Semileptonic transition of $B \to D_2^*(2460)\ell\bar{\nu}$ in QCD sum rules

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Contents

1 Introduction
2 QCD Sum Rules
3 Leptonic Decay Constant of $D_2^*(2460)$ Tensor Meson
   • The physical side of correlation function
   • The QCD side of correlation function
4 Semileptonic Transition of $B \rightarrow D_2^*(2460)\ell\bar{\nu}$
   • The physical side of correlation function
   • The QCD side of correlation function
5 Conclusions
Our Motivations:

- The semileptonic decays of $B$ meson are very promising tools in constraining the standard model parameters:
  - determination of the elements of the CKM matrix
  - understanding the origin of the CP violation
  - new physics effects

- The BaBar Collaboration has recently measured the ratios for the branching fractions of the $B$ to charmed pseudoscalar $D$ and vector $D^*$ mesons at $\tau$ channel to those of the $e$ and $\mu$ channels [1]. The obtained results deviate at the level of $3.4 \sigma$ from the existing theoretical predictions in SM [1,2].
Over the last few years, the radially excited charmed mesons have been in the focus of much attention both theoretically and experimentally. In 2010, BaBar Collaboration reported their isolation of a number of orbitally excited charmed [3]. This report has stimulated the theoretical works devoted to the semileptonic decays of $B$ meson into the orbitally excited charmed meson. As the decays of $B$ meson into orbitally excited charmed mesons can provide a substantial contribution to the total semileptonic decay width.
QCD Sum Rules:

- Among the non-perturbative methods, QCD Sum Rule provide the most powerful information about the hadron properties.
- In 1979, the QCD sum rule proposed by Shifman, Vainshtein, and Zakharov to calculate the non-perturbative contributions in meson physics [4].
- This method is generalized to baryons by Ioffe in 1981 [5].
- In 1986, it is generalized to finite temperature and density by Shaposhnikov and Bochkarev [6].
In the QCD sum rule, hadrons are represented by their interpolating quark currents. The main object in this approach is the so called correlation function expressed in terms of these interpolating currents:

\[
\Pi(q^2) = i \int d^4x e^{iq \cdot x} \langle 0 \mid \mathcal{T} \left\{ J(x) \bar{J}(0) \right\} \mid 0 \rangle
\]  

(1)

\( \mathcal{T} \): time ordering operator
\( J(x) \): quark current
Following the general idea of the QCD sum rule approach, the correlation function is calculated via two different ways:

- **phenomenological or physical side**: This correlation function is calculated in the framework of the operator product expansion (OPE), where the short- and long-distance quark-gluon interactions are separated.

- **theoretical or QCD side**: The correlator is calculated in hadronic language by inserting a complete set of hadronic states.

The sum rules for the physical quantities is obtained matching these two representations of the correlation function via dispersion relation.
Leptonic Decay Constant of $D_2^*(2460)$ Tensor Meson:

In order to obtain the branching ratio of transition of $B \rightarrow D_2^*(2460)\ell\bar{\nu}$, we need the leptonic decay constant of $D_2^*(2460)$:

The starting point is to consider the following two-point correlation function:

$$\Pi_{\mu\nu,\alpha\beta}(q^2) = i \int d^4 x \ e^{i q \cdot (x-y)} \langle 0 \mid T[J_{\mu\nu}(x)\bar{J}_{\alpha\beta}(y)] \mid 0 \rangle, \quad (2)$$

the interpolating current of the $D_2^*(2460)$ tensor meson:

$$J_{\mu\nu}(x) = \frac{i}{2} \left[ \bar{u}(x)\gamma_\mu \overset{\leftrightarrow}{D}_\nu (x)c(x) + \bar{u}(x)\gamma_\nu \overset{\leftrightarrow}{D}_\mu (x)c(x) \right], \quad (3)$$
Content

1. Introduction

2. QCD Sum Rules

3. Leptonic Decay Constant of $D_2^*(2460)$ Tensor Meson
   - The physical side of correlation function
   - The QCD side of correlation function

4. Semileptonic Transition of $B \rightarrow D_2^*(2460)\ell\bar{\nu}$
   - The physical side of correlation function
   - The QCD side of correlation function

5. Conclusions

Hayriye Sundu Pamuk

Semileptonic transition of $B \rightarrow D_2^*(2460)\ell\bar{\nu}$ in QCD sum rules
In the physical side, the correlation function is obtained inserting complete set of hadronic state having the same quantum numbers as the interpolating current $j_{\mu\nu}$ into Eq. (2). After performing integral over four-x, we obtain the physical side of correlation function as following form:

$$
\Pi_{\mu\nu,\alpha\beta} = \frac{\langle 0 | J_{\mu\nu}(0) | D^*_2(2460) \rangle \langle D^*_2(2460) | \bar{J}_{\alpha\beta}(0) | 0 \rangle}{m^2_{D^*_2(2460)} - q^2} + \cdot \cdot \cdot \quad (4)
$$

$$
\langle 0 | J_{\mu\nu}(0) | D^*_2(2460) \rangle = f_{D^*_2(2460)} m^3_{D^*_2(2460)} \epsilon_{\mu\nu}. \quad (5)
$$

Combining Eq. (4) and Eq. (5) and performing summation over polarization tensor via:

$$
\Pi_{\mu\nu,\alpha\beta} = \frac{f^2_{D^*_2(2460)} m^6_{D^*_2(2460)}}{m^2_{D^*_2(2460)} - q^2} \left\{ \frac{1}{2} (g_{\mu\alpha} g_{\nu\beta} + g_{\mu\beta} g_{\nu\alpha}) \right\} + \text{oth. str.} \quad (6)
$$
Content

1. Introduction
2. QCD Sum Rules
3. Leptonic Decay Constant of $D_2^*(2460)$ Tensor Meson
   - The physical side of correlation function
   - The QCD side of correlation function
4. Semileptonic Transition of $B \to D_2^*(2460)\ell\bar{\nu}$
   - The physical side of correlation function
   - The QCD side of correlation function
5. Conclusions
The correlation function in QCD side, is calculated in deep Euclidean region, $q^2 \ll 0$, by the help of operator product expansion (OPE) where the short and long distance contributions are separated. The short distance effects are calculated using the perturbation theory, while the long distance effects are parameterized in terms of quark and gluon condensates.

\[
\Pi(q^2) = \int ds \frac{\rho^{\text{pert}}(s) + \rho^{\text{nonpert}}(s)}{s - q^2}
\]

the spectral density: $\rho(s) = \frac{1}{\pi} Im[\Pi(s)]$ (7)
Now, we proceed to calculate the spectral density $\rho(s)$. Making use of the tensor current presented in Eq. (3) into the correlation function in Eq. (2) and contracting out all quark fields applying the Wick’s theorem, we get:

$$\Pi = \frac{i}{4} \int d^4xe^{iq(x-y)} \left\{ \text{Tr} \left[ S_u(y-x)\gamma_\mu \bar{D}_\nu(x) \bar{D}_\beta(y)S_c(x-y)\gamma_\alpha \right] \right.$$ 

$$+ [\beta \leftrightarrow \alpha] + [\nu \leftrightarrow \mu] + [\beta \leftrightarrow \alpha, \nu \leftrightarrow \mu] \right\}. \quad (8)$$
the heavy and light quarks propagators:

\[
S^{ij}_c(x - y) = \frac{i}{(2\pi)^4} \int d^4k e^{-ik \cdot (x-y)} \left\{ \frac{k + mc}{k^2 - m_c^2} \delta_{ij} + \cdots \right\}, \quad (9)
\]

\[
S^{ij}_u(x - y) = i \frac{x - y}{2\pi^2 (x-y)^4} \delta_{ij} - \frac{m_u}{4\pi^2 (x-y)^2} \delta_{ij}
- \frac{\langle \bar{u}u \rangle}{12} \left[ 1 - i \frac{m_u}{4} (x - y) \right] \delta_{ij}
- \frac{(x - y)^2}{192} m_u^2 \langle \bar{u}u \rangle \left[ 1 - i \frac{m_u}{6} (x - y) \right] \delta_{ij} + \cdots, \quad (10)
\]

The gluon condensates are also ignored since their contributions are suppressed by large denominators, so they play minor roles in calculations.
After dimensional regularization and taking the imaginary part and selecting the coefficient of the aforesaid structure, the spectral densities are obtained as:

\[ \rho^{pert}(s) = \frac{N_c}{960 \pi^2 s^3} (m_c^2 - s)^4 (2m_c^2 + 3s), \]  

(11) and

\[ \rho^{nonpert}(s) = -\frac{N_c}{48s} m_c m_0^2 \langle \bar{u}u \rangle. \]  

(12)
After achieving the correlation function in two different ways, we match these two different representations to obtain two-point QCD sum rules. In order to suppress contributions of the higher states and continuum, we apply Borel transformation with respect to the initial momentum squared, $q^2$, to both sides of the sum rules and use the quark-hadron duality assumption. As a result, the following sum rule for the meson-current coupling constant of the $D_2^*(2460)$ tensor meson is obtained:

$$f_{D_2^*}^2 e^{-m_{D_2^*}^2/M^2} = \frac{1}{m_{D_2^*}^6} \int_{m_c^2}^{s_0} ds \left( \rho^{\text{pert}}(s) + \rho^{\text{nonpert}}(s) \right) e^{-s/M^2}, \quad (13)$$

The sum rules contain two auxiliary parameters:

- $7.6 \leq s_0 \leq 8.7$
- $3 \text{ GeV}^2 \leq M^2 \leq 6 \text{ GeV}^2$
Introduction

QCD Sum Rules

Leptonic Decay Constant of $D_2^*(2460)$ Tensor Meson

Semileptonic Transition of $B \to D_2^*(2460)\ell\nu$ Conclusions

The physical side of correlation function

The QCD side of correlation function

The semileptonic transition of $B \to D_2^*(2460)\ell\nu$ in QCD sum rules

The figure shows the dependence of $f_{D_2^*(2460)}$ on $M^2(\text{GeV}^2)$ for different models.

- **Toplam** (black line)
- **Pertubatif** (red line)
- **Non-Pertubatif** (d≤5) (blue line)
- **Non-Pertubatif** (d>5) (brown line)
- **Yuksek Durumlar ve Sureklilik** (green line)

The graph plots $f_{D_2^*(2460)}$ against $M^2(\text{GeV}^2)$ from 3.0 to 6.0.
<table>
<thead>
<tr>
<th>Present Work</th>
<th>Experiment [7]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{D^*_2(2460)}$</td>
<td>(2.50 ± 0.48) GeV</td>
</tr>
<tr>
<td>$f_{D^*_2(2460)}$</td>
<td>0.0317 ± 0.0092</td>
</tr>
</tbody>
</table>
Semileptonic Transition of $B \rightarrow D_2^*(2460)\ell\bar{\nu}$:

$$\mathcal{H}_{\text{eff}}^{\text{tree}} = \frac{G_F}{\sqrt{2}} V_{bc} \bar{c}\gamma_{\mu}(1 - \gamma_5)b\bar{\ell}\gamma^\mu(1 - \gamma_5)\nu$$

(14)
Tree-point correlation function in the QCD sum rules:

$$\Pi_{\mu\alpha\beta} = i^2 \int d^4x \int d^4y e^{-ipx} e^{-ip'y} \langle 0 \mid \mathcal{T} [J^{D^*_2}_{\alpha\beta}(y)J^{tr}_\mu(0)J^B(x)] \mid 0 \rangle, \quad (15)$$

$$J^{tr}_\mu(0) = \bar{c}(0)\gamma_\mu(1 - \gamma_5)b(0) \quad (16)$$

$$J^B(x) = \bar{u}(x)\gamma_5b(x) \quad (17)$$

$$J^{D^*_2}_{\alpha\beta}(y) = \frac{i}{2} \left[ \bar{u}(y)\gamma_\alpha \overset{\leftrightarrow}{D}_\beta(y)c(y) + \bar{u}(y)\gamma_\beta \overset{\leftrightarrow}{D}_\alpha(y)c(y) \right], \quad (18)$$
Introduction

QCD Sum Rules

Leptonic Decay Constant of $D_2^*(2460)$ Tensor Meson

Semileptonic Transition of $B \to D_2^*(2460)\ell\nu$

Conclusions

Content

1. Introduction
2. QCD Sum Rules
3. Leptonic Decay Constant of $D_2^*(2460)$ Tensor Meson
   - The physical side of correlation function
   - The QCD side of correlation function
4. Semileptonic Transition of $B \to D_2^*(2460)\ell\nu$
   - The physical side of correlation function
   - The QCD side of correlation function
5. Conclusions
On the phenomenological side, the correlation function is obtained inserting two complete sets of intermediate states with the same quantum numbers as the interpolating currents $J^B$ and $J^{D^*_2}$ into Eq. (15). After performing four-integrals over $x$ and $y$, we get

$$
\Pi_{\mu\alpha\beta}^{\text{Phy}}(q^2) = \frac{\langle 0 | J^{D^*_2}(0) | D^*_2(p', \epsilon) \rangle \langle D^*_2(p', \epsilon) | J^{tr}_\mu(0) | B(p) \rangle}{(p^2 - m_B^2)(p'^2 - m_{D^*_2}^2)} \times \langle B(p) | J^\dagger_B(0) | 0 \rangle + \cdots ,
$$

(19)
Semileptonic transition of $B \rightarrow D^*_2(2460)\ell\bar{\nu}$ in QCD sum rules

The physical side of correlation function

The QCD side of correlation function

\[ \langle 0 \mid J^{D^*_2} (0) \mid D^*_2(p', \epsilon) \rangle = m^3_{D^*_2} f_{D^*_2} \epsilon_{\alpha\beta} \]

\[ \langle B(p) \mid J^\dagger_B (0) \mid 0 \rangle = -i \frac{f_B m_B^2}{m_u + m_b} \]

\[ \langle D^*_2(p', \epsilon) \mid J^{tr}_\mu (0) \mid B(p) \rangle = h(q^2) \epsilon_{\mu\nu\lambda\eta} \epsilon^{*\nu\theta} P_\theta P^\lambda q_\eta - iK(q^2) \epsilon^{*\mu\nu} P^\nu 
- i\epsilon^*_{\lambda\eta} P^\lambda P^\eta \left[ P_\mu b_+(q^2) + q_\mu b_-(q^2) \right], \]

(20)
the final representation of the physical side is obtained as:

\[
\Pi_{\mu\alpha\beta}^{\text{Phys}}(q^2) = \frac{f_{D_2^*} f_B m_{D_2^*} m_B^2}{8(m_b + m_u)(p^2 - m_B^2)(p'^2 - m_{D_2^*}^2)}
\times \left\{ \frac{2}{3} \left[ - \Delta K(q^2) + \Delta' b_-(q^2) \right] q_\mu g_{\beta\alpha} \\
+ \frac{2}{3} \left[ (\Delta - 4m_{D_2^*}^2) K(q^2) + \Delta' b_+(q^2) \right] P_\mu g_{\beta\alpha} \\
+ i(\Delta - 4m_{D_2^*}^2) h(q^2) \varepsilon_{\lambda\nu\beta\mu} P_\lambda P_\alpha q_\nu \\
+ \Delta K(q^2) q_\alpha g_{\beta\mu} + \text{other structure} \right\} + \ldots, \quad (21)
\]

where \(\Delta\) and \(\Delta'\):

\[
\Delta = m_B^2 + 3m_{D_2^*(2460)}^2 - q^2,
\]
\[
\Delta' = m_B^4 - 2m_B^2(m_{D_2^*(2460)}^2 + q^2) + (m_{D_2^*(2460)}^2 - q^2)^2 \quad (22)
\]
Introduction

QCD Sum Rules

Leptonic Decay Constant of $D_2^\ast(2460)$ Tensor Meson

Semileptonic Transition of $B \to D_2^\ast(2460)\ell\nu$

Conclusions

Hayriye Sundu Pamuk

Semileptonic transition of $B \to D_2^\ast(2460)\ell\nu$ in QCD sum rules
On the QCD side, the correlation function is calculated by expanding the time ordering product of the $B$ and $D_2^*(2460)$ mesons’ currents and the transition current via operator product expansion (OPE) in deep Euclidean region where the short (perturbative) and long distance (nonperturbative) contributions are separated. By inserting the previously represented currents into Eq. (2) and after contracting out all quark fields applying the Wick’s theorem, we obtain:

$$\Pi_{QCD}^{\mu\alpha\beta}(q^2) = -\frac{i^3}{4} \int d^4 x \int d^4 y e^{-ip \cdot x} e^{ip' \cdot y}$$

$$\times \left\{ Tr \left[ S_{ik}^u(x-y) \gamma_\alpha \overleftrightarrow{D_{\beta}}(y) S_{ij}^c(y) \gamma_\mu (1 - \gamma_5) S_b(-x)^{jk} \gamma_5 \right] \right\}$$

$$+ \left[ \beta \leftrightarrow \alpha \right].$$

(23)
\[ \Pi_{\mu\alpha\beta}^{QCD}(q^2) = \left( \Pi_1^{pert}(q^2) + \Pi_1^{nonpert}(q^2) \right) q_{\alpha}g_{\beta\mu} \]
\[ + \left( \Pi_2^{pert}(q^2) + \Pi_2^{nonpert}(q^2) \right) q_{\mu}g_{\beta\alpha} \]
\[ + \left( \Pi_3^{pert}(q^2) + \Pi_3^{nonpert}(q^2) \right) P_{\mu}g_{\beta\alpha} \]
\[ + \left( \Pi_4^{pert}(q^2) + \Pi_4^{nonpert}(q^2) \right) \epsilon_{\lambda\nu\beta\mu} P_{\lambda}P_{\alpha}q_{\nu} \]
\[ + \text{other structures.} \]
The physical side of correlation function

The QCD side of correlation function

\[ \Pi_{1}^{pert}(q^2) = \int ds \int ds' \frac{\rho_1(s, s', q^2)}{(s - p^2)(s' - p'^2)}, \quad (25) \]

\[ \rho_1(s, s', q^2) = \int_0^1 dx \int_0^{1-x} dy \left\{ \frac{1}{64\pi^2(x + y - 1)^3} \times \left[ m_b(x + y - 1)^3(8x^2 - 8y^2 + 6x - 6y - 6) \right. \right. \\
+ \left. 3m_c \left( 8x^5 + 6x^4(4y - 3) \right. \right. \\
- \left. 6x(y - 1)^2(3 + 2y + 4y^2) - 2(2 + 3y + 4y^2) \right. \right. \\
\times \left. (y - 1)^3 + 2x^3(1 - 18y + 8y^2) \right. \right. \\
+ \left. x^2(22 - 5y - 16y^3) \right] \right\}, \quad (26) \]
The physical side of correlation function

The QCD side of correlation function

\[ \Pi_{1}^{\text{nonpert}} = \left\{ \begin{array}{l}
\frac{m_{b}^{4} + 4m_{b}^{2}m_{c}^{2} + 2m_{b}^{2}(m_{c}^{2} - q^{2}) + (m_{c}^{2} - q^{2})^{2}}{64r^{2}r'^{2}} \\
\frac{m_{b}^{2}m_{c}^{2}(m_{b}^{2} + m_{c}^{2} - q^{2})}{32r^{2}r'^{3}} - \frac{m_{b}^{2} + 4m_{b}m_{c} + m_{c}^{2} - q^{2}}{64rr'^{2}} \\
\frac{m_{b}^{3}m_{c} + m_{b}^{2}m_{c}^{2} + 2m_{b}m_{c}^{3} + m_{c}^{4} - m_{c}^{2}q^{2}}{32rr'^{3}} \\
\frac{m_{b}^{4} + 2m_{b}^{3}m_{c} + m_{b}^{2}m_{c}^{2} - m_{b}^{2}q^{2}}{32r^{3}r'} + \frac{m_{c}^{2}}{32r'^{3}} - \frac{1}{32r'^{2}} + \frac{1}{32r^{2}} \\
\frac{3m_{b}^{2} + 2m_{b}m_{c} + 3m_{c}^{2} - 3q^{2}}{64r^{2}r'} + \frac{m_{b}^{2}}{32r^{3}} - \frac{1}{32rr'} \right\} m_{0}^{2} \langle \bar{u}u \rangle \\
- \left( \frac{m_{b}^{2} + 2m_{b}m_{c} + m_{c}^{2} - q^{2}}{16rr'} + \frac{1}{16r} + \frac{1}{16r'} \right) \langle \bar{u}u \rangle, \quad (27) \right. \]
In order to suppress the contributions of the higher states and continuum, we apply double Borel transformation with respect to the initial and final momenta squared using

$$\hat{B} \left[ \frac{1}{(p^2 - m_b^2)^m (p'^2 - m_c^2)^n} \right] \rightarrow (-1)^{m+n} \frac{1}{\Gamma[m] \Gamma[n]} e^{-m_b^2/M^2} e^{-m_c^2/M'^2}$$

quark-hadron duality:

$$\rho^{\text{higher states}}(s, s') = \rho^{\text{OPE}}(s, s') \theta(s - s_0) \theta(s' - s'_0) \theta(s'^0 - s^0).$$
Introduction
QCD Sum Rules
Leptonic Decay Constant of $D_2^*$ (2460) Tensor Meson
Semileptonic Transition of $B \to D_2^* (2460) \ell \nu$
Conclusions

The physical side of correlation function
The QCD side of correlation function

$\begin{align*}
  b_+ &= \frac{-12(m_b + m_u)}{f_B f_{D_2^*} m_B^2 m_{D_2^*}^2 \left( m_B^4 + (m_{D_2^*}^2 - q^2)^2 - 2m_B^2 (m_{D_2^*}^2 + q^2) \right)} e^{\frac{m_B^2}{M^2}} e^{\frac{m_{D_2^*}^2}{M'_{D_2^*}^2}} \\

  \left\{ \begin{array}{l}
    \int_{s_0^2}^s ds \int_{s_0'^2}^{s'} ds' \int_0^1 dx \int_0^{1-x} dy e^{-s/M^2} e^{-s'/M'_{D_2^*}^2} \\
    \frac{1}{128\pi^4 (x + y - 1)^3} \left( m_b (x + y - 1)^3 (3 - 6x - 2x^2 + 6y + 2y^2) \\
    - 3m_c \left( 6x^4(y - 1) - 3x(y - 1)^2 (1 + 2y^2) (y - 1)^3 (1 + 2y^2) \right) \\
    + x^3 (5 - 12y + 4y^2) + x^2 (1 + 4y - 4y^3) + 2x^5 \right) \right]\Theta[L(s, s', q^2)] \\
    - e^{-\frac{m_B^2}{M^2}} e^{-\frac{m_{D_2^*}^2}{M'_{D_2^*}^2}} f_B f_{D_2^*} m_B^2 m_{D_2^*}^2 (m_B^2 + 3m_{D_2^*}^2 + q^2) \\
    12(m_b + m_u) \end{array} \right\}
\end{align*}$

Hayriye Sundu Pamuk

Semileptonic transition of $B \to D_2^* (2460) \ell \nu$ in QCD sum rules
The sum rules for the form factors contain four auxiliary parameters:

\[ 31 \text{ GeV}^2 \leq s_0 \leq 35 \text{ GeV}^2 \]  
(31)

\[ 7 \text{ GeV}^2 \leq s'_0 \leq 9 \text{ GeV}^2 \]  
(32)

\[ 10 \text{ GeV}^2 \leq M^2 \leq 20 \text{ GeV}^2 \]  
(33)

\[ 5 \text{ GeV}^2 \leq M'^2 \leq 15 \text{ GeV}^2 \]  
(34)
\[
\frac{d\Gamma}{dq^2} = \frac{\lambda(m_B^2, m_{D_2^*}^2, q^2)}{4m_{D_2^*}^2} \left( \frac{q^2 - m_\ell^2}{q^2} \right)^2 \sqrt{\lambda(m_B^2, m_{D_2^*}^2, q^2)} \frac{G_F^2 V_{cb}^2}{384m_B^3\pi^3} \\
\left\{ \frac{1}{2q^2} \left[ 3m_\ell^2 \lambda(m_B^2, m_{D_2^*}^2, q^2)[V_0(q^2)]^2 \right. \right. \\
+ \left. \left. (m_\ell^2 + 2q^2) \left[ \frac{1}{2m_{D_2^*}^2} (m_B^2 - m_{D_2^*}^2 - q^2)(m_B - m_{D_2^*})V_1(q^2) \right. \right. \right. \\
- \left. \left. \frac{\lambda(m_B^2, m_{D_2^*}^2, q^2)}{m_B - m_{D_2^*}} V_2(q^2) \right] \right\}^2 + \frac{2}{3}(m_\ell^2 + 2q^2) \lambda(m_B^2, m_{D_2^*}^2, q^2) \\
\times \left[ \left| \frac{A(q^2)}{m_B - m_{D_2^*}} - \frac{(m_B - m_{D_2^*})V_1(q^2)}{\sqrt{\lambda(m_B^2, m_{D_2^*}^2, q^2)}} \right|^2 \ldots \right\} \right\}, \quad (35)
\]
where

\[ A(q^2) = -(m_B - m_{D*}) h(q^2), \]
\[ V_1(q^2) = -\frac{k(q^2)}{m_B - m_{D*}}, \]
\[ V_2(q^2) = (m_B - m_{D*}) b_+(q^2), \]
\[ V_0(q^2) = \frac{m_B - m_{D*}}{2m_{D*}} V_1(q^2) - \frac{m_B + m_{D*}}{2m_{D*}} V_2(q^2) - \frac{q^2}{2m_{D*}} b_-(q^2) \]

(36)
Our calculations show that the form factors are truncated at \( q^2 \simeq 5 \text{GeV}^2 \). In order to estimate the decay width of the \( B \to D_2^*(2460) \ell \nu \) transition, we have to obtain their fit functions in the whole physical region, \( m_{\ell}^2 \leq q^2 \leq (m_B - m_{D_2^*})^2 \).

\[
f(q^2) = f_0 \exp\left[ c_1 \frac{q^2}{m_{\text{fit}}^2} + c_2 \left( \frac{q^2}{m_{\text{fit}}^2} \right)^2 \right] \tag{37}
\]
Table: Parameters appearing in the fit function of the form factors.
### Introduction

QCD Sum Rules

Leptonic Decay Constant of $D_2^*$ (2460) Tensor Meson

Semileptonic Transition of $B \to D_2^* (2460) \ell \nu$

### Conclusions

<table>
<thead>
<tr>
<th></th>
<th>$\Gamma$(GeV)</th>
<th>$Br$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to D_2^*(2460)<em>{\tau\bar{\nu}</em>\tau}$</td>
<td>$7.11 \times 10^{-17}$</td>
<td>$0.18 \times 10^{-3}$</td>
</tr>
<tr>
<td>$B \to D_2^*(2460)<em>{\mu\bar{\nu}</em>\mu}$</td>
<td>$3.96 \times 10^{-16}$</td>
<td>$0.99 \times 10^{-3}$</td>
</tr>
<tr>
<td>$B \to D_2^*(2460)_{e\bar{\nu}_e}$</td>
<td>$3.98 \times 10^{-16}$</td>
<td>$1.01 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Hayriye Sundu Pamuk

Semileptonic transition of $B \to D_2^* (2460) \ell \nu$ in QCD sum rules
Conclusions

- The orders of branching fractions show that this transition can be detected at LHCb for all lepton channels.
- Considering the recent experimental progress especially at LHC we hope we will have experimental data on the branching fraction of the semileptonic $B \to D_s^*(2460) \ell \nu$ transition in near future, comparison of which with the results of our work can give more information about the nature and internal structure of the $D_s^*(2460)$ tensor meson.
THANKS ....
REFERENCES