Charm Physics with future tau-charm factories

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Overview

- Motivation;
- Understanding QCD in charmed hadrons;
- CP violation in charm decays;
- SM in rare charm decays;
- From B anomalies to NP in charm;
- Signatures of NP in chargned current and FCNC charm decays;
- Dark Matter search in rare charm decays;
- Summary.

Motivation to study charm physics

Experiments

Study tau and charm physics at $e^+ e^-$ collider at

Super tau- charm factories
Novosibirsk (2-5 GeV)

HIEPA –super tau charm facility
University of Science and Technology of China
(2-7 GeV)

and at B machines one always gets D

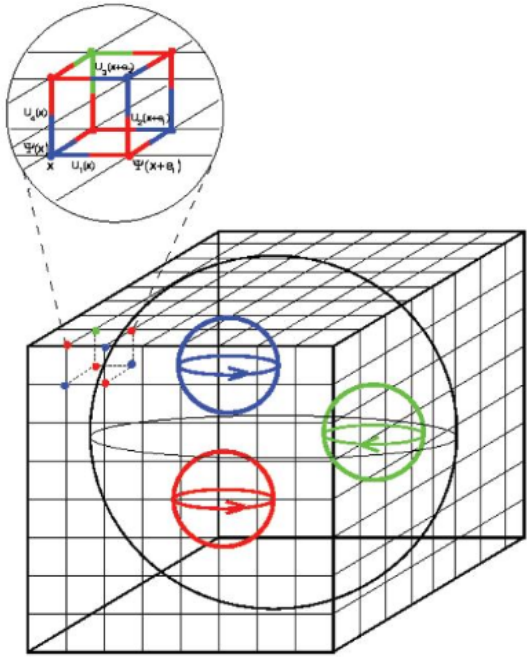
LHCb, (ATLAS, CMS)
Belle2

Theory goals

Deepening our knowledge of SM → QCD

Charm spectroscopy- tetraquark states decay constants, form-factors, mixing parameters…

QCD (lattice) in action!



Search for New Physics

B meson puzzles → Solution by New Physics

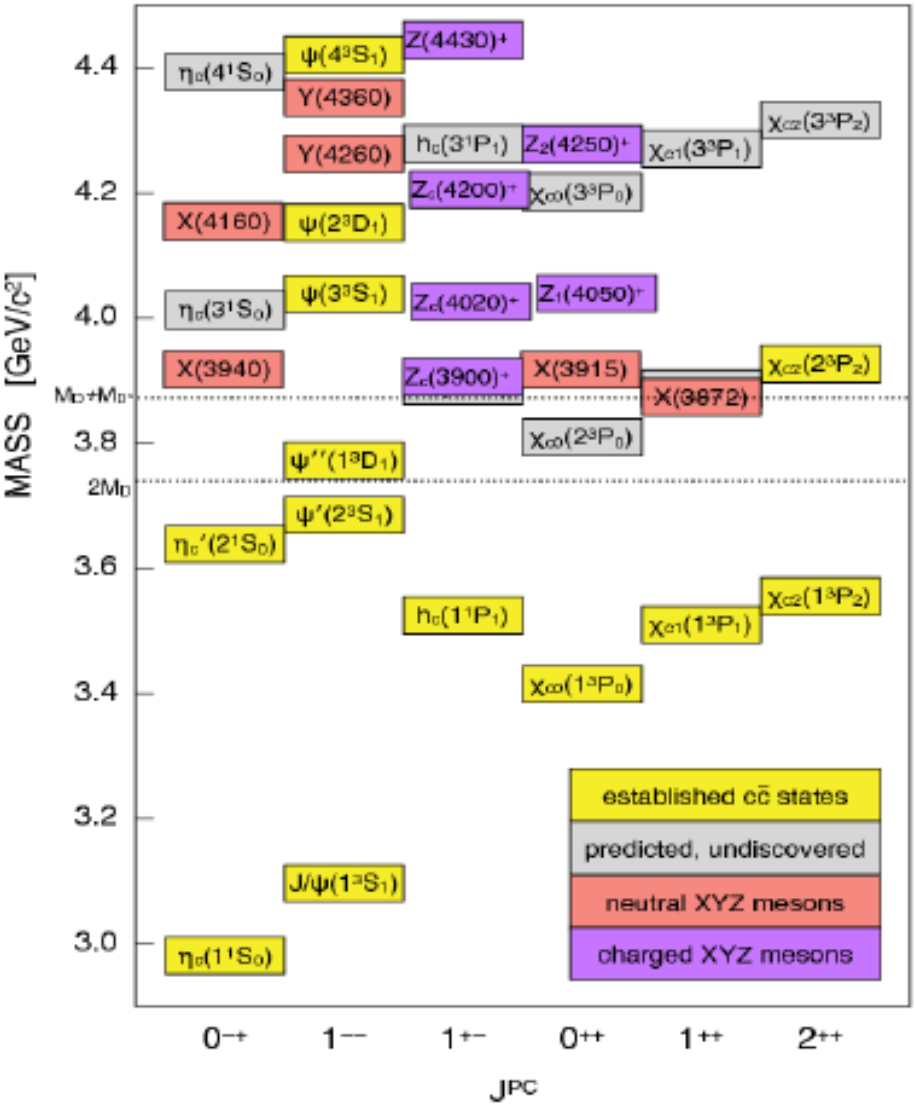
B meson puzzles → Tests of Lepton flavour universality

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

How about charm?

- CP violation in the up sector;
- 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.
- Can one see NP in charm decays not being present in B meson ?

QCD in action:
Charmonium and Exotic Spectroscopy with Charm Quarks in Lattice QCD



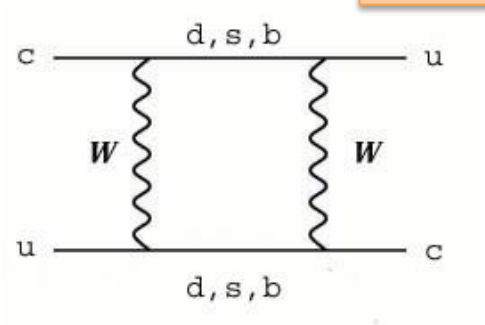
- Plethora of unexpected charmonium-like (X , Y , Z) states discovered experimentally

- Masses and widths of some D_s states significantly lower than those expected from quark model.

- Tetraquarks? Molecules? Cusps? Hybrids?

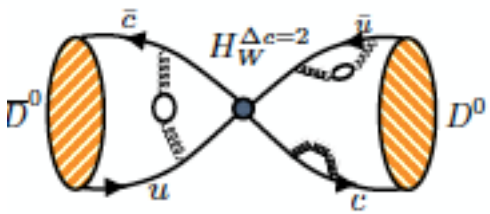
- First principles calculations using lattice QCD to understand these states.

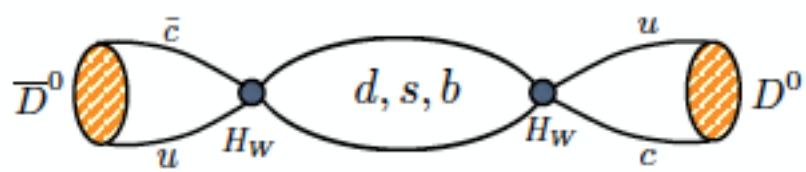
Mixing and indirect CP violation



- intermediate down-type quarks;
- due to CKM contribution of b – quark negligible;
- in the SU(3) limit 0;

$$M_{12} - \frac{i}{2}\Gamma_{12} \propto \langle D^0 | H_W^{\Delta c=2} | \overline{D}^0 \rangle + \sum_n \frac{\langle D^0 | H_W^{\Delta c=1} | n \rangle \langle n | H_W^{\Delta c=1} | \overline{D}^0 \rangle}{M_D - E_n + i\epsilon}$$





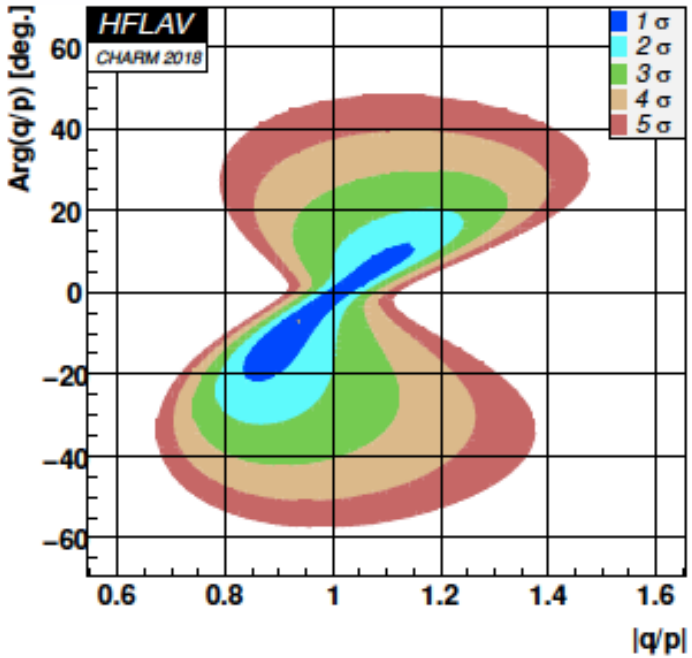
Short distance
Lattice QCD helps !

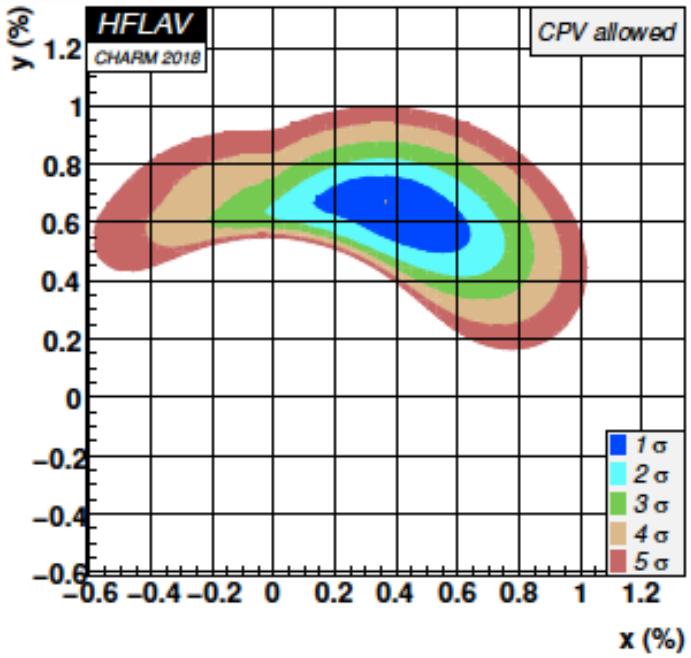
Long distance
difficult to determine

Lattice determined

$$\langle \mathcal{O}_i \rangle \equiv \langle D^0 | \mathcal{O}_i | \overline{D}^0 \rangle (\mu) = e_i M_D^2 \, f_D^2 B_D^{(i)}(\mu)$$

Possible NP effect difficult to isolate!



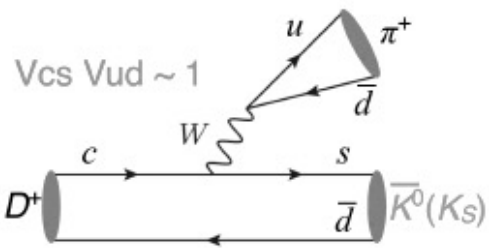


$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

- $|q/p \neq| 1$ would indicate CPV in mixing.
- $\mathrm{Arg}(q/p) \neq 0$ would indicate CPV from interference mixing/decay.
- Mixing parameters $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/(2\Gamma)$.

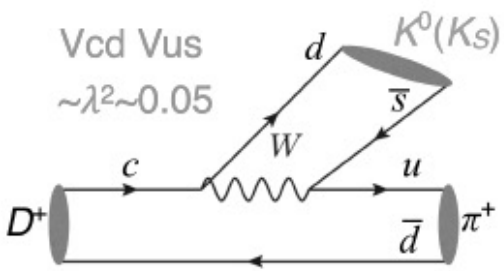
SM features of CPV in D

- CPV in D - $\bar{D}$ mixing suppressed due to $\mathcal{O}(V_{cb}V_{ub}^*/V_{cs}V_{us}^*) \sim 10^{-3}$
- direct CPV suppressed due to $\mathcal{O}([V_{cb}V_{ub}^*/V_{cs}V_{us}^*]\alpha_s/\pi) \sim 10^{-4}$



$$A_{CP}^{D^+\to K_S^0\pi^+} = (-0.363\pm0.094\pm0.067)\%$$

Belle, 1203.6409, mainly attributed to the K mixing



Nierste &Schacht, 1708.03572

$$A_{CP}^{dir}(D\to K_S K^{0*}) \leq 0.3\%$$

1707.09297, Wang, F.S. Yu, and H.N.Li,
the time-dependent and time-integrated CP asymmetries in $D \to f K_S(\to \pi^+\pi^-)$
the interference CF and the DCS amplitudes with the K mixing, Effect of the order 10^{-3}.
Proposal: search for the difference of the time-integrated CP asymmetries in the mode with π and K.
NP might be present!

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
Considered charm quark EDM and CEDM

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

$|d_c| \lesssim 4.4 \times 10^{-17} e\,$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!

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

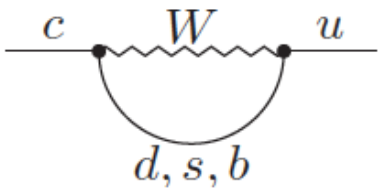
3) SM values at m_c

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

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

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

Rare charm decays much rarer than rare B decays.
For same statistics much less events.



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

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

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

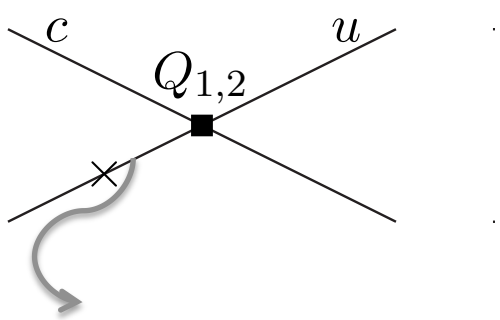
Q_7 contributes to $c \to u\gamma$ and $c \to u l^+ l^-$

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

GIM suppression

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

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

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

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

Belle, 1603.03257

Hiller& de Boer 1701. 06392

LQs give as large

contributions as SM

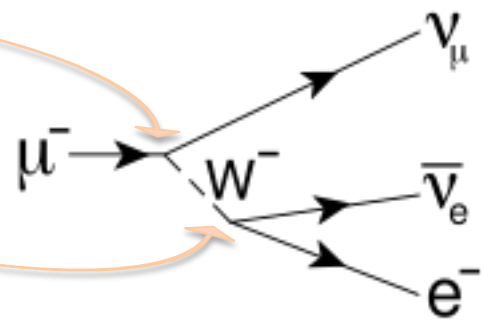
$$A_{CP}(D^0 \to \rho^0\gamma) = 0.056 \pm 0.152 \pm 0.006\,,$$

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

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

From B anomalies to NP in charm
Lepton Flavour Universality (LFU)

the same coupling of lepton
and its neutrino with
W for all three lepton generations!



$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \qquad \Gamma(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = \Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$$

valid for quarks too!

Basic property of the SM: universal g

$$\mathcal{L}_f = \bar{f} i D_\mu \gamma^\mu f \qquad f = l_L^i,\ q_L^i,\ \ i = 1, 2, 3$$

for each of three generations in weak interactions

$$D_\mu = \partial_\mu + ig\frac{1}{2}\vec{\tau}\cdot\vec{W}_\mu + ig'\frac{1}{2}Y_W B_\mu$$

the same for all SM fermions

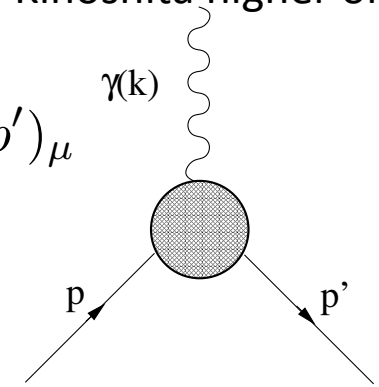
$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

$$\frac{g^2}{8m_W^2} = \frac{G_F}{\sqrt{2}}$$

Muon anomalous magnetic moment

(Schwinger α/π,
Kinoshita higher orders in α)

$$ie\bar{u}_\ell(p')\left[\gamma^\mu - \frac{a_\ell}{2m_\ell} i\sigma^{\mu\nu} q_\nu\right] u_\ell(p)\epsilon^*_\mu, \qquad q_\mu = (p-p')_\mu$$



Dirac equation predicts g=2 $\quad a = (g-2)/2$

$$a_\mu^{th} - a_\mu^{exp} = -(3.06 \pm 0.76) \times 10^{-8}$$

4 σ

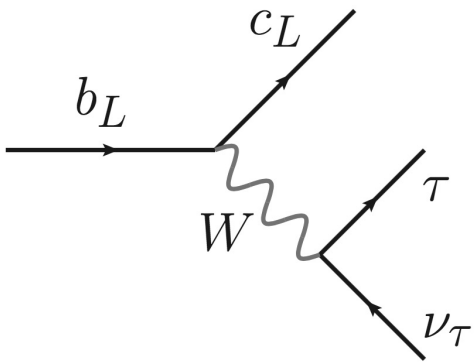
Theory: uncertainty in hadronic contributions to the muon g − 2, (Jägerlehner, 1809.07413).
Lattice QCD great progress vacuum polarization and light-by-light study (RBC & UKQCD, 1801.07224, Wittig 1807.09370).

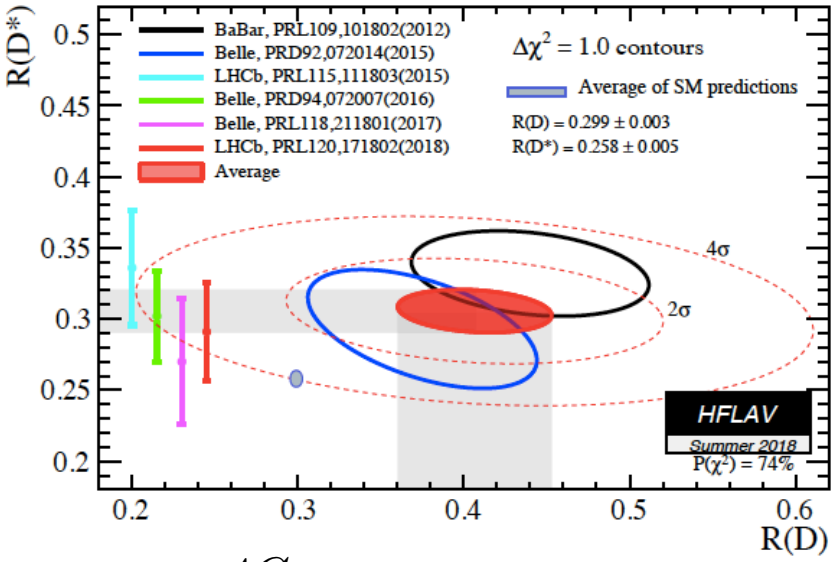
Fermilab and J-Park experiments are expected to clarify existing discrepancy!

B physics anomalies: experimental results ≠ SM predictions!

charged current (SM tree level)

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$ 3.8σ



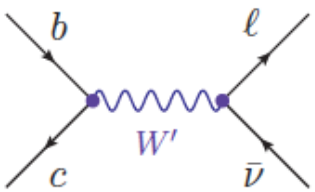


Freytsis, et al., 1506.08896, S.F. et al., 1206.1872;
Di Luzio & Nardecchia, 1706.01868,
Bernlochner et al., 1703.05330,
F. Feruglio et al., 1806.10155, 1606.00524.

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb}[(1+g_{V_L})(\bar{c}_L\gamma_\mu b_L)(\bar{l}_L\gamma^\mu\nu_L) + g_{V_R}(\bar{c}_R\gamma_\mu b_R)(\bar{l}_L\gamma^\mu\nu_L)$$
$$+g_{S_R}(\bar{c}_L b_R)(\bar{l}_R\nu_L) + g_{T_R}(\bar{c}_L\sigma_{\mu\nu}b_R)(\bar{l}_R\sigma^{\mu\nu}\nu_L)]$$

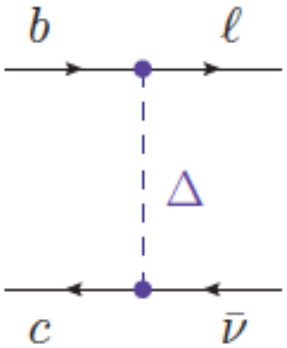
Assuming NP at scale Λ_{NP} (Di Luzio, Nardecchia, 1706.0!868)

$$\frac{4G_F}{\sqrt{2}} V_{cb}\, g_V \to \frac{2}{\Lambda_{NP}^2}$$



What is the scale of New Physics?

$$\Lambda_{NP} \simeq 3\,\mathrm{TeV}$$



Perturbativity of NP

$$\mathcal{L}_{NP} \supset \frac{C_D}{\Lambda_{NP}^2} (\bar{c}_L \Gamma_\mu b_L)(\tau_L \gamma^\mu \nu_L)$$

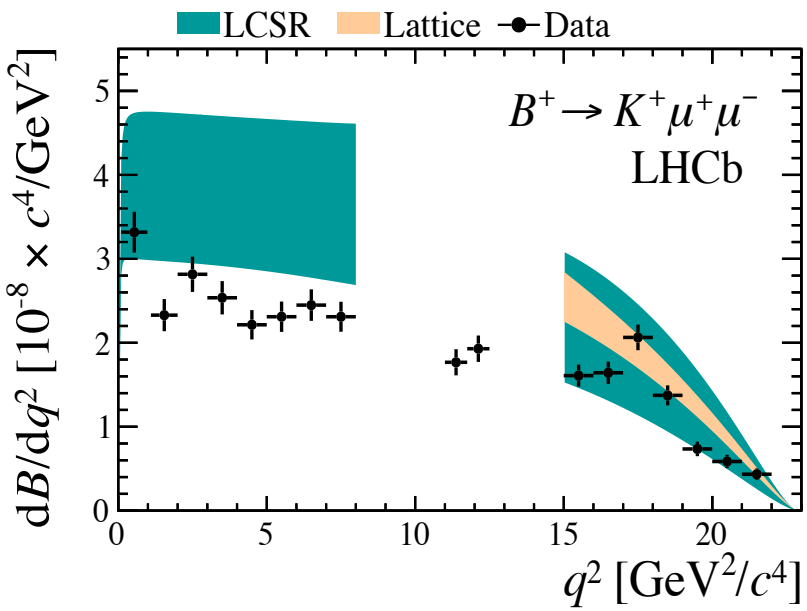
V-A form of NP

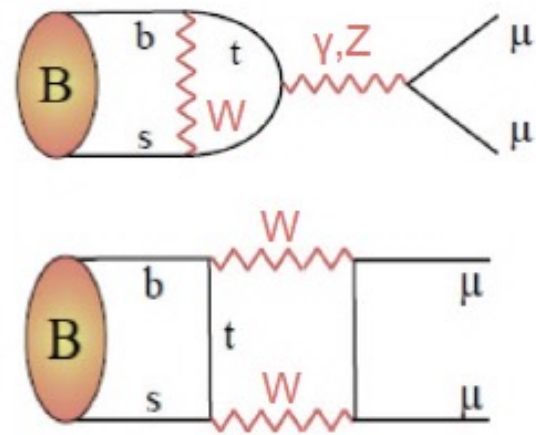
(current)(current) operators
are invariant under QCD running

$\Lambda_{NP} > 3\,\mathrm{TeV}$ C_D becomes non-perturbative!

Hiller et al., 1609.08895 $R_{D(*)}$

FCNC - SM loop process





$$R_K = \frac{\mathcal{B}(B \to K\mu\mu)_{q^2\in[1,6]\mathrm{GeV}^2}}{\mathcal{B}(B \to Kee)_{q^2\in[1,6]\mathrm{GeV}^2}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$

2.4σ

$$R_{K^*}^{\mathrm{low}} = \frac{\mathcal{B}(B \to K\mu\mu)_{q^2\in[0.045,1.1]\mathrm{GeV}^2}}{\mathcal{B}(B \to Kee)_{q^2\in[0.045,1.1]\mathrm{GeV}^2}} = 0.660 \pm^{0.110}_{0.070} \pm 0.024$$

2.2 σ - 2.4σ

$$R_{K^*}^{\mathrm{central}} = \frac{\mathcal{B}(B \to K\mu\mu)_{q^2\in[1.1,6]\mathrm{GeV}^2}}{\mathcal{B}(B \to Kee)_{q^2\in[1.1,6]\mathrm{GeV}^2}} = 0.685 \pm^{0.113}_{0.069} \pm 0.047\,,$$

NP in R_K and R_{K^*}

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,\ldots,10} \left(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu)\right) \right]$$

$$\mu_b = 4.8\,\mathrm{GeV} \qquad C_7^{SM} = 0.29;\ C_9^{SM} = 4.1;\ C_{10}^{SM} = -4.3;$$

Buras et al.,hep-ph/9311345; Altmannshofer et al., 0811.1214; Bobeth et al., hep-ph/9910220

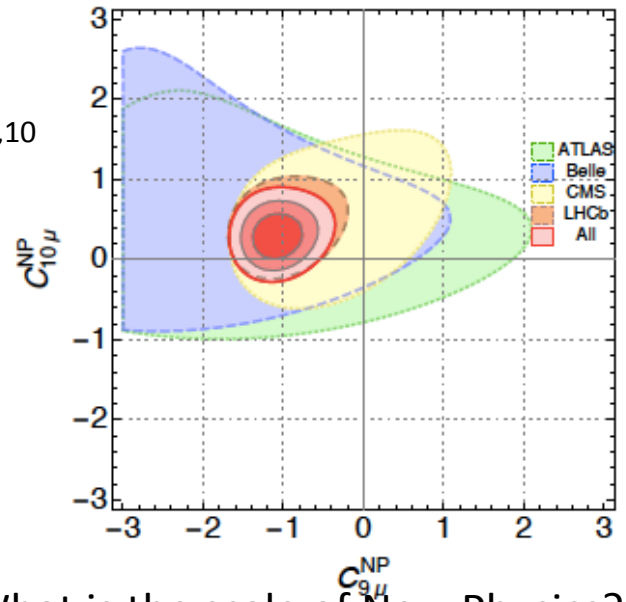
Global analysis suggests NP in $C_{9,10}$

$$C_i = C_i^{SM} + C_i^{NP}$$

$$C_9^{NP} = -C_{10}^{NP} = -0.64$$

best fit point

$$[-0.85, -0.5]$$



Capdevila et al.,1704.05340, Altmannshofer et al., 1704.05435, D'Amico et al., 1704.05438.

What is the scale of New Physics?

$$\mathcal{L}_{NP} = \frac{1}{\Lambda_{NP}^2} \bar{s}_L \gamma^\alpha b_L \bar{\mu}_L \gamma_\alpha \mu_L$$

$$\Lambda_{NP} \simeq 30\,\mathrm{TeV}$$

NP explaining both B anomalies

$$R^{exp}_{D^{(*)}} > R^{SM}_{D^{(*)}}$$

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

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

$$R^{exp}_{K^{(*)}} < R^{SM}_{K^{(*)}}$$

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

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

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

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 2018

$$f_{D^+} = 211.9(1.1) \text{ MeV}$$

$$f_{D_s} = 249.0(1.2) \text{ MeV}$$

$$\frac{f_{D_s}}{f_{D^+}} = 1.173(3)\,.$$

$$|V_{cs}| = 0.997 \pm 0.017$$

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 quark via CKM!

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

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

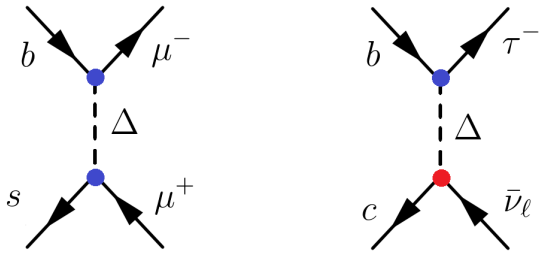
Models of NP explaining B anomalies

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!

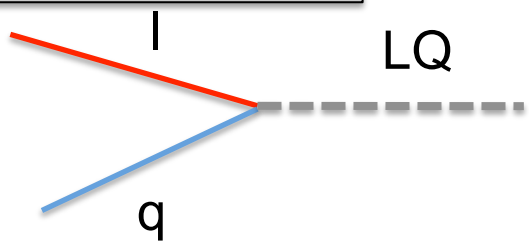
- Is charm physics sensitive on NP explaining B puzzles ?
- Can some NP be present in charm and not in beauty mesons?

Popular scenario: Leptoquarks as a resolution of B anomalies:

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

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

$Q=I_3+Y$



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)

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

$$\frac{R^c_{\tau,\mu,LQ}}{R^c_{\tau,\mu,SM}} = [1 - \frac{v^2}{2M^2_{S3}}\mathrm{Re}((Vy*)_{c\tau}y_{s\tau} - (Vy*)_{c\mu}y_{s\mu})]$$

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

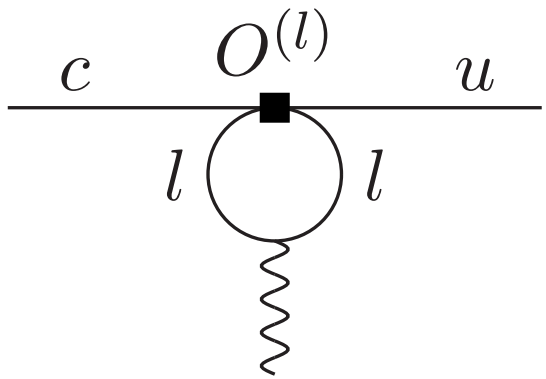
m_{S3} [TeV]	$1 - R^c_{\tau,\mu,LQ}/R^c_{\tau,\mu,SM}$
1.0	3.2%
1.2	2.4%
1.5	1.5%

Doršner, SF, Greljo, Kamenik Košnik, 1603.04993;

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} ~ O(10%). The largest effects arise from τ-loops.

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

NP in $c \to u l^+ l^-$

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

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

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

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

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

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

SF, N. Kosnik, 1510.00965

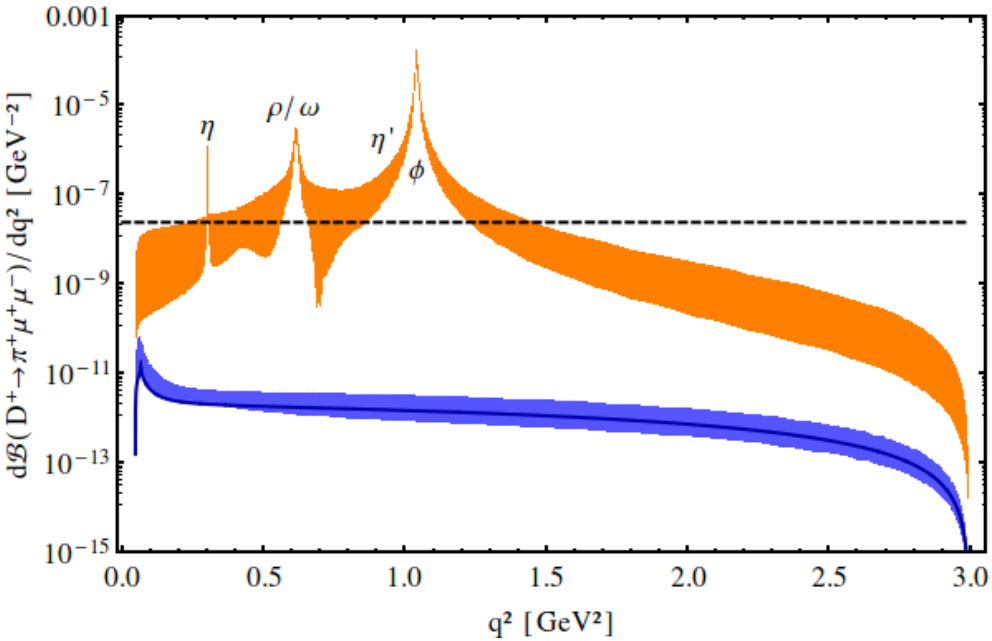
LHCb bound, 1305.5059

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

Helicity suppressed decay!

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

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

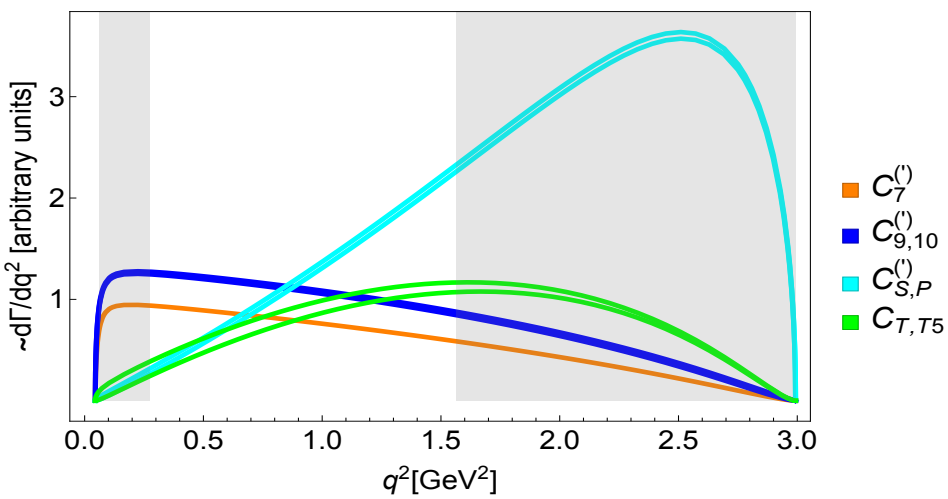


SM prediction: Long distance contributions most important!

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

peaks at ρ,ω,φ and η resonances

de Boer, Hiller, 1510.00311,
SF and Kosnik, 1510.00965



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

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

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

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.

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

Modes sensitive to NP

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

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

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

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

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

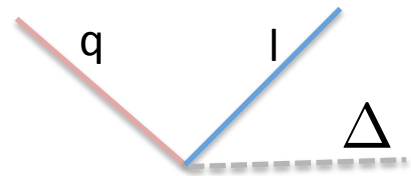
Tests of LFU

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

LHCb , 1806.10793

consistent with SM

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)

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

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

not present in B physics at tree level!

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

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}'	$V_{cb}V_{ub}\lvert C_9',\rvert < 0.001$ $V_{cb}V_{ub}\lvert C_{10}'\rvert < 0.014$

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

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

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

$$l = e, \mu$$

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

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}

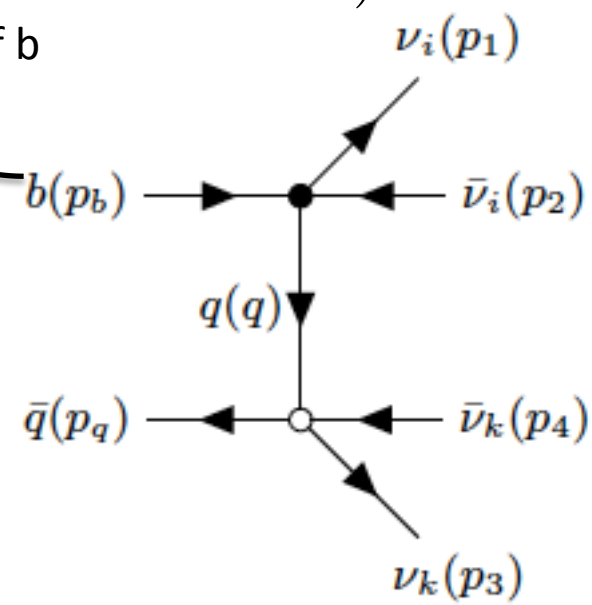
Badin & Petrov 1005.1277 suggested to search for processes with missing energy $\not{E}$ in

$$D^0 \to \gamma \not{E}$$ 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 $\Gamma(D^0 \to$ 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

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

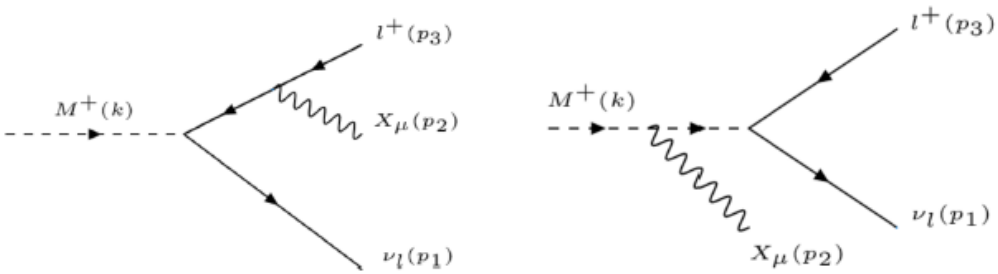
$$v^2 \equiv (v_0^2 + v_X^2), \qquad \bar{v}^2 \equiv (v_s^2 + v_X^2), \qquad c_\beta^2 = \frac{v_X^2}{v^2}$$

- invisble fermions necessary for anomaly cancellation

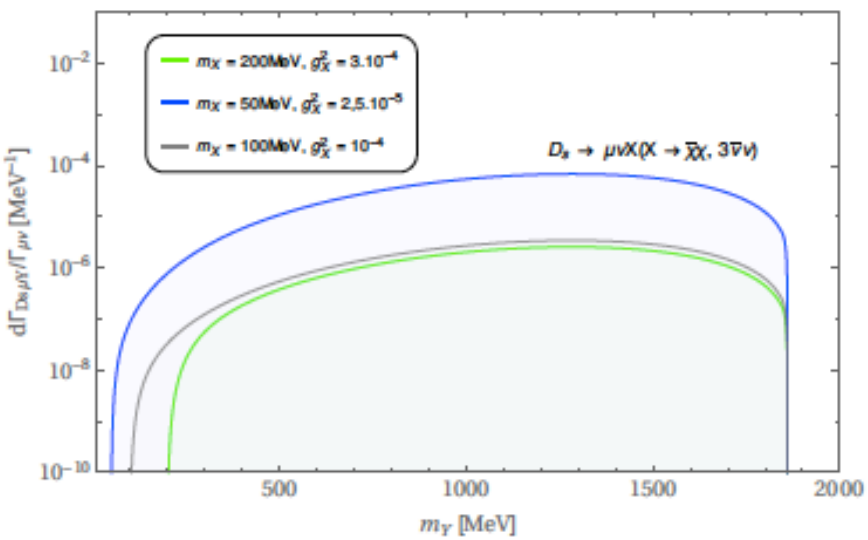
$$\mathcal{L} \longrightarrow -Y_s\, \overline{\chi_L} \chi_R s - Y_s^*\, \overline{\chi_R} \chi_L s^* \,.$$

A_μ and X_μ mix via κ

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



Radiative - not γ but X

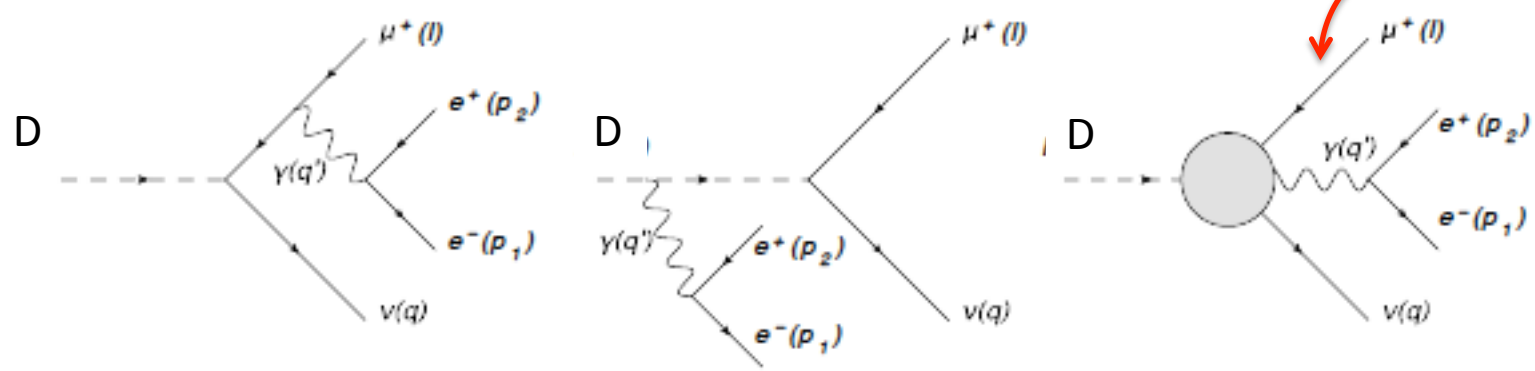


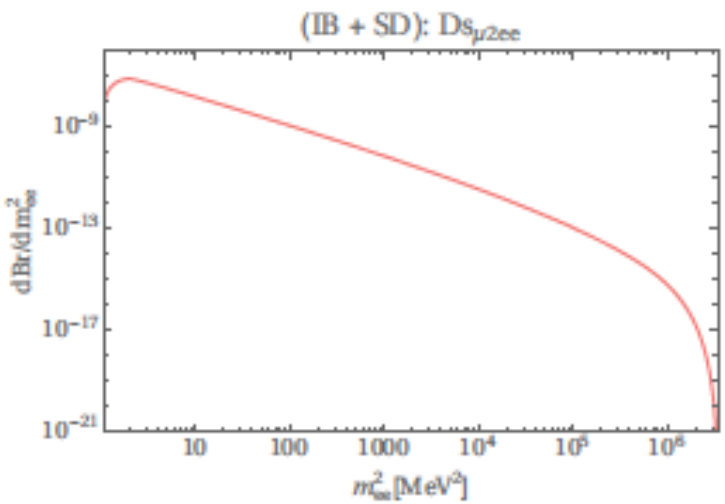
Is it possible to search for decay
D → μ X
X is SM ν_μ + DM gauge boson → invisible fermions
Exp: $D \to \tau\bar{\nu}_\tau \to \mu\bar{\nu}_\mu\nu_\tau\bar{\nu}_\tau$

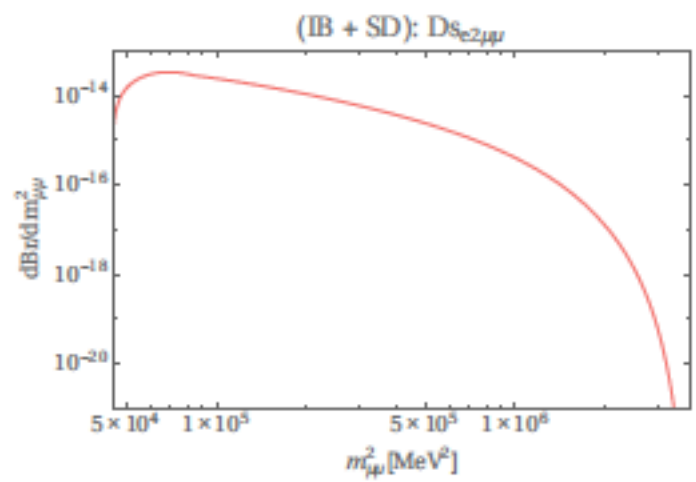
Difficult to differentiate

- 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>







Summary and outlook

- QCD (lattice) a lot of open issues in Charm spectroscopy!
  Improvement on decay constants and form-factors!

- CP-violation in up sector (NP search) more studies on direct CP violation and (C)EDM of c-quark ;

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

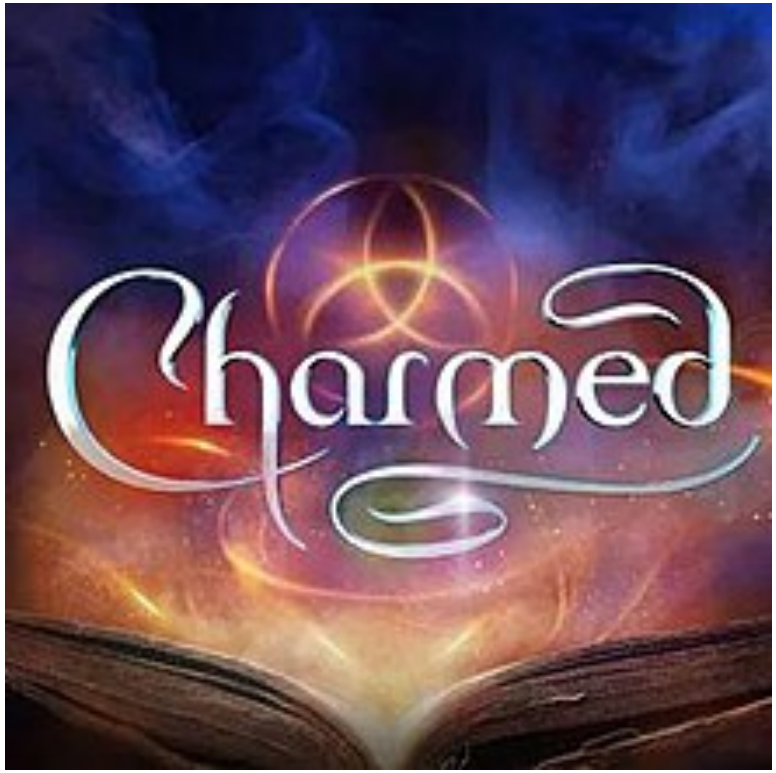
- FCNC transition small contribution of Leptoquarks in charm decays observables;

- To perform all possible test of LFU;

- Few proposals to test DM in charm physics;

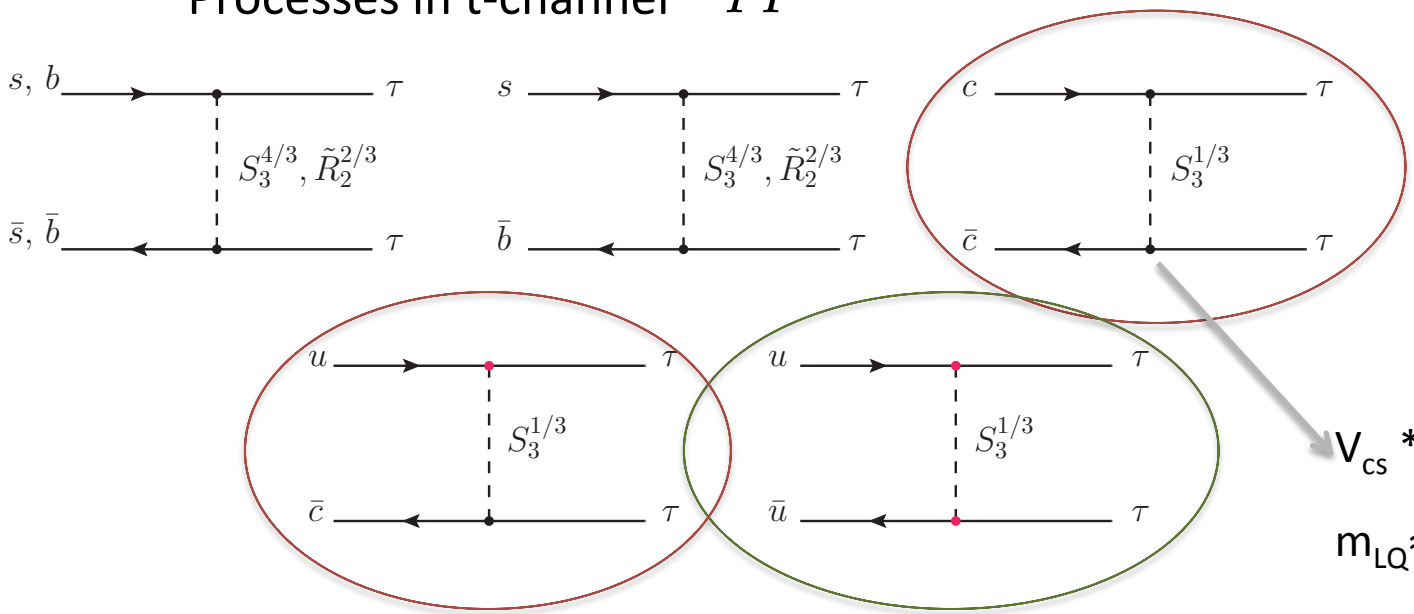
- Charm physics complement any search for NP at low energies!

Thanks!



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

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

y_{CP} definition

$$y_{CP} = \frac{\hat{\Gamma}(D^0 \to h^+h^-) + \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}{2\Gamma} - 1$$

$f = K^+K^-,\ \pi^+\pi^-$ (CP-even)

$$= \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x\sin\phi\right] \approx y + y\left[\frac{1}{2}\left(\left|\frac{q}{p}\right| - 1\right)^2 - \frac{\phi^2}{2}\right] - x\phi\left(\left|\frac{q}{p}\right| - 1\right)$$

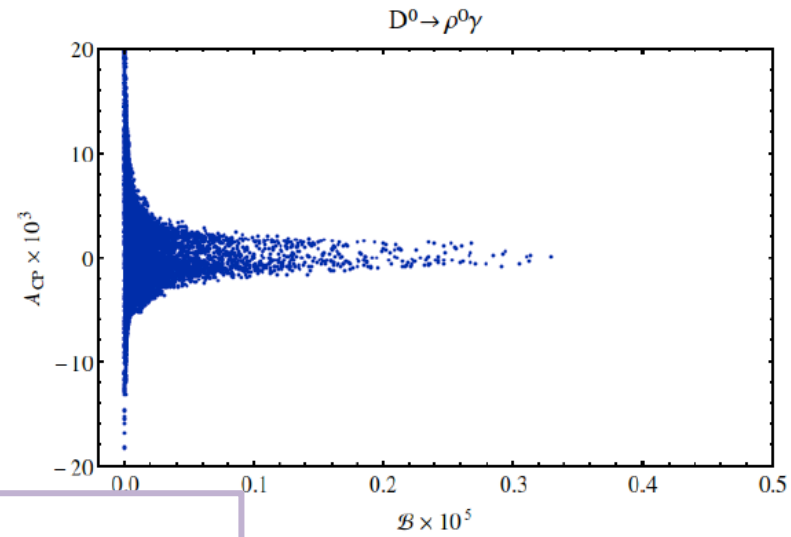
equal to y in the limit of no CPV;

$y_{CP} = (0.57 \pm 0.13 \pm 0.09)\%$ Pajero (LHCb) at CKM 2108

Compatible with world average $(0.835 \pm 0.155)\%$;

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

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



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

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

$\Lambda_c \to p\gamma$

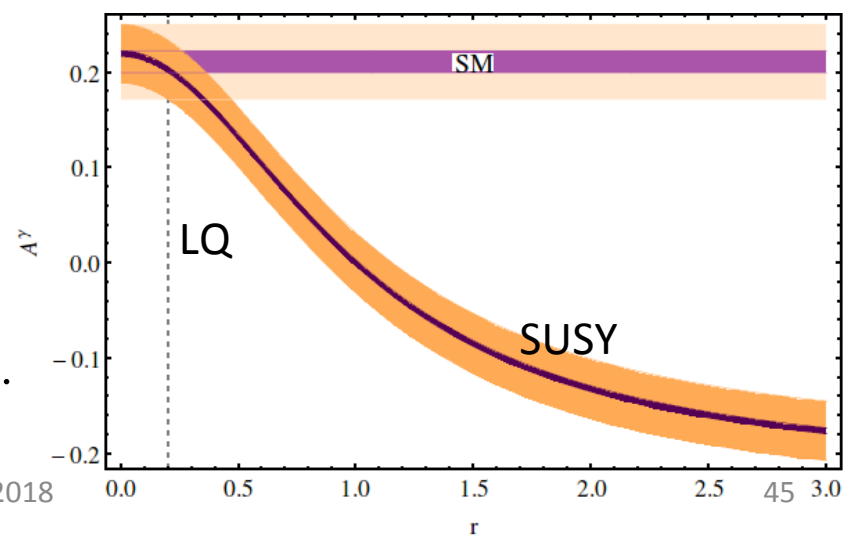
Hiller& de Boer 1701. 06392

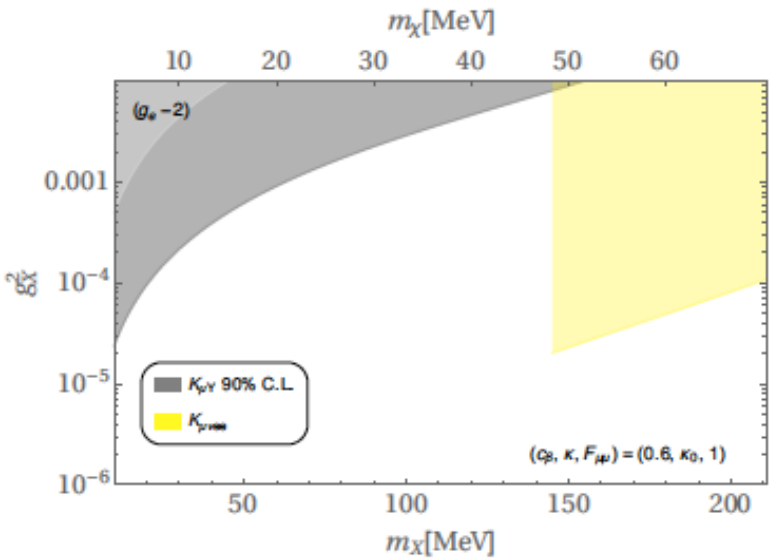
$$\mathcal{B}(\Lambda_c \to p\gamma) \sim \mathcal{O}(10^{-5})$$

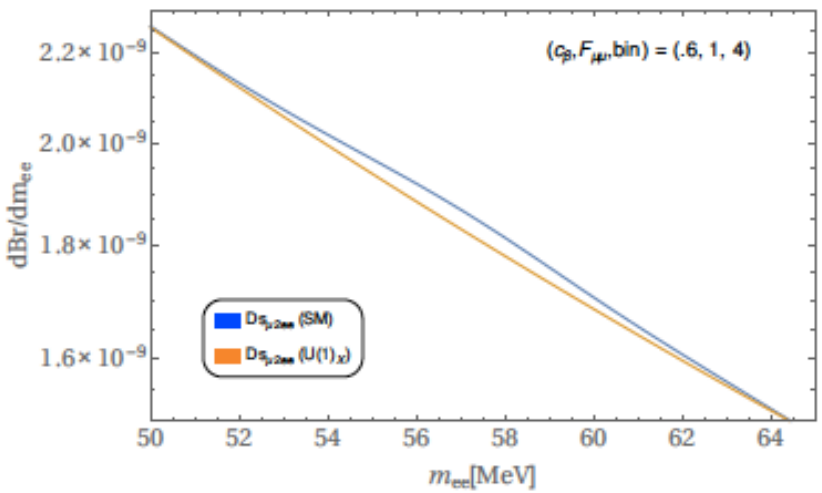
If Λ_c-baryons are produced polarized, such as at the Z, angular asymmetries in $\Lambda_c \to p\gamma$ can probe chirality-flipped contributions

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

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







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

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