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

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Figure 1: Prof. Jusak Tandean and Dr. Geng Li

Motivation

- Flavor-changing neutral current (FCNC) processes of long-lived particles provide a window to observe new physics (NP) beyond the standard model (SM).
  $c \to u$, $s \to d$, and $b \to d(s)$ transitions.
- Experiments have given the constraints on hadronic FCNC decays with missing energy ($\not{E}$).
  $\mathcal{B}(K_L \to \pi^0 \bar{\nu}\nu)_{\text{KOTO}} < 3.0 \times 10^{-9}$ at 90% C.L.
  $\mathcal{B}(K_L \to \pi^0 \bar{\nu}\nu)_{\text{SM}} = (3.4 \pm 0.6) \times 10^{-11}$
  $\mathcal{B}(K^+ \to \pi^+ \bar{\nu}\nu)_{\text{NA62}} = (11.0^{+4.0}_{-3.5}(\text{stat}) \pm 0.3(\text{syst})) \times 10^{-11}$ at 68% C.L.
  $\mathcal{B}(K^+ \to \pi^+ \bar{\nu}\nu)_{\text{E949}} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$
  $\mathcal{B}(K^+ \to \pi^+ \bar{\nu}\nu)_{\text{SM}} = (8.4 \pm 1.0) \times 10^{-11}$
- In the SM, strongly suppressed by the Glashow-Iliopoulos-Maiani (GIM) mechanism.
  $\mathcal{B}(D^0 \to \pi^0 \bar{\nu}\nu) \sim 10^{-15}$
- In light of recent data, specifically $D^0 \to \not{E}$ by Belle and $D^0 \to \pi^0 \not{E}$ and $\Lambda_c^+ \to p \not{E}$ by BESIII. Belle announced $\mathcal{B}(D^0 \to \text{invisibles}) < 9.4 \times 10^{-5}$; BESIII reported $\mathcal{B}(D^0 \to \pi^0 \nu\bar{\nu}) < 2.1 \times 10^{-4}$ and $\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8.0 \times 10^{-5}$, 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.

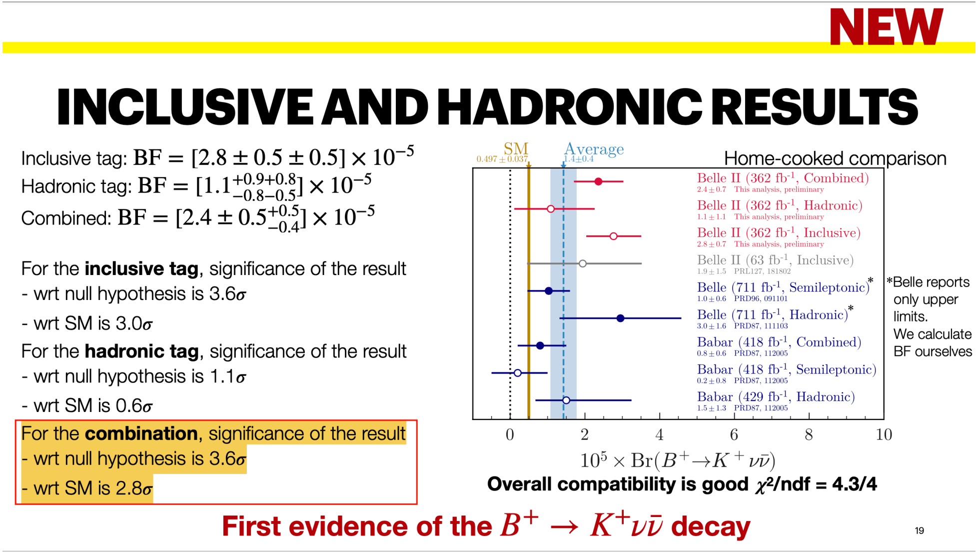

Figure 2: Recent data from Belle II

Effective Lagrangian

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

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

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

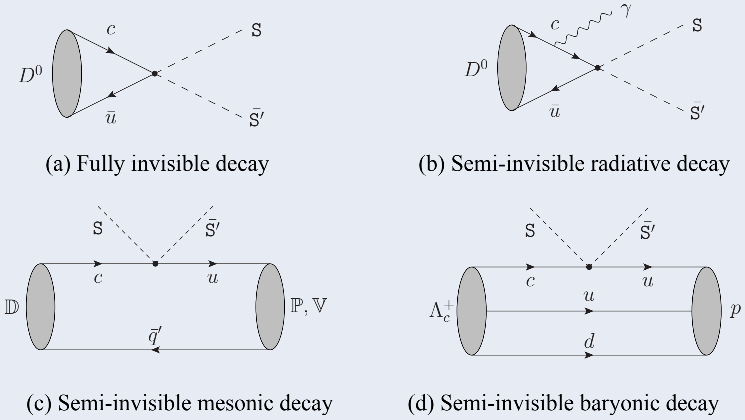

Figure 3: Diagrams of FCNC charmed-hadron decays with two invisible light spin-0 bosons.

(a) Fully invisible decay

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

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

with the mesonic matrix elements

$$\langle 0|\bar{u}\gamma^\mu\gamma_5 c|D^0\rangle = -if_D\, p^\mu_{D^0} , \qquad \langle 0|\bar{u}\gamma_5 c|D^0\rangle = \frac{if_D\, m^2_{D^0}}{m_u + m_c} ,$$

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 $\kappa^{\mathrm{s}}_{\mathrm{SS}'}$ and $\kappa^{\mathrm{v}}_{\mathrm{SS}'}$ 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

$$\mathcal{M}_{D^0\to \mathrm{S}\bar{\mathrm{S}}'} = i\left[\kappa^{\mathrm{a}}_{\mathrm{SS}'}\left(m^2_{\mathrm{S}'} - m^2_{\mathrm{S}}\right) + \kappa^{\mathrm{p}}_{\mathrm{SS}'} m^2_{D^0}\right] f_D .$$

From this follows the rate

$$\Gamma_{D^0\to \mathrm{S}\bar{\mathrm{S}}'} = \frac{\lambda^{1/2}\left(m^2_{D^0}, m^2_{\mathrm{S}}, m^2_{\mathrm{S}'}\right)}{16\pi m^3_{D^0}} \left|\kappa^{\mathrm{a}}_{\mathrm{SS}'}\left(m^2_{\mathrm{S}'} - m^2_{\mathrm{S}}\right) + \kappa^{\mathrm{p}}_{\mathrm{SS}'} m^2_{D^0}\right|^2 f^2_D ,$$

which contains the Källén function

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

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

(b) Semi-invisible radiative decay

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

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

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

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

Since $\langle\gamma|\bar{u}c|D^0\rangle = \langle\gamma|\bar{u}\gamma_5 c|D^0\rangle = 0$, there are no $\kappa^{\mathrm{s,p}}_{\mathrm{SS}'}$ terms.
Evaluating the absolute square of the amplitude times the three-body phase space yields the differential rate

$$\frac{d\Gamma_{D^0\to\gamma \mathrm{S}\bar{\mathrm{S}}'}}{d\hat{s}} = \frac{\alpha_{\mathrm{e}}\, \lambda^{3/2}\left(\hat{s}, m_{\mathrm{S}}^2, m_{\mathrm{S}'}^2\right)}{384\pi^2\, m_{D^0}^5\, \hat{s}^2}\left(m_{D^0}^2-\hat{s}\right)^3 \left(|\kappa^{\mathrm{v}}_{\mathrm{SS}'}|^2 F_V^2 + |\kappa^{\mathrm{a}}_{\mathrm{SS}'}|^2 F_A^2\right),$$

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

$$\mathcal{M}_{\mathbb{D}\to\mathbb{P}\mathrm{S}\bar{\mathrm{S}}'} = \kappa^{\mathrm{v}}_{\mathrm{SS}'} \langle\mathbb{P}|\bar{u}\gamma^\mu c|\mathbb{D}\rangle(\mathrm{k}-\mathrm{k}')_\mu + \kappa^{\mathrm{s}}_{\mathrm{SS}'}\, m_c \langle\mathbb{P}|\bar{u}c|\mathbb{D}\rangle ,$$

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

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

$$\langle\mathbb{P}|\bar{u}\gamma^\mu c|\mathbb{D}\rangle = (p^\mu_{\mathbb{D}} + p^\mu_{\mathbb{P}})f_+ + (p^\mu_{\mathbb{D}} - p^\mu_{\mathbb{P}})(f_0 - f_+)\frac{m^2_{\mathbb{D}} - m^2_{\mathbb{P}}}{q^2_{\mathbb{D}\mathbb{P}}} , \qquad \langle\mathbb{P}|\bar{u}c|\mathbb{D}\rangle = \frac{m^2_{\mathbb{D}} - m^2_{\mathbb{P}}}{m_c - m_u} f_0 ,$$

$$\langle\mathbb{V}|\bar{u}\gamma_\mu c|\mathbb{D}\rangle = \frac{2V}{m_{\mathbb{D}} + m_{\mathbb{V}}}\epsilon_{\mu\beta\eta\theta}\,\varepsilon^{\beta *}_{\mathbb{V}} p^\eta_{\mathbb{V}} p^\theta_{\mathbb{D}} ,$$

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

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

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

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

$$\frac{d\Gamma_{\mathbb{D}\to\mathbb{V}S\bar{S}'}}{d\hat{s}} = \frac{\tilde{\lambda}_{\mathbb{DV}}^{3/2}\tilde{\lambda}_{SS'}^{3/2}}{(8\pi m_{\mathbb{D}}\hat{s})^3}\left\{\frac{\left|\kappa_{SS'}^{\mathrm{a}}\right|^2}{6\,m_{\mathbb{V}}^2}\left[\left(1 + \frac{12\,m_{\mathbb{V}}^2\hat{s}}{\tilde{\lambda}_{\mathbb{DV}}}\right)A_1^2\,\tilde{\mathrm{m}}_+^2 + 2(\hat{s} - \tilde{\mathrm{m}}_+\tilde{\mathrm{m}}_-)A_1A_2 + \frac{\tilde{\lambda}_{\mathbb{DV}}A_2^2}{\tilde{\mathrm{m}}_+^2}\right] + \frac{2A_0^2}{\tilde{\lambda}_{SS'}}\left|\kappa_{SS'}^{\mathrm{a}}\left(m_{S'}^2 - m_S^2\right) + \kappa_{SS'}^{\mathrm{p}}\,\hat{s}\right|^2 + \frac{4\left|\kappa_{SS'}^{\mathrm{v}}\right|^2\hat{s}V^2}{3\,\tilde{\mathrm{m}}_+^2}\right\},$$

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

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

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

(d) Semi-invisible baryonic decays

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

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

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

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

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 $\hat{s} = \hat{q}^2$,

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

(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

$$\frac{d\Gamma_{\Lambda_c^+\to p S\bar{S}'}}{d\hat{s}} = \frac{2\tilde{\lambda}^{1/2}_{\Lambda_c p}\,\tilde{\lambda}^{1/2}_{SS'}}{3(8\pi m_{\Lambda_c}\hat{s})^3}\Big\{\Big[|\kappa^{\rm v}_{SS'}|^2\big(2F_\perp^2\hat{s}+F_+^2M_+^2\big)\hat{\sigma}_- + |\kappa^{\rm a}_{SS'}|^2\big(2G_\perp^2\hat{s}+G_+^2M_-^2\big)\hat{\sigma}_+\Big]\tilde{\lambda}_{SS'}$$
$$+\,3\big|\kappa^{\rm v}_{SS'}\big(m_S^2-m_{S'}^2\big)+\kappa^{\rm s}_{SS'}\hat{s}\big|^2\,\hat{\sigma}_+\,M_-^2\,F_0^2$$
$$+\,3\big|\kappa^{\rm a}_{SS'}\big(m_{S'}^2-m_S^2\big)+\kappa^{\rm p}_{SS'}\hat{s}\big|^2\,\hat{\sigma}_-\,M_+^2\,G_0^2\Big\}\,,$$

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

Numerical results for decays induced by $c \to uS\bar{S}'$

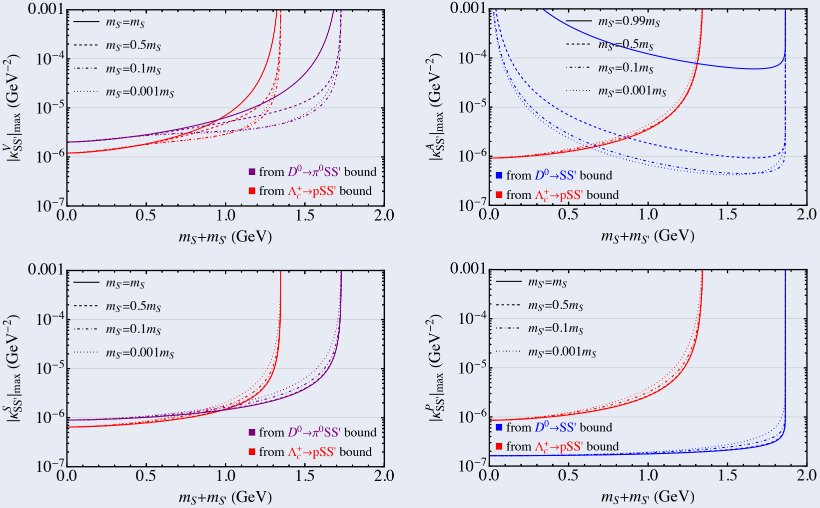

Figure 4: The upper limits on $|\kappa^{\mathrm{v}}_{\mathrm{SS}'}|$ (top left), $|\kappa^{\mathrm{a}}_{\mathrm{SS}'}|$ (top right), $|\kappa^{\mathrm{s}}_{\mathrm{SS}'}|$ (bottom left), and $|\kappa^{\mathrm{p}}_{\mathrm{SS}'}|$ (bottom right) versus $m_{\mathrm{S}}+m_{\mathrm{S}'}$ obtained from the $D^0 \to \mathrm{S}\bar{\mathrm{S}}'$ (blue), $D^0 \to \pi^0\mathrm{S}\bar{\mathrm{S}}'$ (purple), and $\Lambda_c^+ \to p\mathrm{S}\bar{\mathrm{S}}'$ (red) limits for various $m_{\mathrm{S}'}/m_{\mathrm{S}}$ values if only one of $\kappa^{\mathrm{v,a,s,p}}_{\mathrm{SS}'}$ is nonzero at a time.

Prediction of invisible scalars

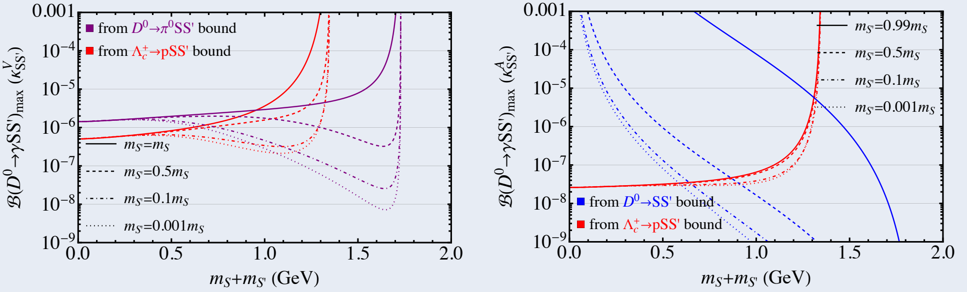

Figure 5: The maximal branching fraction of $D^0 \rightarrow \gamma S\bar{S}'$ due to $|\kappa^{\rm v}_{SS'}|_{\max}$ (left) or $|\kappa^{\rm a}_{SS'}|_{\max}$ (right) alone for various $m_{S'}/m_S$ choices.

Prediction of invisible scalars

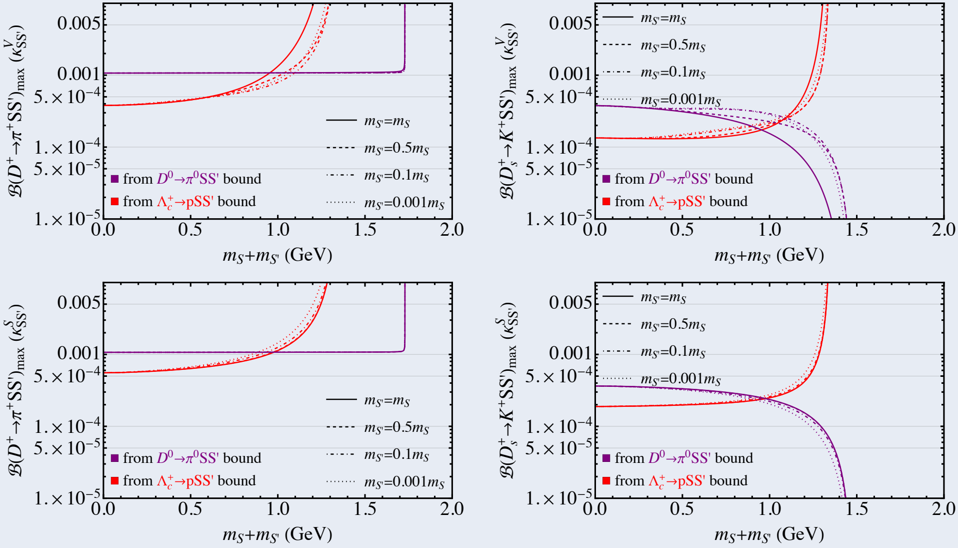

Figure 6: The maximal branching fractions of $D^+ \to \pi^+ S\bar{S}'$ (left column) and $D_s^+ \to K^+ S\bar{S}'$ (right column) due to $|\kappa^V_{SS'}|_{max}$ (top row) or $|\kappa^S_{SS'}|_{max}$ (bottom row) alone for different $m_{S'}/m_S$ values.

Prediction of invisible scalars

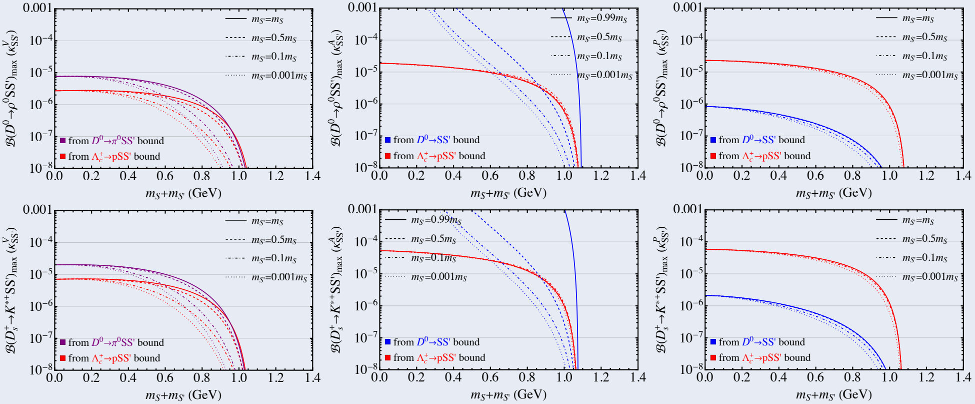

Figure 7: The maximal branching fractions of $D^0 \to \rho^0 S\bar{S}'$ and $D_s^+ \to K^{*+} S\bar{S}'$ due to $|\kappa^{v}_{SS'}|_{max}$ or $|\kappa^{a}_{SS'}|_{max}$ (middle row) or $|\kappa^{p}_{SS'}|_{max}$ alone. The $D^+ \to \rho^+ S\bar{S}'$ curves, not displayed, are approximately $2\tau_{D^+}/\tau_{D^0} \sim 5$ times their $D^0 \to \rho^0 S\bar{S}'$ counterparts.

Prediction of invisible scalars

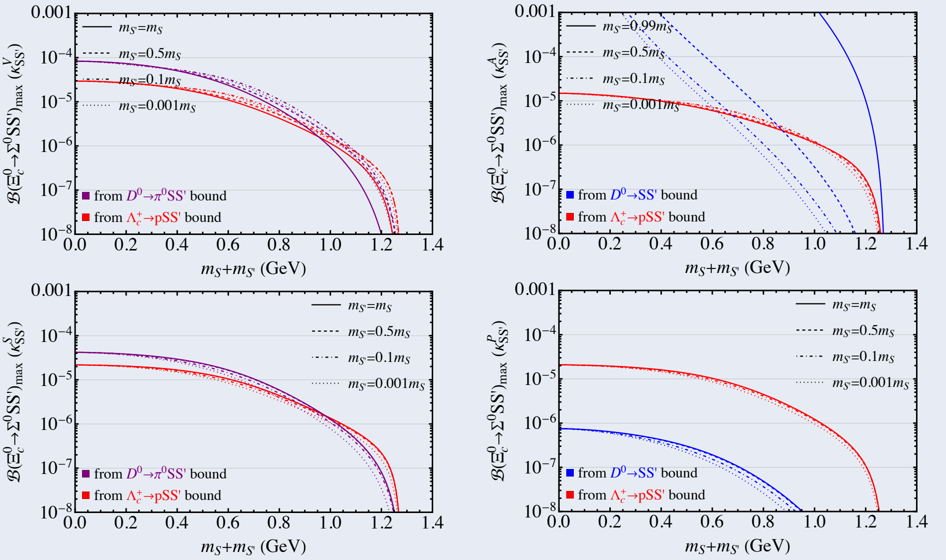

Figure 8: The maximal branching fractions of $\Xi_c^0 \to \Sigma^0 S\bar{S}'$ due to $|\kappa^{\rm v}_{SS'}|_{\max}$ or $|\kappa^{\rm a}_{SS'}|_{\max}$ or $|\kappa^{\rm s}_{SS'}|_{\max}$ or $|\kappa^{\rm p}_{SS'}|_{\max}$ alone. The $\Xi_c^+ \to \Sigma^+ S\bar{S}'$ curves, not shown, are approximately $2\tau_{\Xi_c^+}/\tau_{\Xi_c^0} \sim 6$ times their $\Xi_c^0 \to \Sigma^0 S\bar{S}'$ counterparts.

Prediction of invisible scalars

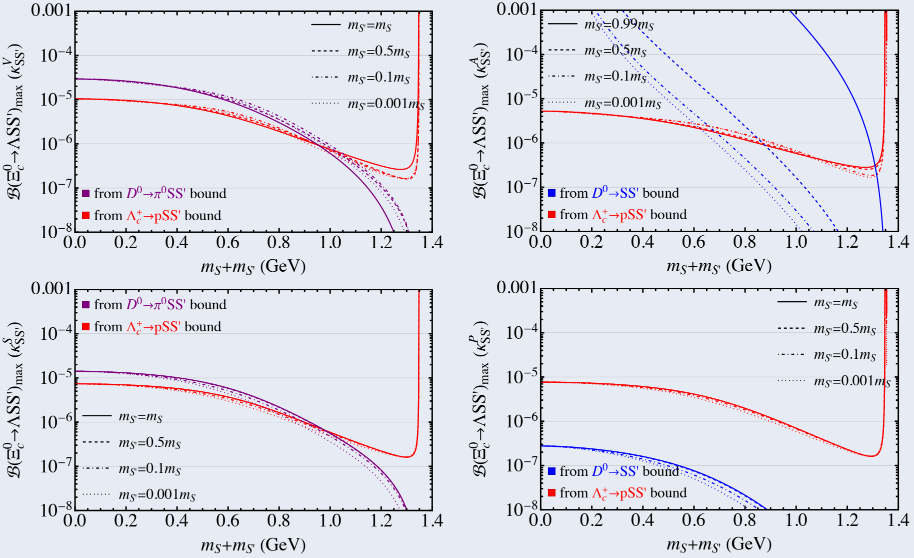

Figure 9: The maximal branching fractions of $\Xi_c^0 \to \Lambda S\bar{S}'$ due to $|\kappa^{\rm v}_{SS'}|_{\max}$ or $|\kappa^{\rm a}_{SS'}|_{\max}$ or $|\kappa^{\rm s}_{SS'}|_{\max}$ or $|\kappa^{\rm p}_{SS'}|_{\max}$ alone.

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

Prediction of invisible scalars

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

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

FCNC charm decay with invisible singlet fermions

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

$$\mathcal{L}_{\mathrm{lq}} = \bar{\mathrm{Y}}_{jl} \overline{\mathcal{U}_j^{\mathrm{c}}} P_R \mathrm{N}_l \bar{S}_1 + \mathrm{H.c.}\,,$$

where $\bar{\mathrm{Y}}_{jl}$ are generally complex elements of the LQ Yukawa matrix $\bar{\mathrm{Y}}$, $\mathcal{U}_{1,2,3} = (u, c, t)$.
The effective Lagrangian for $c \to u \mathrm{N}\bar{\mathrm{N}}'$

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

with the coefficients being given by

$$\mathrm{C}^{\mathrm{V}}_{\mathrm{N}_j\mathrm{N}_l} = \mathrm{C}^{\mathrm{A}}_{\mathrm{N}_j\mathrm{N}_l} = \tilde{\mathrm{c}}^{\mathrm{V}}_{\mathrm{N}_j\mathrm{N}_l} = \tilde{\mathrm{c}}^{\mathrm{A}}_{\mathrm{N}_j\mathrm{N}_l} = -\frac{\bar{\mathrm{Y}}^*_{1j}\bar{\mathrm{Y}}_{2l}}{8m^2_{\bar{S}_1}}\,.$$

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

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

in which case only $c \to u \mathrm{N}_2 \bar{\mathrm{N}}_1$ can occur with

$$\mathrm{C}^{\mathrm{V}}_{\mathrm{N}_2\mathrm{N}_1} = \mathrm{C}^{\mathrm{A}}_{\mathrm{N}_2\mathrm{N}_1} = \tilde{\mathrm{c}}^{\mathrm{V}}_{\mathrm{N}_2\mathrm{N}_1} = \tilde{\mathrm{c}}^{\mathrm{A}}_{\mathrm{N}_2\mathrm{N}_1} = -\frac{\bar{\mathrm{y}}^*_{u2}\bar{\mathrm{y}}_{c1}}{8m^2_{\bar{S}_1}} \equiv \mathrm{k}_{\mathrm{NN}'}\,,$$

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_is

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

- 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

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

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 $\mathrm{f} = \mathrm{f}' = \nu_\ell$ and $m_{\rm f} = m_{\rm f'} = 0$,

$$\mathrm{C}^{\rm V}_{\rm ff'} = -\mathrm{C}^{\rm A}_{\rm ff'} = -\tilde{\mathrm{c}}^{\rm V}_{\rm ff'} = \tilde{\mathrm{c}}^{\rm A}_{\rm ff'} = \sum_{q=d,s,b} \frac{\alpha_{\rm e} G_{\rm F} \hat{\lambda}_q \bar{D}(r_q, r_\ell)}{4\sqrt{2}\,\pi\,\sin^2\theta_W}\,.$$

We obtained

$$\mathcal{B}(D^0 \to \nu\bar{\nu}) = 0\,, \qquad \mathcal{B}(D^0 \to \gamma\nu\bar{\nu}) = 1.8\times10^{-19}\,,$$
$$\mathcal{B}(D^0 \to \pi^0\nu\bar{\nu}) = 2.5\times10^{-17}\,, \qquad \mathcal{B}(D^0 \to \rho^0\nu\bar{\nu}) = 1.1\times10^{-17}\,,$$
$$\mathcal{B}(D^+ \to \pi^+\nu\bar{\nu}) = 1.3\times10^{-16}\,, \qquad \mathcal{B}(D^+ \to \rho^+\nu\bar{\nu}) = 5.9\times10^{-17}\,,$$
$$\mathcal{B}(D_s^+ \to K^+\nu\bar{\nu}) = 4.5\times10^{-17}\,, \qquad \mathcal{B}(D_s^+ \to K^{*+}\nu\bar{\nu}) = 3.3\times10^{-17}\,,$$
$$\mathcal{B}(\Lambda_c^+ \to p\nu\bar{\nu}) = 7.3\times10^{-17}\,, \qquad \mathcal{B}(\Xi_c^+ \to \Sigma^+\nu\bar{\nu}) = 1.1\times10^{-16}\,,$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^0\nu\bar{\nu}) = 1.8\times10^{-17}\,, \qquad \mathcal{B}(\Xi_c^0 \to \Lambda\nu\bar{\nu}) = 6.5\times10^{-18}\,.$$

Prediction of invisible fermions

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

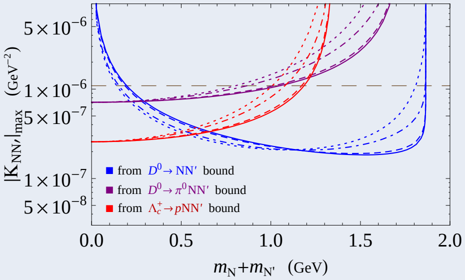

Figure 10: The upper limits on $|k_{NN'}|$ versus $m_N + m_{N'}$, with $N = N_2$ and $N' = N_1$, implied by the $D^0 \to N\bar{N}'$ (blue), $D^0 \to \pi^0 N\bar{N}'$ (purple), and $\Lambda_c^+ \to pN\bar{N}'$ (red) bounds for $m_{N'}/m_N = 0.001$ (dotted curves), 0.1 (dash-dotted curves), 0.5 (dashed curves), 1 (solid curves). The horizontal brown dashed line marks $|k_{NN'}| < 1.1\ \text{TeV}^{-2}$ inferred from collider and perturbativity restrictions.

Prediction of invisible fermions

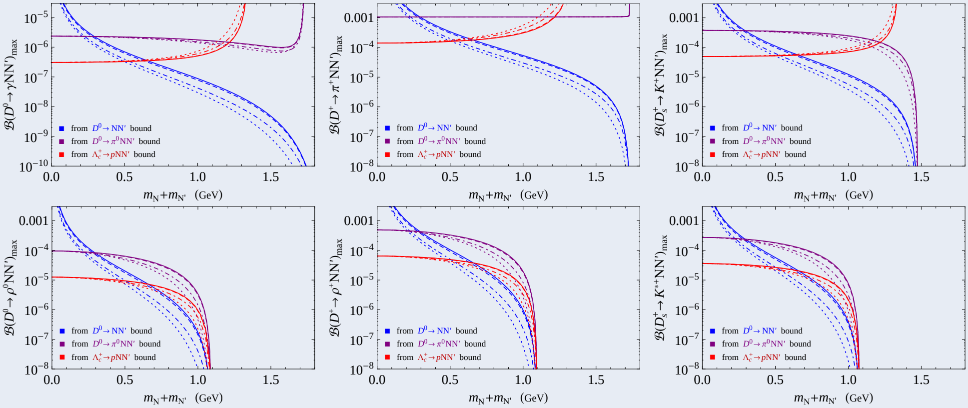

Figure 11: Maximal branching fractions of $D^0 \to (\gamma, \rho^0)N\bar{N}'$, $D^+ \to (\pi^+, \rho^+)N\bar{N}'$, and $D_s^+ \to (K^+, K^{*+})N\bar{N}'$ translated from the $|k_{NN'}|_{max}$ values in Fig. 10 inferred from the $D^0 \to N\bar{N}'$ (blue), $D^0 \to \pi^0 N\bar{N}'$ (purple), and $\Lambda_c^+ \to pN\bar{N}'$ (red) bounds.

Prediction of invisible fermions

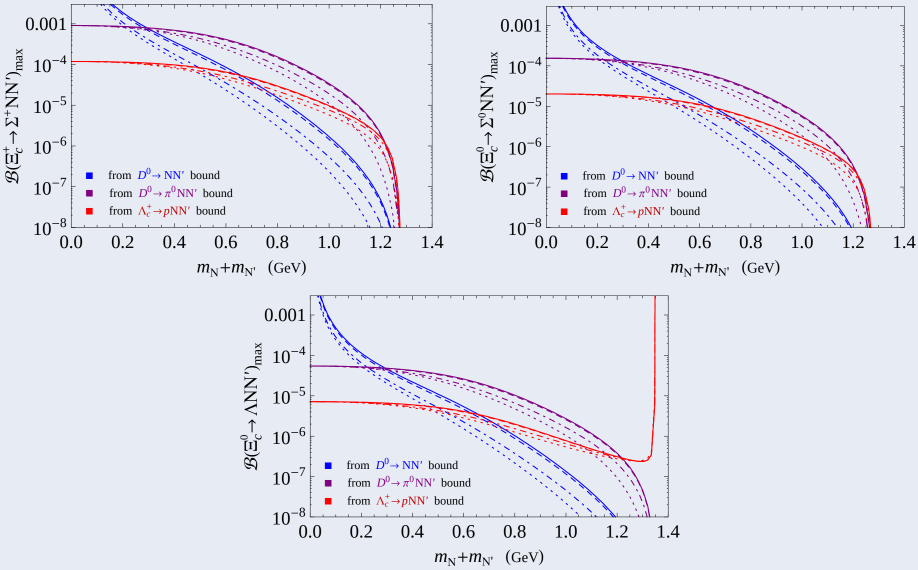

Figure 12: The same as Fig. 9 but for $\Xi_c^{+,0} \to \Sigma^{+,0} N\bar{N}'$ and $\Xi_c^0 \to \Lambda N\bar{N}'$.

Prediction of invisible fermions

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

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

Thanks for your attention!

Let's have a further discussion, please.

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