Weak decays of B meson and charmonium in the light of the search for new physics

(Based on PhD Thesis)

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What I will present today

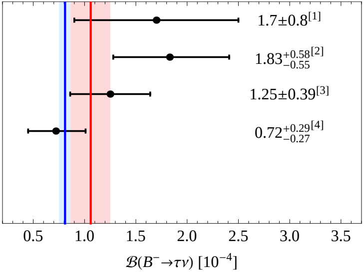
1. **Leptonic decays of B meson: $B^- \to \ell^- \bar{\nu}_\ell$, where $\ell = e, \mu, \tau$**
2. **Semileptonic decays of B meson: $\bar{B}^0 \to D^* \ell \bar{\nu}_\ell$ and $\bar{B}^0 \to D \ell \bar{\nu}_\ell$**
3. **Possible New Physics (NP) in decays $B \to D^{(*)} \tau \nu_\tau$**
4. **Tau plarization as probe for NP in decays $B \to D^{(*)} \tau \nu_\tau$**
5. **Semileptonic decays of charmonium:**

   $J/\psi \to D^- \ell \nu_\ell, \quad J/\psi \to D^{*-} \ell \nu_\ell,$

   $J/\psi \to D_s^- \ell \nu_\ell, \quad J/\psi \to D_s^{*-} \ell \nu_\ell.$
6. **Covariant Confined Quark Model (CCQM): tool for hadronic calculation**

Why study (semi)leptonic B decays?

- **Testing the Standard Model**
- **CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$**
- **Leptonic decay constant f_B and form factors of hadronic transitions**
- **Possible New Physics (NP) beyond the SM**



- **Experiments:**

  [1] BABAR semilep. tag [3] Belle semilep. tag

  [2] BABAR had. tag [4] Belle had. tag

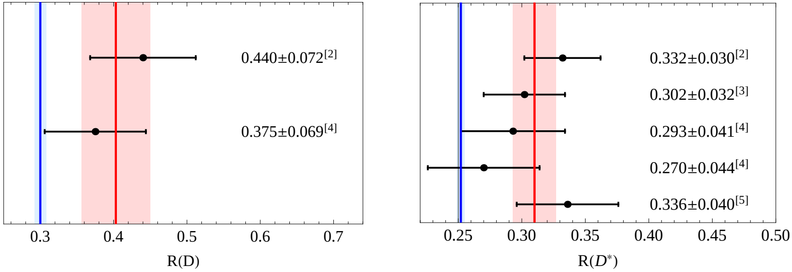
  [ArXiv:0912.2453, 1207.0698, 1503.05613, 1208.4678]

  Average: $\mathcal{B}(B^- \to \tau\bar{\nu}) = (1.09 \pm 0.24) \times 10^{-4}$ [HFAG, 17]

- **SM prediction: $(0.81 \pm 0.06) \times 10^{-4}$** [UTfit Collab.]

Why study (semi)leptonic B decays?

Ratios of branching fractions $R(D^{(*)}) \equiv \dfrac{\mathcal{B}(\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{(*)}\mu^-\bar{\nu}_\mu)}$



[2] BABAR had. tag [3] Belle semilep. tag [4] Belle had. tag [5] LHCb

- **Average ratios**

$$R(D)|_{\rm expt} = 0.403 \pm 0.047, \qquad R(D^*)|_{\rm expt} = 0.310 \pm 0.017,$$

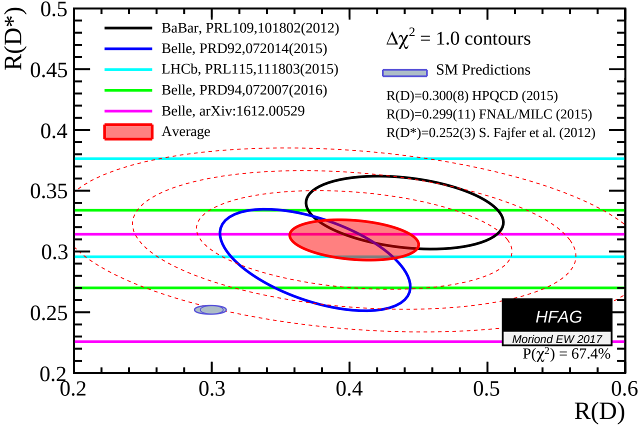
- **SM expectations**

$$R(D)|_{\rm SM} = 0.300 \pm 0.008, \qquad R(D^*)|_{\rm SM} = 0.252 \pm 0.003,$$

$\rightarrow$ **SM excess: 1.9 σ and 3.2 σ, respectively.**

Why study (semi)leptonic B decays?

$R(D)$-$R(D^*)$ correlation: SM excess $\approx 4\,\sigma$



Theoretical attempts to explain the excess:

- **Specific NP models: two-Higgs-doublet models (2HDMs), Minimal Supersymmetric Standard Model (MSSM), Leptoquark models, etc.**
- **Model-independent approach: impose general SM+NP effective Hamiltonian for transition $b \to c\ell\bar{\nu}$ (*this work!*).**

Covariant Confined Quark Model

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

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

$$\mathcal{L}_{\rm int} = g_H \cdot H(x) \cdot J_H(x)$$

- **Quark current**

$$J_H(x) = \int dx_1 \int dx_2\, F_H(x; x_1, x_2) \cdot \bar{q}^a_{f_1}(x_1)\, \Gamma_H\, q^a_{f_2}(x_2)$$

- **Vertex Function**

$$F_H(x; x_1, x_2) = \delta(x - w_1 x_1 - w_2 x_2)\, \Phi_H((x_1 - x_2)^2)$$

where $w_i = m_{q_i}/(m_{q_1} + m_{q_2})$
Translational invariant: $F_H(x + c; x_1 + c, x_2 + c) = F_H(x; x_1, x_2)$

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

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

where Λ_H characterizes the meson size.

Compositeness condition

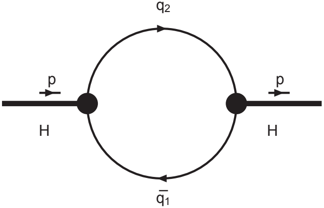
- **Compositeness condition** $Z_H = 0$

Salam 1962; Weinberg 1963

Z_H – wave function renormalization constant of the meson H.

$$Z_H^{1/2} = < H_{\rm bare} | H_{\rm dressed} > = 0$$

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



$$\Pi_P(p) = 3g_P^2 \int \frac{dk}{(2\pi)^4 i} \widetilde{\Phi}_P^2(-k^2) \mathrm{tr}[S_1(k + w_1 p)\gamma^5 S_2(k - w_2 p)\gamma^5]$$

$$\Pi_V(p) = g_V^2 [g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}] \int \frac{dk}{(2\pi)^4 i} \widetilde{\Phi}_V^2(-k^2) \mathrm{tr}\,[S_1(k + w_1 p)\gamma_\mu S_2(k - w_2 p)\gamma_\nu]$$

Matrix elements

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

j **external momenta;**
n **quark propagators;**
ℓ **loop integrations;**
m **vertices.**
In the momentum space it will be represented as

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

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

$\tilde{k}_i$ **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:

$$\frac{m+\not{k}}{m^2-k^2} = (m+\not{k})\int\limits_0^\infty d\alpha\,\exp[-\alpha(m^2-k^2)]$$

- Choose a simple Gaussian form for the vertex function

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

where the parameter Λ characterizes the hadron size.

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

$$k^0 \to e^{i\frac{\pi}{2}}k_4 = ik_4\,, \qquad k^2 = (k^0)^2 - \vec{k}^2 \to -k_E^2 \le 0\,.$$

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

$$p^0 \to e^{i\frac{\pi}{2}}p_4 = ip_4\,, \qquad p^2 = (p^0)^2 - \vec{p}^2 \to -p_E^2 \le 0$$

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:

$$\prod_{i=1}^{n}\int \frac{d^4k_i}{i\pi^2} e^{kAk+2kr} = \prod_{i=1}^{n}\int \frac{d^4k_i^E}{\pi^2} e^{-k_E A k_E - 2k_E r_E} = \frac{1}{|A|^2} e^{-rA^{-1}r}$$

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

- Use the identity

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

to move the exponent to the left.

- Employ the commutator

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

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

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

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

Infrared confinement & Model parameters

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

where F stands for the whole structure of a given diagram. The set of Schwinger parameters α_i can be turned into a simplex by introducing an additional t–integration via the identity $1 = \int_0^\infty dt\,\delta(t - \sum_{i=1}^n \alpha_i)$

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

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

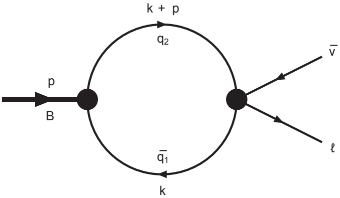
$$\Pi^c = \int_0^{1/\lambda^2} dt t^{n-1} \int_0^1 d^n\alpha\,\delta\Big(1 - \sum_{i=1}^n \alpha_i\Big)\, F(t\alpha_1,\ldots,t\alpha_n)$$

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

MODEL PARAMETERS:

$m_{u/d}$	m_s	m_c	m_b	Λ_{D^*}	$\Lambda_{D_s^*}$	Λ_D	Λ_{D_s}	$\Lambda_{J/\psi}$	Λ_B	λ
0.241	0.428	1.67	5.04	1.53	1.56	1.60	1.75	1.74	1.96	0.181

Leptonic decays of B meson



$$\frac{3g}{4\pi^2}\int\frac{d^4k}{4\pi^2 i}\widetilde{\Phi}(-k^2)\mathrm{tr}\left[O^\mu S_1(k+w_1p)\gamma^5 S_2(k-w_2p)\right] = f_P p^\mu$$

$$\frac{3g}{4\pi^2}\int\frac{d^4k}{4\pi^2 i}\widetilde{\Phi}(-k^2)\mathrm{tr}\left[O^\mu S_1(k+w_1p)\not\epsilon_V S_2(k-w_2p)\right] = f_V m_V \epsilon_V^\mu$$

Leptonic decay constants (all in MeV)

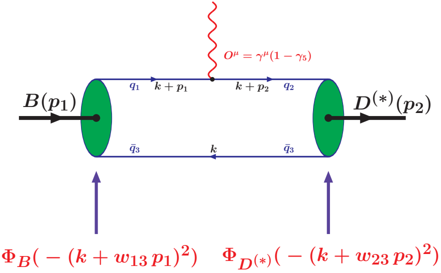
	This work	Other	Ref.
f_B	193.1	190.6±4.7	PDG 2014
f_{B_s}	238.7	242.0(9.5)	LAT [Bazavov:2011]
		259(32)	HPQCD LAT [Gray:2005]
f_{B_c}	489.0	$489 \pm 4 \pm 3$	LAT [Chiu:2007km]
f_{B^*}	196.0	$196(24)^{+39}_{-2}$	LAT [Becirevic:1998]
		186.4 ± 3.2	QCDSR [Lucha:2014]
$f_{B_s^*}$	229.0	$229(20)^{+41}_{-16}$	LAT [Becirevic:1998ua]
		215.2 ± 3.0	QCD SR [Lucha:2014nba]
f_{B_s}/f_B	1.236	1.20(3)(1)	HPQCD LAT [Gray:2005]
		1.229(26)	LAT [Bazavov:2011]
f_D	206.1	204.6±5.0	PDG 2014
f_{D^*}	244.3	$278 \pm 13 \pm 10$	LAT [Becirevic:2012]
		$245(20)^{+3}_{-2}$	LAT [Becirevic:1998]
		$252.2 \pm 22.3 \pm 4$	QCD SR [Lucha:2014]
f_{D_s}	257.5	257.5±4.6	PDG 2014
$f_{D_s^*}$	272.0	311±9	LAT [Becirevic:2012]
		$272(16)^{+3}_{-20}$	LAT [Becirevic:1998]
		$305.5 \pm 26.8 \pm 5$	QCD SR [Lucha:2014]
f_{D_s}/f_D	1.249	1.258±0.038	PDG 2014
$f_{D_s^*}/f_{D^*}$	1.113	1.16±0.02±0.06	LAT [Becirevic:2012]
$f_{J/\psi}$	415.0	418±9	LAT & QCD SR [Becirevic:2013]

Branching fractions of leptonic B decays

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell)\Big|_{\rm SM} = \frac{\Gamma(B^- \to \ell^- \bar{\nu}_\ell)}{\Gamma_{tot}} = \frac{G_F^2}{8\pi} m_B m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

	This work	Data	Ref.
$B^- \to e^- \bar{\nu}_e$	$1.16 \cdot 10^{-11}$	$< 0.98 \cdot 10^{-6}$	PDG
		$(0.88 \pm 0.12) \cdot 10^{-11}$	UTfit
		$(0.90 \pm 0.12) \cdot 10^{-11}$	CKMfitter
$B^- \to \mu^- \bar{\nu}_\mu$	$0.49 \cdot 10^{-6}$	$< 1.0 \cdot 10^{-6}$	PDG
		$(0.38 \pm 0.05) \cdot 10^{-6}$	UTfit
		$(0.38 \pm 0.05) \cdot 10^{-6}$	CKMfitter
$B^- \to \tau^- \bar{\nu}_\tau$	$1.10 \cdot 10^{-4}$	$(1.06 \pm 0.19) \cdot 10^{-4}$	PDG
		$(0.81 \pm 0.06) \cdot 10^{-4}$	UTfit
		$(0.85 \pm 0.12) \cdot 10^{-4}$	CKMfitter

Semileptonic decays of B meson

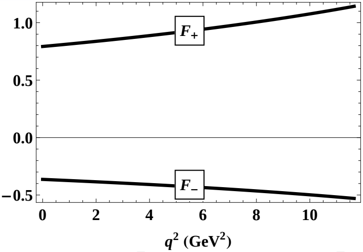


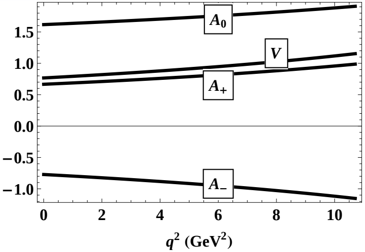
$$
\begin{aligned}
\langle D(p_2)|\bar{c}O^\mu b|B(p_1)\rangle &\equiv T^\mu = \\
= \quad & N_c\, g_B\, g_D \int \frac{d^4k}{(2\pi)^4 i} \times \\
\times \quad & \widetilde{\Phi}_B\Big(-(k+w_{13}p_1)^2\Big)\, \widetilde{\Phi}_D\Big(-(k+w_{23}p_2)^2\Big) \\
\times \quad & \mathrm{tr}\Big[O^\mu\, S_1(k+p_1)\, \gamma^5\, S_3(k)\, \gamma^5\, S_2(k+p_2)\Big] \\
= \quad & F_+(q^2) P^\mu + F_-(q^2) q^\mu,
\end{aligned}
$$

$$
\begin{aligned}
\langle D^*(p_2,\epsilon_2)\,|\,\bar{c}\,O^\mu\,b\,|\,B(p_1)\rangle &\equiv T^\mu = \\
= \quad & N_c\, g_B\, g_{D^*} \int \frac{d^4k}{(2\pi)^4 i}\, \widetilde{\Phi}_B\Big(-(k+w_{13}p_1)^2\Big)\, \widetilde{\Phi}_{D^*}\Big(-(k+w_{23}p_2)^2\Big) \\
\times \quad & \mathrm{tr}\Big[O^\mu\, S_1(k+p_1)\, \gamma^5\, S_3(k)\, \not\epsilon^{\,\dagger}\, S_2(k+p_2)\Big] \\
= \quad & \frac{\epsilon^\dagger_\alpha}{m_1+m_2}\Big(-g^{\mu\alpha} Pq A_0(q^2) + P^\mu P^\alpha A_+(q^2) + q^\mu P^\alpha A_-(q^2) + i\varepsilon^{\mu\alpha Pq} V(q^2)\Big),
\end{aligned}
$$

Where $P = p_1 + p_2$, $q = p_1 - p_2$, and ϵ_2 - polarization vector of D^* so that $\epsilon_2^\dagger \cdot p_2 = 0$. The particles are on-shell: $p_1^2 = m_1^2 = m_B^2$, $p_2^2 = m_2^2 = m_{D^{(*)}}^2$.

Form factors



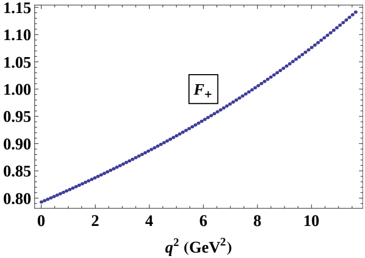


Form factors for $\bar{B}^0 \to D$ (left) and $\bar{B}^0 \to D^*$ (right) in the full momentum transfer range $0 \le q^2 \le q^2_{max} = (m_{\bar{B}^0} - m_{D^{(*)}})^2$.

- **Dipole interpolation**

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

- **The dipole interpolation works very well for all form factors:**
  dotted: calculated by FORTRAN
  solid: interpolation



The parameters of the dipole interpolation $F(q^2) = \dfrac{F(0)}{1 - as + bs^2}$:

	F_+	F_-	A_0	A_+	A_-	V
$F(0)$	0.78	−0.36	1.62	0.67	−0.77	0.77
a	0.74	0.76	0.34	0.87	0.89	0.90
b	0.038	0.046	−0.16	0.057	0.070	0.075
$F(q^2_{\rm max})$	1.14	−0.53	1.91	0.99	−1.15	1.15
$F^{HQL}(q^2_{\rm max})$	1.14	−0.54	1.99	1.12	−1.12	1.12

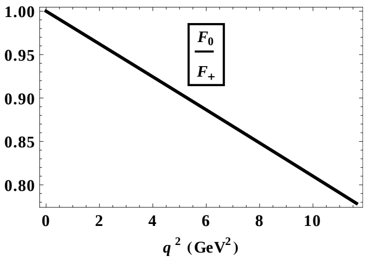
Linear q^2 behavior [Becirevic:2012]

$$F_0(q^2) = F_+(q^2) + \frac{q^2}{Pq} F_-(q^2)$$

$$\frac{F_0(q^2)}{F_+(q^2)} = 1 - \alpha q^2,$$

where the slope $\alpha = 0.020(1)\ \mathrm{GeV}^{-2}$ based on lattice results of the two FFs.

Our value: $\alpha = 0.019\ \mathrm{GeV}^{-2}$.



Decay distribution and Helicity basis

$$\frac{d\Gamma}{dq^2 d\cos\theta} = \frac{|\mathbf{p}_2|\, v}{(2\pi)^3\, 32\, m_1^2} \cdot \sum_{\rm pol} |M|^2 = \frac{G_F^2}{(2\pi)^3} |V_{cb}|^2 \frac{|\mathbf{p}_2|\, v}{64 m_1^2} H^{\mu\nu} L_{\mu\nu}\,,$$

where $|\mathbf{p}_2| = \lambda^{1/2}(m_1^2, m_2^2, q^2)/2m_1$, $v = 1 - m_\ell^2/q^2$ and θ - polar angle between $\vec{q} = \vec{p}_1 - \vec{p}_2$ and $\vec{p}_\ell$ in the CM system $(\ell^- \bar{\nu}_\ell)$.

$$L_{\mu\nu} = \mathrm{tr}\,[(\not k_1 + m_\ell) O_\mu \not k_2 O_\nu] = 8\left(k_{1\mu}k_{2\nu} + k_{1\nu}k_{2\mu} - k_1 k_2 g_{\mu\nu} + i\varepsilon_{\mu\nu\alpha\beta} k_1^\alpha k_2^\beta\right)$$

$$H^{\mu\nu} = T^\mu T^{\dagger\nu}.$$

The Lorentz contraction can be evaluated in terms of helicity amplitudes. First, we define an orthonormal and complete helicity basis $\epsilon^\mu(m)$ with three spin 1 components orthogonal to the momentum transfer q^μ, i.e. $\epsilon^\mu(m) q_\mu = 0$ for $m = \pm, 0$, and one spin 0 (time)-component $m = t$ with $\epsilon^\mu(t) = q^\mu/\sqrt{q^2}$.

$$\epsilon^\dagger_\mu(m)\epsilon^\mu(n) = g_{mn} \quad (orthonormality)\,, \quad \epsilon_\mu(m)\epsilon^\dagger_\nu(n) g_{mn} = g_{\mu\nu} \quad (completeness)$$

$$H^{\mu\nu} L_{\mu\nu} = \sum_{m,m',n,n'} H(m,n) L(m',n') g_{mm'} g_{nn'}\,, \quad (m,m',n,n' = t,+,0,-)$$

$$L(m,n) = L^{\mu\nu}\epsilon_\mu(m)\epsilon^+_\nu(n)$$

$$H(m,n) = H^{\mu\nu}\epsilon^+_\mu(m)\epsilon_\nu(n)$$

$L(m,n)$ and $H(m,n)$ *now can be evaluated in different Lorentz systems:* $L(m,n)$ *- in the* $(\ell^-\bar{\nu}_\ell)$*-CM system whereas* $H(m,n)$ *- in the* B *rest system.*

Helicity Amplitudes

(a) $B \to D$:

$$H(m,n) = \left(\epsilon^{\dagger\mu}(m)T_\mu\right)\cdot\left(\epsilon^{\dagger\nu}(n)T_\nu\right)^\dagger \equiv H_m H_n^\dagger.$$

$$H_t = \frac{1}{\sqrt{q^2}}[(m_1^2 - m_2^2)F_+(q^2) + q^2 F_-(q^2)], \quad H_0 = \frac{2m_1|\mathbf{p}_2|}{\sqrt{q^2}}F_+(q^2), \quad H_\pm = 0$$

(b) $B \to D^*$:

$$\begin{aligned} H(m,n) &= \epsilon^{\dagger\mu}(m)\epsilon^\nu(n)H_{\mu\nu} = \epsilon^{\dagger\mu}(m)\epsilon^\nu(n)T_{\mu\alpha}\epsilon_2^{\dagger\alpha}(r)\epsilon_2^\beta(s)\delta_{rs}T^\dagger_{\beta\nu} \\ &= \epsilon^{\dagger\mu}(m)\epsilon_2^{\dagger\alpha}(r)T_{\mu\alpha}\cdot\left(\epsilon^{\dagger\nu}(n)\epsilon_2^{\dagger\beta}(s)T_{\nu\beta}\right)^\dagger\delta_{rs} \equiv H_{mr}H_{nr}^\dagger. \end{aligned}$$

$$H_t \equiv H_{t0} = \frac{1}{m_1+m_2}\frac{m_1|\mathbf{p}_2|}{m_2\sqrt{q^2}}[(m_1^2-m_2^2)(A_+(q^2)-A_0(q^2)) + q^2A_-(q^2)],$$

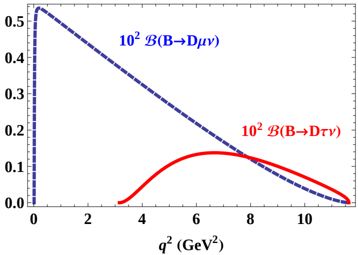
$$H_\pm \equiv H_{\pm\pm} = \frac{1}{m_1+m_2}[-(m_1^2-m_2^2)A_0(q^2) \pm 2m_1|\mathbf{p}_2|V(q^2)],$$

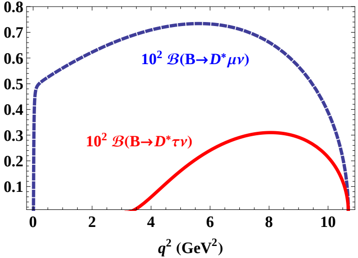
$$H_0 \equiv H_{00} = \frac{1}{m_1+m_2}\frac{1}{m_2\sqrt{q^2}}[(m_2^2-m_1^2)(m_1^2-m_2^2-q^2)A_0(q^2) + 4m_1^2|\mathbf{p}_2|^2A_+(q^2)]$$

Decay distribution in terms of Helicity amplitudes

$$\frac{d\Gamma(B \to D^{(*)}\ell^-\bar{\nu}_\ell)}{dq^2 d\cos\theta} = \frac{G_F^2|V_{cb}|^2|\mathrm{p}_2|q^2}{32(2\pi)^3 m_1^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2 \times$$
$$\times \Big\{(1-\cos\theta)^2|H_+|^2 + (1+\cos\theta)^2|H_-|^2) + 2\sin^2\theta|H_0|^2$$
$$+\frac{m_\ell^2}{q^2}\left[\sin^2\theta(|H_+|^2+|H_-|^2) + 2|H_t - H_0\cos\theta|^2\right]\Big\}$$

$$\frac{d\Gamma(B \to D^{(*)}\ell^-\bar{\nu}_\ell)}{dq^2} = \frac{G_F^2|V_{cb}|^2|\mathrm{p}_2|q^2 v^2}{12(2\pi)^3 m_1^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2 \times$$
$$\times \Big\{(|H_+|^2 + |H_-|^2 + |H_0|^2)(1+\frac{m_\ell^2}{2q^2}) + \frac{3m_\ell^2}{2q^2}|H_t|^2\Big\}$$





Results for the semileptonic branching fractions and their ratios

	Unit	This work	Data	Ref.
$\bar{B}^0 \to D^+\mu^-\bar{\nu}$	10^{-2}	2.79	2.17 ± 0.12	HFAG
			2.21 ± 0.16	BABAR
$\bar{B}^0 \to D^+\tau^-\bar{\nu}_\tau$	10^{-2}	0.75	1.02 ± 0.17	BABAR
$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}$	10^{-2}	6.60	5.05 ± 0.12	HFAG
			5.49 ± 0.30	BABAR
$\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$	10^{-2}	1.57	1.76 ± 0.18	BABAR

	This work	HQET	Data
$R(D)$	0.265	0.300 ± 0.008	0.403 ± 0.047
$R(D^*)$	0.237	0.252 ± 0.003	0.310 ± 0.017

The $\cos\theta$ distribution

- One can define the angular distribution $J(\theta)$ as:

$$\frac{d\Gamma(B\to D^{(*)}\ell^-\bar\nu_\ell)}{dq^2 d\cos\theta} = \frac{G_F^2|V_{cb}|^2|\mathrm{p}_2|q^2}{32(2\pi)^3 m_1^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2 \times J(\theta)$$

$$\boxed{\widetilde{J}(\theta) \equiv \frac{J(\theta)}{\mathcal{H}_{\rm tot}} = \frac{a+b\cos\theta+c\cos^2\theta}{2(a+c/3)}}$$

$$\mathcal{H}_{\rm tot} = (|H_+|^2+|H_-|^2+|H_0|^2)(1+\frac{m_\ell^2}{2q^2}) + \frac{3m_\ell^2}{2q^2}|H_t|^2$$

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

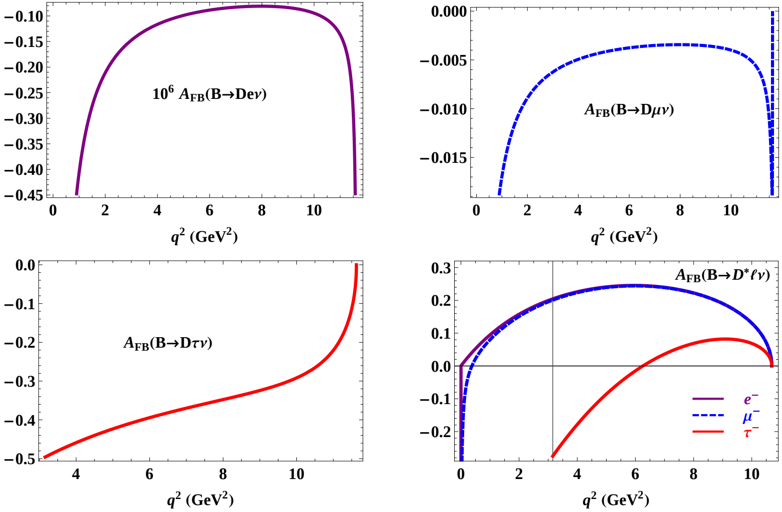
$$\mathcal{A}_{FB}(q^2) = \frac{d\Gamma(F)-d\Gamma(B)}{d\Gamma(F)+d\Gamma(B)} = \frac{\int_0^1 d\cos\theta\, d\Gamma/d\cos\theta - \int_{-1}^0 d\cos\theta\, d\Gamma/d\cos\theta}{\int_0^1 d\cos\theta\, d\Gamma/d\cos\theta + \int_{-1}^0 d\cos\theta\, d\Gamma/d\cos\theta}$$

$$= \frac{b}{2(a+c/3)} = -\frac{3}{4}\frac{|H_+|^2-|H_-|^2+\frac{2m_\ell}{q^2}H_0H_t}{\mathcal{H}_{\rm tot}}$$

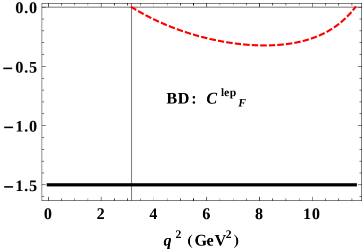
- The *quadratic* coefficient $c/2(a+c/3)$ is obtained by taking the second derivative of $\widetilde{J}(\theta)$. Accordingly, we define a convexity parameter by:

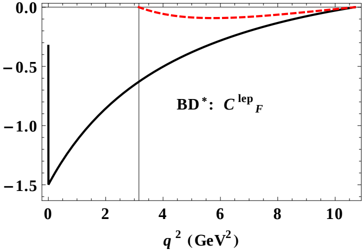
$$C_F^\ell(q^2) = \frac{d^2\widetilde{J}(\theta)}{d\cos\theta^2} = \frac{c}{a+c/3} = \frac{3}{4}\left(1-\frac{m_\ell}{q^2}\right)\frac{|H_+|^2+|H_-|^2-2|H_0|^2}{\mathcal{H}_{\rm tot}}.$$

Forward-Backward Asymmetry $\mathcal{A}_{FB}(q^2)$



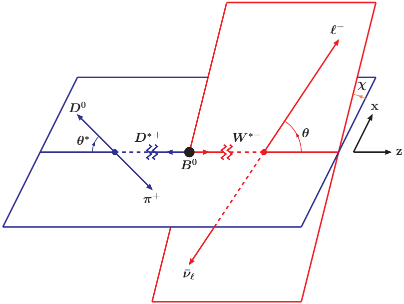
Lepton-side Convexity $C_F^{\ell}(q^2)$





- **Solid:** e^- **mode**
- **Dashed:** τ^- **mode**
- **Grid line:** **the threshold** $q^2 = m_\tau^2$

The $\bar{B}^0 \to D^{*+}(\to D^0\pi^+)\ell^-\bar{\nu}_\ell$ fourfold distribution



One has

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

where

$$|N|^2 = \frac{G_F^2|V_{cb}|^2|\mathrm{p}_2|q^2v^2}{(2\pi)^3 12 m_1^2}\mathcal{B}(D^* \to D\pi)$$

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

where $J_{i(a)}$ $(i = 1, \ldots, 9; a = s, c)$ are coefficient functions depending on q^2 and the helicity amplitudes.

q^2 distribution and $\cos\theta$ distribution

- Firstly, integrating $J(\theta, \theta^*, \chi)$ over all angles one obtains:

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

where J_L and J_T are the longitudinal and transverse polarization amplitudes of D^*:

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

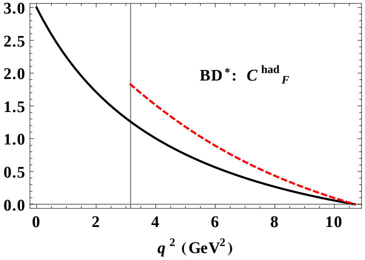
- Secondly, integrating $J(\theta, \theta^*, \chi)$ over $\cos\theta^*$ and χ one recovers the two-fold $(q^2, \cos\theta)$ distribution that gives rise to the forward-backward asymmetry parameter A_{FB} and the lepton-side convexity parameter $C_F^\ell(q^2)$:

$$\mathcal{A}_{FB}(q^2) = \frac{3}{2}\frac{J_{6c} + 2J_{6s}}{J_{\rm tot}}, \qquad C_F^\tau(q^2) = \frac{6(J_{2c} + 2J_{2s})}{J_{\rm tot}}.$$

$\cos\theta^*$ distribution and hadron-side convexity parameter

Integrating $J(\theta,\theta^*,\chi)$ over $\cos\theta$ and χ one obtains the $\cos\theta^*$ distribution. Its normalized form reads $\widetilde{J}(\theta^*) = (a' + c'\cos^2\theta^*)/2(a'+c'/3)$, which can again be characterized by its convexity parameter

$$C_F^h(q^2) = \frac{d^2\widetilde{J}(\theta^*)}{d(\cos\theta^*)^2} = \frac{c'}{a'+c'/3} = \frac{3J_{1c} - J_{2c} - 3J_{1s} + J_{2s}}{J_{\rm tot}/3}$$



The $\cos\theta^*$ distribution can be written as:

$$\widetilde{J}(\theta^*) = \frac{3}{4}\left(2F_L(q^2)\cos^2\theta^* + F_T(q^2)\sin^2\theta^*\right),$$

where $F_L(q^2)$ and $F_T(q^2)$ are the polarization fractions of D^*, given by:

$$F_L(q^2) = \frac{J_L}{J_L+J_T}, \qquad F_T(q^2) = \frac{J_T}{J_L+J_T}.$$

The hadron-side convexity parameter and the polarization fractions of the D^* meson are related by

$$C_F^h(q^2) = \frac{3}{2}\left(3F_L(q^2) - 1\right).$$

χ distribution and trigonometric moments

The normalized χ distribution reads:

$$\widetilde{J}^{(I)}(\chi) = \frac{1}{2\pi}\Big[1 + A_C^{(1)}(q^2)\cos 2\chi + A_T^{(1)}(q^2)\sin 2\chi\Big],$$

where $A_C^{(1)}(q^2) = 4J_3/J_{\rm tot}$ and $A_T^{(1)}(q^2) = 4J_9/J_{\rm tot}$.

Besides, one can also define other angular distributions in the angular variable χ as follows:

$$J^{(II)}(\chi) = \Big[\int_0^1 - \int_{-1}^0\Big] d\cos\theta^* \int_{-1}^1 d\cos\theta \frac{d^4\Gamma}{dq^2 d\cos\theta d\chi d\cos\theta^*},$$

$$J^{(III)}(\chi) = \Big[\int_0^1 - \int_{-1}^0\Big] d\cos\theta^* \Big[\int_0^1 - \int_{-1}^0\Big] d\cos\theta \frac{d^4\Gamma}{dq^2 d\cos\theta d\chi d\cos\theta^*}.$$

The normalized forms of these distributions read:

$$\widetilde{J}^{(II)}(\chi) = \frac{1}{4}\Big[A_C^{(2)}(q^2)\cos\chi + A_T^{(2)}(q^2)\sin\chi\Big],$$

$$\widetilde{J}^{(III)}(\chi) = \frac{2}{3\pi}\Big[A_C^{(3)}(q^2)\cos\chi + A_T^{(3)}(q^2)\sin\chi\Big],$$

where

$$A_C^{(2)}(q^2) = \frac{3J_5}{J_{\rm tot}}, \qquad A_T^{(2)}(q^2) = \frac{3J_7}{J_{\rm tot}}, \qquad A_C^{(3)}(q^2) = \frac{3J_4}{J_{\rm tot}}, \qquad A_T^{(3)}(q^2) = \frac{3J_8}{J_{\rm tot}}.$$

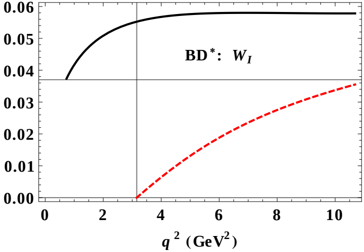
Another method to project the coefficient functions J_i ($i = 3, 4, 5, 7, 8, 9$) out from the full angular decay distribution is to take the appropriate trigonometric moments of the normalized decay distribution $\widetilde{J}(\theta^*, \theta, \chi)$. The trigonometric moments are defined by

$$W_i = \int d\cos\theta d\cos\theta^* d\chi M_i(\theta^*, \theta, \chi)\widetilde{J}(\theta^*, \theta, \chi) \equiv \langle M_i(\theta^*, \theta, \chi)\rangle ,$$

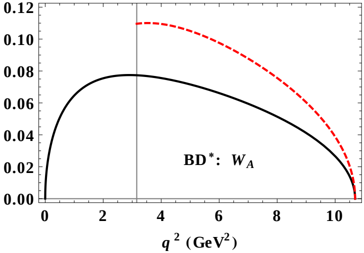
where $M_i(\theta^*, \theta, \chi)$ defines the trigonometric moment that is being taken. One finds

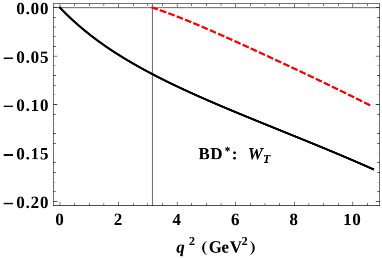
$$\begin{aligned}
W_T(q^2) &\equiv \langle\cos 2\chi\rangle = \frac{2J_3}{J_{\rm tot}} = \frac{1}{2}A_C^{(1)}(q^2),\\
W_{IT}(q^2) &\equiv \langle\sin 2\chi\rangle = \frac{2J_9}{J_{\rm tot}} = \frac{1}{2}A_T^{(1)}(q^2),\\
W_A(q^2) &\equiv \langle\sin\theta\cos\theta^*\cos\chi\rangle = \frac{3\pi}{8}\frac{J_5}{J_{\rm tot}} = \frac{\pi}{8}A_C^{(2)}(q^2),\\
W_{IA}(q^2) &\equiv \langle\sin\theta\cos\theta^*\sin\chi\rangle = \frac{3\pi}{8}\frac{J_7}{J_{\rm tot}} = \frac{\pi}{8}A_T^{(2)}(q^2),\\
W_I(q^2) &\equiv \langle\cos\theta\cos\theta^*\cos\chi\rangle = \frac{9\pi^2}{128}\frac{J_4}{J_{\rm tot}} = \frac{3\pi^2}{128}A_C^{(3)}(q^2),\\
W_{II}(q^2) &\equiv \langle\cos\theta\cos\theta^*\sin\chi\rangle = \frac{9\pi^2}{128}\frac{J_8}{J_{\rm tot}} = \frac{3\pi^2}{128}A_T^{(3)}(q^2).
\end{aligned}$$

Trigonometric moments



In our quark model all helicity amplitudes are real, which implies the vanishing of all terms proportional to $\sin\chi$ and $\sin 2\chi$, namely $J_{7,8,9}$, within the SM. This does not necessarily hold when considering complex NP Wilson coefficients, as can be seen in the next section.





Analyzing New Physics in the decays $B \to D^{(*)}\tau\nu_\tau$

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

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

where the four-fermion operators are written as

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

- **Here, $\sigma_{\mu\nu} = i\,[\gamma_\mu, \gamma_\nu]\,/2$**
- **$P_{L,R} = (1 \mp \gamma_5)/2$ - the left and right projection operators**
- **$V_{L,R}$, $S_{L,R}$, and T_L - complex Wilson coefficients governing NP contributions.**
- **In the SM: $V_{L,R} = S_{L,R} = T_L = 0$.**
- **Assumption: neutrino is always left handed and NP only affects leptons of the third generation.**

Matrix element and NP form factors

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

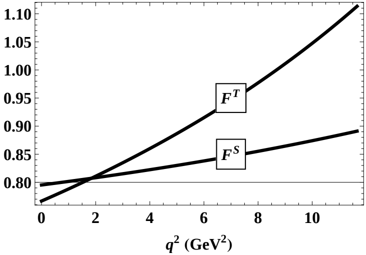
The axial and pseudoscalar hadronic matrix elements do not contribute to $\bar{B}^0\to D$; and the scalar hadronic matrix element does not contribute to $\bar{B}^0\to D^*$.

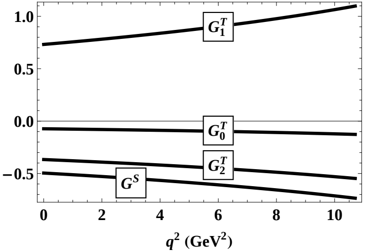
We need more form factors to describe NP operators:

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

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

Form factors for NP operators





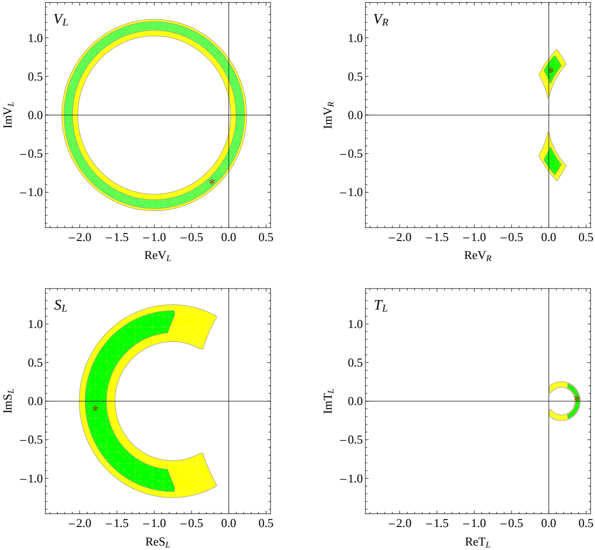
NP form factors for $\bar{B}^0 \to D$ (left) and $\bar{B}^0 \to D^*$ (right) in the full momentum transfer range $0 \le q^2 \le q^2_{max} = (m_{\bar{B}^0} - m_{D^{(*)}})^2$.

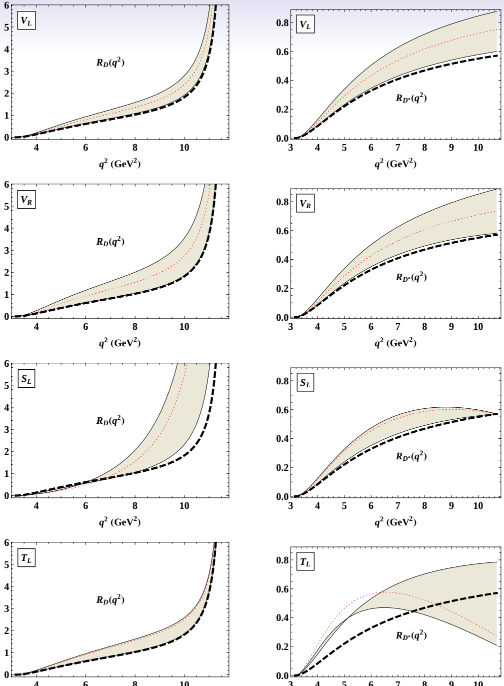
The parameters of the dipole interpolation:

	F^S	F^T	G^S	G_0^T	G_1^T	G_2^T
$F(0)$	0.80	0.77	−0.50	−0.073	0.73	−0.37
a	0.22	0.76	0.87	1.23	0.90	0.88
b	−0.098	0.043	0.060	0.33	0.074	0.064
$F(q^2_{\max})$	0.89	1.11	−0.73	−0.13	1.10	−0.55
$F^{HQL}(q^2_{\max})$	0.88	1.14	−0.62	0	1.12	−0.50

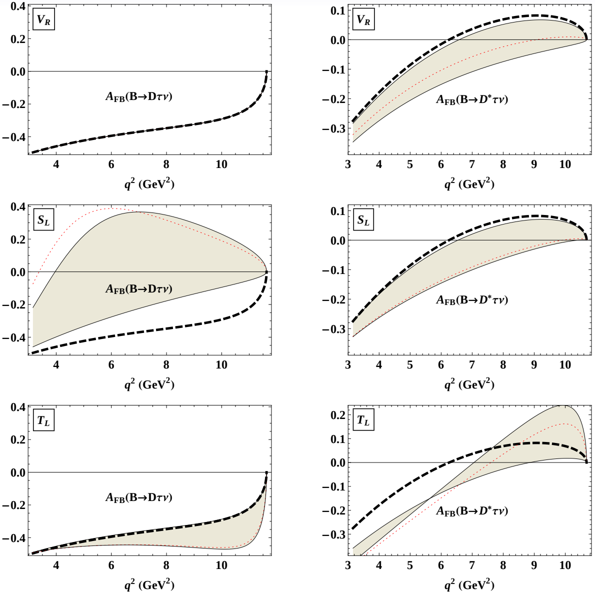
Allowed regions for NP couplings

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.

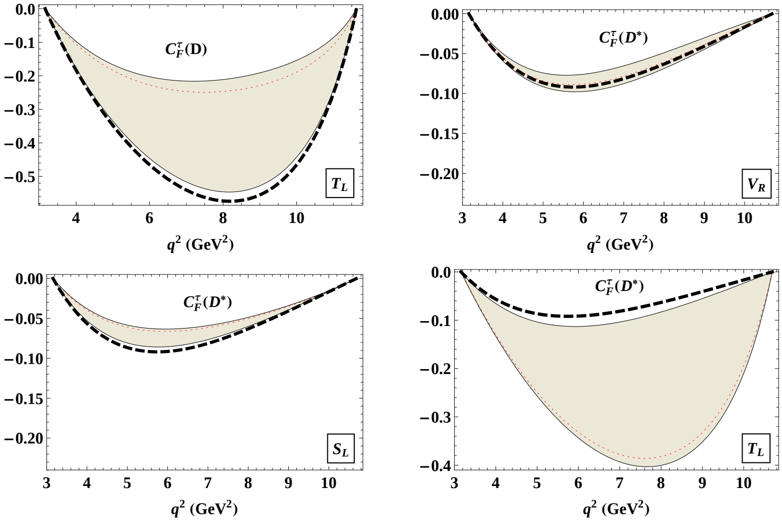



V_L
R_D(q^2)
R_D*(q^2)
V_R
S_L
T_L
q^2 (GeV^2)

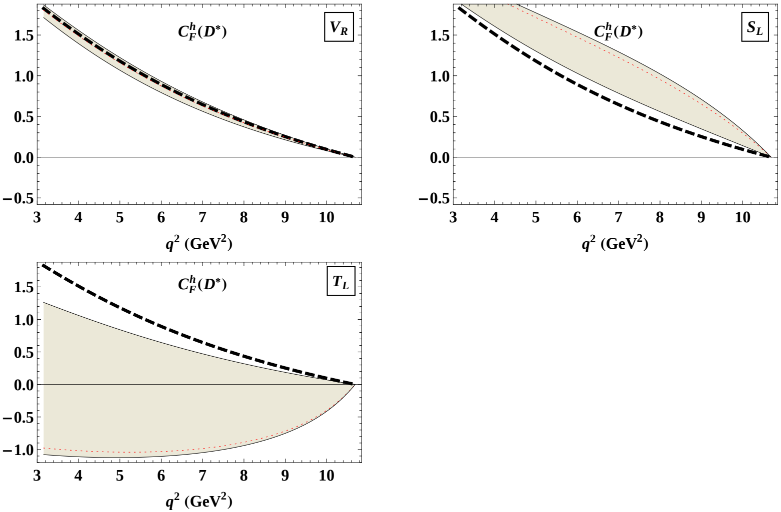
Forward-backward asymmetry $\mathcal{A}_{FB}(q^2)$

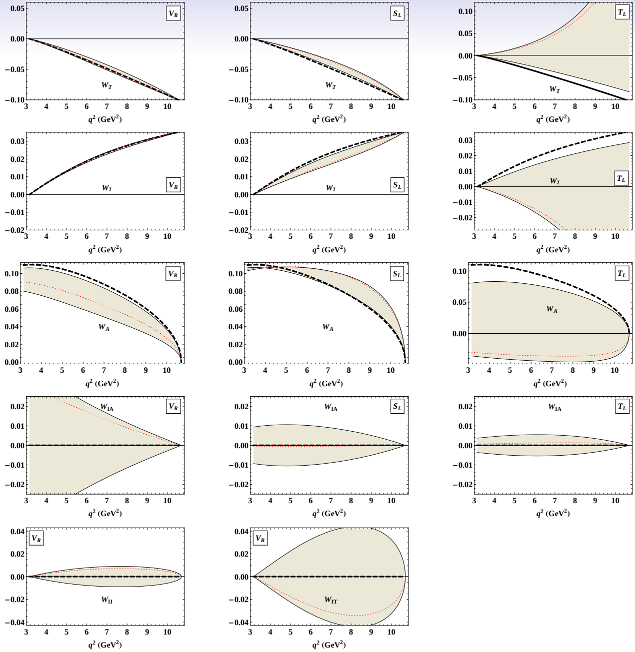


Lepton-side convexity $C_F^\tau(q^2)$



Hadron-side convexity parameter $C_F^h(q^2)$




V_R
S_L
T_L
W_T
W_I
W_A
W_{IA}
W_{II}
W_{IT}
q^2 (GeV^2)

Certain combinations of angular observables where the form factor dependence drops out (at least in most NP scenarios).

$$H_T^{(1)} = \frac{\sqrt{2}J_4}{\sqrt{-J_{2c}(2J_{2s} - J_3)}},$$

which equals to one not only in the SM but also in all NP scenarios except the tensor one. Therefore $H_T^{(1)}(q^2)$ plays a prominent role in confirming the appearance of the tensor operator $\mathcal{O}_{T_L}$ in the decay $\bar{B}^0 \to D^*\tau^-\bar{\nu}_\tau$.

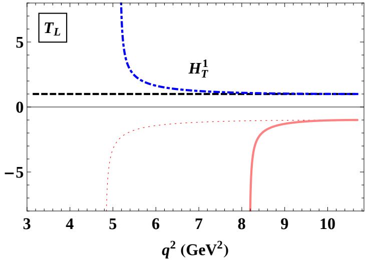


Рис.: The black dashed line is the SM prediction. The red dotted line, which is almost identical to the SM one, represents the best fit value of T_L. The blue dot-dashed line and the red line are the prediction for $T_L = 0.21i$ and $T_L = 0.18 + 0.27i$, respectively.

Tau polarization in the decays $\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau$

- **First measurement by Belle:** [arXiv:1612.00529]

$$P_L^\tau = -0.38 \pm 0.51(\text{stat.})^{+0.21}_{-0.16}(\text{syst.}) \qquad (\text{in } \bar{B}^0 \to D^*\tau^-\bar{\nu}_\tau)$$

- **We define three orthogonal unit vectors as follows:**

$$\vec{e}_L = \frac{\vec{p}_\tau}{|\vec{p}_\tau|}, \qquad \vec{e}_N = \frac{\vec{p}_\tau \times \vec{p}_{D^{(*)}}}{|\vec{p}_\tau \times \vec{p}_{D^{(*)}}|}, \qquad \vec{e}_T = \vec{e}_N \times \vec{e}_L,$$

where $\vec{p}_\tau$ and $\vec{p}_{D^{(*)}}$ - three-momenta of the τ^- and the mesons in the W^- rest frame.

- **Longitudinal (L), normal (N), and transverse (T) polarization four-vectors of the τ^- in the W^- rest frame:**

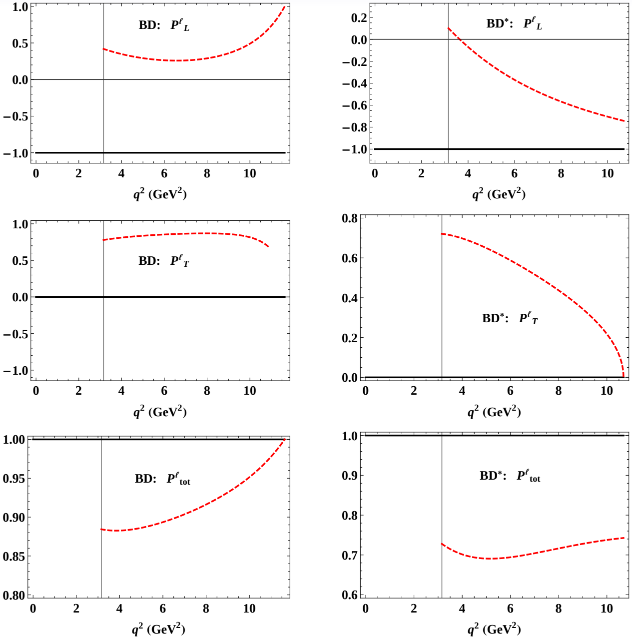
$$s_L^\mu = \left(\frac{|\vec{p}_\tau|}{m_\tau}, \frac{E_\tau}{m_\tau}\frac{\vec{p}_\tau}{|\vec{p}_\tau|}\right), \qquad s_N^\mu = (0, \vec{e}_N), \qquad s_T^\mu = (0, \vec{e}_T).$$

- **The tau polarization components:**

$$P_i(q^2) = \frac{d\Gamma(s_i^\mu)/dq^2 - d\Gamma(-s_i^\mu)/dq^2}{d\Gamma(s_i^\mu)/dq^2 + d\Gamma(-s_i^\mu)/dq^2}, \qquad i = L, N, T, \qquad q^\mu = p_B^\mu - p_{D^{(*)}}^\mu$$

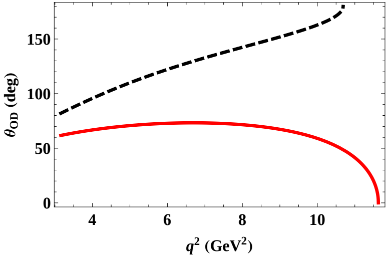
(Note that $P_N(q^2) = 0$ in the SM.)

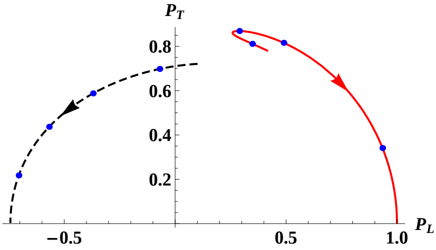
Lepton polarization: $\bar{B}^0 \to D^{(*)} e^- \bar{\nu}_e$ vs. $\bar{B}^0 \to D^{(*)} \tau^- \bar{\nu}_\tau$



Result for tau polarization in the SM

P_L-P_T correlation: $\sin\theta_{OD}/\cos\theta_{OD} = P_T/P_L$. Dashed line - $B \to D^*$, solid line - $B \to D$. The arrows show the direction of increasing q^2. The dots on the dashed line stand for $q^2 = 4, 6, 8, 10$ GeV^2. The dots on the solid line - $q^2 = 4, 8, 10, 11.5$ GeV^2



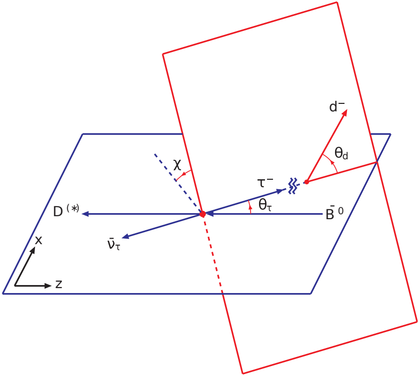


	This work	Other	Ref.
$< P_L^D >$	0.33	0.34 ± 0.03	Alonso *et al.* ArXiv:1702.02773
		0.325 ± 0.009	Tanaka *et al.* ArXiv:1005.4306
$< P_T^D >$	0.84	0.839 ± 0.007	Alonso *et al.* ArXiv:1702.02773
$< P_L^{D^*} >$	-0.50	-0.497 ± 0.013	Tanaka *et al.* arXiv:1212.1878
		$-0.38 \pm 0.51^{+0.21}_{-0.16}$	Belle Collab. arXiv:1612.00529
$< P_T^{D^*} >$	0.46	...	...

Analyzing the polarization of the tau through its decays

As analyzing modes for the τ^- polarization we will consider the four dominant τ^- decay modes

$$\tau^- \to \pi^-\nu_\tau \quad (10.83\%), \qquad \tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau \quad (17.41\%),$$
$$\tau^- \to \rho^-\nu_\tau \quad (25.52\%), \qquad \tau^- \to e^-\bar{\nu}_e\nu_\tau \quad (17.83\%),$$



In W rest frame, θ_τ - angle between $\vec{p}_\tau$ and the direction opposite to the direction of the $D^{(*)}$

In τ rest frame, θ_d - angle between d^- and the longitudinal polarization axis, which is chosen to coincide with the direction of the τ in the W rest frame.

χ - azimuthal angle.

In terms of the angles θ_d and χ, the decay distribution is written as follows:

$$\frac{d\Gamma}{dq^2 d\cos\theta_d d\chi/2\pi} =$$
$$= \quad \mathcal{B}_d \frac{d\Gamma}{dq^2}\frac{1}{2}\left[1 + A_d(P_T(q^2)\sin\theta_d\cos\chi + P_N(q^2)\sin\theta_d\sin\chi + P_L(q^2)\cos\theta_d)\right].$$

Through an analysis of this decay distribution one can determine the components of the q^2-dependent polarization vector $\vec{P}(q^2) = (P_T(q^2), P_N(q^2), P_L(q^2))$.

Upon χ integration, one obtains

$$\frac{d\Gamma}{dq^2 d\cos\theta_d} = \mathcal{B}_d \frac{d\Gamma}{dq^2}\frac{1}{2}\left(1 + A_d P_L(q^2)\cos\theta_d\right)$$

with a polar analyzing power of A_d ($A_d = 1$ for $d = \pi$)

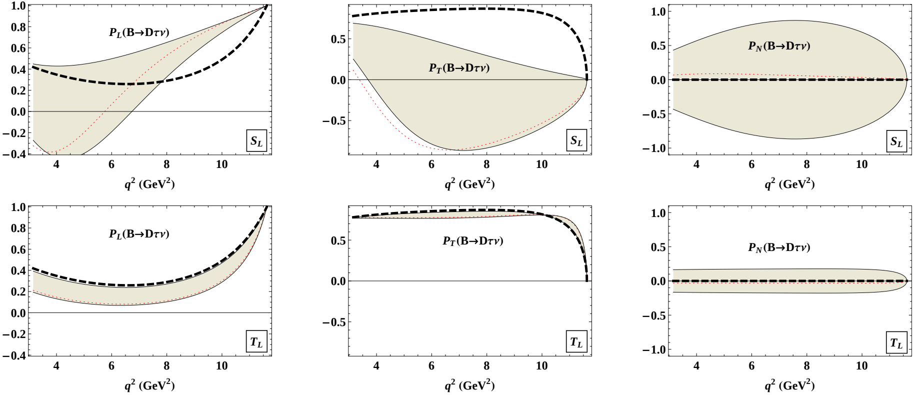
Upon $\cos\theta_d$ integration one has

$$\frac{d\Gamma}{dq^2 d\chi/2\pi} = \mathcal{B}_d \frac{d\Gamma}{dq^2}\left(1 + A_d\frac{\pi}{4}\left(P_T(q^2)\cos\chi + P_N(q^2)\sin\chi\right)\right)$$

with an azimuthal analyzing power of $A_d\pi/4$.

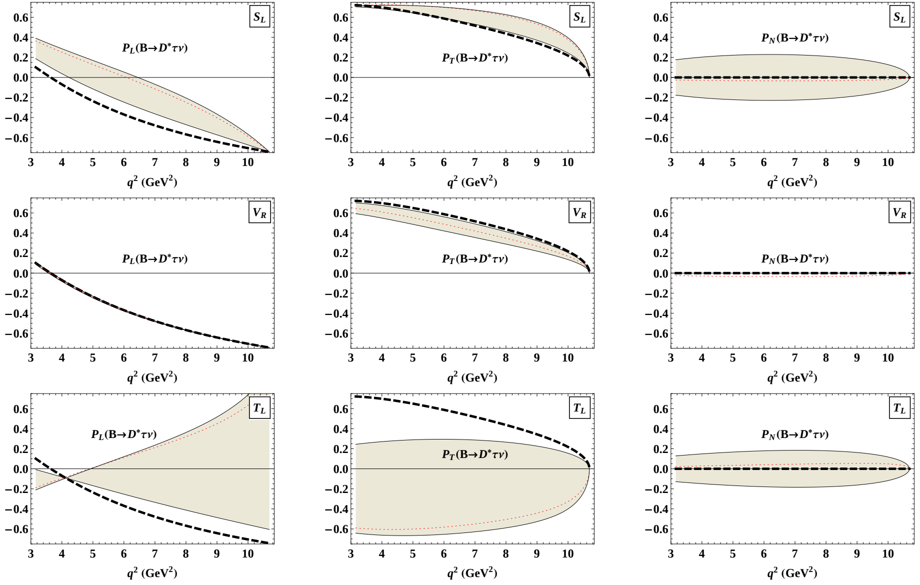
For more details: our recent paper [arXiv:1701.02937].

Longitudinal, transverse, and normal polarization of τ^- in $\bar{B}^0 \to D\tau^-\bar{\nu}_\tau$



- **Thick black dashed lines: SM prediction**
- **Gray bands include NP effects corresponding to the 2σ allowed regions**
- **Red dotted lines represent the best-fit values of the NP couplings**

Longitudinal, transverse, and normal polarization of τ^- in $\bar{B}^0 \to D^*\tau^-\bar{\nu}_\tau$



q^2 averages of the polarization components and the total polarization.

One can also calculate the average polarizations over the whole q^2 region. For example, the average longitudinal polarization $\langle P_L^D \rangle$ is calculated by:

$$\langle P_L^D \rangle = \frac{\int dq^2 C(q^2)\big(P_L^D(q^2)\mathcal{H}_{\rm tot}^D\big)}{\int dq^2 C(q^2)\mathcal{H}_{\rm tot}^D},$$

where $C(q^2) = |\mathrm{p}_2|(q^2 - m_\tau^2)^2/q^2$ is the q^2-dependent piece of the phase-space factor.

	$\bar{B}^0 \to D$			
	$< P_L^D >$	$< P_T^D >$	$< P_N^D >$	$< \lvert\vec{P}^D\rvert >$
SM (CCQM)	0.33	0.84	0	0.91
S_L	$(0.36, 0.67)$	$(-0.68, 0.33)$	$(-0.76, 0.76)$	$(0.89, 0.96)$
T_L	$(0.13, 0.31)$	$(0.78, 0.83)$	$(-0.17, 0.17)$	$(0.79, 0.90)$
	$\bar{B}^0 \to D^*$			
	$< P_L^{D^*} >$	$< P_T^{D^*} >$	$< P_N^{D^*} >$	$< \lvert\vec{P}^{D^*}\rvert >$
SM (CCQM)	-0.50	0.46	0	0.71
S_L	$(-0.40, -0.14)$	$(0.47, 0.62)$	$(-0.20, 0.20)$	$(0.69, 0.70)$
T_L	$(-0.36, 0.24)$	$(-0.61, 0.26)$	$(-0.17, 0.17)$	$(0.23, 0.69)$
V_R	-0.50	$(0.32, 0.43)$	0	$(0.48, 0.67)$

The predicted intervals for the polarizations in the presence of NP are given in correspondence with the 2σ allowed regions of the NP couplings

Semileptonic decays of J/ψ meson

- **Weak decays of J/ψ are rare processes**
- **BESIII Collaboration (10^{10} J/ψ events/year): at 90% C.L.**
  $\mathcal{B}(J/\psi \to D_s^{*-} e^+ \nu_e + c.c.) < 1.8 \times 10^{-6}$ **(first time)** and
  $\mathcal{B}(J/\psi \to D_s^- e^+ \nu_e + c.c.) < 1.3 \times 10^{-6}$ **(30 times more stringent)**

M. Ablikim *et al.*, Phys. Rev. D 90, 112014 (2014)

- **Standard Model prediction: $\approx 10^{-9} - 10^{-10}$**

SanchisLozano:1993, Wang:2007, Shen:2008

- **(Approximate) spin symmetry of heavy mesons**
  $BF \approx 10^{-9}$; $R \equiv \dfrac{\mathcal{B}(J/\psi \to D_s^* \ell\nu)}{\mathcal{B}(J/\psi \to D_s \ell\nu)} \approx 1.5$

Sanchis-Lonzano:1993

- **QCD sum rules (QCD SR)**
  $BFs \approx 10^{-10}$; $R \approx 3.1$

Wang:2007

- **Covariant light-front quark model (LFQM)**
  BFs are 2 − 8 times larger than Wang's

Shen:2008

Our aim: Crosscheck!

Matrix element and Decay width

- **Matrix element**

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{cq} \left\langle D^- \left| \bar{q} O_\mu c \right| J/\psi \right\rangle \left[\bar{\nu_\ell} O^\mu \ell \right], \text{where } q = s, d,\ O^\mu = \gamma^\mu (1 - \gamma_5).$$

- **Decay width**

$$\Gamma\left(J/\psi \to D_{(s)}^{(*)\,-} \ell^+ \nu_\ell\right) = \frac{G_F^2}{(2\pi)^3} \frac{|V_{cq}|^2}{64\, m_1^3} \int_{m_\ell^D}^{(m_{J/\psi} - m_2)^2} dq^2 \int_{s_1^-}^{s_1^+} ds_1\ \frac{1}{3} H_{\mu\nu} L^{\mu\nu},$$

where $s_1 = (p_D + p_\ell)^2$.

- **Lepton tensor**

$$L^{\mu\nu} = \text{tr}\left[(\not{p}_\ell + m_\ell) O^\mu \not{p}_{\nu_\ell} O^\nu \right]$$

- **Hadron tensor**

$$H_{\mu\nu} = \begin{cases} T^{\mathrm{VP}}_{\mu\alpha} \left(-g^{\alpha\alpha'} + \frac{p_1^\alpha p_1^{\alpha'}}{m_1^2} \right) T^{\mathrm{VP}\,\dagger}_{\nu\alpha'} & \text{for } V \to P \\ T^{\mathrm{VV}}_{\mu\alpha\beta} \left(-g^{\alpha\alpha'} + \frac{p_1^\alpha p_1^{\alpha'}}{m_1^2} \right) \left(-g^{\beta\beta'} + \frac{p_2^\beta p_2^{\beta'}}{m_2^2} \right) T^{\mathrm{VV}\,\dagger}_{\nu\alpha'\beta'} & \text{for } V \to V \end{cases}$$

Hadronic transition and Form factors

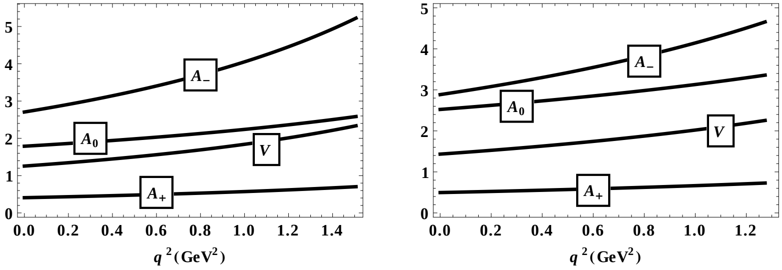
$V \to P$ transition:

$$\left\langle D^-_{(s)}(p_2)\,|\bar{q}O_\mu c|\,J/\psi(\epsilon_1,p_1)\right\rangle \equiv \epsilon_1^\alpha T^{\rm VP}_{\mu\alpha} = \frac{\epsilon_1^\alpha}{m_1+m_2}\times$$
$$\times\left[-g_{\mu\nu}pqA_0(q^2)+p_\mu p_\nu A_+(q^2)+q_\mu p_\nu A_-(q^2)+i\varepsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma V(q^2)\right],$$

$V \to V$ transition:

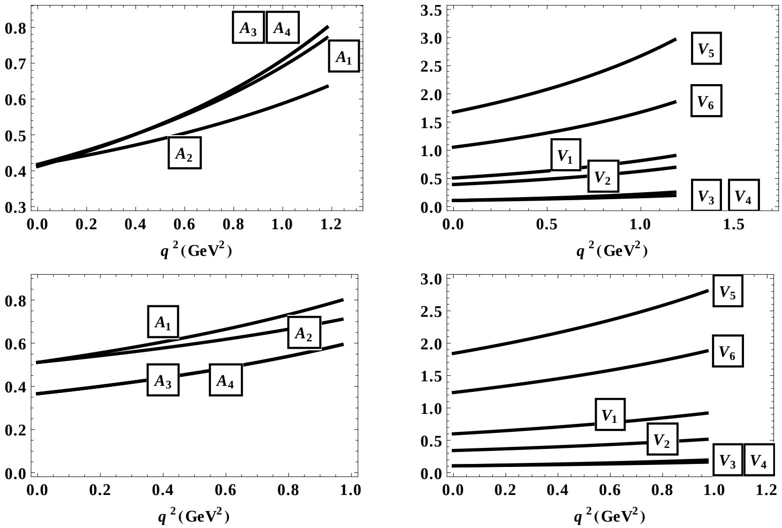
$$\left\langle D^{*-}_{(s)}(\epsilon_2,p_2)\,|\bar{q}O_\mu c|\,J/\psi(\epsilon_1,p_1)\right\rangle \equiv \epsilon_1^\alpha \epsilon_2^{*\,\beta} T^{\rm VV}_{\mu\alpha\beta}$$
$$=\varepsilon_{\mu\nu\alpha\beta}\epsilon_1^\alpha\epsilon_2^{*\beta}\left[\left(p^\nu-\frac{m_1^2-m_2^2}{q^2}q^\nu\right)A_1(q^2)+\frac{m_1^2-m_2^2}{q^2}q^\nu A_2(q^2)\right]$$
$$+\frac{i}{m_1^2-m_2^2}\varepsilon_{\mu\nu\alpha\beta}p_1^\alpha p_2^\beta\left[A_3(q^2)\epsilon_1^\nu\epsilon_2^*\cdot q-A_4(q^2)\epsilon_2^{*\nu}\epsilon_1\cdot q\right]$$
$$+(\epsilon_1\cdot\epsilon_2^*)\left[-p_\mu V_1(q^2)+q_\mu V_2(q^2)\right]$$
$$+\frac{(\epsilon_1\cdot q)(\epsilon_2^*\cdot q)}{m_1^2-m_2^2}\left[\left(p_\mu-\frac{m_1^2-m_2^2}{q^2}q_\mu\right)V_3(q^2)+\frac{m_1^2-m_2^2}{q^2}q_\mu V_4(q^2)\right]$$
$$-(\epsilon_1\cdot q)\epsilon^*_{2\,\mu}V_5(q^2)+(\epsilon_2^*\cdot q)\epsilon_{1\,\mu}V_6(q^2)\,.$$

Form factors



Form factors of the $V \to P$ transitions $J/\psi \to D$ (left) and $J/\psi \to D_s$ (right).

Form factors



Form factors of the $V \to V$ transitions $J/\psi \to D^*$ (up) and $J/\psi \to D_s^*$ (down). Note that in the left panels $A_1(0) = A_2(0)$ and $A_3(q^2) \equiv A_4(q^2)$.

Form factors Comparison

	$J/\psi \to D$: $q^2 = 0$				$J/\psi \to D_s$: $q^2 = 0$			
	A_0	A_+	A_-	V	A_0	A_+	A_-	V
QCD SR	1.09	0.34	–	0.81	1.71	0.35	–	1.07
LFQM	2.75	0.18	–	1.6	3.05	0.13	–	1.8
our	1.79	0.41	2.71	1.26	2.52	0.50	2.88	1.43

Comparison of $J/\psi \to D_{(s)}$ form factors at maximum recoil with those obtained in QCD SR [Wang:2007] and LFQM [Shen:2008].

	$J/\psi \to D^*$: $q^2 = 0$									
	A_1	A_2	A_3	A_4	V_1	V_2	V_3	V_4	V_5	V_6
QCDSR	0.40	0.44	0.86	0.91	0.41	0.63	0.22	0.26	1.37	0.87
our	0.42	0.42	0.41	0.41	0.51	0.39	0.11	0.11	1.68	1.05
	$J/\psi \to D_s^*$: $q^2 = 0$									
QCDSR	0.53	0.53	0.91	0.91	0.54	0.69	0.24	0.26	1.69	1.14
our	0.51	0.51	0.37	0.37	0.60	0.34	0.11	0.11	1.84	1.24

Comparison of $J/\psi \to D^*_{(s)}$ form factors at maximum recoil with those obtained in QCD SR [Wang:2007ys].

Branching Fractions

Mode	Unit	This work	QCD SR	LFQM
$J/\psi \to D^- e^+ \nu_e$	10^{-12}	17.1	$7.3^{+4.3}_{-2.2}$	$51 \sim 57$
$J/\psi \to D^- \mu^+ \nu_\mu$	10^{-12}	16.6	$7.1^{+4.2}_{-2.2}$	$47 \sim 55$
$J/\psi \to D_s^- e^+ \nu_e$	10^{-10}	3.3	$1.8^{+0.7}_{-0.5}$	$5.3 \sim 5.8$
$J/\psi \to D_s^- \mu^+ \nu_\mu$	10^{-10}	3.2	$1.7^{+0.7}_{-0.5}$	$5.5 \sim 5.7$
$J/\psi \to D^{*-} e^+ \nu_e$	10^{-11}	3.0	$3.7^{+1.6}_{-1.1}$	$\cdots$
$J/\psi \to D^{*-} \mu^+ \nu_\mu$	10^{-11}	2.9	$3.6^{+1.6}_{-1.1}$	$\cdots$
$J/\psi \to D_s^{*-} e^+ \nu_e$	10^{-10}	5.0	$5.6^{+1.6}_{-1.6}$	$\cdots$
$J/\psi \to D_s^{*-} \mu^+ \nu_\mu$	10^{-10}	4.8	$5.4^{+1.6}_{-1.5}$	$\cdots$

All in MeV	f_D	f_{D_s}	f_{D^*}	$f_{D_s^*}$
This work	206	258	244	272
QCD SR	166	189	240	262

$$R \equiv \frac{\mathcal{B}(J/\psi \to D_s^* \ell\nu)}{\mathcal{B}(J/\psi \to D_s \ell\nu)} = \begin{cases} 1.5 & \text{M.A. Sanchis-Lonzano} \\ 3.1 & \text{Y.M. Wang} \\ 1.5 & \text{This work} \end{cases}$$

$$R_1 \equiv \frac{\mathcal{B}(J/\psi \to D_s \ell\nu)}{\mathcal{B}(J/\psi \to D \ell\nu)} \quad \text{and} \quad R_2 \equiv \frac{\mathcal{B}(J/\psi \to D_s^* \ell\nu)}{\mathcal{B}(J/\psi \to D^* \ell\nu)}$$

$\simeq |V_{cs}|^2/|V_{cd}|^2 \simeq 18.4$ under $SU(3)$ flavor symmetry limit. Wang's: $R_1 \simeq 24.7$ and $R_2 \simeq 15.1$. This work: $R_1 \simeq 19.3$ and $R_2 \simeq 16.6$.

Summary

- **Leptonic and semileptonic B decays within the SM in the framework of our covariant quark model with particular emphasis on how to isolate heavy lepton mass effects in the semileptonic decays.**
- **How to obtain the full angular decay distributions for $\bar{B}^0 \to D\tau^-\bar{\nu}_\tau$ and the cascade decay process $\bar{B}^0 \to D^{*+}(\to D^0\pi^+)\tau^-\bar{\nu}_\tau$ and how to define various physical observables in these decays.**
- **An analysis of possible NP in the semileptonic decays $\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau$ based on an effective Hamiltonian including NP operators.**
- **Current experimental data of $R(D)$ and $R(D^*)$ prefer the operators $\mathcal{O}_{S_L}$ and $\mathcal{O}_{V_{L,R}}$; the operator $\mathcal{O}_{T_L}$ is less favored; and the operator $\mathcal{O}_{S_R}$ is excluded at 2σ.**
- **Our analysis can serve as a map for setting up various strategies to identify the origins of NP. For example, firstly, one uses the null-tests $W_{IT}(q^2) = 0$ and $H_T^{(1)}(q^2) - 1 = 0$ to probe the operators $\mathcal{O}_{V_R}$ and $\mathcal{O}_{T_L}$, respectively. Secondly, one measures the forward-backward asymmetry in the decay $\bar{B}^0 \to D\tau^-\bar{\nu}_\tau$. If $\mathcal{A}_{FB}^D(q^2)$ has a zero-crossing point, then it is a clear sign of the operator $\mathcal{O}_{S_L}$. The coupling V_L is more difficult to test because it is just a multiplier of the SM operator. However, if the tests above disconfirms $\mathcal{O}_{V_R}$, $\mathcal{O}_{T_L}$, and $\mathcal{O}_{S_L}$ at the same time, then the modification of V_L to $R(D)$ and $R(D^*)$ is a must.**
- **Tau polarization and its role in probing NP in the decays $\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau$.**
- **Prediction for branching fractions of the semileptonic decays of charmonium.**

Conference Presentations

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

- **Oral presentation delivered at the Conference "Hadron Structure and QCD: from Low to High Energies", Gatchina, June 2016,**
- **Oral presentation delivered at the Helmholtz International Summer School " Quantum Field Theory at the Limits: from Strong Fields to Heavy Quarks", Dubna, July 2016.**

Exclusive decays $J/\psi \to D^{(*)}_{(s)}\ell\nu_\ell$ in the Covariant Confined Quark Model:

- **Oral presentation delivered at the Workshop on Dispersion Methods for Hadronic Contributions to QED Effects, Bratislava, Oct. 2015,**
- **Oral presentation at the International Conference on Precision Physics and Fundamental Physical Constants, Budapest, Oct. 2015.**
- **Poster presentation delivered at the 44$^{\text{th}}$ meeting of the Program Advisory Committee for Particle Physics of JINR, Dubna, Dec. 2015.**

Leptonic and semileptonic weak decays of B mesons.

- **Oral presentation delivered at the 6$^{\text{th}}$ Russian Youth Conference "Fundamental and innovative problems of modern physics", Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Nov. 2015.**

Weak decays of B meson and charmonium in a covariant quark model

- **Oral presentation delivered at the laboratory seminar of BLTP-JINR, Dubna, Nov. 2015.**

Publication

1. **M. A. Ivanov, J. G. Körner and C. T. Tran, Exclusive decays $B \to \ell^- \bar{\nu}$ and $B \to D^{(*)}\ell^- \bar{\nu}$ in the covariant quark model, Phys. Rev. D 92, 114022 (2015), arXiv:1508.02678.**
2. **M. A. Ivanov and C. T. Tran, Exclusive decays $J/\psi \to D_{(s)}^{(*)-}\ell^+\nu_\ell$ in a covariant constituent quark model with infrared confinement, Phys. Rev. D 92, 074030 (2015), arXiv:1701.07377.**
3. **M. A. Ivanov, J. G. Körner and C. T. Tran, Analyzing new physics in the decays $\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau$ with form factors obtained from the covariant quark model, Phys. Rev. D 94, 094028 (2016), arXiv:1607.02932.**
4. **M. A. Ivanov, J. G. Körner and C. T. Tran, Probing new physics in $\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau$ using the longitudinal, transverse, and normal polarization components of the tau lepton, Phys. Rev. D 95, 036021 (2017), arXiv:1701.02937.**
5. **C. T. Tran, M. A. Ivanov and J. G. Körner, Analyzing New Physics in $\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau$, HISS Conference Proceeding, arXiv:1702.06910.**
6. **M. A. Ivanov, J. G. Körner and C. T. Tran, Looking for new physics in leptonic and semileptonic decays of B meson, Summited to Physics of Particles and Nuclei Letters.**

Thank you for your attention!

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