U_3 |
|------------------|-------|-------|-------|-------|-------|-------|
| spin | 0 | 0 | 1 | 0 | 1 | 1 |
| $F = 3B + L$ | -2 | -2 | -2 | 0 | 0 | 0 |
| $SU(3)_c$ | 3^* | 3^* | 3^* | 3 | 3 | 3 |
| $SU(2)$ | 1 | 3 | 2 | 2 | 1 | 3 |
| $U(1)_{Y=Q-T_3}$ | $1/3$ | $1/3$ | $5/6$ | $7/6$ | $2/3$ | $2/3$ |



Leptoquark contribution to $B \rightarrow D^{(*)}\tau\bar{\nu}$

General Wilson coefficients (at M_{LQ} scale) for *all possible types of LQs contributing to the $b \rightarrow c\tau\bar{\nu}$ process*:

$$C_{V_1} \simeq \frac{1}{2\sqrt{2}G_F V_{cb}} \left[\frac{g_{1L}^{33} g_{1L}^{23*}}{2M_{S_1}^2} - \frac{g_{3L}^{33} g_{3L}^{23*}}{2M_{S_3}^2} + \frac{h_{1L}^{23} h_{1L}^{33*}}{M_{U_1}^2} - \frac{h_{3L}^{23} h_{3L}^{33*}}{M_{U_3}^2} \right]$$

$$C_{V_2} = 0$$

$$C_{S_1} \simeq \frac{1}{2\sqrt{2}G_F V_{cb}} \left[-\frac{2g_{2L}^{33} g_{2R}^{23*}}{M_{V_2}^2} - \frac{2h_{1L}^{23} h_{1R}^{33*}}{M_{U_1}^2} \right]$$

$$C_{S_2} \simeq \frac{1}{2\sqrt{2}G_F V_{cb}} \left[-\frac{g_{1L}^{33} g_{1R}^{23*}}{2M_{S_1}^2} - \frac{h_{2L}^{23} h_{2R}^{33*}}{2M_{R_2}^2} \right]$$

$$C_T \simeq \frac{1}{2\sqrt{2}G_F V_{cb}} \left[\frac{g_{1L}^{33} g_{1R}^{23*}}{8M_{S_1}^2} - \frac{h_{2L}^{23} h_{2R}^{33*}}{8M_{R_2}^2} \right]$$

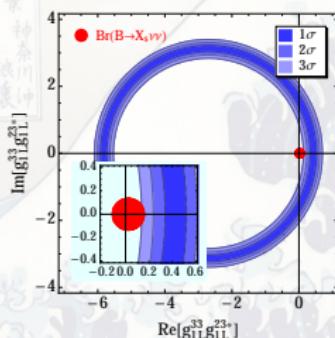
- We neglect $\mathcal{O}(\lambda^2)$ terms and keep only the leading terms proportional to V_{tb} .
- In the simplified scenario with only $R_2^{2/3}$ or $S_1^{1/3}$ LQ contribution,

$$C_{S_2}(M_{\text{LQ}}) = \pm 4C_T(M_{\text{LQ}}) \Rightarrow \text{for } M_{\text{LQ}} \sim 1 \text{ TeV, } C_{S_2}(\mu_b) \simeq \pm 7.8C_T(\mu_b)$$

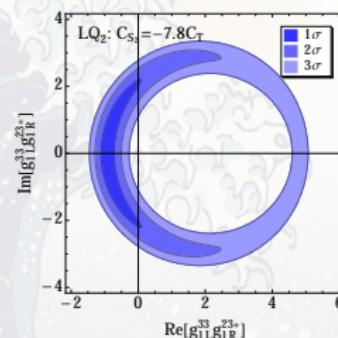
[Sakaki, Tanaka, AT, Watanabe ('13), arXiv:1309.0301]

Constraining leptoquark models

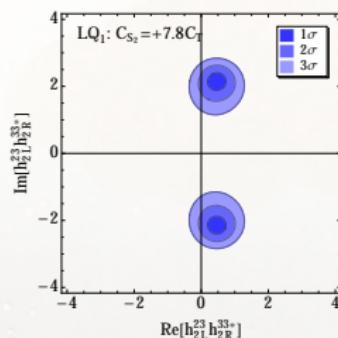
S_1 with only L couplings



S_1 with L, R couplings



R_2 with L, R couplings

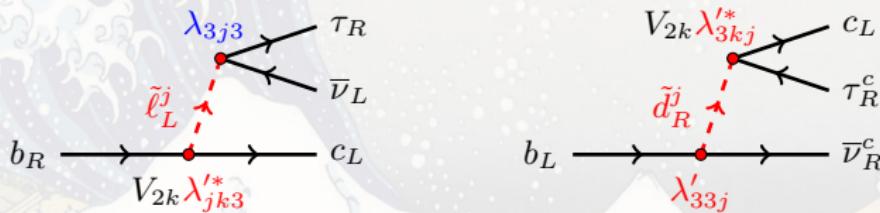


- The constraints on $g_{1(3)L}^{33} g_{1(3)L}^{23*}$ ($S_{1,3}$) from $R(D) \& R(D^*)$ and $\mathcal{B}(B \rightarrow X_s \nu \bar{\nu})$ are consistent only at 3σ level and force the couplings to be rather small.
- The U_3 LQ scenario with $h_{3L}^{23} h_{3L}^{33*}$ is excluded by $R(D) \& R(D^*)$ and $\mathcal{B}(B \rightarrow X_s \nu \bar{\nu})$.
- $h_{1L}^{23} h_{1L}^{33*}$ (U_1) remain unconstrained from $\mathcal{B}(B \rightarrow X_s \nu \bar{\nu})$ and the magnitude of $\mathcal{O}(1)$ can be sufficient to explain the data.
- For $M_{S_1, R_2} \sim 1$ TeV, one can have $g_{1L}^{33} g_{1R}^{23*}, h_{2L}^{23} h_{2R}^{33*} \sim \mathcal{O}(1)$.
- The other V_2 and U_1 LQ scenarios with L, R couplings are disfavoured as in the 2HDM-II.

MSSM with R -parity violation

$$W_{RPV} = \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c$$

$$\begin{aligned} \mathcal{L}_{\text{eff}}^{RPV} &= - \sum_{j,k=1}^3 V_{2k} \left[\frac{\lambda_{3j3} \lambda'_{jk3}^*}{m_{\tilde{\ell}_L^j}^2} (\bar{c}_L b_R) (\bar{\tau}_R \nu_L) + \frac{\lambda'_{33j} \lambda'_{3kj}^*}{m_{\tilde{d}_R^j}^2} (\bar{c}_L \tau_R^c) (\bar{\nu}_R^c b_L) \right] \\ &= - \sum_{j,k=1}^3 V_{2k} \left[\underbrace{\frac{\lambda_{3j3} \lambda'_{jk3}^*}{m_{\tilde{\ell}_L^j}^2} (\bar{c}_L b_R) (\bar{\tau}_R \nu_L)}_{\mathcal{O}_{S_1}} + \underbrace{\frac{\lambda'_{33j} \lambda'_{3kj}^*}{2m_{\tilde{d}_R^j}^2} (\bar{c}_L \gamma^\mu b_L) (\bar{\tau}_L \gamma_\mu \nu_L)}_{\mathcal{O}_{V_1}} \right] \end{aligned}$$



The corresponding Wilson coefficients are

$$C_{S_1} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{j,k=1}^3 V_{2k} \frac{\lambda_{3j3} \lambda'_{jk3}^*}{2m_{\tilde{\ell}_L^j}^2},$$

$$C_{V_1} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{j,k=1}^3 V_{2k} \frac{\lambda'_{33j} \lambda'_{3kj}^*}{2m_{\tilde{d}_R^j}^2}$$

[Tanaka,Watanabe('12), arXiv:1212.1878]

Testing R MSSM

The largest effect on $R(D^{(*)})$ is obtained for RPV couplings for $k = 2$:

$$C_{V_1}^{\text{RMSSM}} \simeq \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{j=1}^3 \frac{\lambda'_{33j} \lambda'^*_{32j}}{2m_{\tilde{d}_R^j}^2}$$

The same RPV couplings appear also in the NP contribution to $b \rightarrow s\nu\bar{\nu}$:

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[C_L^{(\text{SM})} + C_L \right] \mathcal{O}_L$$

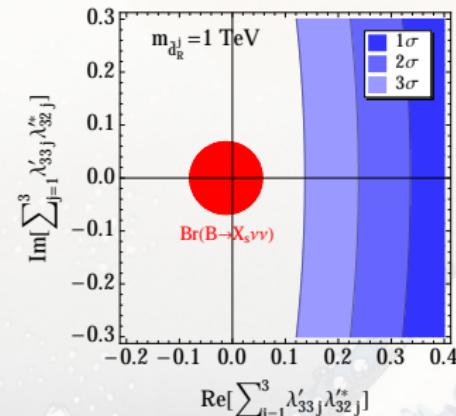
$$\mathcal{O}_L = (\bar{s}_L \gamma^\mu b_L)(\bar{\nu}_L \gamma_\mu \nu_L)$$

$$C_L^{\text{RMSSM}} \simeq \frac{1}{2\sqrt{2}G_F V_{tb} V_{ts}^*} \sum_{j=1}^3 \frac{\lambda'_{33j} \lambda'^*_{32j}}{m_{\tilde{d}_R^j}^2}$$

[Tanaka,Watanabe('12), arXiv:1212.1878]

$$\mathcal{B}^{\text{exp}}(B \rightarrow X_s \nu \bar{\nu}) < 6.4 \times 10^{-4}$$

[ALEPH('00), arXiv:0010022]



- MSSM with RPV is inconsistent with both $B \rightarrow D^{(*)}\tau\bar{\nu}$ and $B \rightarrow X_s \nu \bar{\nu}$ at the same time.
- $\mathcal{L}_{\text{eff}}^{\text{RPV}}$ involves the interaction which induces LFV \Rightarrow one can have ν with flavour different from τ . In this case the conclusion remains same.

- ① Not only FCNC loop processes can provide a window to NP search. Tree-level decays are as good and often even more interesting, especially when the hadronic uncertainties are well controlled.
- ② Excess in $\overline{B} \rightarrow D\tau\bar{\nu}$ and $\overline{B} \rightarrow D^*\tau\bar{\nu}$, observed by *BABAR* and *Belle*, helped discarding 2HDM-II.
- ③ 2HDM of type III with MSSM-like Higgs potential and flavour-violation in the up sector can explain these deviations from the SM.
- ④ Some of the leptoquark models can also explain the observed discrepancy in $R(D)$ and $R(D^*)$ and can provide quite good constraints on leptoquark couplings which are allowed to be $\sim \mathcal{O}(1)$.
- ⑤ MSSM with R -parity violation is not likely to be consistent with both $B \rightarrow D^{(*)}\tau\bar{\nu}$ and $B \rightarrow X_s\nu\bar{\nu}$ at the same time and therefore is disfavoured.
- ⑥ More precise data that will be given in a future super B factory experiment will allow us to identify the relevant NP operator(s) and test some particular NP models if the deviation from the SM persists.

富田徹
三十六景
神奈川沖
波裏

BACKUP SLIDES

How to distinguish between NP scenarios : various observables

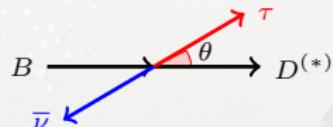
- R ratios (to be improved at Belle II)

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)} \ell \bar{\nu})}$$

- τ forward-backward asymmetry,

$$\mathcal{A}_{\text{FB}} = \frac{\int_0^1 \frac{d\Gamma}{d \cos \theta} d \cos \theta - \int_{-1}^0 \frac{d\Gamma}{d \cos \theta} d \cos \theta}{\int_{-1}^1 \frac{d\Gamma}{d \cos \theta} d \cos \theta} = \frac{\int b_\theta(q^2) dq^2}{\Gamma}$$

$$\frac{d^2 \Gamma}{dq^2 d \cos \theta} = a_\theta(q^2) + b_\theta(q^2) \cos \theta + c_\theta(q^2) \cos^2 \theta$$



- τ polarization parameter by studying further τ decays,

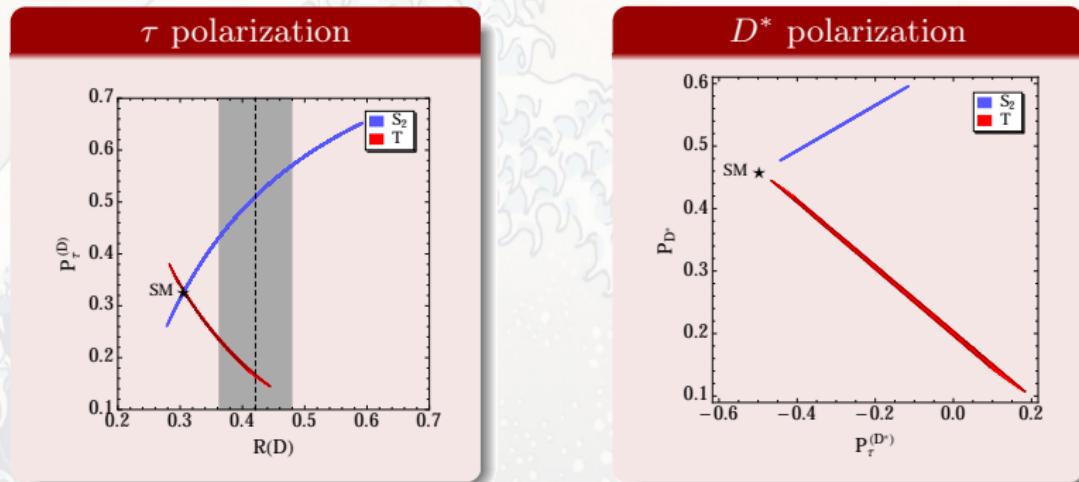
$$P_\tau = \frac{\Gamma(\lambda_\tau=1/2) - \Gamma(\lambda_\tau=-1/2)}{\Gamma(\lambda_\tau=1/2) + \Gamma(\lambda_\tau=-1/2)}$$

- D^* longitudinal polarization using the $D^* \rightarrow D\pi$ decay,

$$P_{D^*} = \frac{\Gamma(\lambda_{D^*}=0)}{\Gamma(\lambda_{D^*}=0) + \Gamma(\lambda_{D^*}=1) + \Gamma(\lambda_{D^*}=-1)}$$

How to distinguish between NP scenarios : correlations (illustration)

Applying the constraints on C_{S_2} or C_T from the χ^2 fit of $R(D)$ & $R(D^*)$ at 3σ level,

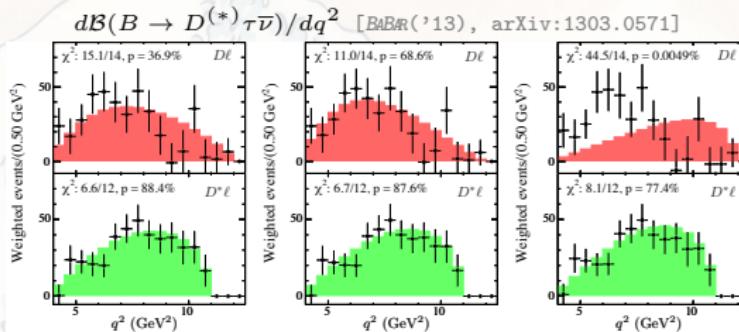


[Sakaki, Tanaka, AT, Watanabe ('13), arXiv:1309.0301]

Measurements of these observables in addition to more precise determination of $R(D^{(*)})$ are the key issue in order to identify the origin of the present excess of $\overline{B} \rightarrow D^{(*)}\tau\nu$.

BUT this is NOT an easy experimental task 😐

Exploring the q^2 dependence for the NP search



- To reduce the FF uncertainties, one can explore the q^2 -dependent ratio

$$R_{D^{(*)}}(q^2) \equiv \frac{d\mathcal{B}(\bar{B} \rightarrow D^{(*)}\tau\bar{\nu})/dq^2}{d\mathcal{B}(\bar{B} \rightarrow D^{(*)}\ell\bar{\nu})/dq^2}$$

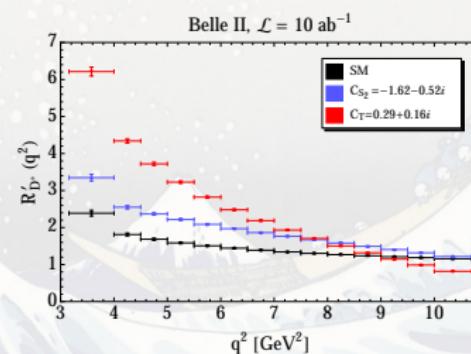
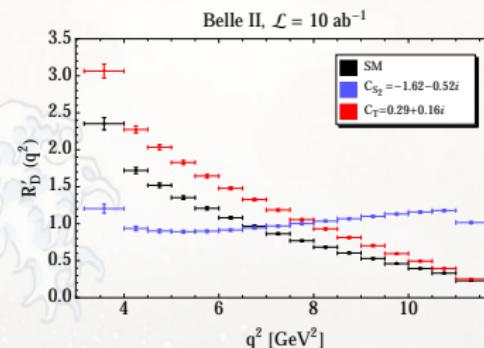
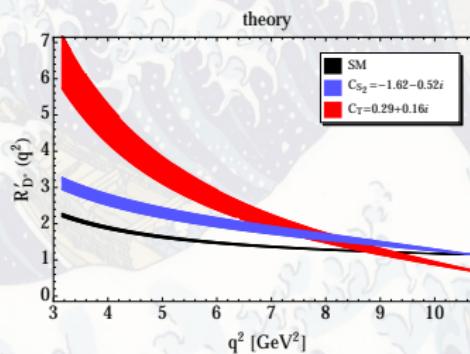
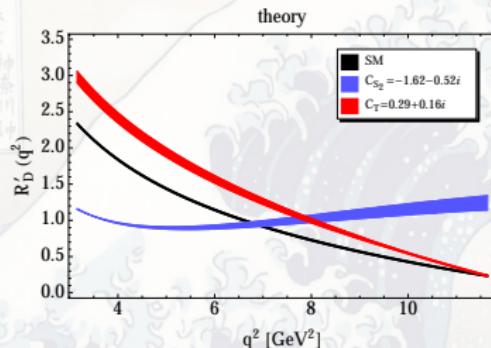
- For our convenience, to remove the divergence of R_D at $q^2 = (m_B - m_D)^2$ [†] and the phase space suppression of $R_{D^{(*)}}$ at $q^2 \sim m_\tau^2$, we introduce

$$\boxed{R'_D(q^2) \equiv R_D(q^2) \times \frac{\lambda_D(q^2)}{(m_B^2 - m_D^2)^2} \times \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2}$$

$$R'_{D^*}(q^2) \equiv R_{D^*}(q^2) \times \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2}}$$

[†] Since the μ -mode is supposed to be SM-like, $\mathcal{B}_\mu^{-1} \propto (H_V^s)^{-2} \propto \lambda_D^{-1}(q^2)$.

Exploring the q^2 dependence for the NP search : $R'_D(q^2)$



[Sakaki,Tanaka,AT,Watanabe, in preparation]

\mathcal{H}_{eff} describing the $b \rightarrow s \nu_j \bar{\nu}_i$ process

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\left(\delta_{ij} C_L^{(\text{SM})} + C_L^{ij} \right) \mathcal{O}_L^{ij} + C_R^{ij} \mathcal{O}_R^{ij} \right]$$

$$\mathcal{O}_L^{ij} = (\bar{s}_L \gamma^\mu b_L)(\bar{\nu}_{jL} \gamma_\mu \nu_{iL}), \quad \mathcal{O}_R^{ij} = (\bar{s}_R \gamma^\mu b_R)(\bar{\nu}_{jL} \gamma_\mu \nu_{iL})$$

- In the SM,

$$C_L^{(\text{SM})} = \frac{\alpha}{2\pi \sin^2 \theta_W} X(m_t^2/M_W^2), \quad C_R^{(\text{SM})} = 0$$

- $S_{1,3}$ and $V_{2\mu}$ LQs give the following contribution to $b \rightarrow s \nu_j \bar{\nu}_i$:

$$C_R^{ij} = - \frac{V_{cs}}{2\sqrt{2}G_F V_{ts}^*} \frac{g_{2L}^{3i} g_{2L}^{2j*}}{M_{V_2}^2}$$

$$C_L^{ij} = - \frac{V_{cs}}{2\sqrt{2}G_F V_{ts}^*} \left[\frac{g_{1L}^{3i} g_{1L}^{2j*}}{2M_{S_1}^2} + \frac{g_{3L}^{3i} g_{3L}^{2j*}}{2M_{S_3}^2} - 2 \frac{h_{3L}^{2i} h_{3L}^{3j*}}{M_{U_3}^2} \right]$$

- For simplicity, after the rotation of the down-type quarks into the mass eigenstate basis, we neglect the subleading $\mathcal{O}(\lambda)$ terms and keep only the $V_{tb} V_{cs}^* \simeq 1$ terms.

[Sakaki, Tanaka, AT, Watanabe ('13), arXiv:1309.0301]

Distributions (simple yet long formulas)

The studied distributions are given by

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

where H_i are the helicity amplitudes,

$$H_i(q^2) \propto \langle D^{(*)} | \mathcal{O}_i | \overline{B} \rangle$$

[Sakaki, Tanaka, AT, Watanabe ('13), arXiv:1309.0301]

Distributions (simple yet long formulas)

The studied distributions are given by

$$\begin{aligned}
 \frac{d\Gamma(\overline{B} \rightarrow D^* \tau \bar{\nu})}{dq^2} = & \frac{G_F^2 |V_{cb}|^2}{192\pi^3 m_B^3} q^2 \sqrt{\lambda_{D^*}(q^2)} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \times \left\{ \right. \\
 & (|1 + C_{V_1}|^2 + |C_{V_2}|^2) \left[\left(1 + \frac{m_\tau^2}{2q^2}\right) (H_{V,+}^2 + H_{V,-}^2 + H_{V,0}^2) + \frac{3}{2} \frac{m_\tau^2}{q^2} H_{V,t}^2 \right] \\
 & - 2\mathcal{R}e[(1 + C_{V_1}) C_{V_2}^*] \left[\left(1 + \frac{m_\tau^2}{2q^2}\right) (H_{V,0}^2 + 2H_{V,+}H_{V,-}) + \frac{3}{2} \frac{m_\tau^2}{q^2} H_{V,t}^2 \right] \\
 & + \frac{3}{2} |C_{S_1} - C_{S_2}|^2 H_S^2 + 8 |C_T|^2 \left(1 + \frac{2m_\tau^2}{q^2}\right) (H_{T,+}^2 + H_{T,-}^2 + H_{T,0}^2) \\
 & + 3\mathcal{R}e[(1 + C_{V_1} - C_{V_2})(C_{S_1}^* - C_{S_2}^*)] \frac{m_\tau}{\sqrt{q^2}} H_S H_{V,t} \\
 & - 12\mathcal{R}e[(1 + C_{V_1}) C_T^*] \frac{m_\tau}{\sqrt{q^2}} (H_{T,0}H_{V,0} + H_{T,+}H_{V,+} - H_{T,-}H_{V,-}) \\
 & \left. + 12\mathcal{R}e[C_{V_2} C_T^*] \frac{m_\tau}{\sqrt{q^2}} (H_{T,0}H_{V,0} + H_{T,+}H_{V,-} - H_{T,-}H_{V,+}) \right\}
 \end{aligned}$$

[Sakaki, Tanaka, AT, Watanabe ('13), arXiv:1309.0301]

Helicity amplitudes

$\bar{B} \rightarrow D\tau\bar{\nu}$ (3 FFs) :

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

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

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

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

with hadronic amplitudes defined as,

$$H_{V_{1,2}, \lambda}^{\lambda_M}(q^2) = \varepsilon_\mu^*(\lambda) \langle M(\lambda_M) | \bar{c} \gamma^\mu (1 \mp \gamma_5) b | \bar{B} \rangle,$$

$$H_{S_{1,2}, \lambda}^{\lambda_M}(q^2) = \langle M(\lambda_M) | \bar{c} (1 \pm \gamma_5) b | \bar{B} \rangle,$$

$$H_{T, \lambda \lambda'}^{\lambda_M}(q^2) = \varepsilon_\mu^*(\lambda) \varepsilon_\nu^*(\lambda') \langle M(\lambda_M) | \bar{c} \sigma^{\mu\nu} (1 - \gamma_5) b | \bar{B} \rangle$$

where λ_M and λ denote the meson and virtual intermediate boson helicities in the B rest frame respectively.

Helicity amplitudes

$\overline{B} \rightarrow D^* \tau \bar{\nu}$ (7 FFs) :

$$H_{V,\pm}(q^2) \equiv H_{V_1,\pm}^\pm(q^2) = -H_{V_2,\mp}^\mp(q^2) = (m_B + m_{D^*}) \textcolor{blue}{A}_1(q^2) \mp \frac{\sqrt{\lambda_{D^*}(q^2)}}{m_B + m_{D^*}} \textcolor{blue}{V}(q^2)$$

$$H_{V,0}(q^2) \equiv H_{V_1,0}^0(q^2) = -H_{V_2,0}^0(q^2) = \frac{m_B + m_{D^*}}{2m_{D^*}\sqrt{q^2}} \left[-(m_B^2 - m_{D^*}^2 - q^2) \textcolor{blue}{A}_1(q^2) \right. \\ \left. + \frac{\lambda_{D^*}(q^2)}{(m_B + m_{D^*})^2} \textcolor{blue}{A}_2(q^2) \right]$$

$$H_{V,t}(q^2) \equiv H_{V_1,t}^0(q^2) = -H_{V_2,t}^0(q^2) = -\sqrt{\frac{\lambda_{D^*}(q^2)}{q^2}} \textcolor{blue}{A}_0(q^2)$$

$$H_S(q^2) \equiv H_{S_1}^0(q^2) = -H_{S_2}^0(q^2) = -\frac{\sqrt{\lambda_{D^*}(q^2)}}{m_b + m_c} \textcolor{blue}{A}_0(q^2)$$

$$H_{T,\pm}(q^2) \equiv \pm H_{T,\pm t}^\pm(q^2) = \frac{1}{\sqrt{q^2}} \left[\pm(m_B^2 - m_{D^*}^2) \textcolor{blue}{T}_2(q^2) + \sqrt{\lambda_{D^*}(q^2)} \textcolor{blue}{T}_1(q^2) \right]$$

$$H_{T,0}(q^2) \equiv H_{T,+-}^0(q^2) = H_{T,0t}^0(q^2) = \frac{1}{2m_{D^*}} \left[-(m_B^2 + 3m_{D^*}^2 - q^2) \textcolor{blue}{T}_2(q^2) \right. \\ \left. + \frac{\lambda_{D^*}(q^2)}{m_B^2 - m_{D^*}^2} \textcolor{blue}{T}_3(q^2) \right]$$