Radiative three-body D-meson decays in and beyond the SM

Nico Adolph
in collaboration with
Gudrun Hiller and Joachim Brod

based on arXiv:2009.14212 and arXiv:2104.08287

Technische Universität Dortmund
Theoretische Physik IV

04.06.2021

Introduction

- Radiative decays are of particular interest for BSM searches in the electromagnetic dipole operators.
- Theoretical studies mainly focused on resonant decays $D \to V\gamma$
- experimental data on $D^0 \to \rho^0/\omega/\overline{K}^*/\Phi\gamma$
- In comparison to the resonant decays $D \to V\gamma$, the three-body decays provide more information due to its decay distributions and angular observables.

Decay channels

- We covered 14 of 18 decay channels $D \to PP\gamma$ $(P = \pi, K)$ which are induced by dimension 6 operators

  CF: $D^0 \to \pi^0 \overline{K}^0 \gamma\,,\; D^0 \to \pi^+ K^- \gamma\,,\; D^+ \to \pi^+ \overline{K}^0 \gamma\,,\; D_s \to \pi^+ \pi^0 \gamma\,,\; D_s \to K^+ \overline{K}^0 \gamma$

  SCS: $D^0 \to \pi^+ \pi^- \gamma\,,\; D^0 \to K^+ K^- \gamma\,,\; D^+ \to \pi^+ \pi^0 \gamma\,,$

  $D^+ \to K^+ \overline{K}^0 \gamma\,, D_s \to \pi^+ K^0 \gamma\,,\; D_s \to K^+ \pi^0 \gamma\,,$

  DCS: $D^+ \to \pi^+ K^0 \gamma\,, D^+ \to K^+ \pi^0 \gamma\,,\; D_s \to K^+ K^0 \gamma$

  Also studied in [Fajfer et al.('02)] and [Fajfer et al.('02)]

- not covered so far

  SCS: $D^0 \to \pi^0 \pi^0 \gamma\,,\; D^0 \to K^0 \overline{K}^0 \gamma$

  DCS: $D^0 \to \pi^0 K^0 \gamma\,, D^0 \to K^+ \pi^- \gamma$

- $D^+ \to K^+ K^0 \gamma$ and $D_s \to \pi^+ \overline{K}^0 \gamma$ are $|\Delta s| = 2$ processes and are not induced by dimension 6 operators

$c \to u\gamma$ Lagrangian

- The weak decays can be described by the effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \left(\sum_{q,q' \in \{d,s\}} V_{cq}^* V_{uq'} \sum_{i=1}^{2} C_i O_i^{(q,q')} + \sum_{i=3}^{6} C_i O_i + \sum_{i=7}^{8} \left(C_i O_i + C_i' O_i' \right) \right) ,$$

The relevant operators are

$$O_1^{(q,q')} = \left(\overline{u}_L \gamma_\mu T^a q_L'\right) \left(\overline{q}_L \gamma^\mu T^a c_L\right) , \quad O_2^{(q,q')} = \left(\overline{u}_L \gamma_\mu q_L'\right) \left(\overline{q}_L \gamma^\mu c_L\right) ,$$

$$O_7 = \frac{e m_c}{16\pi^2} \left(\overline{u}_L \sigma^{\mu\nu} c_R\right) F_{\mu\nu} , \quad O_7' = \frac{e m_c}{16\pi^2} \left(\overline{u}_R \sigma^{\mu\nu} c_L\right) F_{\mu\nu}$$

- $C_{1,2}$ obtain $\mathcal{O}(1)$ values
- $C_{3-8}^{(\prime)}$ can be neglected in the SM due to the GIM mechanism.
- model independent constraints from $D \to \rho\gamma$ and $D \to \pi ll$: $|C_7^{(\prime)}| \lesssim 0.3$ [de Boer, Hiller('18)] [Bause et al.('19)]
- For BSM scenarios with $|C_8^{(\prime)}(\Lambda^{\text{NP}})| \gg |C_7^{(\prime)}(\Lambda^{\text{NP}})|$, data on ΔA_{CP} constraints $|\text{Im}(C_7^{(\prime)})| \simeq |\text{Im}(C_8^{(\prime)})| \lesssim 2 \cdot 10^{-3}$ [Isodori, Kamenik('12)]

General information on $D \to PP\gamma$

- Double differential decay rate for $D(P) \to P_1(p_1)P_2(p_2)\gamma(k,\epsilon^*)$ is given by

$$\frac{\mathrm{d}^2\Gamma}{\mathrm{d}s\mathrm{d}t} = \frac{|A_-|^2 + |A_+|^2}{128(2\pi)^3 m_D^3} f(s,t,m_D,m_1,m_2)$$

$$s = (p_1+p_2)^2\,, \quad t = (p_2+k)^2\,, \quad u = (p_1+k)^2$$

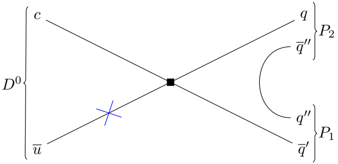
- parity odd ($\mathcal{A}_-$) and parity even ($\mathcal{A}_+$) contributions are defined by the general Lorentz decomposition of the decay amplitude

$$\mathcal{A}(D \to P_1P_2\gamma) = A_-(s,t)\left[(p_1\cdot k)(p_2\cdot\epsilon^*) - (p_2\cdot k)(p_1\cdot\epsilon^*)\right] + A_+(s,t)\epsilon^{\mu\alpha\beta\gamma}\,\epsilon^*_\mu p_{1\alpha}p_{2\beta}k_\gamma\,.$$

QCD models

1. Leading weak annihilation contribution with QCDF methods

$$\mathcal{A}_{\pm}^{WA} \propto \frac{1}{\lambda_{D_{(s)}}} \tilde{C} f^{P_1 P_2}(s)$$



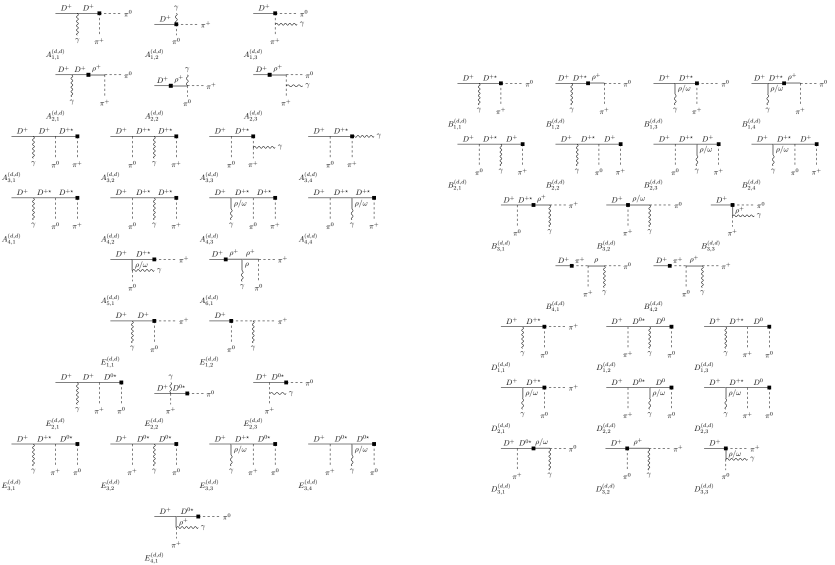
   - $\tilde{C} = \begin{cases} \frac{4}{9} C_1 + \frac{1}{3} C_2 & \text{for } D^0 \\ C_2 & \text{for } D^+_{(s)} \end{cases}$
   - independent of t
   - holds for small invariant masses s

2. Soft photon approximation / Low's Theorem

$$\mathcal{A}_{-}^{Low} = -\frac{e\mathcal{A}(D^+_{(s)} \to P_1 P_2)}{(p_1 \cdot k)(p_2(P) \cdot k)}\,, \qquad \mathcal{A}_{+}^{Low} = 0$$

3. Heavy hadron chiral perturbation theory extended by light vector resonances
   - we replace the model's own bremsstrahlung by $\mathcal{A}^{\text{Low}}$ to enforce the fulfillment of the Low Theorem.

QCD models



- HHχPT Feynman diagrams contributing to the decay $D^+ \to \pi^+\pi^0\gamma$ within the SM.

Observables

1. (Differential) branching ratios
2. Forward-backward asymmetry

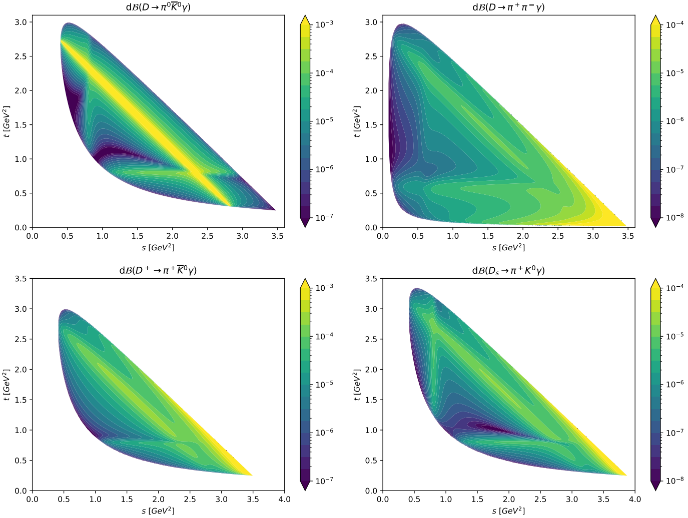
$$A_{\mathrm{FB}}(s) = \frac{\int_{t_{\min}}^{t_0} dt \frac{\mathrm{d}^2\Gamma}{\mathrm{d}s\mathrm{d}t} - \int_{t_0}^{t_{\max}} dt \frac{\mathrm{d}^2\Gamma}{\mathrm{d}s\mathrm{d}t}}{\int_{t_{\min}}^{t_0} dt \frac{\mathrm{d}^2\Gamma}{\mathrm{d}s\mathrm{d}t} + \int_{t_0}^{t_{\max}} dt \frac{\mathrm{d}^2\Gamma}{\mathrm{d}s\mathrm{d}t}}$$

$$t_{\min} \leq t \leq t_0 \quad \leftrightarrow \quad 0 \leq \cos(\theta_{2\gamma}) \leq 1$$

3. CP-asymmetry

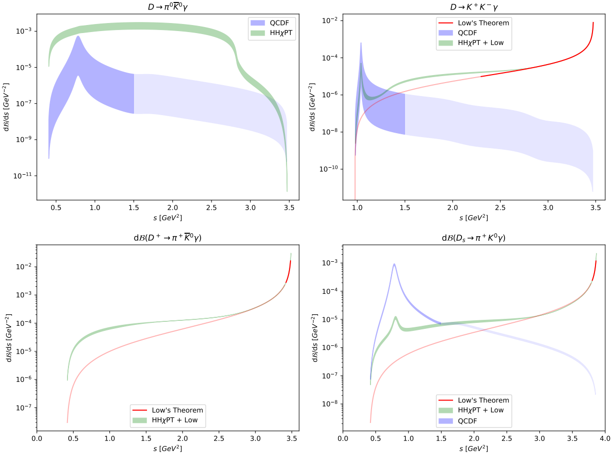
$$A_{\mathrm{CP}}(s) = \int \mathrm{d}t A_{\mathrm{CP}}(s,t)\,, \quad A_{\mathrm{CP}}(s,t) = \frac{1}{\Gamma + \overline{\Gamma}} \left(\frac{\mathrm{d}^2\Gamma}{\mathrm{d}s\mathrm{d}t} - \frac{\mathrm{d}^2\overline{\Gamma}}{\mathrm{d}s\mathrm{d}t} \right) .$$

SM Dalitz plots based on HHχPT

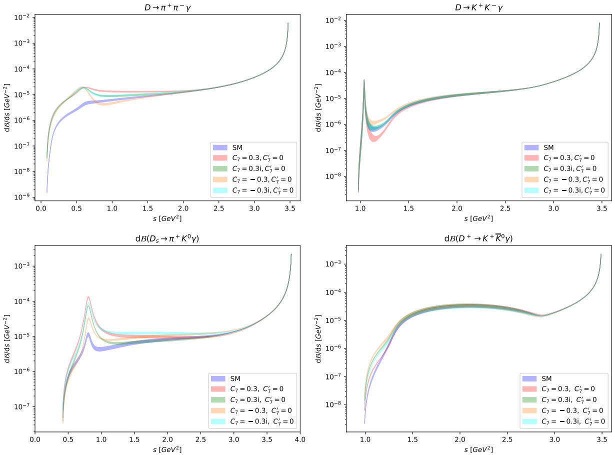


technische universität dortmund

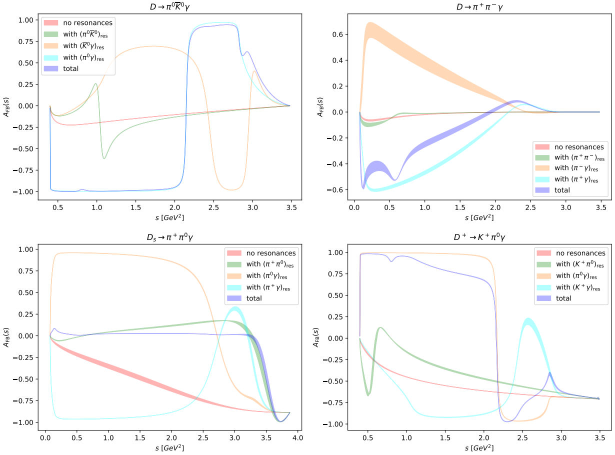
Single differential branching ratios in the SM



BSM impact on branching ratios (HHχPT)

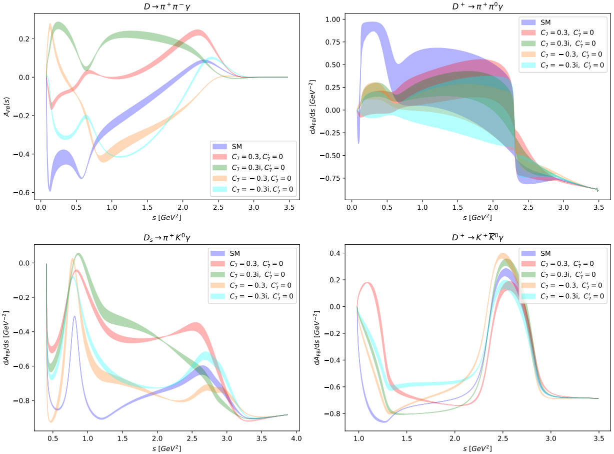


SM A_{FB} based on HHχPT

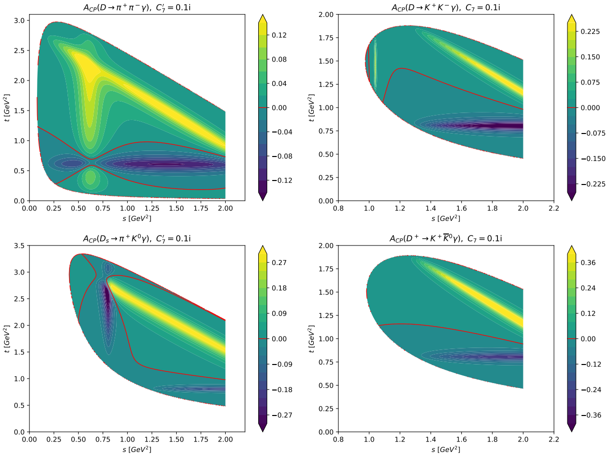


- $A_{\mathsf{FB}} = 0$ in QCDF due to the independence of t

BSM impact on A_{FB} (HHχPT)



A_{CP} based on HHχPT



- About a factor of 1000 larger than the SM predictions
- Constraints from ΔA_{CP} yield a suppression factor of 50 $\to$still 20 times larger than SM

Summary

- CF SM-like decays are well-suited to test QCD frameworks with (differential) branching ratios
- $D \to \pi^0 \overline{K}^0 \gamma$ (CF), $D_s \to \pi^+ \pi^0 \gamma$ (CF) and $D^+ \to K^+ \pi^0 \gamma$ (DCS) are well-suited to test QCD frameworks with A_{FB}
- Best decay channels for testing the SM with A_{FB} are $D \to \pi^+ \pi^- \gamma$, $D^+ \to \pi^+ \pi^0 \gamma$ and $D_s \to \pi^+ K^0 \gamma$
- CP-asymmetries are the most promissing observables to search for new physics.
- Double differential CP-asymmetries are beneficial to avoid cancellations.
- With branching ratios of $\mathcal{O}(10^{-4})$ and $\mathcal{O}(10^{-5})$ for the CF and SCS decays, $\sim 10^6$ and $\sim 10^5$ unreconstructed events can be expected at Belle II (with $50\,\mathrm{ab}^{-1}$)