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 charged current and FCNC charm decays;
• Dark Matter search in rare charm decays;
• Summary.
Motivation to study charm physics

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
Deepening our knowledge of SM → QCD

Theory goals

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

QCD (lattice) in action!
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?
• 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;

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.
- \(\text{Arg}(q/p) \neq 0\) 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 $\mathcal{O}([V_{cb}V_{ub}^*/V_{cs}V_{us}^*] \alpha_s/\pi) \sim 10^{-4}$

$$A^{D+ \rightarrow K^0 \pi^+}_{CP} = (-0.363 \pm 0.094 \pm 0.067)\%$$

Belle, 1203.6409, mainly attributed to the K mixing

1707.09297, Wang, F.S. Yu, and H.N.Li, the time-dependent and time-integrated CP asymmetries in $D \rightarrow f K_S (\rightarrow \pi^+ \pi^-)$ 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 $\pi$ and K.

NP might be present!
CHARM quark electric (chromo-electric) dipole moment

\[ \mathcal{L}_{\text{eff}} = d_q \frac{1}{2} (\bar{q} \sigma_{\mu\nu} i \gamma_5 q) F^{\mu\nu} + \tilde{d}_q \frac{1}{2} (\bar{q} \sigma_{\mu\nu} T^a i \gamma_5 q) g_s G^{\mu\nu}_a + \frac{1}{6} f^{abc} e^{\mu\nu\lambda\rho} G^{a}_{\mu\sigma} G^{b}_{\nu\sigma} G^{c}_{\lambda\rho} \]

quark EDM

quark CEDM

Weingerg operator

Mixing under RGE

Sala, 1312.2589
Considered charm quark EDM and CEDM

CEDM threshold correction to \( w \)

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

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

\[ \lambda_q = V_{uq} V_{cq}^* \]

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 \( C_{7, \ldots, 10} \) at scale \( m_c \) entirely due to mixing of tree-level operators into penguin ones under QCD

3) SM values at \( m_c \)

\[ C_7 = 0.12, \quad C_9 = -0.41 \]

(recent results: de Boer, Hiller, 1510.00311, 1701.06392, De Boer et al, 1606.05521, 1707.00988)
SM in $ c \rightarrow u \gamma$ and $ c \rightarrow ul^+ l^-$

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

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

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

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

GIM suppression

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

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

C. Greub et al., PLB 382 (1996) 415;

$BR(D \rightarrow X_u \gamma) \sim 10^{-8}$
Introduction

Two approaches

1. Compute leading power corrections ($\sim \Lambda_{QCD}/m_c$) a $\sin^b c$

   [Bosch et al. 2001, 2004]

   Power corrections depend on uncertain $A_{D,t)$, the first negative moment of $D$-meson light-cone distribution amplitude.


Figure: Weak annihilation and hard spectator interaction diagrams. Crosses indicate photon emission.

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

Previous works:
S. F. P. Singer and J. Zupan, EPJC 27(2003) 201
Burdman et al. hep-ph/9502329,
Khodjamirian et al, hep-ph/9506242

Table I: Experimental data on $D^0 \to V\gamma$ branching ratios. The corresponding numerical values for the reduced branching ratios $B$, see eqs. (26, 29) and analogously for $C$, are given in the last row.

<table>
<thead>
<tr>
<th>branching ratio</th>
<th>$D^0 \to \rho^0\gamma$</th>
<th>$D^0 \to \omega\gamma$</th>
<th>$D^0 \to \phi\gamma$</th>
<th>$D^0 \to \bar{K}^{*0}\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle [24]†</td>
<td>$(1.77 \pm 0.31) \times 10^{-5}$</td>
<td>–</td>
<td>$(2.76 \pm 0.21) \times 10^{-5}$</td>
<td>$(4.66 \pm 0.30) \times 10^{-4}$</td>
</tr>
<tr>
<td>BaBar [33]†</td>
<td>–</td>
<td>–</td>
<td>$(2.81 \pm 0.41) \times 10^{-5}$</td>
<td>$(3.31 \pm 0.34) \times 10^{-4}$</td>
</tr>
<tr>
<td>CLEO [34]</td>
<td>–</td>
<td>$&lt; 2.4 \times 10^{-4}$</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Hiller & De Boer 1701.06392
CP asymmetry in charm radiative decays

\[ A_{CP}(D \rightarrow V\gamma) = \frac{\Gamma(D \rightarrow V\gamma) - \Gamma(\bar{D} \rightarrow \bar{V}\gamma)}{\Gamma(D \rightarrow V\gamma) + \Gamma(\bar{D} \rightarrow \bar{V}\gamma)} \]

|A^{SM}_{CP}| < 2 \cdot 10^{-3}

Belle, 1603.03257

Hiller & de Boer 1701.06392
LQs give as large contributions as SM

\[ A_{CP}(D^0 \rightarrow \rho^0\gamma) = 0.056 \pm 0.152 \pm 0.006 \],
\[ A_{CP}(D^0 \rightarrow \phi\gamma) = -0.094 \pm 0.066 \pm 0.001 \]
\[ A_{CP}(D^0 \rightarrow \bar{K}^{*0}\gamma) = -0.003 \pm 0.020 \pm 0.000 \]
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!

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^\prime \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \left( \tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau \right) = \Gamma(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau)$$

valid for quarks too!

Basic property of the SM: universal $g$ for each of three generations in weak interactions

$$\mathcal{L}_f = \bar{f} i D_{\mu} \gamma^\mu f \quad f = l^i_L, q^i_L, \ i = 1, 2, 3$$

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

the same for all SM fermions

$$\mathcal{L}_{\text{eff}} f = - \frac{G_F}{\sqrt{2}} J^\dagger_{\mu} J^\mu$$

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

tau-charm 2018
Muon anomalous magnetic moment

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

Dirac equation predicts \( g = 2 \) \[ a = (g - 2)/2 \]

\[ a^\text{th}_\mu - a^\text{exp}_\mu = -(3.06 \pm 0.76) \times 10^{-8} \]

4 \sigma

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)

\[ R_{D(*)} = \frac{BR(B \rightarrow D^{(*)} \tau \nu_\tau)}{BR(B \rightarrow D^{(*)} \mu \nu_\mu)} = 3.8\sigma \]

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.

\[ \mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cb}[ (1 + g_{V_L})(\bar{c}_L \gamma_\mu b_L)(\bar{l}_L \gamma_\mu \nu_L) + g_{V_R}(\bar{c}_R \gamma_\mu b_R)(\bar{l}_L \gamma_\mu \nu_L) + g_{S_R}(\bar{c}_L b_R)(\bar{l}_R \nu_L) + g_{T_R}(\bar{c}_L \sigma_\mu\nu b_R)(\bar{l}_R \sigma_\mu\nu \nu_L) ] \]
Assuming NP at scale $\Lambda_{NP}$ (Di Luzio, Nardecchia, 1706.01868)

\[
\frac{4G_F}{\sqrt{2}} V_{cb} g_V \rightarrow \frac{2}{\Lambda_{NP}^2}
\]

What is the scale of New Physics?

$\Lambda_{NP} \simeq 3 \text{ TeV}$

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

$\Lambda_{NP} > 3 \text{ TeV}$

$C_D$ becomes non-perturbative!

Hiller et al., 1609.08895 R_D(*)

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FCNC - SM loop process

\[ R_K = \frac{\mathcal{B}(B \rightarrow K\mu\mu)_{q^2 \in [1, 6]\, \text{GeV}^2}}{\mathcal{B}(B \rightarrow K\text{ee})_{q^2 \in [1, 6]\, \text{GeV}^2}} = 0.745 \pm 0.090 \pm 0.036 \quad 2.4\sigma \]

\[ R_{K^{*\text{low}}} = \frac{\mathcal{B}(B \rightarrow K\mu\mu)_{q^2 \in [0.045, 1.1]\, \text{GeV}^2}}{\mathcal{B}(B \rightarrow K\text{ee})_{q^2 \in [0.045, 1.1]\, \text{GeV}^2}} = 0.660 \pm 0.110 \pm 0.024 \quad 2.2 \sigma - 2.4\sigma \]

\[ R_{K^{*\text{central}}} = \frac{\mathcal{B}(B \rightarrow K\mu\mu)_{q^2 \in [1.1, 6]\, \text{GeV}^2}}{\mathcal{B}(B \rightarrow K\text{ee})_{q^2 \in [1.1, 6]\, \text{GeV}^2}} = 0.685 \pm 0.113 \pm 0.047 \]
operators.

The contributions of the charged-current operators will finally summarize our findings in Sec. V. In the case of flavor universality violation. In Sec. V, we discuss a model with scalar leptoquark in which the relation \( C^\text{SM}_7 = 0.29; C^\text{SM}_9 = 4.1; C^\text{SM}_{10} = -4.3; \)

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

Global analysis suggests NP in \( C^9_{9,10} \)

\[
C_i = C_i^\text{SM} + C_i^{\text{NP}}
\]

\[
C^\text{NP}_9 = -C^\text{NP}_{10} = -0.64
\]

best fit point

\([-0.85, -0.5]\]

What is the scale of New Physics?

\[
\mathcal{L}^{\text{NP}} = \frac{1}{\Lambda_{NP}^2} \bar{s}_L \gamma^\alpha b_L \bar{\mu}_L \gamma^\alpha \mu_L
\]

\( \Lambda_{NP} \simeq 30 \text{ TeV} \)

Capdevila et al., 1704.05340, Altmannshofer et al., 1704.05435, D'Amico et al., 1704.05438.
NP explaining both B anomalies

\[ R_{D(*)}^{exp} > R_{D(*)}^{SM} \]

\[ L_{NP} = \frac{1}{(\Lambda_D)^2} 2 \bar{c}_L \gamma_\mu b_L \bar{\tau} \gamma_\mu \nu_L \]

\[ \Lambda_D \simeq 3 \text{ TeV} \]

\[ R_{K(*)}^{exp} < R_{K(*)}^{SM} \]

\[ L_{NP} = \frac{1}{(\Lambda_K)^2} \bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma_\mu \mu_L \]

\[ \Lambda_K \simeq 30 \text{ TeV} \]

\[ \Lambda_D \simeq \Lambda_K \equiv \Lambda \]

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

\[ \frac{1}{(\Lambda_K)^2} = \frac{C_K}{\Lambda^2} \]

\[ C_K \simeq 0.01 \]

suppression factor
Charged current charm meson decays and New Physics

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

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%

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

1 % error in

\[ \Gamma(D_s^+ \rightarrow l^+ \nu_l) \]

\[ \Lambda_c \sim 2.5 \text{ TeV} \]

Message:
Even if there is NP at 3 TeV scale the effect on charm leptonic decay can be \sim 1%!
New Physics in charm processes

Constraints from K, B physics

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

Constraints from LHC

NP in charm

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

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

$$Q_{iL} = \begin{bmatrix} V^*_{il} & u_j \\ d_i \\ \vdots \end{bmatrix}$$
Models of NP explaining B anomalies

<table>
<thead>
<tr>
<th>Spin</th>
<th>Color singlet</th>
<th>Color triplet</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2HDM</td>
<td>Scalar LQ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R parity - sbottom</td>
</tr>
<tr>
<td>1</td>
<td>W', Z'</td>
<td>Vector LQ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dark matter?</td>
</tr>
</tbody>
</table>

2HDMII cannot explain $R_D(*)$

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

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?

Olcyr Sumensari (LPT - Orsay)

NP and LF(U)V in B Decays

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Popular scenario: Leptoquarks as a resolution of B anomalies:

\[ \text{LQ} = (\text{SU}(3)_c, \text{SU}(2)_L) \gamma \]

or \( \text{LQ} = (\text{SU}(3)_c, \text{SU}(2)_L, Y) \)

No proton decay at tree level

<table>
<thead>
<tr>
<th>Model</th>
<th>( R_D(*) )</th>
<th>( R_K(*) )</th>
<th>( R_D(<em>) &amp; R_K(</em>) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1 = (\bar{3}, 1)_{1/3} )</td>
<td>\checkmark</td>
<td>\times</td>
<td>\times</td>
</tr>
<tr>
<td>( R_2 = (3, 2)_{7/6} )</td>
<td>\checkmark</td>
<td>\times*</td>
<td>\times</td>
</tr>
<tr>
<td>( S_3 = (\bar{3}, 3)_{1/3} )</td>
<td>\times</td>
<td>\checkmark</td>
<td>\times</td>
</tr>
<tr>
<td>( U_1 = (3, 1)_{2/3} )</td>
<td>\checkmark</td>
<td>\checkmark</td>
<td>\checkmark</td>
</tr>
<tr>
<td>( V_2 = (3, 1)_{2/3} )</td>
<td>\times</td>
<td>\times</td>
<td>\times</td>
</tr>
<tr>
<td>( \tilde{V}<em>2 = (\bar{3}, 2)</em>{-1/6} )</td>
<td>\times</td>
<td>\times</td>
<td>\times</td>
</tr>
<tr>
<td>( U_3 = (3, 3)_{2/3} )</td>
<td>\times</td>
<td>\checkmark</td>
<td>\times</td>
</tr>
</tbody>
</table>

Spin 0

Spin 1

No single scalar LQ to solve simultaneously both anomalies!

Scalar LQ simpler UV completion;

Only \( R_2 \) and \( S_1 \) might explain \( (g-2)_\mu \) (both chiralities are required with the enhancement factor \( m_t/m_\mu \)) Muller 1801.0338.
LQ and charm charged current

Triplet LQ $S_3$ in charm leptonic decays decay

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

$C_V$ modifies CKM

Test of lepton flavour universality (LFU)

$$\frac{R_{\tau,\mu, LQ}^c}{R_{\tau,\mu, SM}^c} = \left[ 1 - \frac{\nu^2}{2M_{S3}^2} \text{Re}( (V y^*)_c \bar{y}_{s\tau} - (V y^*)_c \bar{y}_{s\mu} ) \right]$$

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

<table>
<thead>
<tr>
<th>$m_{S3}$ [TeV]</th>
<th>$1 - \frac{R_{\tau,\mu, LQ}^c}{R_{\tau,\mu, SM}^c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>3.2%</td>
</tr>
<tr>
<td>1.2</td>
<td>2.4%</td>
</tr>
<tr>
<td>1.5</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

Doršner, SF, Greljo, Kamenik Košnik, 1603.04993;
New Physics in FCNC charm decays

Leptoquarks in $c \rightarrow u \gamma$

Hiller & de Boer 1701.06392
SF and Košnik, 1510.00965

Constraints from

\[ \begin{align*}
\tau^- & \rightarrow \pi^- \nu_\tau \\
\tau^- & \rightarrow K^- \nu_\tau \\
\Delta m_D & \\
D^+ & \rightarrow \tau^+ \nu_\tau \\
D_s^+ & \rightarrow \tau^+ \nu_\tau \\
K^+ & \rightarrow \pi^+ \nu \bar{\nu}
\end{align*} \]

Even for $\tau$ in the loop too small contribution!

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

Within LQ models the $c \rightarrow u \gamma$ branching ratios are SM-like with CP asymmetries at $O(0.01)$ for $S_{1,2}$ and $V_{-2}$ and SM-like for $S_3$.

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

$S_3$ can explain $R_{K(*)}$!
NP in $c \rightarrow ul^+l^-$

Most general dimension 6 effective Lagrangian for $c \rightarrow ul^+l^-$

$$O_7 = \frac{em_c}{(4\pi)^2} (\bar{u}\sigma_{\mu\nu}P_Rc) F^{\mu\nu},$$

$$O_9 = \frac{e^2}{(4\pi)^2} (\bar{u}\gamma^\mu P_Lc)(\bar{\ell}\gamma_\mu \ell),$$

$$O_{10} = \frac{e^2}{(4\pi)^2} (\bar{u}\gamma^\mu P_Lc)(\bar{\ell}\gamma_\mu \gamma_5 \ell),$$

$$O_S = \frac{e^2}{(4\pi)^2} (\bar{u}P_Rc)(\bar{\ell}\ell),$$

$$O_P = \frac{e^2}{(4\pi)^2} (\bar{u}P_Rc)(\bar{\ell}\gamma_5 \ell),$$

$$O_T = \frac{e^2}{(4\pi)^2} (\bar{u}\sigma_{\mu\nu}c)(\bar{\ell}\sigma^{\mu\nu} \ell),$$

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

$D^0 \rightarrow \mu^+\mu^-$}

SF, N. Kosnik, 1510.00965

LHCb bound, 1305.5059

$\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 6.2 \cdot 10^{-9}$ 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!

\[ D \to \pi V \to \pi l^+ l^- \]

peaks at \( \rho, \omega, \phi \) and \( \eta \) resonances

deo 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
Figure 2. Comparison of short-distance spectrum sensitivities to different Wilson coefficients. Grey regions indicate the LHCb experimental low- and high- $q^2$ bins.

| $\tilde{C}_i$ | $|\tilde{C}_i|_{\text{max}}$ | $\text{BR}((\pi\mu\mu)_I$ | $\text{BR}((\pi\mu\mu)_{II}$ | $\text{BR}(D^0 \to \mu\mu)$ |
|---|---|---|---|---|
| $\tilde{C}_7$ | 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 |

Table II. Maximal allowed values of the Wilson coefficient moduli, $|\tilde{C}_i| = |V_{ub}V^*_{cb}C_i|$, calculated in the nonresonant regions of $D^+ \to \pi^+ \mu^+\mu^-$ in the low lepton invariant mass region ($q^2 \in [0.0625, 0.276]$ GeV$^2$), denoted by I, in the high invariant mass region ($q^2 \in [1.56, 4.00]$ GeV$^2$), denoted by II, and from the upper bound $\text{BR}(D^0 \to \mu\mu) < 6.2 \times 10^{-9}$.

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

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

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

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

$$|\tilde{C}_9 = \pm \tilde{C}_{10}| = 0.043$$

tau-charm 2018
Test of lepton flavour universality violation in charm FCNC decays

\[
R^I_\pi = \frac{\text{BR}(D^+ \rightarrow \pi^+ \mu^+ \mu^-)}{\text{BR}(D^+ \rightarrow \pi^+ e^+ e^-)}_{q^2 \in [0.25^2, 0.525^2]\text{GeV}^2} \quad R^{II}_\pi = \frac{\text{BR}(D^+ \rightarrow \pi^+ \mu^+ \mu^-)}{\text{BR}(D^+ \rightarrow \pi^+ e^+ e^-)}_{q^2 \in [1.25^2, 1.73^2]\text{GeV}^2}
\]

\[
R^I_{\pi,SM} = 0.87 \pm 0.09
\]

| \left| \tilde{C}_i \right|_{\text{max}} | R^{II}_\pi |
|-----------------|------------------|
| SM              | -                | 0.999 \pm 0.001 |
| \tilde{C}_7     | 1.6              | \sim 6–100     |
| \tilde{C}_9     | 1.3              | \sim 6–120     |
| \tilde{C}_{10}  | 0.63             | \sim 3–30      |
| \tilde{C}_S     | 0.05             | \sim 1–2       |
| \tilde{C}_P     | 0.05             | \sim 1–2       |
| \tilde{C}_T     | 0.76             | \sim 6–70      |
| \tilde{C}_{T5}  | 0.74             | \sim 6–70      |
| \tilde{C}_9 = \pm \tilde{C}_{10} | 0.63 | \sim 3–60 |
| \tilde{C}_9' = -\tilde{C}_{10}'|_{\text{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.

tau-charm 2018
Angular distributions in $D \rightarrow P_1 P_2 l^+ l^-$

LHCb, 1707.08377

De Beor and Hiller, 1805.08516

Modes sensitive to NP

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

Tests of LFU

$LHCb$, 1806.10793

consistent with SM
Scalar LQ in charm FCNC processes

(3,3,-1/3)

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

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

\[ C_{cu}^{LL} \quad \text{100 times smaller than current LHCb bound!} \]

(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:

\[ K \rightarrow \mu \nu, \quad B \rightarrow \tau \nu, \quad \tau \rightarrow \mu \gamma \]

\[ D_s \rightarrow \tau \nu, \quad D \rightarrow \mu^+ \mu^- \]
In the case of $\Delta C=2$ in oscillation there is also a LQ contribution

\[ D^0 - \bar{D}^0 \]

Bound from $\Delta C=2$ slightly stronger, but comparable to the bound coming from

\[ D^0 \rightarrow \mu^+ \mu^- \]

(Vector LQ $\left( 3, 1, 5/3 \right)$)

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

not present in B physics at tree level!

\[ D^0 - \bar{D}^0 \]

Scalar LQ $\left( 3, 2, 7/6 \right)$

\[ \mathcal{H} = C_6 \left( \bar{u}_R \gamma_\mu c_R \right) \left( \bar{u}_R \gamma_\mu c_R \right) \]

\[ \mathcal{H}_2 \left( 3, 2, 7/6 \right) \text{ can explain } R_{D(*)} \]

(Becirevic, Dorsner, SF, Faroughy, Kosnik, Sumensari, 1806.05689 and can generate c quark EDM)

(for loop effects in B
Camargo-Molina, Celis, Faroughy 1805.04917)
<table>
<thead>
<tr>
<th>Model</th>
<th>Effect</th>
<th>Size of the effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar leptoquark (3,2,7/6)</td>
<td>(C_S, C_P, C_S', C_P', C_T, C_{T5},)</td>
<td>(V_{cb}V_{ub}</td>
</tr>
<tr>
<td>Vector leptoquark (3,1,5/3)</td>
<td>(C_9' = C_{10}')</td>
<td>(V_{cb}V_{ub}</td>
</tr>
<tr>
<td>Two Higgs doublet Model type III</td>
<td>(C_S, C_P, C_S', C_P')</td>
<td>(V_{cb}V_{ub}</td>
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<tr>
<td></td>
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<td>(V_{cb}V_{ub}</td>
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<tr>
<td>Z’ model</td>
<td>(C_9', C_{10}')</td>
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</tr>
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<td></td>
<td></td>
<td>(V_{cb}V_{ub}</td>
</tr>
</tbody>
</table>
Lepton flavor violation

\[ c \to u \mu^\pm e^{\mp} \]

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

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

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

LHCb bound, 1512.00322

\[
\begin{align*}
BR(D^0 \to e^+ \mu^- + e^- \mu^+) &< 2.6 \times 10^{-7} \\
BR(D^+ \to \pi^+ e^+ \mu^-) &< 2.9 \times 10^{-6} \\
BR(D^+ \to \pi^+ e^- \mu^+) &< 3.6 \times 10^{-6}
\end{align*}
\]

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

\[
\begin{align*}
|K_{S,P}^{(l)} - K_{S,P}^{(l)'})| &\lesssim 0.4, \\
|K_{9,10}^{(l)} - K_{9,10}^{(l)'})| &\lesssim 6, \\
|K_{T,T5}^{(l)}| &\lesssim 7,
\end{align*}
\]

\[ l = e, \mu \]

1510.00311 (de Beor and Hiller) 
1705.02251 (Sahoo and Mohanta)
Dark Matter in charm decays

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

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

Badin & Petrov 1005.1277 suggested to search for processes with missing energy/\E in

\[ D^0 \to \gamma E \]

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

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

- Request anomalies cancelled:

\[ U(1)^3_X, \ U(1)^2_X U(1)_Y, \ U(1)_X U(1)^2_Y \] and \[ SU(3)^2 U(1)_X \]

- Higgs sector: 2 doublets, one singlet

\[
\phi_0 = \begin{pmatrix} \phi_0^+ \\ v_0 + H_0 + i\chi_0 \end{pmatrix} \quad ; \quad \phi_X = \begin{pmatrix} \phi_X^+ \\ v_X + H_X + i\chi_X \end{pmatrix} \quad ; \quad s = \frac{v_s + H_s + i\chi_s}{\sqrt{2}}
\]

\[
v^2 \equiv (v_0^2 + v_X^2), \quad \bar{v}^2 \equiv (v_s^2 + v_X^2), \quad c_\beta^2 = \frac{v_X^2}{v^2}
\]

- Invisible fermions necessary for anomaly cancellation

\[
\mathcal{L} : -Y_s \bar{\chi}_L \chi_X R S - Y_s^* \bar{\chi}_R \chi_L s^*.
\]
$A_\mu$ and $X_\mu$ mix via $\kappa$

$M^+ \rightarrow \mu^+ \ell^-$

Radiative - not $\gamma$ but $X$

Is it possible to search for decay $D \rightarrow \mu X$

$X$ is SM $\nu_\mu$ + DM gauge boson $\rightarrow$ invisible fermions

Exp: $D \rightarrow \tau \bar{\nu}_\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau \bar{\nu}_\tau$

Difficult to differentiate
• There is a possibility that $X \rightarrow e^+e^-$
• Can one see it in the decays $P \rightarrow \mu \nu X \rightarrow \mu \nu e^+e^-$
• First one should calculate SM values

Thanks D. Melikhov for providing us with $\langle \gamma^* | J_\mu | D_s \rangle$. 

![Diagram of particle interactions](image1)

![Graphs of decay probabilities](image2)
• 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 $\tau\tau$ production

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

Flavour anomalies generate $s\tau$, $b\tau$ and $c\tau$ relatively large couplings.

s quark pdf function for protons are $\sim$ 3 times lagrer contribution then for b quark.

1706.07779, Doršner, SF, Faroughy, Košnik

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

$$\sigma_{sb}(y_{st}, y_{b\tau}) = 12.568 y_{st}^2 y_{b\tau},$$

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

$$\sigma_{cc, w\bar{u}, u\bar{c}}(y_{st}) = 3.987 y_{st}^4 - 5.189 y_{st}^2.$$
\( y_{CP} \) definition

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

\[
f = K^+ K^-, \pi^+ \pi^- \quad (CP\text{-even})
\]

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

equal to \( y \) in the limit of no CPV;

\[
y_{CP} = (0.57 \pm 0.13 \pm 0.09)\% \quad \text{Pajero (LHCb) at CKM 2108}
\]

Compatible with world average \( (0.835 \pm 0.155)\% \);
D^0 \rightarrow \phi \gamma or D^0 \rightarrow K^{0*}\gamma decays (SM-dominated)

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

D^0 \rightarrow \rho^0\gamma

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

\[ \Lambda_c \rightarrow p\gamma \]

Hiller& de Boer 1701. 06392

\[ \mathcal{B}(\Lambda_c \rightarrow p\gamma) \sim \mathcal{O}(10^{-5}) \]

If \( \Lambda_c \)-baryons are produced polarized, such as at the Z, angular asymmetries in \( \Lambda_c \rightarrow p\gamma \) 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 $(g-2)_\mu$ and trident production allow rather small mixing $\kappa \sim 10^{-4}$