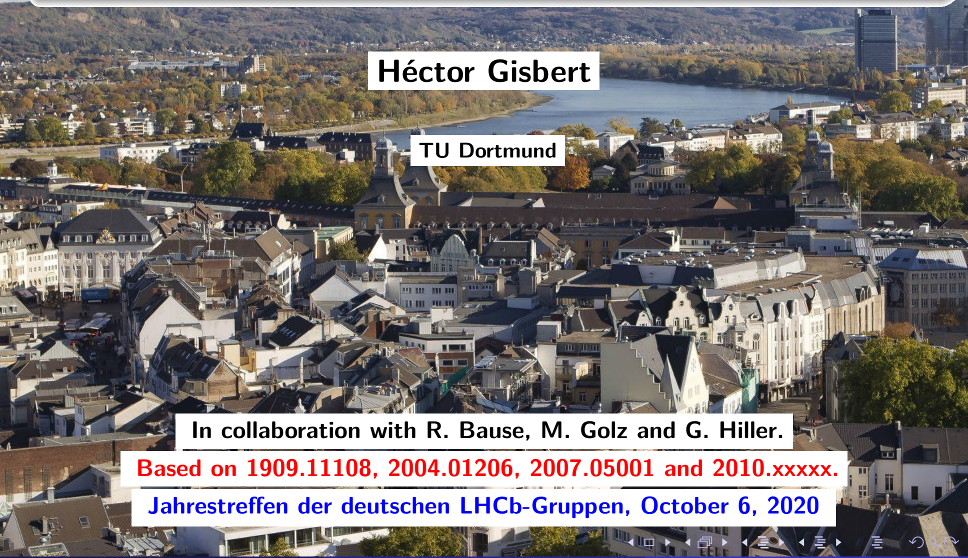
Rare charm decays as probes of New Physics



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Based on 1909.11108, 2004.01206, 2007.05001 and 2010.xxxxx.

Jahrestreffen der deutschen LHCb-Gruppen, October 6, 2020

Charm physics is exceptional

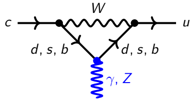
1. **Unique window to explore FCNCs in the up-sector!**

2. **Non-perturbative dynamics** $\to$ **"Null tests" observables $\mathcal{O} \pm \delta\,\mathcal{O}$**

   Bird's-eye view of the playground:[1]

   - SM symmetries: $\mathcal{O}_{\mathrm{SM}} = \mathbf{0}$.
   - Small uncertainties: $\mathcal{O}_{\mathrm{SM}} \gg \delta\,\mathcal{O}_{\mathrm{SM}}$.
   - Large hadronic effects to enhance small NP contributions.
   - Sensitive to specific NP.

3. **Very efficient GIM mechanism:** $\sum_i \lambda_i = 0$ with $\lambda_i \equiv V_{ci}^* V_{ui}$.



$$= \sum_{i=d,s,b} \lambda_i\, f_i \;=\; \lambda_s \left[(f_s - f_d) + \frac{\lambda_b}{\lambda_s} (f_b - f_d) \right]$$

$f_i \sim \frac{m_i^2}{(4\pi)^2 M_W^2}$, $\mathrm{Im}(\lambda_b/\lambda_s) \sim 10^{-3}$

BRs (A_{CP}) are loop-(CKM-) suppressed!

Formidable place to search for BSM physics!

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[1] 1510.00311, 1701.06392, 1802.02769, 1805.08516, 1812.04679, 1909.11108, 2004.01206, 2007.05001, 2009.14212, ...

EFT approach to charm physics de Boer, (2017), PhD thesis, TU Dortmund

1. Dynamical fields ϕ_i at μ_{EW}: $\phi_i^{\mathrm{SM}} = q_i, \ell_i, g, \ldots$
2. Symmetries to build all $O_j(\phi_i)$ up to $(p^2/\mu_{\mathrm{EW}}^2)^n$, $\mathcal{H}_{\mathrm{eff}} = \sum_i C_i\, O_i$

$$O_1^q = (\overline{u}_L \gamma_\mu T^a q_L)(\overline{q}_L \gamma^\mu T^a c_L)\,, \; O_2^q = (\overline{u}_L \gamma_\mu q_L)(\overline{q}_L \gamma^\mu c_L)\,, \; q = d,\, s\,,$$

$$O_7^{(\prime)} = \frac{m_c}{e}(\overline{u}_{L\,(R)}\, \sigma_{\mu\nu}\, c_{R\,(L)})\, F^{\mu\nu}\,, \; O_{9\,(10)}^{(\prime)} = (\overline{u}_{L\,(R)} \gamma_\mu c_{L\,(R)})(\overline{\ell}\, \gamma^\mu (\gamma_5)\, \ell)\,,$$

$$O_{S\,(P)}^{(\prime)} = (\overline{u}_{L\,(R)} c_{R\,(L)})(\overline{\ell}\,(\gamma_5)\,\ell)\,, \; O_{T\,(T5)} = \frac{1}{2}(\overline{u}\, \sigma_{\mu\nu}\, c)(\overline{\ell}\, \sigma^{\mu\nu}\, (\gamma_5)\, \ell)\,.$$

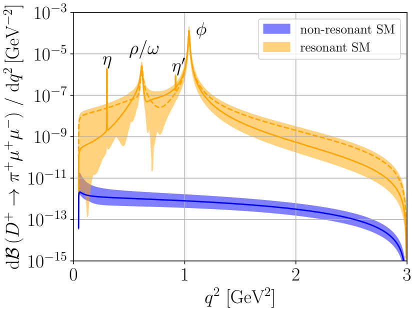
3. Compute $C_i(\mu_{\mathrm{EW}})$ to avoid large $\alpha_s(\mu_{\mathrm{low}}) \log(\mu_{\mathrm{low}}^2/\mu_{\mathrm{EW}}^2)$.

$$m_{q_{\mathrm{light}}} = 0 + \text{GIM mechanism} \Longrightarrow \boxed{C_{7,9,10}^{\mathrm{SM}}(\mu_{\mathrm{EW}}) = 0!}$$

4. RGEs to go down $\mu_{\mathrm{low}} \approx m_c$ (2-step matching at μ_{EW} and m_b).
    - Penguins generated at $\mu = m_b$.
    - $O_{7,9}$ mix with $O_{1,2}$, but O_{10} not $\Rightarrow$ $\boxed{C_{7,9}^{\mathrm{SM}}(\mu_c) \neq 0 \,\&\, C_{10}^{\mathrm{SM}}(\mu_c) = 0}$
5. $\langle O_i(\mu_{\mathrm{low}}) \rangle$ from non-perturbative techniques (Lattice, LCSR, ...)
6. Include resonances: Breit–Wigner distributions + exp. data.

Rare semileptonic charm $c \to u\,\ell^+\ell^-$ decays

e.g. $D^+ \to \pi^+\mu^+\mu^-$



- 1909.11108 ($D \to P\,\ell\ell$)
- 1805.08516 ($D \to P_1 P_2\,\ell\ell$)

- **Dominated by resonances from $D \to \pi M(\to \ell\ell)$,**
  $$C_9^{\mathrm{eff}} \ll C_9^{\mathrm{R}} \to C_9^{\mathrm{SM}} \approx C_9^{\mathrm{R}}$$
- **Current data still allows for large NP effects at large q^2.**[a]
  $$\mathcal{B}_{D^+\to\pi^+\mu^+\mu^-} < 6.7\cdot 10^{-8},\ 90\%\ \mathrm{C.L.}$$
- **Exp. close to R curves, NP searches in BRs are difficult (NP$\times$R increase $\delta\mathcal{B}_{\mathrm{theo}}$)**
- **No NP$\to$ QCD tests!**

[a] LHCb talk of Dominik Mitzel at FPCP 2020.

$\mathcal{B}\vert_{\text{high }q^2} \times 10^9$	SM	$C_{9\,(10)} = 0.5$	$C_{S\,(P)} = 0.1$	$C_{T\,(T5)} = 0.5$	$C_9 = \pm C_{10} = 0.5$
$D^+ \to \pi^+\mu^+\mu^-$	$0.1\ldots1.7$	1.9 ± 0.1	0.48 ± 0.04	1.1 ± 0.2	3.9 ± 0.2
		3.5 ± 3.5	1.4 ± 0.8	2.3 ± 1.5	5.6 ± 3.6
$D_s^+ \to K^+\mu^+\mu^-$	$0.03\ldots0.3$	0.40 ± 0.05	0.15 ± 0.07	0.15 ± 0.05	0.8 ± 0.1
		0.8 ± 0.7	0.3 ± 0.2	0.4 ± 0.3	1.2 ± 0.8

Testing lepton universality with $c \to u\,\ell^+\ell^-$ decays

- **LU can be probed in $c \to u\,\ell^+\ell^-$** **(same as B decays)**

$$R_P^D = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\mathcal{B}(D \to P\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\mathcal{B}(D \to Pe^+e^-)}{dq^2} dq^2}$$

- **Same kinematical limits $\to$ Cancellation of had. uncertainties!**
- **Well control of SM prediction:** $\boxed{R_P^D|_{\text{SM}} \approx 1}$
- **e.g. $D^+ \to \pi^+\,\ell^+\ell^-$ 1909.11108, see 1805.08516 ($D \to P_1 P_2\,\ell^+\ell^-$)**
  - **full q^2:** insensitive to NP.
  - **low q^2:** poor knowledge of resonances $\to$ sizable uncertainties.
  - **high q^2:** induce significant NP effects.

NP effects at low q^2 are huge. With more exp. data, uncertainties could be reduced studying resonance effects.

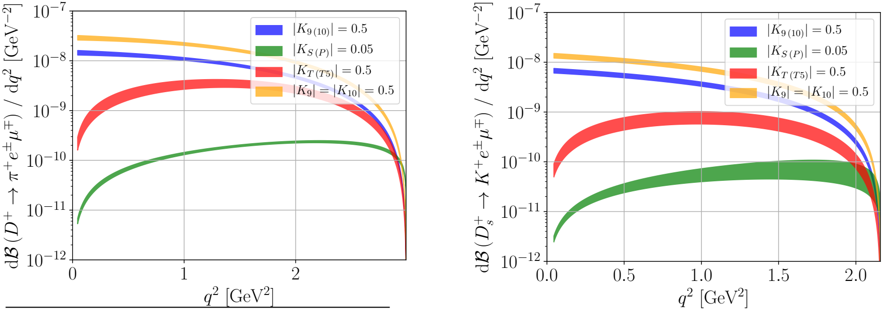
	SM	$\lvert C_9\rvert = 0.5$	$\lvert C_{10}\rvert = 0.5$	$\lvert C_9\rvert = \pm\lvert C_{10}\rvert = 0.5$	$\lvert C_{S(P)}\rvert = 0.1$	$\lvert C_T\rvert = 0.5$	$\lvert C_{T5}\rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(10^{-2})$	SM-like	SM-like	SM-like	SM-like	SM-like	SM-like
low q^2	$0.95 \pm \mathcal{O}(10^{-2})$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$0.9 \ldots 1.4$	$\mathcal{O}(10)$	$1.0 \ldots 5.9$
high q^2	$1.00 \pm \mathcal{O}(10^{-2})$	$0.2 \ldots 11$	$3 \ldots 7$	$2 \ldots 17$	$1 \ldots 2$	$1 \ldots 5$	$2 \ldots 4$

Testing lepton flavor violation with $c \to u\,\ell^+\ell'^-$ $(\ell \neq \ell')$ decays

- **Forbidden in SM! Any signal would cleanly signal LFV!**
- **Extend LFC EFT via $\bar{\ell}\, A_{\text{Dirac}}\, \ell \to \bar{\ell}\, A_{\text{Dirac}}\, \ell'$.**
- **Experimental bounds:**[2]

$$\mathcal{B}(D^+ \to \pi^+ e^- \mu^+) < 2.2 \cdot 10^{-7},\ 90\%\ \text{C.L.}$$
$$\mathcal{B}(D_s^+ \to K^+ e^- \mu^+) < 9.4 \cdot 10^{-7},\ 90\%\ \text{C.L.}$$

1909.11108



[2] LHCb talk of Dominik Mitzel at FPCP 2020.

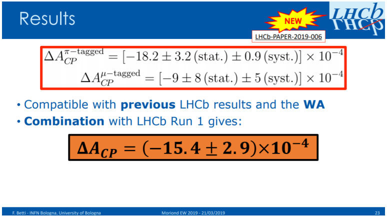
CP-asymmetries in rare charm decays

CKM suppressed in the SM! $\rightarrow \mathrm{Im}(\lambda_b/\lambda_s) \sim 10^{-3}$!

Hadronic decays

$$A_{\mathrm{CP}}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

- $\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(K^+K^-) - A_{\mathrm{CP}}(\pi^+\pi^-)$

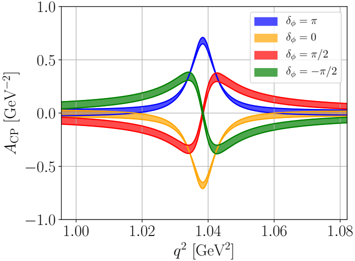


Moriond EW 2019

Semileptonic decays

$$A_{\mathrm{CP}}(q^2) = \frac{1}{\Gamma + \overline{\Gamma}}\left(\frac{d\Gamma}{dq^2} - \frac{d\overline{\Gamma}}{dq^2}\right)$$

- **Not measured!** 1909.11108



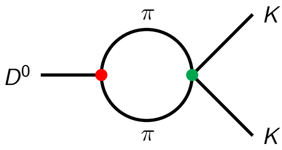
$D_s^+ \to K^+\mu^+\mu^-$

$\Delta A_{\rm CP}$ predictions in the SM

$$\Delta A_{\rm CP}^{\rm SM} \approx r \, \sin\phi_{\rm CKM} \, \sin\delta_{\rm QCD}$$

$$r = r_{\rm CKM} \, r_{\rm QCD}$$

- $\sin\phi_{\rm CKM} \sim {\rm Im}(\lambda_b/\lambda_s) \sim 10^{-3}$.
- $\sin\delta_{\rm QCD} \sim \mathcal{O}(1)$, large strong phases.
- $r_{\rm CKM} = \left|\frac{\lambda_d}{\lambda_s}\right| = 1$, ratio of CKM factors.
- What is the ratio of rescattering $r_{\rm QCD}$?



Light Cone Sum Rules (LCSR)

$$r_{\rm QCD} \sim \mathcal{O}\left(\frac{\alpha_s}{\pi}\right) \sim 10^{-1}$$

$$\Delta A_{\rm CP}^{\rm SM} \sim 10^{-4}$$

Not explains exp. value

Low energy QCD

$$r_{\rm QCD} \sim 1$$

$$\Delta A_{\rm CP}^{\rm SM} \sim 10^{-3}$$

Compatible with exp. value

SM prediction of $\Delta A_{\rm CP}$ is not well established!

ΔA_{CP} from a different perspective

- Theoretical description of hadronic modes is challenging!
- Value of $\Delta A_{\mathrm{CP}}^{\mathrm{SM}}$ depends on who you ask!
- Assuming $\Delta A_{\mathrm{CP}}^{\mathrm{SM}} \sim 10^{-4}$,

$$\Delta A_{\mathrm{CP}}^{\mathrm{NP}} \sim 10^{-3}!$$

NP effects should be observed in other observables!

- Idea:

$$\underbrace{\text{Null tests}}_{\text{Symmetries “softly” broken}} + \text{correlations with other modes!}$$

CP–asymmetries and future sensitivities

Plan:

1. **Explain ΔA_{CP} with a quite generic BSM extension.**
2. **Patterns from hadronic decays: U-spin and isospin breaking.**
3. **Work out experimental projections:**

$\times 10^{-4}$	Data	σ_{LHCb} 1808.08865	$\sigma_{\text{Belle II}}$ 1808.10567
ΔA_{CP}	-15.4 ± 2.9 1903.08726	$1.3\,(0.3)$	–
$\Delta A_{\text{CP}}^{\text{HFLAV}}$	-16.4 ± 2.8 1909.12524	$1.3\,(0.3)$	–
$A_{\text{CP}}(D^0 \to K^+K^-)$	-9 ± 11 1909.12524	$3\,(0.7)$	3
$A_{\text{CP}}(D^0 \to \pi^+\pi^-)$	-1 ± 14 1909.12524	$3\,(0.7)$	5
$A_{\text{CP}}(D^0 \to \pi^0\pi^0)$	-3 ± 64 1909.12524	–	9
$A_{\text{CP}}(D^+ \to \pi^+\pi^0)$	$+290 \pm 290 \pm 30$ 0906.3198	–	17

A_{CP} and future sensitivities σ at LHCb Run 1-3 (Run 1-5) and Belle II with 50 ab^{-1}.

A rich phenomenological BSM extension: Z'–models

- **Gauge symmetry:** $SU(3)_C \times SU(2)_L \times U(1)_Y \times \underbrace{U(1)'}_{g_4}$
- **Representations:**

$$Q_i = (3, 2, 1/6, F_{Q_i}) \, , \quad u_i = (3, 1, 2/3, F_{u_i}) \, , \quad d_i = (3, 1, -1/3, F_{d_i}) \, ,$$
$$L_i = (1, 2, -1/2, F_{L_i}) \, , \quad e_i = (1, 1, -1, F_{e_i}) \, , \quad \nu_i = (1, 1, 0, F_{\nu_i}) \, .$$

- **Z' Lagrangian (in the gauge basis):**

$$\mathcal{L}_{Z'} = g_4 \sum_i \sum_{\psi_i} F_{\psi_i} \, (\bar{\psi}_i \gamma^\mu \psi_i) \, Z'_\mu \, , \quad \psi = Q, L, u, d, e, \nu \, .$$

- **Charge F_ψ assignment:**
  - Guarantee anomaly-cancellation.
  - Avoid kinetic mixing at one-loop.

model	F_{Q_i}			F_{u_i}			F_{d_i}			F_{L_i}			F_{e_i}			F_{ν_i}		
2	3	3	-6	-8	4	4	-10	10	0	-6	5	1	0	0	0	0	0	0
4	-1	-1	2	-1	2	-1	0	0	0	-1	1	0	-2	2	0	-2	-1	3
5	-1	-1	2	-1	2	-1	2	-1	-1	-1	1	0	-1	1	0	0	0	0
9	0	0	0	-11	-2	13	7	7	-14	-8	3	5	-6	16	-10	0	0	0
10	0	0	0	-13	6	7	-1	-14	15	-15	15	0	-14	18	-4	0	0	0
10μ	0	0	0	-13	6	7	-1	-14	15	-15	0	15	-14	-4	18	0	0	0

From gauge to mass basis via rotations

- **Rotations:** 4 unitary matrices, $V_u^\dagger V_u = V_d^\dagger V_d = U_u^\dagger U_u = U_d^\dagger U_d = I$

$$(u'_L)_i = (V_u)_{ij}\,(u_L)_j\,, \qquad (u'_R)_i = (U_u)_{ij}\,(u_R)_j\,,$$

$$(d'_L)_i = (V_d)_{ij}\,(d_L)_j\,, \qquad (d'_R)_i = (U_d)_{ij}\,(d_R)_j\,. \qquad \boxed{V_{\rm CKM} = V_u^\dagger V_d}$$

- Z' **Lagrangian for charm FCNCs (in the mass basis):**

$$\begin{aligned}\mathcal{L}_{Z'} \supset \quad & \left(g_L^{uc}\,\bar{u}_L\gamma^\mu c_L Z'_\mu + g_R^{uc}\,\bar{u}_R\gamma^\mu c_R Z'_\mu + \text{h.c.}\right)\\ & + g_L^d\,\bar{d}_L\gamma^\mu d_L Z'_\mu + g_R^d\,\bar{d}_R\gamma^\mu d_R Z'_\mu\\ & + g_L^s\,\bar{s}_L\gamma^\mu s_L Z'_\mu + g_R^s\,\bar{s}_R\gamma^\mu s_R Z'_\mu\\ & + \sum_{\ell=e,\mu,\tau}\left(g_L^{\ell\ell}\bar{\ell}_L\gamma^\mu\ell_L + g_R^{\ell\ell}\bar{\ell}_R\gamma^\mu\ell_R\right) Z'_\mu\end{aligned}$$

$$\boxed{g_L^{d,s} = g_4\,F_{Q_{1,2}}, \quad g_R^{d,s} = g_4\,F_{d_{1,2}}, \quad g_L^{\ell\ell} = g_4\,F_{L_\ell}, \quad g_R^{\ell\ell} = g_4\,F_{e_\ell}}$$

- **Avoid strong constraints in the kaon sector** $\rightarrow$ $\boxed{V_d = U_d = I}$

$$\boxed{g_L^{uc} = g_4\,\Delta F_L\,\lambda} \qquad \boxed{g_R^{uc} = g_4\,\Delta F_R\,\sin\theta_u\,\cos\theta_u\,e^{i\,\phi_R}}$$

with $\Delta F_L = F_{Q_2} - F_{Q_1}$ and $\Delta F_R = F_{u_2} - F_{u_1}$.

Z'–effects for $\Delta A_{\rm CP}$

$$\Delta A_{\rm CP}^{\rm NP} = A_{\rm CP}^{\rm NP}\left(K^+K^-\right) - A_{\rm CP}^{\rm NP}\left(\pi^+\pi^-\right)$$

with (assuming maximal strong phases $\sin\delta_{\pi,K} \sim 1$)

$$A_{\rm CP}^{\rm NP}\left(K^+K^-\right) \sim \left(\frac{g_4}{M_{Z'}}\right)^2 \sin\phi_R\, \Delta\widetilde{F}_R \left[c_K\, F_{Q_2} + d_K\, F_{d_2}\right]$$

$$A_{\rm CP}^{\rm NP}\left(\pi^+\pi^-\right) \sim \left(\frac{g_4}{M_{Z'}}\right)^2 \sin\phi_R\, \Delta\widetilde{F}_R \left[c_\pi\, F_{Q_1} + d_\pi\, F_{d_1}\right]$$

with $\Delta\widetilde{F}_R = \sin\theta_u \cos\theta_u \Delta F_R$ and

$$c_K = \frac{\chi_K}{a_K}\, r_1 \sim +\mathcal{O}(1)\,, \quad c_\pi = -\frac{\chi_\pi}{a_\pi}\, r_1 \sim -\mathcal{O}(1)\,,$$

$$d_K = \frac{1}{a_K}\, r_2 \sim -\mathcal{O}(0.1)\,, \quad d_\pi = -\frac{1}{a_\pi}\, r_2 \sim +\mathcal{O}(0.1)\,.$$

a_P is tree-level amplitude fixed by $\mathcal{B}(D^0 \to P^+P^-)_{\rm exp}$ and $r_{1,2}$ encode RGE effects.

$D^0 - \overline{D}^0$ mixing constraints

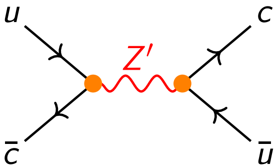
- **Amplitude:** $\langle D^0 | \mathcal{H}_{\text{eff}}^{\Delta c=2} | \overline{D}^0 \rangle = M_{12} - \frac{i}{2}\Gamma_{12}$
- **3 physical quantities:**
  $x_{12} = 2\frac{|M_{12}|}{\Gamma}\,, \; y_{12} = \frac{|\Gamma_{12}|}{\Gamma}\,, \; \phi_{12} = \arg\left(\frac{M_{12}}{\Gamma_{12}}\right)\,.$
- **Require NP contributions to saturate the current world averages (HFLAV):**

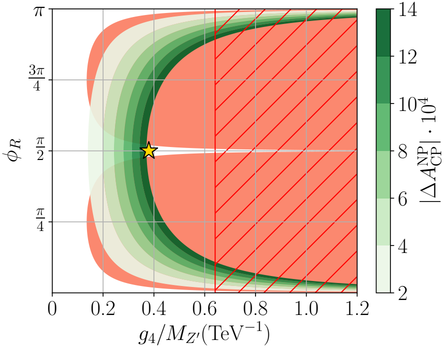
$$x_{12}^{\text{NP}} \leq x_{12}\,, \quad x_{12}^{\text{NP}} \sin\phi_{12}^{\text{NP}} \leq x_{12}\sin\phi_{12}$$

- **Constraint from x_{12}:**
  $\left|(g_L^{uc})^2 + (g_R^{uc})^2 - X\, g_L^{uc}\, g_R^{uc}\right| \lesssim 6\cdot 10^{-7}\left(\frac{M_{Z'}}{\text{TeV}}\right)^2$
- **Avoided via aligment:** $g_L^{uc} \sim X\, g_R^{uc}$
- **Implies:** $\text{Arg}(g_L^{uc}) \sim \text{Arg}(g_R^{uc})$
- **BUT kaon constraints kill $\text{Arg}(g_L^{uc})$!**
- $g_L^{uc} = 0 \;\rightarrow\; \Delta F_L = 0 \;\rightarrow\; F_{Q_1} = F_{Q_2}$!
  ⋆: **Model 2 with $\Delta A_{CP}^{\text{NP}} \sim 10^{-3}$**

$\Delta F_R = 12,\; \phi_R \sim \pi/2\,,\; g_4/M_{Z'} \sim 0.38/\text{TeV}\,,\; \theta_u \sim 1\cdot 10^{-4}\,.$

Same couplings as rare $|\Delta c| = |\Delta u| = 1$ decays!

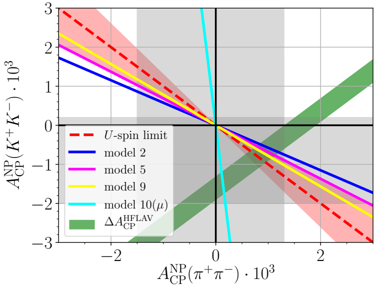




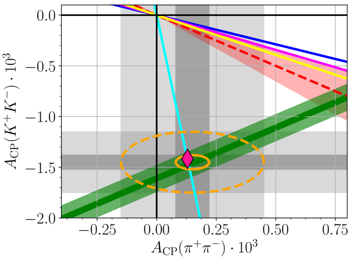
U-spin patterns in $D^0 \to \pi^+\pi^-$, K^+K^-

- **U-spin symmetry:** invariant under $d \Longleftrightarrow s$.
- **Obviously is broken** (by M_P and f_P, $\pi^+ = u\,\bar{d}$ and $K^+ = u\,\bar{s}$).
- **Z' model:** U–spin breaking arises for $F_{Q_1} \neq F_{Q_2}$ or $F_{d_1} \neq F_{d_2}$!
- **U-spin sum rule** (broken $\delta U_{\text{break}} \lesssim 30\,\%$ 1308.4143):

$$A_{\text{CP}}(D^0 \to K^+K^-) + A_{\text{CP}}(D^0 \to \pi^+\pi^-) = 0 + \delta U_{\text{break}}$$



Green and gray bands are the $1\,\sigma$ experimental world averages (HFLAV).



Future experimental projections over model $10(\mu)$. Ligher (darker) bands correspond to LHCb Run 1-3 (1-5).

Isospin breaking patterns in $D^+ \to \pi^+\pi^0$

- **Isospin symmetry:** invariant under $u \Longleftrightarrow d$.
- **Softly broken** (10% by $m_u \neq m_d$ and QED corrections).
- **Z' model:** Isospin breaking arises for $F_{u_1} \neq F_{d_1}$!

$$A_{\mathrm{CP}}^{\mathrm{NP}}(\pi^+\pi^0) \sim \frac{g_4^2}{M_{Z'}^2} \Delta\widetilde{F}_R \, d_{\pi'} \, (F_{d_1} - F_{u_1})$$

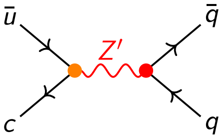
Models 9 and 10(μ):

$$A_{\mathrm{CP}}^{\mathrm{NP}}(\pi^+\pi^0) \sim (1-2) \cdot \Delta A_{\mathrm{CP}}^{\mathrm{NP}}$$

for $\Delta A_{\mathrm{CP}}^{\mathrm{NP}} \sim 10^{-3}$ is within the projected sensitivity of Belle II,

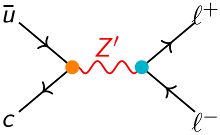
$$\sigma(A_{\mathrm{CP}}(\pi^+\pi^0))_{\text{Belle II}} = 1.7 \cdot 10^{-3} \text{ for } 50\text{ab}^{-1} .$$

Further opportunities: Semileptonic decays vs ΔA_{CP}



Share same couplings!

$\Longleftrightarrow$



$$\widetilde{C}_i^{(\prime)}\,(M_{Z'}) \sim \frac{\sqrt{2}}{G_F}\,\frac{g^{uc}_{L,R}\,g_4}{4\,M^2_{Z'}}$$

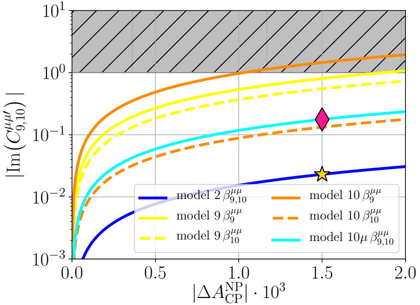
$$C^{\ell\ell}_{9,10}\,(M_{Z'}) = \frac{\sqrt{2}}{G_F}\,\frac{g^{uc}_{L}\,g^{\ell\ell}_{L,R}}{4\,M^2_{Z'}}$$

- ***Z′*–models:**

$$\mathrm{Im}(C^{\ell\ell\,\prime}_{9/10}) \sim \frac{\pi}{\sqrt{2}\,G_F\,\alpha_e}\,\beta^{\ell\ell}_{9/10}\cdot\Delta A^{NP}_{CP}$$

where

$$\beta^{\ell\ell}_{9/10} = \frac{F_{e_i} \pm F_{L_i}}{c_K\,F_{Q_2} + d_K\,F_{d_2} - c_\pi\,F_{Q_1} - d_\pi\,F_{d_1}}\ .$$



Large ΔA^{NP}_{CP} implies large effects in $c \to u\ell^+\ell^-$, and viceversa.

Rare charm dineutrino modes $c \to u\,\nu\bar{\nu}$

- $c \to u\,\nu\bar{\nu}$ are GIM-suppressed in the SM:[3]

Any observation would cleanly signal NP!

- **Well-suited for e^+e^-–colliders** such as **Belle II** and future **FCC-ee**.

- **What is the new physics reach?**

h_c	$f(c \to h_c)$	$N(h_c)_{\text{FCC-ee}}$	$N(h_c)_{\text{Belle II}}$
D^0	0.59	$6 \cdot 10^{11}$	$8 \cdot 10^{10}$
D^+	0.24	$3 \cdot 10^{11}$	$3 \cdot 10^{10}$
D_s^+	0.10	$1 \cdot 10^{11}$	$1 \cdot 10^{10}$
Λ_c^+	0.06	$7 \cdot 10^{10}$	$8 \cdot 10^{9}$

⋆ Fragmentation fractions $f(c \to h_c)$, 1509.01061

⋆ Number of $c\bar{c}$: Abada:2019lih

- $N(c\bar{c})_{\text{Belle II}} = 65 \cdot 10^9$ for $50\,\text{ab}^{-1}$.
- $N(c\bar{c})_{\text{FCC-ee}} = 550 \cdot 10^9$.

⋆ $N(h_c) = 2\,f(c \to h_c)\,N(c\bar{c})$.

$\Downarrow$

$$N(h_c) \sim 10^{11}!$$

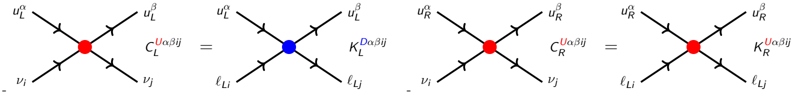
[3] hep-ph/0112235, 0908.1174

Link neutrinos to charged leptons modes via $SU(2)_L$

$$\mathcal{B} \propto \sum_{\nu=i,j} \left(|\mathcal{C}_L^{Uij}|^2 + |\mathcal{C}_R^{Uij}|^2 \right) = \mathrm{Tr}\left[\mathcal{C}_L^U \, \mathcal{C}_L^{U\dagger} + \mathcal{C}_R^U \, \mathcal{C}_R^{U\dagger} \right]$$

$$= \mathrm{Tr}\left[\mathcal{K}_L^D \mathcal{K}_L^{D\dagger} + \mathcal{K}_R^U \mathcal{K}_R^{U\dagger} \right] + \mathcal{O}(\lambda) = \sum_{\ell=i,j} \left(|\mathcal{K}_L^{Dij}|^2 + |\mathcal{K}_R^{Uij}|^2 \right) + \mathcal{O}(\lambda)$$

1. **SU(2) relates up, down, neutrinos and charged leptons.**



2. **Mass basis:** $\mathcal{C}_L^U = W^\dagger \, \mathcal{K}_L^D \, W + \mathcal{O}(\lambda), \quad \mathcal{C}_R^U = W^\dagger \, \mathcal{K}_R^U \, W$

3. **Unitarity $WW^\dagger = W^\dagger W = I$**

$c \to u \ell \ell$ ⟶ $c \to u \nu \bar{\nu}$ ⟵ $d \to s \ell \ell$

⋆ **Independent of PMNS matrix and subleading $\mathcal{O}(\lambda)$ corrections!**

⋆ **Prediction of dineutrino rates for different leptonic flavor structures $\mathcal{K}_{L,R}^{ij}$ can be probed with lepton-specific measurements!**

Possible leptonic flavor structures for $\mathcal{K}^{ij}_{L,R}$

i) ***Lepton-universality*** **(LU).**

$$\begin{pmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & k \end{pmatrix}$$

ii) ***Charged lepton flavor conservation*** **(cLFC).**

$$\begin{pmatrix} k_{11} & 0 & 0 \\ 0 & k_{22} & 0 \\ 0 & 0 & k_{33} \end{pmatrix}$$

iii) $\mathcal{K}^{ij}_{L,R}$ **arbitrary.**

$$\begin{pmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{pmatrix}$$

Upper limits on dineutrino modes can probe lepton unversality!

- **Bounds on lepton specific WCs for $\ell, \ell' = e, \mu, \tau$.**[4]

		ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
	$\lvert\mathcal{K}_A^{P\ell\ell'}\rvert$						
$s \to d$	$\lvert\mathcal{K}_L^{D\ell\ell'}\rvert$	3.5	1.9	6.7	2.0	6.1	6.6
$c \to u$	$\lvert\mathcal{K}_R^{U\ell\ell'}\rvert$	2.9	1.6	5.6	1.6	4.7	5.1

- $\mathcal{B} \propto x = \sum_{\ell,\ell'} \left(|\mathcal{K}_L^{D\ell\ell'}|^2 + |\mathcal{K}_R^{U\ell\ell'}|^2 \right) + \mathcal{O}(\lambda) = \sum_{\ell,\ell'} R^{\ell\ell'} + \mathcal{O}(\lambda)$

$$x = 3\, R^{\mu\mu} \lesssim 34\,, \quad \text{(Lepton Universality)}$$

$$x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} \lesssim 196\,, \quad \text{(charged Lepton Flavor Conservation)}$$

$$x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} + 2\left(R^{e\mu} + R^{e\tau} + R^{\mu\tau}\right) \lesssim 716.$$

LU is fixed by the most stringent bound (muons).

[4] From high-p_T bounds: 2003.12421, 2002.05684

Dineutrino branching ratios upper limits

$$\mathcal{B}(h_c \to F\, \nu\bar{\nu}) = A_+^{h_c F}\, x_+ + A_-^{h_c F}\, x_-\,, \quad x_\pm = \sum_{i,j} |\mathcal{C}_L^{Uij} \pm \mathcal{C}_R^{Uij}|^2 < 2\,x\,.$$

$N_i = \eta_{\text{eff}}\, \mathcal{B}_i\, N(h_c)$, $N(c\bar{c})_{\text{Belle II}} = 65 \cdot 10^9$ for $50\,\text{ab}^{-1}$, $N(c\bar{c})_{\text{FCC-ee}} = 550 \cdot 10^9$.

$h_c \to F$	$\mathcal{B}^{\text{max}}_{\text{LU}}$ $[10^{-7}]$	$\mathcal{B}^{\text{max}}_{\text{cLFC}}$ $[10^{-6}]$	$\mathcal{B}^{\text{max}}$ $[10^{-6}]$	$N^{\text{max}}_{\text{LU}}/\eta_{\text{eff}}$	$N^{\text{max}}_{\text{cLFC}}/\eta_{\text{eff}}$	$N^{\text{max}}/\eta_{\text{eff}}$
$D^0 \to \pi^0$	6.1	3.5	13	47 k (395 k)	270 k (2.3 M)	980 k (8.3 M)
$D^+ \to \pi^+$	25	14	52	77 k (650 k)	440 k (3.7 M)	1.6 M (14 M)
$D_s^+ \to K^+$	4.6	2.6	9.6	6 k (50 k)	34 k (290 k)	120 k (1.1 M)
$D^0 \to \pi^0\pi^0$	1.5	0.8	3.1	11 k (95 k)	64 k (540 k)	230 k (2.0 M)
$D^0 \to \pi^+\pi^-$	2.8	1.6	5.9	22 k (180 k)	120 k (1.0 M)	450 k (3.8 M)
$D^0 \to K^+K^-$	0.03	0.02	0.06	0.2 k (1.9 k)	1.3 k (11 k)	4.8 k (40 k)
$\Lambda_c^+ \to p^+$	18	11	39	14 k (120 k)	82 k (700 k)	300 k (2.6 M)
$\Xi_c^+ \to \Sigma^+$	36	21	76	28 k (240 k)	160 k (1.4 M)	590 k (5.0 M)
$D^0 \to X$	12	6.8	25	91 k (770 k)	520 k (4.4 M)	1.9 M (16 M)
$D^+ \to X$	30	17	63	94 k (800 k)	540 k (4.6 M)	2.0 M (17 M)
$D_s^+ \to X$	13	7.3	27	17 k (140 k)	95 k (810 k)	350 k (2.9 M)

Final remarks

- ⋆ **Charm physics provide a unique window to explore FCNCs in the up-sector.**
- ⋆ **Null tests put charm physics at the same level as NP tests in other sectors.**
- ⋆ **Plenty of opportunities to probe NP:**
  - **LFV and LU with charm decays.**
  - **Patterns in hadronic decays:**
    - **Softly broken symmetries.**
    - **Correlations with other modes.**
  - **New ideas presented: probes with $\mathcal{B}(c \to u\nu\bar{\nu})$.**
- ⋆ **Take-home message:**

Unique phenomenology, formidable (and complementary) place to search for BSM physics!

Thank you for your attention!

BACKUP

$|\Delta c| = |\Delta u| = 1$ FCNC couplings $g^{uc}_{L,R}$

- Avoid strong constraints in the kaon sector $\rightarrow$ $V_d = U_d = I$

$$V_{CKM} = V_u^\dagger \rightarrow (V_{\mathrm{CKM}})_{2\times 2} = \begin{pmatrix} \cos\Phi_u & \sin\Phi_u \\ -\sin\Phi_u & \cos\Phi_u \end{pmatrix}, \quad \sin\Phi_u = \lambda \approx 0.2\,.$$

$$(U_u)_{2\times 2} = \begin{pmatrix} \cos\theta_u & \sin\theta_u e^{-i\,\phi_R} \\ -\sin\theta_u e^{i\,\phi_R} & \cos\theta_u \end{pmatrix} \rightarrow \boxed{\text{1 CP-phase in RH up sector}}$$

- After rotation:

$$g_L^{uc} = g_4\,(V_{\mathrm{CKM}}\,F_Q\,V^\dagger_{\mathrm{CKM}})_{12} = g_4\,(F_{Q_2} - F_{Q_1})\,\sin\Phi_u\,\cos\Phi_u\,,$$

$$g_R^{uc} = g_4\,(U_u^\dagger\,F_u\,U_u)_{12} = g_4\,(F_{u_2} - F_{u_1})\,\sin\theta_u\,\cos\theta_u\,e^{i\,\phi_R}\,,$$

- CP violation BSM generated by RH up rotation in g_R^{uc},

$$\boxed{g_L^{uc} = g_4\,\Delta F_L\,\lambda} \quad \boxed{g_R^{uc} = g_4\,\Delta F_R\,\sin\theta_u\,\cos\theta_u\,e^{i\,\phi_R}}$$

with $\Delta F_L = F_{Q_2} - F_{Q_1}$ and $\Delta F_R = F_{u_2} - F_{u_1}$.

Beyond the usual four-fermion operators

New $U(1)'$ charges require new operators, like EW penguins.

High-energy scales

8 additional operators:

$$\widetilde{Q}_7 = (\bar{u}c)_{V-A} \sum_q F_{u_i,d_i} (\bar{q}q)_{V+A} \,, \qquad \widetilde{Q}'_7 = (\bar{u}c)_{V+A} \sum_q F_{Q_i} (\bar{q}q)_{V-A} \,,$$

$$\widetilde{Q}_8 = (\bar{u}_\alpha c_\beta)_{V-A} \sum_q F_{u_i,d_i} (\bar{q}_\beta q_\alpha)_{V+A} \,, \qquad \widetilde{Q}'_8 = (\bar{u}_\alpha c_\beta)_{V+A} \sum_q F_{Q_i} (\bar{q}_\beta q_\alpha)_{V-A},$$

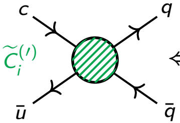
$$\widetilde{Q}_9 = (\bar{u}c)_{V-A} \sum_q F_{Q_i} (\bar{q}q)_{V-A} \,, \qquad \widetilde{Q}'_9 = (\bar{u}c)_{V+A} \sum_q F_{u_i,d_i} (\bar{q}q)_{V+A} \,,$$

$$\widetilde{Q}_{10} = (\bar{u}_\alpha c_\beta)_{V-A} \sum_q F_{Q_i} (\bar{q}_\beta q_\alpha)_{V-A} \,, \qquad \widetilde{Q}'_{10} = (\bar{u}_\alpha c_\beta)_{V+A} \sum_q F_{u_i,d_i} (\bar{q}_\beta q_\alpha)_{V+A},$$

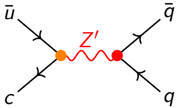
with $q = u, c, d, s, b$ and α, β are color indices.

Matching and RGEs

Matching condition at high-energy scales:



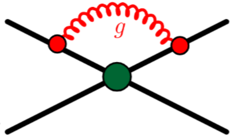
$$\Leftarrow \boxed{\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \sum_i \widetilde{C}_i^{(\prime)} \widetilde{Q}_i^{(\prime)} = \mathcal{L}_{Z'}} \Leftarrow$$



$$\widetilde{C}_{7,9}(M_{Z'}) = \frac{\sqrt{2}}{G_F} \frac{g_4\, g_L^{uc}}{4\, M_{Z'}^2}, \quad \widetilde{C}'_{7,9}(M_{Z'}) = \frac{\sqrt{2}}{G_F} \frac{g_4\, g_R^{uc}}{4\, M_{Z'}^2}, \quad \widetilde{C}_{8,10}^{(\prime)}(M_{Z'}) = 0\,.$$

QCD plays a role at low-energy: RGEs mix different operators

$$\left(\frac{\lambda^a}{2}\right)_{\alpha\beta} \left(\frac{\lambda^a}{2}\right)_{\gamma\delta} = \delta_{\alpha\delta}\,\delta_{\beta\gamma} - \frac{1}{N_C}\,\delta_{\alpha\beta}\,\delta_{\gamma\delta}$$



Anomalous dimension

$$\Rightarrow \quad \gamma_F^0 \quad \Rightarrow$$

$$\begin{aligned}
\widetilde{C}_7^{(\prime)}(m_c) &= 0.829\, \widetilde{C}_7^{(\prime)}(M_{Z'})\,, \\
\widetilde{C}_8^{(\prime)}(m_c) &= 1.224\, \widetilde{C}_7^{(\prime)}(M_{Z'})\,, \\
\widetilde{C}_9^{(\prime)}(m_c) &= 1.404\, \widetilde{C}_9^{(\prime)}(M_{Z'})\,, \\
\widetilde{C}_{10}^{(\prime)}(m_c) &= -0.718\, \widetilde{C}_9^{(\prime)}(M_{Z'})\,.
\end{aligned}$$

Estimation of hadronic matrix elements (HME)

Factorization of currents: $Q_i = (\bar{q}_1\,\Gamma_1\,q_2)\,(\bar{q}_3\,\Gamma_2\,q_4)$

$$\left\langle P^+\,P^- \middle| Q_i \middle| D^0 \right\rangle = \left\langle P^+ \middle| (\bar{q}_1\,\Gamma_1\,q_2) \middle| 0 \right\rangle \left\langle P^- \middle| (\bar{q}_3\,\Gamma_2\,q_4) \middle| D^0 \right\rangle B_i^{P^+P^-}$$

where $B_i^{P^+P^-}$ parametrizes the deviation of the true HME from $B_i^{P^+P^-}|_{\text{naïve}} = 1$.

After Fierz identities in the flavor and color space:

$$\left\langle P^+P^- \middle| Q_i \middle| D^0 \right\rangle_{\text{Penguin}} = (\text{factor}) \times (\text{HME}_{\text{Tree}})$$

then it cancels in the CP-asymmetry: $A_{\text{CP}} \propto \frac{\text{HME}_{\text{Penguin}}}{\text{HME}_{\text{Tree}}}$.

What does the "factor" contain?

- **Chiral factor (Hadronization):**
  - Non-enhanced: $\widetilde{Q}_{9,10}$
  - Enhanced: $\widetilde{Q}_{7,8}$

$$\left\langle P^+P^- \middle| Q_i^{(V-A)\times(V+A)} \middle| D^0 \right\rangle \propto \frac{2\,M_P^2}{m_c\,(m_{q_1}+m_{q_2})}$$

- **Color factor (Fierz):**
  - Non-suppressed: $\widetilde{Q}_{8,10}$
  - Suppressed: $\widetilde{Q}_{7,9}$

$$\left(\frac{\lambda^a}{2}\right)_{\alpha\beta}\left(\frac{\lambda^a}{2}\right)_{\gamma\delta} = \delta_{\alpha\delta}\,\delta_{\beta\gamma} - \frac{1}{N_C}\,\delta_{\alpha\beta}\,\delta_{\gamma\delta}$$

$\delta\mathcal{B}$ vs $\mathcal{B}$: exp. projections and theo. predictions