Charm decays

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From beauty to charm

- From Elba island to Novosibirsk: $\sim 6.000\,\text{km}$, two weeks

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- From Elba island to Novosibirsk: $\sim 6.000\,\text{km}$, two weeks
- Experimentally, b-machines are also charm-machines, see next talks
- Theoretically, adopt results from b-physics
  - but, decays into τ-leptons suppressed/forbidden, $1/m_c$-counting questionable, short-long distance behavior challenging, ...
- Presently, charm is little sister of beauty in the flavor family: Both can learn from each other, *e.g.*, complementary in BSM searches, charm represents uniquely up-type sector, insights into QCD from charm

Charm decays

Selection/recent developments

1. Leptonic and semileptonic decays
2. Hadronic two-body decays
3. Rare decays
   - back to beauty

Leptonic and semileptonic decays

"determine SM parameters"

Leptonic and semileptonic decays

CKM matrix $\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$,

decay constants f_D, form factors f_+ and f_0

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- Singly-Cabibbo-suppressed decays:

  GIM-cancellation $(V_{ud}V_{cd}^* + V_{us}V_{cs}^*) \ll 1$ and

  weak phases $|V_{ub}V_{cb}^*| \ll 1$

Leptonic and semileptonic decays

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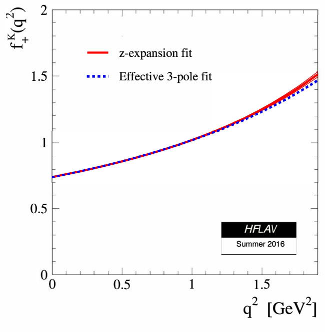
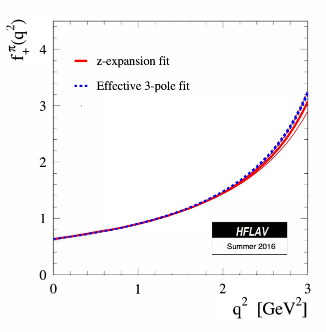
- $\mathcal{A}(D \to l\nu) \sim V_{cq}^* \langle 0|\bar{q}\gamma_\mu\gamma_5 c|D(p')\rangle = V_{cq}^*[ip'_\mu f_D]$
- $\mathcal{A}(D \to Pl\nu) \sim V_{cq}^* \langle P(p)|q\gamma_\mu c|D(p')\rangle =$
  $V_{cq}^* \left[f_+(q^2) \left((p'+p)_\mu - \frac{m_D^2 - m_P^2}{q^2} q_\mu \right) + f_0(q^2) \frac{m_D^2 - m_P^2}{q^2} q_\mu \right]$,
  $q^2 = (p'-p)^2$
- $f_0(q^2)$ suppressed in charm decays

Form factors

Interplay of experiments and lattice QCD.





precise, in agreement with lattice QCD, recently, $(N_f = 2+1+1)$ [ETM: 1706.03017].

f_0 only from lattice QCD.

Decay constants

	f_D [MeV]	f_{D_s} [MeV]
HFLAV 2016 (exp)	203.7(4.9)	257.1(4.6)
FLAG 2016 ($N_f = 2+1+1$)	212.15(1.45)	248.83(1.27)

Experiments (assuming CKM unitarity) and lattice QCD compatible at 2σ.

Recent ($N_f = 2 + 1$) [RBC/UKQCD: 1701.02644], ($N_f = 2 + 1 + 1$) [Fermilab Lattice/MILC: 1712.09262] computations with individual uncertainties similar to 2016 averaged ones.

QCD sum rule calculations compatible, with larger uncertainties, *e.g.*, $f_D = (208 \pm 10)$ MeV, $f_D = (240 \pm 10)$ MeV [Wang: 1506.01993].

Hadronic two-body decays

"test the SM"

Hadronic two-body decays

with $D \to P_1 P_2$, $P_{1,2} = \pi, K$.

For singly-Cabibbo-suppressed decays:

$\mathcal{A} = \lambda_{sd} A_{sd} - \frac{\lambda_b}{2} A_b, \qquad \lambda_q = V_{cq}^* V_{uq}, \ \lambda_{sd} = \frac{\lambda_s - \lambda_d}{2}$

$SU(3)_F$-symmetry relates different decay modes.

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$SU(3)_F$-symmetry relates different decay modes.

Branching ratios, *here*, [Nierste et al: 1503.06759, 1508.00074, 1506.04121, 1708.03572]:

- Topological amplitudes + diagrammatic $SU(3)_F$-breaking
- Fit to branching ratio data + $1/N_c$ input
- Results: $SU(3)_F$-limit excluded by more than 5σ. Around 30% $SU(3)_F$-breaking in decay amplitudes sufficient.

Hadronic two-body decays

CP asymmetries: $a_{CP}^{\text{dir}} = \text{Im}\frac{\lambda_b}{\lambda_{sd}}\,\text{Im}\frac{A_b}{A_{sd}}$ $\quad (\text{Im}\frac{\lambda_b}{\lambda_{sd}} \simeq -6 \times 10^{-4})$

- $|A_{sd}|$ from branching ratio fit
- CP asymmetries require additional combinations of amplitudes, not provided by branching ratio fit
  - but, sum rules correlate different CP asymmetries eliminating these combinations
- Two strategies:
  - Falsify SM with sum rules, or clean predictions
  - Discover CP-violation in charm: large SM predictions favored

Also, $A_{CP}(D^+ \to \pi^+\pi^0) \simeq 0$ from isospin sum rules, *e.g.*, [Grossmann et al: 1204.3557], compatible with
$a_{CP}^{\text{dir}} = +0.0231 \pm 0.0124 \pm 0.0023$ [Belle: 1712.00619]

Hadronic two-body decays

Discover CP-violation in charm:

- $D^0 \to K_s K_s$: $|a_{CP}^{\rm dir}| \leq 1.1\%$ [Nierste et al: 1508.00074]
  from sizable tree level exchange, and since $A_{sd} = 0$ in $SU(3)_F$-limit while $A_b \neq 0$.
  Experimentally, $A_{CP} = -0.0002 \pm 0.0154$, statistical uncertainty dominant [Belle: 1705.05966], see Giulia's poster for LHCb measurement.
- $D \to K_s K^{*0}$: $|a_{CP}^{\rm dir}| \leq 0.3\%$ [Nierste et al: 1708.03572]
  Experimentally favored (charged tracks from prompt $K_s K^{*0}$ decay, Dalitz plot analysis, no flavor tagging required), first study [LHCb: 1509.06628].

Many more works, *e.g.*, [Brod et al: 1203.6659, Hiller et al: 1211.3734, Khodjamirian et al: 1706.07780].

Progress in lattice QCD [Hansen et al: 1204.0826].

Summary "SM decays"

- Decay constants and $D \to P$ form factors precisely known from experiments and (recent) lattice QCD computations with competing uncertainties.

- Sizable $SU(3)_F$-breaking in two-body hadronic decays from branching ratio fit.
- SM CP asymmetries can be $\sim 1\%$ in $D^0 \to K_s K_s$ and $D \to K_s K^{*0}$.

Rare decays

"search BSM physics"

SM anatomy - perturbative:

- Lagrangian $\mathcal{L}_{\text{eff}}^{\text{weak}} \sim \sum_i C_i P_i$ and operators, *e.g.*,

$$P_{2(1)} \sim (\bar{u}_L \gamma_\mu (T^a) q_L)(\bar{q}_L \gamma^\mu (T^a) c_L)\,,$$
$$P_7^{(\prime)} \sim (\bar{u}_{L(R)} \sigma^{\mu\nu} c_{R(L)}) F_{\mu\nu}\,,$$
$$P_{9(10)} \sim (\bar{u}_L \gamma_\mu c_L)(\bar{\ell} \gamma^\mu (\gamma_5) \ell)\,.$$

  Two-step matching (m_W, m_b), light quarks (b, s, d) in loops.

- (Effective) Wilson coefficients $C_i^{(\text{eff})}$ known at same order as in b-physics [Greub et al: 9603417, Fajfer et al: 0209250, SdB et al: 1606.05521, 1707.00988].

Rare decays

SM anatomy - $c \to u$ characteristics:

- $C_{10} \simeq 0$ (broken by, *e.g.*, electromagnetic effects)

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SM anatomy - $c \to u$ characteristics:

- $C_{10} \simeq 0$ (broken by, *e.g.*, electromagnetic effects)
- Largest contribution to $C_{7,9}^{\text{eff}}$ [SdB: 1707.00988]:

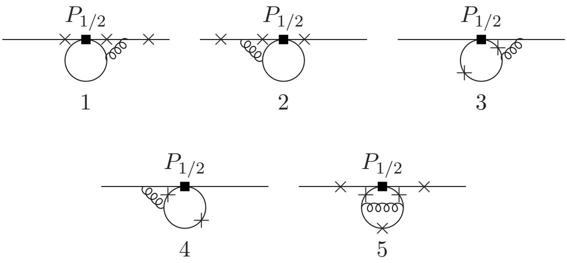
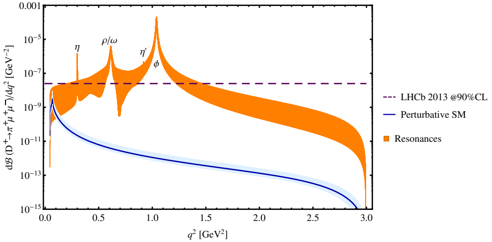


Figure: Diagrams for heavy to light quark transitions at two loop QCD. The boxes denote operator insertions of $P_{1/2}$. The crosses indicate the emission of a photon, which may then couple to a lepton pair.

Calculation valid for arbitrary momentum transfer and also for b-decays.

SM anatomy - from partons to hadrons:



[1510.00311] updated

Resonances evade GIM-mechanism, dominate branching ratios, uncertain, *e.g.*, [Feldmann et al: 1705.05891].

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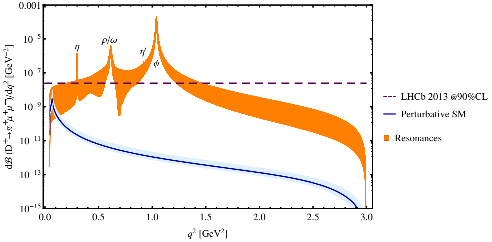

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Resonances evade GIM-mechanism, dominate branching ratios, uncertain, *e.g.*, [Feldmann et al: 1705.05891].

<u>But</u>, SM features of rare charm decays:

- "Resonance-catalyzed" observables [Fajfer et al: 1208.0759]
- SM weak phases are small
- Symmetries of QCD, QED

Rare decays

Where to search for (heavy) BSM physics:

- Windows in branching ratios, *e.g.*, at high q^2
- Null tests based on (approximate) symmetries
- Extract SM contribution from SM-dominated modes and use $SU(3)_F$

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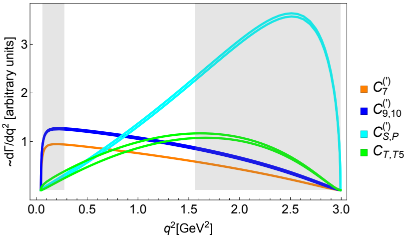
with different decays/observables to probe SM, sort BSM models

Figure: Comparison of short-distance spectrum sensitivities to different Wilson coefficient in $D^+ \to \pi^+\mu^+\mu^-$.



[1510.00965]

Branching ratios

$D^0 \to \mu^+\mu^-$:

- Strongest constraints on difference of (pseudo)scalar Wilson coefficients from $\mathcal{B}_{\text{exp}} < 6.2 \times 10^{-9}$ [LHCb: 1305.5059]
- SM branching ratio commonly estimated orders of magnitude below $\mathcal{B}_{\text{exp}}$ [Burdman et al: 0112235, Fajfer et al: 0104236, Paul et al: 1008.3141]
- $\mathcal{B}_{\text{BSM}} \lesssim \mathcal{B}_{\text{exp}}$, *e.g.*, two Higgs doublet and leptoquark models [Burdman et al: 0112235, Golowich et al: 0903.2830, Paul et al: 1008.3141, 1212.4849, Wang et al: 1409.0181, SdB et al: 1510.00311, Fajfer et al: 1510.00965]

$e^+e^- \to D^{0*}$: Probes (axial)vector Wilson coefficients, $\mathcal{B}_{\text{SM}} \sim 10^{-18}$, $\mathcal{B}_{Z'} < 2.5 \times 10^{-11}$ [Khodjamirian et al: 1509.07123]

SM null tests

for $c \to u\ell\ell^{(\prime)}$ induced decays, *e.g.*, $D \to P\ell\ell$, $D \to PP\ell\ell$:

- **CP-asymmetries** $A_{CP}^{\mathrm{SM}} \sim \frac{\mathrm{Im}\lambda_b}{\lambda_s} \sim 10^{-3}$
- **Angular distributions**, *e.g.*, dilepton forward-backward asymmetry; involve C_{10}, (pseudo)scalar and tensor operators, all suppressed in SM

SM null tests

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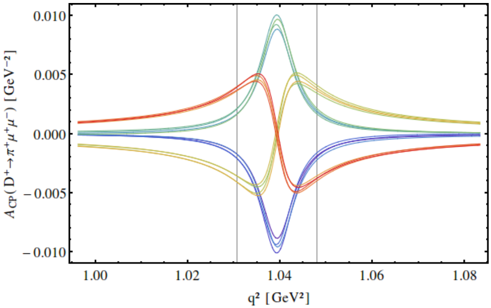
- **CP-asymmetries**.
- **Angular distributions**.
- **Lepton-universality**, ratios muons/electrons equal one + percent [Fajfer et al: 1510.00965]; experimentally, same cuts required, electrons less constrained, *e.g.*, [BESIII: 1802.09752]
- **Lepton-flavor-violation**, also quarkonium decays; absent in SM [Burdman et al: 0112235, SdB et al: 1510.00311, Hazard et al: 1607.00815, 1711.05314].
- **Decays into neutrinos** vanish in SM; also probe dark matter [Burdman et al: 0112235, Badin et al: 1005.1277, Paul et al: 1212.4849, SdB et al: 1510.00311, Belle: 1611.09455].

model	A_{CP}	A_{FB}
Leptoquark models	$\gtrsim A_{CP}^{\mathrm{SM}}$	$\lesssim 8 \times 10^{-1}$
Little Higgs model	$\lesssim \mathcal{O}(10^{-3})$	$\lesssim \mathcal{O}(5 \times 10^{-3})$
Minimal SUSY SM	$\lesssim \mathcal{O}(10^{-3})$	$\lesssim \mathcal{O}(10^{-1})$
Up vector-like quark singlet	–	$\lesssim 10^{-3}$
Warped extra dimension	$\lesssim \mathcal{O}(10^{-2})$	$\lesssim \mathcal{O}(5 \times 10^{-2})$
Z' boson	–	~ 0
SM	$< \mathcal{O}(10^{-3})$	~ 0

[Fajfer et al: 9805461, 0106333, 0511048, 0610032, 0706.1133, 0810.4858, 1510.00965, Burdman et al: 0112235, Paul et al: 1101.6053, 1212.4849, Bigi et al: 1110.2862, Delaunay et al: 1207.0474, Cappiello et al: 1209.4235, Wang et al: 1409.0181, SdB et al: 1510.00311, Guo et al: 1703.08799, Sahoo et al: 1705.02251]

Example: "Resonance-catalyzed" CP asymmetry

Scalar leptoquark (3,3,-1/3) + flavor pattern (inspired by b-decays [de Medeiros Varzielas et al: 1503.01084]) + constraints from Kaon decays ($SU(2)_L$)



[1510.00311]

probes C_9^{BSM} independent of strong phases ($\pi/2, \pi, 0, 3/2\pi$) around ϕ

Radiative (rare) decays

$c \to u\gamma$ induced decays:

- Branching ratios dominated by long-distance effects, uncertain [Burdman et al: 9502329, Khodjamirian et al: 9506242, Fajfer et al: 9705327, 9801279, 0012116, 0209250, Dimou et al: 1212.2242, SdB et al: 1701.06392, Biswas et al: 1702.05059, Dias et al: 1711.09924].
  $B_c \to B_u^*\gamma$ and $\Gamma(D^0 \to \rho^0\gamma)/\Gamma(D^0 \to \omega\gamma)$ could be modes to search for BSM physics [Fajfer et al: 9901252, 0006054].
- CP-asymmetries [Isidori et al: 1205.3164, Lyon et al: 1210.6546, SdB et al: 1701.06392]:
  $A_{CP}^{\rm SM} < \mathcal{O}(10^{-3}), \quad A_{CP}^{\rm BSM} \lesssim 10\%,$
  $A_{CP}^{\rm exp}(D^0 \to \rho^0\gamma) = 0.056 \pm 0.152$, statistical uncertainty dominant [Belle: 1603.03257].

Radiative (rare) decays

Photon polarization, C_7'/C_7 (following b-analyses [Gronau et al: 0107254, 0205065, 1704.05280, Hiller et al: 0108074, Müheim et al: 0802.0876, Kou et al: 1011.6593, 1604.07708, 1802.09443, LHCb: 1402.6852]):

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- Time-dependent analysis: Relate SM-dominated $\bar{D}^0 \to \bar{K}^{*0}\gamma$ to $\bar{D}^0 \to (\rho^0/\omega, \phi)\gamma$ using data + $SU(3)_F$ and extract BSM contribution [Lyon et al: 1210.6546, SdB et al: 1802.02769]

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- Up-down asymmetry: $D \to \bar{K}_1(\to \bar{K}\pi\pi)\gamma$, experimentally, no dependence on strong phases between C_7 and C_7', heavier resonances phase space suppressed, but D-tagging required [SdB et al: 1802.02769]

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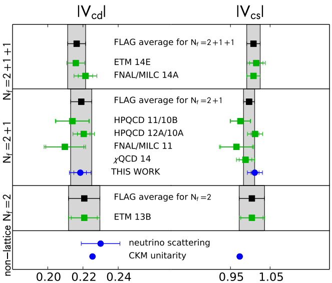
- Look into the future: Photon forward-backward asymmetry in $\Lambda_c \to p\gamma$ [SdB et al: 1701.06392]

Summary "BSM decays"

- BSM physics links flavor sectors.
- The structure of charm flavor-changing-neutral-current transitions allows to uniquely probe the SM and BSM physics with many decays and observables - despite branching ratios being dominated by long-distance effects.
- Not to forget: Rare charm decays may help to improve our understanding of QCD/check theoretical frameworks.
- The little sister of beauty is growing up: Rare charm decays at the level of rare b-decays back twenty years.
- Many experiments, *e.g.*, Belle (II), BESIII, LHCb and theoretical works ongoing, *e.g.*, [SdB, Hiller: $D \to PP\ell\ell$, to appear].

CKM elements V_{cd} and V_{cs}

Figure: From leptonic decays, HPQCD 11/10B for semileptonic decays. Update of FLAG 2016 including [RBC/UKQCD: 1701.02644].



[1701.02644]

Uncertainties one order of magnitude larger than from CKM unitarity.

Recently, $(N_f = 2+1+1)$ computations [ETM: 1706.03657, Fermilab Lattice/MILC: 1712.09262].

While lattice is including QED effects non-perturbatively, more precise experimental measurements are needed for CKM elements from leptonic decays.

$D \to V$ and $\Lambda_c \to N$ form factors

$D \to V$ form factors:

- Experimental results for $D \to \rho$ [CLEO-c: 1112.2884], $D \to \omega$ [BESIII: 1508.00151] and $D \to K^*$ [BESIII: 1512.08627]
- Lattice QCD [Flynn et al: 9710057, UKQCD: 0109035]
- Light-cone sum rules [Wu et al: 0604007]

Mostly, older results, at $q^2 = 0$, with large uncertainties and not fully compatible.

Recently, $\Lambda_c \to N$ form factors from lattice QCD [Meinel: 1712.05783].

From $D^0 \to e^+e^-$ to $e^+e^- \to D^{0*}$

- $D^0 \to e^+e^-$?
  Helicity suppressed, misidentification from $\mathcal{O}(\alpha m_D^2/m_e^2)$ enhanced $D^0 \to e^+e^-\gamma$ with soft photons [Fajfer et al: 0209250].
- $D^{0*} \to e^+e^-$?
  No helicity suppression, but D^{0*} decays strongly/electromagnetically (for $D^{0*} \to \mu^+\mu^-$ also misidentification from $D^{0*} \to \pi^+\pi^-$).
- $e^+e^- \to D^{0*}$! [Khodjamirian et al: 1509.07123]