Charm Physics

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Overview

Understanding QCD in charmed hadrons;

CP violation in charm;

SM in rare charm decays;

Dark Matter search in rare charm decays;

From B anomalies to NP in charm;

Signatures of NP in chargned current and FCNC charm decays;

Summary and Outlook

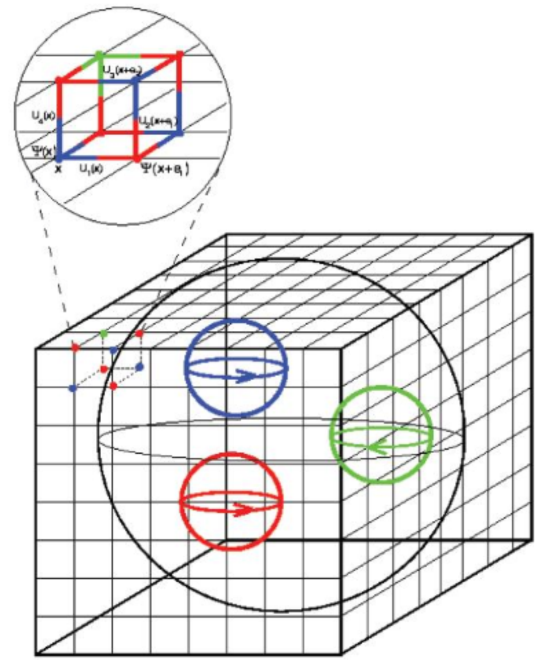
Theory goals

Deepening our knowledge of SM → QCD

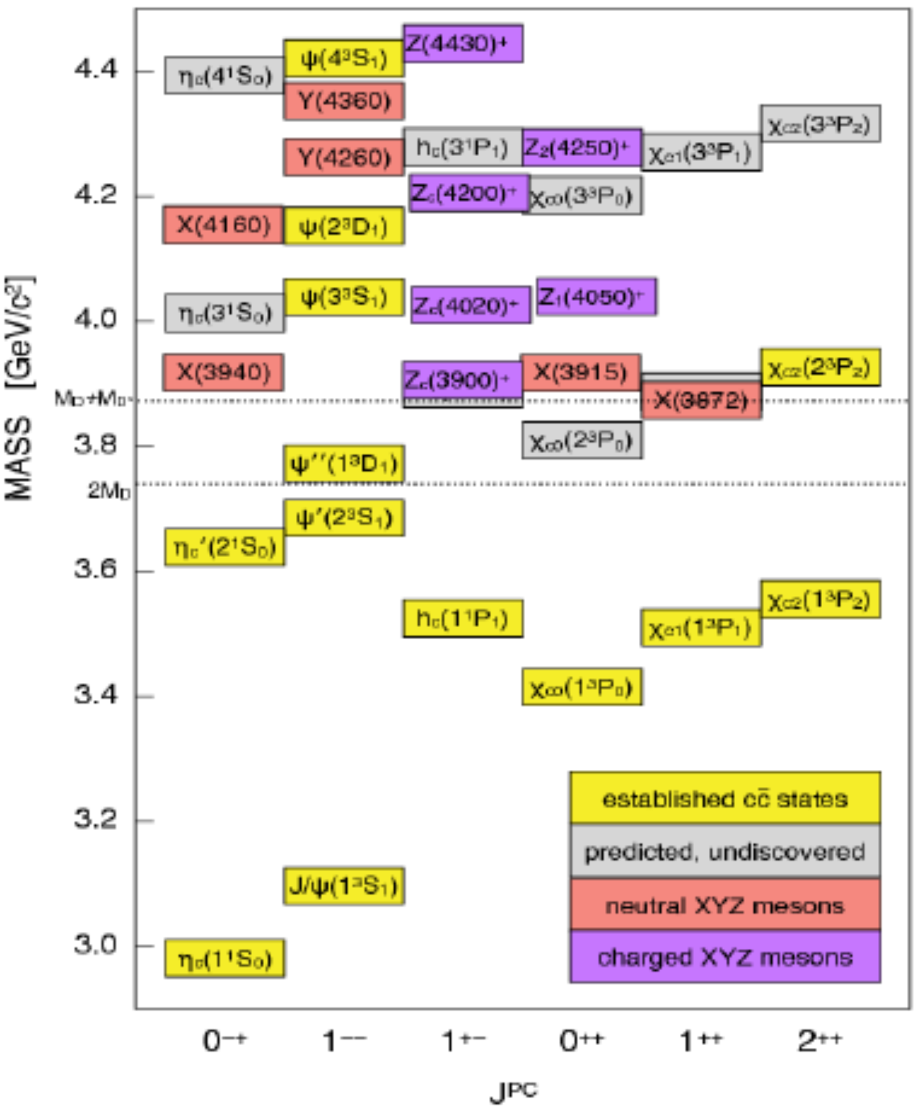
Charm spectroscopy- tetraquark states
decay constants, form-factors, mixing parameters…

↓

QCD (lattice) in action!



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.

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

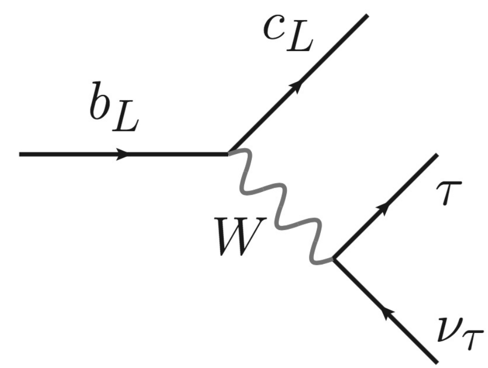
How about charm?

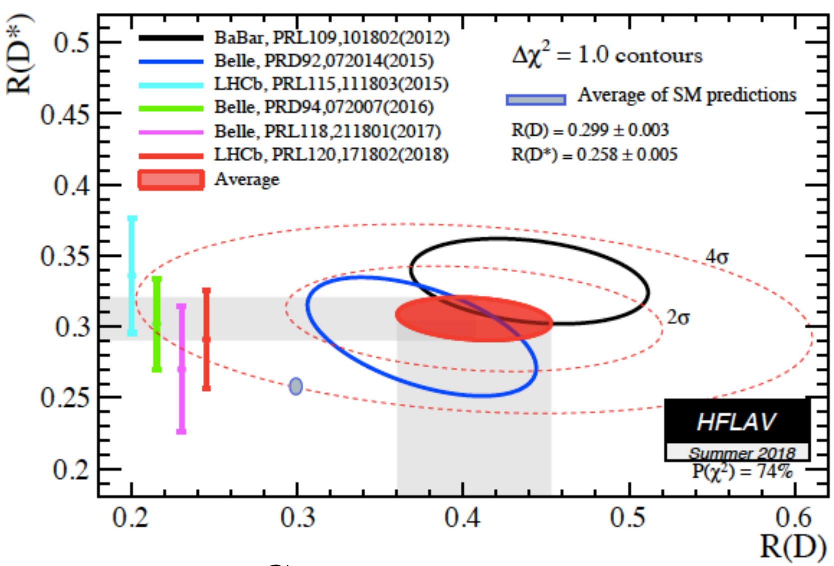
- CP violation in the up sector;
- Charm offers tests of possible NP in up sector at low-energies;
- If NP couples to weak doublets of quarks, CKM connects it with charm sector.
- Can one see NP in charm decays not being present in B meson ?

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



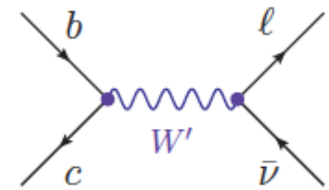


Freytsis, et al., 1506.08896, S.F. et al., 1206.1872;
Di Luzio & Nardecchia, 1706.01868,
Bernlochner et al., 1703.05330,
F. Feruglio et al., 1806.10155,
1606.00524.

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

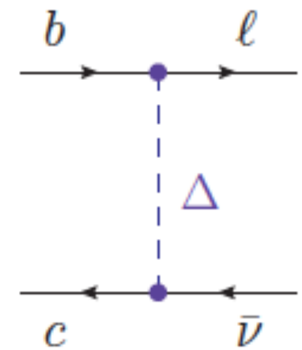
Assuming NP at scale Λ_{NP} (Di Luzio, Nardecchia, 1706.0!868)

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



What is the scale of New Physics?

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



Perturbativity of NP

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

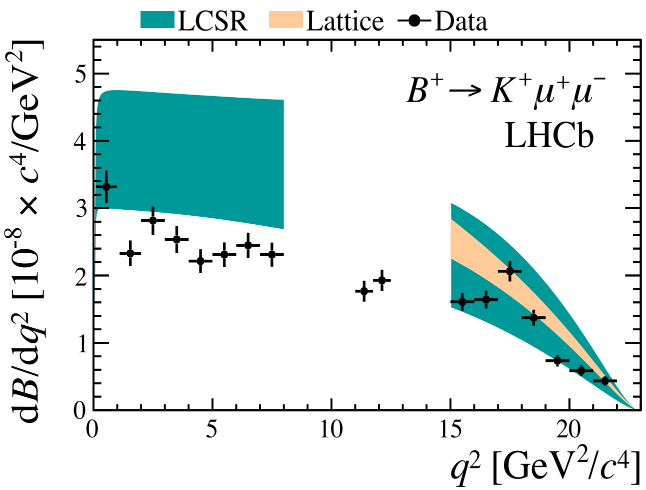
V-A form of NP

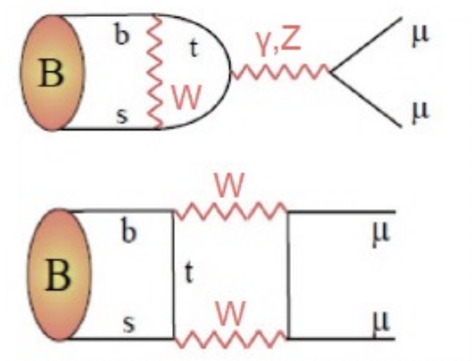
(current)(current) operators are invariant under QCD running

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

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

FCNC - SM loop process





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

2.4σ

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

What is the scale of New Physics?

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

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

NP explaining both B anomalies

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

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

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

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

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

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

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

NP in FCNC $B \to K^{(*)} \mu^+ \mu^-$ has to be suppressed

$$\frac{1}{(\Lambda^K)^2} = \frac{C_K}{\Lambda^2} \qquad C_K \simeq 0.01$$

suppression factor

Charged current charm meson decays and New Physics

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

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

PDG 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 $V_{cb}^{*} V_{ub}$.

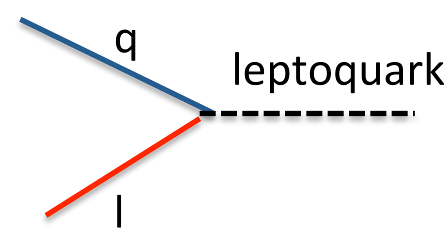
$$Q_{iL} = \begin{bmatrix} V^{*}_{iJ}\, u_J \\ d_i \end{bmatrix}_L$$

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? 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?

LQ and charm charged current

Triplet LQ S_3 in charm leptonic decays decay

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

C_V modifies CKM

Test of lepton flavour universality (LFU)

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

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

S_3=(3,3,-1/3)

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;

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

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

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

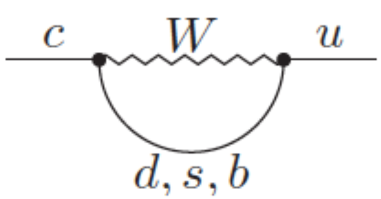
SM effective Hamiltonian for rare charm decays -FCNC

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

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

Tree-level 4-quark operators

(Short-distance) penguin operators



1) At scale m_W all penguin contributions vanish due to GIM;

2) SM contributions to $C_{7\ldots10}$ at scale m_c entirely due to mixing of tree-level operators into penguin ones under QCD

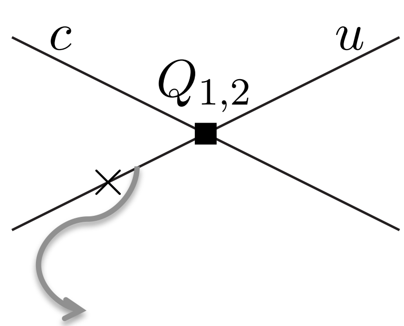
3) SM values at m_c

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

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

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

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][† 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

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

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

Hiller& de Boer 1701. 06392

LQs give as large

contributions as SM

Belle, 1603.03257

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

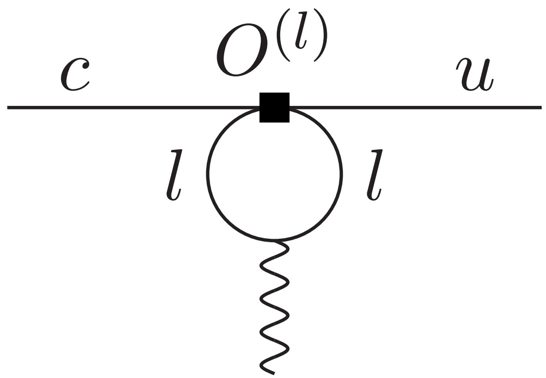
$$A_{CP}(D^0 \to \phi\gamma) = -0.094 \pm 0.066 \pm 0.001$$

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

New Physics in FCNC charm decays

Leptoquarks in $c \to u\gamma$

Hiller& de Boer 1701. 06392
SF and Košnik, 1510.00965



Constraints from

$$\tau^- \to \pi^- \nu_\tau$$
$$\tau^- \to K^- \nu_\tau$$
$$\Delta m_D$$
$$D^+ \to \tau^+ \nu_\tau$$
$$D_s^+ \to \tau^+ \nu_\tau$$
$$K^+ \to \pi^+ \nu \bar{\nu}$$

Even for τ in the loop too small contribution!

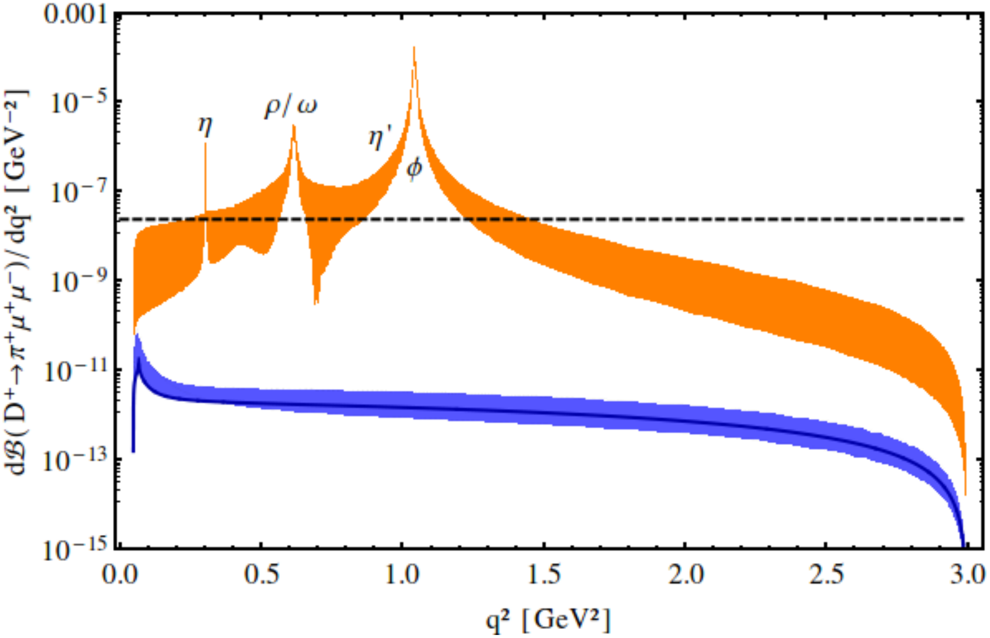
Masses of $m_{LQ} \approx 1$ TeV.

S_3 = (3,3,-1/3

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 $R_{K(*)}$!

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

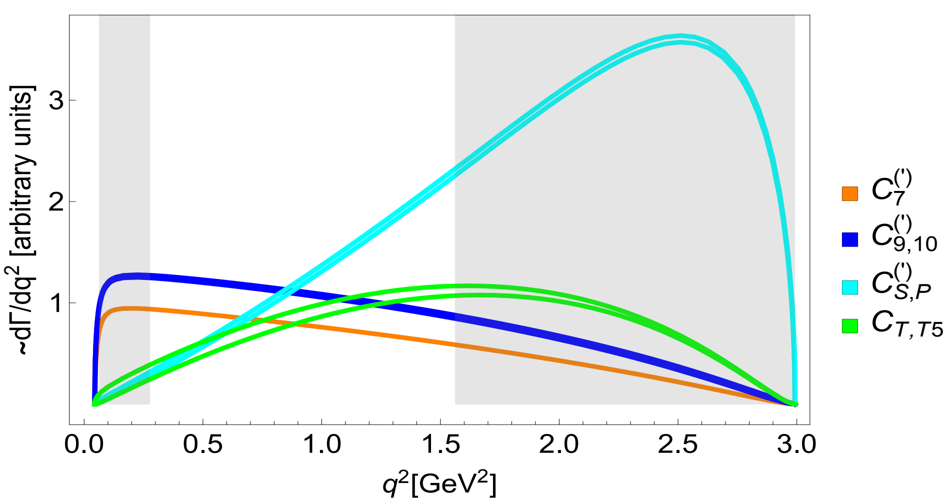


SM prediction: Long distance contributions most important!

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

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

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

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

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

Lepton flavor violation

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

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

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

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

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

LHCb bound, 1512.00322

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

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

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

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

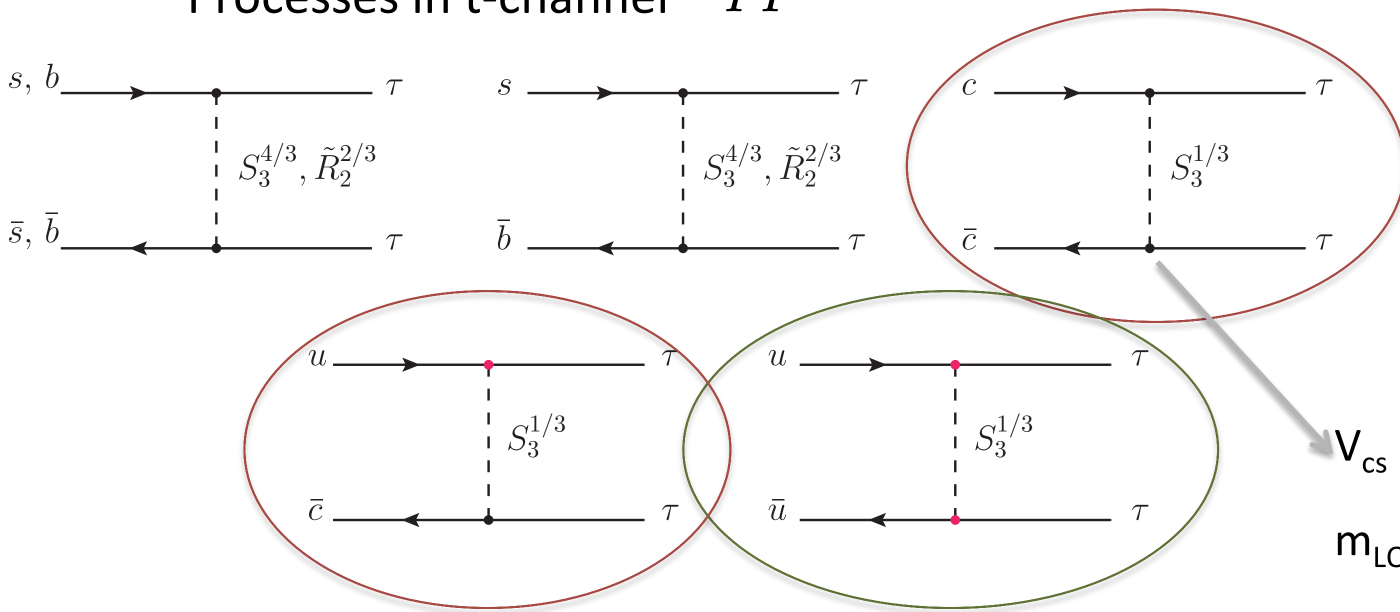
$$\left|K_{9,10}^{(l)} - K_{9,10}^{(l)\prime}\right| \lesssim 6\,, \quad \left|K_{T,T5}^{(l)}\right| \lesssim 7\,,$$

$$l = e, \mu$$

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

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

$$\sigma_{s\bar{s}}(y_{s\tau}) = 12.042\, y_{st}^4 + 5.126\, y_{st}^2\,,$$

$$\sigma_{s\bar{b}}(y_{s\tau}, y_{b\tau}) = 12.568\, y_{s\tau}^2 y_{b\tau}^2\,,$$

$$\sigma_{b\bar{b}}(y_{b\tau}) = 3.199\, y_{b\tau}^4 + 1.385\, y_{b\tau}^2\,,$$

$$\sigma_{c\bar{c},u\bar{u},u\bar{c}}(y_{s\tau}) = 3.987\, y_{s\tau}^4 - 5.189\, y_{s\tau}^2\,.$$

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!

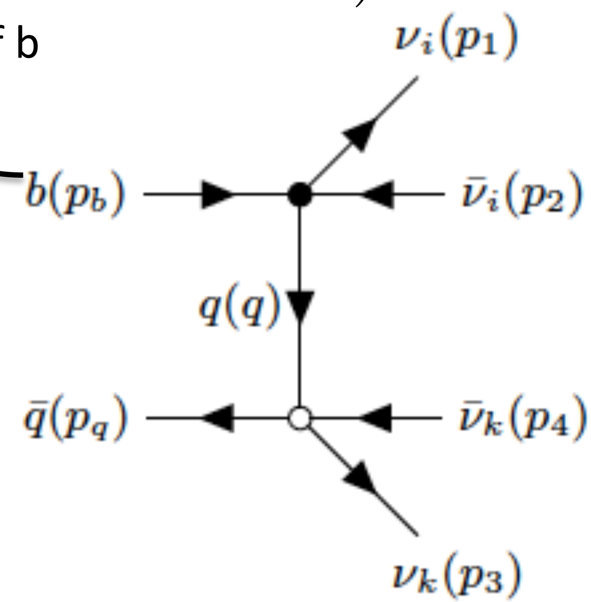
Bhattacharya, Grant and Petrov 1809.04606

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

c instead of b

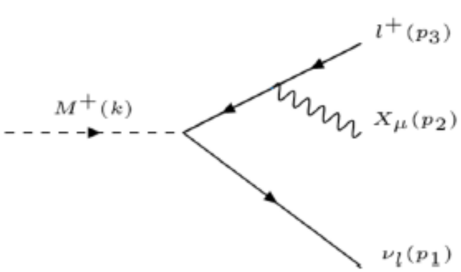
The SM contributions to invisible widths of heavy mesons $\Gamma(D^0 \to$ missing energy) are completely dominated by the four-neutrino transitions $D^0 \to \nu\bar{\nu}\nu\bar{\nu}$.

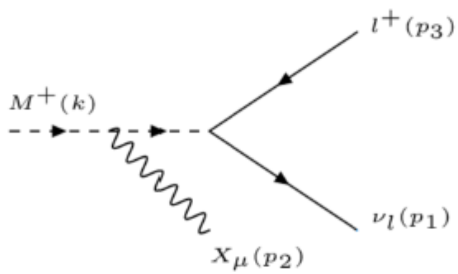
$$\mathcal{B}(D^0 \to \nu\bar{\nu}\nu\bar{\nu}) = (2.96 \pm 0.39) \times 10^{-27}$$



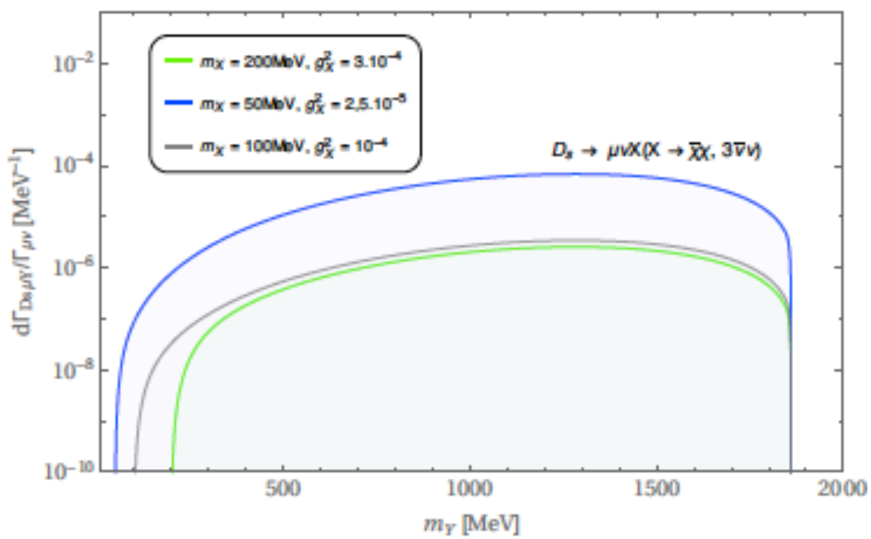
A_μ and X_μ mix via κ

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





Radiative - not γ but X

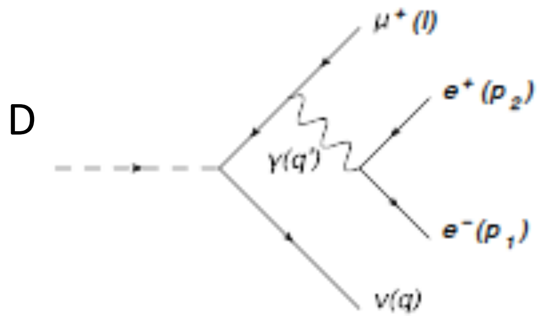


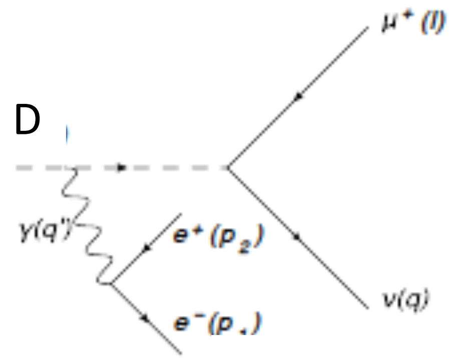
Is it possible to search for decay
D → μ X
X is SM ν_μ + DM gauge boson → invisible fermions
Exp: $D \to \tau\bar{\nu}_\tau \to \mu\bar{\nu}_\mu\nu_\tau\bar{\nu}_\tau$

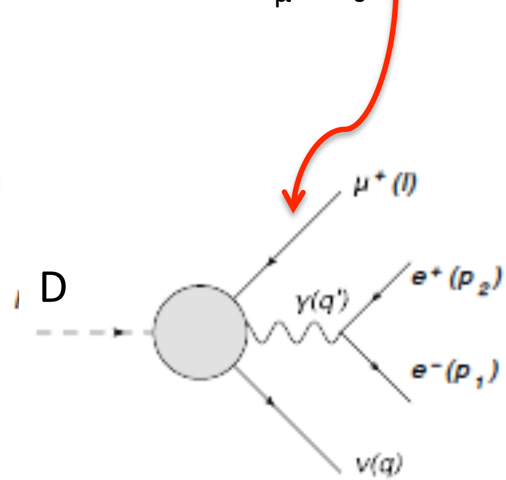
Difficult to differentiate

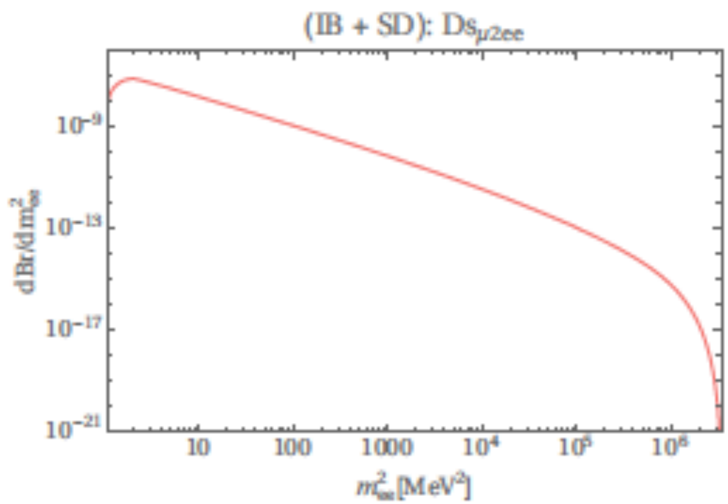
- There is a possibility that X → e^+e^-
- Can one see it in the decays P→μ νX → μυ e^+e
- First one should calculate SM values

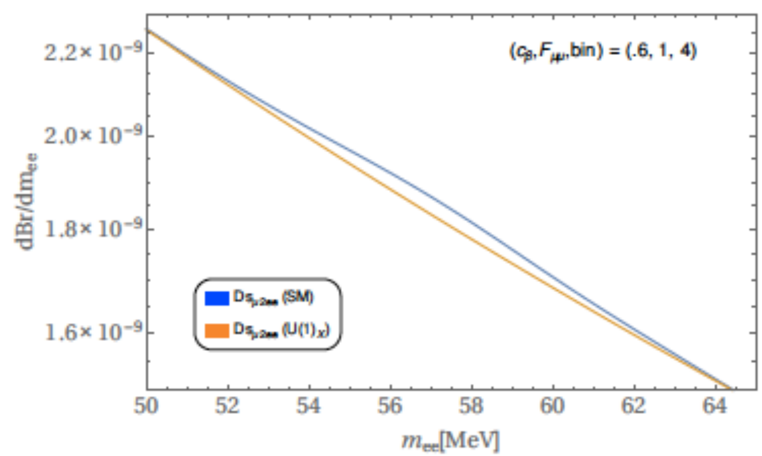
Thanks D. Melikhov for providing us with <γ*| J_μ| D_s>







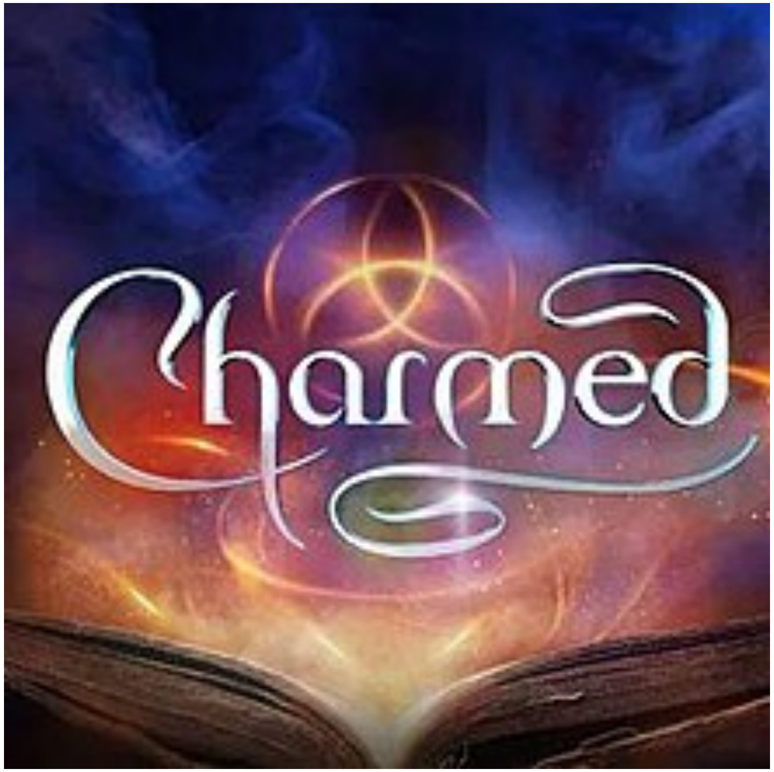




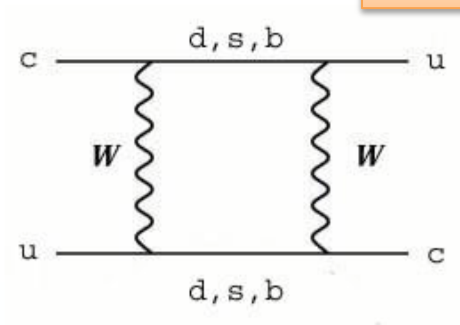
Summary and outlook

- 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!

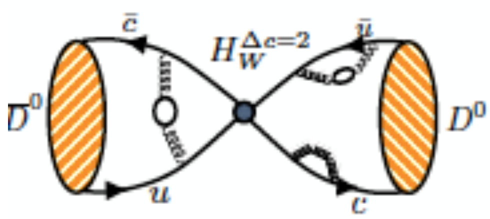


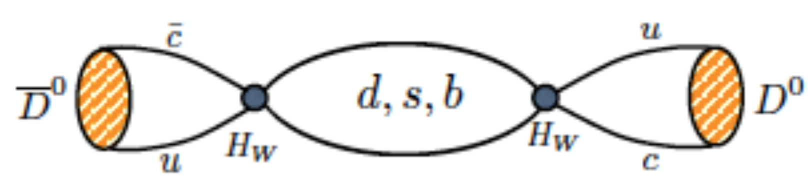
Mixing and indirect CP violation



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

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





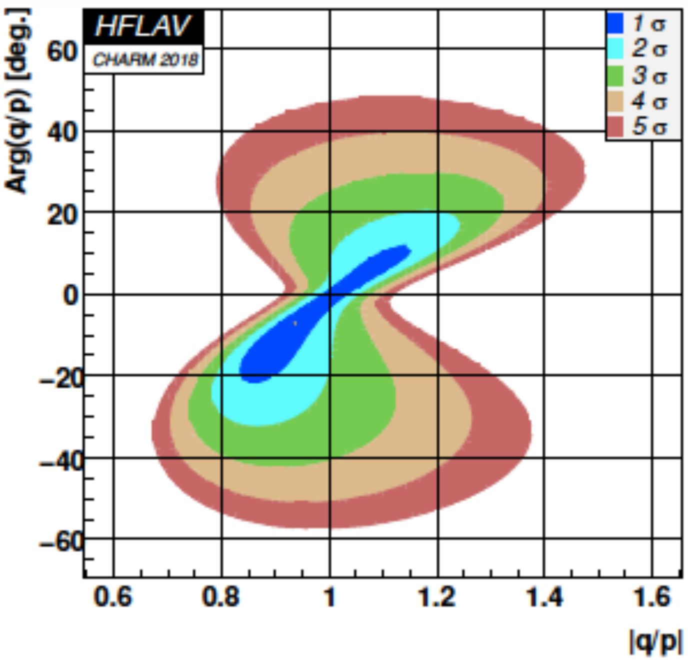
Short distance
Lattice QCD helps !

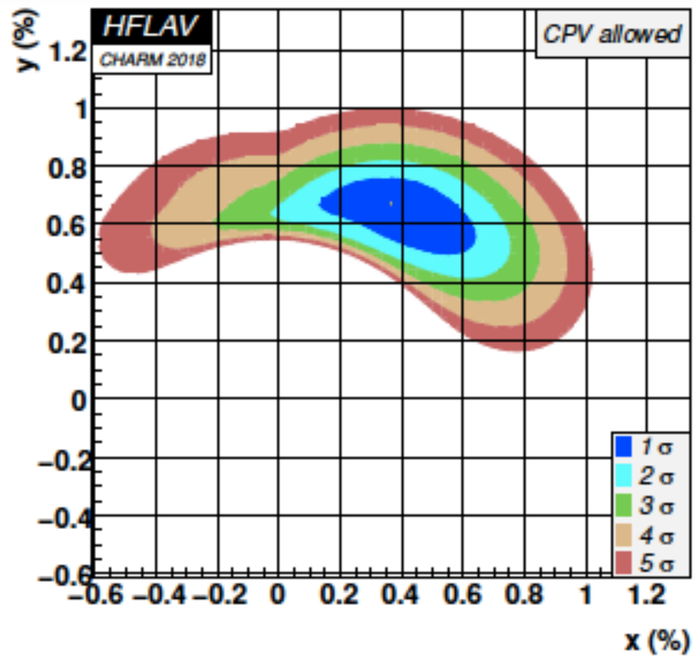
Long distance
difficult to determine

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!



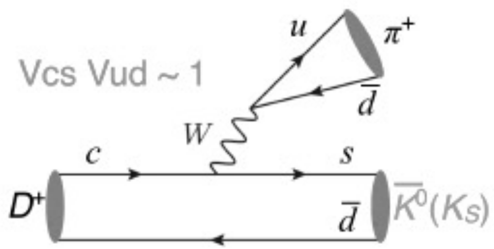


$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

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

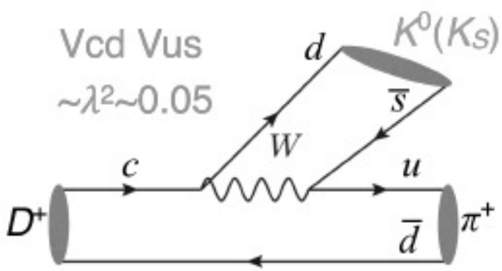
SM features of CPV in D

- 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

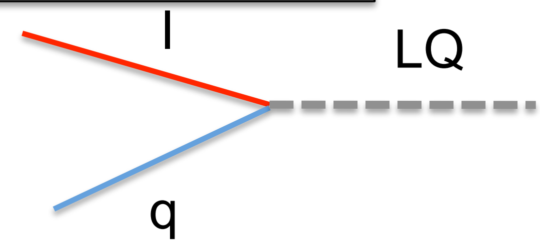


Nierste &Schacht, 1708.03572

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

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!

Popular scenario: Leptoquarks as a resolution of B anomalies:



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

$Q=I_3+Y$

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

no proton decay at tree level

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$	
$S_1 = (\bar{3},1)_{1/3}$	✓	✗	✗	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!

Doršner, SF, Greljo, Kamenik , Košnik, 1603.04993

Scalar LQ → simpler UV completion;

Only R_2 and S_1 might explain $(g\text{-}2)_\mu$ (both chiralities are required with the enhancement factor m_t/m_μ) Muller 1801.0338.

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 $C_{10}^{(')}$

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

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

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

Tests of LFU

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

LHCb , 1806.10793
consistent with SM