# BSM searches with rare charm decays

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based on works with Gudrun Hiller, arXiv:1510.00311 [hep-ph]
and SdB, B. Müller, D. Seidel to appear, DO-TH 15/11, QFET-2015-27

LIO conference on Flavour, 24.11.2015

# Flavour

Flavour related questions

- Hierarchy of fermion masses/Yukawas?
- Flavour mixing/CP violation solely due to CKM?
- (Different) structures in CKM and PMNS?
- Lepton Non-Universality (LNU) in $R(K)$, $R(D^*)$?

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and answers via?

- Lepton Flavour Violating (LFV) decays.
- Link SM-anomalies in $b$-physics to charm Flavour Changing Neutral Currents (FCNC).
- Quark – lepton interface.

# Present Status on Charm FCNCs

High precision experiments at
LHCb, BaBar, Belle II, CLEO-c, BESIII, ...

Most stringent limit to date
$\mathcal{B}^{\text{nr}}(D^+ \to \pi^+\mu^+\mu^-) < 7.3 \times 10^{-8}$ @CL=90% [LHCb 2013].

Rare in the SM due to GIM suppression.

Precise measurements of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and
$D^0 \to K^+K^-\mu^+\mu^-$ are possible [LHCb 2015], [Cappiello et al. 2013].

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Ask for/Probe convergence of calculations by means of $\Lambda_{\text{QCD}}/m_c$.

Two orders of magnitude difference in calculations of the branching ratios [Burdman et al. 2002], [Fajfer et al. 2003], [Paul et al. 2011]
is resolved, this talk [SdB, B. Müller, D. Seidel to appear, DO-TH 15/11, QFET-2015-27].

# and this Talk

Study $c \to ull'$ transitions

- in the SM $(l = l')$.
- and BSM sensitivity model-independently.
- within Leptoquark models supplemented by flavour patterns.

How much $b$eauty is in rare $c$harm decays?

# (N)NLO Calculation

[SdB, B. Müller, D. Seidel to appear, DO-TH 15/11, QFET-2015-27]

Matching at $\mu_W$ ($P_{1,2}$: $W$-induced current-current operators)

$$\mathcal{L}_{\text{eff}}^{\text{weak}}\Big|_{\mu_W \geq \mu > \mu_b} = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s,b} V_{cq}^* V_{uq} \times \left(\tilde{C}_1(\mu) P_1^{(q)}(\mu) + \tilde{C}_2(\mu) P_2^{(q)}(\mu)\right)$$

and matching at $\mu_b$ ($P_{3-10}$: $b$-induced penguin operators)

$$\mathcal{L}_{\text{eff}}^{\text{weak}}\Big|_{\mu_b > \mu \geq \mu_c} = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s} V_{cq}^* V_{uq} \times \left(\tilde{C}_1(\mu) P_1^{(q)}(\mu) + \tilde{C}_2(\mu) P_2^{(q)}(\mu) + \sum_{i=3}^{10} \tilde{C}_i(\mu) P_i(\mu)\right).$$

# SM Wilson Coefficients at $\mu_c = m_c$

| | $j=1$ | $j=2$ | $j=7$ | $j=8$ | $j=9$ |
|---|---|---|---|---|---|
| $\tilde{C}_j^{(0)}$ | -1.0275 | 1.0925 | 0 | 0 | -0.0030 |
| $(\alpha_s/(4\pi))\,\tilde{C}_j^{(1)}$ | 0.3214 | -0.0549 | 0.0035 | -0.0019 | -0.0064 |
| $(\alpha_s/(4\pi))^2\,\tilde{C}_j^{(2)}$ | 0.0766 | -0.0037 | 0.0002 | -0.0003 | -0.0037 |
| $\tilde{C}_j$ | -0.6295 | 1.0339 | 0.0037 | -0.0022 | -0.0131 |

Table: Additionally, $\tilde{C}_3 = -0.0080$, $\tilde{C}_4 = -0.0924$, $\tilde{C}_5 = 0.0005$, $\tilde{C}_6 = 0.0012$ and $\boldsymbol{\tilde{C}_{10} = 0}$.

$\tilde{C}_1$ and $\tilde{C}_2$ partially cancel in effective Wilson coefficients.

# Non-resonant SM Branching Ratios

Effective GIM suppression in non-resonant decays, e.g.

| $q^2$-bin | $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)^{\text{SM}}_{\text{nr}}$ | 90% CL limit |
|---|---|---|
| full $q^2$ | $3.7 \cdot 10^{-12} \, (\pm 3, {}^{+16}_{-15}, \pm 1, {}^{+4}_{-1}, {}^{+158}_{-1}, {}^{+16}_{-12})$ | $7.3 \cdot 10^{-8}$ |
| low $q^2$ | $7.4 \cdot 10^{-13} \, (\pm 4, {}^{+23}_{-21}, {}^{+10}_{-11}, {}^{+11}_{-1}, {}^{+238}_{-23}, {}^{+6}_{-5})$ | $2.0 \cdot 10^{-8}$ |
| high $q^2$ | $7.4 \cdot 10^{-13} \, (\pm 6, {}^{+15}_{-14}, \pm 6, {}^{+2}_{-1}, {}^{+136}_{-45}, {}^{+27}_{-20})$ | $2.6 \cdot 10^{-8}$ |

Table: Full $q^2$: $(2m_\mu)^2 \leq q^2 \leq (m_{D^+} - m_{\pi^+})^2$ , low $q^2$: $0.250^2$ GeV$^2 \leq q^2 \leq 0.525^2$ GeV$^2$ and high $q^2$: $q^2 \geq 1.25^2$ GeV$^2$.
Non-negligible uncertainties are labelled as $(m_c,\, m_s,\, \mu_W,\, \mu_b,\, \mu_c,\, f_+)$ [%], where $\mu_c$ is varied as $m_c/\sqrt{2} \leq \mu_c \leq \sqrt{2} m_c$.

# and Resonant Modes

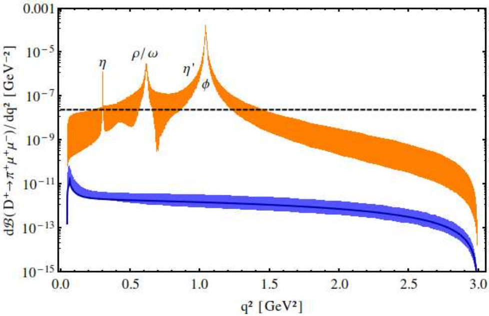



Figure: The solid blue curve is the non-resonant SM prediction at $\mu_c = m_c$ and the lighter blue band its $\mu_c$-uncertainty. The orange band represents the pure resonant modes modelled via a Breit-Wigner shape to fit the data and varying the relative strong phases. The dashed black line denotes the 90% CL experimental upper limit.

# Lorentz Structures

$$\mathcal{L}_{\text{eff}}^{\text{weak}}(\mu \sim m_c) = \frac{4G_F}{\sqrt{2}} \frac{\alpha_e}{4\pi} \sum_i C_i^{(l)} Q_i^{(l)},$$

$$\begin{aligned}
Q_9^{(l)} &= (\bar{u}\gamma_\mu P_L c)\left(\bar{l}\gamma^\mu l\right), & Q_9^{(l)\prime} &= (\bar{u}\gamma_\mu P_R c)\left(\bar{l}\gamma^\mu l\right), \\
Q_{10}^{(l)} &= (\bar{u}\gamma_\mu P_L c)\left(\bar{l}\gamma^\mu \gamma_5 l\right), & Q_{10}^{(l)\prime} &= (\bar{u}\gamma_\mu P_R c)\left(\bar{l}\gamma^\mu \gamma_5 l\right), \\
Q_S^{(l)} &= (\bar{u}P_R c)\left(\bar{l}l\right), & Q_S^{(l)\prime} &= (\bar{u}P_L c)\left(\bar{l}l\right), \\
Q_P^{(l)} &= (\bar{u}P_R c)\left(\bar{l}\gamma_5 l\right), & Q_P^{(l)\prime} &= (\bar{u}P_L c)\left(\bar{l}\gamma_5 l\right), \\
Q_T^{(l)} &= \frac{1}{2}(\bar{u}\sigma^{\mu\nu} c)\left(\bar{l}\sigma_{\mu\nu} l\right), & Q_{T5}^{(l)} &= \frac{1}{2}(\bar{u}\sigma^{\mu\nu} c)\left(\bar{l}\sigma_{\mu\nu}\gamma_5 l\right)
\end{aligned}$$

and analogue for LFV decays.

$D \to Pll$ and $D^0 \to ll$ are correlated via $C_{10}^{(\prime)}$ and $C_{S,P}^{(\prime)}$.

# Window in Branching Ratio

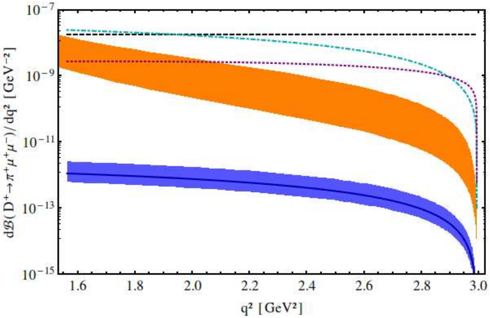



Figure: The solid blue curve is the non-resonant SM prediction at $\mu_c = m_c$ and the lighter blue band its $\mu_c$-uncertainty, the dashed black line denotes the 90% CL experimental upper limit and the orange band represents the resonant modes. The additional curves show $|C_9| = |C_{10}| = 0.6$ (dot-dashed cyan curve) and $C_i^{(\prime)} = 0.05$ (dotted purple curve).

# Null Tests of SM

$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{4}(1 - F_H)(1 - \cos^2\theta) + A_{FB}\cos\theta + \frac{1}{2}F_H$

($\theta$ is the angle between $l^-$ and $D$ in dilepton center-of-mass frame).

At high $q^2$ ($q^2 \geq 1.25\,\text{GeV}^2$)

$$|A_{\text{FB}}(D^+ \to \pi^+\mu^+\mu^-)| \lesssim 0.6\,,$$
$$F_H(D^+ \to \pi^+\mu^+\mu^-) \lesssim 1.5\,.$$

LFV and dineutrino modes are close to their experimental limits
$\mathcal{B}(D^+ \to \pi^+e^\pm\mu^\mp) \lesssim 3 \cdot 10^{-6}$ [BaBar 2011],
$\mathcal{B}(D^+ \to \pi^+\nu\bar{\nu}) \sim 10^{-5}$ sensitivity at BESIII.

LNU [Fajfer et al. 2015] and CP-asymmetries, in Leptoquark models.

# Leptoquark Models

Bottom-up approach ($\mathcal{L}_{LQ} \supset$)

$$\left(\lambda_{S_1 L} \mathbf{Q}_L^T i\tau_2 \mathbf{L}_L + \lambda_{S_1 R} q_R l_R\right) S_1^\dagger + ... + \lambda_{V_3} \bar{\mathbf{Q}}_L \gamma_\mu \vec{\tau} \mathbf{L}_L \cdot \left(\vec{V_3}^\mu\right)^\dagger .$$

- Collider experiments set $M \gtrsim 1$ TeV.
- Couplings to quark doublets constrained by rare kaon decays.
- Couplings to electrons **and** muons constrained by $\mu \to e\gamma$ and $\mu - e$ conversion in nuclei.
- Update and extend charm (up) constraints of [Davidson et al. 1994].

SM-anomalies in $R(K)$ and $R(D^*)$ could be softened by $S_1$ [Bauer et al. 2015] and $V_3$ [Fajfer et al. 2015].

# Flavour Patterns

Inspired by Frogatt-Nielsen $U(1)$ (quarks, rows) and $A_4$ (leptons, columns) symmetries [de Medeiros Varzielas et al. 2015]

$$\lambda_{i,ii,iii} \sim \begin{pmatrix} \rho_d\kappa & \rho_d & \rho_d \\ \rho\kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}, \quad \begin{pmatrix} 0 & * & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix}, \quad \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix} \dots$$

Study 1) couplings to quark singlets and 2) couplings to quark doublets.

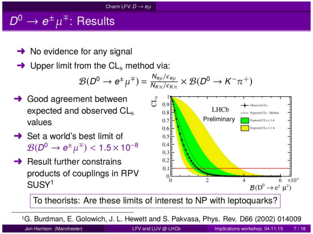
# Branching Ratios

| | $\mathcal{B}(D^+ \to \pi^+ \mu^+ \mu^-)$ | $\mathcal{B}(D^0 \to \mu^+ \mu^-)$ |
|---|---|---|
| i) | SM-like | SM-like |
| ii.1) | $\lesssim 7 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$ | $\lesssim 3 \cdot 10^{-9}$ |
| ii.2) | SM-like | $\lesssim 4 \cdot 10^{-13}$ |
| iii.1) | SM-like | SM-like |
| iii.2) | SM-like | SM-like |
| exp. | $< 7.3 \cdot 10^{-8}$ $(2.6 \cdot 10^{-8})$ | $< 6.2 \cdot 10^{-9}$ |

Table: Branching ratios on the full $q^2$-range (high $q^2$-range) for different classes of leptoquark couplings. All $c \to ue^+e^-$ branching ratios are "SM-like" in the models studied. Additionally, $\mathcal{B}(D^0 \to \tau^\pm e^\mp) \sim 5 \cdot 10^{-9} \times$ |Wilson coefficient|$^2$.

# Branching Ratios

| | $\mathcal{B}(D^+ \to \pi^+ e^\pm \mu^\mp)$ | $\mathcal{B}(D^0 \to \mu^\pm e^\mp)$ | $\mathcal{B}(D^+ \to \pi^+ \nu\bar{\nu})$ |
|---|---|---|---|
| i) | $\lesssim 2 \cdot 10^{-13}$ | $\lesssim 7 \cdot 10^{-15}$ | $\lesssim 3 \cdot 10^{-13}$ |
| ii.1) | 0 | 0 | $\lesssim 8 \cdot 10^{-8}$ |
| ii.2) | 0 | 0 | $\lesssim 4 \cdot 10^{-12}$ |
| iii.1) | $\lesssim 2 \cdot 10^{-6}$ | $\lesssim 4 \cdot 10^{-8}$ | $\lesssim 2 \cdot 10^{-6}$ |
| iii.2) | $\lesssim 8 \cdot 10^{-15}$ | $\lesssim 2 \cdot 10^{-16}$ | $\lesssim 9 \cdot 10^{-15}$ |
| exp. | $\lesssim 3 \cdot 10^{-6}$ | $< 1.5 \cdot 10^{-8}$ (pre.) | $\sim 10^{-5}$ |




, Francesco's talk

# CP Asymmetries

$$A_{CP} \sim \mathrm{Im}[V_{cd}^* V_{ud} \Delta_9^*]\mathrm{Im}[c_d] f_+ + \mathrm{Im}[V_{cs}^* V_{us} \Delta_9^*]\mathrm{Im}[c_s] f_+ + (\mathrm{SM} \simeq 0)$$

$$\Delta_9 = C_9^{BSM} + C_9', \quad c_{d,s} = \frac{4\pi}{\alpha_s} 2 C_7^{\mathrm{eff}(d,s)} f_T \frac{m_c}{m_D} + C_9^{\mathrm{R}}|_{\rho,\phi} \frac{f_+}{V_{c(d,s)}^* V_{u(d,s)}}.$$

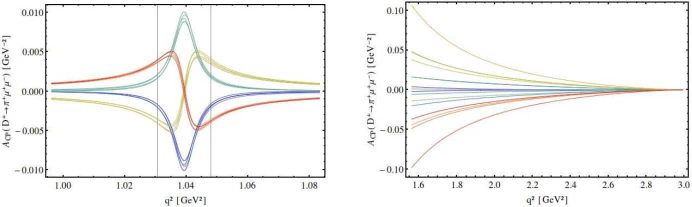



Figure: $A_{CP}$ normalized to the shown bins for case ii.2) around $\phi$ (left plot) and at high $q^2$ (right plot). From yellow (upper curves above $\phi$) to red (lower curves above $\phi$) each bunch represents $\delta_\phi = \pi/2, \pi, 0, 3/2\pi$.

Probe $Q_9 \sim \bar{u}cll$ independent of strong phases of $\phi$ and small $C_9$ as linked to $K/B$ physics at high $q^2$.

# Conclusion

(N)NLO calculation of the non-resonant SM $c \to ull$ branching ratios to resolve discrepancies in the literature.

BSM sensitivity in rare charm decays via

- $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$ above the resonances.
- angular observables.
- CP asymmetries.
- dineutrino and LFV modes.

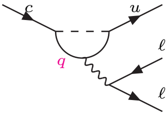
Leptoquark models link kaon/bottom physics (LNU) and direct searches as a bottom-up approach.

BSM physics depend on flavour patterns and vice versa.

# $C_9$ and Branching Ratios in the Literature

Scales are not consistently factorized, e.g. [Burdman et al. 2002], [Paul et al. 2011], [Wang et al. 2015]

$C_9(\mu_W) = \sum_{q=d,s,b} V_{cq}^* V_{uq} C_{9,\mathrm{IL}}^{(q)} \simeq -0.29,$

$C_{9,\mathrm{IL}}^{(q)} \sim$ 


yields discrepancies in branching ratios

$\mathcal{B}^{\mathrm{nr,SM}}_{D^+\to\pi^+\mu\mu} = 6 \cdot 10^{-12}$ [Fajfer et al. 2006],

$\mathcal{B}^{\mathrm{nr,SM}}_{D^+\to\pi^+\mu\mu} = [4.59, 8.04] \cdot 10^{-10}$ [Wang et al. 2015].

# SM Operator Basis

$$P_{1,2}^{(q)} = (\bar{u}_L \gamma_{\mu_1} T^a q_L)(\bar{q}_L \gamma^{\mu_1} T^a c_L)\,,$$

$$P_{3,4} = (\bar{u}_L \gamma_{\mu_1} T^a c_L) \sum_{\{q:m_q<\mu\}} (\bar{q} \gamma^{\mu_1} T^a q)\,,$$

$$P_{5,6} = (\bar{u}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} T^a c_L) \sum_{\{q:m_q<\mu\}} (\bar{q} \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} T^a q)\,,$$

$$P_7 = \frac{e}{g^2} m_c (\bar{u}_L \sigma^{\mu_1 \mu_2} c_R) F_{\mu_1 \mu_2}\,,$$

$$P_8 = \frac{1}{g} m_c (\bar{u}_L \sigma^{\mu_1 \mu_2} T^a c_R) G^a_{\mu_1 \mu_2}\,,$$

$$P_{9,10} = \frac{e^2}{g^2} (\bar{u}_L \gamma_{\mu_1} c_L) \left(\bar{l} \gamma^{\mu_1} \gamma_5 l\right)\,.$$