Measurement of charm rare decays

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on behalf of the LHCb collaboration

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Overview

- A brief introduction on charm rare decays and LHCb
- LHCb results:
  - $D^0 \to \mu^+\mu^-$
  - $D^0 \to \pi^+\pi^-\mu^+\mu^-$
  - $D^+_{(s)} \to \pi^+\mu^+\mu^- / D^+_{(s)} \to \pi^-\mu^+\mu^+$
- Future prospects
- Conclusions

Importance of charm rare decays

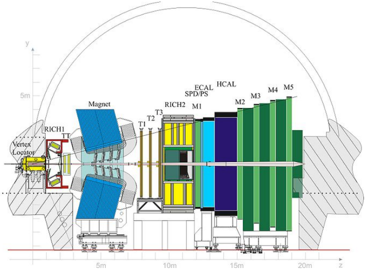
Why charm rare decays

- Flavour Changing Neutral Current (FCNC) processes:
  - highly suppressed in the SM
  - only allowed at loop level
  - affected by GIM suppression $\rightarrow$ D decays more suppressed than B decays, due to the absence of a heavy down-type quark
- Charm$\rightarrow$ investigate up-type quark FCNCs$\rightarrow$ studies complementary to those in B and K sectors
- New Physics could enhance SM branching fraction predictions
- Multibody semileptonic decays: angular asymmetries studies
  - A_{CP} and A_{FB} could be enhanced by some NP effects (to $\mathcal{O}(1\%)$ and sometimes $\mathcal{O}(5\%)$)

LHCb

Large Hadron Collider-beauty

- Single-arm forward spectrometer
- b- and c-hadrons rare decays, CP violation, quark model test
- investigating the physics beyond the Standard Model (matter-antimatter asymmetry)
- reduced luminosity $\rightarrow$ few p-p interactions per bunch crossing (better reconstructibility of events)



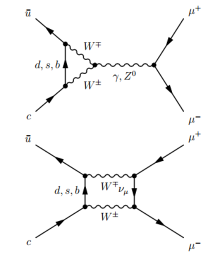
Why LHCb is a very suitable detector:

- Excellent muon identification
- $1.9 < \eta < 4.9$
- High momentum resolution: $0.4\% < \frac{\delta p}{p} < 0.6\%$
- Very good performance in reconstruction of vertices
- High performance trigger: flexible and configurable
- $5(2) \cdot 10^{12} D^0 (D^+)$ in LHCb acceptance in $3 fb^{-1}$ of integrated luminosity at $\sqrt{s} = 7 - 8$TeV

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

Phys.Lett.B, Vol.725, 2013, 15–24

SM contributions



- SM short distance contribution $\mathcal{O} \sim 10^{-18}$
- SM long distance prediction $\mathcal{O} \sim 10^{-11}$ (dominated by the two-photon intermediate state)
- Previous limit $\mathcal{O} \sim 10^{-7}$
  Belle Collaboration [PRD 81 (2010) 091102R]

- Signal channel: $D^{*+} \to D^0(\mu^+\mu^-)\pi^+$
- Normalization channel: $D^{*+} \to D^0(\pi^+\pi^-)\pi^+$
- Control channels: $D^{*+} \to D^0(K^-\pi^+)\pi^+$, $D^0 \to K^+\pi+$, $J/\Psi \to \mu^+\mu^-$ (muon identification and trigger efficiency)
- Peaking background (2- or 3-body D^0 decays, hadrons misidentified as muons)$\to$ tight particle identification criteria
- Combinatorial background $\to$ multivariate selection (θ_D,χ^2_{IP} of D^0 and muons tracks, minimum muons p_T,...)

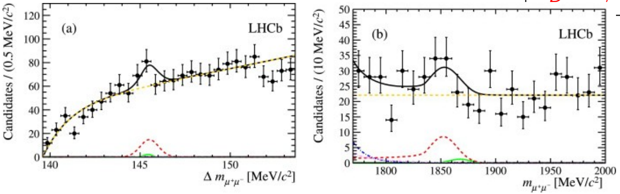
$D^0 \to \mu^+\mu^-$: results

Phys.Lett.B, Vol.725, 2013, 15–24

Total distribution
Combinatorial background
Signal
$D^{*+} \to D^0(K^-\pi^+)\pi^+$
$D^{*+} \to D^0(\pi^-\pi^+)\pi^+$

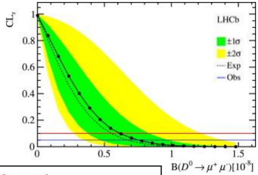
Unbinned maximum likelihood fit of two-dimensional distributions of:

- $\Delta m_{\mu^+\mu^-} = m_{\mu^+\mu^-\pi^+} - m_{\mu^+\mu^-}$
- $m_{\mu^+\mu^-}$



Upper limit ($\sqrt{s}$=7 *TeV*, 0.9 fb^{-1}):

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2(7.6) \cdot 10^{-9} \text{ at } 90\%(95\%) \text{ CL}$$



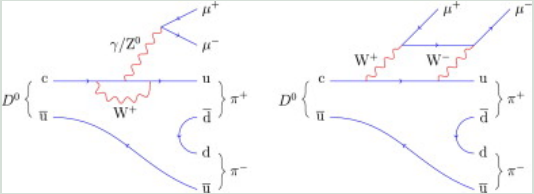
2 orders of magnitude above SM predictions

Improved by a factor 20

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

Phys.Lett.B, Vol.728, 2014, 234-243

SM contributions



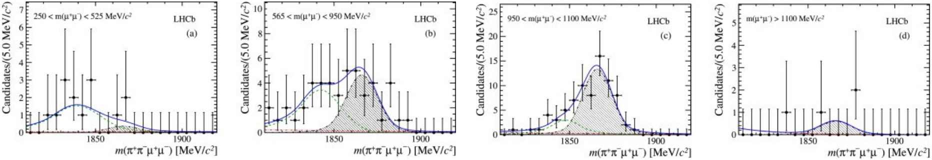
- SM prediction $\mathcal{O}(\lesssim 10^{-9})$
- Previous limit $\mathcal{O}(\sim 10^{-5})$ E791 Collaboration [PRL 86(2001)3969]

- Signal: $D^{*+} \to D^0(\pi^+\pi^-\mu^+\mu^-)\pi^+$
- Control leakage from resonant regions into low and high dimuon mass
- Signal regions away from η, ρ^0 and ϕ resonances ($250 < m_{\mu\mu} < 525 MeV/c^2$, $m_{\mu\mu} > 1100 MeV/c^2$)
- Peaking background $D^0 \to \pi^+\pi^-\pi^+\pi^-$ + combinatorial
- Reference sample: $D^0 \to \pi^+\pi^-\phi(\to \mu^+\mu^-)$
- Combined multivariate analysis (θ_D,χ^2 of D^0 decay vertex and fligh distance,p and p_T of all tracks,...) and muon particle identification

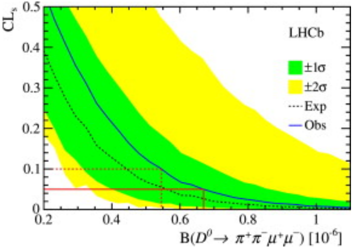
$D^0 \to \pi^+\pi^-\mu^+\mu^-$: results

Phys.Lett.B, Vol.728, 2014, 234-243

Unbinned maximum likelihood of two-dimensional distributions of $m_{\pi\pi\mu\mu}$ and $\Delta m = m_{\pi\pi\mu\mu\pi} - m_{\pi\pi\mu\mu}$:



Total distribution
Filled area - Signal
$D^0 \to \pi^+\pi^-\pi^+\pi^-$
Non peaking background



Upper limit ($\sqrt{s} = 7$ TeV, 1 fb^{-1}):

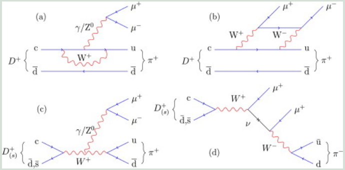
$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 5.5(6.7) \cdot 10^{-7}$ at 90%(95%) CL

x70 improvement — 2 orders of magnitude above SM predictions

$D^+_{(s)} \to \pi^+\mu^+\mu^- / D^+_{(s)} \to \pi^-\mu^+\mu^+$: strategy

Phys.Lett.B, Vol.724, 2013, 203-212

SM contributions

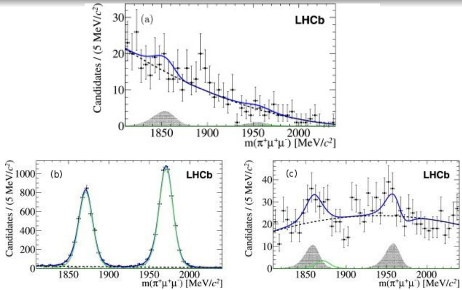


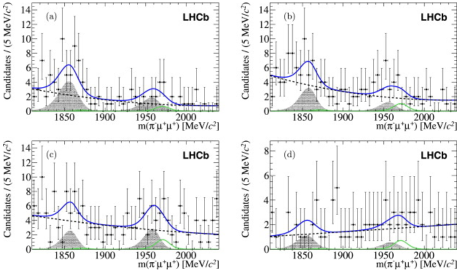
- Previous limits: $D^+ \to \pi^-\mu^+\mu^+$ $\mathcal{O} \sim (10^{-6})$ Babar Collaboration[PRD 84(2011)072006]
  $D^+_s \to \pi^-\mu^+\mu^+$ $\mathcal{O} \sim (10^{-5})$ Babar Collaboration[PRD 84(2011)072006]
  $D^+ \to \pi^+\mu^+\mu^-$ $\mathcal{O} \sim (10^{-6})$ D0 Collaboration [PRL 100(2008)101801]
  $D^+_s \to \pi^+\mu^+\mu^-$ $\mathcal{O} \sim (10^{-5})$ FOCUS Collaboration [PRB 572 (2003)21]

- Control leakage from resonant regions
- Control channel $D^+_{(s)} \to \pi^+(\phi \to \mu^+\mu^-)$
- Peaking background $D^+_{(s)} \to \pi^+\pi^+\pi^-$
- Multivariate analysis (θ_D,χ^2 of $D^+_{(s)}$ decay vertex and fligh distance,p and p_T of all tracks,...) + particle identification selection

$D^+_{(s)} \to \pi^+\mu^+\mu^- / D^+_{(s)} \to \pi^-\mu^+\mu^+$: results I

Phys.Lett.B, Vol.724, 2013, 203-212





Binned maximum likelihood fit

- $D^+_{(s)} \to \pi^+\mu^+\mu^-$ in m($\mu^+\mu^-$) bins:
  - a) low-m($\mu^+\mu^-$) 250-525 MeV/c^2
  - b) ϕ 850-1850 MeV/c^2
  - c) high-m($\mu^+\mu^-$) 1250-2000 MeV/c^2

Total distribution
Signal
Solid area-Peaking background
Dashed line-Non peaking background

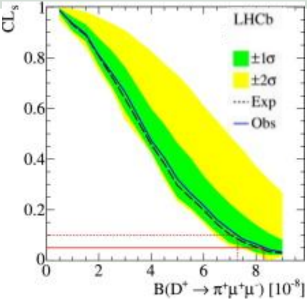
- $D^+_{(s)} \to \pi^-\mu^+\mu^+$ in m($\mu^+\pi^-$) bins:
  - a) 250-1140 MeV/c^2
  - b) 1140-1340 MeV/c^2
  - c) 1340-1550 MeV/c^2
  - d) 1540-2000 MeV/c^2

$D^+_{(s)} \to \pi^+\mu^+\mu^- / D^+_{(s)} \to \pi^-\mu^+\mu^+$: results II

Phys.Lett.B, Vol.724, 2013, 203-212

Upper limits ($\sqrt{s} = 7\,TeV, 1fb^{-1}$):

$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3(8.3)\cdot 10^{-8} \text{ at } 90\%(95\%) \text{ CL}$$
$$\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-) < 4.1(4.8)\cdot 10^{-7} \text{ at } 90\%(95\%) \text{ CL}$$
$$\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 2.2(2.5)\cdot 10^{-8} \text{ at } 90\%(95\%) \text{ CL}$$
$$\mathcal{B}(D_s^+ \to \pi^-\mu^+\mu^+) < 1.2(1.4)\cdot 10^{-7} \text{ at } 90\%(95\%) \text{ CL}$$



Improved by a factor 50

1 order of magnitude above largest NP predictions for $D_s^+ \to \pi^+\mu^+\mu^-$

Future prospects: ongoing

Analyses in progress or planned

- Lepton Flavour Violation $D^0 \to e^{\pm}\mu^{\mp}$
- $D^0 \to K^{\mp}\pi^{\pm}\mu^+\mu^-$
- Update of $D^0 \to \mu^+\mu^-$
- $\Lambda \to p\mu\mu$
- $D^0 \to \phi\gamma$
- ...and some others planned

Future prospects: run II and upgrade

- LHCb Run II: $8 fb^{-1}$, $\sqrt{s} = 13 TeV$
- LHCb Upgrade: $50 fb^{-1}$, $\sqrt{s} = 14 TeV$

Predictions on branching fractions's upper limits:

Assuming the same efficiency and signal-to-background ratio:

Mode	Run I	Run II	Upgrade
$D^0 \to hh'\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	10^{-8}
$D^0 \to \mu^+\mu^-$	few 10^{-9}	fewer 10^{-9}	10^{-10}
$D^+ \to \pi^+\mu^+\mu^-$	few 10^{-8}	fewer 10^{-8}	10^{-9}
$D_s^+ \to K^+\mu^+\mu^-$	few 10^{-7}	fewer 10^{-7}	10^{-8}
$\Lambda \to p\mu\mu$	few 10^{-7}	fewer 10^{-7}	10^{-8}
$D^0 \to e\mu$	few 10^{-8}	fewer 10^{-8}	10^{-9}
$\sigma_{A_{CP}}(D^0 \to \phi\gamma)$	10%	5%	?

Future prospects: run II and upgrade

Predictions on asymmetries sensitivity:

Assuming the same efficiency and signal-to-background ratio:

Mode	Run II	Upgrade
$D^+ \to \pi^+\mu^+\mu^-$	0.6%(30000 events)	0.2%(300000 events)
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	3%(1500 events)	1%(15000 events)
$D^0 \to K^-\pi^+\mu^+\mu^-$	1%(10000 events)	0.3%(100000 events)
$D^0 \to K^+\pi^-\mu^+\mu^-$	40%(30 events)	12%(300 events)
$D^0 \to K^+K^-\mu^+\mu^-$	11%(150 events)	4%(1500 events)

These predictions could improve under the upgrade conditions:

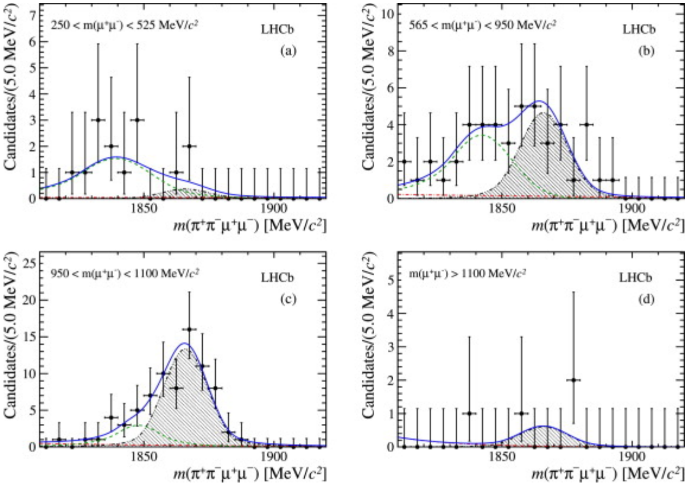
- offline reconstruction quality available in a fully software trigger ($\epsilon \sim x3$)
- other improvements in the analyses
- combinations of modes might matter more than individual sensitivities

Conclusions

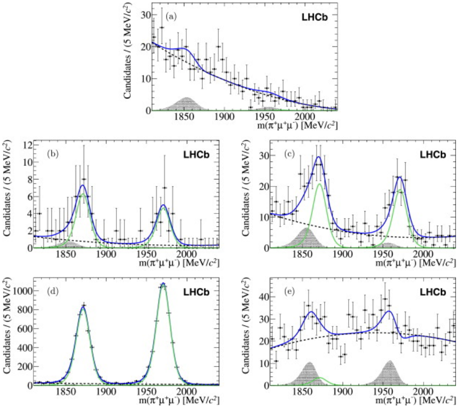
- The results shown are all best world limits
- Results on $D^0 \to e\mu$ and $D^0 \to K\pi\mu\mu$ will become public very soon
- Upgrades ongoing or planned
- Wait for Run II data

Backup Slides

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



$D^+_{(s)} \to \pi^+\mu^+\mu^-$



Trigger conditions	Bin description	$m(\mu^+\mu^-)$ range [MeV/c^2]	D^+ yield	D_s^+ yield
Triggers without $m(\mu^+\mu^-) > 1.0$ GeV/c^2	low-$m(\mu^+\mu^-)$	250 – 525	-3 ± 11	1 ± 6
	η	525 – 565	29 ± 7	22 ± 5
	ρ/ω	565 – 850	96 ± 15	87 ± 12
	ϕ	850 – 1250	2745 ± 67	3855 ± 86
All triggers	ϕ	850 – 1250	3683 ± 90	4857 ± 90
	high-$m(\mu^+\mu^-)$	1250 – 2000	16 ± 16	-17 ± 16

$D^+_{(s)} \to \pi^+\mu^+\mu^-$

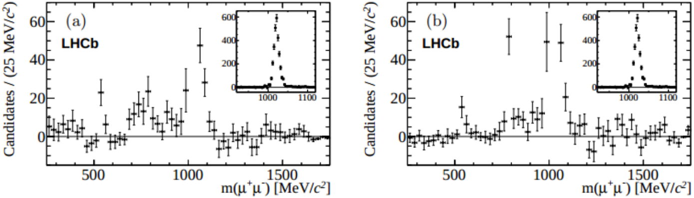
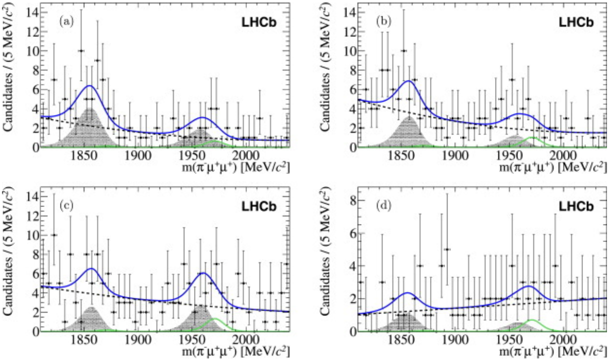


Figure 4: Background-subtracted m($\mu^+\mu^-$) spectrum of (a) $D^+ \to \pi^+\mu^+\mu^-$ and (b) $D_s^+ \to \pi^+\mu^+\mu^-$ candidates that pass the final selection. The inset shows the ϕ contribution, and the main figure shows the η and the ρ/ω contributions. The non-peaking structure of the low and high-$m(\mu^+\mu^-)$ regions is also visible.

$D^+_{(s)} \to \pi^- \mu^+ \mu^+$



Bin description	$m(\mu^+ x^-)$ range [MeV/c^2]	D^+ yield	D_s^+ yield
ϕ	$850 - 1250$	2771 ± 65	3885 ± 85
bin 1	$250 - 1140$	7 ± 6	4 ± 4
bin 2	$1140 - 1340$	-3 ± 6	3 ± 5
bin 3	$1340 - 1550$	-1 ± 6	6 ± 6
bin 4	$1540 - 2000$	0 ± 4	4 ± 5

NP predictions

Model name	Main characteristics	Affected observables
Minimal Supersymmetric Model with R-parity violation (MSSM$\not{R}$)	$c \to u\mu^+\mu^-$ current is possible at tree level via down-type squark. It has a very large impact on C_9 and C_{10}, quantified in [49, 50], and updated in [52] in the light of the constraints brought in 2007 by the discovery of the D^0 mixing. In the light of recent constraints from $K \to \pi\nu\nu$ decays and charm decays, there is now little hope to get sizeable contributions from this kind of NP to the decays we are interested in. See for instance [54].	For $D^+ \to \pi^+\mu^+\mu^-$: $\mathcal{B} = 6.5 \times 10^{-6}$ [52], recently measured $\mathcal{B} <$ 7.3×10^{-8}@90%CL [13]. New constraints from $D^0 \to \mu^+\mu^-$: $\mathcal{B} = 2 \times 10^{-8}$ [55]
Extra up-like quark singlet	New quark doublet or singlet, extended CKM matrix. The FCNC possible at tree level with cuZ coupling. A study of their impact can be found in [56], with an update in [52]. Large effects on C_9 and C_{10} were predicted there.	For $D^+ \to \pi^+\mu^+\mu^-$: $\mathcal{B} = 1.6 \times 10^{-9}$ [52]. For $D^0 \to \rho^0 l^+ l^-$: $\mathcal{A}_{FB} \sim$ few %
Littlest Higgs Model	Particular version of models with cuZ coupling, where the Higgs boson is a pseudo-Nambu-Goldstone boson of spontaneously broken global symmetry. It contains a new massive gauge boson and a new up-like quark $\tilde{t}$. Weak currents are modified, CKM is extended to be 4×3 [56, 57]. The model modifies coefficients C_9 and C_{10}. In particular, C_{10}, while $\simeq 0$ in the SM becomes of the order of C_9 [56].	For $D^+ \to \pi^+\mu^+\mu^-$: $\mathcal{B} = 8.0 \times 10^{-11}$ [57]; For $D^0 \to \rho^0\mu^+\mu^-$: $\mathcal{A}_{FB} \sim \mathcal{O}(10^{-3})$ [57]
Leptoquark model	Carrying both lepton and baryon numbers, new bosons can couple to a lepton and a quark [58].	For $D^+ \to \pi^+\mu^+\mu^-$: $\mathcal{B} = 9.4 \times 10^{-8}$ [58]
Randall-Sundrum model with a warped extra dimension	New gauge bosons appear, that mediate flavour violation. It brings a small contribution to C_9, which at the most could be comparable to the SM value (for some marginal values of the models parameters). On the other hand, as in other models, the tiny C_{10} is enhanced by several orders of magnitude [51].	For $D \to X_u\mu^+\mu^-$: $\mathcal{A}_{FB}$, $\mathcal{A}_{CP} \sim$ few % $\mathcal{A}_{FB}^{CPa} > \mathcal{O}(10\%)$ [51]

NP predictions

Olga Kochebina PhD Thesis

Model name	Main characteristics	Affected observables
Minimal Supersymmetric Model with R-parity conservation (MSSM R)	New sources of flavour symmetry breaking. In the mass insertion approach, off-diagonal elements in the squark mass matrix yield flavour changing couplings $(\delta^q_{i,j})_{H,H'}$. They allow squarks of flavour i, of helicity H and type q (up or down), to turn spontaneously into a squarks of flavour j, of helicity H' and type q. Loop amplitudes as that in Figure 1.19(a) are then possible. They enhance C_7, C_8 and C_9. This is discussed in [49, 59–61].	For $D^0 \to \rho^0\mu^+\mu^-$: $\mathcal{B} \simeq 1.3 \times 10^{-6}$ [49]
Littlest Higgs Model with T-parity (LHT)	LH Model with additional T-parity. Enhancement of the C_9 and C_7 is very small. The main effect is in fact on C_{10}, which is enhanced by orders of magnitude.	For $D \to X_u\mu^+\mu^-$: $\mathcal{A}_{FB} \sim \mathcal{O}(0.5\%)$, $\mathcal{A}^{CP}_{FB}$ up to $\mathcal{O}(10\%)$ [47]
Generic models with generated weak phases	Models that generate weak phases acquired by C_7 and C_9 without sensitive impact on C_{10} [46].	For $D^+ \to \pi(\mu^+\mu^-)_\phi$: $\mathcal{A}_{CP} \sim \mathcal{O}(1\%$-$10\%)$ [46]
Generic Z-mediated models	Loop amplitudes with an internal $Z^{(\prime)}$ and an internal top quark (Figure 1.19(b)) can bring C_9 and C_{10} up to $O(1)$, if the couplings they involve are tuned to reproduced the measured value of ΔA_{CP} [18].	For $D^+ \to h^+h^{(\prime)-}\mu^+\mu^-$ [18]: $\mathcal{A}_{T_{odd}}$ up to 8%, $\mathcal{A}_{FB}$ up to 3%

Table 1.6: Overview of the NP theoretical models that have FCNC at loop level. The estimates of affected observables are presented as well

NP predictions

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[18] L. Cappiello, O. Cata, and G. D'Ambrosio, *Standard Model prediction and new physics tests for $D^0 \to h^+h^-l^+l^-$ ($h = \pi, K$: $l = e, \mu$)*, JHEP **1304** (2013) 135, arXiv:1209.4235.

[46] S. Fajfer and N. Kosnik, *Resonance catalyzed CP asymmetries in $D \to Pl^+l^-$*, Phys. Rev. **D87** (2013) 054026, arXiv:1208.0759.

[47] A. Paul, I. I. Bigi, and S. Recksiegel, *On $D \to X_u l^+l^-$ within the Standard Model and Frameworks like the Littlest Higgs Model with T Parity*, Phys. Rev. **D83** (2011) 114006, arXiv:1101.6053.

NP predictions

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[49] G. Burdman, E. Golowich, J. L. Hewett, and S. Pakvasa, *Rare charm decays in the standard model and beyond*, Phys. Rev. **D66** (2002) 014009, arXiv:hep-ph/0112235.

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[51] A. Paul, A. de La Puente, and I. I. Bigi, *Manifestations of Warped Extra Dimension in Rare Charm Decays and Asymmetries*, arXiv:1212.4849.

[52] S. Fajfer, N. Kosnik, and S. Prelovsek, *Updated constraints on new physics in rare charm decays*, Phys. Rev. **D76** (2007) 074010, arXiv:0706.1133.

[53] LHCb Collaboration, R. Aaij et al., *Evidence for CP violation in time-integrated $D^0 \to h^- h^+$ decay rates*, Phys. Rev. Lett. **108** (2012) 111602, arXiv:1112.0938.

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[56] S. Fajfer and S. Prelovsek, *Search for new physics in rare D decays*, Conf. Proc. **C060726** (2006) 811, arXiv:hep-ph/0610032.

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[60] J. Lyon and R. Zwicky, *Anomalously large $\mathcal{O}_8$ and long-distance chirality from $A_{\rm CP}[D^0 \to (\rho^0, \omega)\gamma](t)$*, arXiv:1210.6546.

[61] G. F. Giudice, G. Isidori, and P. Paradisi, *Direct CP violation in charm and flavor mixing beyond the SM*, JHEP **1204** (2012) 060, arXiv:1201.6204.