$c \to ull$

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08.12.2014

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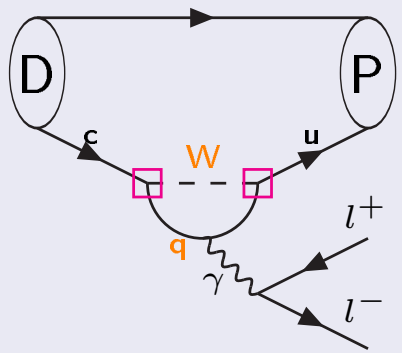
Charm decays

Rare semileptonic decays, e.g.

$D \to P l^+ l^- \quad D = c\{u,d,s\},\ P \in \{\pi, K\},\ l \in \{e,\mu\}$

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

SM FCNC



loop-suppressed

GIM-suppressed

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

- Suppressed in SM
- Up-type quark decay
- Sensitive to high energy scales
- Test of theoretical concepts

$\rightsquigarrow$ High precision physics (LHCb, CMS, BaBar, Belle II, CLEO-c, BESIII, ...)

Effective Lagrangian

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

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

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

SM dim6 operator basis

[hep-ph/9612313]

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

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

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

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

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

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

QCD calculation in a nutshell

- @$\mu \sim m_W$: match SM onto effective theory (NNLO)

  [hep-ph/9910220]

- $\mu \sim m_W \to \mu \sim m_b$: evolve via RGE (NNLO)

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

- @$\mu \sim m_b$: integrate b-quark (NLO)

- $\mu \sim m_b \to \mu \sim m_c$: resum logarithms to all order in perturbation theory (NNLO)

- @$\mu \sim m_c$: absorb $Q_{1-6,8}$ into $C^{\text{eff}}_{7,9,10}$ (NNLO)

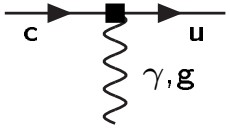
  [hep-ph/9603417], [arXiv:0810.4077]

Wilson coefficients at $\mu \sim m_c$ (preliminary)

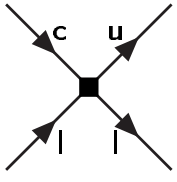
C_1	C_2
-0.600	+1.026

C_3	C_4	C_5	C_6
+0.003	-0.015	-0.000	-0.002

C_7	C_8
+0.008	-0.004



C_9	C_{10}
-0.005	0



Phenomenological analysis

Inclusive branching fractions (preliminary)

decay mode	$\mathcal{B}_{c\to ull}\frac{\mathcal{B}(D\to X_q l\nu)}{\mathcal{B}_{c\to q l\nu}}$
$D^+ \to X_u^+ e^+ e^-$	$1 \cdot 10^{-9}$
$D^+ \to X_u^+ \mu^+ \mu^-$	$3 \cdot 10^{-10}$
$D^0 \to X_u^+ e^+ e^-$	$5 \cdot 10^{-10}$
$D^0 \to X_u^+ \mu^+ \mu^-$	$1 \cdot 10^{-10}$
$D_s^+ \to X_u^+ e^+ e^-$	$5 \cdot 10^{-10}$
$D_s^+ \to X_u^+ \mu^+ \mu^-$	$1 \cdot 10^{-10}$

Exclusive decays

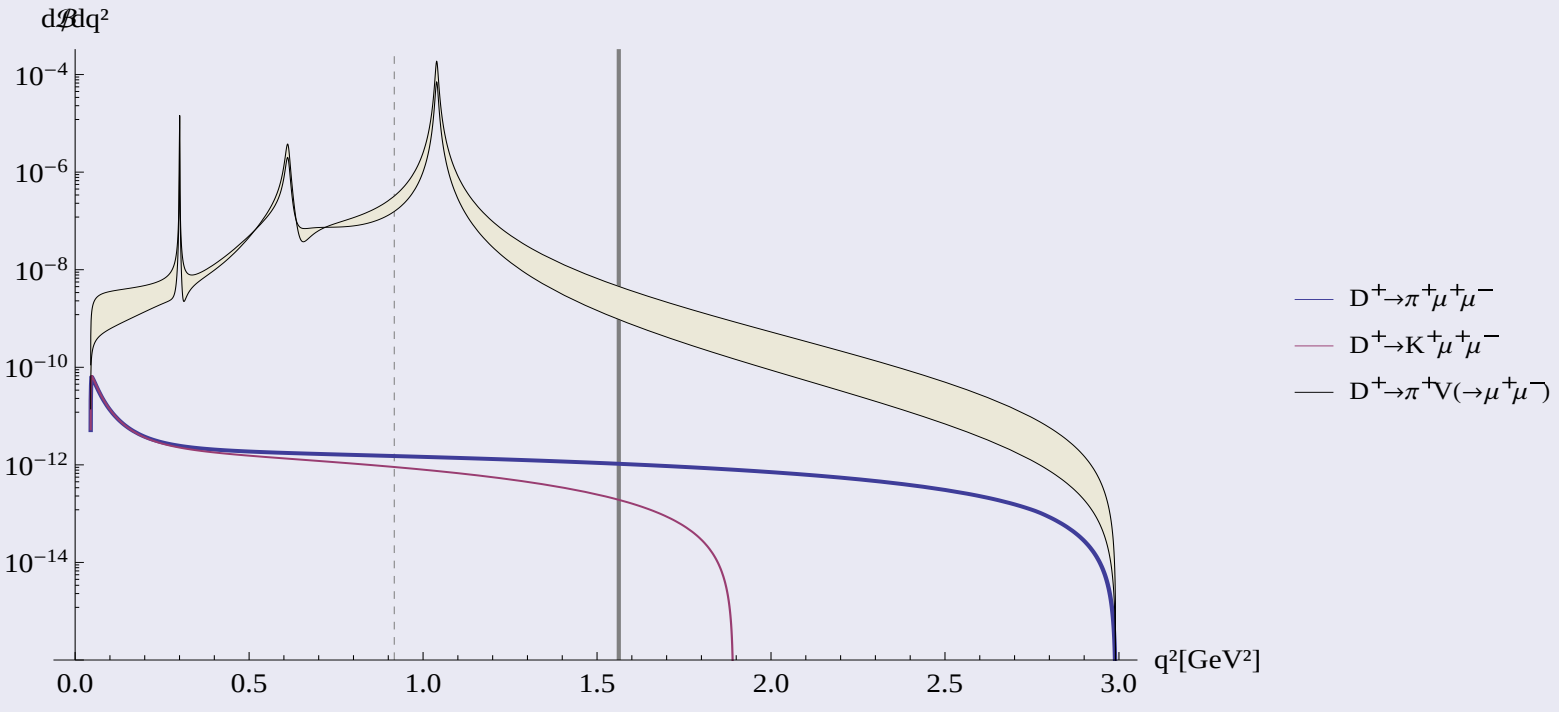
$$i\mathcal{A}(D \to Pll) \sim \sum C^{\text{eff}}_{7,9,10} \langle P|Q_{7,9,10}|D\rangle$$

- Hadronic matrix elements parametrized by means of three form factors
- Form factor relations (Isgur-Wise, $\mathcal{O}(\alpha_s)$ at low recoil)

  [hep-ph/0404250]
- (Single) form factor $\rightsquigarrow$ z-series parametrization

  [hep-ph/0906.2983]

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



[hep-ph/0511048]

$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)_{[1.25,2]} < 2.6 \times 10^{-8} \quad \text{@CL=90\%} \quad \text{[LHCb 2013]}$$

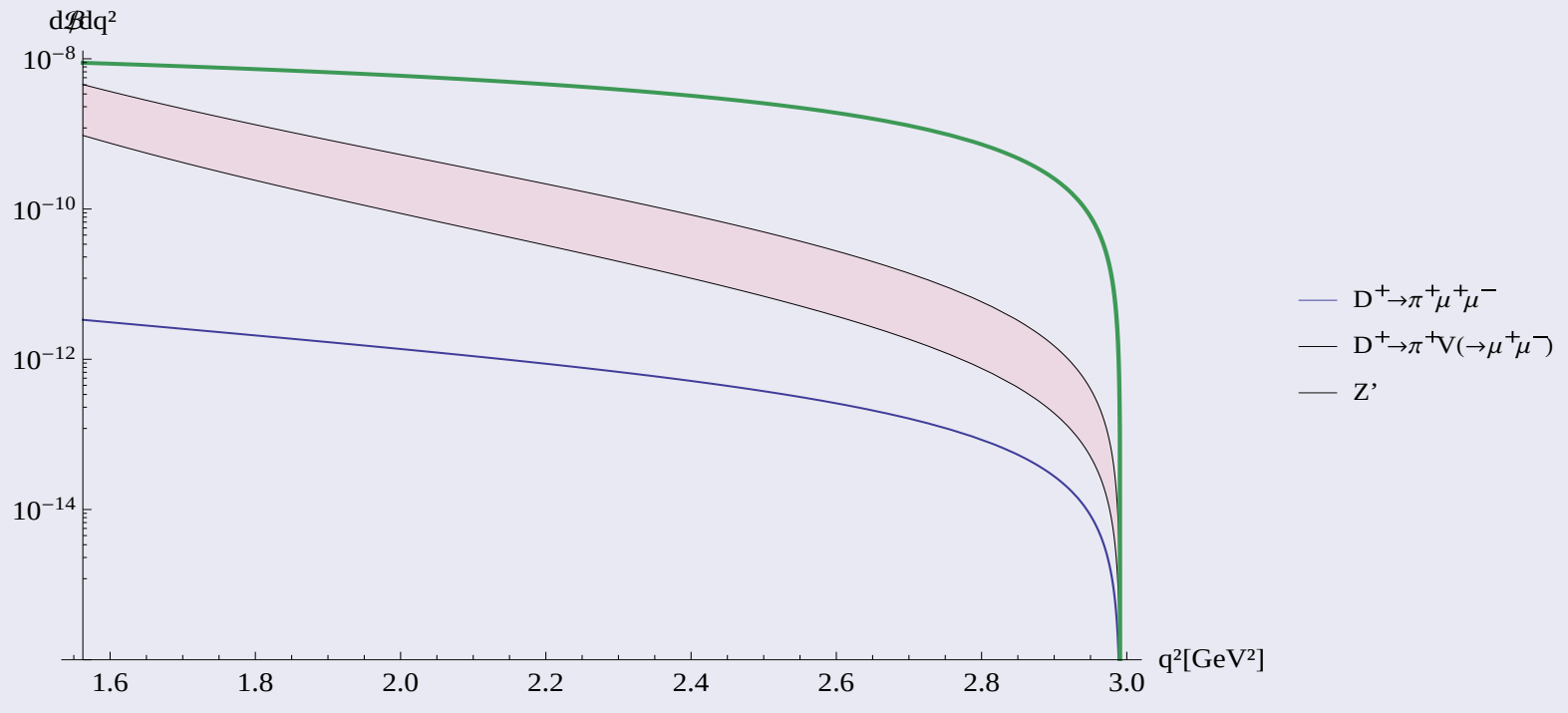
$\sqrt{q^2} \geq 1.25\,\text{GeV}$ (preliminary)

decay mode	branching fraction
$D^+ \to \pi^+ l^+ l^-$	$1 \cdot 10^{-12}$
$D^+ \to K^+ l^+ l^-$	$8 \cdot 10^{-14}$
$D^0 \to \pi^+ l^+ l^-$	$5 \cdot 10^{-13}$
$D^0 \to K^+ l^+ l^-$	$3 \cdot 10^{-14}$
$D_s^+ \to \pi^+ l^+ l^-$	$1 \cdot 10^{-12}$
$D_s^+ \to K^+ l^+ l^-$	$2 \cdot 10^{-13}$

BSM: neutral Z' gauge boson

$$\mathcal{L}_{Z'} \supset g_L^{(cu)} \bar{u} \not{Z}' P_L c + g_R^{(cu)} \bar{u} \not{Z}' P_R c + g_V^{(l)} \bar{l} \not{Z}' l + g_A^{(l)} \bar{l} \not{Z}' \gamma_5 l$$

$g_L^{(cu)} \sim 0.1,\ g_V^{(l)} \sim 0.1,\ m_{Z'} \sim 100\,\text{GeV}$ (preliminary)



What's done

Studied rare semileptonic charm to pseudoscalars decays, e.g.

$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)_{\text{LHCb}} < 2.6 \times 10^{-8}$

$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) \sim 10^{-12}$

at low recoil.

$\rightsquigarrow$ Any signal is BSM physics!?

What's to do

- Check and improve calculations, uncertainties ...
- Think of BSM physics
- $D \to \rho ll$, $\Lambda_c \to p\mu\mu$, ...?
- Looking for future experiments

$c \to ull$ in literature, e.g.

$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) = [4.59, 8.04] \cdot 10^{-10}$ [arXiv:1409.0181]

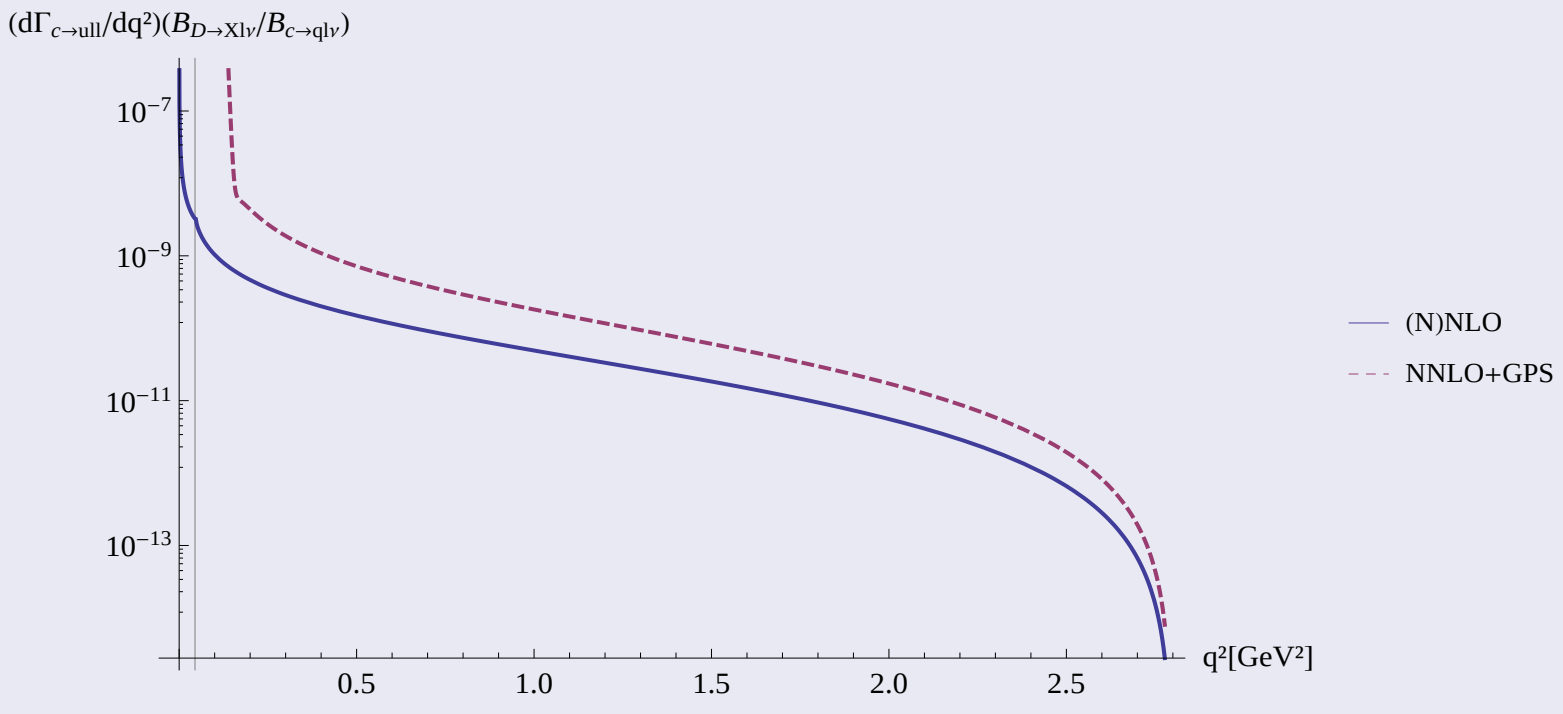
due to absorbing light quark fields into Wilson coefficients at $\mu \sim m_W$, i.e.

$$\sum_{q\in\{d,s,b\}} V_{cq}V_{uq}^* C_9^{(q)}(m_W) \approx V_{cs}V_{us}^* \frac{-2}{9} \ln \frac{m_s^2}{m_d^2} \approx -0.29$$

$2m_l \leq \sqrt{q^2} \leq m_D - m_P$ (preliminary)

decay mode	$\mathcal{B}_{l=e}$	$\mathcal{B}_{l=\mu}$
$D^+ \to \pi^+ l^+ l^-$	$8 \cdot 10^{-12}$	$4 \cdot 10^{-12}$
$D^+ \to K^+ l^+ l^-$	$7 \cdot 10^{-12}$	$3 \cdot 10^{-12}$
$D^0 \to \pi^+ l^+ l^-$	$3 \cdot 10^{-12}$	$2 \cdot 10^{-12}$
$D^0 \to K^+ l^+ l^-$	$3 \cdot 10^{-12}$	$1 \cdot 10^{-12}$
$D_s^+ \to \pi^+ l^+ l^-$	$5 \cdot 10^{-12}$	$3 \cdot 10^{-12}$
$D_s^+ \to K^+ l^+ l^-$	$4 \cdot 10^{-12}$	$2 \cdot 10^{-12}$

Inclusive differential decay distribution (preliminary)



Greub, Pilipp, Schupbach [arXiv:0810.4077]