BSM searches with (semi)leptonic charm decays

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Overview

SM in rare charm decays

NP

NP in D meson in rare charm decays

NP in B anomalies → NP in charm
D^0 - $\bar{D}^0$ and rare charm decays

$D \to P\, l^+ l^-$
$D \to l^+ l^-$
$D \to P_1 P_2\, l^+ l^-$
$D \to$ invisibles

Summary and Outlook

NP in rare charm decays – from B to D

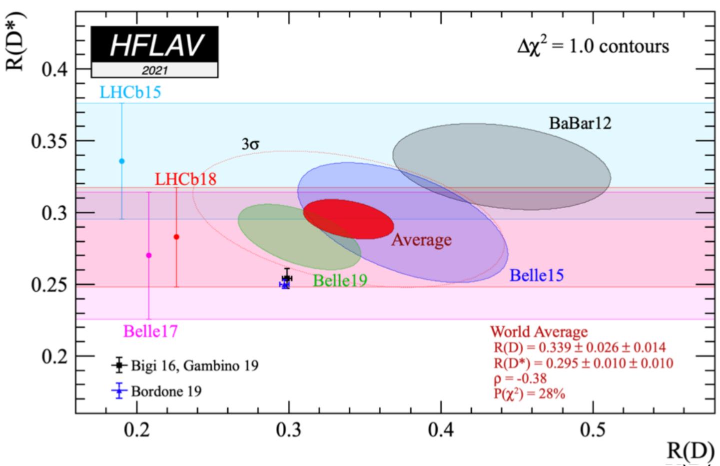
Search for NP in up sector
- at low energies (charm factories)
- at high energies LHC

B anomalies explained by NP

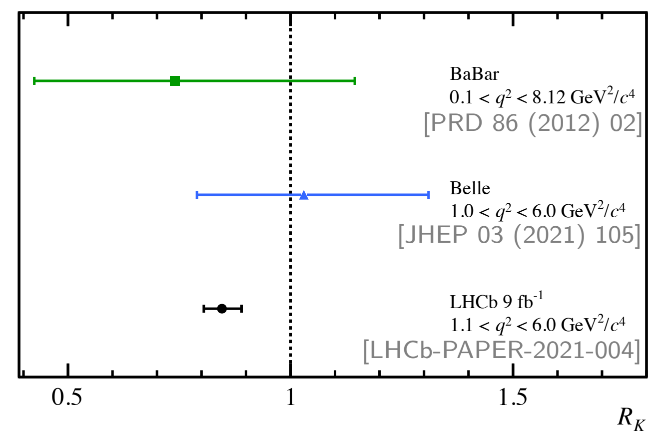
Can this NP be seen in charm rare decays, D^0 - $\bar{D}^0$ oscillations ...

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

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



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



3.1σ

NP explaining both B anomalies

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

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

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

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

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

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

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

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

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

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

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

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

$$\downarrow$$

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

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!

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

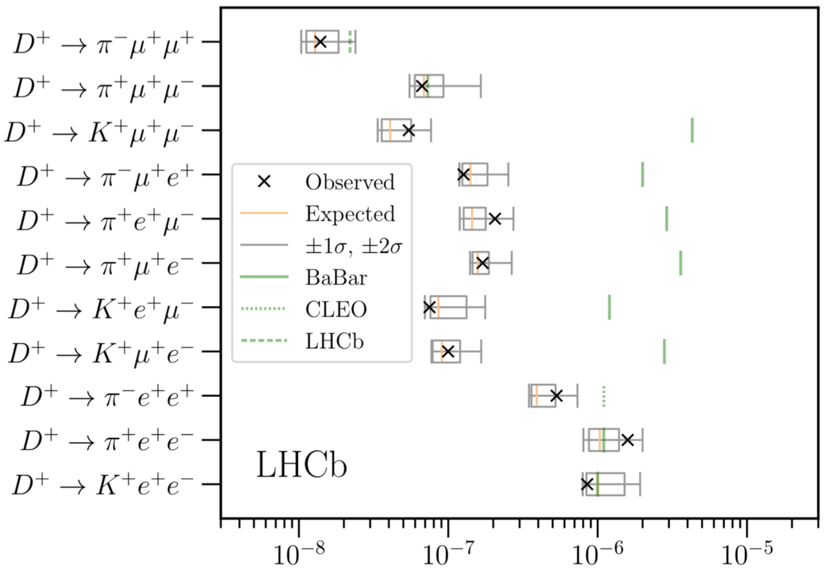
Effects of NP in charm suppressed by $V_{cb}^* V_{ub}$!

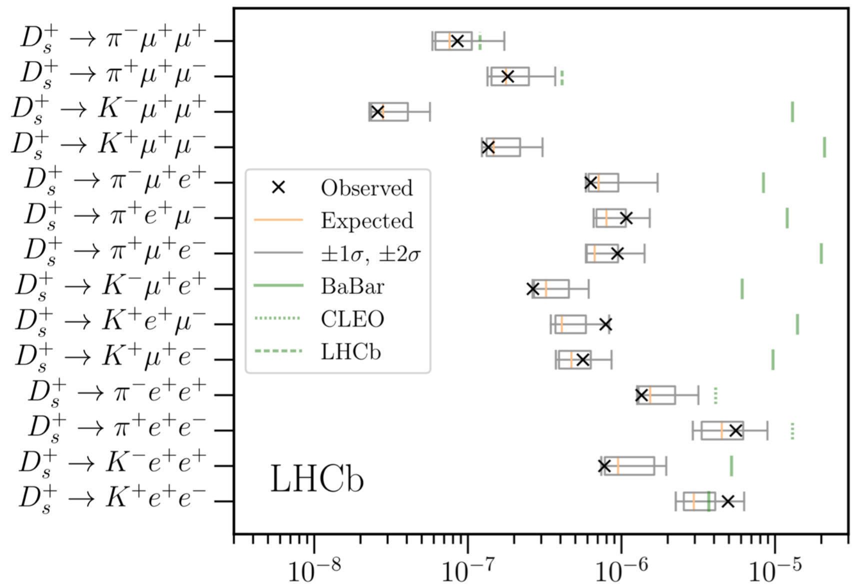
Recent experimental results

Current upper limit

$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ @ 90% CL

2011.00217 LHCb





$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3\ (1.6) \times 10^{-8}$ @90 (95)% CL

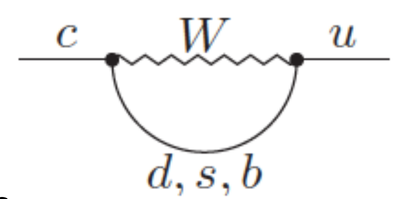
$\mathcal{B}(D^0 \to \pi^-\pi^+\mu^+\mu^-) = (9.64\pm0.48\pm0.51\pm0.97)\times10^{-7}$
$\mathcal{B}(D^0 \to K^-K^+\mu^+\mu^-) = (1.54\pm0.27\pm0.09\pm0.16)\times10^{-7}$

From
Fontana at CHARM 2021

SM effective Hamiltonian for rare charm decays -FCNC

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

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



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

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

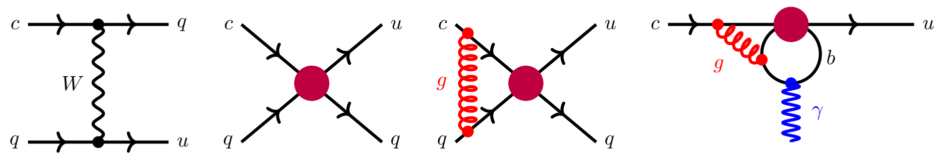
$$Q_1^{(q)} = (\bar u_L \gamma_{\mu_1} T^a q_L)(\bar q_L \gamma^{\mu_1} T^a c_L)\,, \qquad Q_2^{(q)} = (\bar u_L \gamma_{\mu_1} q_L)(\bar q_L \gamma^{\mu_1} c_L)\,,$$

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

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

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

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



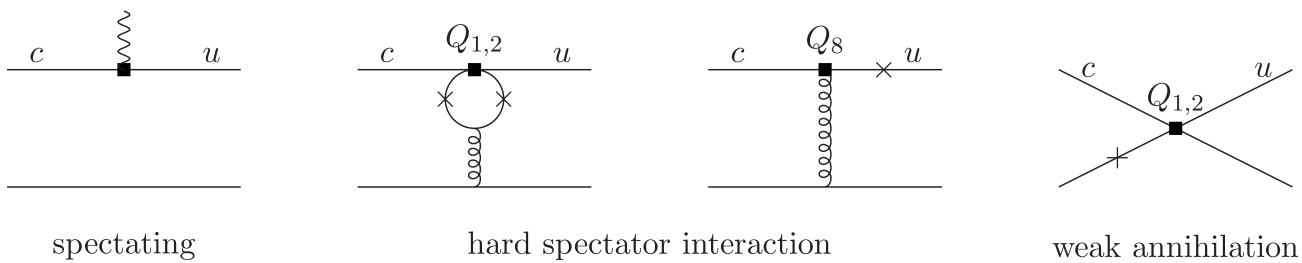
- matching of SM contributions onto Weak Effective Theory at $\mu = M_W$;
- RG-evolution of Wilson coefficients from M_W to m_b,
- integrating out the b quark and second matching at $\mu = m_b$,
- RG-evolution of Wilson coefficients from m_b to the charm scale μ_c.

(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

DeBoer & Hiller 1701.06392
C. Greub et al., PLB 382 (1996) 415;

SD contributions



Leading hard spectator within QCD factorization adopted from B physics

SD dynamics SM

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

DeBeor& Hiller 1510.00311

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

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

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

Gisbert et al. 2011.09478,

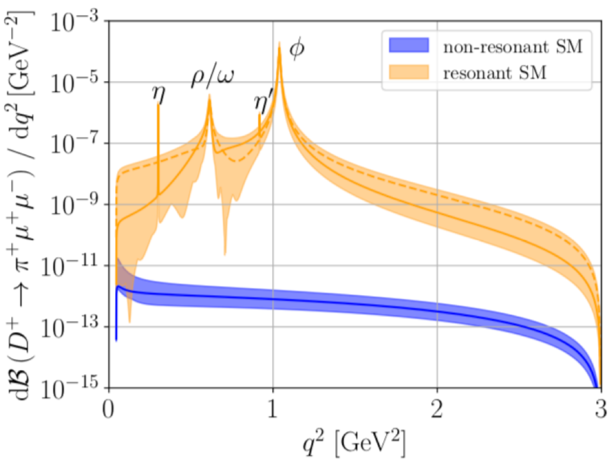
$D \to P\mu^+\mu^-$

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

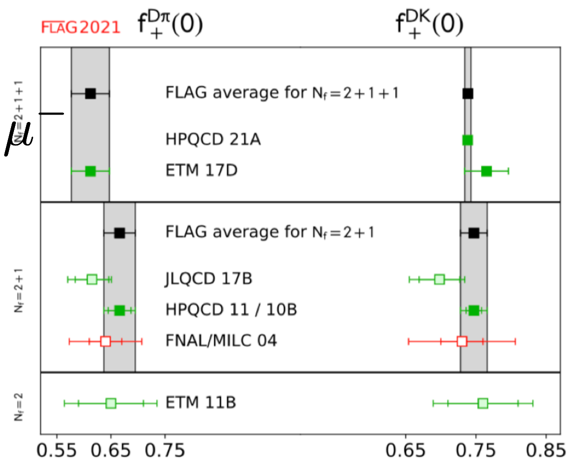
LD dynamics: Resonance contributions

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

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



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

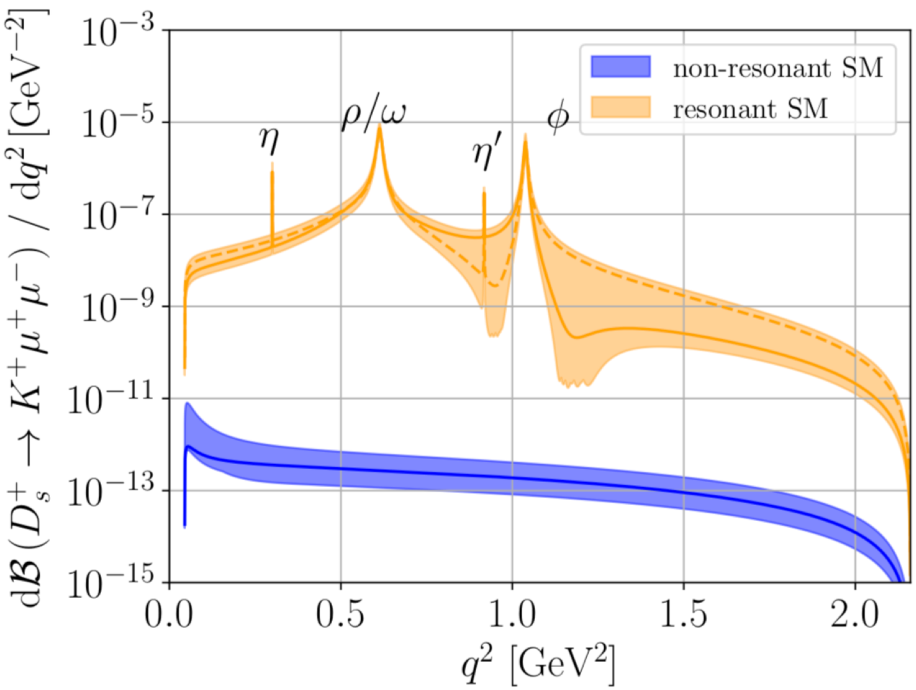


Gisbert et al.,2011.09478
de Boer, Hiller, 1510.00311,
SF and Kosnik, 1510.00965
Bause et al, 1909.11108

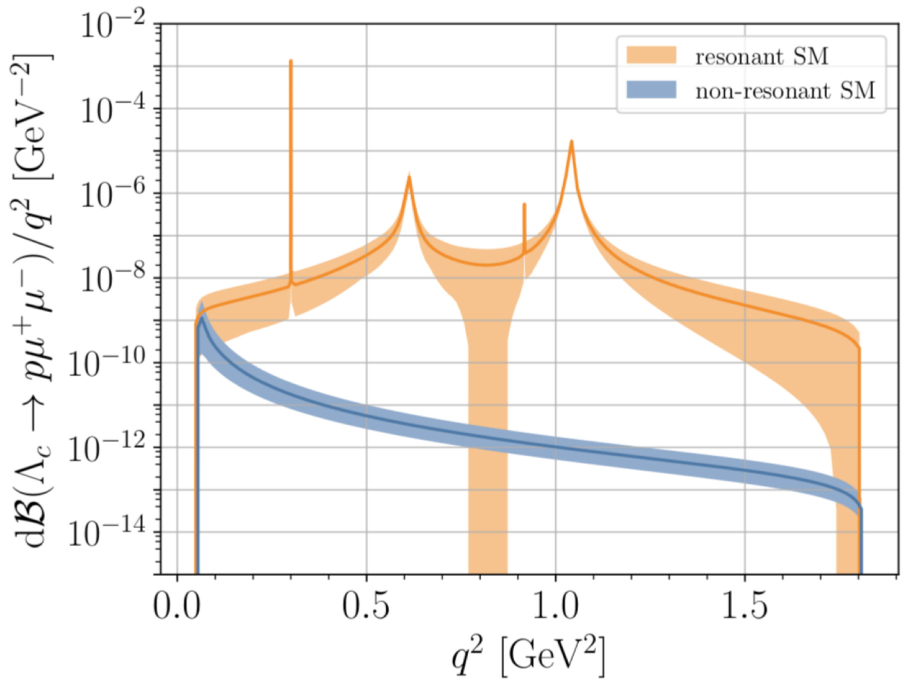
Lattice for form factors
FLAG2021 -2111.09849

$D_s \to K^+\mu^+\mu^-$

$\Lambda_c \to p\mu^+\mu^-$



From Bause et al., 1909.11108



From Golz et al., 2107.13010

Tests of Lepton Flavour Universality

$$R_P^D = \frac{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(D\to P\mu^+\mu^-)}{dq^2} dq^2}{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(D\to Pe^+e^-)}{dq^2} dq^2}$$

	SM	$\lvert C_9\rvert = 0.5$	$\lvert C_{10}\rvert = 0.5$	$\lvert C_9\rvert = \pm\lvert C_{10}\rvert = 0.5$	$\lvert C_{S(P)}\rvert = 0.1$	$\lvert C_T\rvert = 0.5$	$\lvert C_{T5}\rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	SM-like	SM-like	SM-like	SM-like
low q^2	$0.95 \pm \mathcal{O}(\%)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$0.9 \ldots 1.4$	$\mathcal{O}(10)$	$1.0 \ldots 5.9$
high q^2	$1.00 \pm \mathcal{O}(\%)$	$0.2 \ldots 11$	$3 \ldots 7$	$2 \ldots 17$	$1 \ldots 2$	$1 \ldots 5$	$2 \ldots 4$

R^D_π in the SM and in NP scenarios for different q^2–bins

SF and Košnik, 1510.00965
Bause et al, 1909.11108

	SM	$\lvert C_9\rvert = 0.5$	$\lvert C_{10}\rvert = 0.5$	$\lvert C_9\rvert = \pm\lvert C_{10}\rvert = 0.5$	$\lvert C_{S(P)}\rvert = 0.1$	$\lvert C_T\rvert = 0.5$	$\lvert C_{T5}\rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	SM-like	SM-like	SM-like	SM-like
low q^2	$0.94 \pm \mathcal{O}(\%)$	$0.1 \ldots 3.0$	$1.3 \ldots 1.5$	$0.5 \ldots 3.6$	SM-like	$0.7 \ldots 1.2$	SM-like
high q^2	$1.00 \pm \mathcal{O}(\%)$	$0.2 \ldots 16$	$3 \ldots 11$	$2 \ldots 26$	$1.5 \ldots 3.7$	$1 \ldots 6$	$1.6 \ldots 4.1$

R^{Ds}_{K*} in the SM and in NP scenarios for different q^2–bins

Angular observables

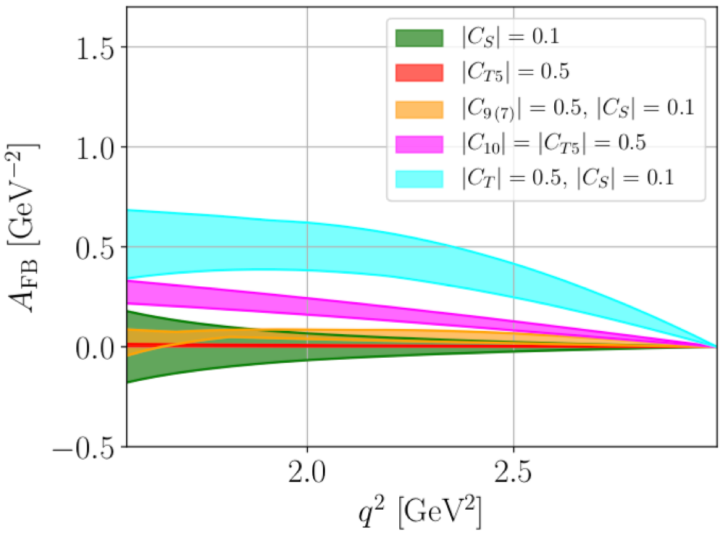
$$\frac{\mathrm{d}\Gamma(D\to\pi\ell\ell)}{\mathrm{d}q^2\,\mathrm{d}\cos\theta} = N\,\lambda^{1/2}\beta_\ell\left[a_\ell(q^2)+b_\ell(q^2)\cos\theta+c_\ell(q^2)\cos^2\theta\right]\,,\qquad N=\frac{G_F^2|\lambda_b|^2\alpha^2}{(4\pi)^5 m_D^3}$$

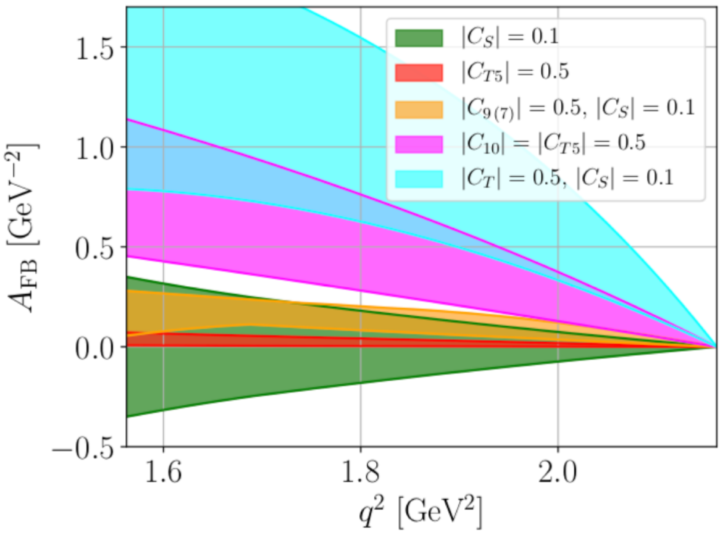
Combinations of Wilson coefficents and Form-factors

$$\frac{\mathrm{dBR}}{\mathrm{d}q^2}(D\to\pi\ell\ell) = \tau_D\,2N\lambda^{1/2}\beta_\ell\left[a_\ell(q^2)+\frac{1}{3}c_\ell(q^2)\right]\,,$$

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

SF and Košnik, 1510.00965
Bause et al, 1909.11108





SM &NP 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

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

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

Gisbert et al. 2011.09478

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

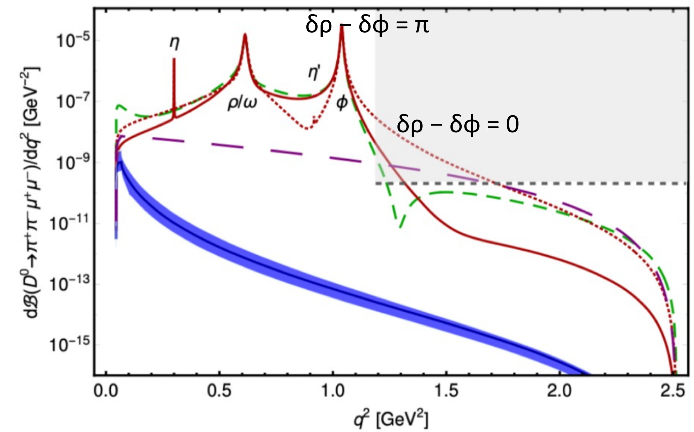
LHCb, 1707.08377

De Beor and Hiller, 1805.08516

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

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

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



uncertainty due to strong phases

- 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 $C_{10}^{(\prime)}$

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

LHCb , 1806.10793
consistent with SM

Tests of LFU

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

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

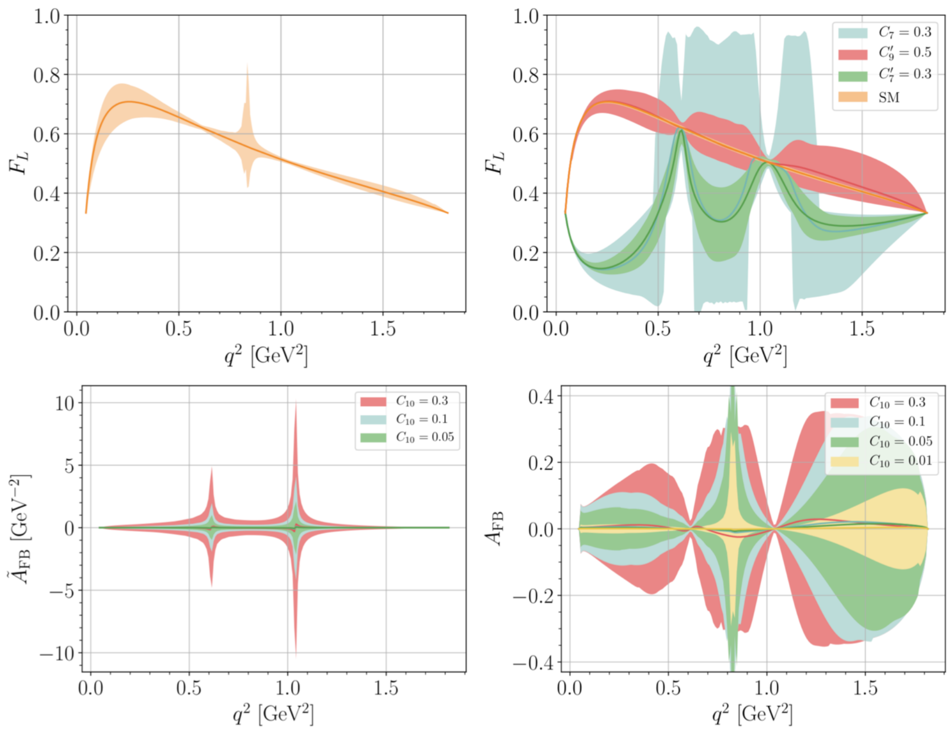
$$R^{D\,\mathrm{SM}}_{KK} = 1.00 \pm \mathcal{O}(\%)$$

Other tests of NP

Golz et al., 2107.13010
Golz 2109.07155

Angular observables in $\Lambda_c \to p\mu\mu$

The upper row shows the fraction of longitudinally polarized dimuons F_L in the SM (left) and in various NP scenarios (right)



See Golz's talk at CKM 2021

The lower row shows the forward- backward asymmetry $\tilde{A}_{FB}$ (left) and A_{FB} (right) in NP scenarios with decreasing C_{10} Wilson coefficient

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

$\lvert\tilde{C}_i\rvert_{max}$	$BR(D \to \pi\mu\mu)$	$BR(D \to \mu\mu)$
$\lvert\tilde{C}_7\rvert_{max}$	1.4	-
$\lvert\tilde{C}_9\rvert_{max}$	1.2	-
$\lvert\tilde{C}_{10}\rvert_{max}$	0.83	0.51
$\lvert\tilde{C}_S\rvert_{max}$	0.34	0.038
$\lvert\tilde{C}_P\rvert_{max}$	0.33	0.038
$\lvert\tilde{C}_T\rvert_{max}$	0.76	-
$\lvert\tilde{C}_{T5}\rvert_{max}$	0.69	-
$\lvert\tilde{C}_9\rvert_{max} = \pm\tilde{C}_{10}\rvert_{max}$	0.73	0.51

Best bounds from
$D^0 \to \mu^+\mu^-$

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

Model of NP	Effect on W.C.	Size of the effect
Scalar leptoquark (3,2,7/6)	$C_S, C_P, C_S', C_P', C_T, C_{T5}, C_9, C_{!0}, C_9', C_{10}'$	$V_{cb}V_{ub}\|C_{9,}\ C_{10}\| < 0.31$
Vector leptoquark (3,1,5/3)	$C_9' = C_{10}'$	$V_{cb}V_{ub}\|C_9'_{,}\ C_{10}'\| < 0.22$
Two Higgs doublet Model type III	C_S, C_P, C_S', C_P'	$V_{cb}V_{ub}\|C_S - C_S'\| < 0.0045$ $V_{cb}V_{ub}\|C_P - C_P'\| < 0.0045$
Z' model	C_9', C_{10}'	$V_{cb}V_{ub}\|C_9'_{,}\| < 0.001$ $V_{cb}V_{ub}\|C_{10}'\| < 0.012$

Lepton flavor violation

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

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

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

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

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

LHCb bound, 1512.00322

$\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.3\ (1.6) \times 10^{-8}$ @90 (95)% CL

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

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

$$l = e, \mu$$

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

Charm meson decays to invisible fermions

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

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

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

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

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

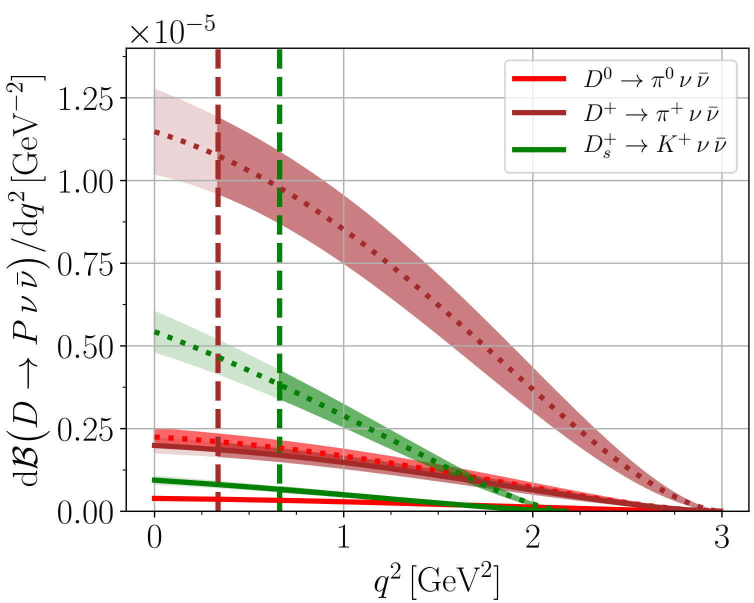
$$x_U^{\pm} = \sum_{i,j}\left|\mathcal{C}_L^{Uij} \pm \mathcal{C}_R^{Uij}\right|^2$$

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)

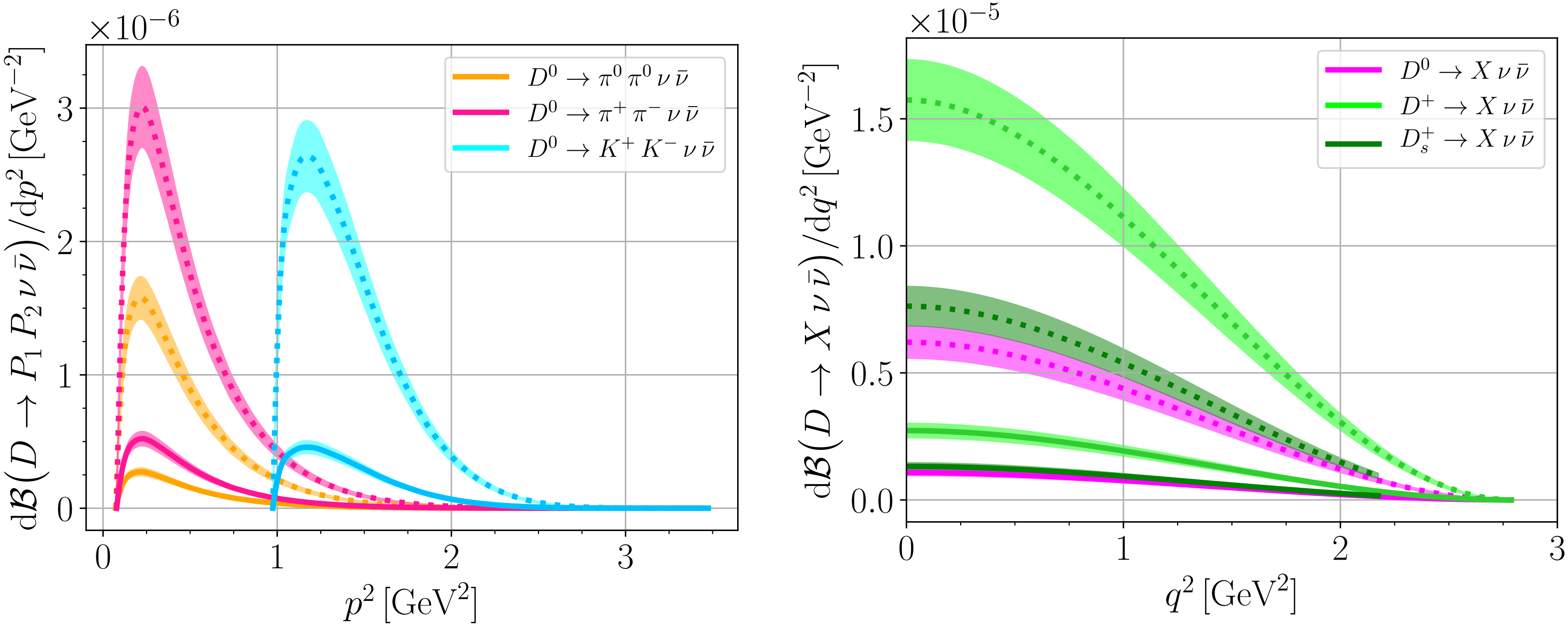
$x_U \lesssim 716\,,$ (general) matrix 3x3



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

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

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

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

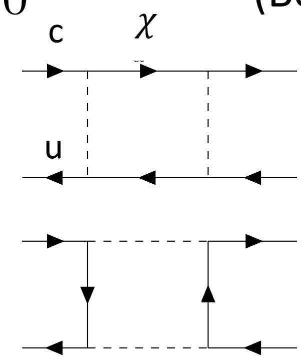
Constraints from charm mixing

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

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

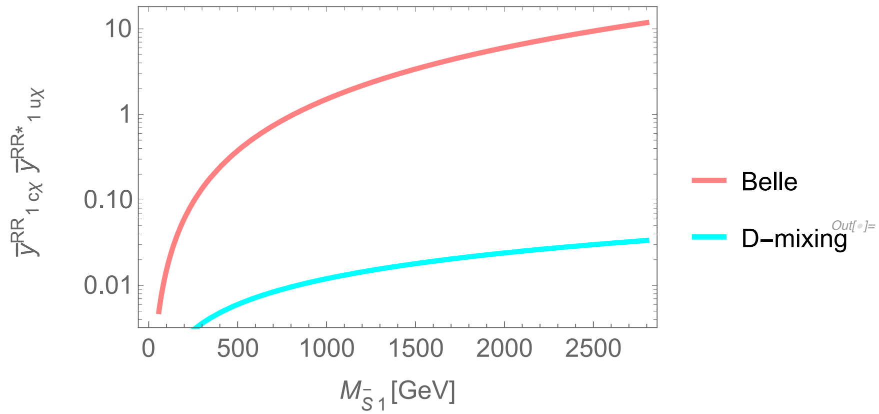
(Belle, 1611.09455)

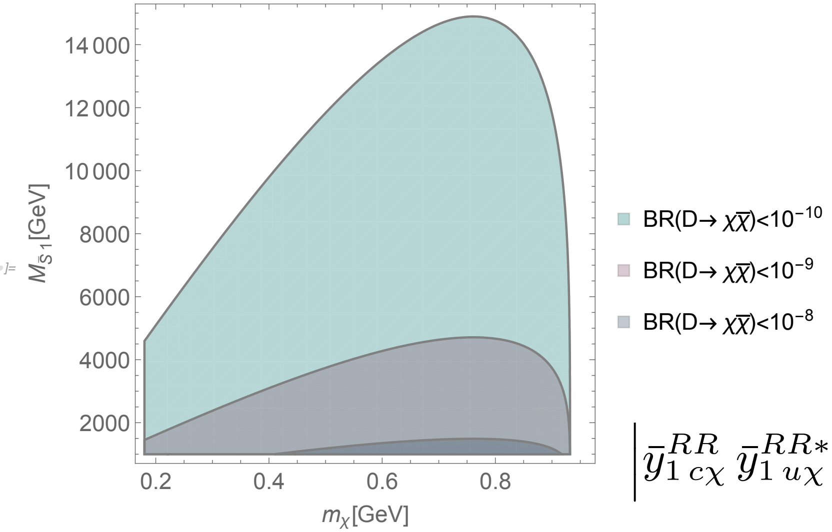
m_χ (GeV)	$\mathcal{B}(D^0 \to \chi\bar{\chi})_{D-\bar{D}}$
0.18	$< 1.1\times 10^{-9}$
0.50	$< 7.4\times 10^{-9}$
0.80	$< 1.1\times 10^{-8}$



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

Main message: charm mixing leads to stron constraints

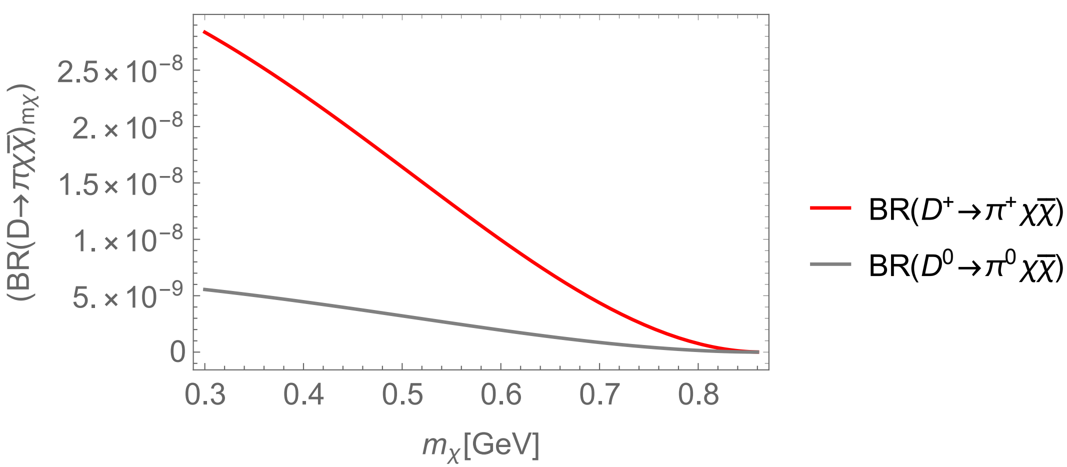




$$\left|\bar{y}^{RR}_{1\,c\chi}\,\bar{y}^{RR*}_{1\,u\chi}\right| = 1$$

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!

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!

Thanks!

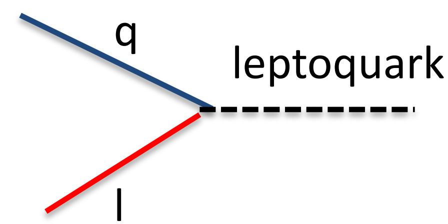
HVALA

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? Summary.

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!

$(SU(3)_c, SU(2)_L, U(1)_Y)$

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

CHARM quark electric (chromo-electric) dipole moment

$$\mathcal{L}_{\rm eff} = d_q \frac{1}{2}(\bar{q}\sigma_{\mu\nu} i\gamma_5 q)F^{\mu\nu} + \tilde{d}_q \frac{1}{2}(\bar{q}\sigma_{\mu\nu} T^a i\gamma_5 q) g_s G_a^{\mu\nu} + w \frac{1}{6} f^{abc}\epsilon^{\mu\nu\lambda\rho} G^a_{\mu\sigma} G^{b\sigma}_{\nu} G^c_{\lambda\rho}$$

quark EDM | quark CEDM | Weingerg operator

Mixing under RGE

$$w = \frac{g_s^3}{32\pi^2}\frac{\tilde{d}_q}{m_q};$$

CEDM threshold correction to w

Sala, 1312.2589, Gisbert & Ruiz-Vidal, 1905.02513
Considered charm quark EDM and CEDM

$\boxed{|\tilde{d}_c| \lesssim 1.0 \times 10^{-22} \text{cm}}$ from neutron EDM

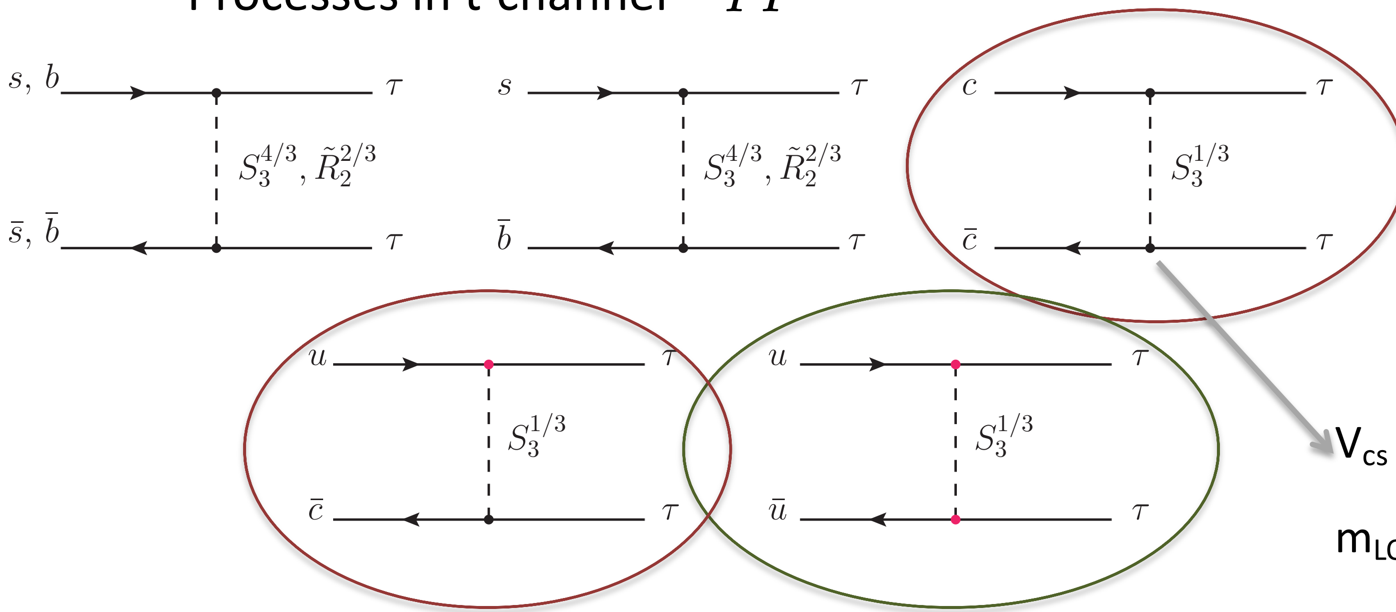
$\boxed{|d_c| \lesssim 4.4 \times 10^{-17} e\,\text{cm}}$ from $B \to X_s\gamma$

In 1809.09114, Dekens et al, NP from B anomalies creates c-quark EDM, which can be related to neutron (lattice computation of c –bar c content of neutron) or Hg EDM!

More studies of charm quark EDM(CEDM) – new source of CP violation!

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