

FCNC charmed-hadron decays with invisible singlet particles in light of recent data

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FCNC

charmed-hadron
decays with invisible
singlet particles in
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Motivation

Effective Lagrangian

Fully invisible decay

Semi-invisible radiative decay

Semi-invisible mesonic decays

Semi-invisible baryonic
decays

Numerical results for decays
induced by $c \rightarrow u\bar{S}\bar{S}'$

Prediction of invisible scalars

FCNC charm decay with
invisible singlet fermions

Predictions of the standard
model

Prediction of invisible
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Figure 1: Prof. Jusak Tandean and Dr. Geng Li

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- ▶ Flavor-changing neutral current (FCNC) processes of long-lived particles provide a window to observe new physics (NP) beyond the standard model (SM).

$c \rightarrow u$, $s \rightarrow d$, and $b \rightarrow d(s)$ transitions.

- ▶ Experiments have given the constraints on hadronic FCNC decays with missing energy ($\cancel{E}$).

$$\mathcal{B}(K_L \rightarrow \pi^0 \bar{\nu} \nu)_{\text{KOTO}} < 3.0 \times 10^{-9} \text{ at 90\% C.L.}$$

$$\mathcal{B}(K_L \rightarrow \pi^0 \bar{\nu} \nu)_{\text{SM}} = (3.4 \pm 0.6) \times 10^{-11}$$

$$\mathcal{B}(K^+ \rightarrow \pi^+ \bar{\nu} \nu)_{\text{NA62}} = (11.0_{-3.5}^{+4.0}(\text{stat}) \pm 0.3(\text{syst})) \times 10^{-11} \text{ at 68\% C.L.}$$

$$\mathcal{B}(K^+ \rightarrow \pi^+ \bar{\nu} \nu)_{\text{E949}} = (17.3_{-10.5}^{+11.5}) \times 10^{-11}$$

$$\mathcal{B}(K^+ \rightarrow \pi^+ \bar{\nu} \nu)_{\text{SM}} = (8.4 \pm 1.0) \times 10^{-11}$$

- ▶ In the SM, strongly suppressed by the Glashow-Iliopoulos-Maiani (GIM) mechanism.

$$\mathcal{B}(D^0 \rightarrow \pi^0 \bar{\nu} \nu) \sim 10^{-15}$$

- ▶ In light of recent data, specifically $D^0 \rightarrow \cancel{E}$ by Belle and $D^0 \rightarrow \pi^0 \cancel{E}$ and $\Lambda_c^+ \rightarrow p \cancel{E}$ by BESIII. Belle announced $\mathcal{B}(D^0 \rightarrow \text{invisibles}) < 9.4 \times 10^{-5}$; BESIII reported $\mathcal{B}(D^0 \rightarrow \pi^0 \nu \bar{\nu}) < 2.1 \times 10^{-4}$ and $\mathcal{B}(\Lambda_c^+ \rightarrow p \gamma') < 8.0 \times 10^{-5}$, all at 90% C. L.

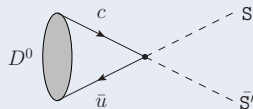
- ▶ More distant in the future, searches with greater levels of sensitivity would presumably be feasible at the proposed super tau-charm factory (STCF), Circular Electron Positron Collider (CEPC), and Future Circular Collider (FCC), etc.

Effective Lagrangian

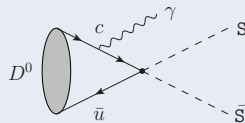
The leading-order low-energy effective $|\Delta C|=1$ operators containing invisible bosons are expressible

$$\mathcal{L}_{SS'} = -(\kappa_{SS'}^v \bar{u} \gamma_\mu c + \kappa_{SS'}^a \bar{u} \gamma_\mu \gamma_5 c) i(S^\dagger \partial^\mu S' - \partial^\mu S^\dagger S') - (\kappa_{SS'}^s \bar{u} c + \kappa_{SS'}^p \bar{u} \gamma_5 c) m_c S^\dagger S' + \text{H.c.},$$

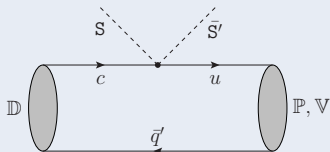
where $\kappa_{SS'}^x$, $x = v, a, s, p$, are in general complex coefficients.



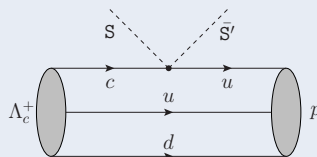
(a) Fully invisible decay



(b) Semi-invisible radiative decay



(c) Semi-invisible mesonic decay



(d) Semi-invisible baryonic decay

Figure 2: Diagrams of FCNC charmed-hadron decays with two invisible light spin-0 bosons.

(a) Fully invisible decay

The **amplitude** for the invisible channel $D^0 \rightarrow S\bar{S}'$ can be expressed as

$$\mathcal{M}_{D^0 \rightarrow S\bar{S}'} = \kappa_{SS'}^a \langle 0 | \bar{u} \gamma^\mu \gamma_5 c | D^0 \rangle (k - k')_\mu + \kappa_{SS'}^p m_c \langle 0 | \bar{u} \gamma_5 c | D^0 \rangle ,$$

with the **mesonic matrix elements**

$$\langle 0 | \bar{u} \gamma^\mu \gamma_5 c | D^0 \rangle = -i f_D p_{D^0}^\mu , \quad \langle 0 | \bar{u} \gamma_5 c | D^0 \rangle = \frac{i f_D m_{D^0}^2}{m_u + m_c} ,$$

where f_D stands for the D^0 **decay constant** and $p_X (m_X)$ is the momentum (mass) of X . There are no contributions of $\kappa_{SS'}^s$ and $\kappa_{SS'}^v$ because $\langle 0 | \bar{u} \gamma^\mu c | D^0 \rangle = \langle 0 | \bar{u} c | D^0 \rangle = 0$.

Neglecting m_u compared to m_c then leads to

$$\mathcal{M}_{D^0 \rightarrow S\bar{S}'} = i [\kappa_{SS'}^a (m_{S'}^2 - m_S^2) + \kappa_{SS'}^p m_{D^0}^2] f_D .$$

From this follows the **rate**

$$\Gamma_{D^0 \rightarrow S\bar{S}'} = \frac{\lambda^{1/2}(m_{D^0}^2, m_S^2, m_{S'}^2)}{16\pi m_{D^0}^3} |\kappa_{SS'}^a (m_{S'}^2 - m_S^2) + \kappa_{SS'}^p m_{D^0}^2|^2 f_D^2 ,$$

which contains the Källén function

$$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2(xy + xz + yz) .$$

Evidently, $D^0 \rightarrow S\bar{S}'$ can in general probe $\kappa_{SS'}^p$ and $\kappa_{SS'}^a$, which accompany the parity-odd quark bilinears in $\mathcal{L}_{SS'}$, but the sensitivity to $\kappa_{SS'}^a$ will be lost if $m_{S'} = m_S$.

(b) Semi-invisible radiative decay

The amplitude for $D^0 \rightarrow \gamma S\bar{S}'$ is

$$\mathcal{M}_{D^0 \rightarrow \gamma S\bar{S}'} = \kappa_{SS'}^v \langle \gamma | \bar{u} \gamma_\mu c | D^0 \rangle (k - k')^\mu + \kappa_{SS'}^a \langle \gamma | \bar{u} \gamma^\mu \gamma_5 c | D^0 \rangle (k - k')_\mu,$$

where $k^{(\prime)}$ designates the momentum of $S^{(\prime)}$ and

$$\langle \gamma | \bar{u} \gamma_\mu c | D^0 \rangle = \frac{eF_V}{m_{D^0}} \epsilon_{\mu\zeta\eta\theta} \varepsilon_\gamma^{\zeta*} p_{D^0}^\eta p_\gamma^\theta, \quad \langle \gamma | \bar{u} \gamma^\mu \gamma_5 c | D^0 \rangle = \frac{ieF_A}{m_{D^0}} (p_\gamma \cdot p_{D^0} \varepsilon_\gamma^{\mu*} - \varepsilon_\gamma^* \cdot p_{D^0} p_\gamma^\mu),$$

Since $\langle \gamma | \bar{u} c | D^0 \rangle = \langle \gamma | \bar{u} \gamma_5 c | D^0 \rangle = 0$, there are no $\kappa_{SS'}^{s,p}$ terms.

Evaluating the absolute square of the amplitude times the [three-body phase space](#) yields the [differential rate](#)

$$\frac{d\Gamma_{D^0 \rightarrow \gamma S\bar{S}'}}{d\hat{s}} = \frac{\alpha_e \lambda^{3/2}(\hat{s}, m_S^2, m_{S'}^2)}{384\pi^2 m_{D^0}^5 \hat{s}^2} (m_{D^0}^2 - \hat{s})^3 (|\kappa_{SS'}^v|^2 F_V^2 + |\kappa_{SS'}^a|^2 F_A^2),$$

which is to be integrated over $(m_S + m_{S'})^2 \leq \hat{s} \leq m_{D^0}^2$. Thus, the invisible scalars' mass range covered by this mode is $0 \leq m_S + m_{S'} < m_{D^0}$, the same as that in the $D^0 \rightarrow S\bar{S}'$ case.

(c) Semi-invisible mesonic decays

Initial mesons $\mathbb{D} = D^0, D^+, D_s^+$, and the final mesons $\mathbb{P} = \pi^0, \pi^+, K^+$ or $\mathbb{V} = \rho^0, \rho^+, K^{*+}$.

The **amplitudes** are

$$\mathcal{M}_{\mathbb{D} \rightarrow \mathbb{P} \bar{S} \bar{S}'} = \kappa_{\bar{S} \bar{S}'}^{\bar{V}} \langle \mathbb{P} | \bar{u} \gamma^\mu c | \mathbb{D} \rangle (k - k')_\mu + \kappa_{\bar{S} \bar{S}'}^{\bar{S}} m_c \langle \mathbb{P} | \bar{u} c | \mathbb{D} \rangle,$$

$$\mathcal{M}_{\mathbb{D} \rightarrow \mathbb{V} \bar{S} \bar{S}'} = \kappa_{\bar{S} \bar{S}'}^{\bar{V}} \langle \mathbb{V} | \bar{u} \gamma_\mu c | \mathbb{D} \rangle (k - k')^\mu + \kappa_{\bar{S} \bar{S}'}^{\bar{a}} \langle \mathbb{V} | \bar{u} \gamma^\mu \gamma_5 c | \mathbb{D} \rangle (k - k')_\mu + \kappa_{\bar{S} \bar{S}'}^{\bar{p}} m_c \langle \mathbb{V} | \bar{u} \gamma_5 c | \mathbb{D} \rangle,$$

which involve the momentum $k^{(\prime)}$ of $S^{(\prime)}$ and the **mesonic matrix elements**

$$\langle \mathbb{P} | \bar{u} \gamma^\mu c | \mathbb{D} \rangle = (p_{\mathbb{D}}^\mu + p_{\mathbb{P}}^\mu) f_+ + (p_{\mathbb{D}}^\mu - p_{\mathbb{P}}^\mu) (f_0 - f_+) \frac{m_{\mathbb{D}}^2 - m_{\mathbb{P}}^2}{q_{\mathbb{D}\mathbb{P}}^2}, \quad \langle \mathbb{P} | \bar{u} c | \mathbb{D} \rangle = \frac{m_{\mathbb{D}}^2 - m_{\mathbb{P}}^2}{m_c - m_u} f_0,$$

$$\langle \mathbb{V} | \bar{u} \gamma_\mu c | \mathbb{D} \rangle = \frac{2V}{m_{\mathbb{D}} + m_{\mathbb{V}}} \epsilon_{\mu\beta\eta\theta} \varepsilon_{\mathbb{V}}^{\beta*} p_{\mathbb{V}}^\eta p_{\mathbb{D}}^\theta,$$

$$\langle \mathbb{V} | \bar{u} \gamma^\mu \gamma_5 c | \mathbb{D} \rangle = i(m_{\mathbb{D}} + m_{\mathbb{V}}) \varepsilon_{\mathbb{V}}^{\mu*} A_1 - \left[\frac{p_{\mathbb{D}}^\mu + p_{\mathbb{V}}^\mu}{m_{\mathbb{D}} + m_{\mathbb{V}}} A_2 + \frac{p_{\mathbb{D}}^\mu - p_{\mathbb{V}}^\mu}{q_{\mathbb{D}\mathbb{V}}^2} (A_3 - A_0) 2m_{\mathbb{V}} \right] i \varepsilon_{\mathbb{V}}^* \cdot p_{\mathbb{D}},$$

$$\langle \mathbb{V} | \bar{u} \gamma_5 c | \mathbb{D} \rangle = \frac{-2iA_0 m_{\mathbb{V}}}{m_c + m_u} \varepsilon_{\mathbb{V}}^* \cdot p_{\mathbb{D}},$$

where f_+ and f_0 [V, A_0, A_1 , and A_2] are **form factors**.

(c) Semi-invisible mesonic decays

Accordingly, from the absolute squares of the amplitudes, we arrive at

$$\frac{d\Gamma_{\mathbb{D} \rightarrow \mathbb{P}\bar{S}\bar{S}'}}{d\hat{s}} = \frac{2\tilde{\lambda}_{\mathbb{D}\mathbb{P}}^{1/2}\tilde{\lambda}_{\bar{S}\bar{S}'}^{1/2}}{(8\pi m_{\mathbb{D}}\hat{s})^3} \left[\frac{1}{3} |\kappa_{\bar{S}\bar{S}'}^v|^2 \tilde{\lambda}_{\mathbb{D}\mathbb{P}} \tilde{\lambda}_{\bar{S}\bar{S}'} f_+^2 + |\kappa_{\bar{S}\bar{S}'}^v (m_{\mathbb{S}}^2 - m_{\mathbb{S}'}^2) + \kappa_{\bar{S}\bar{S}'}^s \hat{s}|^2 (m_{\mathbb{D}}^2 - m_{\mathbb{P}}^2)^2 f_0^2 \right],$$

$$\begin{aligned} \frac{d\Gamma_{\mathbb{D} \rightarrow \mathbb{V}\bar{S}\bar{S}'}}{d\hat{s}} = & \frac{\tilde{\lambda}_{\mathbb{D}\mathbb{V}}^{3/2}\tilde{\lambda}_{\bar{S}\bar{S}'}^{3/2}}{(8\pi m_{\mathbb{D}}\hat{s})^3} \left\{ \frac{|\kappa_{\bar{S}\bar{S}'}^a|^2}{6m_{\mathbb{V}}^2} \left[\left(1 + \frac{12m_{\mathbb{V}}^2\hat{s}}{\tilde{\lambda}_{\mathbb{D}\mathbb{V}}} \right) A_1^2 \tilde{m}_+^2 + 2(\hat{s} - \tilde{m}_+ \tilde{m}_-) A_1 A_2 + \frac{\tilde{\lambda}_{\mathbb{D}\mathbb{V}} A_2^2}{\tilde{m}_+^2} \right] \right. \\ & \left. + \frac{2A_0^2}{\tilde{\lambda}_{\bar{S}\bar{S}'}} |\kappa_{\bar{S}\bar{S}'}^a (m_{\mathbb{S}'}^2 - m_{\mathbb{S}}^2) + \kappa_{\bar{S}\bar{S}'}^p \hat{s}|^2 + \frac{4|\kappa_{\bar{S}\bar{S}'}^v|^2 \hat{s} V^2}{3\tilde{m}_+^2} \right\}, \end{aligned}$$

to be integrated over $(m_{\mathbb{S}} + m_{\mathbb{S}'})^2 \leq \hat{s} = (k + k')^2 \leq (m_{\mathbb{D}} - m_{\mathbb{P},\mathbb{V}})^2$, respectively, with

$$\tilde{\lambda}_{XY} = \lambda(m_X^2, m_Y^2, \hat{s}), \quad \tilde{m}_{\pm} = m_{\mathbb{D}} \pm m_{\mathbb{V}}.$$

$\mathbb{D} \rightarrow \mathbb{P}\bar{S}\bar{S}'$ can probe not only $\kappa_{\bar{S}\bar{S}'}^v$, but also $\kappa_{\bar{S}\bar{S}'}^s$, which is inaccessible to $D^0 \rightarrow \bar{S}\bar{S}', \gamma\bar{S}\bar{S}'$ as well as to $\mathbb{D} \rightarrow \mathbb{V}\bar{S}\bar{S}'$. However, the latter is sensitive to the other three parameters, $\kappa_{\bar{S}\bar{S}'}^{v,p,a}$.

(d) Semi-invisible baryonic decays

Of interest here are $\Lambda_c^+ \rightarrow p\bar{S}\bar{S}'$ and $\Xi_c^{+,0} \rightarrow \Sigma^{+,0}\bar{S}\bar{S}'$ plus $\Xi_c^0 \rightarrow \Lambda\bar{S}\bar{S}'$,

$$\begin{aligned} \mathcal{M}_{\Lambda_c^+ \rightarrow p\bar{S}\bar{S}'} &= \kappa_{\bar{S}\bar{S}'}^v \langle p|\bar{u}\gamma^\mu c|\Lambda_c^+\rangle (k - k')_\mu + \kappa_{\bar{S}\bar{S}'}^a \langle p|\bar{u}\gamma^\mu \gamma_5 c|\Lambda_c^+\rangle (k - k')_\mu \\ &+ \kappa_{\bar{S}\bar{S}'}^s m_c \langle p|\bar{u}c|\Lambda_c^+\rangle + \kappa_{\bar{S}\bar{S}'}^p m_c \langle p|\bar{u}\gamma_5 c|\Lambda_c^+\rangle, \end{aligned}$$

where $k^{(\prime)}$ is again the momentum of $S^{(\prime)}$ and the **baryonic matrix elements** are expressible as

$$\begin{aligned} \langle p|\bar{u}\gamma^\mu c|\Lambda_c^+\rangle &= \bar{u}_p \left\{ \left[\gamma^\mu - \frac{M_+ \hat{p}^\mu - M_- \hat{q}^\mu}{M_+^2 - \hat{q}^2} \right] F_\perp + \left[\hat{p}^\mu - \frac{M_+ M_- \hat{q}^\mu}{\hat{q}^2} \right] \frac{M_+ F_+}{M_+^2 - \hat{q}^2} + \frac{M_- \hat{q}^\mu}{\hat{q}^2} F_0 \right\} u_{\Lambda_c}, \\ \langle p|\bar{u}\gamma^\mu \gamma_5 c|\Lambda_c^+\rangle &= \bar{u}_p \left\{ \left[\gamma^\mu + \frac{M_- \hat{p}^\mu - M_+ \hat{q}^\mu}{M_-^2 - \hat{q}^2} \right] G_\perp - \left[\hat{p}^\mu - \frac{M_+ M_- \hat{q}^\mu}{\hat{q}^2} \right] \frac{M_- G_+}{M_-^2 - \hat{q}^2} - \frac{M_+ \hat{q}^\mu}{\hat{q}^2} G_0 \right\} \gamma_5 u_{\Lambda_c}, \\ \langle p|\bar{u}c|\Lambda_c^+\rangle &= \frac{M_- F_0}{m_c - m_u} \bar{u}_p u_{\Lambda_c}, \quad \langle p|\bar{u}\gamma_5 c|\Lambda_c^+\rangle = \frac{M_+ G_0}{m_c + m_u} \bar{u}_p \gamma_5 u_{\Lambda_c}, \end{aligned}$$

where u_p and u_{Λ_c} designate the Dirac spinors of the baryons, $F_{\perp,+ ,0}$ and $G_{\perp,+ ,0}$ symbolize form factors which depend on $\hat{s} = \hat{q}^2$,

$$M_\pm = m_{\Lambda_c} \pm m_p, \quad \hat{p} = p_{\Lambda_c} + p_p, \quad \hat{q} = p_{\Lambda_c} - p_p.$$

(d) Semi-invisible baryonic decays

After averaging (summing) the absolute square of the amplitude over the initial (final) baryon polarizations and multiplying by the three-body phase space, we find the **differential rate**

$$\begin{aligned} \frac{d\Gamma_{\Lambda_c^+ \rightarrow p S \bar{S}'}}{d\hat{s}} = & \frac{2\tilde{\lambda}_{\Lambda_c p}^{1/2} \tilde{\lambda}_{S S'}^{1/2}}{3(8\pi m_{\Lambda_c} \hat{s})^3} \left\{ \left[|\kappa_{SS'}^v|^2 (2F_\perp^2 \hat{s} + F_+^2 M_+^2) \hat{\sigma}_- + |\kappa_{SS'}^a|^2 (2G_\perp^2 \hat{s} + G_+^2 M_-^2) \hat{\sigma}_+ \right] \tilde{\lambda}_{SS'} \right. \\ & + 3|\kappa_{SS'}^v|^2 (m_S^2 - m_{S'}^2) + \kappa_{SS'}^s \hat{s} \hat{\sigma}_+ M_-^2 F_0^2 \\ & \left. + 3|\kappa_{SS'}^a|^2 (m_{S'}^2 - m_S^2) + \kappa_{SS'}^p \hat{s} \hat{\sigma}_- M_+^2 G_0^2 \right\}, \end{aligned}$$

where $\hat{\sigma}_\pm = M_\pm^2 - \hat{s}$. It is to be integrated over $(m_S + m_{S'})^2 \leq \hat{s} \leq (m_{\Lambda_c} - m_p)^2$.

Numerical results for decays induced by $c \rightarrow u\bar{S}\bar{S}'$

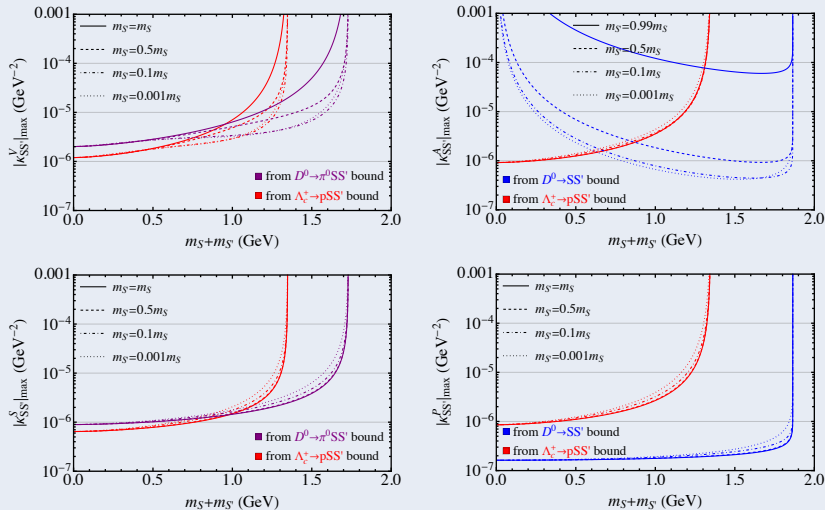


Figure 3: The upper limits on $|\kappa_{SS'}^V|$ (top left), $|\kappa_{SS'}^A|$ (top right), $|\kappa_{SS'}^S|$ (bottom left), and $|\kappa_{SS'}^P|$ (bottom right) versus $m_S + m_{S'}$ obtained from the $D^0 \rightarrow SS'$ (blue), $D^0 \rightarrow \pi^0 SS'$ (purple), and $\Lambda_c^+ \rightarrow p SS'$ (red) limits for various $m_{S'}/m_S$ values if only one of $\kappa_{SS'}^{v,a,s,p}$ is nonzero at a time.

Prediction of invisible scalars

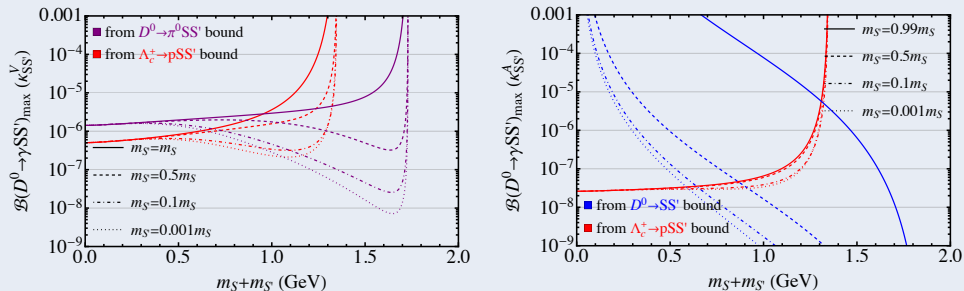


Figure 4: The maximal branching fraction of $D^0 \rightarrow \gamma SS'$ due to $|\kappa_{SS'}^V|_{\max}$ (left) or $|\kappa_{SS'}^A|_{\max}$ (right) alone for various $m_{S'}/m_S$ choices.

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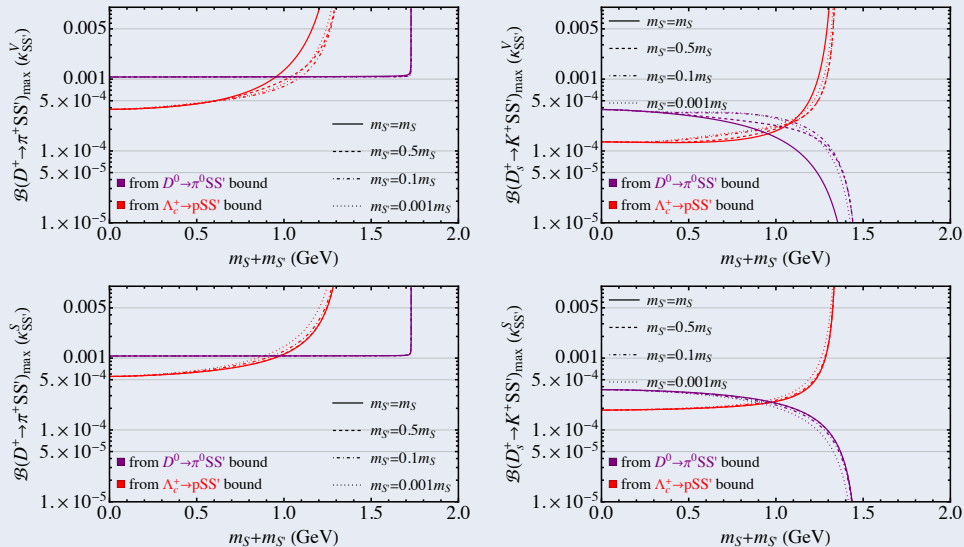


Figure 5: The maximal branching fractions of $D^+ \rightarrow \pi^+ SS'$ (left column) and $D_s^+ \rightarrow K^+ SS'$ (right column) due to $|\kappa_{SS'}^V|_{\max}$ (top row) or $|\kappa_{SS'}^S|_{\max}$ (bottom row) alone for different $m_{S'}/m_S$ values.

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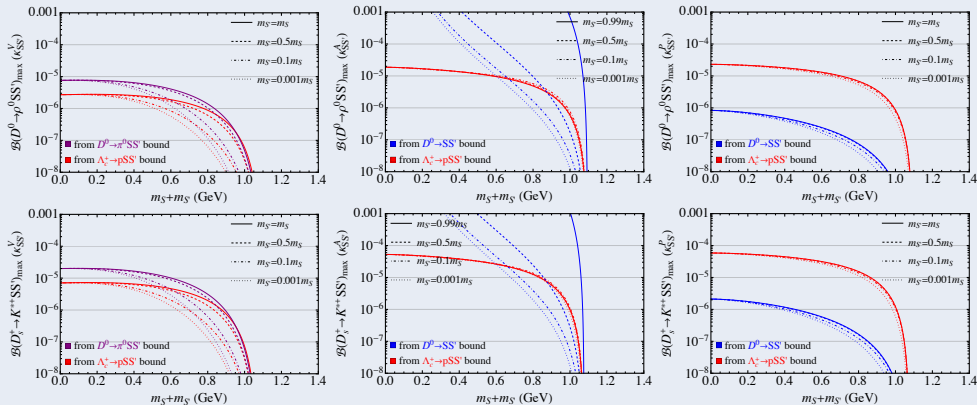


Figure 6: The maximal branching fractions of $D^0 \rightarrow \rho^0 \bar{S}\bar{S}'$ and $D_s^+ \rightarrow K^{*+} \bar{S}\bar{S}'$ due to $|\kappa_{SS'}^V|_{\max}$ or $|\kappa_{SS'}^A|_{\max}$ (middle row) or $|\kappa_{SS'}^P|_{\max}$ alone. The $D^+ \rightarrow \rho^+ \bar{S}\bar{S}'$ curves, not displayed, are approximately $2\tau_{D^+}/\tau_{D^0} \sim 5$ times their $D^0 \rightarrow \rho^0 \bar{S}\bar{S}'$ counterparts.

Prediction of invisible scalars

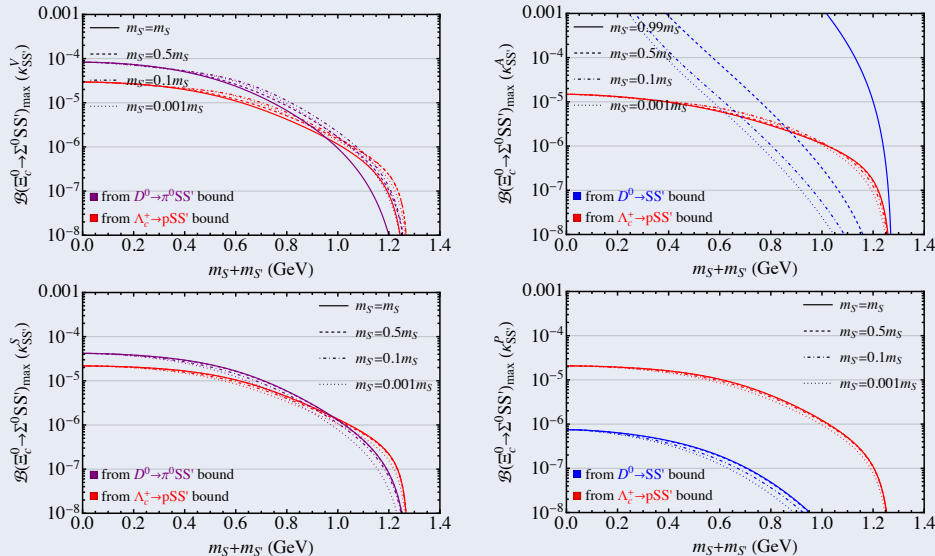


Figure 7: The maximal branching fractions of $\Xi_c^0 \rightarrow \Sigma^0 S \bar{S}'$ due to $|\kappa_{SS'}^V|_{\max}$ or $|\kappa_{SS'}^A|_{\max}$ or $|\kappa_{SS'}^S|_{\max}$ or $|\kappa_{SS'}^P|_{\max}$ alone. The $\Xi_c^+ \rightarrow \Sigma^+ S \bar{S}'$ curves, not shown, are approximately $2\tau_{\Xi_c^+}/\tau_{\Xi_c^0} \sim 6$ times their $\Xi_c^0 \rightarrow \Sigma^0 S \bar{S}'$ counterparts.

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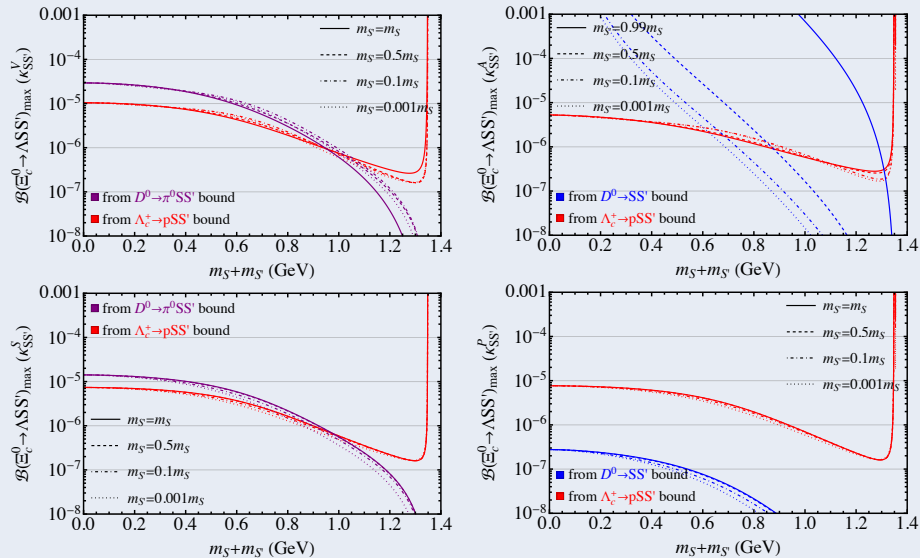


Figure 8: The maximal branching fractions of $\Xi_c^0 \rightarrow \Lambda \bar{S} S'$ due to $|\kappa_{SS'}^V|_{\max}$ or $|\kappa_{SS'}^A|_{\max}$ or $|\kappa_{SS'}^S|_{\max}$ or $|\kappa_{SS'}^P|_{\max}$ alone.

Prediction of invisible scalars

Table 1: The upper limits on branching fractions, in units of 10^{-5} , of various charmed-hadron decays induced by the $c \rightarrow u\bar{S}\bar{S}'$ operators for $m_{S'} = m_S = 0$ if the $\Lambda_c^+ \rightarrow p\bar{S}\bar{S}'$ bound is absent and, in brackets, if it is taken into account and the stronger. Only one of the coefficients $\kappa_{SS'}^{v,a,s,p}$ of the operators is taken to be nonzero at a time. A dash entry under $\kappa_{SS'}^x \neq 0$ means that $\kappa_{SS'}^x$ does not affect the decay.

Decay modes	$\kappa_{SS'}^v \neq 0$	$\kappa_{SS'}^a \neq 0$	$\kappa_{SS'}^s \neq 0$	$\kappa_{SS'}^p \neq 0$
$D^0 \rightarrow \bar{S}\bar{S}'$	-	-	-	9.4 [Input]
$D^0 \rightarrow \gamma\bar{S}\bar{S}'$	0.14 (0.050)	(0.0026)	-	-
$D^0 \rightarrow \pi^0\bar{S}\bar{S}'$	21 [Input] (7.5)	-	21 [Input] (11)	-
$D^+ \rightarrow \pi^+\bar{S}\bar{S}'$	107 (38)	-	107 (55)	-
$D_s^+ \rightarrow K^+\bar{S}\bar{S}'$	38 (13)	-	36 (19)	-
$D^0 \rightarrow \rho^0\bar{S}\bar{S}'$	0.74 (0.26)	(1.8)	-	0.081
$D^+ \rightarrow \rho^+\bar{S}\bar{S}'$	3.8 (1.4)	(9.4)	-	0.42
$D_s^+ \rightarrow K^{*+}\bar{S}\bar{S}'$	2.0 (0.71)	(5.3)	-	0.21
$\Lambda_c^+ \rightarrow p\bar{S}\bar{S}'$	23 (8.0 [Input])	(8.0 [Input])	15 (8.0 [Input])	0.29
$\Xi_c^+ \rightarrow \Sigma^+\bar{S}\bar{S}'$	49 (17)	(8.7)	25 (13)	0.44
$\Xi_c^0 \rightarrow \Sigma^0\bar{S}\bar{S}'$	8.3 (2.9)	(1.5)	4.2 (2.2)	0.075
$\Xi_c^0 \rightarrow \Lambda\bar{S}\bar{S}'$	2.9 (1.0)	(0.52)	1.4 (0.74)	0.028

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Table 2: The same as Table I but for $m_{S'} = 0.1 m_S = 0.05 \text{ GeV}$.

Decay modes	$\kappa_{SS'}^v \neq 0$	$\kappa_{SS'}^a \neq 0$	$\kappa_{SS'}^s \neq 0$	$\kappa_{SS'}^p \neq 0$
$D^0 \rightarrow S\bar{S}'$	-	9.4 [Input] (3.5)	-	9.4 [Input]
$D^0 \rightarrow \gamma S\bar{S}'$	0.14 (0.063)	0.0081 (0.0030)	-	-
$D^0 \rightarrow \pi^0 S\bar{S}'$	21 [Input] (9.3)	-	21 [Input] (13)	-
$D^+ \rightarrow \pi^+ S\bar{S}'$	107 (47)	-	107 (68)	-
$D_s^+ \rightarrow K^+ S\bar{S}'$	34 (15)	-	32 (20)	-
$D^0 \rightarrow \rho^0 S\bar{S}'$	0.23 (0.10)	2.9 (1.1)	-	0.024
$D^+ \rightarrow \rho^+ S\bar{S}'$	1.2 (0.55)	15 (5.6)	-	0.12
$D_s^+ \rightarrow K^{*+} S\bar{S}'$	0.62 (0.27)	8.1 (3.0)	-	0.060
$\Lambda_c^+ \rightarrow p S\bar{S}'$	18 (8.0 [Input])	22 (8.0 [Input])	13 (8.0 [Input])	0.14
$\Xi_c^+ \rightarrow \Sigma^+ S\bar{S}'$	22 (9.9)	13 (4.7)	10 (6.5)	0.12
$\Xi_c^0 \rightarrow \Sigma^0 S\bar{S}'$	3.8 (1.7)	2.2 (0.80)	1.7 (1.1)	0.020
$\Xi_c^0 \rightarrow \Lambda S\bar{S}'$	1.4 (0.61)	0.82 (0.30)	0.61 (0.39)	0.0078

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FCNC charm decay with invisible singlet fermions

The **leptoquark** $\bar{S}_1$ transforms as $(\bar{3}, 1, -2/3)$ under the SM gauge groups $SU(3)_{\text{color}} \times SU(2)_L \times U(1)_Y$. We write the Lagrangian for the renormalizable interaction of $\bar{S}_1$ with $N_{1,2,3}$ and the quarks as

$$\mathcal{L}_{\text{lq}} = \bar{Y}_{jl} \bar{\mathcal{U}}_j^c P_R N_l \bar{S}_1 + \text{H.c.},$$

where $\bar{Y}_{jl}$ are generally complex elements of the **LQ Yukawa matrix** $\bar{Y}$, $\mathcal{U}_{1,2,3} = (u, c, t)$.

The **effective Lagrangian** for $c \rightarrow u N \bar{N}'$

$$\mathcal{L}_{\text{ff}'} = -\bar{u} \gamma^\mu c \bar{f} \gamma_\mu (C_{\text{ff}'}^V + \gamma_5 C_{\text{ff}'}^A) f' - \bar{u} \gamma^\mu \gamma_5 c \bar{f} \gamma_\mu (\tilde{c}_{\text{ff}'}^V + \gamma_5 \tilde{c}_{\text{ff}'}^A) f',$$

with the **coefficients** being given by

$$C_{N_j N_l}^V = C_{N_j N_l}^A = \tilde{c}_{N_j N_l}^V = \tilde{c}_{N_j N_l}^A = -\frac{\bar{Y}_{1j}^* \bar{Y}_{2l}}{8m_{\bar{S}_1}^2}.$$

To evade the stringent restrictions from **D^0 - $\bar{D}^0$ mixing**, we choose one of the simplest examples,

$$\bar{Y} = \begin{pmatrix} 0 & \bar{y}_{u2} & 0 \\ \bar{y}_{c1} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

in which case only $c \rightarrow u N_2 \bar{N}_1$ can occur with

$$C_{N_2 N_1}^V = C_{N_2 N_1}^A = \tilde{c}_{N_2 N_1}^V = \tilde{c}_{N_2 N_1}^A = -\frac{\bar{y}_{u2}^* \bar{y}_{c1}}{8m_{\bar{S}_1}^2} \equiv k_{NN'},$$

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Full model-independent D-6 effective Lagrangian

- Full model-independent D-6 effective Lagrangian

$$\mathcal{L}_{eff} = \sum_{i=1}^9 g_{fi} Q_i,$$

where the subscript f represents fermion which can be [Majorana](#) or [Dirac](#) type.

- There are [nine](#) independent effective operators Q_i s

$$\begin{aligned} Q_1 &= (\bar{q}_f q)(\bar{\chi}\chi), & Q_2 &= (\bar{q}_f \gamma^5 q)(\bar{\chi}\chi), & Q_3 &= (\bar{q}_f q)(\bar{\chi}\gamma^5 \chi), \\ Q_4 &= (\bar{q}_f \gamma^5 q)(\bar{\chi}\gamma^5 \chi), & Q_5 &= (\bar{q}_f \gamma_\mu q)(\bar{\chi}\gamma^\mu \gamma^5 \chi), & Q_6 &= (\bar{q}_f \gamma_\mu \gamma^5 q)(\bar{\chi}\gamma^\mu \gamma^5 \chi), \\ Q_7 &= (\bar{q}_f \gamma_\mu q)(\bar{\chi}\gamma^\mu \chi), & Q_8 &= (\bar{q}_f \gamma_\mu \gamma^5 q)(\bar{\chi}\gamma^\mu \chi), & Q_9 &= (\bar{q}_f \sigma_{\mu\nu} q)(\bar{\chi}\sigma^{\mu\nu} \chi). \end{aligned}$$

- More information on

[1] [Geng Li](#), Chia-Wei Liu, Chao-Qiang Geng. Bottomed baryon decays with invisible Majorana fermions. [Phys.Rev.D 106 \(2022\) 11, 115007](#).

[2] [Geng Li](#), Tianhong Wang, Yue Jiang, Jing-Bo Zhang, Guo-Li Wang. Spin-1/2 invisible particles in heavy meson decays. [Phys.Rev.D 102 \(2020\) 9, 095019](#).

Predictions of the standard model

In the SM, the FCNC decays with **neutrinos** arising from loop diagrams by the effective Hamiltonian

$$\mathcal{H}_{c \rightarrow u \nu \bar{\nu}}^{\text{SM}} = \frac{\alpha_e G_F}{\sqrt{2} \pi \sin^2 \theta_W} \sum_{\ell=e, \mu, \tau} \sum_{q=d, s, b} \hat{\lambda}_q \bar{D}(r_q, r_\ell) \bar{u} \gamma^\eta P_L c \bar{\nu}_\ell \gamma_\eta P_L \nu_\ell,$$

where $r_f = m_f^2/m_W^2$ and with the loop function

$$\bar{D}(x, y) = \frac{x(4-y)^2}{8(1-y)^2} \frac{y \ln y}{x-y} + \frac{x(4-x)^2}{8(1-x)^2} \frac{x \ln x}{y-x} + \frac{4-2x+x^2}{8(1-x)^2} x \ln x - \frac{4+2x+5y-2xy}{8(1-x)(1-y)} x.$$

Accordingly, with $f = f' = \nu_\ell$ and $m_f = m_{f'} = 0$,

$$C_{\text{ff}'}^{\text{V}} = -C_{\text{ff}'}^{\text{A}} = -\tilde{c}_{\text{ff}'}^{\text{V}} = \tilde{c}_{\text{ff}'}^{\text{A}} = \sum_{q=d, s, b} \frac{\alpha_e G_F \hat{\lambda}_q \bar{D}(r_q, r_\ell)}{4\sqrt{2} \pi \sin^2 \theta_W}.$$

We obtained

$$\begin{aligned} \mathcal{B}(D^0 \rightarrow \nu \bar{\nu}) &= 0, & \mathcal{B}(D^0 \rightarrow \gamma \nu \bar{\nu}) &= 1.8 \times 10^{-19}, \\ \mathcal{B}(D^0 \rightarrow \pi^0 \nu \bar{\nu}) &= 2.5 \times 10^{-17}, & \mathcal{B}(D^0 \rightarrow \rho^0 \nu \bar{\nu}) &= 1.1 \times 10^{-17}, \\ \mathcal{B}(D^+ \rightarrow \pi^+ \nu \bar{\nu}) &= 1.3 \times 10^{-16}, & \mathcal{B}(D^+ \rightarrow \rho^+ \nu \bar{\nu}) &= 5.9 \times 10^{-17}, \\ \mathcal{B}(D_s^+ \rightarrow K^+ \nu \bar{\nu}) &= 4.5 \times 10^{-17}, & \mathcal{B}(D_s^+ \rightarrow K^{*+} \nu \bar{\nu}) &= 3.3 \times 10^{-17}, \\ \mathcal{B}(\Lambda_c^+ \rightarrow p \nu \bar{\nu}) &= 7.3 \times 10^{-17}, & \mathcal{B}(\Xi_c^+ \rightarrow \Sigma^+ \nu \bar{\nu}) &= 1.1 \times 10^{-16}, \\ \mathcal{B}(\Xi_c^0 \rightarrow \Sigma^0 \nu \bar{\nu}) &= 1.8 \times 10^{-17}, & \mathcal{B}(\Xi_c^0 \rightarrow \Lambda \nu \bar{\nu}) &= 6.5 \times 10^{-18}. \end{aligned}$$

Prediction of invisible fermions

The allowed $|k_{NN'}|$ range for each $(m_N, m_{N'})$ pair is below the lowest curve.

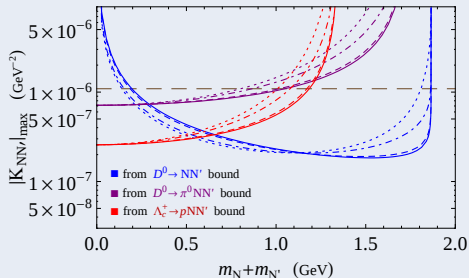


Figure 9: The upper limits on $|k_{NN'}|$ versus $m_N + m_{N'}$, with $N = N_2$ and $N' = N_1$, implied by the $D^0 \rightarrow N\bar{N}'$ (blue), $D^0 \rightarrow \pi^0 N\bar{N}'$ (purple), and $\Lambda_c^+ \rightarrow p N\bar{N}'$ (red) bounds for $m_{N'}/m_N = 0.001$ (dotted curves), 0.1 (dash-dotted curves), 0.5 (dashed curves), 1 (solid curves). The horizontal brown dashed line marks $|k_{NN'}| < 1.1 \text{ TeV}^{-2}$ inferred from collider and perturbativity restrictions.

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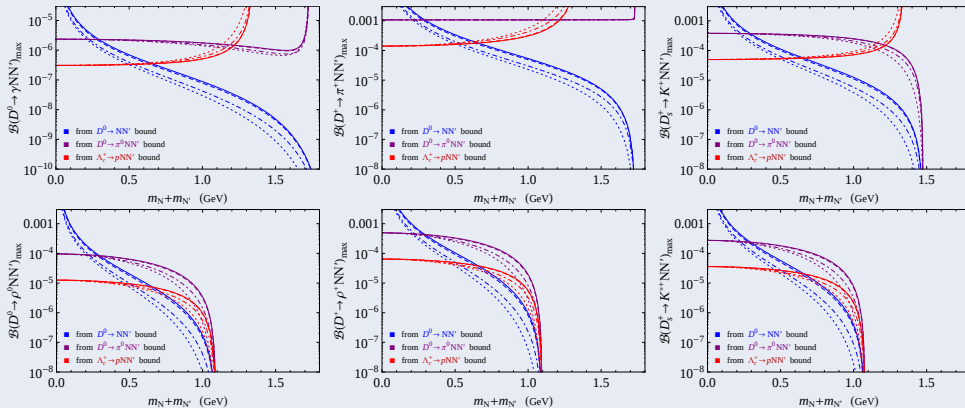


Figure 10: Maximal branching fractions of $D^0 \rightarrow (\gamma, \rho^0)N\bar{N}'$, $D^+ \rightarrow (\pi^+, \rho^+)N\bar{N}'$, and $D_s^+ \rightarrow (K^+, K^{*+})N\bar{N}'$ translated from the $|k_{NN'}|_{\max}$ values in Fig. 9 inferred from the $D^0 \rightarrow N\bar{N}'$ (blue), $D^0 \rightarrow \pi^0 N\bar{N}'$ (purple), and $\Lambda_c^+ \rightarrow p N\bar{N}'$ (red) bounds.

Prediction of invisible fermions

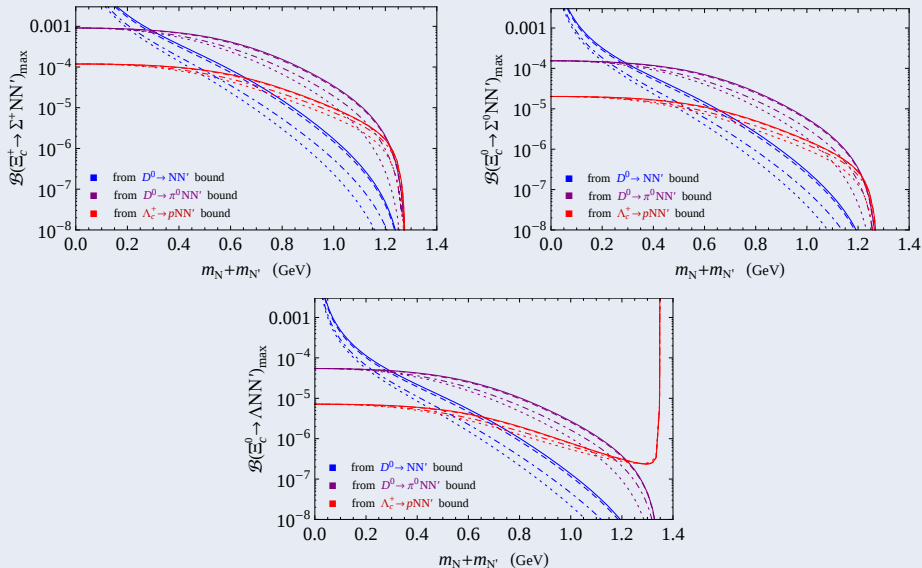


Figure 11: The same as Fig. 9 but for $\Xi_c^{+,0} \rightarrow \Sigma^{+,0} NN'$ and $\Xi_c^0 \rightarrow \Lambda NN'$.

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Table 3: The upper limits on the branching fractions, in units of 10^{-5} , of various charmed-hadron decays induced by the $c \rightarrow uN\bar{N}'$ interactions and evaluated with the lowest $|k_{NN'}|_{\max}$ for $m_{N'} = m_N = 0$ and $m_{N'} = 0.1 m_N = 0.05$ GeV if the $\Lambda_c^+ \rightarrow pN\bar{N}'$ bound is absent and, in brackets, if it is included and the strongest.

Decay modes	$m_{N'} = m_N = 0$	$m_{N'} = 0.1 m_N = 0.05$ GeV
$D^0 \rightarrow N\bar{N}'$	-	9.4 [Input]
$D^0 \rightarrow \gamma N\bar{N}'$	0.15 (0.020)	0.021
$D^0 \rightarrow \pi^0 N\bar{N}'$	21 [Input] (2.8)	3.1
$D^+ \rightarrow \pi^+ N\bar{N}'$	107 (14)	16
$D_s^+ \rightarrow K^+ N\bar{N}'$	38 (4.9)	4.9
$D^0 \rightarrow \rho^0 N\bar{N}'$	9.6 (1.3)	0.68
$D^+ \rightarrow \rho^+ N\bar{N}'$	49 (6.4)	3.5
$D_s^+ \rightarrow K^{*+} N\bar{N}'$	27 (3.6)	1.9
$\Lambda_c^+ \rightarrow pN\bar{N}'$	61 (8.0 [Input])	7.2
$\Xi_c^+ \rightarrow \Sigma^+ N\bar{N}'$	91 (12)	5.4
$\Xi_c^0 \rightarrow \Sigma^0 N\bar{N}'$	15 (2.0)	0.91
$\Xi_c^0 \rightarrow \Lambda N\bar{N}'$	5.5 (0.71)	0.34

Summary

- ▶ We have studied the **light invisible scalars and fermions** in the **FCNC** decays of the **long-lived charmed hadrons**.
- ▶ Fully invisible decay; Semi-invisible radiative decay; Semi-invisible mesonic (baryonic) decay.
- ▶ Highly **suppressed** SM background.
- ▶ The **bounds of the coupling constants** are extracted from very recent data.
- ▶ Based on these bounds, we have **predicted** the upper limits of other channels.

Prospect

- ▶ Upper limits? **No signal has been found.**
- ▶ Leptonic decay or other modes.

Thanks for your attention!

Thanks for your attention!

Let's have a further discussion, please.

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July 28, 2023

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