Radiative charm decays and BSM physics

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Overview

- Motivation;
- SM in rare charm decays: $D \to V\gamma$; $D \to \pi ll$, $D \to \mu\mu$;
- From B anomalies to charm physics;
- Signatures of NP in chargned current and FCNC charm decays;
- Dark Matter search in rare charm decays;
- Summary.

Motivation

B meson puzzles → Solution by New Physics

B meson puzzles → Tests of Lepton flavour universality

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

How about charm?

- In experiments producing B mesons there are always D mesons;
- Charm offers tests of possible NP in up sector at low-energies;
- If NP couples to weak doublets of quarks, CKM connects it with charm sector.
- Lattice QCD made progress for charm meson coupling constants and some form-factors
- Can one see NP in charm decays not being present in B meson ?

SM effective Hamiltonian for rare charm decays -FCNC

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

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

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)

De Beor talk!

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

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

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

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

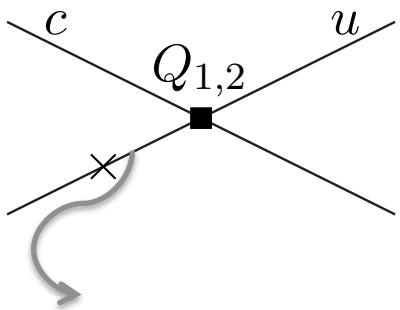
$$Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

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

all three operators contribute to $c \to u l^+ l^-$

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 [24]†	$(1.77 \pm 0.31) \times 10^{-5}$	–	$(2.76 \pm 0.21) \times 10^{-5}$	$(4.66 \pm 0.30) \times 10^{-4}$
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

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

Talk of De Boer at CKM 2018 on 20 Sept.!

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

Hiller& de Boer 1701. 06392
SF& Singer, hep-ph/9705327,
SF, Prelovsek &hep-ph/9801279
Burdman et al. hep-ph/9502329,
Khodjamirian et al, hep-ph/9506242

$$D^0 \to \mu^+\mu^- \,, D_s \to \mu\nu \,,$$
$$D \to \mu\nu \,, K_L \to \mu^+\mu^-$$

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

For example $$\mathcal{L}_{eff} = \frac{4G_F}{\sqrt{2}} \bar{Q}_{Li}\gamma_\mu Q_{Lk}\, \bar{l}_{Ln}\gamma^\mu l_{Lm}$$

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

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

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

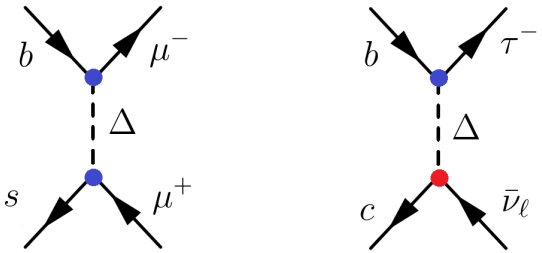
Models of NP explaining B anomalies

Spin	Color singlet	Color tripet
0	2HDM	Scalar LQ ~~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

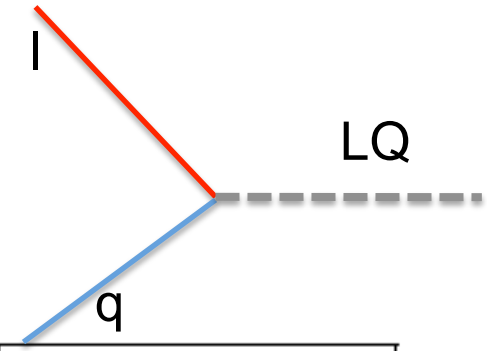
Leptoquarks?



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?

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	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$	
$S_1 = (\bar{3},1)_{1/3}$	✓	✗	✗	Spin 0
$R_2 = (3,2)_{7/6}$	✓	✗*	✗	
$S_3 = (\bar{3},3)_{1/3}$	✗	✓	✗	
$U_1 = (3,1)_{2/3}$	✓	✓	✓	Spin 1
$V_2 = (3,1)_{2/3}$	✗	✗	✗	
$\widetilde{V}_2 = (\bar{3},2)_{-1/6}$	✗	✗	✗	
$U_3 = (3,3)_{2/3}$	✗	✓	✗	

No single scalar LQ to solve simultaneously both anomalies!

Scalar LQ → simpler UV completion;

Doršner, SF, Greljo, Kamenik , Košnik, 1603.04993

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.

LQ and charm charged current

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)

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

$$\frac{R^c_{\tau,\mu,LQ}}{R^c_{\tau,\mu,SM}} = [1 - \frac{v^2}{2m^2_{S3}}((Vy^*_3)_{s\tau}(y^*_3)_{s\tau} - Vy^*_3)_{s\mu}(y^*_3)_{s\mu})]$$

Comes from the fit of $R_{K(*)}$ with S_3

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;

Scalar or tensor currents

$$\mathcal{L}_{eff} = -\frac{4\,G_F}{\sqrt{2}} V_{cq} \left[g_S(\mu)\,(\bar{c}_R q_L)(\bar{\ell}_R \nu_L) + g_T(\mu)\,(\bar{c}_R \sigma_{\mu\nu} q_L)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \right],$$

$$\mathcal{B}(D_s \to \tau\nu) = \tau_{D_s} \frac{m_{D_s} m_\tau^2 G_F^2 |V_{cq}|^2}{8\pi} (1 - \frac{m_\tau^2}{m_{D_s}}^{\;2})|1 + \frac{m_{D_s}^2}{m_\tau(m_c + m_s)} g_S|^2$$

Scalar leptogquarks $\tilde{R}_2(3,2,1/6)$, $R_2(3,2,7/6)$ can produce scalar and tensor couplings

$$\mathcal{L}_{R_2} = (V g_R)_{ij} \bar{u}^i P_R e^j R_2^{5/3} + (g_R)_{ij} \bar{d}^i P_R e^j R_2^{2/3}$$
$$+ (g_L)_{ij} \bar{u}^i P_L \nu^j R_2^{2/3} - (g_L)_{ij} \bar{u}^i P_L e^j R_2^{5/3} + \text{h.c.}\,,$$

In B physics branching ratio B (Bc) →τ υ very constraining for NP!

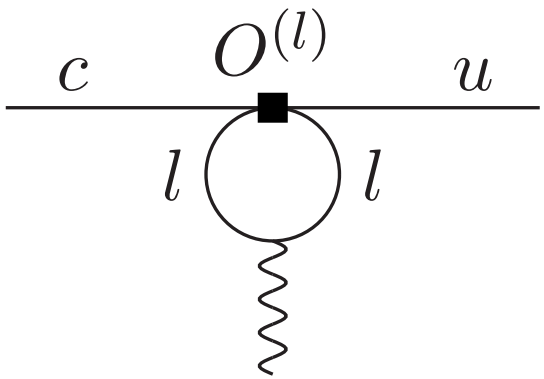
In explaining B anomalies couplings present in rare D do not appear. One can make full low-energy study, without B mesons as done in 0906.5585 and exclude, it by the bounds from

$$D^0 \to \mu^+\mu^-\,, D_s \to \mu\nu\,, D \to \mu\nu\,, K_L \to \mu^+\mu^-$$

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 $V_{\sim 2}$ and SM-like for S_3.

Vector LQ $V_{\sim 1}$ $A_{CP} \sim$ O(10%). The largest effects arise from τ-loops.

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

CP asymmetry in charm radiative decays

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

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

Belle, 1603.03257

Hiller& de Boer 1701. 06392

LQs give as large

contributions as SM

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

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

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

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

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

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

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

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

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

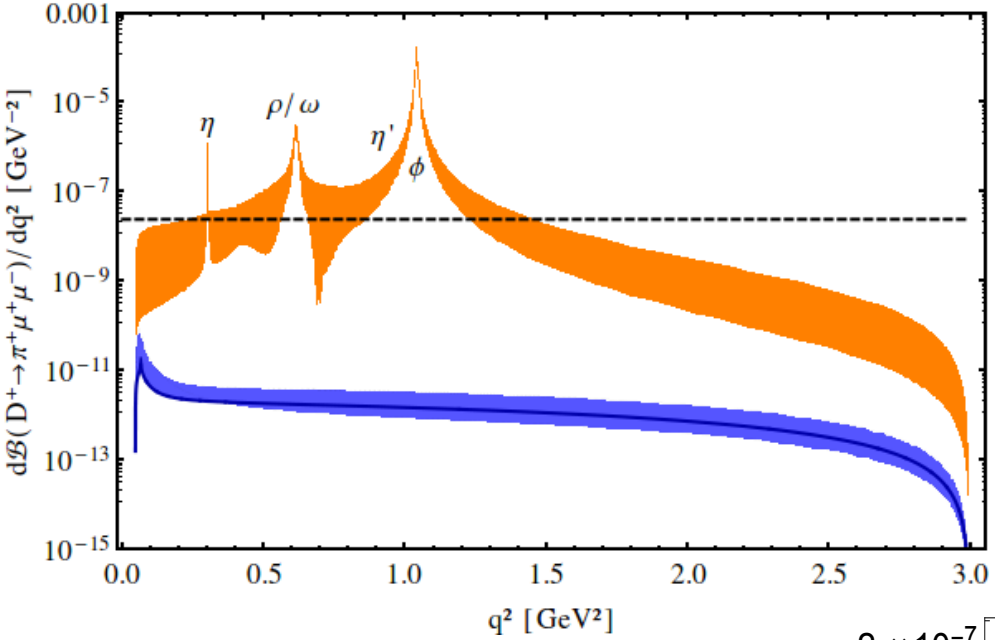
SF, N. Kosnik, 1510.00965

LHCb bound, 1305.5059

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

Helicity suppressed decay!

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



SM prediction: Long distance contributions most important!

peaks at ρ,ω,φ and η resonances

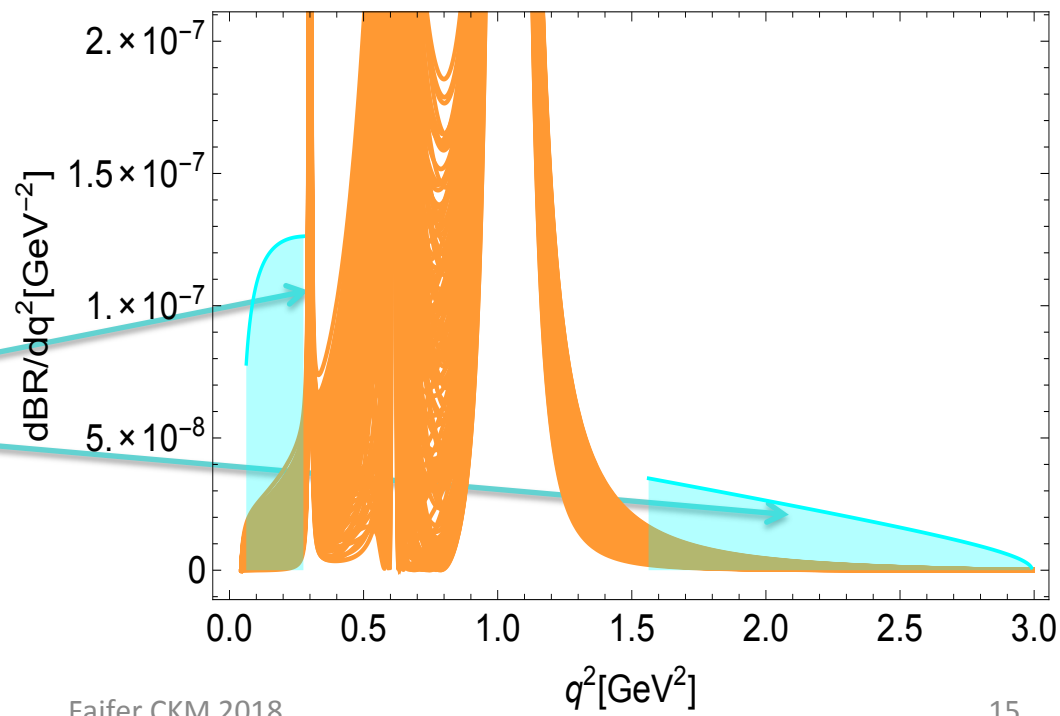
$$D \to \pi V \to \pi l^+ l^-$$

de Boer, Hiller, 1510.00311,

SF and Kosnik, 1510.00965

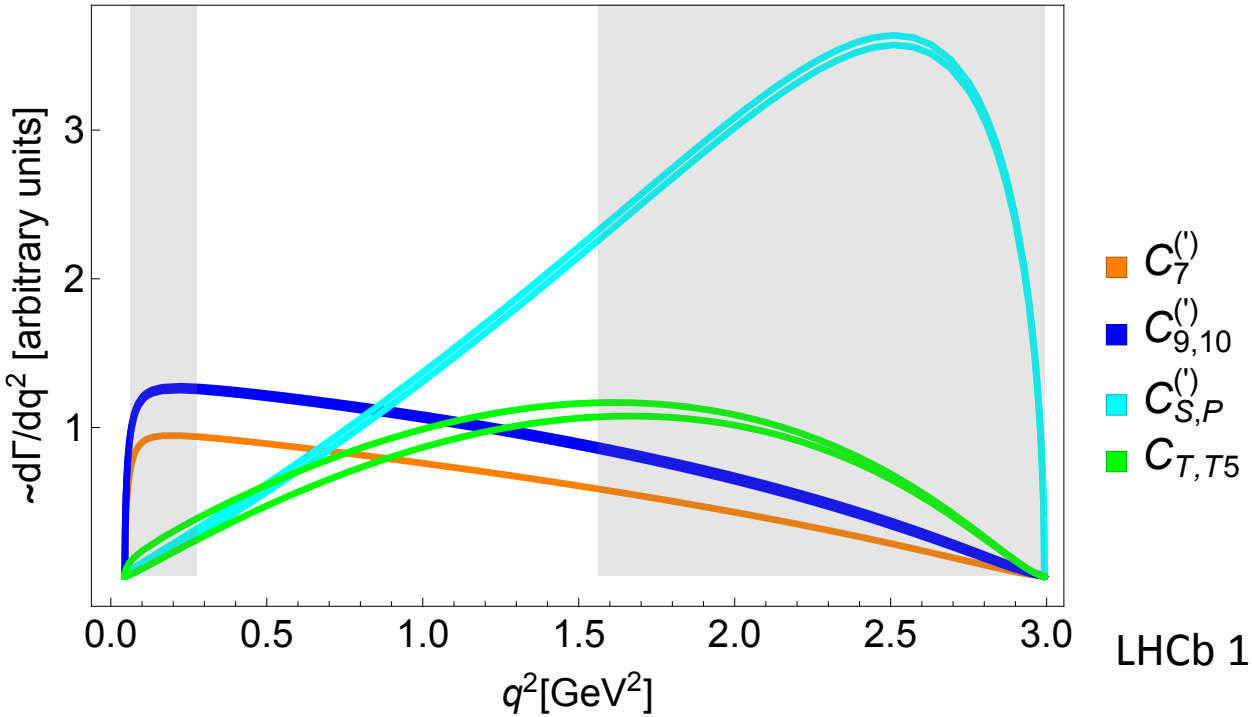
LHCb bound- assumption – constant amplitude

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 :

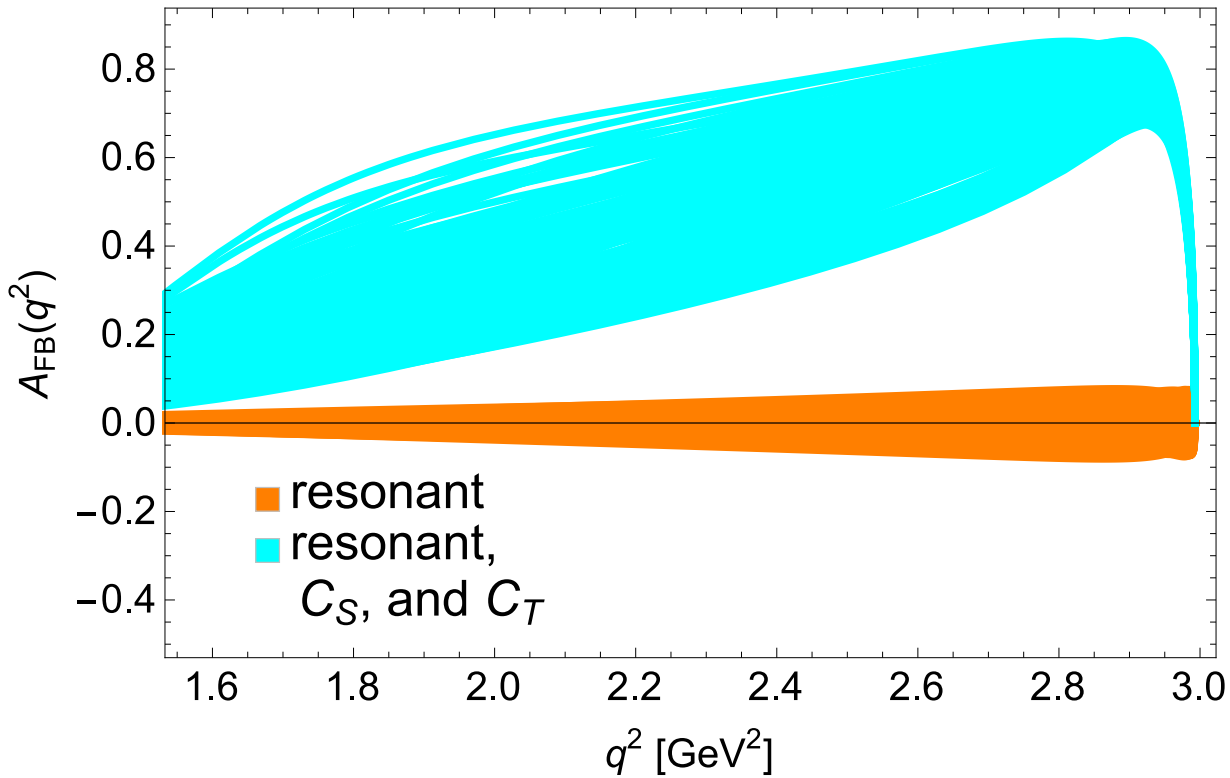


LHCb 1304.6365

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

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

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



$b_l(q^2)$

S,T$_5$ necessary!

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

	$\lvert\tilde{C}_i\rvert_{\max}$		
	$\mathrm{BR}(\pi\mu\mu)_{\mathrm{I}}$	$\mathrm{BR}(\pi\mu\mu)_{\mathrm{II}}$	$\mathrm{BR}(D^0 \to \mu\mu)$
$\tilde{C}_7$	2.4	1.6	-
$\tilde{C}_9$	2.1	1.3	-
$\tilde{C}_{10}$	1.4	0.92	0.63
$\tilde{C}_S$	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

Best bounds from

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

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

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

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

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

	$\lvert\tilde{C}_i\rvert_{\rm max}$	$R_\pi^{\rm II}$
SM	-	0.999 ± 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
$\tilde{C}'_9 = -\tilde{C}'_{10}\big\vert_{\rm LQ(3,2,7/6)}$	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

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

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

R_2 (3,2,7/6) can explain $R_{D(*)}$
(D. Becirevic et al. 1806.05689)

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

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

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

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

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

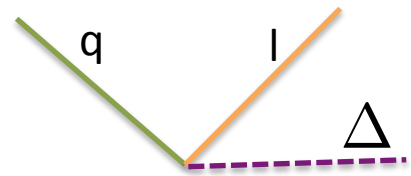
$$D^0 \to \mu^+\mu^-$$

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

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

at LQ mass scale

Scalar Leptoquaks 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:

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

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

Vector Leptoquark (3,1,5/3)

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

not present in B physics at tree level!

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

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

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

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

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

$D \to \pi \mu^+ \mu^-$ In the high q^2 region branching ratio is 1.4×10^{-8}
two times smaller then the experimental bound

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

Dark Matter in charm decays

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

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

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

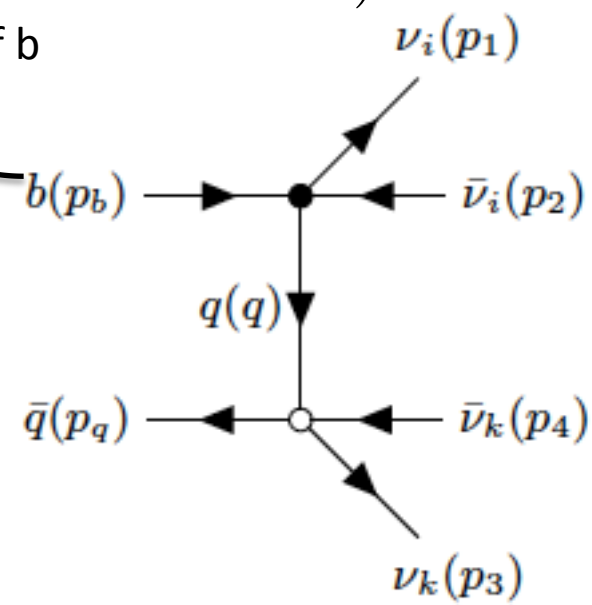
$$D^0 \to \gamma \not{E}$$ could be SM neutrinos or DM!

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 $D^0 \to \nu\bar{\nu}\nu\bar{\nu}$.



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

$U(1)_X$ dark sector

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

Gauge group SU(3) x SU(2) X $U(1)_Y$ X $U(1)_X$

- Request anomalies cancelled:

$$U(1)_X^3,\ U(1)_X^2 U(1)_Y,\ U(1)_X U(1)_Y^2 \text{ and } SU(3)^2 U(1)_X$$

- Higgs sector: 2 doublets, one singlet

$$\phi_0 = \begin{pmatrix} \varphi_0^+ \\ \frac{v_0 + H_0 + i\chi_0}{\sqrt{2}} \end{pmatrix}; \qquad \phi_X = \begin{pmatrix} \varphi_X^+ \\ \frac{v_X + H_X + i\chi_X}{\sqrt{2}} \end{pmatrix}; \qquad s = \frac{v_s + H_s + i\chi_s}{\sqrt{2}}$$

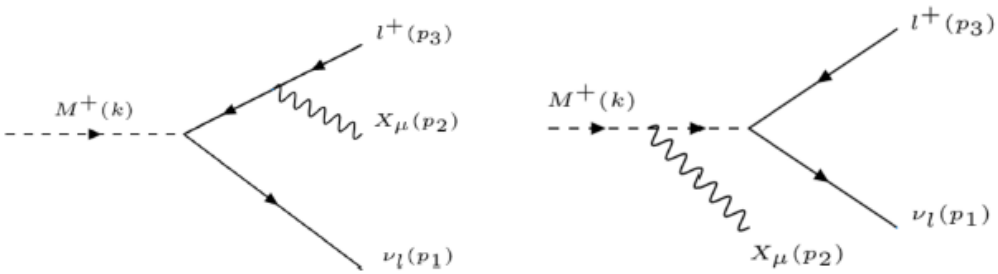
$$v^2 \equiv (v_0^2 + v_X^2), \qquad \bar{v}^2 \equiv (v_s^2 + v_X^2), \qquad c_\beta^2 = \frac{v_X^2}{v^2}$$

- invisble fermions necessary for anomaly cancellation)

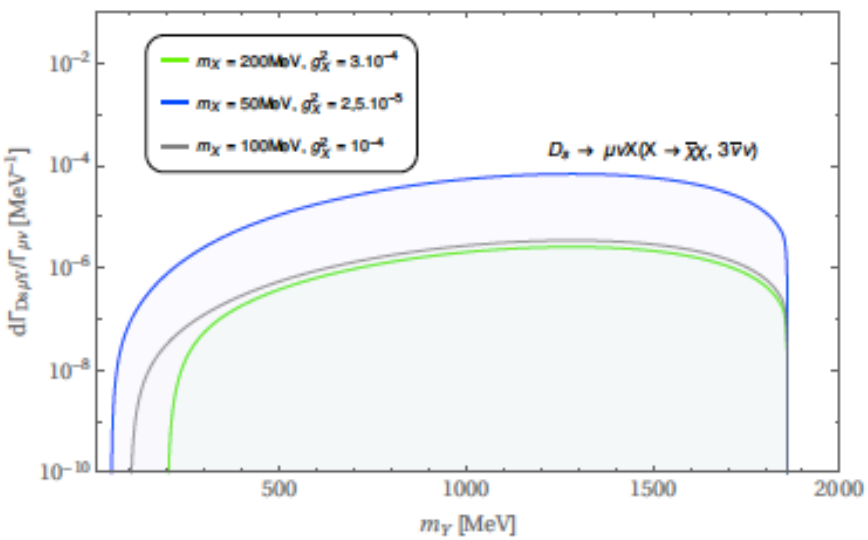
$$\mathcal{L} \longrightarrow -Y_s\, \overline{\chi_L} \chi_R s - Y_s^*\, \overline{\chi_R} \chi_L s^* \cdot$$

A_μ and X_μ mix via κ

$$M^+ \to \mu^+ \not{E}$$



Radiative - not γ but X

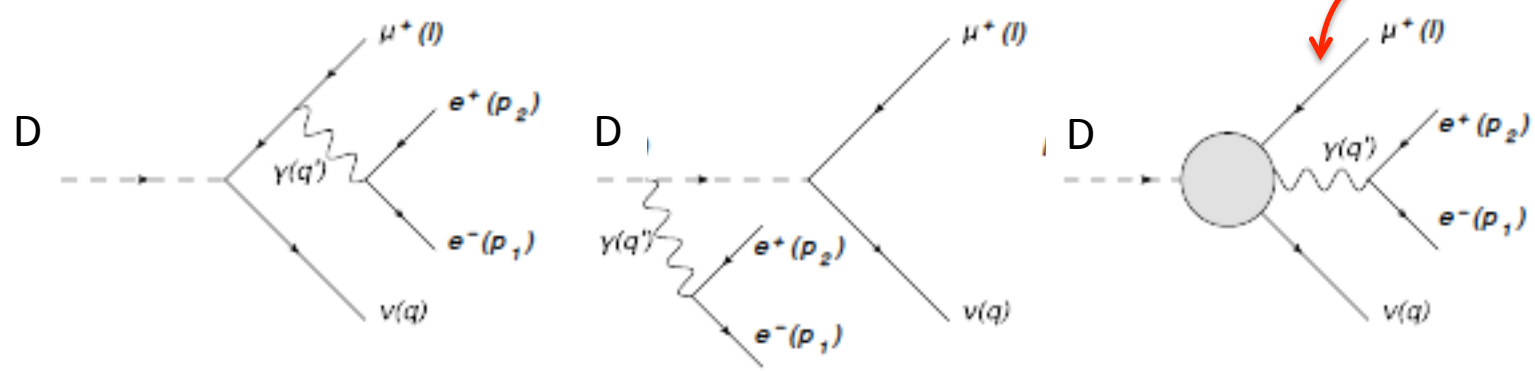


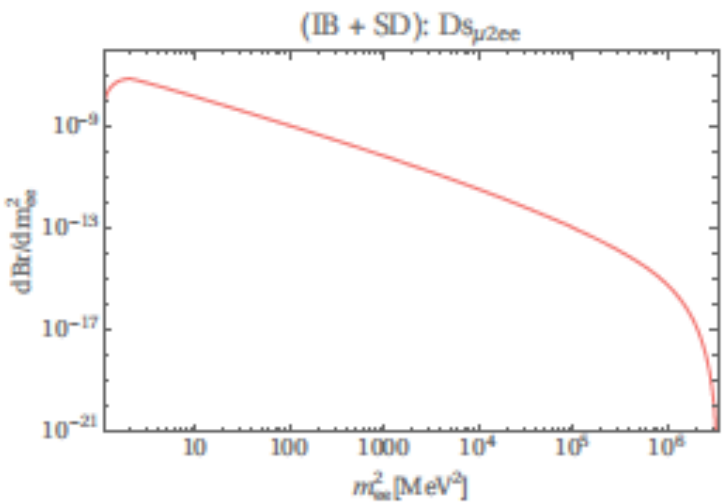
Is it possible to search for decay
D → μ X
X is SM ν_μ + DM gauge boson → invisible fermions
Exp: $D \to \tau\bar{\nu}_\tau \to \mu\bar{\nu}_\mu\nu_\tau\bar{\nu}_\tau$

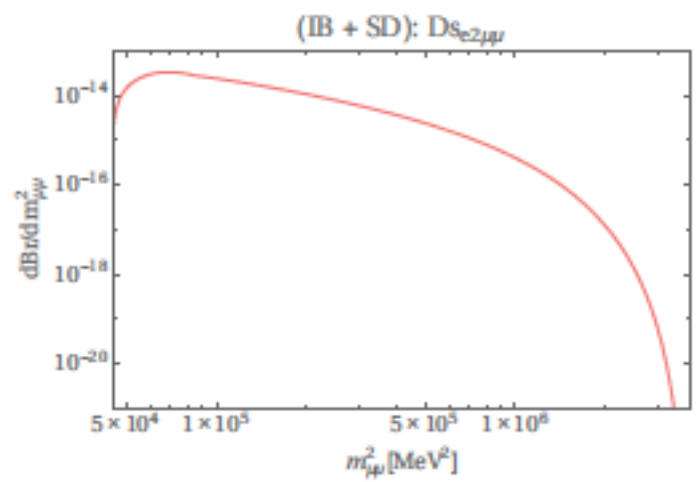
Difficult to differentiate

- There is a possibility that X → e^+e^-
- Can one see it in the decays P→μ νX → μυ e^+e
- First one should calculate SM values

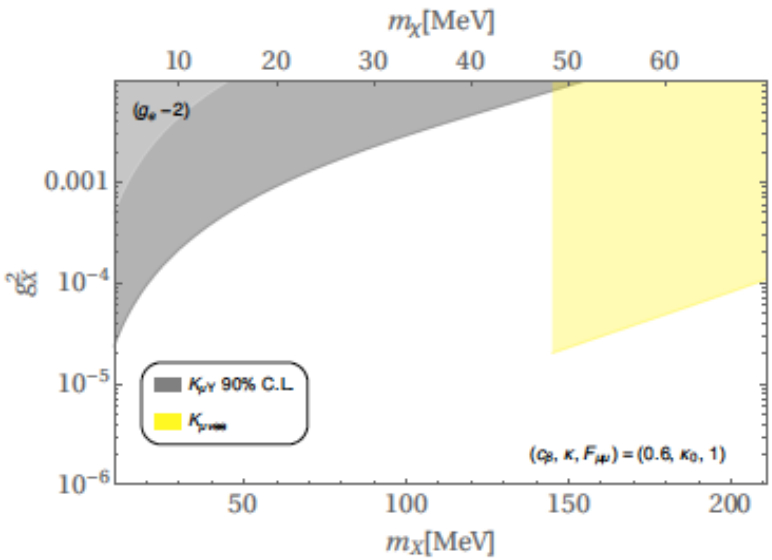
Thanks D. Melikhov for providing us with <γ* | J_μ | D_s>

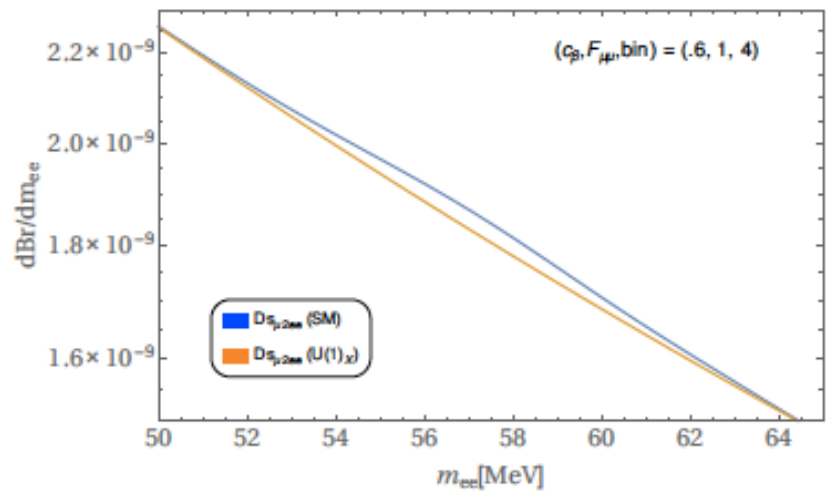






Preliminary!



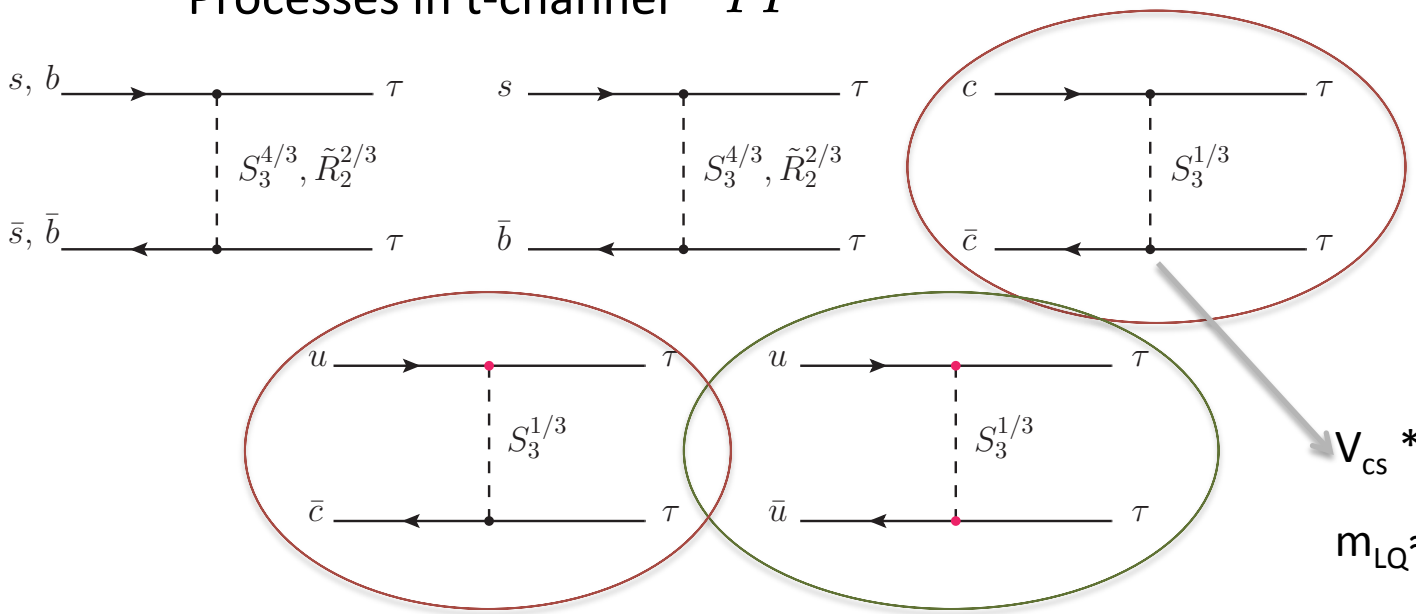


For certain choice of parameters, $M_\chi \approx 50$ MeV

Constraints from $(g\text{-}2)_\mu$ and trident production allow rather small mixing $\kappa \sim 10^{-4}$

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

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

Summary

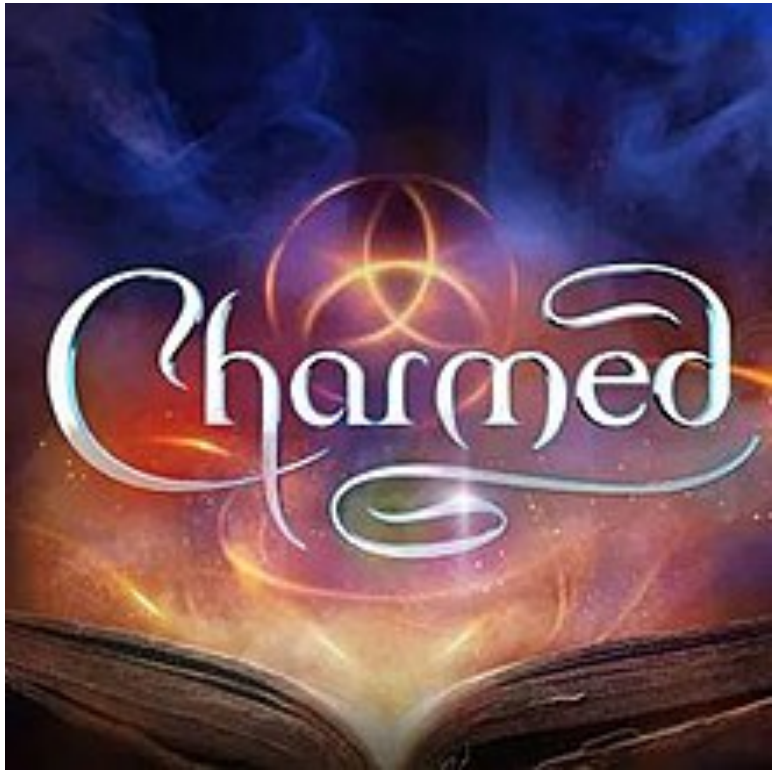
- New physics explaining B anomalies, give rather small effects in charge current transitions ;

- FCNC transition small contribution of Leptoquarks in charm decays observables;

- Few proposals to test DM in charm physics;

- NP searches at LHC: charm quark important.

Thanks!



Lepton flavor violation

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

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

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

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

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

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

$$l = e, \mu$$

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

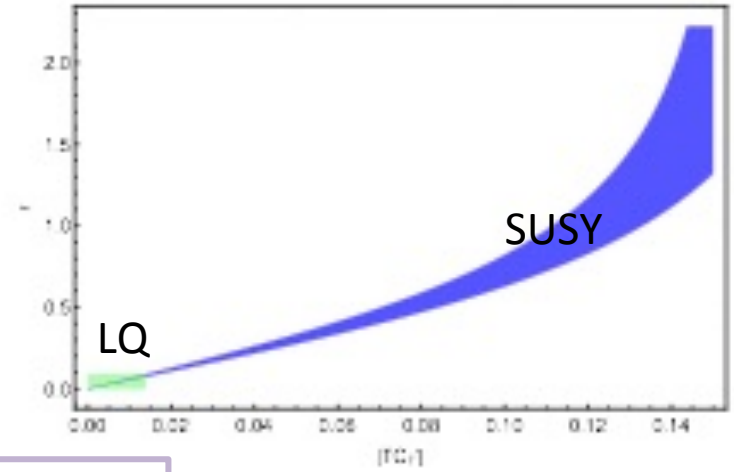
$D^0 \to \phi\gamma$ or $D^0 \to \bar{K}^{0*}\gamma$ decays (SM-dominated)

the polarization fraction r

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

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

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



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

$\Lambda_c \to p\gamma$

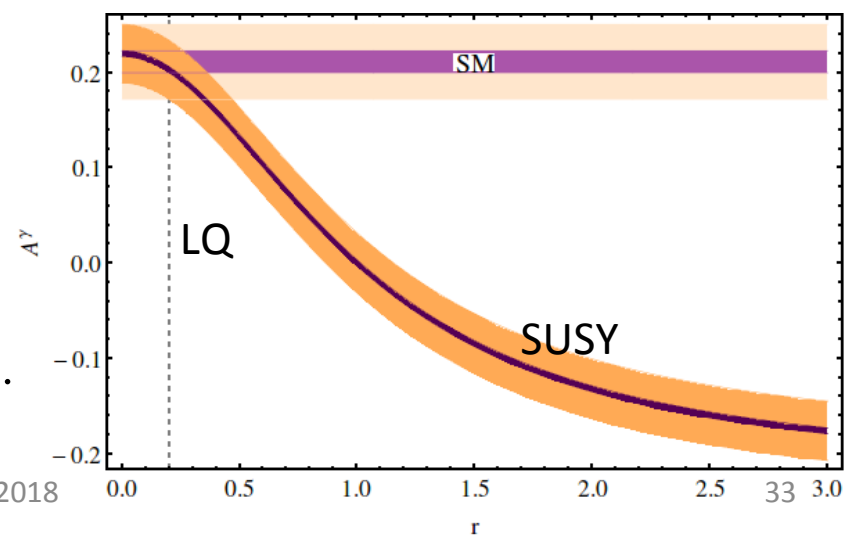
Hiller& de Boer 1701. 06392

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

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

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

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



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

De Beor and Hiller, 1805.08516

LHCb result (1707.08377)

Modes sensitive to NP

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

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

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

$$D^0 \to \pi^+\pi^- l^+ l^-\,, \quad D^0 \to K^+K^- l^+ l^-\,,$$

$$D^+ \to K^+\bar{K}^0 l^+ l^-\,,$$

$$D_s \to K^+\pi^0 l^+ l^-\,, \quad D_s \to K^0\pi^+ l^+ l^-\,,$$

- study of angular distributions 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 $C_{10}^{(\prime)}$

Tests of LFU

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

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

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

only upper limits exists