Searching new physics in $c \to ul^+l^-$ decays with non-universal Z' model

22nd Conference on Flavor Physics and CP Violation (FPCP 2024)

Chulalongkorn University

Bangkok, Thailand

May 27-31, 2024

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OUTLINE

Motivation

- Recent results from the LHCb have provided the limit of the branching ratio of lepton flavour violating decays $D^0 \to \mu^\mp e^\pm$ as $\boldsymbol{\mathcal{B}(D^0 \to \mu^\mp e^\pm) < 1.3 \times 10^{-8}}$ at 90% confidence level [1].

- The SM calculation including the short distance effects for the decays $D \to l^+ l^-$ predicts the branching fractions to be of the order of 10^{-18} [2].

- For the leptonic decays $\boldsymbol{D^0 \to e^+ e^-}$ and $\boldsymbol{D^0 \to \mu^+ \mu^-}$, the experimental bounds for the branching fractions are constrained at $\boldsymbol{7.9 \times 10^{-8}}$ [3] and at $\boldsymbol{3.1 \times 10^{-9}}$ [4], respectively.

- Effective GIM (Glashow-Iliopoulos-Maiani) suppression in $c \to u$ decays make these channels sensitive to new physics effects [5].

Motivation

- The rare charm decays $\boldsymbol{D_s^+ \to K^+ e^- e^+, D_s^+ \to K^+ e^- \mu^+, D^0 \to e^- e^+}$ and $\boldsymbol{D^0 \to e^- \mu^+}$ have been studied in $U(1)'$ model, $2HDM$ model, and unparticle model where only Z' model and $2HDM$ model significantly increased the branching ratios [6].

- The decays $\boldsymbol{D^{+(0)} \to \pi^{+(0)} \mu^+ \mu^-}$, $\boldsymbol{D^0 \to \mu e, \tau e}$ and $\boldsymbol{D^{+(0)} \to \pi^{+(0)} \mu^- e^+}$ have been investigated in leptoquark model and Z' model [7].

- Along with $\boldsymbol{D \to \pi l^+ l^-}$, $\boldsymbol{D_s \to K l^+ l^-}$ has also been studied in leptoquark model, SUSY models and flavourful Z' model [8].

[6] Xing-Dao Guo, Xi-Qing Hao, Hong-Wei Ke, Ming-Gang Zhao and Xue-Qian Li, *Chinese Phys. C* **41** 093107 (2017)

Non-universal Z' model

- The gauge group $SU(3) \times SU(2) \times U(1)$ of SM is extended to $\boldsymbol{SU(3) \times SU(2) \times U(1) \times U'(1)}$.

- Extending the gauge group introduces a new particle, the $\boldsymbol{Z'}$ **boson.**

- Z' boson is a massive, charge neutral, colourless, hypothetical particle.

- Z' boson couples to quarks as well as leptons through FCNC (flavour changing neutral current) transitions.

Search for Z' boson

Experimental searches

- ATLAS collaboration [9]
  1. $M_{Z'} \sim 0.5 - 2.5$ TeV
  2. $M_{Z'_{SSM}} > 1.90$ TeV
  3. $M_{Z'_{SFM}} > 1.82 - 2.17$ TeV at $\sqrt{s} = 13$ TeV
- CMS collaboration [10]
  1. $M_{Z'_{SSM}} > 4.50$ TeV
  2. $M_{Z'_{\psi}} > 3.90$ TeV
- EW data of weak neutral current processes and mixing between $Z - Z'$: $M_{Z'} > \mathcal{O}(500)$ GeV [11]
- Tevatron: $M_{Z'} > \mathcal{O}(800)$ GeV [12]

Theoretical searches

- Sahoo et al.: $M_{Z'} \sim 1352 - 1665$ GeV [13]
- Allanach: $M_{Z'} \sim 0.8 - 1.8$ TeV [14]
- Luzio et al.: $M_{Z'} \leq 9$ TeV [15]

[14] B. Allanach, LHC di-lepton searches for Z' bosons which explain measurements of $b \to sl^+ l^-$ transitions, arXiv: 2404.14748 [hep-ph] (2024)

Theoretical Framework

We have studied the decays $D^+ \to \pi^+\mu^+\mu^-$, $D^0 \to \pi^0\mu^+\mu^-$, $D_s^+ \to K^+\mu^+\mu^-$, $D^+ \to \rho^+\mu^+\mu^-$ and $D^0 \to \rho^0\mu^+\mu^-$ in non-universal Z' model

Effective Hamiltonian for $c \to ul^+l^-$ transition [8, 16]

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}\left[\sum_{i=7,9,10,S,P}(C_i\mathcal{O}_i + C'_i\mathcal{O}'_i) + \sum_{i=T,T_5} C_i\mathcal{O}_i + \sum_{q=d,s} V_{cq}^* V_{uq}\sum_{i=1}^{2} C_i\mathcal{O}_i^q\right]$$

The differential decay distribution of $D \to Pl^+l^-$ in standard model is given by [8, 16]

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\alpha^2\beta_l}{1024\pi^5 M_D^3}\left\{\frac{2}{3}\left|C_9 + C_7\frac{2m_c}{M_D+M_P}\frac{f_T}{f_+}\right|^2\left(1+\frac{2m_l^2}{q^2}\right)\lambda f_+^2 + |C_{10}|^2\left[\frac{2}{3}\left(1-\frac{4m_l^2}{q^2}\right)\lambda f_+^2 + \frac{4m_l^2}{q^2}(M_D^2-M_P^2)^2 f_0^2\right]\right\}$$

The decay rate for $D \to \rho l^+l^-$ is given by [17]

$$\begin{aligned}\frac{d\Gamma}{d\hat{s}} &= \frac{G_F^2\alpha^2 M_D^2}{2^{10}\pi^5}\left\{\frac{|A|^2}{3}\hat{s}\lambda\left(1+\frac{2\hat{m}_l^2}{\hat{s}}\right) + |E|^2\hat{s}\frac{\hat{u}(\hat{s})^2}{3}\right.\\
&+ \frac{1}{4\hat{M}_\rho^2}\left[|B|^2\left(\lambda - \frac{\hat{u}(\hat{s})^2}{3} + 8\hat{M}_\rho^2(\hat{s}+2\hat{m}_l^2)\right)\right.\\
&+ \left.|F|^2\left(\lambda - \frac{\hat{u}(\hat{s})^2}{3} + 8\hat{M}_\rho^2(\hat{s}-4\hat{m}_l^2)\right)\right]\\
&+ \frac{\lambda}{4\hat{M}_\rho^2}\left[|C|^2\left(\lambda - \frac{\hat{u}(\hat{s})^2}{3}\right)\right.\\
&+ \left.|G|^2\left(\lambda - \frac{\hat{u}(\hat{s})^2}{3} + 4\hat{m}_l^2(2+2\hat{m}_l^2-\hat{s})\right)\right]\\
&- \frac{1}{2\hat{M}_\rho^2}\left[Re(BC^*)\left(\lambda - \frac{\hat{u}(\hat{s})^2}{3}\right)(1-\hat{M}_\rho^2-\hat{s})\right.\\
&+ \left.Re(FG^*)\left(\left(\lambda - \frac{\hat{u}(\hat{s})^2}{3}\right)(1-\hat{M}_\rho^2-\hat{s}) + 4\hat{m}_l^2\lambda\right)\right]\\
&- \left.\frac{2\hat{m}_l^2\lambda}{\hat{M}_\rho^2}\left[Re(FH^*) - Re(GH^*)(1-\hat{M}_\rho^2)\right] + \frac{\hat{m}_l^2}{\hat{M}_\rho^2}\hat{s}\lambda|H|^2\right\}\end{aligned}$$

Theoretical framework

Effective Hamiltonian for $c \to u l^+ l^-$ transition in Z' model [7]

$$H_{Z'} = H^q_{Z'} + H^\ell_{Z'}$$

$$H^q_{Z'} = g_{Z'1}\bar{u}_L\gamma_\mu c_L Z'^\mu + g_{Z'2}\bar{u}_R\gamma_\mu c_R Z'^\mu + h.c.$$

$$H^\ell_{Z'} = g'_{Z'1}\bar{\ell}_L\gamma_\mu \ell_L Z'^\mu + g'_{Z'2}\bar{\ell}_R\gamma_\mu \ell_R Z'^\mu + h.c.$$

New Physics (NP) Wilson coefficients [8]

$$C^{NP}_{9(10)} = -\frac{\pi}{\sqrt{2}G_F\alpha}\frac{g_{Z'1}(g'_{Z'1} \pm g'_{Z'2})}{M^2_{Z'}}$$

$$C'^{NP}_{9(10)} = -\frac{\pi}{\sqrt{2}G_F\alpha}\frac{g_{Z'2}(g'_{Z'1} \pm g'_{Z'2})}{M^2_{Z'}}$$

Estimation of NP couplings in Z' model

Quark coupling

$D^0 - \overline{D^0}$ **mixing**

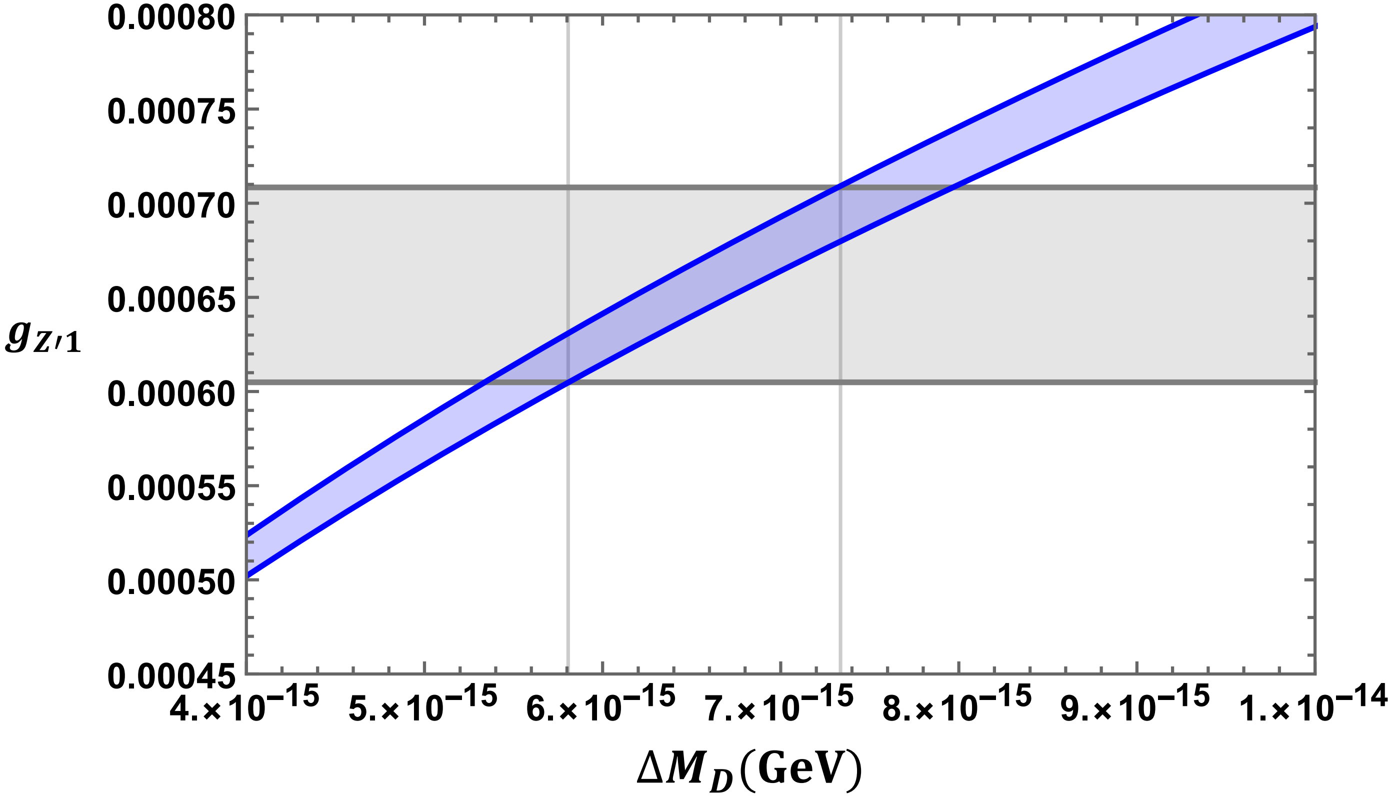


Fig 1. Determination of quark coupling

$$\Delta M_D^{Z'} = \frac{f_D^2 M_D B_D r(m_c, M_{Z'})}{3} \frac{g_{Z'1}^2}{M_{Z'}^2} [7, 18]$$

$$\Delta M_D = (99.7 \pm 11.6) \times 10^8\ \hbar s^{-1} [19]$$

$$g_{Z'1} = 6.47 \times 10^{-4}$$

Estimation of NP couplings in Z' model

Leptonic coupling

$\boldsymbol{D^0 \to \mu^+\mu^-}$ **process**

$$\mathcal{B}(D^0 \to \mu^+\mu^-)|_{Z'} = \tau_D \frac{f_D^2 m_\mu^2 M_D}{32\pi M_{Z'}^4} \sqrt{1 - \frac{4m_l^2}{M_D^2}} (g_{Z'1} - g_{Z'2})^2 (g'_{Z'2} - g'_{Z'2})^2$$ [7, 18]

$$g'_{Z'1} \leq 35.31$$

Estimation of NP couplings in Z' model

Decay mode	Experimental upper limit [19]
$D^+ \to \pi^+\mu^+\mu^-$	6.7×10^{-8}
$D^0 \to \pi^0\mu^+\mu^-$	1.8×10^{-4}
$D_s^+ \to K^+\mu^+\mu^-$	1.4×10^{-7}
$D^+ \to \rho^+\mu^+\mu^-$	5.6×10^{-4}
$D^0 \to \rho^0\mu^+\mu^-$	2.2×10^{-5}

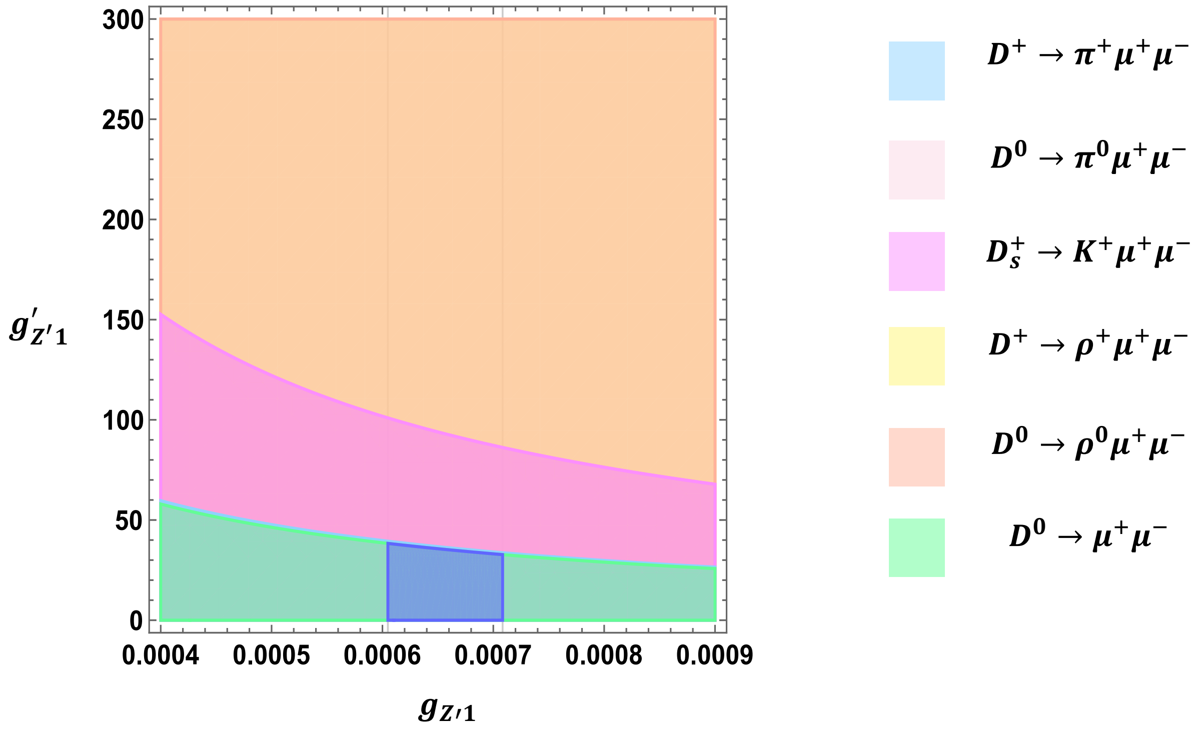
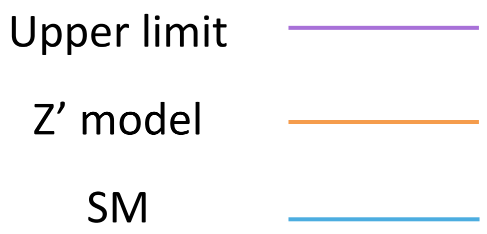


Fig. 2: Plot of leptonic coupling $g'_{Z'1}$ vs quark coupling $g_{Z'1}$. The blue region shows the allowed region of the couplings, constrained from $D^+ \to \pi^+\mu^+\mu^-$, $D^0 \to \pi^0\mu^+\mu^-$, $D_s^+ \to K^+\mu^+\mu^-$, $D^+ \to \rho^+\mu^+\mu^-$, $D^0 \to \rho^0\mu^+\mu^-$ and $D^0 \to \mu^+\mu^-$ decays

Estimation of branching fraction



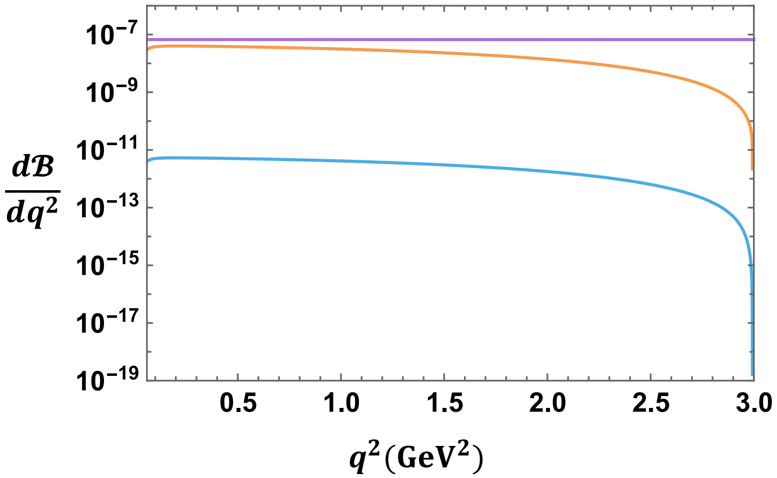


Fig. 3a

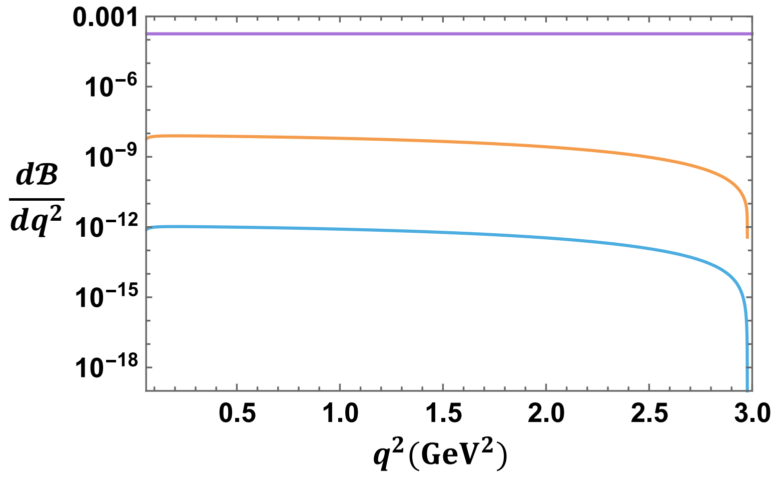


Fig. 3b

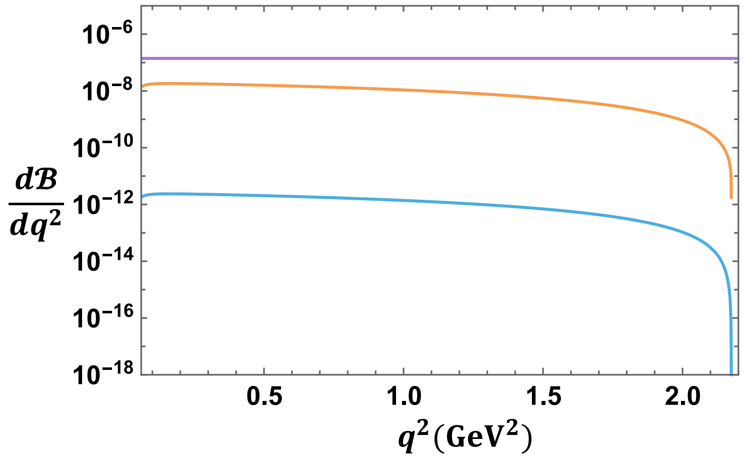
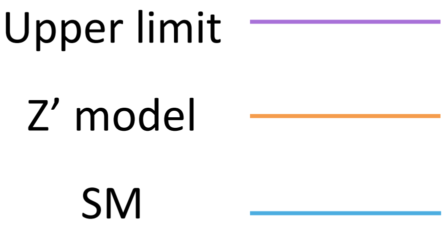


Fig. 3c

Fig. 3: Variation of differential branching fractions within allowed kinematic region for (a) $D^+ \to \pi^+\mu^+\mu^-$ and (b) $D^0 \to \pi^0\mu^+\mu^-$ (c) $D_s^+ \to K^+\mu^+\mu^-$

Estimation of branching fraction



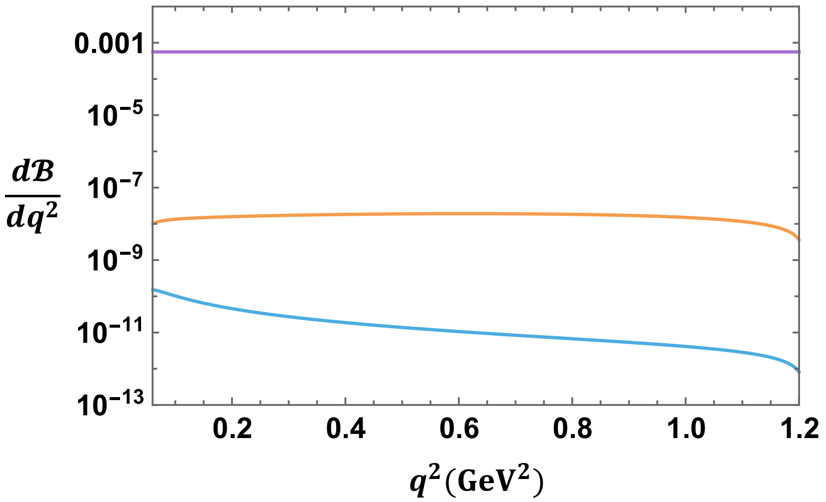


Fig. 4 (a)

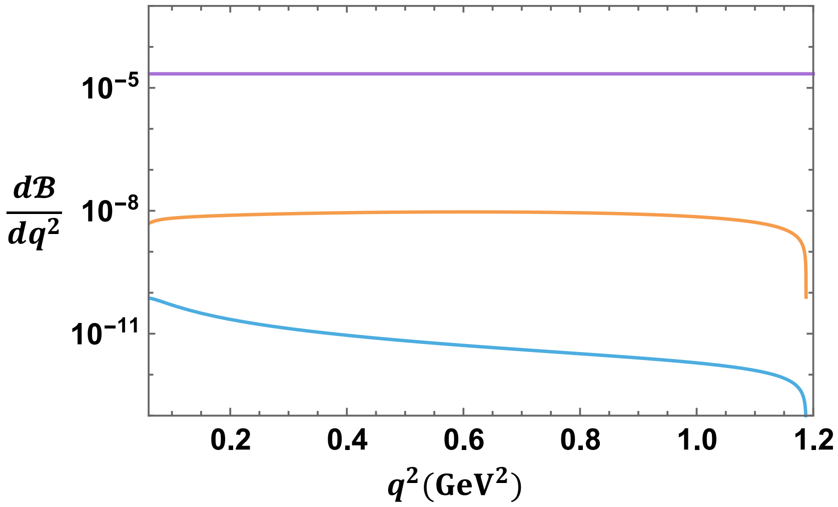


Fig. 4 (b)

Fig. 4: Variation of differential branching fractions within allowed kinematic region for (a) $D^+ \to \rho^+\mu^+\mu^-$and (b) $D^0 \to \rho^0\mu^+\mu^-$

Estimation of forward backward asymmetry

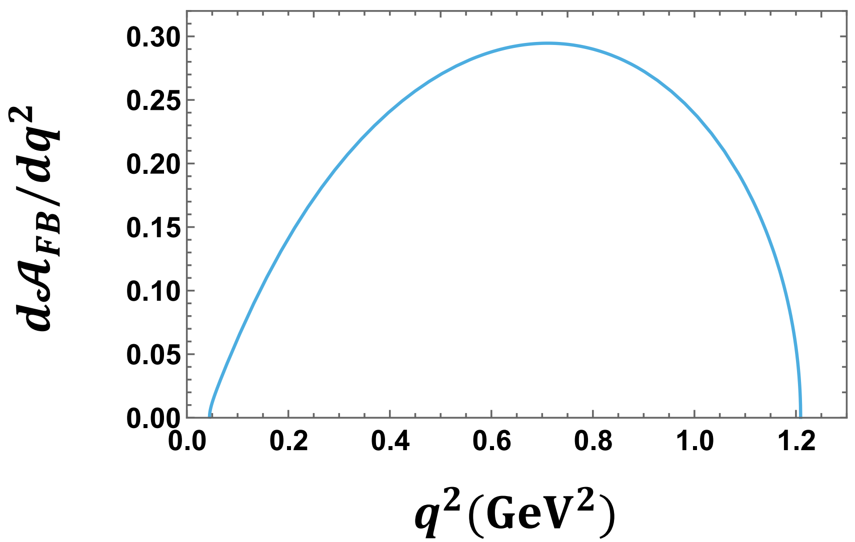


Fig. 5 (a)

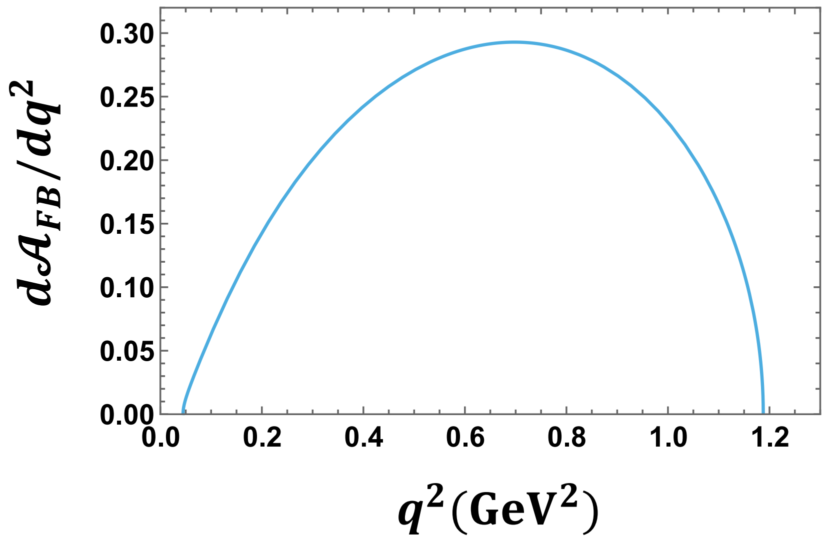


Fig. 5 (b)

Fig. 5: Variation of normalized forward backward asymmetry for (a) $D^+ \to \rho^+\mu^+\mu^-$and (b) $D^0 \to \rho^0\mu^+\mu^-$in non-universal Z' model.

Results

Table 1: Branching ratio values integrated in the allowed q^2 region

Decay mode	SM	Z' model	Experimental upper limit [19]
$D^+ \to \pi^+\mu^+\mu^-$	8.29×10^{-12}	6.33×10^{-8}	6.7×10^{-8}
$D^0 \to \pi^0\mu^+\mu^-$	1.62×10^{-12}	1.24×10^{-8}	1.8×10^{-4}
$D_s^+ \to K^+\mu^+\mu^-$	2.56×10^{-12}	2.00×10^{-8}	1.4×10^{-7}

Table 2: Branching ratio values integrated in the allowed q^2 region

Decay mode	SM	Z' model	Experimental upper limit [19]
$D^+ \to \rho^+\mu^+\mu^-$	2.39×10^{-11}	1.85×10^{-8}	5.6×10^{-4}
$D^0 \to \rho^0\mu^+\mu^-$	1.16×10^{-11}	8.92×10^{-8}	2.2×10^{-5}

Table 3: Normalized forward backward asymmetry values integrated in the allowed q^2 region

Decay mode	Normalized forward backward asymmetry in Z' model
$D^+ \to \rho^+\mu^+\mu^-$	0.252
$D^0 \to \rho^0\mu^+\mu^-$	0.246

Conclusions

- We have calculated the differential branching ratio and forward backward asymmetry for the decays $D^+ \to \pi^+\mu^+\mu^-$, $D^0 \to \pi^0\mu^+\mu^-$, $D_s^+ \to K^+\mu^+\mu^-$, $D^+ \to \rho^+\mu^+\mu^-$ and $D^0 \to \rho^0\mu^+\mu^-$ in non-universal Z' model.

- The branching fractions for all the decay channels studied here show a significant enhancement in the Z' model.

- Although forward backward asymmetry is zero for $D \to P\mu^+\mu^-$, the $D \to \rho\mu^+\mu^-$ decays show a variation of the forward backward asymmetry in the Z' model.

- The results in this study indicate that these decays are sensitive to new physics contributions in the Z' model. We expect that our study will contribute more to the present understanding of charm decays.

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Acknowledgement

- I express my sincere gratitude to my supervisor **Dr. S. Sahoo**, Associate Professor, Department of Physics, National Institute of Technology Durgapur, for encouraging and guiding me in research.

- I acknowledge the Department of Science and Technology, Govt. of India for providing INSPIRE Fellowship through IF 200277.

- I am grateful to my seniors, Dr. Swagata Biswas and Mr. Supravat Mahata for always helping me. I also thank my lab mates Mr. Raja Ray and Mr. Hrushikesha Mahapatra.

- I sincerely thank the organizers of the **22nd Conference on Flavor Physics and CP Violation (FPCP 2024), Chulalongkorn University,** for providing me the opportunity to present my work.

Thank you