

## Analyzing New Physics in the decays $\bar{B}^0 \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$

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## Experimental Status

- Ratios of branching fractions

$$R(D^{(*)}) \equiv \mathcal{B}(\bar{B}^0 \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B}^0 \rightarrow D^{(*)} \mu^- \bar{\nu}_\mu)$$

- Experiments

$$R(D)|_{\text{BABAR}} = 0.440 \pm 0.072,$$

$$R(D)|_{\text{BELLE}} = 0.375 \pm 0.069,$$

$$R(D^*)|_{\text{BABAR}} = 0.332 \pm 0.030,$$

$$R(D^*)|_{\text{BELLE}} = 0.293 \pm 0.041,$$

$$R(D^*)|_{\text{LHCb}} = 0.336 \pm 0.040,$$

*(statistical and systematic uncertainties combined in quadrature)*

- Average ratios

$$R(D)|_{\text{expt}} = 0.391 \pm 0.050,$$

$$R(D^*)|_{\text{expt}} = 0.322 \pm 0.022,$$

HFAG 2015

- SM expectations

$$R(D)|_{\text{SM}} = 0.297 \pm 0.017,$$

$$R(D^*)|_{\text{SM}} = 0.252 \pm 0.003,$$

Fajfer et al. 2012, Kamenik et al. 2008

→ SM excess: **1.9  $\sigma$**  and **3.2  $\sigma$** , respectively;

## Theoretical attempts to explain the excess

### 1) Specific NP models: two-Higgs-doublet models (2HDMs), Minimal Supersymmetric Standard Model (MSSM), Leptoquark models, etc.

- W. S. Hou, Enhanced charged Higgs boson effects in  $\mathbf{B} \rightarrow \tau \bar{\nu}_\tau$ ,  $\mathbf{B} \rightarrow \mu \bar{\nu}_\mu$  and  $\mathbf{b} \rightarrow \tau \bar{\nu}_\tau + \mathbf{X}$ , Phys. Rev. D **48**, 2342 (1993).
- Y. Sakaki, M. Tanaka, A. Tayduganov and R. Watanabe, Testing leptoquark models in  $\bar{\mathbf{B}} \rightarrow \mathbf{D}^{(*)} \tau \bar{\nu}$ , Phys. Rev. D **88**, no. 9, 094012 (2013).
- A. Crivellin, C. Greub and A. Kokulu, Explaining  $\mathbf{B} \rightarrow \mathbf{D} \tau \nu$ ,  $\mathbf{B} \rightarrow \mathbf{D}^* \tau \nu$  and  $\mathbf{B} \rightarrow \tau \nu$  in a 2HDM of type III, Phys. Rev. D **86**, 054014 (2012).
- L. Calibbi, A. Crivellin and T. Ota, Effective field theory approach to  $\mathbf{b} \rightarrow \mathbf{s} \ell \ell^{(\prime)}$ ,  $\mathbf{B} \rightarrow \mathbf{K}^{(*)} \nu \bar{\nu}$  and  $\mathbf{B} \rightarrow \mathbf{D}^{(*)} \tau \nu$  with third generation couplings, Phys. Rev. Lett. **115**, 181801 (2015).
- A. Crivellin, J. Heeck and P. Stoffer, A perturbed lepton-specific two-Higgs-doublet model facing experimental hints for physics beyond the Standard Model, Phys. Rev. Lett. **116**, no. 8, 081801 (2016).
- M. Bauer and M. Neubert, One Leptoquark to Rule Them All: A Minimal Explanation for  $\mathbf{R}_{\mathbf{D}^{(*)}}$ ,  $\mathbf{R}_{\mathbf{K}}$  and  $(\mathbf{g} - 2)_\mu$ , Phys. Rev. Lett. **116**, no. 14, 141802 (2016).
- S. Fajfer and N. Košnik, Vector leptoquark resolution of  $\mathbf{R}_{\mathbf{K}}$  and  $\mathbf{R}_{\mathbf{D}^{(*)}}$  puzzles, Phys. Lett. B **755**, 270 (2016).

## Theoretical attempts to explain the excess

### 2) Model-independent approach: general SM+NP effective Hamiltonian for $\mathbf{b} \rightarrow \mathbf{c} l \nu$ is imposed

- A. Datta, M. Duraisamy, and D. Ghosh, Diagnosing New Physics in  $\mathbf{b} \rightarrow \mathbf{c} \tau \nu_\tau$  decays in the light of the recent BaBar result, Phys. Rev. D **86**, 034027 (2012).
- S. Fajfer, J. F. Kamenik, I. Nisandzic, and J. Zupan, Implications of lepton flavor universality violations in B-Decays, Phys. Rev. Lett. **109**, 161801 (2012).
- S. Fajfer, J. F. Kamenik, and I. Nisandzic, On the  $\mathbf{B} \rightarrow \mathbf{D}^* \tau \bar{\nu}_\tau$  sensitivity to New Physics, Phys. Rev. D **85**, 094025 (2012).
- M. Duraisamy and A. Datta, The Full  $\mathbf{B} \rightarrow \mathbf{D}^* \tau^- \bar{\nu}_\tau$  Angular Distribution and CP violating Triple Products, JHEP **1309**, 059 (2013).
- M. Duraisamy, P. Sharma and A. Datta, Azimuthal  $\mathbf{B} \rightarrow \mathbf{D}^* \tau^- \bar{\nu}_\tau$  angular distribution with tensor operators, Phys. Rev. D **90**, no. 7, 074013 (2014).
- M. Tanaka and R. Watanabe, New physics in the weak interaction of  $\bar{\mathbf{B}} \rightarrow \mathbf{D}^{(*)} \tau \bar{\nu}$ , Phys. Rev. D **87**, 034028 (2013).
- P. Biancofiore, P. Colangelo, and F. De Fazio, On the anomalous enhancement observed in  $\mathbf{B} \rightarrow \mathbf{D}^{(*)} \tau \bar{\nu}_\tau$  decays, Phys. Rev. D **87**, 074010 (2013).
- S. Bhattacharya, S. Nandi and S. K. Patra, Optimal-observable analysis of possible new physics in  $\mathbf{B} \rightarrow \mathbf{D}^{(*)} \tau \nu_\tau$ , Phys. Rev. D **93**, no. 3, 034011 (2016).

## Effective Hamiltonian

**Effective Hamiltonian for the quark-level transition  $b \rightarrow c\tau^-\bar{\nu}_\tau$**

$$\mathcal{H}_{\text{eff}} = 2\sqrt{2}G_F V_{cb} [(1 + V_L)\mathcal{O}_{V_L} + V_R\mathcal{O}_{V_R} + S_L\mathcal{O}_{S_L} + S_R\mathcal{O}_{S_R} + T_L\mathcal{O}_{T_L}],$$

where the four-Fermi operators are written as

$$\begin{aligned}\mathcal{O}_{V_L} &= (\bar{c}\gamma^\mu P_L b) (\bar{\tau}\gamma_\mu P_L \nu_\tau), \\ \mathcal{O}_{V_R} &= (\bar{c}\gamma^\mu P_R b) (\bar{\tau}\gamma_\mu P_L \nu_\tau), \\ \mathcal{O}_{S_L} &= (\bar{c}P_L b) (\bar{\tau}P_L \nu_\tau), \\ \mathcal{O}_{S_R} &= (\bar{c}P_R b) (\bar{\tau}P_L \nu_\tau), \\ \mathcal{O}_{T_L} &= (\bar{c}\sigma^{\mu\nu} P_L b) (\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau).\end{aligned}$$

Here,  $\sigma_{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$ ,  $P_{L,R} = (1 \mp \gamma_5)/2$  are the left and right projection operators, and  $V_{L,R}$ ,  $S_{L,R}$ , and  $T_L$  are the complex Wilson coefficients governing the NP contributions. In the SM one has  $V_{L,R} = S_{L,R} = T_L = 0$ . We assume that NP only affects leptons of the third generation.

## Matrix element

The invariant matrix element of  $\bar{B}^0 \rightarrow D^{(*)} \tau \bar{\nu}_\tau$  can be written as

$$\begin{aligned} \mathcal{M} = & \frac{G_F V_{cb}}{\sqrt{2}} \left[ (1 + V_R + V_L) \langle D^{(*)} | \bar{c} \gamma^\mu b | \bar{B}^0 \rangle \bar{\tau} \gamma_\mu (1 - \gamma^5) \nu_\tau \right. \\ & + (V_R - V_L) \langle D^{(*)} | \bar{c} \gamma^\mu \gamma^5 b | \bar{B}^0 \rangle \bar{\tau} \gamma_\mu (1 - \gamma^5) \nu_\tau \\ & + (S_R + S_L) \langle D^{(*)} | \bar{c} b | \bar{B}^0 \rangle \bar{\tau} (1 - \gamma^5) \nu_\tau \\ & + (S_R - S_L) \langle D^{(*)} | \bar{c} \gamma^5 b | \bar{B}^0 \rangle \bar{\tau} (1 - \gamma^5) \nu_\tau \\ & \left. + T_L \langle D^{(*)} | \bar{c} \sigma^{\mu\nu} (1 - \gamma^5) b | \bar{B}^0 \rangle \bar{\tau} \sigma_{\mu\nu} (1 - \gamma^5) \nu_\tau \right]. \end{aligned}$$

Note that the axial and pseudoscalar hadronic currents do not contribute to the  $\bar{B}^0 \rightarrow D$  transition, while the scalar hadronic current does not contribute to the  $\bar{B}^0 \rightarrow D^*$  transition.

## Form factors

Hadronic matrix elements are parametrized by a set of form factors:

$$\langle D(p_2) | \bar{c} \gamma^\mu b | \bar{B}^0(p_1) \rangle = F_+(q^2) P^\mu + F_-(q^2) q^\mu,$$

$$\langle D(p_2) | \bar{c} b | \bar{B}^0(p_1) \rangle = (m_1 + m_2) F^S(q^2),$$

$$\langle D(p_2) | \bar{c} \sigma^{\mu\nu} (1 - \gamma^5) b | \bar{B}^0(p_1) \rangle = \frac{i F^T(q^2)}{m_1 + m_2} \left( P^\mu q^\nu - P^\nu q^\mu + i \varepsilon^{\mu\nu\rho\sigma} P^\rho q^\sigma \right),$$

for the  $\bar{B}^0 \rightarrow D$  transition, and

$$\langle D^*(p_2) | \bar{c} \gamma^\mu (1 \mp \gamma^5) b | \bar{B}^0(p_1) \rangle$$

$$= \frac{\epsilon_{2\alpha}^\dagger}{m_1 + m_2} \left( \mp g^{\mu\alpha} P^\rho A_0(q^2) \pm P^\mu P^\alpha A_+(q^2) \pm q^\mu P^\alpha A_-(q^2) + i \varepsilon^{\mu\alpha\rho\sigma} P^\rho q^\sigma V(q^2) \right),$$

$$\langle D^*(p_2) | \bar{c} \gamma^5 b | \bar{B}^0(p_1) \rangle = \epsilon_{2\alpha}^\dagger P^\alpha G^S(q^2),$$

$$\begin{aligned} \langle D^*(p_2) | \bar{c} \sigma^{\mu\nu} (1 - \gamma^5) b | \bar{B}^0(p_1) \rangle = & -i \epsilon_{2\alpha}^\dagger \left[ \left( P^\mu g^{\nu\alpha} - P^\nu g^{\mu\alpha} + i \varepsilon^{\mu\nu\rho\sigma} P^\rho q^\sigma \right) G_1^T(q^2) \right. \\ & \left. + \left( q^\mu g^{\nu\alpha} - q^\nu g^{\mu\alpha} + i \varepsilon^{\mu\nu\rho\sigma} q^\rho q^\sigma \right) G_2^T(q^2) \right. \\ & \left. + \left( P^\mu q^\nu - P^\nu q^\mu + i \varepsilon^{\mu\nu\rho\sigma} P^\rho q^\sigma \right) P^\alpha \frac{G_0^T(q^2)}{(m_1 + m_2)^2} \right], \end{aligned}$$

for the  $\bar{B}^0 \rightarrow D^*$  transition. Here,  $P = p_1 + p_2$ ,  $q = p_1 - p_2$ , and  $\epsilon_2$  is the polarization vector of the  $D^*$  meson so that  $\epsilon_2^\dagger \cdot p_2 = 0$ . The particles are on their mass shells:  $p_1^2 = m_1^2 = m_B^2$  and  $p_2^2 = m_2^2 = m_{D^*}^2$ .



## Covariant Confined Quark Model in a nutshell

G. V. Efimov, M. A. Ivanov, V. E. Lyubovitskij, J. G. Körner, P. Santorelli, ...

- Main assumption: **hadrons interact via quark exchange only**
- Interaction Lagrangian

$$\mathcal{L}_{\text{int}} = g_H \cdot \mathbf{H}(x) \cdot \mathbf{J}_H(x)$$

- Quark current

$$\mathbf{J}_H(x) = \int dx_1 \int dx_2 \mathbf{F}_H(x; x_1, x_2) \cdot \bar{q}_{f_1}^a(x_1) \Gamma_H q_{f_2}^a(x_2)$$

- Vertex Function

$$\mathbf{F}_H(x; x_1, x_2) = \delta(x - w_1 x_1 - w_2 x_2) \Phi_H((x_1 - x_2)^2)$$

where  $w_i = m_{q_i} / (m_{q_1} + m_{q_2})$

Translational invariant:  $\mathbf{F}_H(x + c; x_1 + c, x_2 + c) = \mathbf{F}_H(x; x_1, x_2)$

- Nonlocal Gaussian-type vertex functions with fall-off behavior in Euclidean space to temper high energy divergence of quark loops

$$\tilde{\Phi}_H(-k^2) = \int dx e^{ikx} \Phi_H(x^2) = e^{k^2/\Lambda_H^2}$$

where  $\Lambda_H$  characterizes the meson size.

## Covariant Confined Quark Model in a nutshell

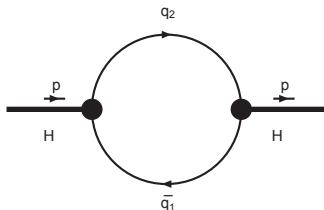
- Compositeness condition  $Z_H = 0$

Salam 1962; Weinberg 1963

$Z_H$  – wave function renormalization constant of the meson H.

$$Z_H^{1/2} = \langle H_{\text{bare}} | H_{\text{dressed}} \rangle = 0$$

- $Z_H = 1 - \tilde{\Pi}'(m_H^2) = 0$  where  $\tilde{\Pi}(p^2)$  is the meson mass operator.



$$\Pi_P(p) = 3g_P^2 \int \frac{dk}{(2\pi)^4 i} \tilde{\Phi}_P^2(-k^2) \text{tr}[S_1(k+w_1p)\gamma^5 S_2(k-w_2p)\gamma^5]$$

$$\Pi_V(p) = g_V^2 \left[ g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2} \right] \int \frac{dk}{(2\pi)^4 i} \tilde{\Phi}_V^2(-k^2) \text{tr}[S_1(k+w_1p)\gamma_\mu S_2(k-w_2p)\gamma_\nu]$$

## The matrix elements

- Matrix elements are described by a set of Feynman diagrams which are convolutions of quark propagators and vertex functions.
- Let  $\Pi$  be the matrix element corresponding to the Feynman diagram:

$j$  external momenta;

$n$  quark propagators;

$\ell$  loop integrations;

$m$  vertices.

In the momentum space it will be represented as

$$\Pi(p_1, \dots, p_j) = \int [d^4 k]^\ell \prod_{i_1=1}^m \Phi_{i_1+n}(-K_{i_1+n}^2) \prod_{i_3=1}^n S_{i_3}(\tilde{k}_{i_3} + \tilde{p}_{i_3})$$

$$K_{i_1+n}^2 = \sum_{i_2} (\tilde{k}_{i_1+n}^{(i_2)} + \tilde{p}_{i_1+n}^{(i_2)})^2$$

$\tilde{k}_i$  are linear combinations of the loop momenta  $k_i$

$\tilde{p}_i$  are linear combinations of the external momenta  $p_i$

- Use the Schwinger representation of the propagator:

$$\frac{m + \not{k}}{m^2 - k^2} = (m + \not{k}) \int_0^\infty d\alpha \exp[-\alpha(m^2 - k^2)]$$

- Choose a simple Gaussian form for the vertex function

$$\Phi(-K^2) = \exp(K^2/\Lambda^2)$$

where the parameter  $\Lambda$  characterizes the hadron size.

- We imply that the loop integration  $k$  proceed over Euclidean space:

$$k^0 \rightarrow e^{i\frac{\pi}{2}} k_4 = ik_4, \quad k^2 = (k^0)^2 - \vec{k}^2 \rightarrow -k_E^2 \leq 0.$$

- We also put all external momenta  $p$  to Euclidean space:

$$p^0 \rightarrow e^{i\frac{\pi}{2}} p_4 = ip_4, \quad p^2 = (p^0)^2 - \vec{p}^2 \rightarrow -p_E^2 \leq 0$$

so that the quadratic momentum form in the exponent becomes negative-definite and the loop integrals are absolutely convergent.

- Convert the loop momenta in the numerator into derivatives over external momenta:

$$k_i^\mu e^{2kr} = \frac{1}{2} \frac{\partial}{\partial r_{i\mu}} e^{2kr},$$

- Move the derivatives outside of the loop integrals.
- Calculate the scalar loop integral:

$$\prod_{i=1}^n \int \frac{d^4 k_i}{i\pi^2} e^{k_i A k_i + 2k_i r} = \prod_{i=1}^n \int \frac{d^4 k_i^E}{\pi^2} e^{-k_{iE} A k_{iE} - 2k_{iE} r^E} = \frac{1}{|A|^2} e^{-r A^{-1} r}$$

where a symmetric  $n \times n$  real matrix  $A$  is positive-definite.

- Use the identity

$$P \left( \frac{1}{2} \frac{\partial}{\partial r} \right) e^{-r A^{-1} r} = e^{-r A^{-1} r} P \left( \frac{1}{2} \frac{\partial}{\partial r} - A^{-1} r \right)$$

to move the exponent to the left.

- **Employ the commutator**

$$\left[ \frac{\partial}{\partial r_{i\mu}}, r_{j\nu} \right] = \delta_{ij} g_{\mu\nu}$$

to make differentiation in

$$P \left( \frac{1}{2} \frac{\partial}{\partial r} - A^{-1} r \right)$$

for any polynomial **P**. The necessary commutations of the differential operators are done by a FORM program.

- **One obtains**

$$\Pi = \int_0^\infty d^n \alpha F(\alpha_1, \dots, \alpha_n),$$

where **F** stands for the whole structure of a given diagram.

## Infrared confinement

One obtains 
$$\Pi = \int_0^{\infty} d^n \alpha F(\alpha_1, \dots, \alpha_n),$$

where **F** stands for the whole structure of a given diagram. The set of Schwinger parameters  $\alpha_i$  can be turned into a simplex by introducing an additional **t**-integration via the identity

$$1 = \int_0^{\infty} dt \delta(t - \sum_{i=1}^n \alpha_i)$$

$$\Pi = \int_0^{\infty} dt t^{n-1} \int_0^1 d^n \alpha \delta\left(1 - \sum_{i=1}^n \alpha_i\right) F(t\alpha_1, \dots, t\alpha_n).$$

Cut off the upper integration at  $1/\lambda^2$

$$\Pi^c = \int_0^{1/\lambda^2} dt t^{n-1} \int_0^1 d^n \alpha \delta\left(1 - \sum_{i=1}^n \alpha_i\right) F(t\alpha_1, \dots, t\alpha_n)$$

The infrared cut-off has removed all possible thresholds in the quark loop diagram.

## Form factors

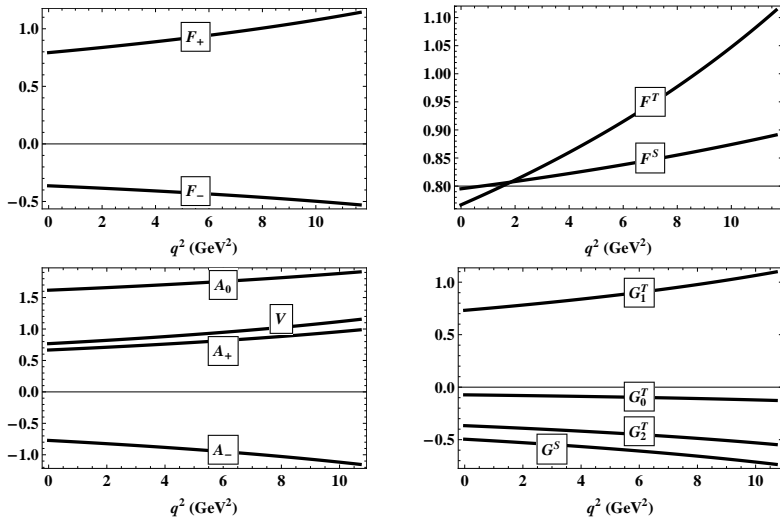


Figure : Form factors of the transitions  $\bar{\mathbf{B}}^0 \rightarrow \mathbf{D}$  (upper panels) and  $\bar{\mathbf{B}}^0 \rightarrow \mathbf{D}^*$  (lower panels) in the full momentum transfer range  $0 \leq q^2 \leq q_{\max}^2 = (m_{\bar{\mathbf{B}}^0} - m_{\mathbf{D}^{(*)}})^2$ .



## Form factors

- Dipole interpolation

$$F(q^2) = \frac{F(0)}{1 - as + bs^2}, \quad s = \frac{q^2}{m_{D^{(*)}}^2}.$$

- The dipole interpolation works very well for all form factors

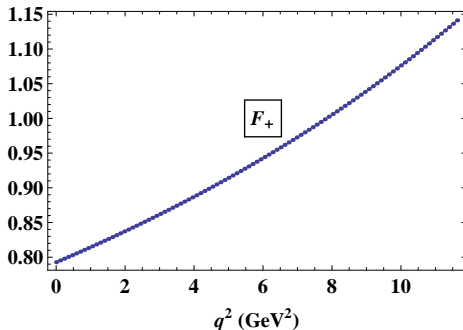
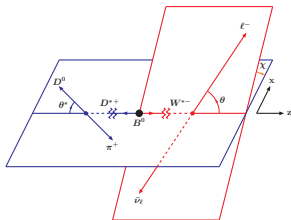


Figure : Comparison of  $F_+(q^2)$  form factor for  $\bar{B}^0 \rightarrow D$  transition calculated by FORTRAN code (dotted) with the interpolation (solid).

The parameters of the dipole interpolation are listed in the following tables:

	$F_+$	$F_-$	$F^S$	$F^T$
$F(0)$	0.79	-0.36	0.80	0.77
a	0.75	0.77	0.22	0.76
b	0.039	0.046	-0.098	0.043

	$A_0$	$A_+$	$A_-$	$V$	$G^S$	$G_0^T$	$G_1^T$	$G_2^T$
$F(0)$	1.62	0.67	-0.77	0.77	-0.50	-0.073	0.73	-0.37
a	0.34	0.87	0.89	0.90	0.87	1.23	0.90	0.88
b	-0.16	0.057	0.070	0.075	0.060	0.33	0.074	0.064

The  $\bar{B}^0 \rightarrow D^{*+}(\rightarrow D^0\pi^+)\tau^-\bar{\nu}_\tau$  four-fold distribution

One has

$$\frac{d^4\Gamma(\bar{B}^0 \rightarrow D^{*+}(\rightarrow D^0\pi^+)\tau^-\bar{\nu}_\tau)}{dq^2 d\cos\theta d\chi d\cos\theta^*} = \frac{9}{8\pi} |N|^2 J(\theta, \theta^*, \chi),$$

where

$$|N|^2 = \frac{G_F^2 |V_{cb}|^2 |p_2| q^2 v^2}{(2\pi)^3 12m_1^2} \mathcal{B}(D^* \rightarrow D\pi).$$

## The three-angle distribution

The full angular distribution  $J(\theta, \theta^*, \chi)$  is written as

$$\begin{aligned}
 J(\theta, \theta^*, \chi) &= J_{1s} \sin^2 \theta^* + J_{1c} \cos^2 \theta^* + (J_{2s} \sin^2 \theta^* + J_{2c} \cos^2 \theta^*) \cos 2\theta \\
 &\quad + J_3 \sin^2 \theta^* \sin^2 \theta \cos 2\chi + J_4 \sin 2\theta^* \sin 2\theta \cos \chi \\
 &\quad + J_5 \sin 2\theta^* \sin \theta \cos \chi + (J_{6s} \sin^2 \theta^* + J_{6c} \cos^2 \theta^*) \cos \theta \\
 &\quad + J_7 \sin 2\theta^* \sin \theta \sin \chi + J_8 \sin 2\theta^* \sin 2\theta \sin \chi + J_9 \sin^2 \theta^* \sin^2 \theta \sin 2\chi,
 \end{aligned}$$

where  $J_{i(a)}$  ( $i = 1, \dots, 9$ ;  $a = s, c$ ) are coefficient functions depending on  $q^2$ , the form factors and the NP couplings.

## Experimental constraints on $R(D^{(*)})$

Firstly, integrating it over all angles one obtains

$$\frac{d\Gamma(\bar{B}^0 \rightarrow D^{*} \tau^{-} \bar{\nu}_{\tau})}{dq^2} = |N|^2 J_{\text{tot}} = |N|^2 (J_L + J_T),$$

where  $J_L$  and  $J_T$  are the longitudinal and transverse polarization amplitudes of the  $D^*$  meson, and given by

$$J_L = 3J_{1c} - J_{2c}, \quad J_T = 2(3J_{1s} - J_{2s}).$$

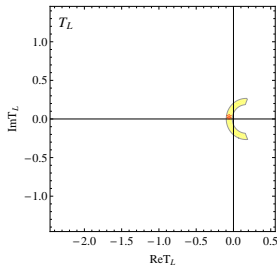
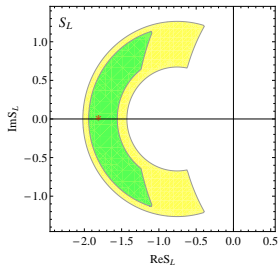
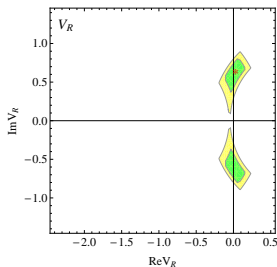
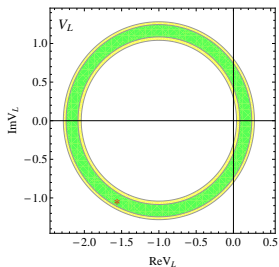
Then we calculate the ratios

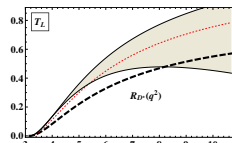
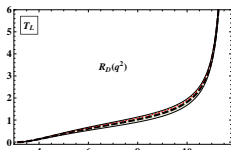
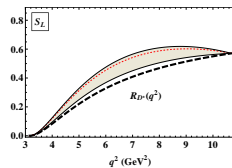
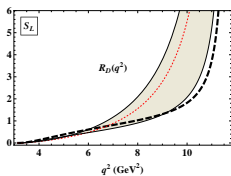
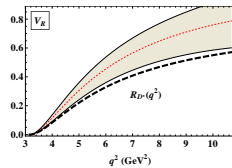
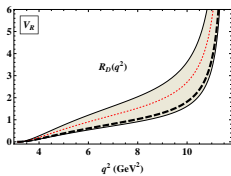
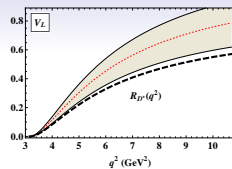
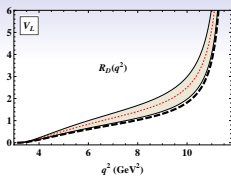
$$R_{D^{(*)}}(q^2) = \frac{d\Gamma(\bar{B}^0 \rightarrow D^{(*)} \tau^{-} \bar{\nu}_{\tau})}{dq^2} \bigg/ \frac{d\Gamma(\bar{B}^0 \rightarrow D^{(*)} \mu^{-} \bar{\nu}_{\mu})}{dq^2}.$$

and compare with experiments to find the constraints on the space of NP couplings.

## Allowed regions for NP couplings

Assuming that besides the SM contribution, **only one of the NP operators is switched on at a time**, and NP only affects the tau modes.





## $\cos \theta$ distribution, forward-backward asymmetry & lepton-side convexity

The normalized form of the  $\cos \theta$  distribution reads

$$\tilde{J}(\theta) = \frac{a + b \cos \theta + c \cos^2 \theta}{2(a + c/3)}.$$

The linear coefficient  $b/2(a + c/3)$  can be projected out by defining a forward-backward asymmetry given by

$$\mathcal{A}_{\text{FB}}(q^2) = \frac{(\int_0^1 - \int_{-1}^0) d \cos \theta d\Gamma/d \cos \theta}{(\int_0^1 + \int_{-1}^0) d \cos \theta d\Gamma/d \cos \theta} = \frac{b}{2(a + c/3)} = \frac{3}{2} \frac{J_{6c} + 2J_{6s}}{J_{\text{tot}}},$$

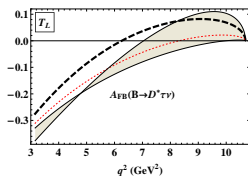
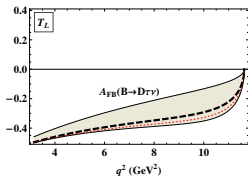
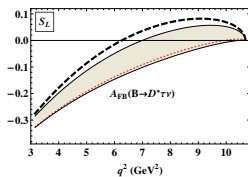
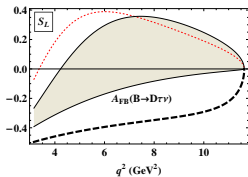
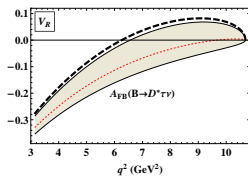
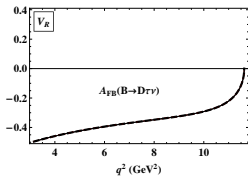
where  $J_{\text{tot}} = 3J_{1c} + 6J_{1s} - J_{2c} - 2J_{2s}$ .

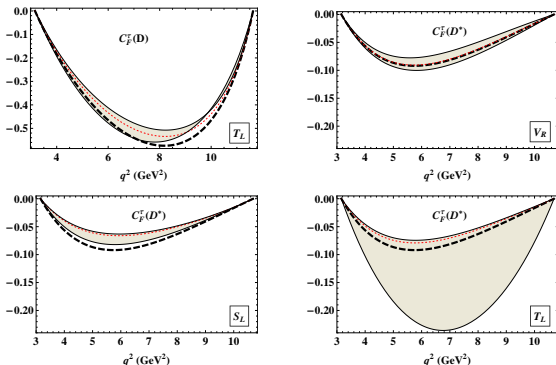
The quadratic coefficient  $c/2(a + c/3)$  is obtained by taking the second derivative of  $\tilde{J}(\theta)$ . Accordingly, we define a convexity parameter as follows:

$$C_F^{\tau}(q^2) = \frac{d^2 \tilde{J}(\theta)}{d(\cos \theta)^2} = \frac{c}{a + c/3} = \frac{6(J_{2c} + 2J_{2s})}{J_{\text{tot}}}.$$



# Forward-backward asymmetry $\mathcal{A}_{FB}(q^2)$



Lepton-side convexity  $C_F^T(q^2)$ 

and many more angular observables can be defined from the  $\cos \theta^*$  and  $\chi$  distributions which can help discriminate between different NP scenarios...

## Summary and discussion

- **We have provided a thorough analysis of possible NP in the semileptonic decays  $\bar{B}^0 \rightarrow D^{(*)-} \tau^- \bar{\nu}_\tau$  using the form factors obtained from our covariant quark model.**
- **Our analysis can serve as a map for setting up various strategies to identify the origins of NP. In the future when more precise data will be collected, one can adopt the strategies described here as a useful tool to discover NP in these decays if the deviation from the SM still remains.**