Rare charm decays

稀有魅力衰减

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Overview

SM in rare charm decays

NP

NP in D meson in rare charm decays

NP in B anomalies $\rightarrow$ NP in charm
Impact of D^0 - $\bar{D}^0$ on rare charm decays
Signatures of NP in FCNC charm decays

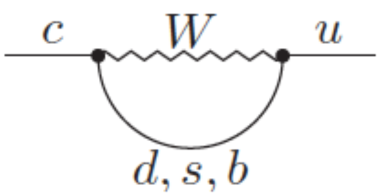
$D \rightarrow V \gamma$
$D \rightarrow P_1 P_2 \gamma$
$D \rightarrow P l^+ l^-$
$D \rightarrow l^+ l^-$
$D \rightarrow P_1 P_2 l^+ l^-$
$D \rightarrow$ invisibles

Summary and Outlook

SM effective Hamiltonian for rare charm decays -FCNC

$$\mathcal{H}_{\text{eff}} = \lambda_d \mathcal{H}^d + \lambda_s \mathcal{H}^s - \frac{4G_F \lambda_b}{\sqrt{2}} \sum_{i=3,\ldots,10,S,P,\ldots} C_i \mathcal{O}_i$$

$$\lambda_q = V_{uq} V_{cq}^*$$



Tree-level 4-quark operators   (Short-distance) penguin operators

1) At scale m_W all penguin contributions vanish due to GIM;

2) SM contributions to $C_{7\ldots10}$ at scale m_c entirely due to mixing of tree-level operators into penguin ones under QCD

3) SM values at m_c

Effective weak Lagrangian

$$\mathcal{L}_{\rm eff}^{\rm weak} = \frac{4G_F}{\sqrt{2}}\left(\sum_{q\in\{d,s\}} V_{cq}^* V_{uq} \sum_{i=1}^{2} C_i Q_i^{(q)} + \sum_{i=3}^{6} C_i Q_i + \sum_{i=7}^{8}(C_i Q_i + C_i' Q_i')\right)$$

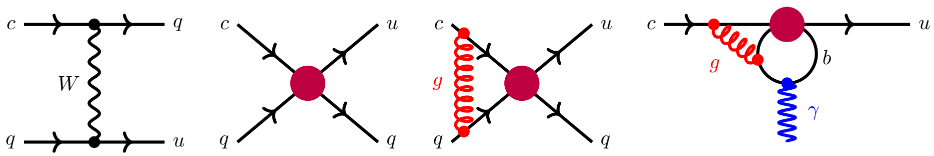
$$Q_1^{(q)} = (\bar u_L \gamma_{\mu_1} T^a q_L)(\bar q_L \gamma^{\mu_1} T^a c_L)\,, \qquad Q_2^{(q)} = (\bar u_L \gamma_{\mu_1} q_L)(\bar q_L \gamma^{\mu_1} c_L)\,,$$

$$Q_3 = (\bar u_L \gamma_{\mu_1} c_L) \sum_{\{q:m_q<\mu_c\}} (\bar q \gamma^{\mu_1} q)\,, \qquad Q_4 = (\bar u_L \gamma_{\mu_1} T^a c_L) \sum_{\{q:m_q<\mu_c\}} (\bar q \gamma^{\mu_1} T^a q)\,,$$

$$Q_5 = (\bar u_L \gamma_{\mu_1}\gamma_{\mu_2}\gamma_{\mu_3} c_L) \sum_{\{q:m_q<\mu_c\}} (\bar q \gamma^{\mu_1}\gamma^{\mu_2}\gamma^{\mu_3} q)\,, \qquad Q_6 = (\bar u_L \gamma_{\mu_1}\gamma_{\mu_2}\gamma_{\mu_3} T^a c_L) \sum_{\{q:m_q<\mu_c\}} (\bar q \gamma^{\mu_1}\gamma^{\mu_2}\gamma^{\mu_3} T^a q)\,,$$

$$Q_7 = \frac{e\, m_c}{16\pi^2}(\bar u_L \sigma^{\mu_1\mu_2} c_R) F_{\mu_1\mu_2}\,, \qquad Q_7' = \frac{e\, m_c}{16\pi^2}(\bar u_R \sigma^{\mu_1\mu_2} c_L) F_{\mu_1\mu_2}\,,$$

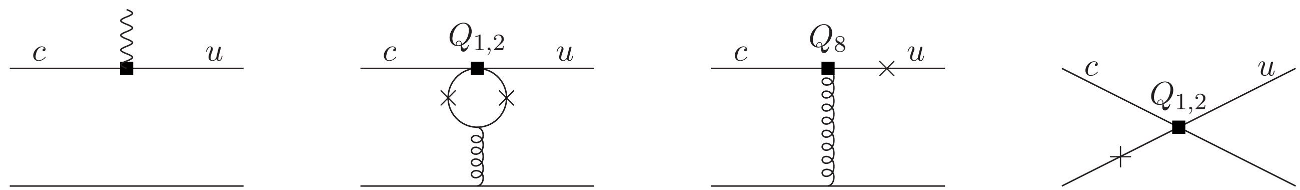
$$Q_8 = \frac{g_s\, m_c}{16\pi^2}(\bar u_L \sigma^{\mu_1\mu_2} T^a c_R) G^a_{\mu_1\mu_2}\,, \qquad Q_8' = \frac{g_s\, m_c}{16\pi^2}(\bar u_R \sigma^{\mu_1\mu_2} T^a c_L) G^a_{\mu_1\mu_2}\,,$$



- matching of SM contributions onto Weak Effective Theory at $\mu = M_W$;
- RG-evolution of Wilson coefficients from M_W to m_b,
- integrating out the b quark and second matching at $\mu = m_b$,
- RG-evolution of Wilson coefficients from m_b to the charm scale μ_c.

(recent results: Gisbert et al. 2011.09478, de Boer, Hiller, 1510.00311, 1701.06392, De Boer et al, 1606.05521, 1707.00988
SF& Singer, hep-ph/9705327, hep-ph/9901252, SF, Prelovsek & Singer hep-ph/9801279)

SM Corrections: hard spectator and weak annihilation



spectating   hard spectator interaction   weak annihilation

Leading hard spectator within QCD factorization adopted from B physics

$\lambda_D \sim \Lambda_{\text{QCD}} \sim \mathcal{O}(0.1\,\text{GeV})$ scale dependence varied $\mu_c \in [m_c/\sqrt{2}, \sqrt{2}m_c]$

$$C_7^{\text{HSI},\rho} \in [0.00051 + 0.0014i, 0.00091 + 0.0020i] \cdot \frac{\text{GeV}}{\lambda_D},$$
$$C_7^{\text{HSI},\omega} \in [0.00030 + 0.0010i, 0.00098 + 0.0020i] \cdot \frac{\text{GeV}}{\lambda_D},$$
$$C_7^{\text{HSI},K^{*+}} \in [0.00032 + 0.0013i, 0.00096 + 0.0022i] \cdot \frac{\text{GeV}}{\lambda_D}.$$

$$C_7^{\text{WA},\rho^0} \in [-0.010, -0.0011] \cdot \frac{\text{GeV}}{\lambda_D}$$
$$C_7^{\text{WA},\omega} \in [0.0097, 0.0011] \cdot \frac{\text{GeV}}{\lambda_D},$$
$$C_7^{\text{WA},\rho^+} \in [0.029, 0.038] \cdot \frac{\text{GeV}}{\lambda_D},$$
$$C_7^{\text{WA},K^{*+}} \in [-0.034, -0.047] \cdot \frac{\text{GeV}}{\lambda_D}$$

hard spectator interaction- adopted from B

DeBoer & Hiller 1701.06392

SD contributions C. Greub et al., PLB 382 (1996) 415;

$D \to V\gamma$

branching ratio	$D^0 \to \rho^0\gamma$	$D^0 \to \omega\gamma$	$D^+ \to \rho^+\gamma$	$D_s \to K^{*+}\gamma$
two-loop QCD	$(0.14 - 2.0) \cdot 10^{-8}$	$(0.14 - 2.0) \cdot 10^{-8}$	$(0.75 - 1.0) \cdot 10^{-8}$	$(0.32 - 5.5) \cdot 10^{-8}$
HSI+WA	$(0.11 - 3.8) \cdot 10^{-6}$	$(0.078 - 5.2) \cdot 10^{-6}$	$(1.6 - 1.9) \cdot 10^{-4}$	$(1.0 - 1.4) \cdot 10^{-4}$
hybrid	$(0.041 - 1.17) \cdot 10^{-5}$	$(0.042 - 1.12) \cdot 10^{-5}$	$(0.017 - 2.33) \cdot 10^{-4}$	$(0.053 - 1.54) \cdot 10^{-4}$
*	$(0.1 - 1) \cdot 10^{-5}$	$(0.1 - 0.9) \cdot 10^{-5}$	$(0.4 - 6.3) \cdot 10^{-5}$	$(1.2 - 5.1) \cdot 10^{-5}$
**	$(0.1 - 0.5) \cdot 10^{-5}$	$0.2 \cdot 10^{-5}$	$(2 - 6) \cdot 10^{-5}$	$(0.8 - 3) \cdot 10^{-5}$
***	$3.8 \cdot 10^{-6}$	–	$4.6 \cdot 10^{-6}$	–
data†	$(1.77 \pm 0.31) \cdot 10^{-5}$	$< 2.4 \cdot 10^{-4}$	–	–

Hiller & De Boer 1701.06392

* SF& Singer, hep-ph/9705327, hep-ph/9901252, SF, Prelovsek & Singer hep-ph/9801279
** Burdman et al. hep-ph/9502329,
*** Khodjamirian et al., hep-ph/9506242

Hybrid model: LD effects included in form-factors for $D \to V\gamma$

"poor convergence of the $1/m_c$ and α_s-expansion prohibits a sharp conclusion without further study "

Note: all SM th. predictions for
BR($D^0 \to \rho^0\gamma$) smaller than exp. rates!

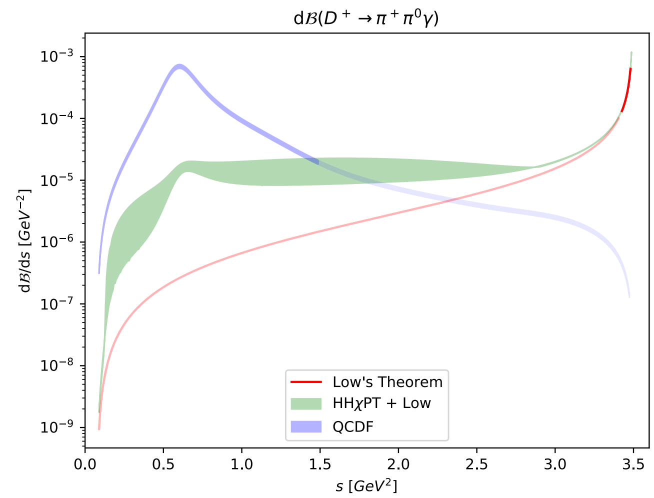
$D \to P_1 P_2 \gamma$

CF: $D_s \to \pi^+\pi^0\gamma\,,\ D_s \to K^+\overline{K}^0\gamma\,,\ D^+ \to \pi^+\overline{K}^0\gamma\,,\ (D^0 \to \pi^0\overline{K}^0\gamma\,,$

SCS: $D^+ \to \pi^+\pi^0\gamma\,,\ D_s \to \pi^+K^0\gamma\,,\ D_s \to K^+\pi^0\gamma\,,$

$D^+ \to K^+\overline{K}^0\gamma\,, (D^0 \to \pi^+\pi^-\gamma\,,\ D^0 \to K^+K^-\gamma)$

DCS: $D^+ \to \pi^+K^0\gamma\,, D^+ \to K^+\pi^0\gamma\,,\ D_s \to K^+K^0\gamma$



"sizable effects of the dipole operators can be seen for differential branching ratios and forward backward asymmetries – it is difficult to claim sensitivity to NP due to the uncertainties of the leading order calculation and the intrinsic uncertainty of the Breit-Wigner contributions." – Adolph & Hiller 2104.08287, Adolph et al., 2009.14212, SF et al., hep-ph/0204306, [hep-ph/0210423.

CP asymmetry in charm radiative decays

CP asymmetries in c → uγ transitions constitute SM null tests

$$A_{CP}(D \to V\gamma) = \frac{\Gamma(D \to V\gamma) - \Gamma(\bar{D} \to \bar{V}\gamma)}{\Gamma(D \to V\gamma) + \Gamma(\bar{D} \to \bar{V}\gamma)}$$

$$|A_{CP}^{\text{SM}}| < 2 \cdot 10^{-3}$$

large uncertainties!

Experiment

Belle, 1603.03257

$$A_{CP}(D^0 \to \rho^0\gamma) = 0.056 \pm 0.152 \pm 0.006\,,$$

$$A_{CP}(D^0 \to \phi\gamma) = -0.094 \pm 0.066 \pm 0.001$$

$$A_{CP}(D^0 \to \bar{K}^{*0}\gamma) = -0.003 \pm 0.020 \pm 0.000$$

Hiller& de Boer 1701. 06392

LQs might give as large

contributions as SM

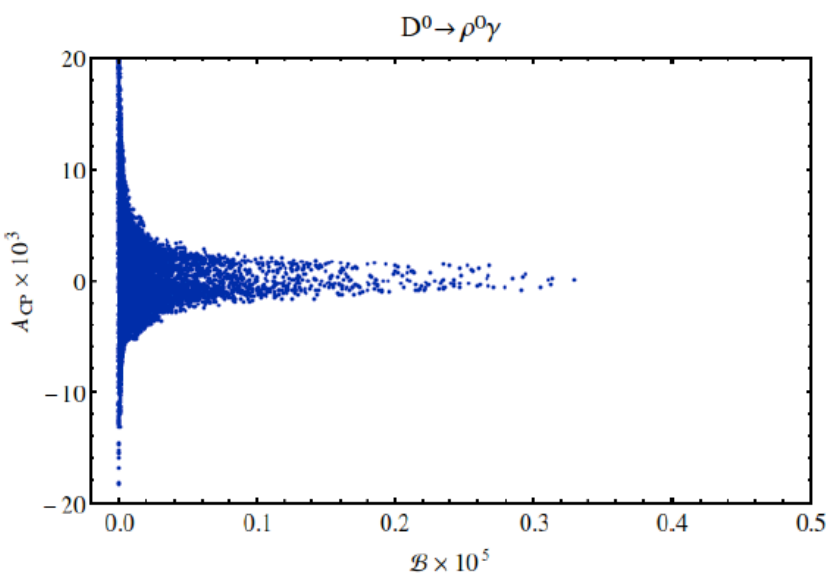
the polarization fraction r

$D^0 \to \phi\gamma$ or $D^0 \to \bar{K}^{0*}\gamma$ decays (SM-dominated)

$$A^{\rm SM}_{L,R}(\rho^0) = A_{L,R}(\bar{K}^{*0}) \times [\text{U-spin corrections}]$$

$D^0 \to \rho^0\gamma$

the photon polarization and therefore A_Δ in $D^0 \to \rho^0(\to \pi^+\pi^-)\gamma$ becomes a null test of the SM.



Authors varied the form factor, the two-loop QCD and hard spectator interaction plus weak annihilation within uncertainties, where $\lambda_D \in [0.1, 0.6]$ GeV, A_7-contributions and relative strong phases.

Chromo-magnetic operator important for the CP asymmetry

$$A_{CP}\big|_{\langle Q_8, Q_8' \rangle} \sim -\mathrm{Im}\left[2C_8 + \frac{1}{2}C_8'\right]$$

$D \to \pi l^+ l^-$

SD dynamics
SM

$$\mathcal{C}_7^{\rm eff}(q^2 \approx 0) \simeq -0.0011 - 0.0041\,{\rm i}$$

$$\mathcal{C}_9^{\rm eff}(q^2) \simeq -0.021\left[V_{cd}^* V_{ud}\, L(q^2, m_d, \mu_c) + V_{cs}^* V_{us}\, L(q^2, m_s, \mu_c)\right],$$

$\mathcal{C}_{10}^{\rm SM} = 0$ Only for D, different for B and K in SM

$$\mathcal{C}_i^{\prime\,\rm SM} = \mathcal{C}_S^{\rm SM} = \mathcal{C}_T^{\rm SM} = \mathcal{C}_{T5}^{\rm SM} = \mathcal{C}_{10}^{\rm SM} = 0$$

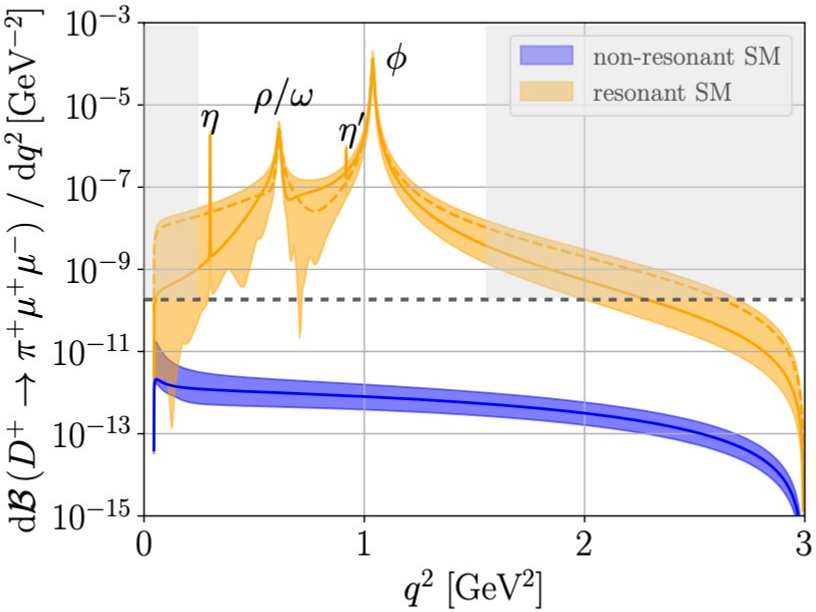
Gisbert et al. 2011.09478,

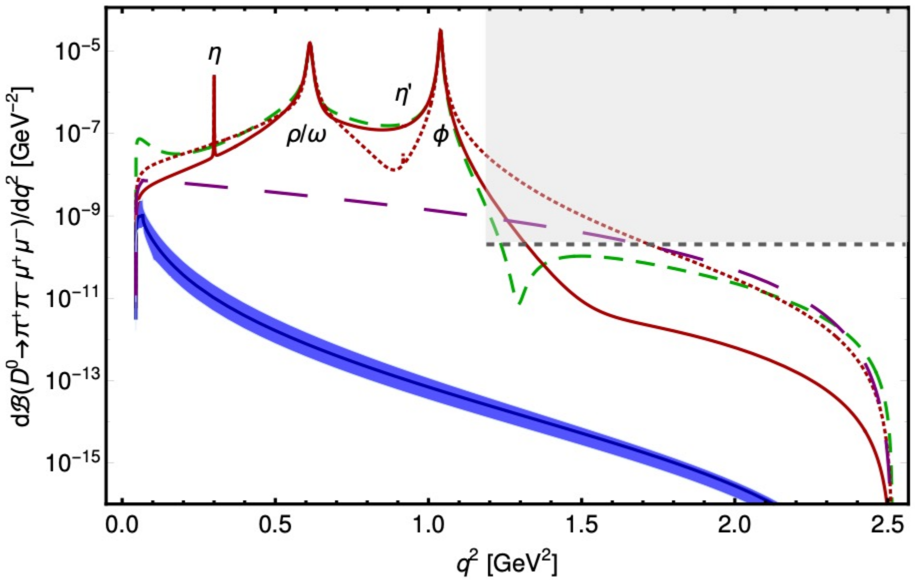
LD dynamics: Resonance contributions

$$\mathcal{C}_9^R = a_{\rho^0}\, e^{{\rm i}\,\delta_{\rho^0}} \left(\frac{1}{q^2 - m_{\rho^0}^2 + {\rm i}\, m_{\rho^0}\Gamma_{\rho^0}} - \frac{1}{3}\frac{1}{q^2 - m_\omega^2 + {\rm i}\, m_\omega \Gamma_\omega} \right) + \frac{a_\phi\, e^{{\rm i}\,\delta_\phi}}{q^2 - m_\phi^2 + {\rm i}\, m_\phi \Gamma_\phi}$$

$$\mathcal{C}_P^R = \frac{a_\eta\, e^{{\rm i}\,\delta_\eta}}{q^2 - m_\eta^2 + {\rm i}\, m_\eta \Gamma_\eta} + \frac{a_{\eta'}}{q^2 - m_{\eta'}^2 + {\rm i}\, m_{\eta'} \Gamma_{\eta'}}$$

$D \to \pi l^+ l^-$





SM prediction: Long distance contributions most important!

peaks at ρ,ω,φ and η resonances

Gisbert etal.,2011.09478
de Boer, Hiller, 1510.00311,
SF and Kosnik, 1510.00965
Bause et al, 1909.11108

Lattice for form factors
HFLAV, 1909.12524

SM in $D \to \ell^+\ell^-$

Belle &LHCb Experiment:

$$\mathcal{B}(D^0 \to e^+e^-) < 7.9 \times 10^{-8}$$
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$$
$$\mathcal{B}(D^0 \to \mu^\pm e^\mp) < 1.3 \times 10^{-8}$$

Helicity suppression

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{G_F^2\,\alpha_e^2\,m_D^5\,f_D^2}{64\,\pi^3\,m_c^2\,\Gamma_D}\sqrt{1-\frac{4\,m_\mu^2}{m_D^2}}\left[\left(1-\frac{4\,m_\mu^2}{m_D^2}\right)\left|\mathcal{C}_S^{(\mu)}-\mathcal{C}_S^{(\mu)\prime}\right|^2 + \left|\mathcal{C}_P^{(\mu)}-\mathcal{C}_P^{(\mu)\prime}+\frac{2m_\mu m_c}{m_D^2}\left(\mathcal{C}_{10}^{(\mu)}-\mathcal{C}_{10}^{(\mu)\prime}\right)\right|^2\right],$$

$$\mathcal{B}(D^0 \to \mu^+\mu^-)_{\rm LD} \approx 8\,\alpha^2 \cdot \left(\frac{m_\mu^2}{m_D^2}\right)\cdot \log^2\left(\frac{m_\mu^2}{m_D^2}\right)\cdot \mathcal{B}(D^0 \to \gamma\gamma) \sim 10^{-11}$$

Gisbert et al. 2011.09478,

NP in rare charm decays – from B to D

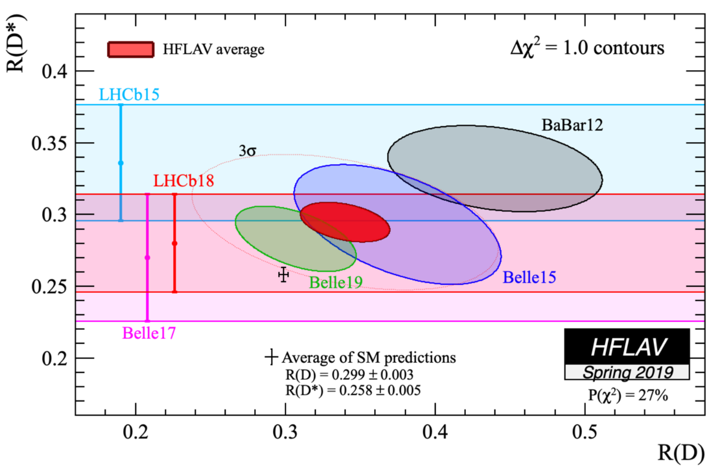
Search for NP in up sector
- at low energies (charm factories)
- at high energies LHC

B anomalies explained by NP

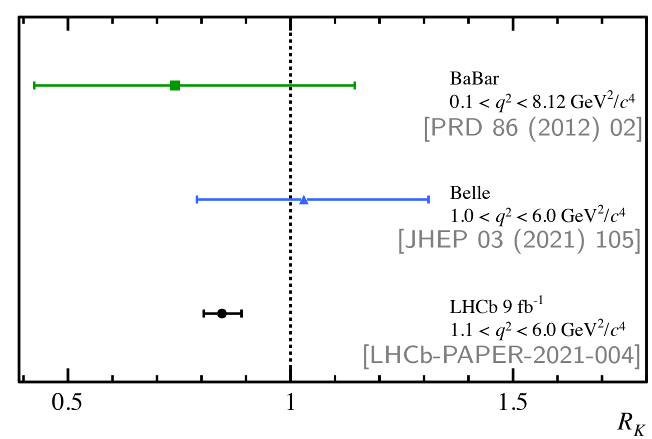
Can this NP be seen in charm rare decays, D^0 - $\bar{D}^0$ oscillations ...

Unfortunately GIM mechanism is in the action for FCNC in charm physics !

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell \in (e,\mu)}$$



$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\bigg|_{q^2 \in [q^2_{\rm min}, q^2_{\rm max}]}$$



3.1σ

NP explaining both B anomalies

$$R_{D^{(*)}}^{exp} > R_{D^{(*)}}^{SM}$$

$$\mathcal{L}_{NP} = \frac{1}{(\Lambda^D)^2} 2\, \bar{c}_L \gamma_\mu b_L \bar{\tau} \gamma^\mu \nu_L$$

$$\Lambda^D \simeq 3\,\mathrm{TeV}$$

$$R_{K^{(*)}}^{exp} < R_{K^{(*)}}^{SM}$$

$$\mathcal{L}_{NP} = \frac{1}{(\Lambda^K)^2} \bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L$$

$$\Lambda^K \simeq 30\,\mathrm{TeV}$$

$$\Lambda^D \simeq \Lambda^K \equiv \Lambda$$

NP in FCNC $B \to K^{(*)} \mu^+ \mu^-$ has to be suppressed

$$\frac{1}{(\Lambda^K)^2} = \frac{C_K}{\Lambda^2} \qquad C_K \simeq 0.01$$

suppression factor

Charged current charm meson decays and New Physics

$$\mathcal{L}_{SM} = \frac{4G_F}{\sqrt{2}} V_{cs} \bar{s}_L \gamma^\mu c_L \, \bar{\nu}_l \gamma_\mu l$$

$$\mathcal{L}_{NP} = \frac{2}{\Lambda_c^2} \bar{s}_L \gamma^\mu c_L \, \bar{\nu}_l \gamma_\mu l$$

PDG 2020

$$f_{D^+} = 212.6(7) \text{ MeV}$$

$$f_{D_s} = 249.9(5) \text{ MeV}$$

$$\frac{f_{D_s}}{f_{D^+}} = 1.175(2)$$

$$|V_{cs}| = 0.983(13)(14)(2)$$

Electro-magnetic correction 1-3%

1 % error in

$$\Gamma(D_s^+ \to l^+ \nu_l)$$

↓

$$\Lambda_c \sim 2.5 \text{ TeV}$$

Message:
Even if there is NP at 3 TeV scale
the effect on charm leptonic decay
can be ~ 1%!

New Physics in charm processes

NP in charm

Constraints from K, B physics

Constraints from EW physics, oblique corrections, $Z \to b\bar{b}$

Constraints from LHC

Up-quark in weak doublet "talks" to down quarks via CKM!

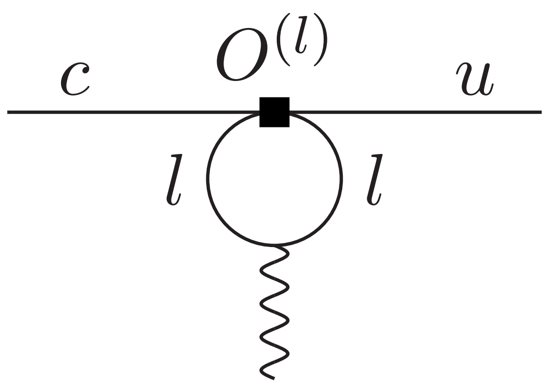
$$Q_{iL} = \begin{bmatrix} V^*_{il}\, u_J \\ d_i \end{bmatrix}_L$$

Effects of NP in charm suppressed by $V_{cb}^* V_{ub}$!

New Physics in FCNC charm decays

Leptoquarks in c → uγ

Hiller& de Boer 1701. 06392
SF and Košnik, 1510.00965



Constraints from

$$\tau^- \to \pi^- \nu_\tau$$
$$\tau^- \to K^- \nu_\tau$$
$$\Delta m_D$$
$$D^+ \to \tau^+ \nu_\tau$$
$$D_s^+ \to \tau^+ \nu_\tau$$
$$K^+ \to \pi^+ \nu \bar{\nu}$$

Even for τ in the loop too small contribution
$(m_\tau/m_{LQ})^2$ suppression!

Within LQ models the c → uγ branching ratios are SM-like with CP asymmetries at (0.01) for $S_{1,2}$ and $\tilde{V}_2$ and SM-like for S_3.
Vector LQ $\tilde{V}_1$ A_{CP} ~ O(10%). The largest effects arise from τ-loops.

S_3 can explain $R_{K(*)}$!

Angular distributions in $D \to P_1 P_2\, l^+ l^-$

LHCb, 1707.08377

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-)|_{[0.565-0.950]\,\mathrm{GeV}} = (40.6 \pm 5.7) \times 10^{-8}$$

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-)|_{[0.950-1.100]\,\mathrm{GeV}} = (45.4 \pm 5.9) \times 10^{-8}$$

$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-)|_{[>0.565]\,\mathrm{GeV}} = (12.0 \pm 2.7) \times 10^{-8}$$

De Beor and Hiller, 1805.08516

- study of angular distributions $\longrightarrow$ SM – null tests
- simpler then in B decays due to dominance of long distance physics (resonances)
- NP induced integrated CP asymmetries can reach few percent
- sensitive on $C_{10}^{(\prime)}$

$$A_{\mathrm{FB}}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\ \ 3.3 \pm 3.7 \pm 0.6)\%,$$
$$A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (-0.6 \pm 3.7 \pm 0.6)\%,$$
$$A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\ \ 4.9 \pm 3.8 \pm 0.7)\%,$$
$$A_{\mathrm{FB}}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$
$$A_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-) = (9 \pm 11 \pm 1)\%,$$
$$A_{CP}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$

LHCb , 1806.10793
consistent with SM

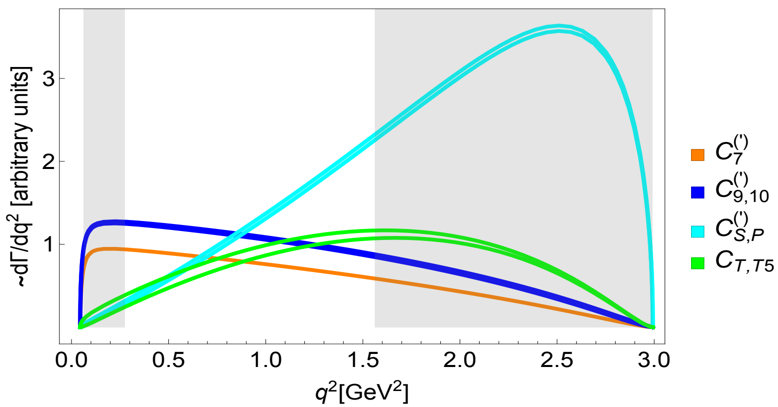
Tests of LFU

$$R^{D}_{P_1P_2} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}/dq^2(D \to P_1P_2\mu^+\mu^-)}{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}/dq^2(D \to P_1P_2e^+e^-)}$$

$$R^{D\,\mathrm{SM}}_{\pi\pi} = 1.00 \pm \mathcal{O}(\%)$$

$$R^{D\,\mathrm{SM}}_{KK} = 1.00 \pm \mathcal{O}(\%)$$

NP bounds from $D \to \pi l^+ l^-$ and $D \to \ell^+ \ell^-$



Maximally allowed values of the Wilson coefficients in the low and high energy bins, according to LHCb 1304.6365 :

$q^2 \in [0.0625, 0.276]\, GeV^2$

0.043

$\lvert\tilde{C}_i\rvert = \lvert V_{ub} V_{cb}^* C_i\rvert$	$\lvert\tilde{C}_i\rvert_{\max}$		
	$\mathrm{BR}(\pi\mu\mu)_{\mathrm{I}}$	$\mathrm{BR}(\pi\mu\mu)_{\mathrm{II}}$	$\mathrm{BR}(D^0 \to \mu\mu)$
$\tilde{C}_7$	2.4 region I	1.6	-
$\tilde{C}_9$	2.1	1.3	-
$\tilde{C}_{10}$	1.4	0.92	0.56
$\tilde{C}_S$	4.5	0.38	0.043
$\tilde{C}_P$	3.6	0.37	0.043
$\tilde{C}_T$	4.1	0.76	-
$\tilde{C}_{T5}$	4.4	0.74	
$\tilde{C}_9 = \pm\tilde{C}_{10}$	1.3	0.81	0.56

region II

$q^2 \in [1.56, 4.00]\, GeV^2$

Best bounds from

$D^0 \to \mu^+ \mu^-$

Model of NP	Effect on W.c.	Size of the effect
Scalar leptoquark (3,2,7/6)	$C_S, C_P, C_S', C_P', C_T, C_{T5}, C_9, C_{!0}, C_9', C_{10}'$	$V_{cb}V_{ub}\|C_{9,}\ C_{10}\| < 0.34$
Vector leptoquark (3,1,5/3)	$C_9' = C_{10}'$	$V_{cb}V_{ub}\|C_9'_{,}\ C_{10}'\| < 0.24$
Two Higgs doublet Model type III	C_S, C_P, C_S', C_P'	$V_{cb}V_{ub}\|C_S - C_S'\| < 0.005$ $V_{cb}V_{ub}\|C_P - C_P'\| < 0.005$
Z' model	C_9', C_{10}'	$V_{cb}V_{ub}\|C_9'_{,}\| < 0.001$ $V_{cb}V_{ub}\|C_{10}'\| < 0.014$

Lepton flavor violation

$$c \to u\mu^{\pm}e^{\mp}$$

1510.00311 (de Beor and Hiller)
1705.02251 (Sahoo and Mohanta)

$$\mathcal{L}_{\rm eff}^{\rm weak}(\mu \sim m_c) = \frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\sum_i \left(K_i^{(e)}O_i^{(e)} + K_i^{(\mu)}O_i^{(\mu)}\right)$$

$$O_9^{(e)} = (\bar{u}\gamma_\mu P_L c)(\bar{e}\gamma^\mu \mu)$$

$$O_9^{(\mu)} = (\bar{u}\gamma_\mu P_L c)(\bar{\mu}\gamma^\mu e)$$

LHCb bound, 1512.00322

$$BR(D^0 \to e^+\mu^- + e^-\mu^+) < 2.6 \times 10^{-7}$$

$$BR(D^+ \to \pi^+ e^+\mu^-) < 2.9 \times 10^{-6}$$

$$BR(D^+ \to \pi^+ e^-\mu^+) < 3.6 \times 10^{-6}$$

$$\left|K_{S,P}^{(l)} - K_{S,P}^{(l)\prime}\right| \lesssim 0.4\,,$$

$$\left|K_{9,10}^{(l)} - K_{9,10}^{(l)\prime}\right| \lesssim 6\,, \quad \left|K_{T,T5}^{(l)}\right| \lesssim 7\,,$$

$$l = e, \mu$$

$$BR(D^0 \to e^{\pm}\tau^{\mp}) < 7 \times 10^{-15}$$

$\Lambda_c \to p\gamma$

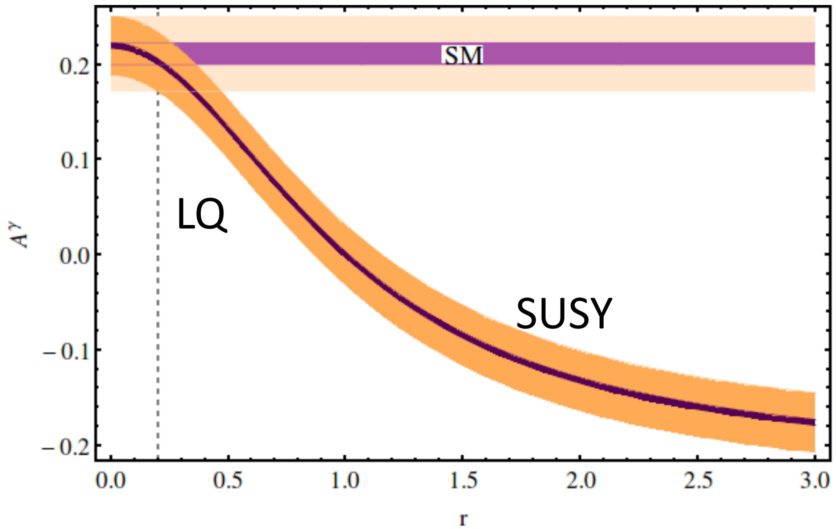
$$\mathcal{B}(\Lambda_c \to p\gamma) \sim \mathcal{O}(10^{-5})$$

Hiller& de Boer 1701. 06392

If Λ_c-baryons are produced polarized, such as at Z, angular asymmetries in $\Lambda_c \to p\gamma$ can probe chirality-flipped contributions

$$A^\gamma = -\frac{P_{\Lambda_c}}{2}\frac{1-|r|^2}{1+|r|^2}$$

$$P_{\Lambda_c} = -0.44.$$



Charm meson decays to invisible fermions

Bause et al. 2010.02225 predicted rather large branching ratios for D decays to π and invisibles, based on Belle result

$$BR(D^0 \to invisibles) < 9.4 \times 10^{-5}$$

SM $\mathcal{B}(D^0 \to \nu\bar{\nu}) = 1.1 \times 10^{-31}$

$D^0 \to \nu\bar{\nu}\nu\bar{\nu}$ dominates over two –body decay

Bhattacharaya et al., 1809.04606

Improvements are expected at BESIII and FCC-ee

But models in 2010.02225 do not consider a "realistic" models in which flavour onbservables define the parameter space.

Dinuetrino charm meson decays

Bause et al., 2007.05001
Bause et al., 2010.02225

$$\mathcal{L}_{\text{eff}} \supset \frac{4\,G_{\text{F}}}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left(\mathcal{C}_L^{Uij}Q_L^{ij} + \mathcal{C}_R^{Uij}Q_R^{ij}\right) + \text{H.c.}$$

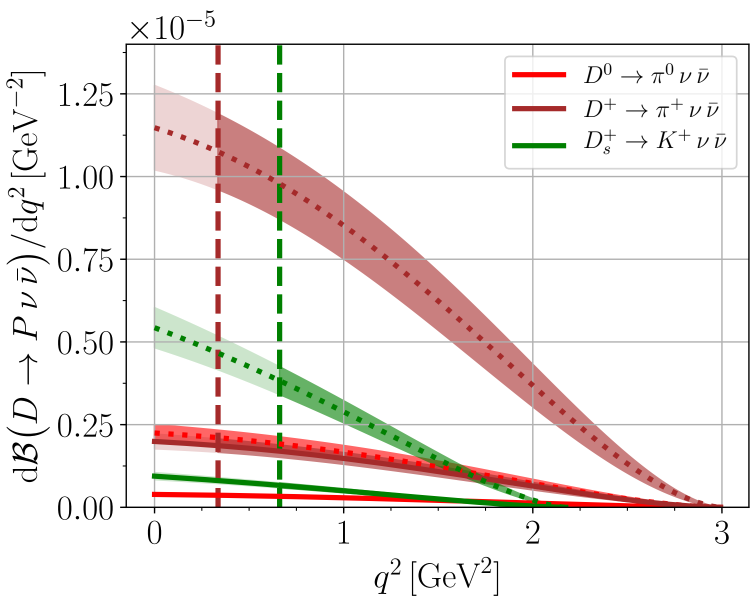
$$Q_{L(R)}^{ij} = \left(\bar{u}_{L(R)}\gamma_\mu c_{L(R)}\right)\left(\bar{\nu}_{jL}\gamma^\mu \nu_{iL}\right)$$

$$\mathcal{B}(c \to u\,\nu\bar{\nu}) = \sum_{i,j}\mathcal{B}(c \to u\,\nu_j\bar{\nu}_i)$$

$$x_U^{\pm} = \sum_{i,j}\left|\mathcal{C}_L^{Uij} \pm \mathcal{C}_R^{Uij}\right|^2$$

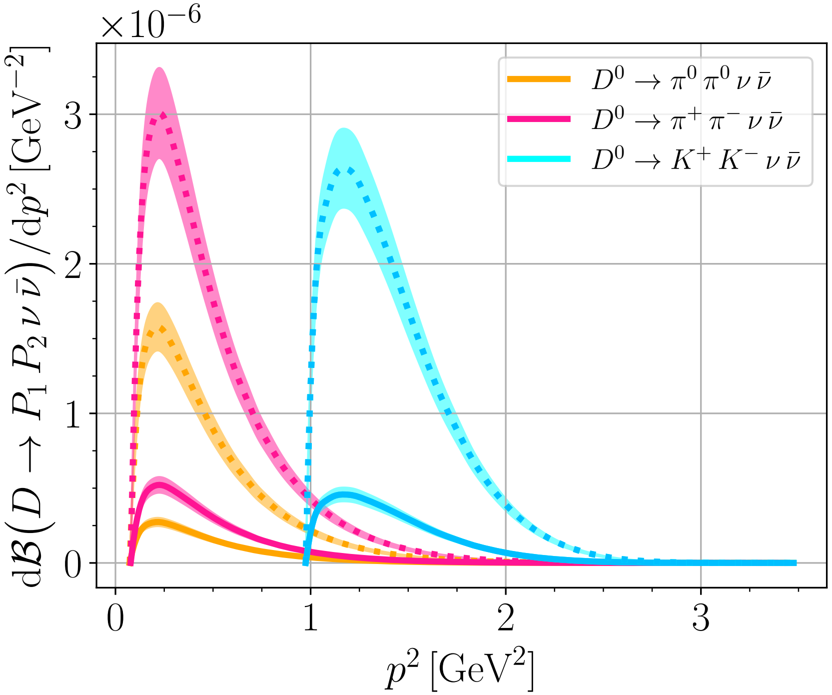
From charged leptons D → P l^+l^-

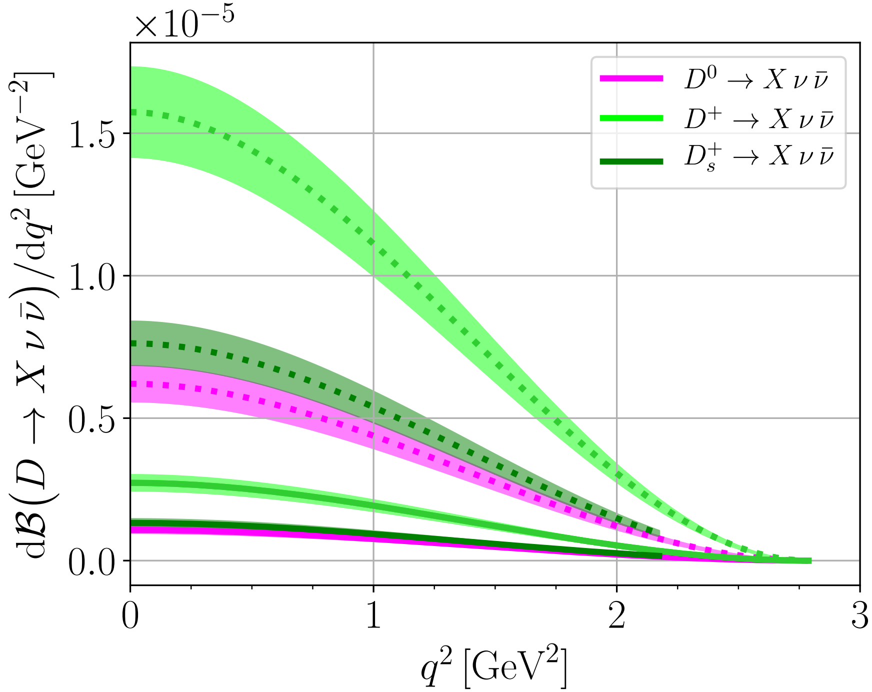
$x_U \lesssim 34\,,$ (LU) diag(k,k,k)
$x_U \lesssim 196\,,$ (cLFC) diag(k_1,k_2,k_2)
$x_U \lesssim 716\,,$ (general) matrix 3x3



Bounds from LHC Drell-Yan study pp → l_1 l_2 (charged leptons)
Fuentes-Martin et al., 2003.12421,
Angelescu et al, 2002.05684;

In down sector rare decays are more constraining.





With massless ν_R $\quad \mathcal{B}(D^0 \to \text{inv.}) \lesssim 2 \cdot 10^{-6}$

These limits are data-driven and will go down if improved bounds from charged leptons become available!

Invisible fermions and scalar leptoquarks

SF &A. Novosel, 2101.10712

Cloured Scalar	Invisible fermion
$S_1 = (\bar{3}, 1, 1/3)$	$\bar{d}_R^{C\,i} \chi^j S_1$
$\bar{S}_1 = (\bar{3}, 1, -2/3)$	$\bar{u}_R^{C\,i} \chi^j \bar{S}_1$
$\tilde{R}_2 = (\bar{3}, 2, 1/6)$	$\bar{u}_L^i \chi^j \tilde{R}_2^{2/3}$
$\tilde{R}_2 = (\bar{3}, 2, 1/6)$	$\bar{d}_L^i \chi^j \tilde{R}_2^{-1/3}$

coloured singlet

$$\mathcal{L}(\bar{S}_1) \supset \bar{y}_{1\,ij}^{RR} \bar{u}_R^{C\,i}\, \chi_R^j\, \bar{S}_1 + \text{h.c.}$$

$$\mathcal{L}_{\text{eff}} = \sqrt{2} G_F c^{RR} \left(\bar{u}_R \gamma_\mu c_R\right) \left(\bar{\chi}_R \gamma^\mu \chi_R\right)$$

$$c^{RR} = \frac{v^2}{2M_{\bar{S}_1}^2} \bar{y}_{1\,c\chi}^{RR}\, \bar{y}_{1\,u\chi}^{RR*}$$

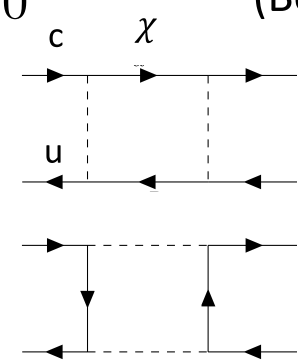
Constraints from charm mixing

$$\left|\bar{y}_{1\,c\chi}^{RR}\, \bar{y}_{1\,u\chi}^{RR*}\right| < 1.2 \times 10^{-5} M_{\bar{S}_1}/GeV$$

$$BR(D^0 \to invisibles) < 9.4 \times 10^{-5}$$

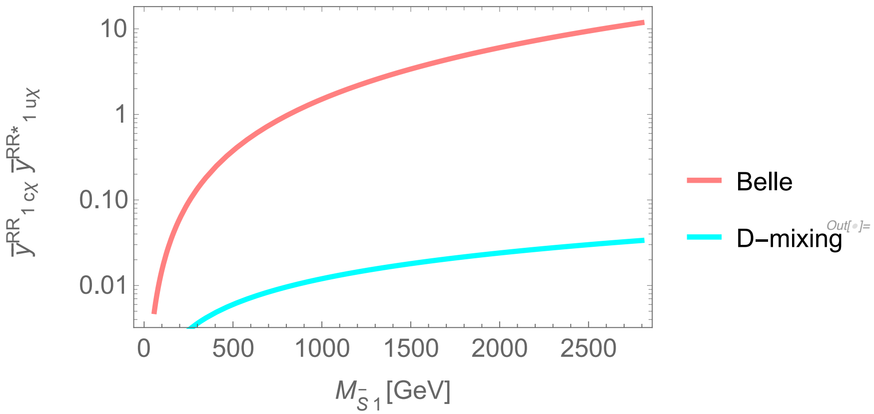
(Belle, 1611.09455)

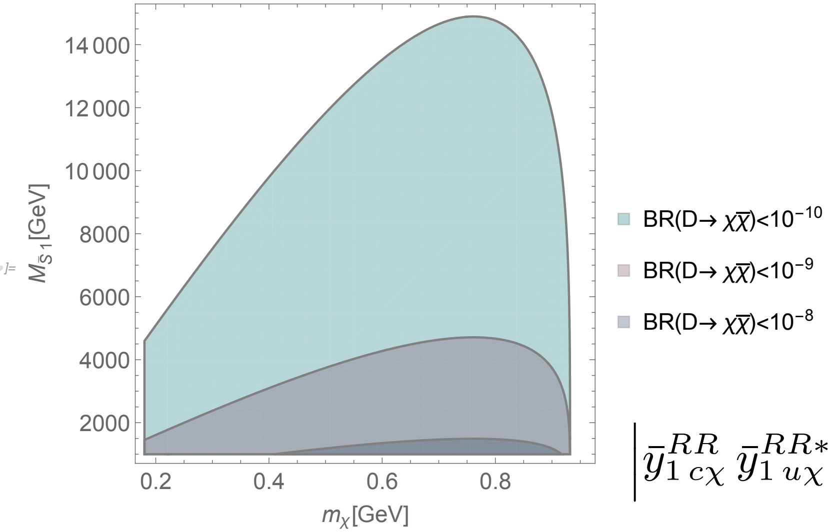
m_χ (GeV)	$\mathcal{B}(D^0 \to \chi\bar{\chi})_{D-\bar{D}}$
0.18	$< 1.1 \times 10^{-9}$
0.50	$< 7.4 \times 10^{-9}$
0.80	$< 1.1 \times 10^{-8}$



Massive $\chi = \nu_R$ model allows to use charm mixing

Main message: charm mixing leads to stron constraints

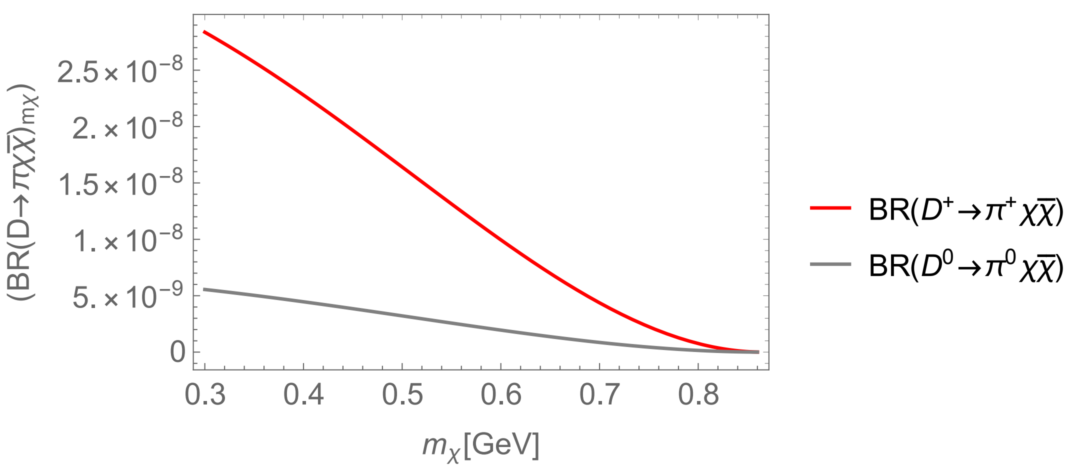




$$\left|\bar{y}^{RR}_{1\,c\chi}\,\bar{y}^{RR*}_{1\,u\chi}\right| = 1$$

m_χ (GeV)	$\mathcal{B}(D^0 \to \chi\bar{\chi}\gamma)_{D-\bar{D}}$	$\mathcal{B}(D^0 \to \chi\bar{\chi}\gamma)_{Belle}$
0.18	$< 2.1 \times 10^{-11}$	$< 1.3 \times 10^{-7}$
0.50	$< 6.9 \times 10^{-12}$	$< 6.3 \times 10^{-9}$
0.80	$< 8.4 \times 10^{-14}$	$< 2.2 \times 10^{-10}$

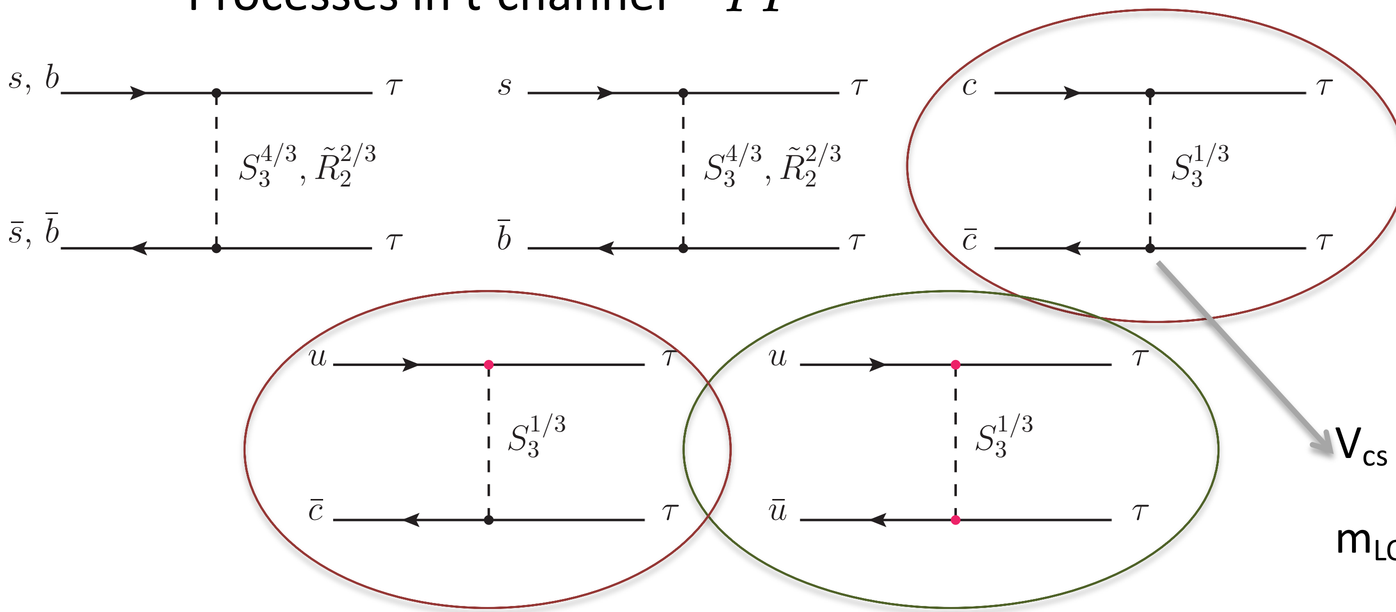
m_χ (GeV)	$\mathcal{B}(D^0 \to \pi^0\chi\bar{\chi})_{D-\bar{D}}$	$\mathcal{B}(D^+ \to \pi^+\chi\bar{\chi})_{D-\bar{D}}$
0.18	$< 5.9 \times 10^{-9}$	$< 3.0 \times 10^{-8}$
0.50	$< 3.2 \times 10^{-9}$	$< 1.6 \times 10^{-8}$
0.80	$< 1.5 \times 10^{-10}$	$< 7.6 \times 10^{-10}$



Mass of scalar leptoquark is within LHC reach!

LHC constraints on charm coupling to LQs: high-mass ττ production

Processes in t-channel $pp \to \tau^+\tau^-$



V_{cs} *$y_{s\tau}$ + V_{bs} *$y_{b\tau}$

$m_{LQ} \approx 1$ TeV

Flavour anomalies generate s τ , bτ and cτ relatively large couplings.

s quark pdf function for protons are ~ 3 times lagrer contribution then for b quark.

1706.07779, Doršner, SF, Faroughy, Košnik

Summary & Outlook

• SM effective weak Lagrangian very precisely known – SD dynamics,
(LD dynamics difficult to explain, without huge involvement of Lattice QCD).

• New physics explaining B anomalies, leads to rather small effects in charge current transitions;

• FCNC transition in charm rare decays suffer from strong GIM suppression, makes search for NP demanding;

• LHC offers tests of FCNC at high energies;

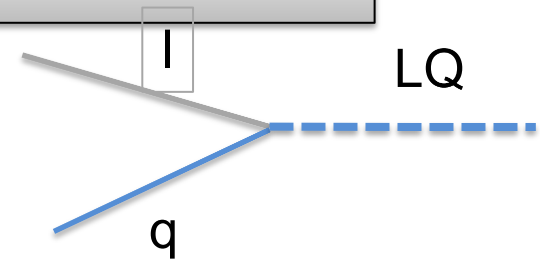
• Few proposals to test DM in charm physics scalar LQ mass in TeV region;

• Charm physics complement any search for NP at low and high energies!

瓦拉

HVALA

Popular scenario: Leptoquarks as a resolution of B anomalies:



LQ=(SU(3)$_c$, SU(2)$_L$)$_Y$

$Q=I_3+Y$

or LQ=(SU(3)$_c$, SU(2)$_L$, Y)

no proton decay at tree level

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1=(\bar{3},1)_{1/3}$	✓	✗	✗
$R_2=(3,2)_{7/6}$	✓	✗*	✗
$S_3=(\bar{3},3)_{1/3}$	✗	✓	✗
$U_1=(3,1)_{2/3}$	✓	✓	✓
$V_2=(3,1)_{2/3}$	✗	✗	✗
$\widetilde{V}_2=(\bar{3},2)_{-1/6}$	✗	✗	✗
$U_3=(3,3)_{2/3}$	✗	✓	✗

Spin 0

Spin 1

No single scalar LQ to solve simultaneously both anomalies! Doršner, SF, Greljo, Kamenik , Košnik, 1603.04993

Scalar LQ → simpler UV completion;

Only R_2 and S_1 might explain $(g-2)_\mu$ (both chiralities are required with the enhancement factor m_t/m_μ) Muller 1801.0338, Doršner, SF & Sumensari, 1910.03877.

Charm Physics Confronts High-p_T Lepton Tails

Fuentas-Martin et al., 2003.12421

$$c \to d^i \bar{e}^\alpha \nu^\beta$$

$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{v^2}\sum_k \mathcal{C}_k\, \mathcal{O}_k$$

$$\mathcal{O}_{lq}^{(3)} = (\bar{l}_L \gamma_\mu \tau^I l_L)(\bar{q}_L \gamma^\mu \tau^I q_L)\,, \qquad \mathcal{O}_{ledq} = (\bar{l}_L e_R)(\bar{d}_R q_L)\,,$$

$$\mathcal{O}_{lequ}^{(1)} = (\bar{l}_L^p e_R)\epsilon_{pr}(\bar{q}_L^r u_R)\,, \qquad \mathcal{O}_{lequ}^{(3)} = (\bar{l}_L^p \sigma_{\mu\nu} e_R)\epsilon_{pr}(\bar{q}_L^r \sigma^{\mu\nu} u_R)$$

$$\mathcal{O}_{\phi q}^{(3)} = (\phi^\dagger\, i \overleftrightarrow{D}_\mu^I\, \phi)(\bar{q}_L \gamma^\mu \tau^I q_L)\,, \qquad \mathcal{O}_{\phi ud} = (\tilde{\phi}^\dagger\, i D_\mu \phi)(\bar{u}_R \gamma^\mu d_R)$$

$$\mathcal{L}_{\rm CC} = -\frac{4G_F}{\sqrt{2}} V_{ci} \left[\left(1+\epsilon_{V_L}^{\alpha\beta i}\right) \mathcal{O}_{V_L}^{\alpha\beta i} + \epsilon_{V_R}^{\alpha\beta i}\, \mathcal{O}_{V_R}^{\alpha\beta i} + \epsilon_{S_L}^{\alpha\beta i}\, \mathcal{O}_{S_L}^{\alpha\beta i} + \epsilon_{S_R}^{\alpha\beta i}\, \mathcal{O}_{S_R}^{\alpha\beta i} + \epsilon_{T}^{\alpha\beta i}\, \mathcal{O}_{T}^{\alpha\beta i} \right] + \text{h.c.},$$

Tree level matching

$$\epsilon_{V_L}^{\alpha\beta i} = -\frac{V_{ji}}{V_{ci}}\,[\mathcal{C}_{lq}^{(3)}]_{\alpha\beta 2j} + \delta_{\alpha\beta}\,\frac{V_{ji}}{V_{ci}}[\mathcal{C}_{\phi q}^{(3)}]_{2j}\,, \qquad \epsilon_{V_R}^{\alpha\beta i} = \frac{1}{2V_{ci}}\,\delta_{\alpha\beta}\,[\mathcal{C}_{\phi ud}]_{2i}\,,$$

$$\epsilon_{S_L}^{\alpha\beta i} = -\frac{V_{ji}}{2V_{ci}}\,[\mathcal{C}_{lequ}^{(1)}]^*_{\beta\alpha j2}\,, \qquad \epsilon_{S_R}^{\alpha\beta i} = -\frac{1}{2V_{ci}}\,[\mathcal{C}_{ledq}]^*_{\beta\alpha i2}\,,$$

$$\epsilon_{T}^{\alpha\beta i} = -\frac{V_{ji}}{2V_{ci}}\,[\mathcal{C}_{lequ}^{(3)}]^*_{\beta\alpha j2}\,,$$

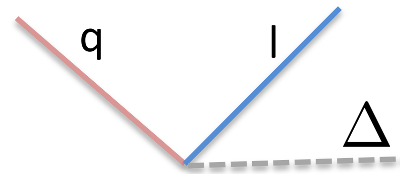
Definitions

$$\frac{m_D}{\lambda_D} = \int_0^1 \mathrm{d}\xi \frac{\Phi_D(\xi)}{\xi}$$ Light cone distribution =function

$$\lambda_B^{\mathrm{HQET}} > 0.172\,\mathrm{GeV\ at\ 90\%\ C.L.}$$

$$C_7^{\mathrm{WA},\rho^0} = -\frac{2\pi^2 Q_u f_D f_{\rho^0}^{(d)} m_\rho}{T m_{D^0} m_c \lambda_D} V_{cd}^* V_{ud} \left(\frac{4}{9} C_1^{(0)} + \frac{1}{3} C_2^{(0)}\right) ,$$
$$C_7^{\mathrm{WA},\omega} = \frac{2\pi^2 Q_u f_D f_\omega^{(d)} m_\omega}{T m_{D^0} m_c \lambda_D} V_{cd}^* V_{ud} \left(\frac{4}{9} C_1^{(0)} + \frac{1}{3} C_2^{(0)}\right) ,$$
$$C_7^{\mathrm{WA},\rho^+} = \frac{2\pi^2 Q_d f_D f_\rho m_\rho}{T m_{D^+} m_c \lambda_D} V_{cd}^* V_{ud}\, C_2^{(0)} ,$$
$$C_7^{\mathrm{WA},K^{*+}} = \frac{2\pi^2 Q_d f_{D_s} f_{K^*} m_{K^*}}{T m_{D_s} m_c \lambda_D} V_{cs}^* V_{us}\, C_2^{(0)} ,$$

Scalar LQ in charm FCNC processes



(3,3,-1/3)

$$\mathcal{L}_{\bar{c}u\bar{\ell}\ell} = -\frac{4G_F}{\sqrt{2}}\left[c_{cu}^{LL}(\bar{c}_L\gamma^\mu u_L)(\bar{\ell}_L\gamma_\mu\ell_L)\right] + \text{h.c.},$$

$$C_{cu}^{LL} = -\frac{v^2}{2m_{S_3}^2}(V_{cs}^* g_{s\mu} + V_{cb}^* b_{b\mu})(V_{us}g_{s\mu} + V_{ub}b_{b\mu})$$

C_{cu}^{LL} 100 times smaller than current LHCb bound!

(3,1,-1/3)

(3,1,-1/3) introduced by Bauer and Neubert in 1511.01900 to explain both B anomalies. In 1608.07583, Becirevic et al., showed that model cannot survive flavor constraints:

$$K \to \mu\nu,\ B \to \tau\nu,\ \tau \to \mu\gamma$$

$$D_s \to \tau\nu,\ D \to \mu^+\mu^-$$

Scalar LQ (3,2,7/6)

In the case of Δ C= 2 in $D^0 - \bar{D}^0$ oscillation there is also a LQ contribution

$$\mathcal{H} = C_6(\bar{u}_R\gamma^\mu c_R)(\bar{u}_R\gamma_\mu c_R)$$

R_2 (3,2,7/6) can explain $R_{D(*)}$ (Becirevic, Dorsner, SF,Faroughy, Kosnik, Sumensari, 1806.05689 and can generate c quark EDM)

Bound from ΔC =2 slightly stronger, but comparable to the bound coming from

$$D^0 \to \mu^+\mu^-$$

Vector LQ(3,1,5/3)

$$\mathcal{L} = Y_{ij}\,(\bar{\ell}_i\gamma_\mu P_R u_j)\,V^{(5/3)\mu} + \mathrm{h.c.}\,.$$

(for loop effects in B Camargo-Molina, Celis, Faroughy 1805.04917)

not present in B physics at tree level!

$$D^0 - \bar{D}^0$$