Rare Semileptonic Charm Decays

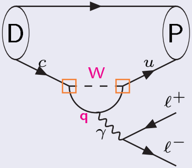
Stefan de Boer

TU Dortmund

CHARM 2015, 20.05.2015

$c \to u\ell\ell$

FCNC, in the SM:



Loop-suppressed

GIM-suppressed:

$$V_{cd}V_{ud}^* + V_{cs}V_{us}^* \sim \mathcal{O}\left(\lambda^5\right) \qquad \lambda \sim 0.22$$

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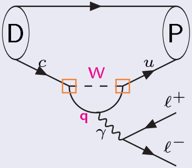

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$\rightsquigarrow$ Sensitive to BSM!

Complementary to rare b and s decays.

Check for theoretical tools.

Branching Fractions

High precision experiments:

(LHCb, CMS, BaBar, Belle II, CLEO-c, BESIII, ...)

Non-resonant [LHCb 2013] :

$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3 \times 10^{-8}$ @CL=90%

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$\mathcal{B}^{\text{nr,SM}}_{D^+\to\pi^+\mu\mu} = 6 \cdot 10^{-12}$ [Fajfer et al., 2005]

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Also: [Paul et al., 2011]

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$\rightsquigarrow$ Redo calculation!

Effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD}\times\text{QED}}\Big|_{\{q: m_q<\mu, \ell\}} + \mathcal{L}_{\text{eff}}^{\text{weak}} :$$

$$\mathcal{L}_{\text{eff}}^{\text{weak}}\Big|_{\mu\sim m_W} = \frac{4G_F}{\sqrt{2}} \sum_{q\in\{d,s,b\}} V_{cq}V_{uq}^{*} \times \Big(C_1(\mu)Q_1^{(q)}(\mu) + C_2(\mu)Q_2^{(q)}(\mu)\Big)$$

$$Q_1^{(q)} = (\overline{u}_L\gamma_{\mu_1}T^a q_L)(\overline{q}_L\gamma^{\mu_1}T^a c_L)\,,$$

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nNLO QCD Calculation in a Nutshell

Wilson coefficients:

- $\mu \sim m_W$: Match SM onto effective theory.

[In collaboration with Dirk Seidel.]

[hep-ph/9910220], [hep-ph/0411071], [hep-ph/0504194], [hep-ph/0612329]

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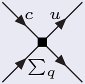
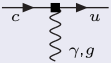
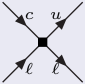
$Q_{3-6} \sim$ 

, $Q_{7,8} \sim$ 

, $Q_{9,10} \sim$ 

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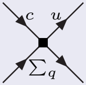
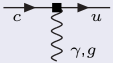
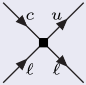
$Q_{3-6} \sim$ 

, $Q_{7,8} \sim$ 

, $Q_{9,10} \sim$ 

).

- $\mu \sim m_b \to \mu \sim m_c$: Scale via RGE.

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NNLO QCD Calculation in a Nutshell

Matrix elements at $\mu \sim m_c$:

- Relate $\langle Q_{1-6,8} \rangle \sim \langle Q_{7,9,10} \rangle$ perturbatively.

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- Parametrize form factor (f_+) via z-expansion (parameters fitted via $D \to \pi \ell \nu_\ell$).

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Branching Fractions

Ours (preliminary) :

$$\mathcal{B}^{\text{nr,SM}}_{D^+\to X_u^+ ee} \approx 1\cdot 10^{-9}\,, \quad \mathcal{B}^{\text{nr,SM}}_{D^+\to X_u^+ \mu\mu} \approx 2\cdot 10^{-10}$$

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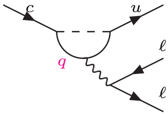
Burdman et al. and Wang et al.:

$$C_9(\mu_W) = \sum_q V_{cq}V^*_{uq}C^{(q)}_{9,\mathsf{IL}} \approx -0.29 \qquad C^{(q)}_{9,\mathsf{IL}} \sim$$



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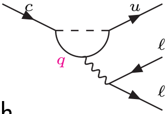
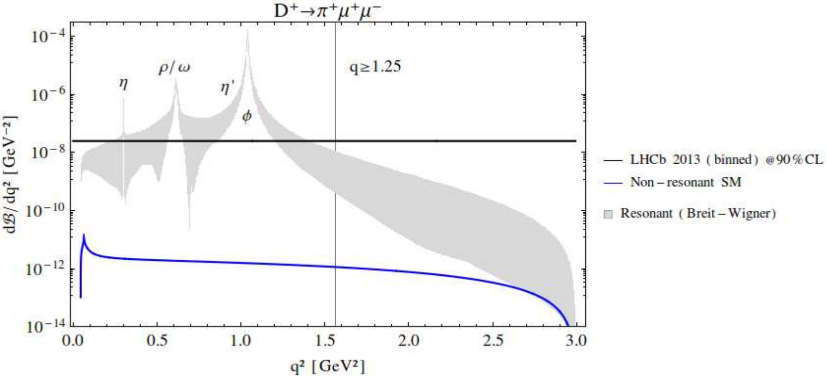


$\rightsquigarrow$ Not consistent within effective theory approach.

Decay Distribution (preliminary)



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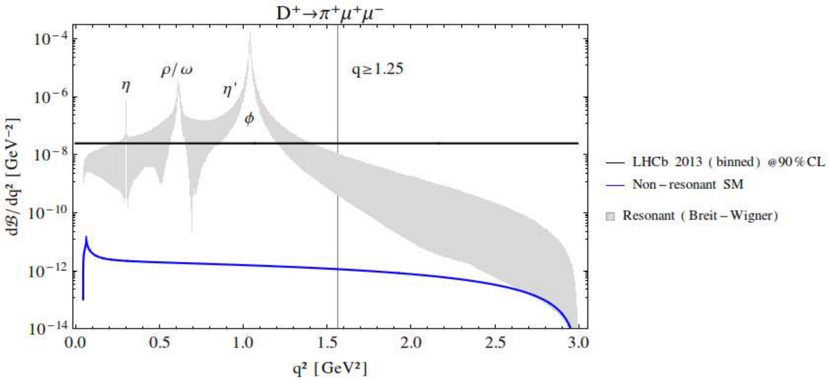

Ours:

$$\mathcal{B}^{\text{nr,SM}}_{D^+\to\pi^+\mu\mu}\big|_{q\geq 1.25\,\text{GeV}} \approx 7.5\cdot 10^{-13}\,{}^{+15\%}_{-14\%}(\bar{m}_s)\,{}^{+138\%}_{-46\%}(\mu_c)\,{}^{+27\%}_{-20\%}(f_+)$$

BSM: Leptoquarks

Scalar (3,3,-1/3) leptoquark: $\lambda_{S_3}(\mathbf{Q}_L^T i\tau_2\vec{\tau}\mathbf{L}_L)\cdot\vec{S_3}^{\dagger} \subset \mathcal{L}_{LQ}$

Vector (3,1,-5/3) leptoquark: $\lambda_{\tilde{V}_1}\bar{q}_R\gamma_\mu\ell_R(\tilde{V}_1^\mu)^\dagger \subset \mathcal{L}_{LQ}$

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Constrain masses via collider experiments: $M \gtrsim 1$ TeV

Constrain couplings via $\mathcal{B}(D^+ \to \pi^+ e^\pm \mu^\mp)$, $\mathcal{B}(D^0 \to \mu^+\mu^-)$, $\mathcal{B}(D^0 \to \mu^\pm e^\mp)$, x_D, y_D, atomic parity violation ...

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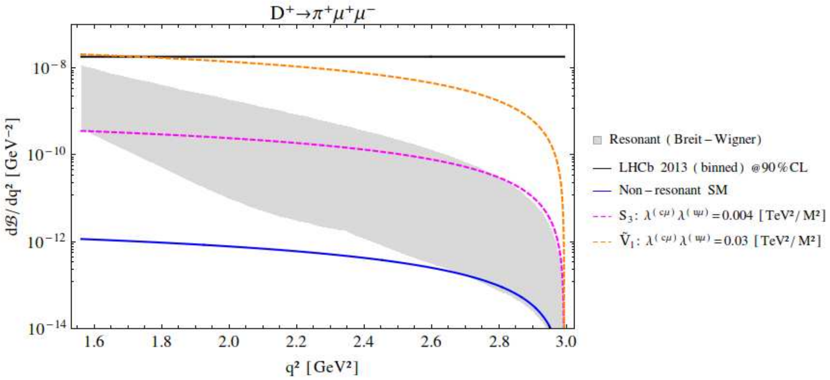
Apply hierarchical flavor pattern for S_3 [de Medeiros Varzielas and Hiller, 2015] .

BSM: Leptoquarks (preliminary)



$$\mathcal{B}^{S_3}_{D^+ \to \pi^+ ll}|_{q \geq 1.25\,\text{GeV}} \approx 2.4 \cdot 10^{-10}$$

$$\mathcal{B}^{\tilde{V}_1}_{D^+ \to \pi^+ ll}|_{q \geq 1.25\,\text{GeV}} \approx 1.4 \cdot 10^{-8}$$

Conclusion

$\mathcal{B}^{\mathsf{nr,exp}}(D^+ \to \pi^+\mu^+\mu^-) \lesssim 10^{-8}$

$\mathcal{B}^{\mathsf{nr,SM}}_{D^+\to\pi^+\mu\mu} \sim 10^{-12}$

$\rightsquigarrow$ Any signal is BSM physics!? Sensitivity to leptoquarks!?

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Outlook

- Extend this study.
- $D \to \rho\ell\ell$, $\Lambda_c \to p\ell\ell$, ...
- Look forward to experiments :)
- Let me know of your ideas!

Effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD}\times\text{QED}}\big|_{\{q:m_q<\mu,\ell\}} + \mathcal{L}_{\text{eff}}^{\text{weak}}$$

$$\mathcal{L}_{\text{eff}}^{\text{weak}}\big|_{m_W\geq\mu>m_b} = \frac{4G_F}{\sqrt{2}} \sum_{q\in\{d,s,b\}} V_{cq}V_{uq}^* \times \left(C_1(\mu)Q_1^{(q)}(\mu) + C_2(\mu)Q_2^{(q)}(\mu)\right)$$

$$\mathcal{L}_{\text{eff}}^{\text{weak}}\big|_{m_b>\mu\geq m_c} = \frac{4G_F}{\sqrt{2}} \sum_{q\in\{d,s\}} V_{cq}V_{uq}^* \times \left(C_1(\mu)Q_1^{(q)}(\mu) + C_2(\mu)Q_2^{(q)}(\mu) - \sum_{i=3}^{10} C_i(\mu)Q_i(\mu)\right)$$

SM dim 6 Operator Basis

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

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

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

$$Q_7 = \frac{e}{g^2} m_c (\overline{u}_L \sigma^{\mu_1 \mu_2} c_R) F_{\mu_1 \mu_2}$$

$$Q_8 = \frac{1}{g} m_c (\overline{u}_L \sigma^{\mu_1 \mu_2} T^a c_R) G^a_{\mu_1 \mu_2}$$

$$Q_{9,10} = \frac{e^2}{g^2} (\overline{u}_L \gamma_{\mu_1} c_L) \, (\overline{\ell} \gamma^{\mu_1} \gamma_5 \ell)$$

Branching Fraction

Theoretical status:

$$\mathcal{B}^{\text{nr,SM}}_{D^+\to\pi^+\mu\mu}|_{q\geq 1.25\,\text{GeV}} = [1.18, 2.08]\cdot 10^{-10}$$ [Wang et al., 2014]

No scale uncertainties.

S_3 Flavor Pattern

[de Medeiros Varzielas and Hiller, 2015] :

$$\lambda^{[\rho\kappa]} \sim \lambda_0 \begin{pmatrix} \rho_d\kappa & \rho_d & \rho_d \\ \rho\kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}$$

$$\rho_d \lesssim 0.02\,,\ \kappa \lesssim 0.5\,,\ 10^{-4} \lesssim \rho \lesssim 1\,,\ \kappa/\rho \lesssim 0.5\,,\ \rho_d/\rho \lesssim 1.6$$

$|\lambda_0^2 \rho\rho_d|$ constraint via rare Kaon decay and $|\lambda_0^2\rho||1-\kappa^2|$ fixed by means of R_K.