# Theoretical overview on rare charm decays

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# Overview

- Motivation;
- SM rare charm decays: $D \to V\gamma$; $D \to \pi ll$, $D \to \mu\mu$;
- Signatures of NP in rare charm decays;
- New proposals to test NP in rare charm decays;
- Charm physics at LHC and $e^+e^-$ colliders;
- Summary.

# Motivation

## Anomalies in flavour physics

$R_{D(*)}$ puzzle: Charged current $b \longrightarrow c\, \tau \upsilon_{\tau}$

$R_{K(*)}$ puzzle: FCNC transition $b \longrightarrow s\, l^+ l^-$

$(g-2)_{\mu}$ discrepancy SM prediction and experimental result

tests of LFU conservation in $\pi$ and K physics hold up to 1 percent!

## Impact of NP on RARE CHARM decays?

## B physics anomalies: experimental results ≠ SM predictions!

charged current SM tree level

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$ 3.9σ

$$\frac{BR(B_c \to J/\Psi\tau\nu_\tau)}{BR(B_c \to J/\Psi\mu\nu_\mu)} = 0.71 \pm 0.17 \pm 0.18$$

13 Sept. 2017
LHCb result
~2 σ

FCNC - SM loop process

$P_5'$ in $B \to K^*\mu^+\mu^-$ (angular distribution functions) 3σ

$$R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)}$$

in the dilepton invariant mass bin
$1\ \mathrm{GeV}^2 \leq q^2 \leq 6\ \mathrm{GeV}^2$ ~4σ

Muon anomalous magnetic moment

$$\left.\begin{aligned} a_\mu^{\exp} &= 1.16592080(63) \times 10^{-3} \\ a_\mu^{\rm SM} &= 1.16591803(70) \times 10^{-3} \end{aligned}\right\} \quad \Delta a_\mu = (2.8 \pm 0.9) \times 10^{-9}$$

~3σ

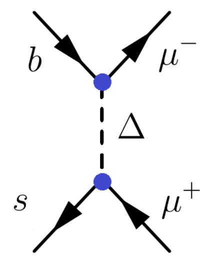
# Models of NP explaining B anomalies

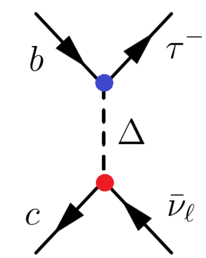
| Spin | Color singlet | Color tripet |
|---|---|---|
| 0 | 2HDM | Scalar LQ<br>$\not{R}$ parity - sbottom |
| 1 | W' ,Z' | Vector LQ |
| | | Dark matter? |

2HDMII cannot explain $R_{D(*)}$

New gauge bosons, W', Z'- difficult to construct UV complete theory

Leptoquarks?




Nature of anomaly requires NP in quark and lepton sector!
It seems that LQs are ideal candidates to explain all
B anomalies at tree level!

- Is charm physics sensitive on NP explaining B puzzles ?
- Can some NP be present in charm and not in beauty mesons?

## SM effective Hamiltonian for rare charm decays

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

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

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

3) SM values at $m_c$

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

4) All operators' contributions to $D \to \pi ll$ can be absorbed into $q^2$ dependent effective Wilsons $C_{7,9\text{eff}}(q^2)$

## SM in $c \to u\gamma$ and $c \to ul^+l^-$

Effective Lagrangian $$\mathcal{L}_{\rm eff}^{\rm SD} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} \sum_{i=7,9,10} C_i Q_i$$

$$Q_7 = \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu} (1 + \gamma_5) c,$$

$$Q_9 = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \ell,$$

$$Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

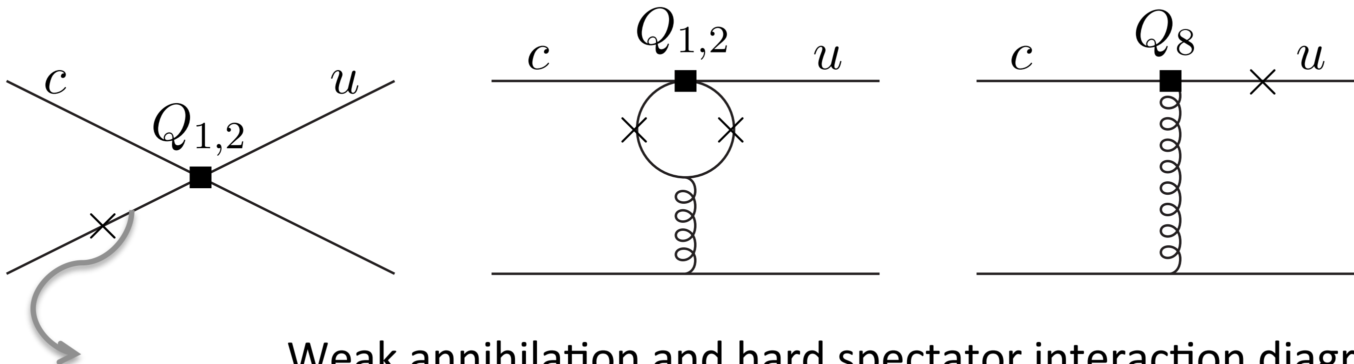
$Q_7$ contributes to $c \to u\gamma$ and $c \to ul^+l^-$

all three operators contribute to

$c \to ul^+l^-$

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

| 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 | $(1.77 \pm 0.31) \times 10^{-5}$ | – | $(2.76 \pm 0.21) \times 10^{-5}$ | $(4.66 \pm 0.30) \times 10^{-4}$ |
| BaBar | – | – | $(2.81 \pm 0.41) \times 10^{-5}$ | $(3.31 \pm 0.34) \times 10^{-4}$ |
| CLEO | – | $< 2.4 \times 10^{-4}$ | – | – |




photon emission

Weak annihilation and hard spectator interaction diagrams.

recent work: Hiller & De Boer 1701.06392
previuos works: G. Burdman et al., PRD 66 (2002) 014009;
S. F. P. Singer and J. Zupan, EPJC 27(2003) 201

Two approaches:

1) Compute leading power corrections (~ $\Lambda_{QCD}/m_c$) as in b-physics, QCD factorization (Bosch & Buchalla hep-ph0408231);

2) Model resonant amplitudes as a hybrid of factorization, heavy quark effective theory and chiral theory, where SU(3) flavor symmetry is broken via measured parameters (SF, S. Prelovsek and P. Singer, hep-ph/9801279);

| branching ratio | $D^0 \to \rho^0\gamma$ | $D^0 \to \omega\gamma$ |
|---|---|---|
| two-loop QCD | $(0.14 - 2.0) \cdot 10^{-8}$ | $(0.14 - 2.0) \cdot 10^{-8}$ |
| HSI+WA | $(0.11 - 3.8) \cdot 10^{-6}$ | $(0.078 - 5.2) \cdot 10^{-6}$ |
| hybrid | $(0.041 - 1.17) \cdot 10^{-5}$ | $(0.042 - 1.12) \cdot 10^{-5}$ |
| [5, 6] | $(0.1 - 1) \cdot 10^{-5}$ | $(0.1 - 0.9) \cdot 10^{-5}$ |
| [8] | $(0.1 - 0.5) \cdot 10^{-5}$ | $0.2 \cdot 10^{-5}$ |
| $[9]^a$ | $3.8 \cdot 10^{-6}$ | – |
| data$^\dagger$ | $(1.77 \pm 0.31) \cdot 10^{-5}$ | $< 2.4 \cdot 10^{-4}$ |

| branching ratio | $D^0 \to \phi\gamma$ | $D^0 \to \bar{K}^{*0}\gamma$ |
|---|---|---|
| WA | $(0.0074 - 1.2) \cdot 10^{-5}$ | $(0.011 - 1.6) \cdot 10^{-4}$ |
| hybrid | $(0.24 - 2.8) \cdot 10^{-5}$ | $(0.26 - 4.6) \cdot 10^{-4}$ |
| [5, 6] | $(0.4 - 1.9) \cdot 10^{-5}$ | $(6 - 36) \cdot 10^{-5}$ |
| [8] | $(0.1 - 3.4) \cdot 10^{-5}$ | $(7 - 12) \cdot 10^{-5}$ |
| $[9]^a$ | – | $1.8 \cdot 10^{-4}$ |
| Belle $[15]^\dagger$ | $(2.76 \pm 0.21) \cdot 10^{-5}$ | $(4.66 \pm 0.30) \cdot 10^{-4}$ |
| BaBar $[39]^{\dagger b}$ | $(2.81 \pm 0.41) \cdot 10^{-5}$ | $(3.31 \pm 0.34) \cdot 10^{-4}$ |

From Hiller& de Boer 1701. 06392

[5] SF& Singer, hep-ph/9705327,
[6] SF, Prelovsek &hep-ph/9801279
[8] Burdman et al. hep-ph/9502329,
[9] Khodjamirian et al, hep-ph/9506242

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

# New Physics in rare charm decays

NP in charm

Constraints from K, B physics

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

Constraints from LHC

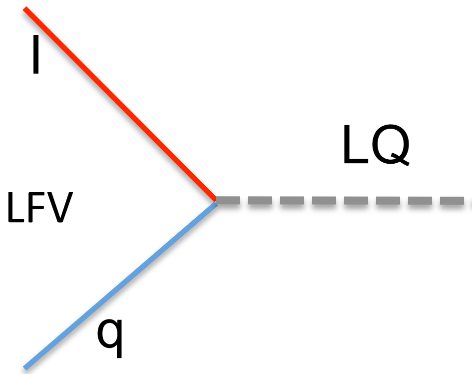
If there is NP in down- quark sector then effects can be seen in charm if NP mediator is a doublet or triplet of the weak isospin.

Up quark weak doublet “talks” to down quark via CKM!

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

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

# Leptoquarks in $R_{K(*)}$ and $R_{D(*)}$




Suggested by many authors: naturally accommodate LUV and LFV

color SU(3), weak isospin SU(2) , weak hypercharge U(1)

| $SU(3)\times SU(2)\times U(1)$ | Spin | Symbol | Type | $3B+L$ |
|---|---|---|---|---|
| $(\overline{\mathbf{3}},\mathbf{3},1/3)$ | 0 | $S_3$ | $LL\,(S_1^L)$ | $-2$ |
| $(\mathbf{3},\mathbf{2},7/6)$ | 0 | $R_2$ | $RL\,(S_{1/2}^L),\ LR\,(S_{1/2}^R)$ | 0 |
| $(\mathbf{3},\mathbf{2},1/6)$ | 0 | $\tilde{R}_2$ | $RL\,(\tilde{S}_{1/2}^L),\ \overline{LR}$ | 0 |
| $(\overline{\mathbf{3}},\mathbf{1},4/3)$ | 0 | $\tilde{S}_1$ | $RR\,(\tilde{S}_0^R)$ | $-2$ |
| $(\overline{\mathbf{3}},\mathbf{1},1/3)$ | 0 | $S_1$ | $LL\,(S_0^L),\ RR\,(S_0^R),\ \overline{RR}$ | $-2$ |
| $(\overline{\mathbf{3}},\mathbf{1},-2/3)$ | 0 | $\bar{S}_1$ | $\overline{RR}$ | $-2$ |
| $(\mathbf{3},\mathbf{3},2/3)$ | 1 | $U_3$ | $LL\,(V_1^L)$ | 0 |
| $(\overline{\mathbf{3}},\mathbf{2},5/6)$ | 1 | $V_2$ | $RL\,(V_{1/2}^L),\ LR\,(V_{1/2}^R)$ | $-2$ |
| $(\overline{\mathbf{3}},\mathbf{2},-1/6)$ | 1 | $\tilde{V}_2$ | $RL\,(\tilde{V}_{1/2}^L),\ \overline{LR}$ | $-2$ |
| $(\mathbf{3},\mathbf{1},5/3)$ | 1 | $U_1$ | $RR\,(V_0^R)$ | 0 |
| $(\mathbf{3},\mathbf{1},2/3)$ | 1 | $U_1$ | $LL\,(V_0^L),\ RR\,(V_0^R),\ \overline{RR}$ | 0 |
| $(\mathbf{3},\mathbf{1},-1/3)$ | 1 | $\bar{U}_1$ | $\overline{RR}$ | 0 |

$Q=I_3+Y$

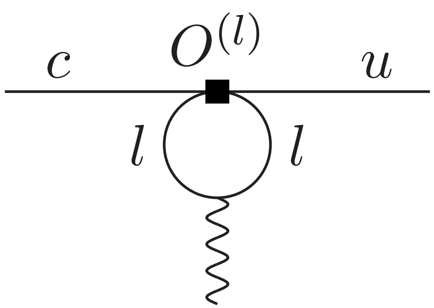
F=3B +L fermion number; F=0 no proton decay at tree level (see Assad et al, 1708.06350)

Doršner, SF, Greljo, Kamenik Košnik, (1603.04993)

# New Physics in radiative charm decays

Leptoqaurks in radiative charm decays

Hiller& de Boer 1701. 06392




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

| couplings/mass | constraint | observable |
|---|---|---|
| $\lvert\lambda_{S_3}^{(u\tau)}\rvert$ | $\sim [0.0, 0.2]$ | $\tau^- \to \pi^- \nu_\tau$ |
| $\mathrm{Re}[\lambda_{SR}^{(u\tau)}(\lambda_{SL}^{(u\tau)})^*]$ | $\sim [0.00, 0.09]$ | |
| $\mathrm{Re}[\lambda_{S_1L,S_3}^{(u\tau)}(\lambda_{S_1L,S_3}^{(c\tau)})^*]$ | $\sim [-0.2, 0.2]$ | $\tau^- \to K^- \nu_\tau$ |
| $\mathrm{Re}[\lambda_{SR}^{(u\tau)}(\lambda_{SL}^{(c\tau)})^*]$ | $\sim [-0.07, 0.04]$ | |
| $\lvert\mathrm{Im}[\lambda_{SR}^{(u\tau)}(\lambda_{SL}^{(c\tau)})^*]\rvert$ | $\sim [0.0, 0.7]$ | |
| $\lvert\mathrm{Re}[\lambda_{SL,SR}^{(u\tau)}(\lambda_{SL,SR}^{(c\tau)})^*]\rvert$ | $\sim [0, 0.02]$ | $\Delta m_{D^0}$ |
| $\lvert\mathrm{Re}[\lambda_{S_3}^{(u\tau)}(\lambda_{S_3}^{(c\tau)})^*]\rvert$ | $\sim [0, 0.007]$ | |
| $\mathrm{Re}[\lambda_{SR}^{(u\tau)}(\lambda_{SL}^{(c\tau)})^*]$ | $\lesssim 0.3$ | $D^+ \to \tau^+ \nu_\tau$ |
| $\mathrm{Re}[\lambda_{SR}^{(c\tau)}(\lambda_{SL}^{(c\tau)})^*]$ | $\sim [-1, 0.09]$ | $D_s \to \tau^+ \nu_\tau$ |
| $\lvert\lambda_{S_3}^{(c\tau)}\rvert$ | $\sim [0.0, 0.4]$ | |
| $\lvert\lambda_{S_1L,S_3}^{(u\tau)}\lambda_{S_1L,S_3}^{(c\tau)}\rvert$ | $\lesssim 4 \cdot 10^{-4}$ | $(K^+ \to \pi^+ \bar{\nu}\nu)/(K^+ \to \pi^0 \bar{e}\nu)$ |

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 $V_{\tilde{2}}$ and SM-like for $S_3$.
Vector LQ $V_{\tilde{1}}$ $A_{CP}$ ~ O(10%). The largest effects arise from τ-loops.

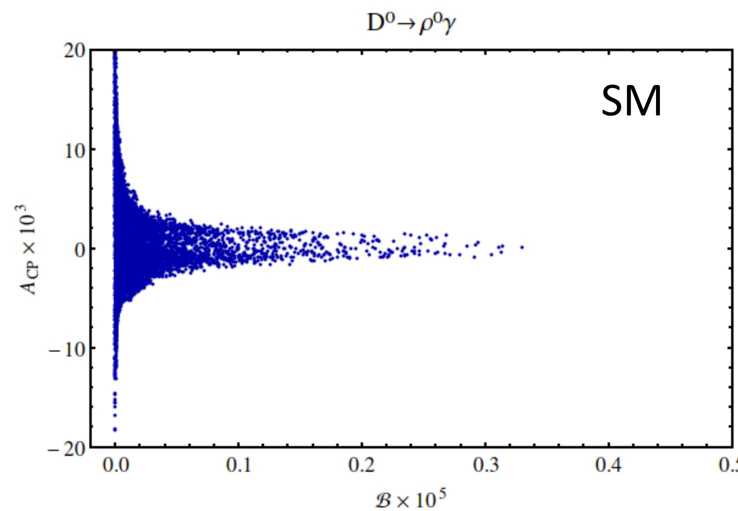
$S_3$ can explain $R_{K(*)}$ !

## CP asymmetry in charm radiative decays

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

From Hiller& de Boer 1701. 06392

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




Belle, 1603.03257

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

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

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

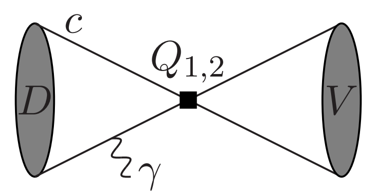
NP contributions

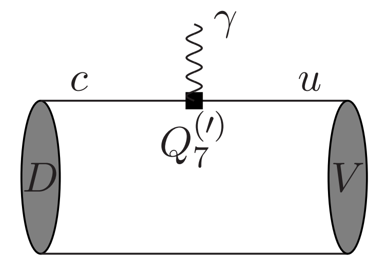
| model | branching ratio | CP-asymmetry | constraints |
|---|---|---|---|
| LQ | SM-like | $\lesssim \mathcal{O}(10\%)$ | [SdB et al. 2015] |
| SUSY | $\lesssim 2 \cdot 10^{-5}$ | $\lesssim 0.2$ | $D^0 \to \rho^0\gamma$ |

SUSY:gluino induced contributions within the mass insertion approximation
F. Gabbiani, et al., hep-ph/9604387, S. Prelovsek &Wyler, hep-ph/0012116

# The photon polarization in radiative D decays

Untagged, time-dependent analysis of $D^0$- decays into CP eigenstates can probe the photon polarization by means of the charm mesons' finite width difference




$$\Gamma(D \to V\gamma) = \Gamma(D \to V\gamma_L) + \Gamma(D \to V\gamma_R)$$

$$\mathcal{A}_{L,R} = \mathcal{A}(D \to V\gamma_{L,R}) = \sum_j A_{L,R}^{(j)} e^{i\delta_{L,R}^{(j)}} e^{i\phi_{L,R}^{(j)}}$$

$$\Gamma(t) = \mathcal{N} e^{-\Gamma t}\left(\cosh[\Delta\Gamma t/2] + A^{\Delta}\sinh[\Delta\Gamma t/2] + \zeta C\cos[\Delta m t] - \zeta S\sin[\Delta m t]\right)$$

$$\Delta\Gamma = \Gamma_H - \Gamma_L > 0 \qquad \Delta m = m_H - m_L \qquad \begin{array}{l} \xi = +1 \;\; V = \rho^0, \phi, \bar{K}^{*0}(K_S^0\pi^0) \\ \xi = -1 \;\; V = \bar{K}^{*0}(K_L^0\pi^0) \end{array}$$

$$A^{\Delta} \simeq 2\xi \frac{A_L A_R}{|A_L|^2 + |A_R|^2} \cos(\delta_L - \delta_R)\cos(\phi_L - \phi_R)$$

strong and weak phases

$$r = \frac{A_R}{A_L}$$

De Boer &Hiller 1802.02769, proposal

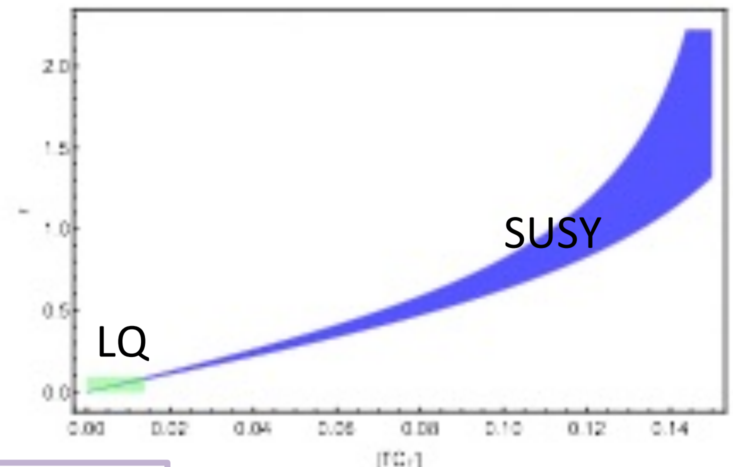
$D^0 \to \phi\gamma$ or $D^0 \to \bar{K}^{0*}\gamma$ decays (SM-dominated)

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

the polarization fraction r

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

$$r = \left|\frac{a' + TC_7'}{a + TC_7}\right|$$




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

$\Lambda_c \to p\gamma$

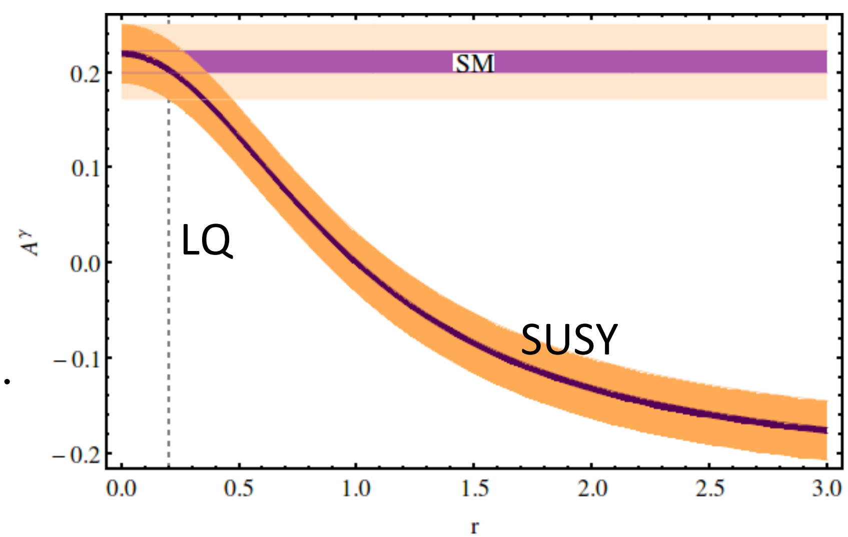
Hiller& de Boer 1701. 06392

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

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

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

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



## SM in $c \to u l^+ l^-$

$$Q_7 = \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu}(1+\gamma_5) c,$$

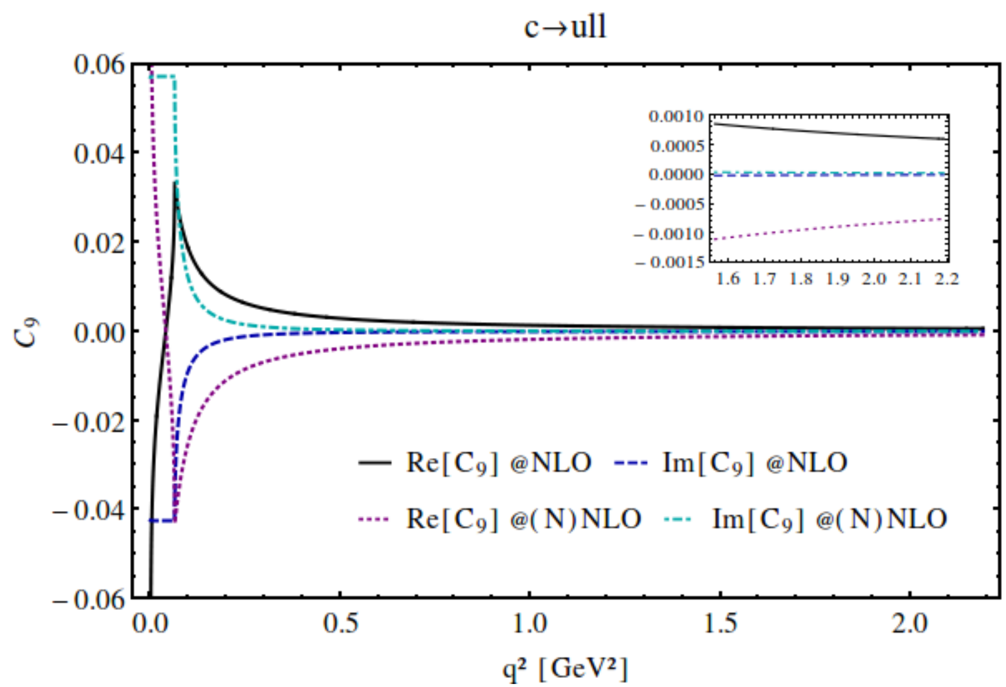
$$Q_9 = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \ell,$$

In SM contribute all these operators,
but SM $C_{10} \approx 0$

$$Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

$$\boxed{\tilde{C}_i(\mu) = \tilde{C}_i^{(0)}(\mu) + \frac{\alpha_s(\mu)}{4\pi} \tilde{C}_i^{(1)}(\mu) + \left(\frac{\alpha_s(\mu)}{4\pi}\right)^2 \tilde{C}_i^{(2)}(\mu) + \mathcal{O}\left(\alpha_s^3(\mu)\right)}$$

de Boer, Hiller, 1510.00311:
SM update:
(N)NLO QCD SM Wilson coefficients)



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

Most general dimension 6 effective Lagrangian for $c \to u l^+ l^-$

$$\mathcal{H}_{\rm eff} = \lambda_d \mathcal{H}^d + \lambda_s \mathcal{H}^s + \lambda_b \mathcal{H}^{\rm peng} \qquad \mathcal{H}^{\rm peng} = -\frac{4G_F}{\sqrt{2}} \sum_{i=3,\dots,10} C_i \mathcal{O}_i$$

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

$$\mathcal{O}_7 = \frac{e m_c}{(4\pi)^2} (\bar{u}\sigma_{\mu\nu} P_R c) F^{\mu\nu}, \qquad \mathcal{O}_S = \frac{e^2}{(4\pi)^2} (\bar{u} P_R c)(\bar{\ell}\ell),$$

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2} (\bar{u}\gamma^\mu P_L c)(\bar{\ell}\gamma_\mu \ell), \qquad \mathcal{O}_P = \frac{e^2}{(4\pi)^2} (\bar{u} P_R c)(\bar{\ell}\gamma_5 \ell),$$

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} (\bar{u}\gamma^\mu P_L c)(\bar{\ell}\gamma_\mu \gamma_5 \ell), \qquad \mathcal{O}_T = \frac{e^2}{(4\pi)^2} (\bar{u}\sigma_{\mu\nu} c)(\bar{\ell}\sigma^{\mu\nu} \ell),$$

$$\mathcal{O}_{T5} = \frac{e^2}{(4\pi)^2} (\bar{u}\sigma_{\mu\nu} c)(\bar{\ell}\sigma^{\mu\nu} \gamma_5 \ell)$$

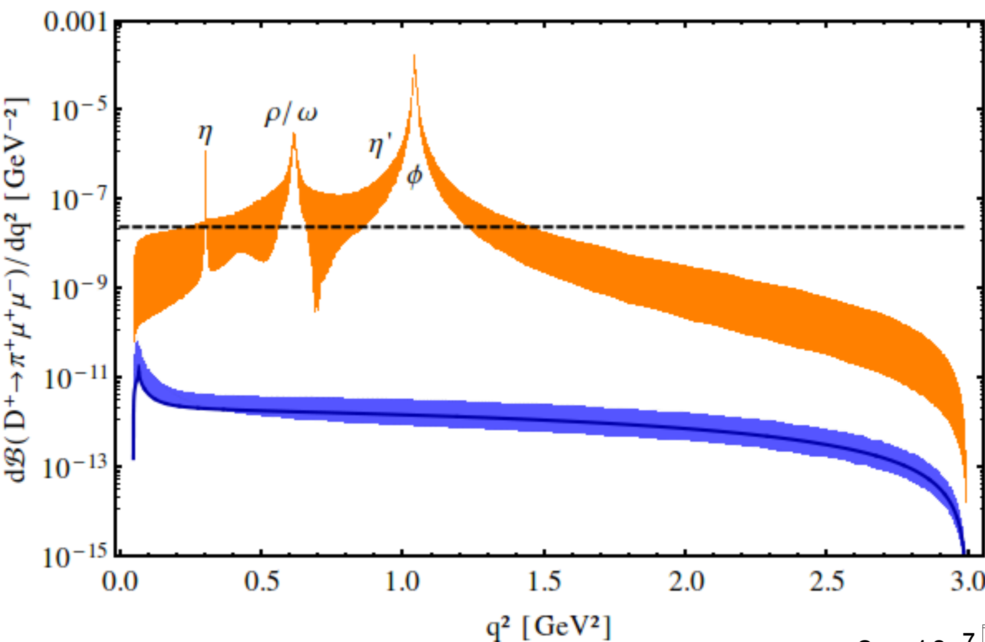
SF, N. Kosnik, 1510.00965

LHCb bound, 1305.5059

$$\boxed{\mathcal{B}(D^0 \to \mu^+ \mu^-) < 6.2 \cdot 10^{-9} \text{ at CL=90\%}}$$

Helicity suppressed decay!

$$\boxed{|C_S - C_S'|^2 + |C_P - C_P' + 0.1(C_{10} - C_{10}')|^2 \lesssim 0.007}$$




SM prediction: Long distance contributions most important!

peaks at ρ,ω,φ and η resonances

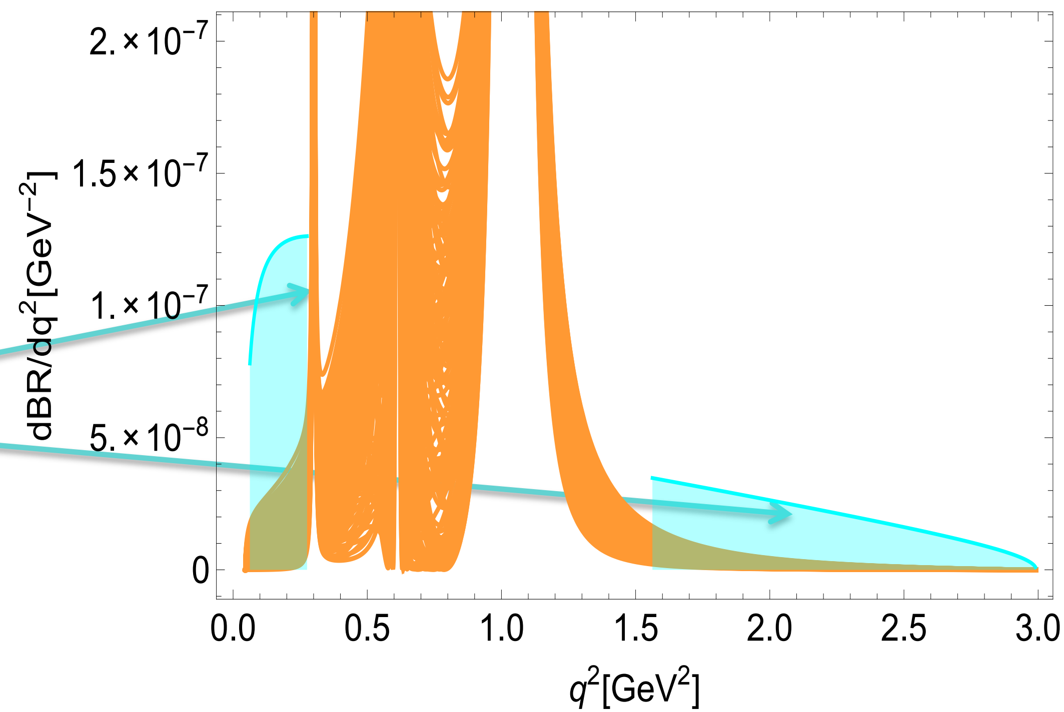
$$D \to \pi V \to \pi l^+ l^-$$

de Boer, Hiller, 1510.00311,

SF and Kosnik, 1510.00965

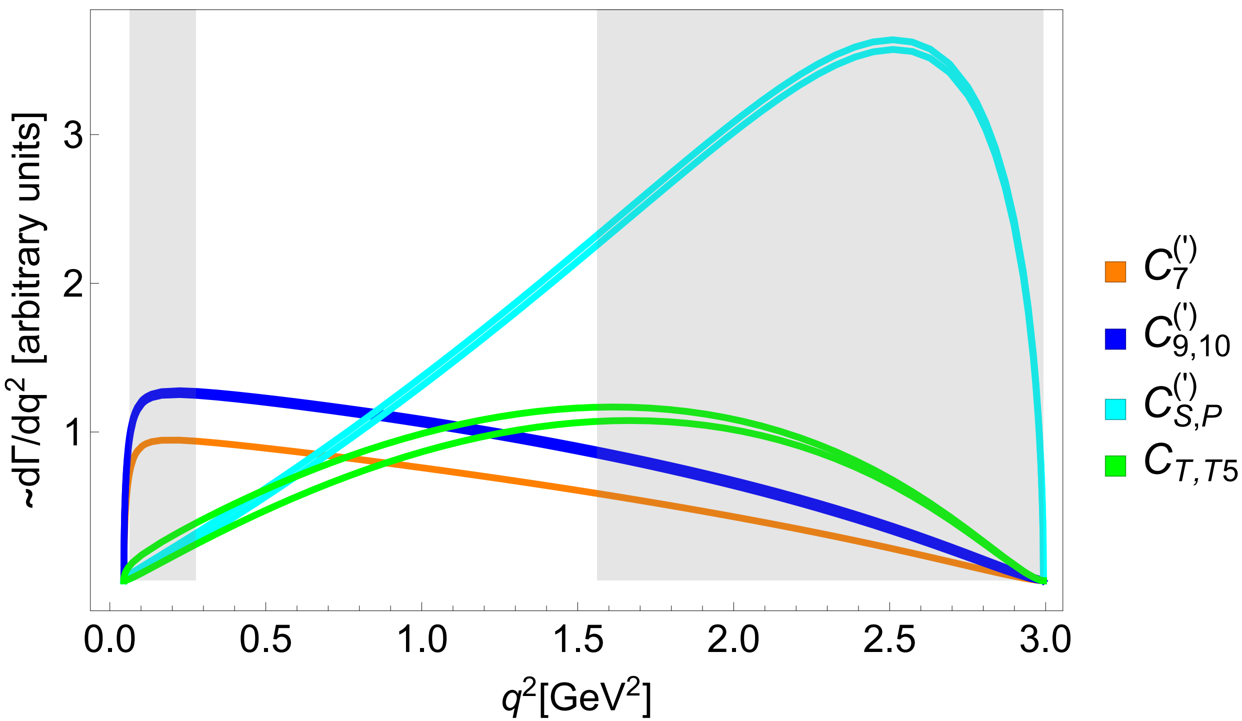
LHCb bound- assumption – constant amplitude

LHCb 1304.6365




(SF and Kosnik, 1510.00965)

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

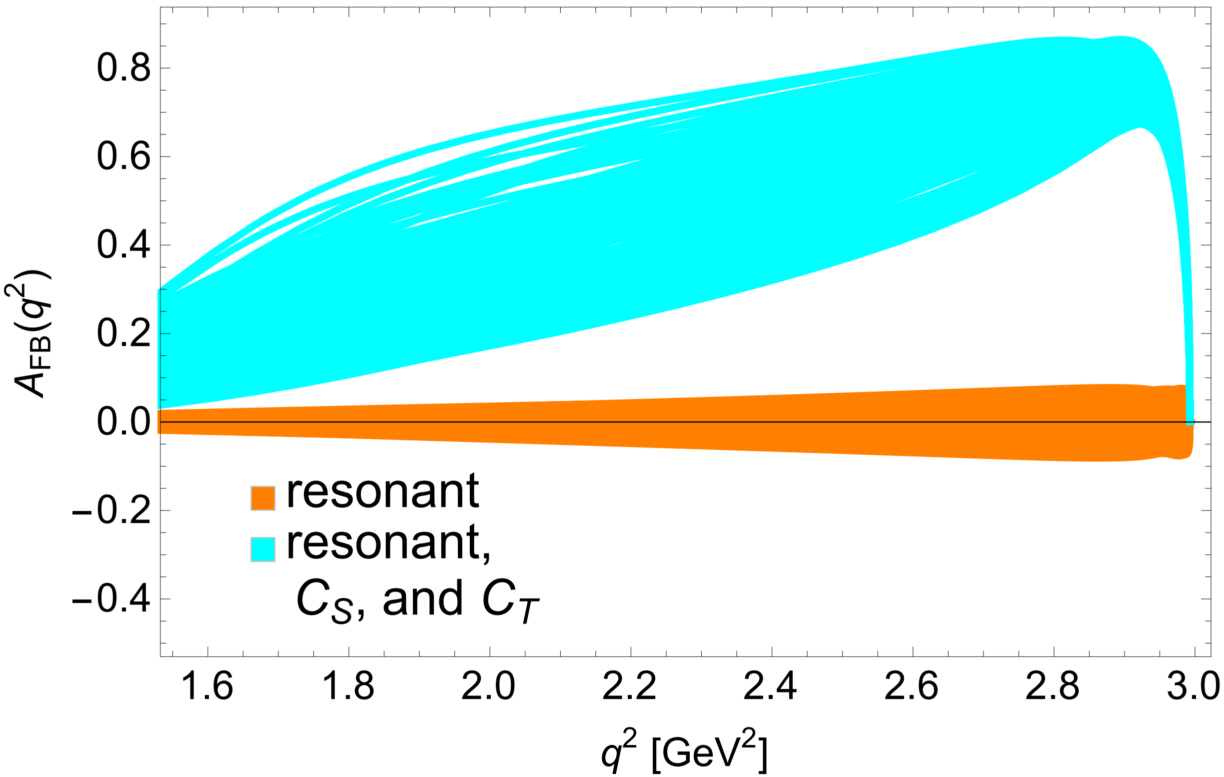



$$\mathrm{BR}(\pi^+\mu^+\mu^-)_{\mathrm{I}} \equiv \mathrm{BR}(D^+ \to \pi^+\mu^+\mu^-)_{q^2\in[0.0625,0.276]\ \mathrm{GeV}^2} < 2.5\times 10^{-8}$$

$$\mathrm{BR}(\pi^+\mu^+\mu^-)_{\mathrm{II}} \equiv \mathrm{BR}(D^+ \to \pi^+\mu^+\mu^-)_{q^2\in[1.56,4.00]\ \mathrm{GeV}^2} < 2.9\times 10^{-8}$$

LHCb 1304.6365

$$A_{\rm FB}(q^2) \equiv \frac{\left(\int_0^1 - \int_{-1}^0\right) \mathrm{d}\cos\theta \, \frac{\mathrm{d}\Gamma(D\to\pi\ell\ell)}{\mathrm{d}q^2 \, \mathrm{d}\cos\theta}}{\mathrm{d}\Gamma(D \to \pi\ell\ell)/\mathrm{d}q^2} = \frac{b_\ell(q^2)}{a_\ell(q^2) + \frac{1}{3}c_\ell(q^2)}$$




$b_l(q^2)$

S,$T_5$ necessary!

Forward-backward asymmetry for the resonant background itself (orange) and in the scenario $C_S = 0.049/\lambda_b$ $C_T = 0.2/\lambda_b$

| | $\lvert\tilde{C}_i\rvert_{\max}$ | | |
|---|---|---|---|
| | BR$(\pi\mu\mu)_{\mathrm{I}}$ | BR$(\pi\mu\mu)_{\mathrm{II}}$ | 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 | 0.63 |
| $\tilde{C}_S$ | 4.5 | 0.38 | 0.049 |
| $\tilde{C}_P$ | 3.6 | 0.37 | 0.049 |
| $\tilde{C}_T$ | 4.1 | 0.76 | - |
| $\tilde{C}_{T5}$ | 4.4 | 0.74 | - |
| $\tilde{C}_9 = \pm\tilde{C}_{10}$ | 1.3 | 0.81 | 0.63 |

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

region I

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

region II

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

$$\mathrm{BR}(D^0 \to \mu^+\mu^-) < 7.6 \times 10^{-9}$$

## Test of lepton flavour universality violation in charm FCNC decays

In 1510.0311 (de Beor and Hiller) it was pointed out that bounds on electron-positron mode are weaker:

$$BR(D^+ \to \pi^+ e^+ e^-) < 1.1 \times 10^{-6}$$

$$BR(D^0 \to e^+ e^-) < 7.9 \times 10^{-8}$$

$$\left| C_{S,P}^{(e)} - C_{S,P}^{(e)\prime} \right| \lesssim 0.3\,,$$

$$\left| C_{9,10}^{(e)} - C_{9,10}^{(e)\prime} \right| \lesssim 4\,,$$

$$\left| C_{T,T5}^{(e)} \right| \lesssim 5\,, \quad \left| C_7 \left( C_9^{(e)} - C_9^{(e)\prime} \right) \right| \lesssim 2\,.$$

In 1510.0965 (S.F. and N. Košnik) it was suggested, assuming as in the case $B \to K e^+ e^-$ that NP does not affect electron-positron mode, that tests of LFU can be performed either in I or II bin

$$R_\pi^{\mathrm{I}} = \frac{\mathrm{BR}(D^+ \to \pi^+ \mu^+ \mu^-)_{q^2 \in [0.25^2, 0.525^2]\mathrm{GeV}^2}}{\mathrm{BR}(D^+ \to \pi^+ e^+ e^-)_{q^2 \in [0.25^2, 0.525^2]\mathrm{GeV}^2}}$$

$$R_\pi^{\mathrm{II}} = \frac{\mathrm{BR}(D^+ \to \pi^+ \mu^+ \mu^-)_{q^2 \in [1.25^2, 1.73^2]\mathrm{GeV}^2}}{\mathrm{BR}(D^+ \to \pi^+ e^+ e^-)_{q^2 \in [1.25^2, 1.73^2]\mathrm{GeV}^2}}$$

$$R_\pi^{\mathrm{I}} = \frac{\mathrm{BR}(D^+ \to \pi^+\mu^+\mu^-)_{q^2\in[0.25^2,0.525^2]\mathrm{GeV}^2}}{\mathrm{BR}(D^+ \to \pi^+e^+e^-)_{q^2\in[0.25^2,0.525^2]\mathrm{GeV}^2}} \quad R_\pi^{\mathrm{II}} = \frac{\mathrm{BR}(D^+ \to \pi^+\mu^+\mu^-)_{q^2\in[1.25^2,1.73^2]\mathrm{GeV}^2}}{\mathrm{BR}(D^+ \to \pi^+e^+e^-)_{q^2\in[1.25^2,1.73^2]\mathrm{GeV}^2}}$$

$$R_\pi^{I,SM} = 0.87 \pm 0.09$$

| | $\lvert\tilde{C}_i\rvert_{\max}$ | $R_\pi^{\mathrm{II}}$ |
|---|---|---|
| SM | - | $0.999 \pm 0.001$ |
| $\tilde{C}_7$ | 1.6 | $\sim 6$–$100$ |
| $\tilde{C}_9$ | 1.3 | $\sim 6$–$120$ |
| $\tilde{C}_{10}$ | 0.63 | $\sim 3$–$30$ |
| $\tilde{C}_S$ | 0.05 | $\sim 1$–$2$ |
| $\tilde{C}_P$ | 0.05 | $\sim 1$–$2$ |
| $\tilde{C}_T$ | 0.76 | $\sim 6$–$70$ |
| $\tilde{C}_{T5}$ | 0.74 | $\sim 6$–$60$ |
| $\tilde{C}_9 = \pm\tilde{C}_{10}$ | 0.63 | $\sim 3$–$60$ |
| $\tilde{C}'_9 = -\tilde{C}'_{10}\big\rvert_{\mathrm{LQ}(3,2,7/6)}$ | 0.34 | $\sim 1$–$20$ |

Assumptions:

- $e^+e^-$ modes are SM-like;
- NP enters in $\mu^+\mu^-$ mode only;
- listed Wilson coefficients are maximally allowed by current LHCb data.

## Scalar Leptoquaks (3,2,7/6) contributes to FCNC decay

$$\mathcal{L}^{(5/3)} = (\bar{\ell}_R Y_L u_L)\,\Delta^{(5/3)*} - (\bar{u}_R Y_R \ell_L)\,\Delta^{(5/3)} + \mathrm{h.c.}$$

generates S, P, T,$T_5$, V and A

$R_2$ (3,2,7/6) can explain
$R_{D(*)}$ and $R_{K(*)}$ within certain setups !

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

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

$$C_6(m_\Delta) = -\frac{\left(Y^{R*}_{c\mu} Y^{R}_{u\mu}\right)^2}{64\pi^2 m_\Delta^2} = -\frac{(G_F\alpha)^2}{32\pi^4}\, m_\Delta^2 (\tilde{C}'_{10})^2$$

$$|C_6(m_\Delta)| < 2.5 \times 10^{-13}\ \mathrm{GeV}^{-2} \quad \Longrightarrow \quad |\tilde{C}'_9, \tilde{C}'_{10}| < 0.34$$

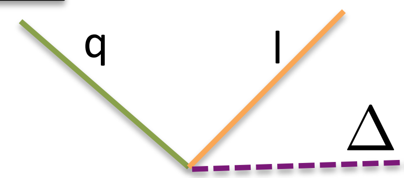
Bound from ΔC =2 slightly stronger,
but comparable to the bound coming from

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

$$\boxed{-\tilde{C}'_{10} = \tilde{C}'_9 = 0.63\,,}$$

$$4\tilde{C}_T = 4\tilde{C}_{T5} = \tilde{C}_P = \tilde{C}_S = -0.049$$

## Scalar Leptoquaks (3,3,-1/3) in charm FCNC processes




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

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

$C_{cu}^{LL}$ 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:

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

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

## Confronting charm charged current and FCNC processes:

Triplet LQ $S_3$ in charm leptonic decays decay

$$\mathcal{L}_{\bar{u}^i d^j \bar{\ell} \nu_k} = -\frac{4G_F}{\sqrt{2}} \left[ (V_{ij} U_{\ell k} \underbrace{+ g^L_{ij;\ell k})}_{C_V \text{ modifies CKM}} (\bar{u}^i_L \gamma^\mu d^j_L)(\bar{\ell}_L \gamma_\mu \nu^k_L) \right]$$

Test of lepton flavour universality (LFU)

$$R^c_{\tau,\mu} = \frac{\Gamma(D_s \to \tau\nu)}{\Gamma(D_s \to \mu\nu)}$$

$$\boxed{\frac{R^c_{\tau,\mu,LQ}}{R^c_{\tau,\mu,SM}} = [1 - \frac{v^2}{2m^2_{S3}}((V y_3^*)_{s\tau}(y_3^*)_{s\tau} - V y_3^*)_{s\mu}(y_3^*)_{s\mu})]}$$

| $m_{S3}$ [TeV] | $1 - R^c_{\tau,\mu,LQ}/R^c_{\tau,\mu,SM}$ |
|---|---|
| 1.0 | 3.2% |
| 1.2 | 2.4% |
| 1.5 | 1.5% |

Doršner, SF, Greljo, Kamenik Košnik, 1603.04993

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

not present in B physics!

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

$$C_9' = C_{10}' = \frac{\pi}{\sqrt{2} G_F \lambda_b \alpha} \frac{Y_{\mu c} Y_{\mu u}^*}{m_V^2}$$

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

$$C_6(m_V) = \frac{(Y_{\mu u} Y_{\mu c}^*)^2}{32\pi^2 m_V^2} = \frac{(G_F \alpha)^2}{16\pi^4} m_V^2 (\tilde{C}_{10}')^2$$

$$\boxed{|\tilde{C}_9', \tilde{C}_{10}'| < 0.24}$$

$D \to \pi\mu^+\mu^-$ In the high q² region branching ratio is $1.4 \times 10^{-8}$ two times smaller then the experimental bound

## Two Higgs doublet model type III

Two neutral scalars, h and H, one pseudoscalar A, two charged $H^{\pm}$;
Flavor changing neutral couplings at tree level generated.

$$\tan\beta = \frac{v_u}{v_d}$$

$$\mathcal{L} = \frac{y_{ij}^{(\ell)H_k}}{\sqrt{2}} H_k \bar{\ell}_{L,i} \ell_{R,j} + \frac{y_{ij}^{(u)H_k}}{\sqrt{2}} H_k \bar{u}_{L,i} u_{R,j} + \mathrm{h.c.} \qquad H_k = (H, h, A)$$

$$-C_P = C_S = \frac{\pi}{4\sqrt{2} G_F \alpha \lambda_b} \frac{m_\mu}{v} \frac{\epsilon_{12}^{u*} \tan\beta}{m_H^2}$$

$$C'_P = C'_S = \frac{\pi}{4\sqrt{2} G_F \alpha \lambda_b} \frac{m_\mu}{v} \frac{\epsilon_{21}^{u} \tan\beta}{m_H^2}$$

from $\mathrm{BR}(D^0 \to \mu^+\mu^-)$

$$|\tilde{C}_S - \tilde{C}'_S| \leq 0.05$$

$$|\tilde{C}_P - \tilde{C}'_P| \leq 0.05$$

## Z' model

Anomalies in B decays often explained by Z'.

$D^0 - \bar{D}^0$ transitions constrain $\quad C_6(m_{Z'}) = \dfrac{|C^u|^2}{2m_{Z'}^2}$

$c \to u\mu^+\mu^-$

$m_{Z'} \sim 1\ \mathrm{TeV} \quad |C_9| \lesssim 8 \quad |C_{10}| \lesssim 100$ negligible effects!

| 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

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

1510.0311 (de Beor and Hiller)
1705.02251 (Sahoo and Mohanta)

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

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

$$BR(D^0 \to e^+\mu^- + e^-\mu^+) < 2.6 \times 10^{-7}$$
$$BR(D^+ \to \pi^+e^+\mu^-) < 2.9 \times 10^{-6}$$
$$BR(D^+ \to \pi^+e^-\mu^+) < 3.6 \times 10^{-6}$$

$$\left|K_{S,P}^{(l)} - K_{S,P}^{(l)\prime}\right| \lesssim 0.4\,,$$
$$\left|K_{9,10}^{(l)} - K_{9,10}^{(l)\prime}\right| \lesssim 6\,, \quad \left|K_{T,T5}^{(l)}\right| \lesssim 7\,,$$

$$l = e, \mu$$

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

## Dark Matter in charm decays

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!

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

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

Model of DM: gauge boson +scalar
SSB $U(1)_d$

$$\mathcal{L} = -\frac{1}{4} V_{\alpha\beta} V^{\alpha\beta} + |D_\mu \phi|^2 + \bar{\mu}_R i D \cdot \gamma \mu_R$$
$$-\frac{\kappa}{2} V_{\alpha\beta} F^{\alpha\beta} - \bar{L} \mu_R H_{SM} \frac{\phi}{\Lambda} + h.c.$$

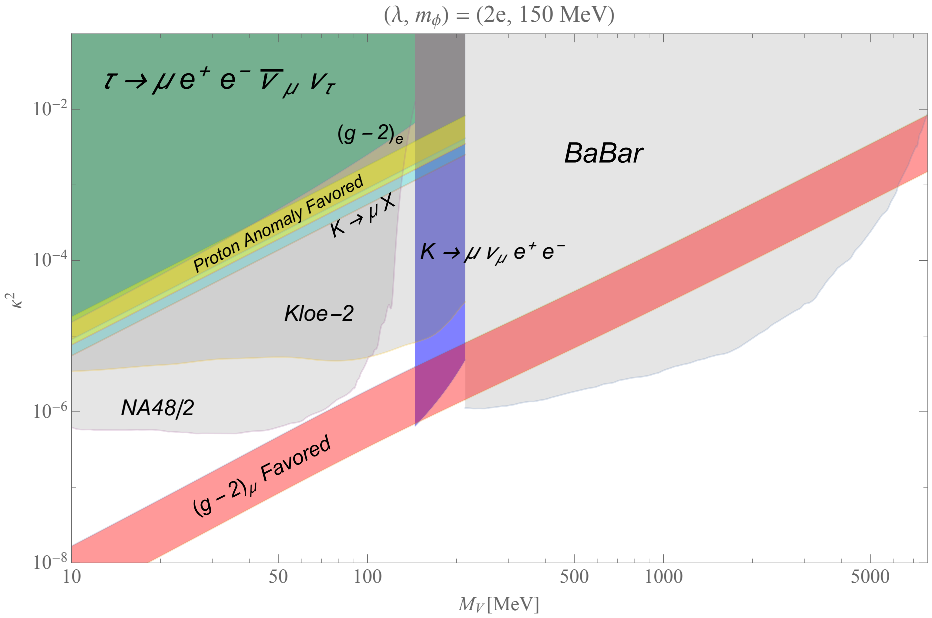
$$D_\alpha = \partial_\alpha + i g_R V_\alpha + i e Q_{EM} A_\alpha$$

V is the gauge boson, neutral under the SM gauge group and charged under $U(1)_d$
κ is a mixing angle between dark boson and photon

New "dark" Higgs with the condensate

$$\langle \phi \rangle = \frac{v_R}{\sqrt{2}}$$

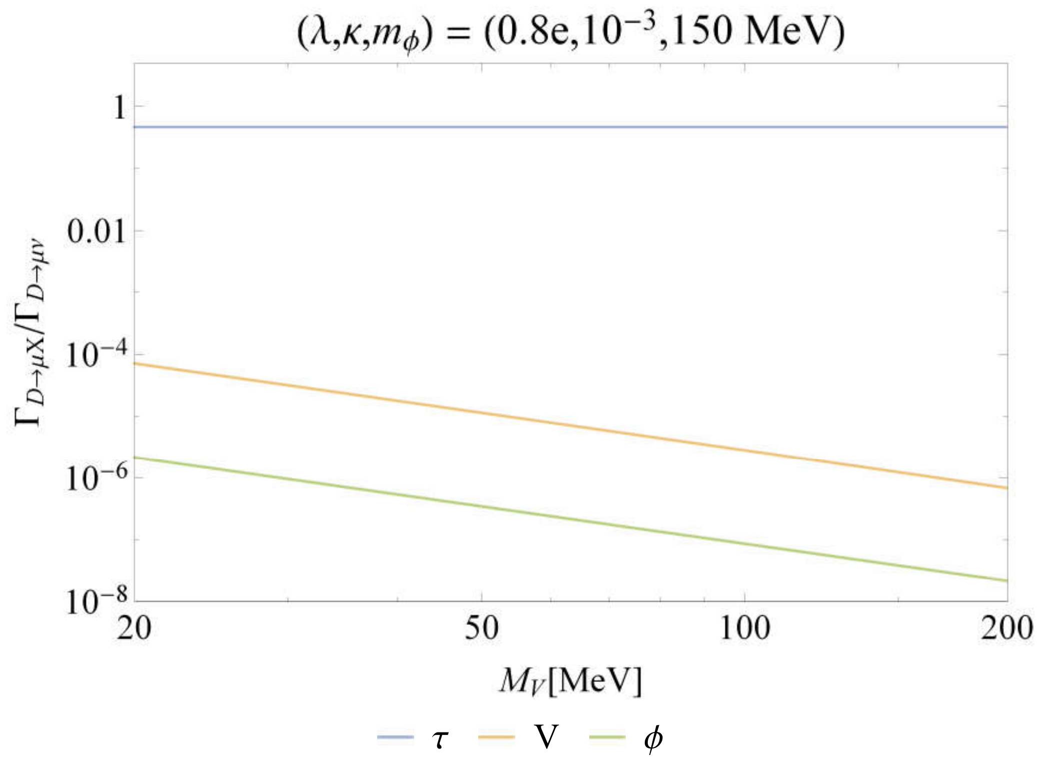
F. C. Correia, SF, 1609.0860,
Batell et al.1103.0721




color areas are excluded
(for proton charge radius an $(g\text{-}2)_\mu$
yellow and red are favored)!

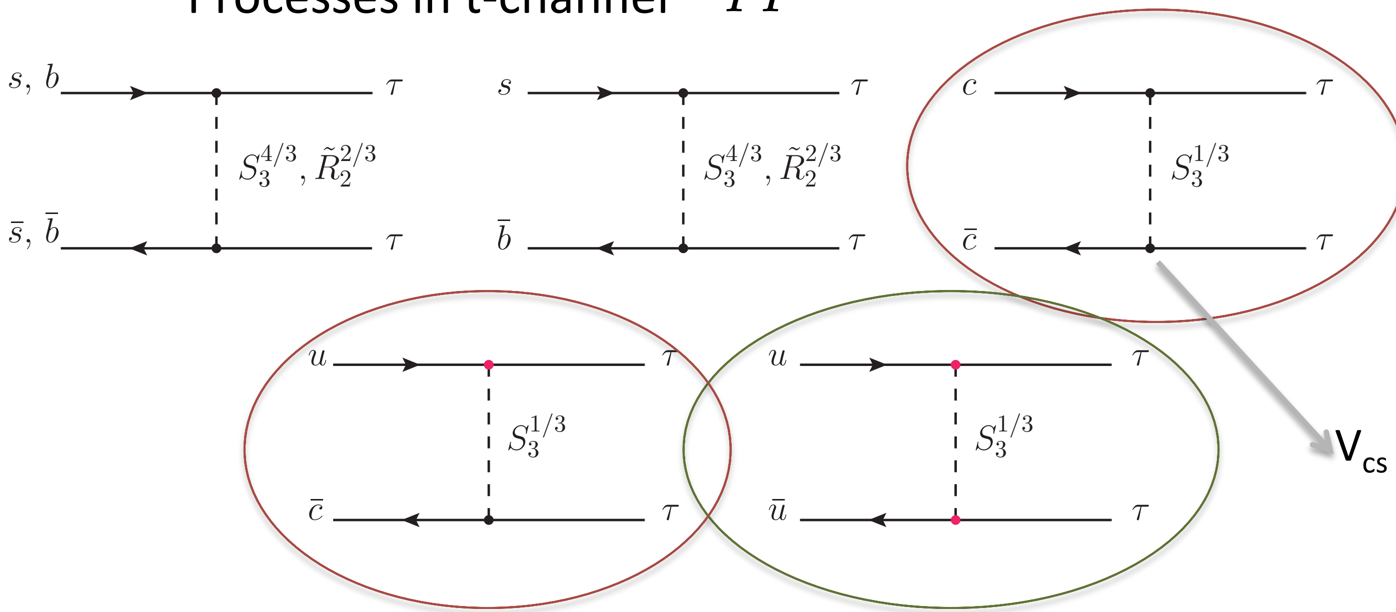
Is it possible to search for decay
$D \to \mu X$
X is DM gauge boson + DM scalar + SM $\nu_\mu$

Exp: $D \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau\nu_\tau$ -



## LHC constraints on $S_3$: high-mass ττ production

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




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

$$\sigma_{s\bar{s}}(y_{s\tau}) = 12.042\, y_{st}^4 + 5.126\, y_{st}^2 \,,$$
$$\sigma_{s\bar{b}}(y_{s\tau}, y_{b\tau}) = 12.568\, y_{s\tau}^2 y_{b\tau}^2 \,,$$
$$\sigma_{b\bar{b}}(y_{b\tau}) = 3.199\, y_{b\tau}^4 + 1.385\, y_{b\tau}^2 \,,$$
$$\sigma_{c\bar{c},u\bar{u},u\bar{c}}(y_{s\tau}) = 3.987\, y_{s\tau}^4 - 5.189\, y_{s\tau}^2 \,.$$

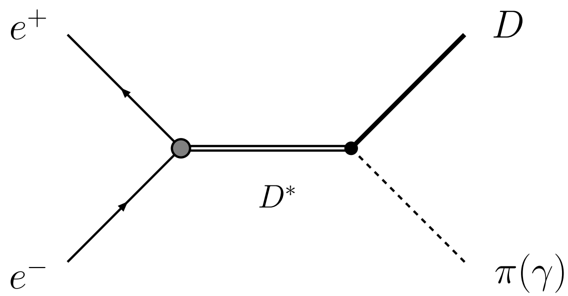
Flavour anomalies generate s τ , bτ and cτ relatively large couplings.
s quark pdf function for protons are ~ 3 times lagrer contribution then for b quark.

$m_{LQ} \approx 1$ TeV

# Direct probes of flavor-changing neutral currents in $e^+e^-$ collisions

Khodjamirian, Mannel, A Petrov, 1509.07123

Due to helicity suppression difficult to measure branching ratio $D^0 \to e^+e^-$




Single charm production can test

$$\mathcal{H} = \frac{\lambda'}{M^2}(\bar{c}\gamma_\mu u)(\bar{e}\gamma^\mu e),$$

$$\mathcal{B}^{SD}_{D^*\to e^+e^-} \approx 2.0 \times 10^{-19}$$

Small in SM, NP might increase it!

$$\mathcal{B}^{Z'}_{D^*\to e^+e^-} < 2.5 \times 10^{-11}$$

# Summary

- SM progress - treatment of radiative and semileptonic D decays (NNLO calculation) hard spectator and weak annihilation amplitudes ;

- new proposal to measure gamma polarization in $D^0 \to \rho^0\gamma$ and $\Lambda_c \to p\gamma$;

- NP proposals developed; Leptoquarks in radiative and semileptonic decays;

- New physics particles explaining B anomalies, give rather small effects;

- Few proposals to test DM in charm physics suggested to observe effects of DM;

NP searches at LHC: charm quark important.

# Thanks!