# Rare semileptonic charm D decays and possible new physics in charm

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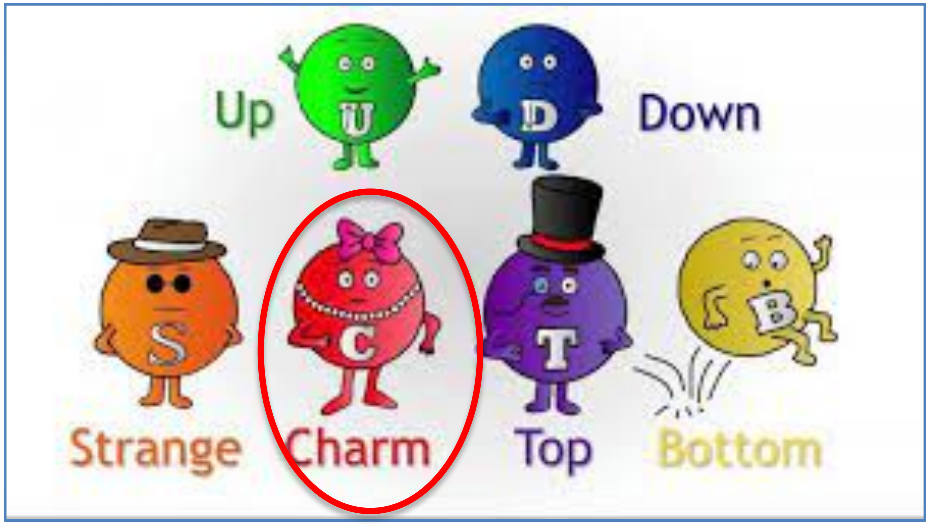



The 10th International Workshop on CHARM Physics, UNAM's Zoom 31st to June the 4th, 2021

# Overview

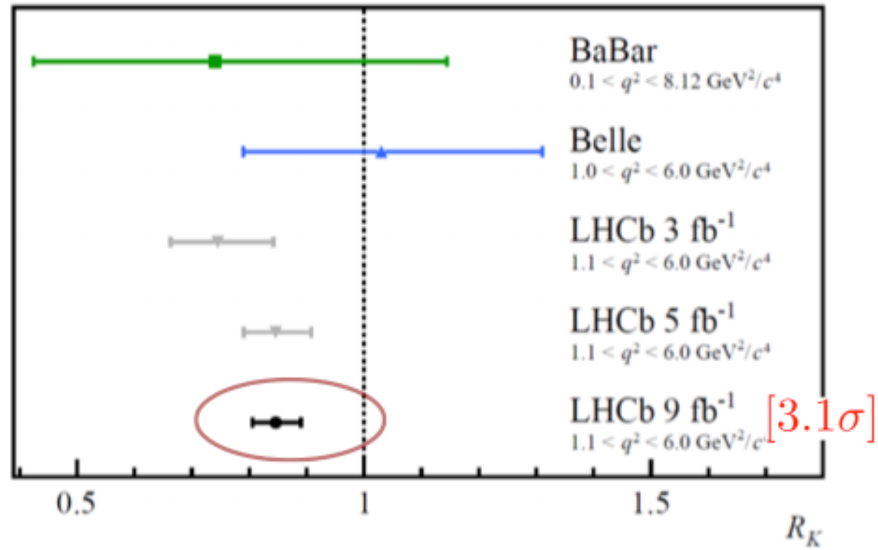
SM in rare charm decays;
NP in D meson in rare semileptonic decays;
D meson decays to invisibles
$D \to V \gamma$,
$D \to P l^+ l^-$,
$D \to P_1 P_2 l^+ l^-$,
$D \to$ invisibles

From B anomalies to NP in charm;
Impact of $D^0$ - $D^0$ on rare charm decays
Signatures of NP FCNC charm decays.

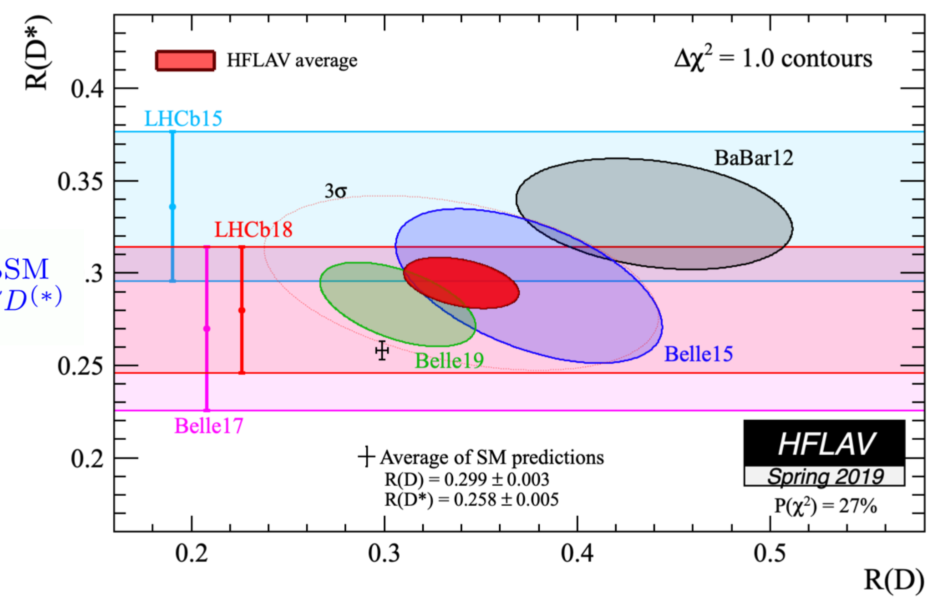
Summary and Outlook

B meson anomalies

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\Bigg|_{q^2\in[q^2_{\rm min},q^2_{\rm max}]} \quad \& \quad R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$$




$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \quad \& \quad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$



## 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!

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

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

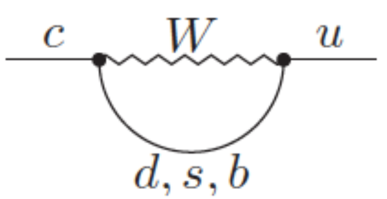
## SM effective Hamiltonian for rare charm decays -FCNC

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

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

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 $m_c$

$$C_7 = 0.12, \qquad C_9 = -0.41$$

(recent results: de Boer, Hiller, 1510.00311, 1701.06392, De Boer et al, 1606.05521) 1707.00988 )

C. Greub et al., PLB 382 (1996) 415; $BR(D \to X_u \gamma) \sim 10^{-8}$

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

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

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

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

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

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

At leading order in $\alpha_s$

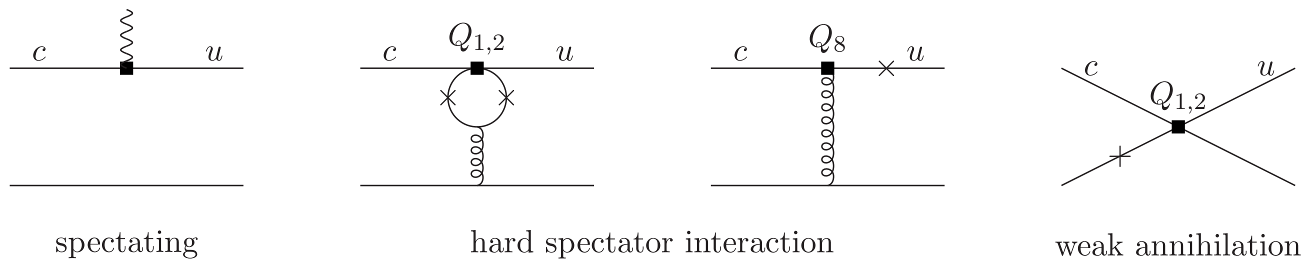
$$C_1^{(0)} \in [-1.28, -0.83]\,, \quad C_2^{(0)} \in [1.14, 1.06]\,,$$

$$C_8^{(0)\text{eff}} \in [0.47\cdot 10^{-5} - 1.33\cdot 10^{-5} i, 0.21\cdot 10^{-5} - 0.61\cdot 10^{-5}]$$

$$C_7^{\text{eff}} \in [-0.00151 - (0.00556i)_{\text{s}} + (0.00005i)_{\text{CKM}}, -0.00088 - (0.00327i)_{\text{s}} + (0.00002i)_{\text{CKM}}]$$

two-loop QCD

## Corrections: hard spectator and weak annihilation




## Leading hard spectator within QCD factorization adopted from B physics

$\lambda_D \sim \Lambda_{\rm QCD} \sim \mathcal{O}(0.1\,{\rm GeV})$

$\mu_c \in \; [m_c/\sqrt{2}, \sqrt{2} m_c]$

$$C_7^{{\rm HSI},\rho} \in [0.00051 + 0.0014i, 0.00091 + 0.0020i] \cdot \frac{\rm GeV}{\lambda_D}\,,$$

$$C_7^{{\rm HSI},\omega} \in [0.00030 + 0.0010i, 0.00098 + 0.0020i] \cdot \frac{\rm GeV}{\lambda_D}\,,$$

$$C_7^{{\rm HSI},K^{*+}} \in [0.00032 + 0.0013i, 0.00096 + 0.0022i] \cdot \frac{\rm GeV}{\lambda_D}\,.$$

$$C_7^{{\rm WA},\rho^0} \in [-0.010, -0.0011] \cdot \frac{\rm GeV}{\lambda_D}$$

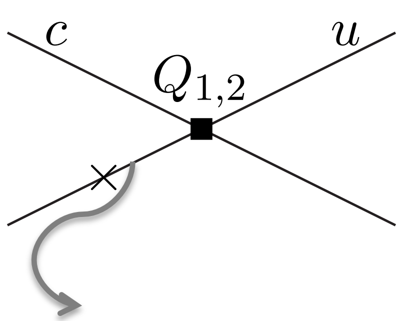
$$C_7^{{\rm WA},\omega} \in [0.0097, 0.0011] \cdot \frac{\rm GeV}{\lambda_D}\,,$$

$$C_7^{{\rm WA},\rho^+} \in [0.029, 0.038] \cdot \frac{\rm GeV}{\lambda_D}\,,$$

$$C_7^{{\rm WA},K^{*+}} \in [-0.034, -0.047] \cdot \frac{\rm GeV}{\lambda_D}$$

DeBoer & Hiller 1701.06392

| branching ratio | $D^0 \to \rho^0\gamma$ | $D^0 \to \omega\gamma$ | $D^0 \to \phi\gamma$ | $D^0 \to \bar{K}^{*0}\gamma$ |
|---|---|---|---|---|
| Belle [24]$^\dagger$ | $(1.77 \pm 0.31) \times 10^{-5}$ | – | $(2.76 \pm 0.21) \times 10^{-5}$ | $(4.66 \pm 0.30) \times 10^{-4}$ |
| BaBar [33]$^{\dagger\, a}$ | – | – | $(2.81 \pm 0.41) \times 10^{-5}$ | $(3.31 \pm 0.34) \times 10^{-4}$ |
| CLEO [34] | – | $< 2.4 \times 10^{-4}$ | – | – |




photon emission

Hiller & De Boer 1701.06392

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

previuos works:
SF& Singer, hep-ph/9705327, SF, Prelovsek &hep-ph/9801279
S. F. P. Singer and J. Zupan, EPJC 27(2003) 201 Burdman et al. hep-ph/9502329,
Khodjamirian et al, hep-ph/9506242

# CP asymmetry in charm radiative decays

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

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

Hiller& de Boer 1701. 06392

LQs give as large

contributions as SM

Belle, 1603.03257

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

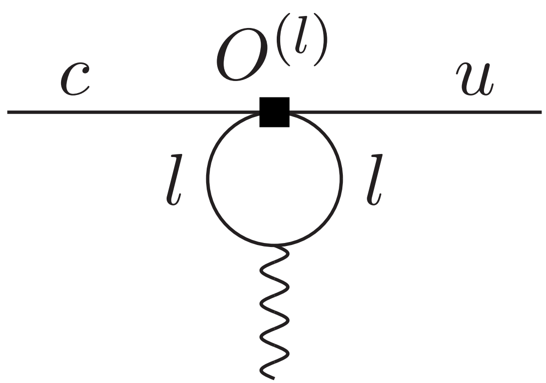
$$A_{CP}(D^0 \to \phi\gamma) = -0.094 \pm 0.066 \pm 0.001$$

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

# New Physics in FCNC charm decays

Leptoquarks in $c \to u\gamma$

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!

Masses of $m_{LQ} \approx 1$ TeV.

Within LQ models the $c \to u\gamma$ branching ratios are SM-like with CP asymmetries at O(0.01) for $S_{1,2}$ and $\tilde{V}_2$ and SM-like for $S_3$.

Vector LQ $\tilde{V}_1$ $A_{CP} \sim O(10\%)$. 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 $C_{10}^{(')}$

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

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

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

Tests of LFU

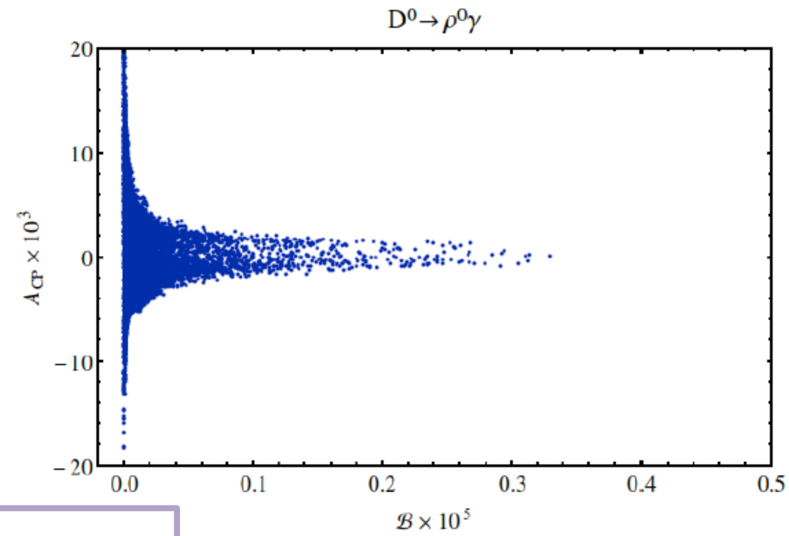
$$R^D_{P_1 P_2} = \frac{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} d\mathcal{B}/dq^2(D \to P_1 P_2 \mu^+\mu^-)}{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} d\mathcal{B}/dq^2(D \to P_1 P_2 e^+e^-)}$$

LHCb , 1806.10793
consistent with SM

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

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

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




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

**$\Lambda_c \to p\gamma$**

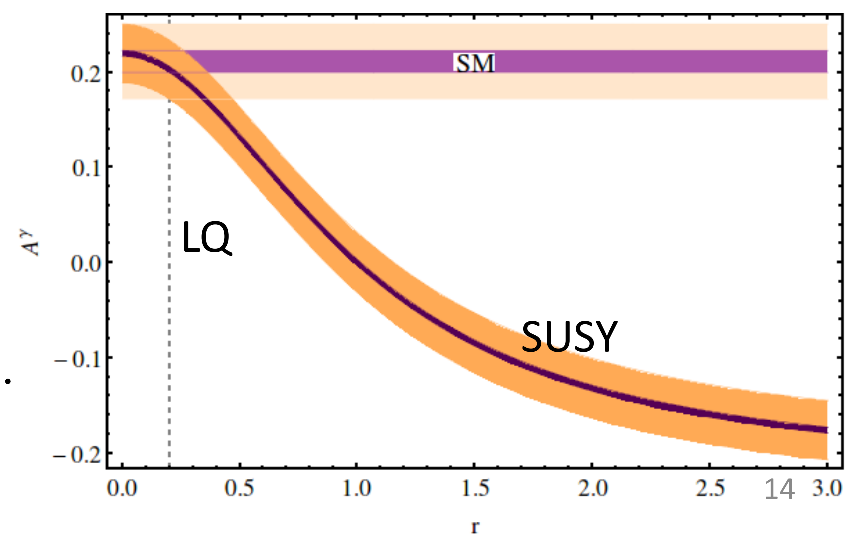
Hiller& de Boer 1701. 06392

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

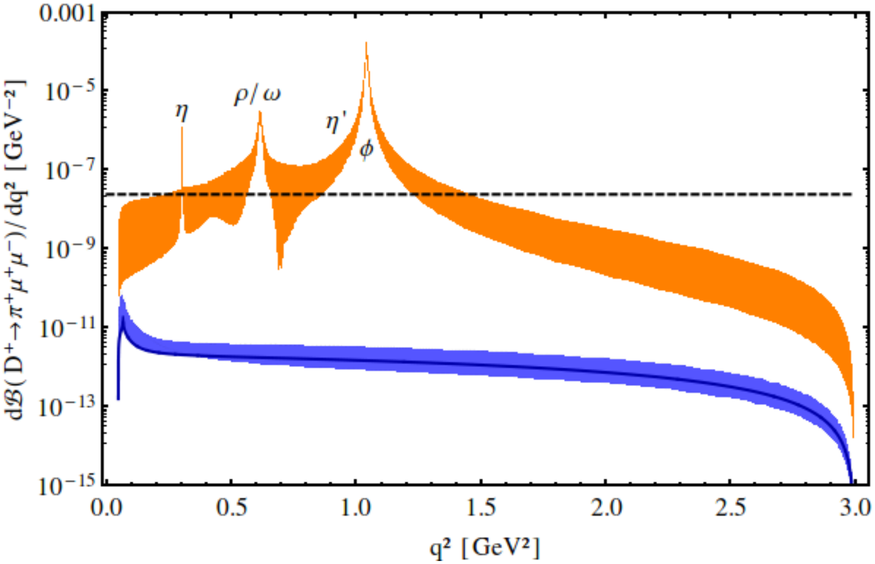
If $\Lambda_c$-baryons are produced polarized, such as at the Z, angular asymmetries in $\Lambda_c \to p\gamma$ can probe chirality-flipped contributions

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

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



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

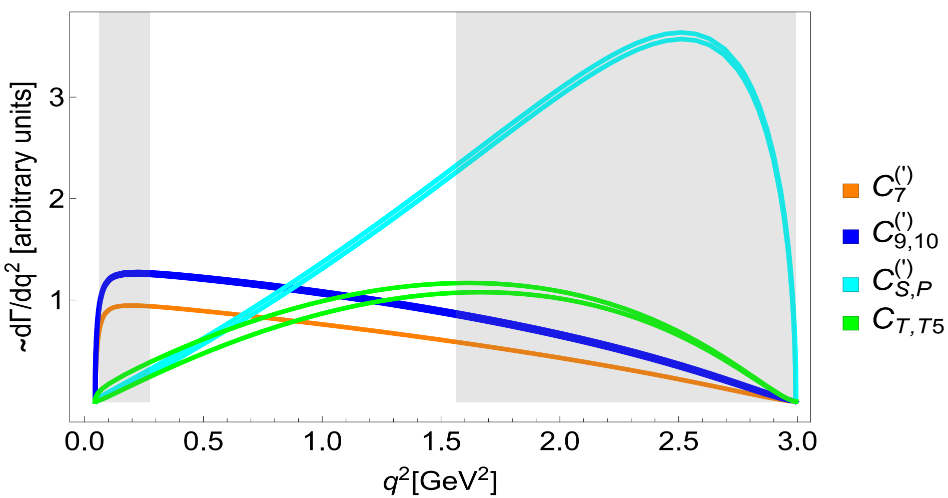



SM prediction: Long distance contributions most important!

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

peaks at ρ,ω,φ and η resonances

de Boer, Hiller, 1510.00311,
SF and Kosnik, 1510.00965
Bause et al, 1909.11108




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

LHCb 1304.6365

| | $\lvert\tilde{C}_i\rvert_{\max}$ | | |
|---|---|---|---|
| | $\mathrm{BR}(\pi\mu\mu)_{\mathrm{I}}$ | $\mathrm{BR}(\pi\mu\mu)_{\mathrm{II}}$ | $\mathrm{BR}(D^0 \to \mu\mu)$ |
| $\tilde{C}_7$ | 2.4 | 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 |

Best bounds from

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

$$|\tilde{C}_i| = |V_{ub}V_{cb}^* C_i|$$

0.043

region I

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

region II

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

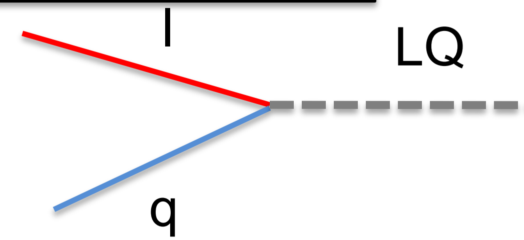
$$BR(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$$

# 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

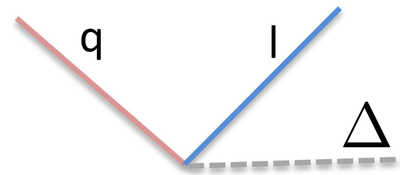
No single scalar LQ to solve simultaneously both anomalies!

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 $m_t/m_\mu$) Muller 1801.0338.

# 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

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

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

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

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

## Vector LQ(3,1,5/3)

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

not present in B physics at tree level!

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

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

| Model | Effect | 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 | $C_S, C_P, C_S', C_P'$ | $V_{cb}V_{ub}\|C_S - C_S'\| < 0.005$<br>$V_{cb}V_{ub}\|C_P - C_P'\| < 0.005$ |
| Z' model | $C_9', C_{10}'$ | $V_{cb}V_{ub}\|C_9'{}_{,}\| < 0.001$<br>$V_{cb}V_{ub}\|C_{10}'\| < 0.014$ |

# 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

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

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

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

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

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

$$l = e, \mu$$

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

## Charm meson decays to invisible fermions

Bause et al. 2010.02225 predicted rather large branching ratios for D decays to $\pi$ 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.

# Dark Matter in charm decays

Belle collaboration 1611.09455
BR($D^0 \to$ invisible) $< 9.4 \times 10^{-5}$

SM: BR($D^0 \to \nu\nu$) = $1.1 \times 10^{-30}$

Badin & Petrov 1005.1277 suggested to search for processes with missing energy $\not{E}$ in

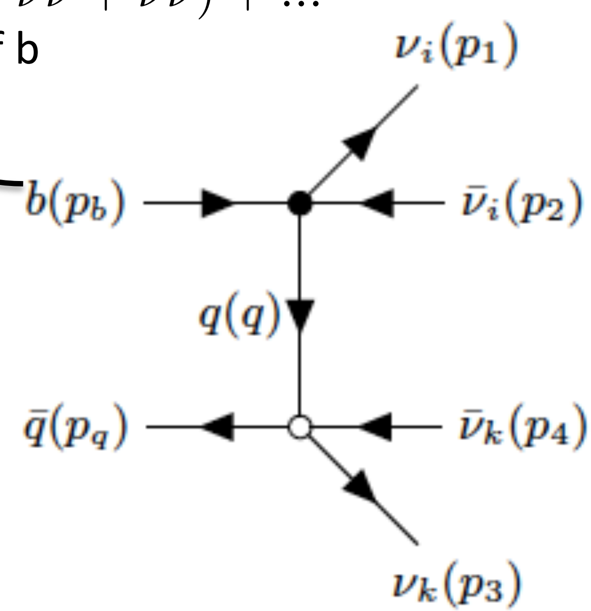
$$D^0 \to \gamma \not{E}$$ → could be SM neutrinos or DM!

Bhattacharya, Grant and Petrov 1809.04606

$$\mathcal{B}(D \to invisibles) = \mathcal{B}(D \to \nu\bar{\nu}) + \mathcal{B}(D \to \nu\bar{\nu} + \nu\bar{\nu}) + \ldots$$

c instead of b

The SM contributions to invisible widths of heavy mesons Γ($D^0 \to$ missing energy ) are completely dominated by the four-neutrino transitions $D^0 \to \nu\bar{\nu}\nu\bar{\nu}$.




$$\mathcal{B}(D^0 \to \nu\bar{\nu}\nu\bar{\nu}) = (2.96 \pm 0.39) \times 10^{-27}$$

## Dinuetrino charm meson decays

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

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

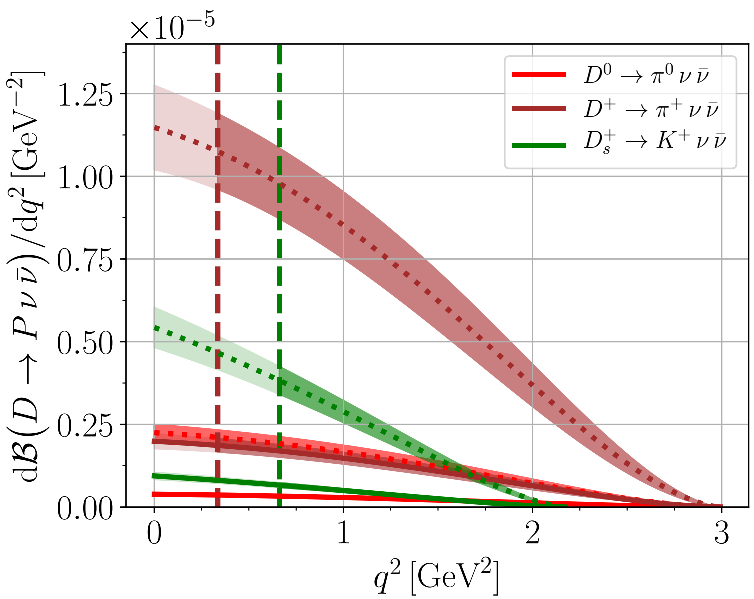
$$Q_{L(R)}^{ij} = \left(\bar{u}_{L(R)}\gamma_\mu c_{L(R)}\right)\left(\bar{\nu}_{jL}\gamma^\mu \nu_{iL}\right)$$

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

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

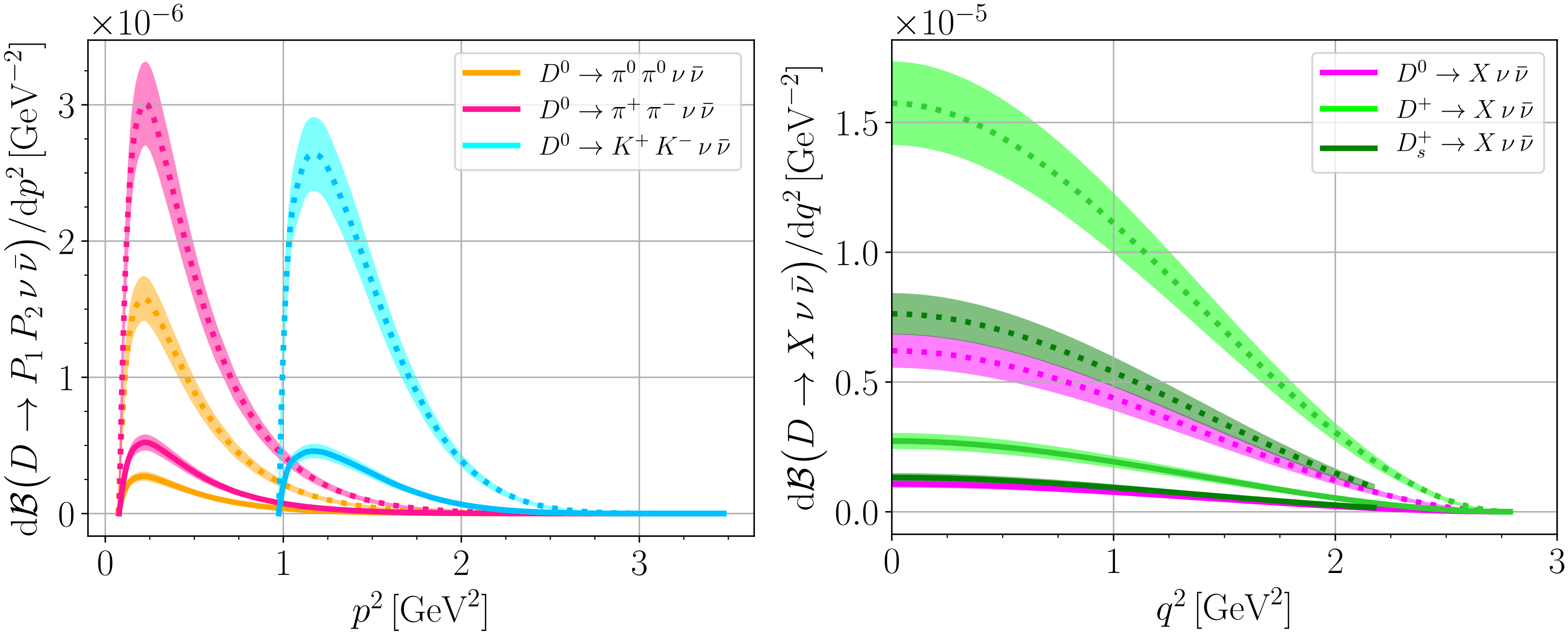
From charged leptons D → P $l^+l^-$

$$x_U \lesssim 34\,, \quad \text{(LU)}$$
$$x_U \lesssim 196\,, \quad \text{(cLFC)}$$
$$x_U \lesssim 716\,, \quad \text{(general)}$$




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 $\nu_R$ $\mathcal{B}(D^0 \to \mathrm{inv.}) \lesssim 2 \cdot 10^{-6}$

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

Massive $\nu_R$ model allows to use charm mixing

SF &A. Novosel 2101.10712

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

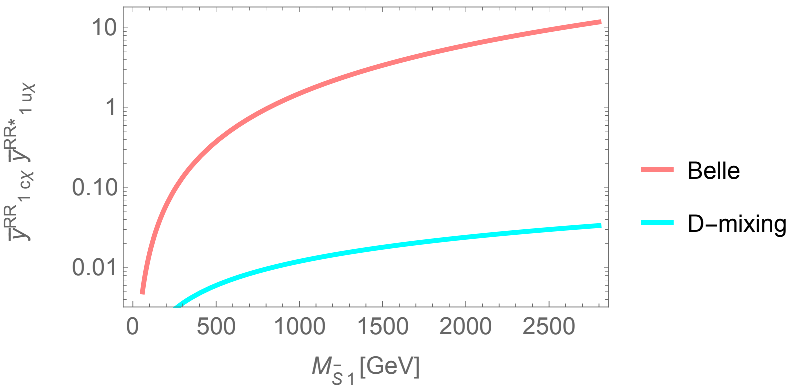
$$\mathcal{L}_{\text{eff}} = \sqrt{2} G_F c^{RR} \left(\bar{u}_R \gamma_\mu c_R\right) \left(\bar{\chi}_R \gamma^\mu \chi_R\right)$$

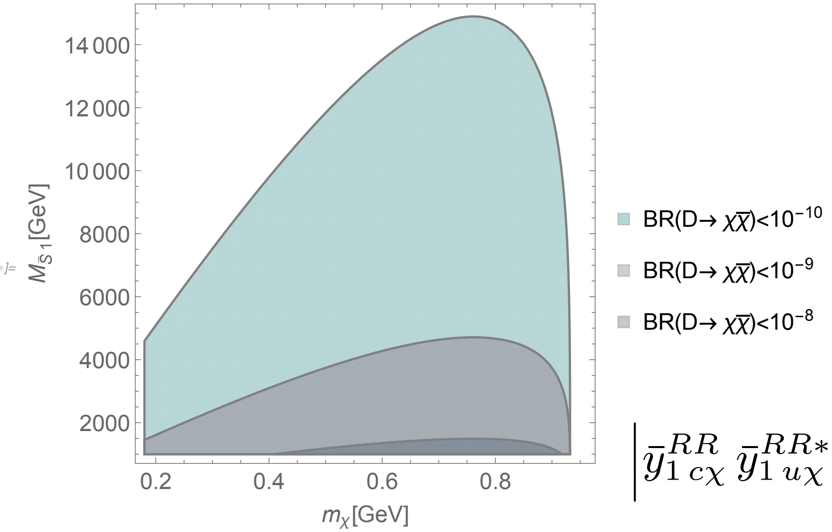
$$c^{RR} = \frac{v^2}{2M^2_{\bar{S}_1}} \bar{y}^{RR}_{1\,c\chi} \bar{y}^{RR*}_{1\,u\chi}$$

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

$BR(D^0 \to invisibles) < 9.4 \times 10^{-5}$ (Belle, 1611.09455)

| $m_\chi$ (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 | $< 1.1 \times 10^{-8}$ |

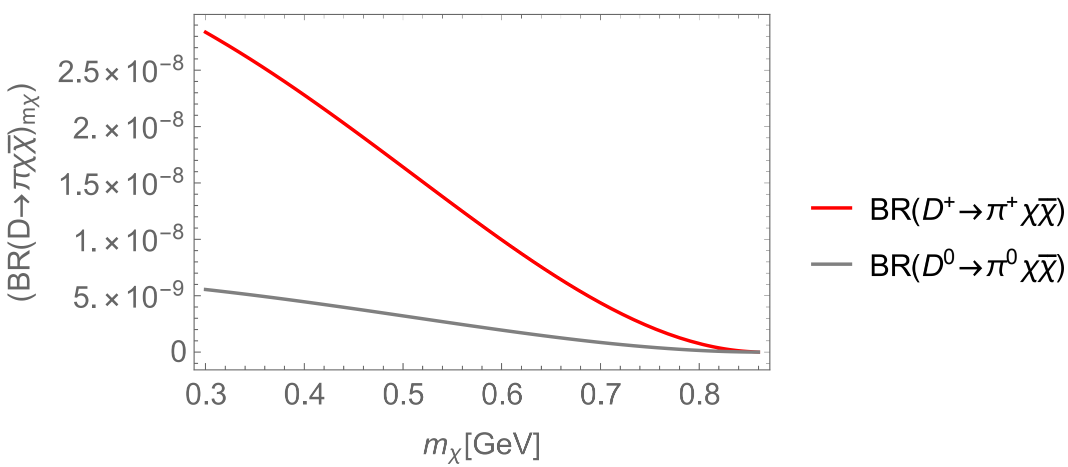



$$\left|\bar{y}^{RR}_{1\,c\chi}\;\bar{y}^{RR*}_{1\,u\chi}\right| = 1$$

| $m_\chi$ (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 | $< 8.4 \times 10^{-14}$ | $< 2.2 \times 10^{-10}$ |

| $m_\chi$ (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 | $< 1.5 \times 10^{-10}$ | $< 7.6 \times 10^{-10}$ |



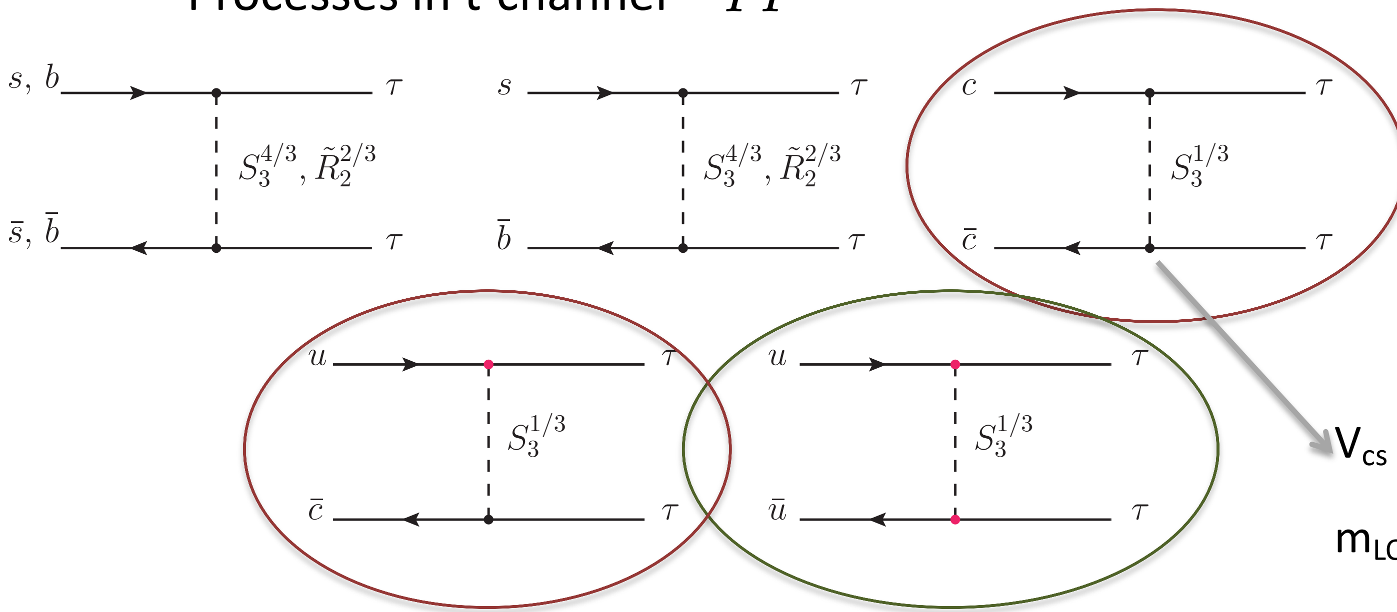
# Summary & Outlook

- 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;
- It is necassary to perform all possible test of LFU;
- LHC offers tests of FCNC at high energies;
- Few proposals to test DM in charm physics;
- Charm physics complement any search for NP at low energies!

Through every rift of discovery some seeming anomaly drops out of the darkness, and falls, as a golden link into the great chain of order.
**Edwin Hubbel Chapin**

# LHC constraints on $S_3$: 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