Semileptonic decay of heavy flavor mesons

康现伟

Beijing Normal Uni.

Based on
PRD2014, EPJC2017, PLB2018, EPJC2018,
JHEP2021, PRD2022

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- Motivation
- Theoretical tools
- physical observables
- Prospects on experiments

Motivation

- Extraction of CKM matrix element

  compared to pure hadronic decay, clean

  compared to pure leptonic decay, larger Br

  $B \to e\,\nu_e$ helicity suppression

- Experimental side, measurably easily

  Belle, **LHCb**, BES, STCF

- Form factor is crucial, related to understanding of QCD

  quark model, dispersion relation, sum rule, PQCD

  different parameterizations of form factor, pole model or z-expansion

Form factor: general Lorentz structure

$$\mathcal{M}(D_{(s)} \to P(V)\ell\nu_\ell) = \frac{G_F}{\sqrt{2}} V_{cq} H^\mu L_\mu,$$

where $L_\mu = \bar{\nu}_\ell \gamma_\mu (1-\gamma_5)\ell$ and $H^\mu = \langle P(V)|\bar{q}\gamma_\mu(1-\gamma_5)c|D_{(s)}\rangle$.

- For $D_{(s)}$ transitions to pseudoscalar P (π, K, η, η') mesons

$$\langle P(p_P)|\bar{q}\gamma^\mu c|D_{(s)}(p_{D_{(s)}})\rangle = f_+(q^2)\left[p^\mu_{D_{(s)}} + p^\mu_P - \frac{M^2_{D_{(s)}} - M^2_P}{q^2}\, q^\mu\right] + f_0(q^2)\frac{M^2_{D_{(s)}} - M^2_P}{q^2}\, q^\mu,$$

$$\langle P(p_P)|\bar{q}\gamma^\mu\gamma_5 c|D_{(s)}(p_{D_{(s)}})\rangle = 0, \tag{16}$$

Parity conservation

- For $D_{(s)}$ transitions to vector V $(\rho, \omega, K^*, \phi)$ mesons

$$\langle V(p_V)|\bar{q}\gamma^\mu c|D_{(s)}(p_{D_{(s)}})\rangle = \frac{2iV(q^2)}{M_{D_{(s)}} + M_V}\epsilon^{\mu\nu\rho\sigma}\epsilon^*_\nu p_{D_{(s)}\rho} p_{V\sigma},$$

$$\begin{aligned}\langle V(p_V)|\bar{q}\gamma^\mu\gamma_5 c|D_{(s)}(p_{D_{(s)}})\rangle = {} & 2M_V A_0(q^2)\frac{\epsilon^*\cdot q}{q^2}\, q^\mu + (M_{D_{(s)}} + M_V)A_1(q^2)\left(\epsilon^{*\mu} - \frac{\epsilon^*\cdot q}{q^2}\, q^\mu\right) \\ & - A_2(q^2)\frac{\epsilon^*\cdot q}{M_{D_{(s)}} + M_V}\left[p^\mu_{D_{(s)}} + p^\mu_V - \frac{M^2_{D_{(s)}} - M^2_V}{q^2}\, q^\mu\right]. \end{aligned} \tag{17}$$

- for P->P transition, only vector current contributes, due to the parity conservation

- all the dynamic information is contained in the form factor. Calculation of form factor is a central task of theorists.

- No full description in QCD theory: various models, typically a limited range of applicability, and a combination of them give a better picture of underline physics

- experimental extraction of form factors

Parametrization of form factor

Calculated in a typically limited range, extrapolate to further assuming an asymptotic behavior:

Heavy meson ChPT, large q^2 region, due to soft pion
QCD light Sum rule for small q^2 region for B->π

But there exits models that enable predicting the form factor in the whole kinematic region: covariant confined quark model (CCQM), and relativistic quark model (RQM) introduced below

Calculated numerically, discrete points $(q^2,\ F(q^2))$

For convenient use, approximate by some analytical expression, i.e., parametrization of form factor, without loss of accuracy in this step

Nowadays double-pole form

$$F(q^2) = \frac{F(0)}{\left(1 - \sigma_1 \frac{q^2}{M^2_{D^*_{(s)}}} + \sigma_2 \frac{q^4}{M^4_{D^*_{(s)}}}\right)},$$

z-expansion: based on rather general properties of the form factors including QCD dispersion relations and analyticity

$$z(t, t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}.$$

$$F_i(t) = \frac{1}{P(t)\phi(t, t_0)} \sum_{k=0}^{K} a_k(t_0)[z(t, t_0)]^k,$$

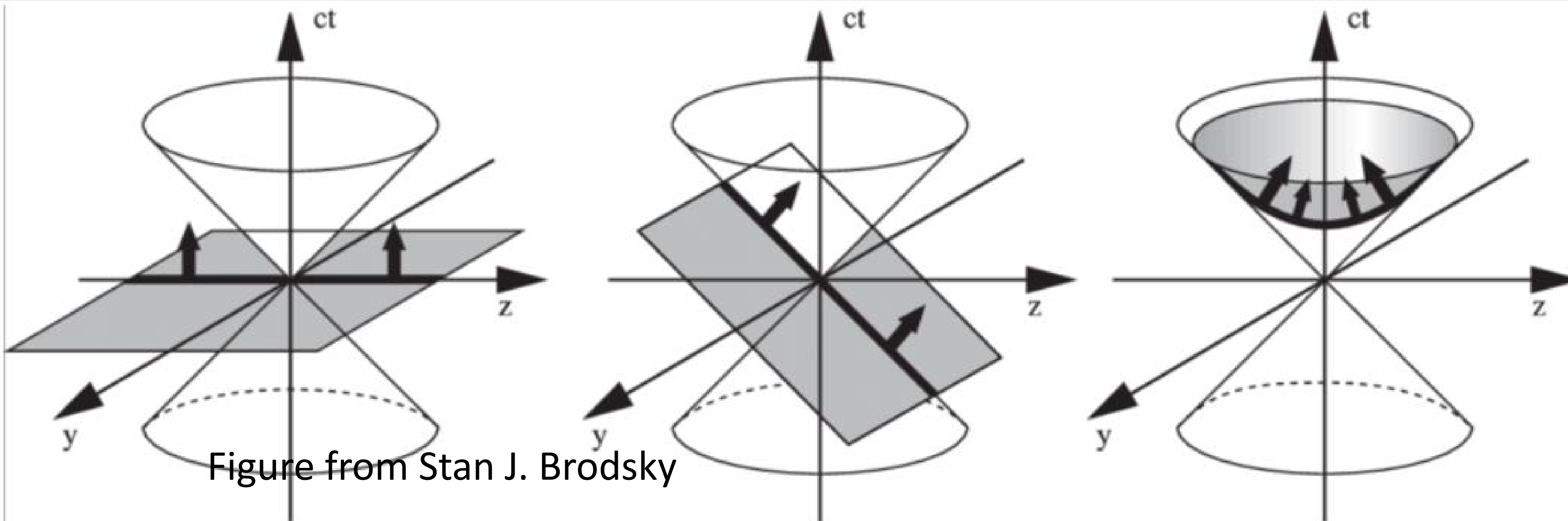
Experimental status

	current	planned
D^+D^-	$(8.296 \pm 0.031 \pm 0.064) \times 10^6$	$\sim 5 \times 10^7$
$D^0\bar{D}^0$	$(10.597 \pm 0.028 \pm 0.087) \times 10^6$	$\sim 6.4 \times 10^7$
$D_s\bar{D}_s$	$\sim 3.3 \times 10^6$	$\sim 2 \times 10^7$

TABLE I. The total numbers of D^+D^-, $D^0\bar{D}^0$, $D_s^+D_s^-$ pairs from BESIII collaboration, where in the data-taking plan the future data samples will be 6 times as large as the current ones. The number of $D\bar{D}$ pair is from Ref. [27].

	Belle	BelleII
$B\bar{B}$	$(7.72 \pm 0.11) \times 10^8$	$\sim 3.9 \times 10^{10}$
$B_s\bar{B}_s$	$(6.53 \pm 0.66) \times 10^6$	$\sim 3.3 \times 10^8$

TABLE II. The total numbers of $B\bar{B}$ and $B_s^+B_s^-$ pairs from Belle collaboration, while BelleII will have the data samples of 50 times as large as Belle by the mid of next decade. The number of $B\bar{B}$ and $B_s\bar{B}_s$ pairs for Belle collaboration are from Refs. [15, 16].



The instant form	The front form	The point form
$\tilde{x}^0 = ct$	$\tilde{x}^0 = ct+z$	$\tilde{x}^0 = \tau \quad , \quad ct = \tau\cosh\omega$
$\tilde{x}^1 = x$	$\tilde{x}^1 = x$	$\tilde{x}^1 = \omega \quad , \quad x = \tau\sinh\omega\,\sin\theta\,\cos\phi$
$\tilde{x}^2 = y$	$\tilde{x}^2 = y$	$\tilde{x}^2 = \theta \quad , \quad y = \tau\sinh\omega\,\sin\theta\,\sin\phi$
$\tilde{x}^3 = z$	$\tilde{x}^3 = ct-z$	$\tilde{x}^3 = \phi \quad , \quad x = \tau\sinh\omega\,\cos\theta$

$$\tilde{g}_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \qquad \tilde{g}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & \frac{1}{2} \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \frac{1}{2} & 0 & 0 & 0 \end{pmatrix} \qquad \tilde{g}_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -\tau^2 & 0 & 0 \\ 0 & 0 & -\tau^2\sinh^2\omega & 0 \\ 0 & 0 & 0 & -\tau^2\sinh^2\omega\,\sin^2\theta \end{pmatrix}$$

Generalized Hamiltonian dynamics

Paul A.M. Dirac (Cambridge U.) (1950)

Published in: *Can.J.Math.* 2 (1950) 129-148

Theoretical tools (1)

Covariant Light Front Quark Model (CLFQM): relativistic feature compared to ISGW nonrelativistic quark model.

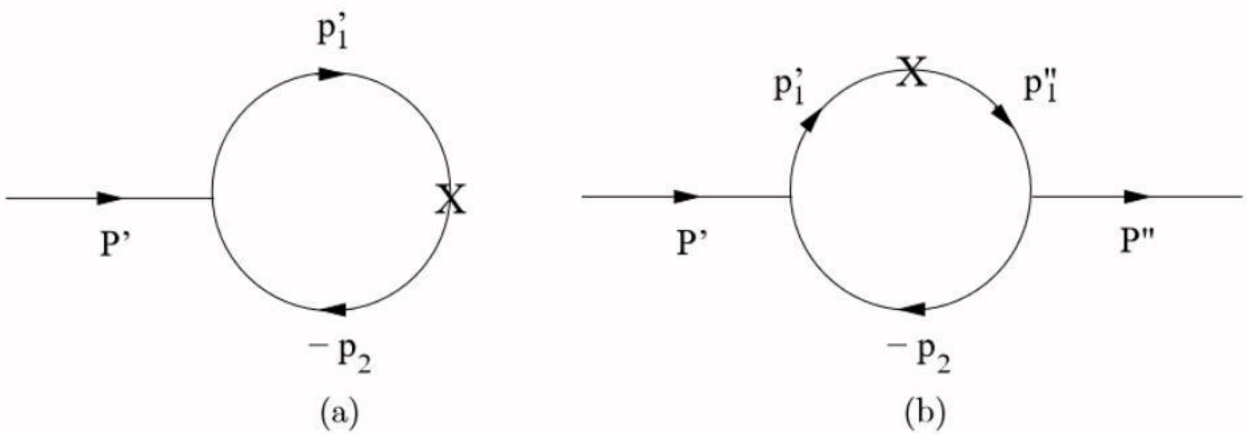


FIG. 1: Feynman diagrams for (a) meson decay and (b) meson transition amplitudes, where $P'^{(\prime\prime)}$ is the incoming (outgoing) meson momentum, $p_1'^{(\prime\prime)}$ is the quark momentum, p_2 is the anti-quark momentum and X denotes the corresponding $V-A$ current vertex.

Feynman rule

1. Momentum variables expressed in the light front coordinates

2. Wave function of the (axial-vector, vector, scalar, pseudo-scalar) meson encodes the bound state nature of qqbar

3. Vertex comes from the SM, Melosh transformation:

The connection between spin states in the rest frame and infinite momentum frame Or between spin states in the conventional equal time dynamics and the light-front dynamics

4. Fermion internal line denotes a spin-1/2 propagator as usual

5. quark masses as parameters, but fixed for all calculations

$$\varphi' = \varphi'(x_2, p'_\perp) = 4\left(\frac{\pi}{\beta'^2}\right)^{\frac{3}{4}}\sqrt{\frac{dp'_z}{dx_2}}\exp\left(-\frac{p'^2_z + p'^2_\perp}{2\beta'^2}\right),$$

$$\varphi'_p = \varphi'_p(x_2, p'_\perp) = \sqrt{\frac{2}{\beta'^2}}\,\varphi', \qquad \frac{dp'_z}{dx_2} = \frac{e'_1 e_2}{x_1 x_2 M'_0}.$$

Parameter β characterizing the size of hadron, will be fixed by decay constant

Definition of decay constant

The decay constants for $J = 0, 1$ mesons are defined by the matrix elements

$$\langle 0|A_\mu|P(P')\rangle \equiv \mathcal{A}^P_\mu = if_P P'_\mu, \qquad \langle 0|V_\mu|S(P')\rangle \equiv \mathcal{A}^S_\mu = f_S P'_\mu,$$

$$\langle 0|V_\mu|V(P',\varepsilon')\rangle \equiv \mathcal{A}^V_\mu = M'_V f_V \varepsilon'_\mu, \quad \langle 0|A_\mu|{}^{3(1)}A(P',\varepsilon')\rangle \equiv \mathcal{A}^{{}^3A({}^1A)}_\mu = M'_{{}^3A({}^1A)} f_{{}^3A({}^1A)} \varepsilon'_\mu,$$

Expression for decay constant

$$f_P = 2\frac{\sqrt{2N_c}}{16\pi^3}\int dx_2 d^2p'_\perp \frac{1}{\sqrt{x_1x_2}\widetilde{M'_0}}(m'_1x_2+m_2x_1)\,\varphi'(x_2,p'_\perp)$$

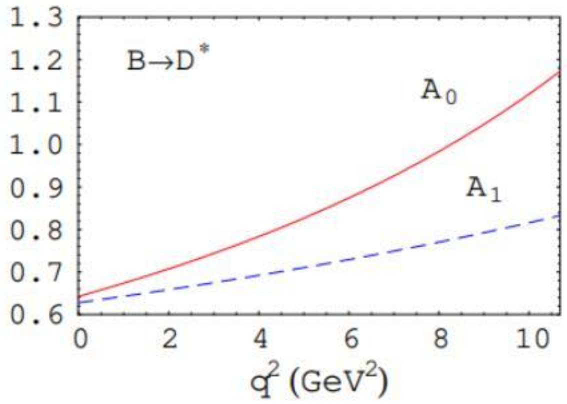
The values for decay constant are available from experiment, lattice, or another theory calculation.

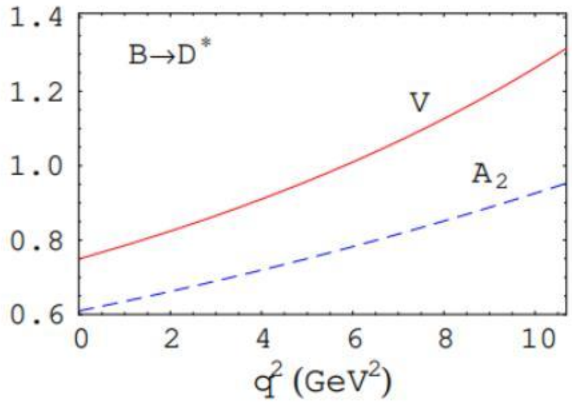
Expression for form factors

To be specific, we give the explicit forms of $u_\pm(q^2)$ obtained in the covariant light-front model

$$\begin{aligned}
u_+(q^2) &= \frac{N_c}{16\pi^3}\int dx_2 d^2p'_\perp \frac{h'_P h''_S}{x_2\hat{N}'_1\hat{N}''_1}\Big[-x_1(M'^2_0+M''^2_0)-x_2q^2 \\
&\quad +x_2(m'_1+m''_1)^2+x_1(m'_1-m_2)^2+x_1(m''_1+m_2)^2\Big], \\
u_-(q^2) &= \frac{N_c}{16\pi^3}\int dx_2 d^2p'_\perp \frac{2h'_P h''_S}{x_2\hat{N}'_1\hat{N}''_1}\Bigg\{x_1x_2M'^2+p'^2_\perp+m'_1m_2+(m''_1+m_2)(x_2m'_1+x_1m_2) \\
&\quad -2\frac{q\cdot P}{q^2}\left(p'^2_\perp+2\frac{(p'_\perp\cdot q_\perp)^2}{q^2}\right)-2\frac{(p'_\perp\cdot q_\perp)^2}{q^2}+\frac{p'_\perp\cdot q_\perp}{q^2}\Big[M''^2-x_2(q^2+q\cdot P) \\
&\quad -(x_2-x_1)M'^2+2x_1M'^2_0-2(m'_1-m_2)(m'_1-m''_1)\Big]\Bigg\}. \qquad (3.20)
\end{aligned}$$

F	$F(0)$	$F(q^2_{\rm max})$	a	b	F	$F(0)$	$F(q^2_{\rm max})$	a	b
F_1^{BD}	0.67	1.22	1.25	0.39	F_0^{BD}	0.67	0.92	0.65	0.00
V^{BD^*}	0.75	1.32	1.29	0.45	$A_0^{BD^*}$	0.64	1.17	1.30	0.31
$A_1^{BD^*}$	0.63	0.83	0.65	0.02	$A_2^{BD^*}$	0.61	0.95	1.14	0.52





Results from Chua and Cheng, hep-ph/0310359, PRD2004

A big caution: <u>form factor not directly observables in experiment, while branching ratio is. Further observables.</u>

Relativistic Quark Model (RQM)

Theoretical tool (2)

developed by Ebet, Faustov, Galkin, e.g., refers to1705.07741, my recent collaborator

wave function Ψ_{Λ_Q}, which satisfy the relativistic quasipotential equation of the Schrödinger type [8]

$$\left(\frac{b^2(M)}{2\mu_R} - \frac{\mathbf{p}^2}{2\mu_R}\right)\Psi_{\Lambda_Q}(\mathbf{p}) = \int \frac{d^3q}{(2\pi)^3} V(\mathbf{p},\mathbf{q};M)\Psi_{\Lambda_Q}(\mathbf{q}), \qquad (1)$$

where the relativistic reduced mass and and the center-of-mass system relative momentum squared on the mass shell are given by

$$\mu_R = \frac{M_{\Lambda_Q}^4 - (m_Q^2 - m_d^2)^2}{4M_{\Lambda_Q}^3},$$

$$b^2(M) = \frac{[M_{\Lambda_Q}^2 - (m_Q + m_d)^2][M_{\Lambda_Q}^2 - (m_Q - m_d)^2]}{4M_{\Lambda_Q}^2}.$$

1. Based on quasipotential approach, 4 dimension reduced to 3 dimension

2. Wave function is solvable, not just assume a Gaussian type function

Expression for form factor: overlap between initial and final state wave functions

$$\langle\Lambda(P)|J_\mu^W|\Lambda_b(Q)\rangle = \int \frac{d^3p\, d^3q}{(2\pi)^6}\bar{\Psi}_{\Lambda\,\mathbf{P}}(\mathbf{p})\Gamma_\mu(\mathbf{p},\mathbf{q})\Psi_{\Lambda_b\,\mathbf{Q}}(\mathbf{q}),$$

$$\begin{aligned}
f_1^{TV(1)}(q^2) = & -\int \frac{d^3p}{(2\pi)^3}\bar{\Psi}_F\left(\mathbf{p}+\frac{2\epsilon_d}{E_F+M_F}\mathbf{\Delta}\right)\sqrt{\frac{\epsilon_Q(p)+m_Q}{2\epsilon_Q(p)}}\sqrt{\frac{\epsilon_q(p+\Delta)+m_q}{2\epsilon_q(p+\Delta)}}\\
&\times\left\{\frac{\epsilon_d}{E_F+M_F}\left[\frac{M_F}{\epsilon_q(p+\Delta)+m_q}+\frac{M_I}{\epsilon_Q(p)+m_Q}\right.\right.\\
&\left.+\frac{(M_I+M_F)\epsilon_d}{(\epsilon_q(p+\Delta)+m_q)(\epsilon_Q(p)+m_Q)}\frac{E_F-M_F}{E_F+M_F}\right]\\
&+\frac{\mathbf{p\Delta}}{\mathbf{\Delta}^2}\left[\frac{M_F}{\epsilon_q(p+\Delta)+m_q}-\frac{M_I}{\epsilon_Q(p)+m_Q}\right]\\
&\left.-\frac{1}{3}\frac{M_I+M_F}{E_F+M_F}\frac{\mathbf{p}^2}{(\epsilon_q(p+\Delta)+m_q)(\epsilon_Q(p)+m_Q)}\right\}\Psi_I(\mathbf{p});
\end{aligned}$$

$\mathbf{\Delta} = \mathbf{P}-\mathbf{Q};\ \epsilon(p)=\sqrt{m^2+\mathbf{p}^2}$ $\quad M_I, M_F$ mass of initial and final meson

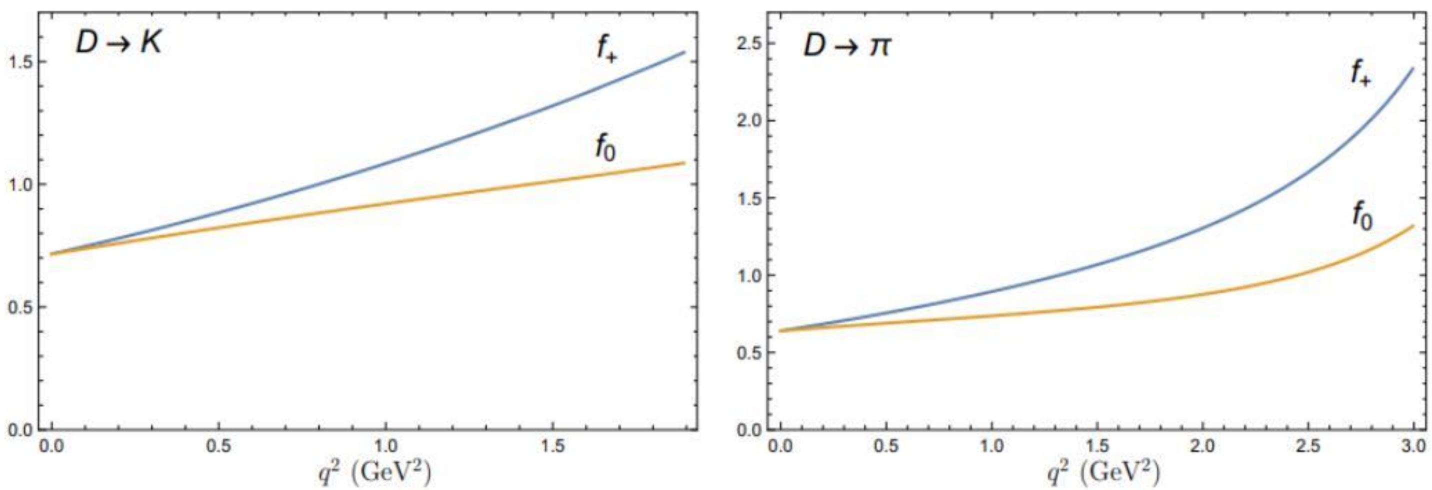
$$|\mathbf{\Delta}| = \sqrt{\frac{(M_I^2+M_F^2-q^2)^2}{4M_I^2}-M_F^2},$$

in the rest frame of mother particle

As it should be, the form factor depends only on q^2

TABLE I: Form factors of the weak D meson transitions.

Decay	Form factor	$F(0)$	$F(q^2_{\max})$	σ_1	σ_2
$D \to K$	f_+	0.716	1.538	0.902	1.07
	f_0	0.716	1.086	0.360	1.657
$D \to K^*$	V	0.927	1.305	0.356	-0.490
	A_0	0.655	1.048	0.432	-0.840
	A_1	0.608	0.660	0.410	0.166
	A_2	0.520	0.623	0.582	-0.917



Features of RQM

1. form factor are calculated in the framework of quarsipotential approach

2. systematic account of the relativistic effects including transformation of the meson wave function from the rest to moving reference frame and contributions of the intermediate negative-energy states.

3**. meson wave functions are taken from previous studies of meson spectroscopy. Parameters have been fixed.**

4. **calculated in the whole range of the transferred momentum q^2**

Helicity formalism

- To conveniently express observables, otherwise may be cumbersome.
- Conveniently work in the partial-wave basis
- The polarization observables are clearly identified.
- Often used in the experimental analysis (partial wave analysis)

Polarization for the virtual W boson has 4 components

orthonormality property

$$\epsilon^{\dagger}_{\mu}(\lambda_W)\epsilon^{\mu}(\lambda'_W) = g_{\lambda_W \lambda'_W}, \quad (\lambda_W, \lambda'_W = t, \pm, 0) \tag{7}$$

and satisfy the completeness relation

$$\epsilon_{\mu}(\lambda_W)\epsilon^{\dagger}_{\nu}(\lambda'_W) g_{\lambda_W \lambda'_W} = g_{\mu\nu}. \tag{8}$$

We can rewrite the contraction of leptonic and hadronic tensors by using the orthonormality and completeness relations as

$$\begin{aligned} L^{\mu\nu}H_{\mu\nu} &= L_{\mu'\nu'} g^{\mu'\mu} g^{\nu'\nu} H_{\mu\nu} \\ &= L_{\mu'\nu'} \epsilon^{\mu'}(\lambda_W)\epsilon^{\dagger\mu}(\lambda''_W) g_{\lambda_W \lambda''_W} \epsilon^{\dagger\nu'}(\lambda'_W)\epsilon^{\nu}(\lambda'''_W) g_{\lambda'_W \lambda'''_W} H_{\mu\nu} \\ &= L\left(\lambda_W, \lambda'_W\right) g_{\lambda_W \lambda''_W} g_{\lambda'_W \lambda'''_W} H\left(\lambda''_W \lambda'''_W\right), \end{aligned} \tag{9}$$

where $L(\lambda_W, \lambda'_W)$ and $H(\lambda_W, \lambda'_W)$ are the leptonic and hadronic tensors in the helicity-component space:

$$L\left(\lambda_W, \lambda'_W\right) = \epsilon^{\mu}(\lambda_W)\epsilon^{\dagger\nu}(\lambda'_W) L_{\mu\nu}, \quad H\left(\lambda_W, \lambda'_W\right) = \epsilon^{\dagger\mu}(\lambda_W)\epsilon^{\nu}(\lambda'_W) H_{\mu\nu}. \tag{10}$$

Calculations of hadronic current and leptonic current are performed in different frames!

$D \to P$ transition, we obtain

$$H_t = \frac{1}{\sqrt{q^2}}(m_1^2 - m_2^2)F_0(q^2),$$
$$H_\pm = 0,$$
$$H_0 = \frac{2m_1|\vec{p}_2|}{\sqrt{q^2}}F_1(q^2).$$

the transition $D \to V l^+ \nu_l$:

$$H_t \equiv \epsilon^{\dagger\mu}(t)\epsilon_2^{\dagger\nu}(0)T_{\mu\nu} = -\frac{2m_1|\vec{p}_2|}{\sqrt{q^2}}A_0(q^2),$$
$$H_\pm \equiv \epsilon^{\dagger\mu}(\pm)\epsilon_2^{\dagger\nu}(\pm)T_{\mu\nu} = -(m_1+m_2)A_1(q^2) \pm \frac{2m_1|\vec{p}_2|}{m_1+m_2}V(q^2),$$
$$H_0 \equiv \epsilon^{\dagger\mu}(0)\epsilon_2^{\dagger\nu}(0)T_{\mu\nu} = -\frac{m_1+m_2}{2m_2\sqrt{q^2}}\left(m_1^2 - m_2^2 - q^2\right)A_1(q^2) + \frac{1}{m_1+m_2}\frac{2m_1^2|\vec{p}_2|^2}{m_2\sqrt{q^2}}A_2(q^2).$$

Observables

Then, we obtain the twofold differential decay distribution on q^2 and $\cos\theta$:

$$\frac{d\Gamma\left(D \to P(V) l^+ \nu_l\right)}{dq^2 d\cos\theta} = \frac{G_F^2 |V_{cq}|^2 |\vec{p}_2| q^2 v^2}{32(2\pi)^3 m_1^2} \times \left[\left(1+\cos^2\theta\right)\mathcal{H}_U + 2\sin^2\theta\mathcal{H}_L + 2\cos\theta\mathcal{H}_P \right.$$
$$\left. +2\delta_l\left(\sin^2\theta\mathcal{H}_U + 2\cos^2\theta\mathcal{H}_L + 2\mathcal{H}_S - 4\cos\theta\mathcal{H}_{SL}\right)\right].$$

Further integrating over $\cos\theta$, the differential q^2 distribution will be

$$\frac{d\Gamma\left(D \to P(V) l^+ \nu_l\right)}{dq^2} = \frac{G_F^2 |V_{cq}|^2 |\vec{p}_2| q^2 v^2}{12(2\pi)^3 m_1^2} \times \mathcal{H}_{tot},$$

with $\mathcal{H}_{tot} = \mathcal{H}_U + \mathcal{H}_L + \delta_l\left(\mathcal{H}_U + \mathcal{H}_L + 3\mathcal{H}_S\right)$.

$$\mathcal{A}_{FB}^l(q^2) = \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{dq^2 d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{dq^2 d\cos\theta}}{\int_0^1 d\cos\theta \frac{d\Gamma}{dq^2 d\cos\theta} + \int_{-1}^0 d\cos\theta \frac{d\Gamma}{dq^2 d\cos\theta}}$$
$$= \frac{3}{4}\frac{H_P - 4\delta_l H_{SL}}{H_{tot}}.$$

the longitudinal polarization vector:

$$s_L^\mu = \frac{1}{m_l}\left(|\vec{k}_1|,\ E_1 \sin\theta,\ 0,\ E_1 \cos\theta\right)$$

Polarized differential decay rate

$$\frac{d\Gamma(s_L)}{dq^2} = \frac{G_F^2|V_{cq}|^2|\vec{p}_2|q^2v^2}{12(2\pi)^3m_1^2}\left[-3\delta_l\,|H_t|^2 + (1-\delta_l)\left(|H_+|^2 + |H_-|^2 + |H_0|^2\right)\right]$$
$$= \frac{G_F^2|V_{cq}|^2|\vec{p}_2|q^2v^2}{12(2\pi)^3m_1^2}\left[\mathcal{H}_U + \mathcal{H}_L - \delta_l\left(\mathcal{H}_U + \mathcal{H}_L + 3\mathcal{H}_S\right)\right].$$

Longitudinal polarization of lepton

$$P_L^l(q^2) = \frac{\mathcal{H}_U + \mathcal{H}_L - \delta_l\left(\mathcal{H}_U + \mathcal{H}_L + 3\mathcal{H}_S\right)}{\mathcal{H}_{tot}}$$

Longitudinal polarization of vector meson

$$F_L^l(q^2) = \frac{d\Gamma(\lambda_V = 0)/dq^2}{d\Gamma/dq^2} = \frac{(1+\delta_l)\mathcal{H}_L + 3\delta_l\mathcal{H}_S}{\mathcal{H}_{tot}},$$

Polarization observables are very sensitive to different New Physics models. ***Discriminator***

Branching ratio is not the whole landscape, and we need more observables both in theory and experiment

TABLE X: Our predictions for $F_L^\tau(D^*_{(s)})$ and $P_L^\tau(D^{(*)}_{(s)})$, compared with other models as well as experimental values. In parenthesis, we also include the value of $F_L^e(D^*)$ for $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$.

Observables	Approach	$\bar{B} \to D\tau^-\bar{\nu}_\tau$	$\bar{B} \to D^*\tau^-\bar{\nu}_\tau\ (e^-\bar{\nu}_e)$	$B_s \to D_s\tau^-\bar{\nu}_\tau$	$B_s \to D_s^*\tau^-\bar{\nu}_\tau$
$F_L^\tau(D^*_{(s)})$	CLFQM	-	0.451 (0.521)	-	0.453
	SM1 [70]	-	0.46 ± 0.04	-	-
	SM2 [71]	-	0.455	-	0.433
	PQCD [72]	-	0.43	-	0.43
	Belle [73]	-	$0.60 \pm 0.08 \pm 0.04$ (0.56 ± 0.02)	-	-
$P_L^\tau(D^{(*)}_{(s)})$	CLFQM	0.32	-0.51	0.33	-0.51
	SM1	0.325 ± 0.09 [74]	-0.497 ± 0.013 [75]	-	-
	SM2 [71]	0.352	-0.501	-	-0.520
	PQCD [72]	0.30	-0.53	0.30	-0.53
	Belle [76]	-	$-0.38 \pm 0.51^{+0.21}_{-0.16}$	-	-

differential decay rates

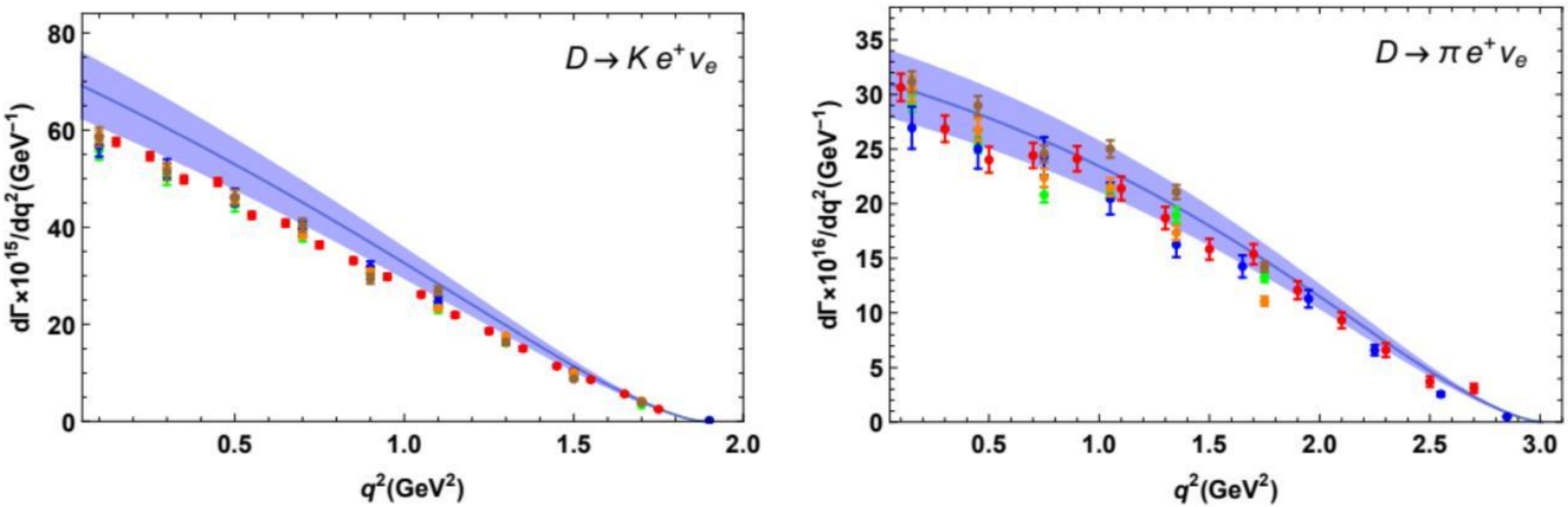
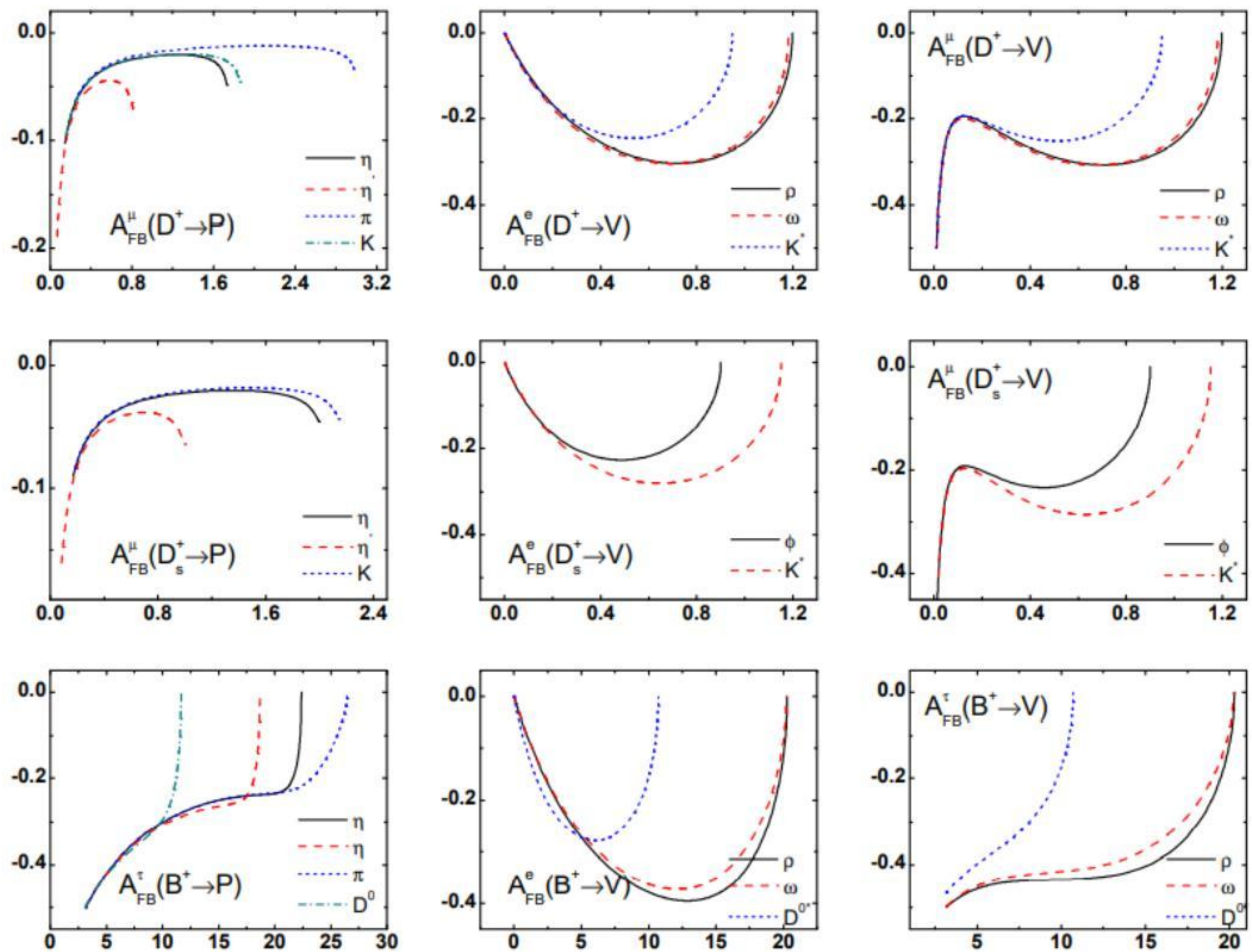
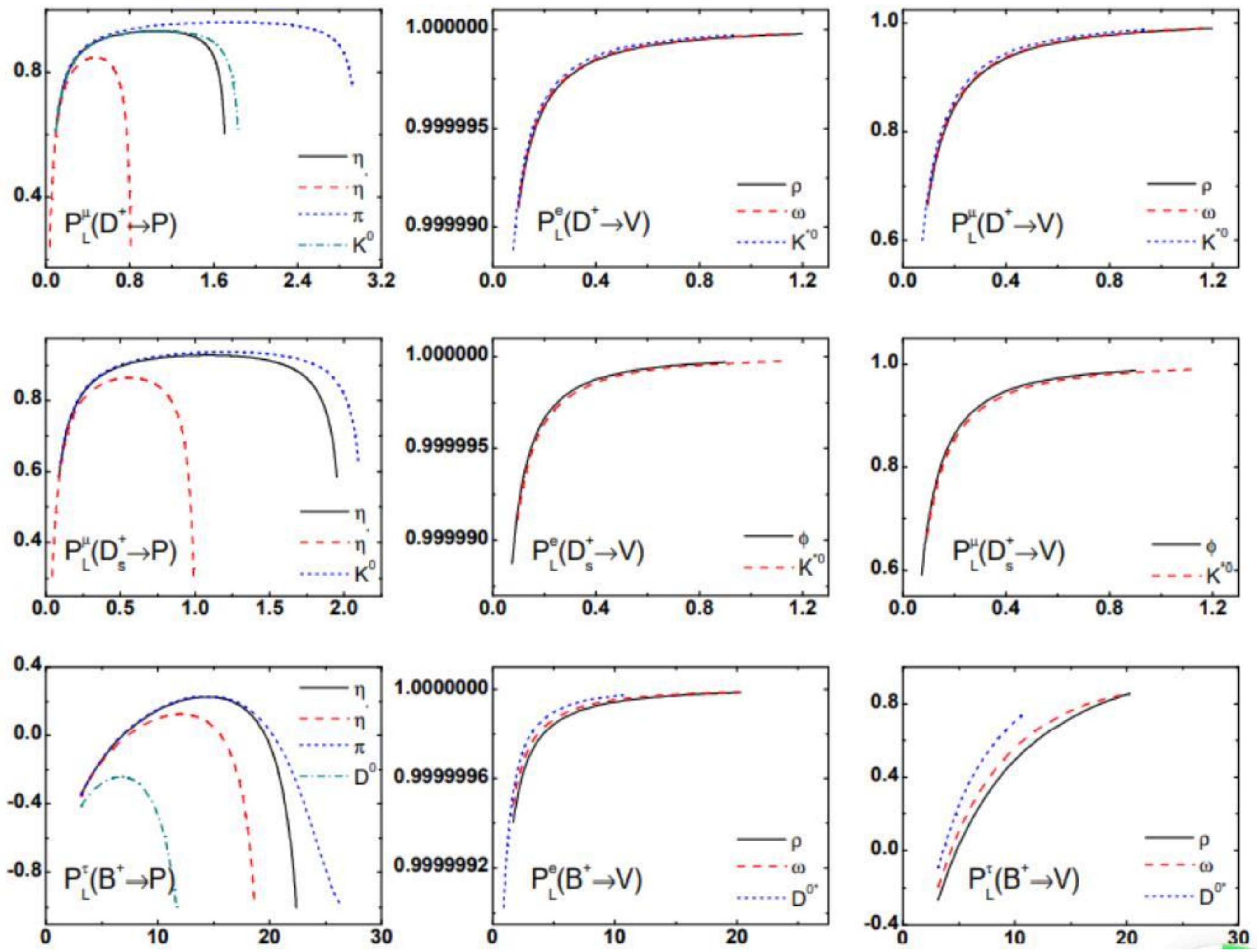


FIG. 4: The differential decay rate for the decays $D \to K e^+ \nu_e$ and $D \to \pi e^+ \nu_e$. The solid line indicates our central values and the band indicates the estimated uncertainty. We have used the experimental data from BES III for neutral D^0 [83] (red dots with error bars) and charged D^+ [50] (green dots with error bars), BaBar [84, 85] (blue dots and error bars) and CLEO [86] for neutral D^0 (orange dots and error bars) and charged D^+ (brown dots with error bars).

Forward-backward asymmetry



Longitudinal polarization



- Forward-backward asymmetry, lepton polarization, and convexity parameters for semileptonic decays of $\bar{B}^0 \to D^+ l^- \bar{\nu}_l$ and $\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$

		$\langle \mathcal{A}^e_{FB} \rangle$	$\langle \mathcal{A}^\tau_{FB} \rangle$	$\langle P^e_L \rangle$	$\langle P^\tau_L \rangle$	$\langle P^e_T \rangle$	$\langle P^\tau_T \rangle$	$\langle C^e_F \rangle$	$\langle C^\tau_F \rangle$
$\bar{B}^0 \to D^+ l^- \bar{\nu}_l$	CLFQM	-1.04×10^{-6}	-0.36	-1	0.32	1.06×10^{-3}	0.84	-1.5	-0.27
	CCQM	-1.17×10^{-6}	-0.36	-1	0.33		0.84	-1.5	-0.26
$\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$	CLFQM	0.22	0.054	-1	-0.51	0.46×10^{-3}	0.47	-0.42	-0.056
	CCQM	0.19	0.027	-1	-0.50		0.46	-0.47	-0.062

Comparison between CLFQM and RQM: work in the same way for heavy to heavy transition, but differ for heavy to light transition, which should be due to the different treatment of relativistic effects.

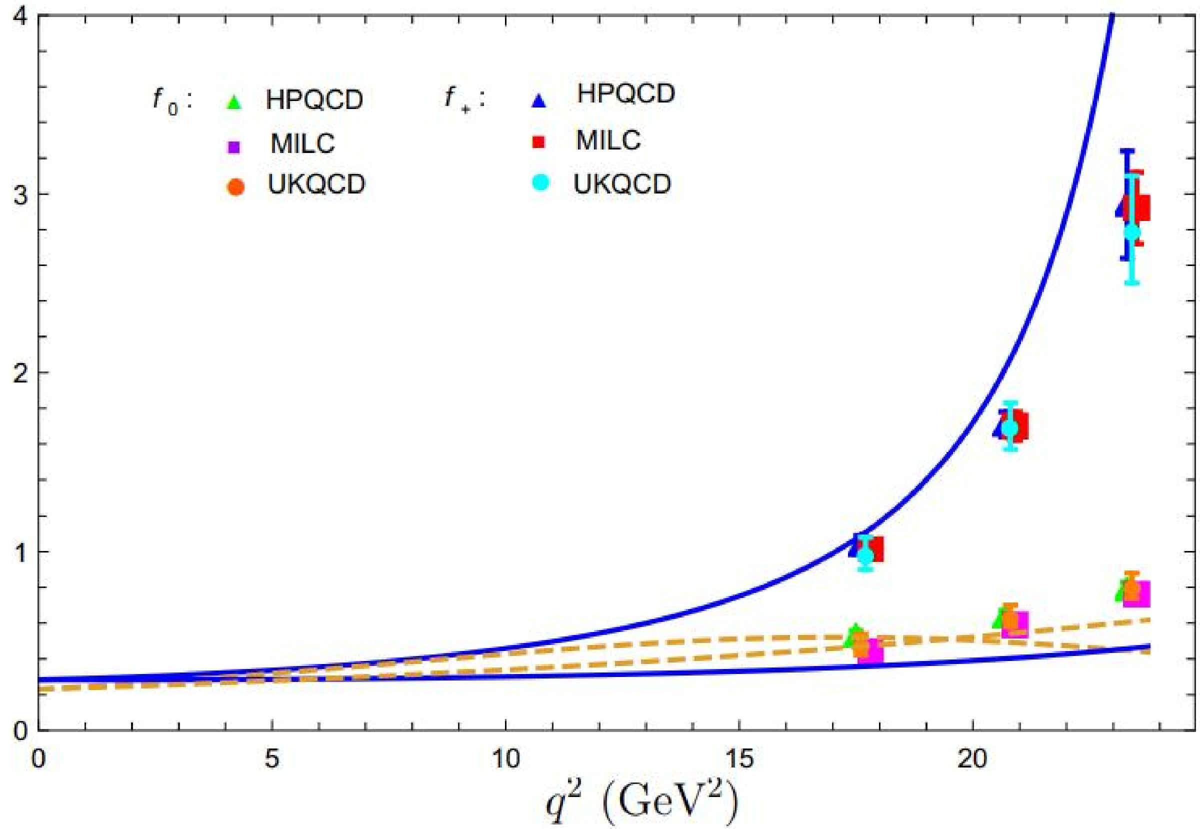


FIG. 2: Same as in Fig. 1, but for the form factors of the weak $B_s \to K$ transitions. For the orange dashed lines, the upper one below $q^2 < 15$ GeV^2 corresponds to $f_+(q^2)$, and the lower one $f_0(q^2)$. HPQCD, MILC and UKQCD data are from Refs. [29], [36] and [32], respectively.

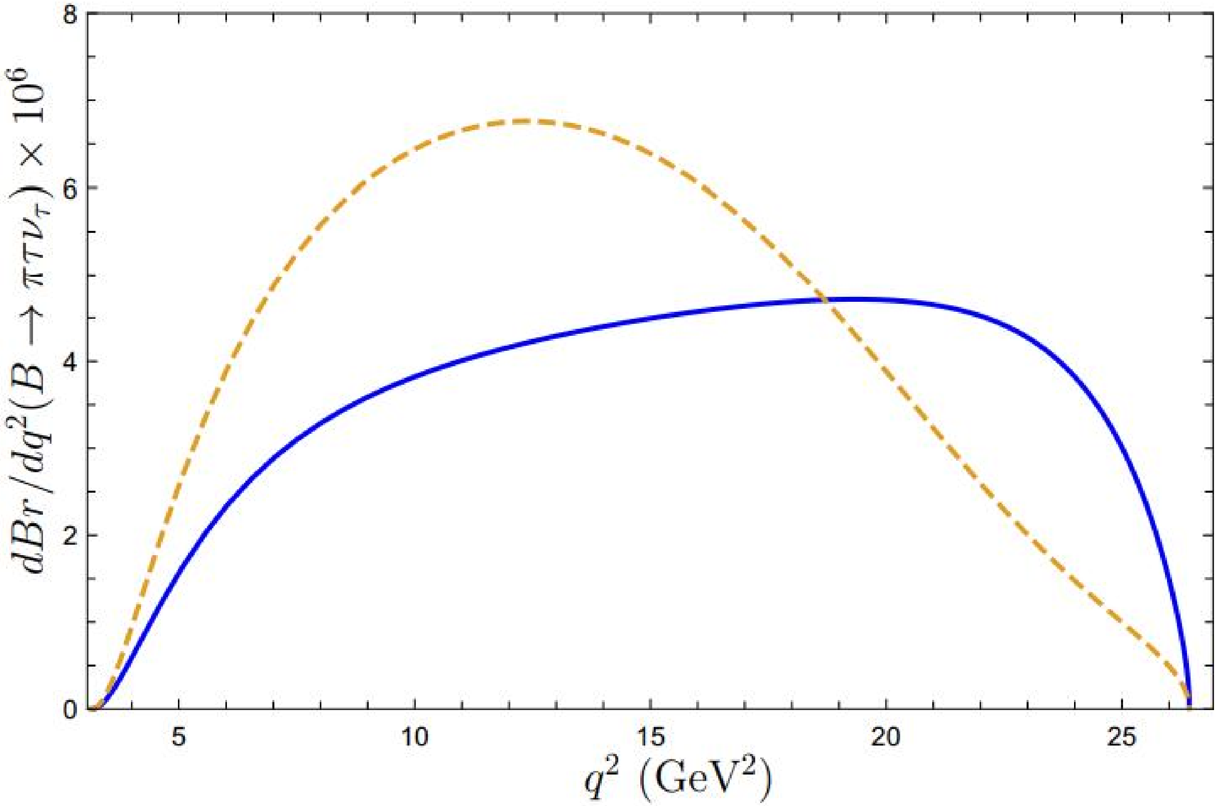


FIG. 4: Differential branching fractions of the semileptonic $B \to \pi\tau\nu_\tau$ decay. Comparison of theoretical predictions (RQM – solid blue lines, CLFQM – orange dashed lines).

Further remarks

- How to reliably treat baryon semileptonic baryon decay?

  two more assumptions:

    1) quark-diquark picture,

    2) how to fix the parameter in the wave function

- Error uncertainty, to disentangle NP signal from SM. Hard to quantify! High precision is required!

R_D, R_{D^*} and New Physics?

Experiment	R(D*)	R(D)	Rescaled Correlation (stat/syst/total)
BaBar	0.332 ± 0.024 ± 0.018	0.440 ± 0.058 ± 0.042	-0.45/-0.07/-0.31
BELLE	0.293 ± 0.038 ± 0.015	0.375 ± 0.064 ± 0.026	-0.56/-0.11/-0.50
LHCb	0.336 ± 0.027 ± 0.030	-	-
BELLE	$0.270 \pm 0.035\ ^{+0.028}_{-0.025}$	-	-
LHCb	0.280 ± 0.018 ± 0.029	-	-
BELLE	0.283 ± 0.018 ± 0.014	0.307 ± 0.037 ± 0.016	-0.53/-0.51/-0.51
Average .txt	**0.295 ± 0.011 ± 0.008**	**0.340 ± 0.027 ± 0.013**	**-0.39/-0.34/-0.38**

From heavy flavor averaging group

From heavy flavor averaging group

	R(D)	R(Di*)
)8 [arXiv:1606.08030 [hep-ph]]	0.299 ± 0.003	
.Rev. D95 (2017) no.11, 115008 [arXiv:1703.05330 [hep-ph]]	0.299 ± 0.003	0.257 ± 0.003
[arXiv:1707.09509 [hep-ph]]		0.260 ± 0.008
arXiv:1707.09977 [hep-ph]]	0.299 ± 0.004	0.257 ± 0.005
	0.299 ± 0.003	**0.258 ± 0.005**

The arithmetic average is used only for illustration and doesn't imply consent from the authors of the calculations. **The SM uncertainty is currently subject to debate** that HFLAV is following
without taking a stance in this.

R(D) and R(D^*) exceed the SM predictions given in the last row of the table above, by **1.4σ and 2.5σ** respectively. Considering the R(D)-R(D^*)) correlation of -0.38, the resulting combined χ^2 is 12.33 for 2 degree of freedom, corresponding to a p-value of 2.07×10^{-3}. The difference with the SM predictions reported above,corresponds to about 3.08σ.

Thank you for your attention

Email: xwkang@bnu.edu.cn