The U-Spin-CP Anomaly in charm

based on 2210.16330

in collaboration with R. Bause, H. Gisbert, G. Hiller, D. Litim and T. Steudtner

Tim Höhne

TU Dortmund
Theoretical Physics Department IV

16.03.2023

Outline

1. Introduction
2. Model
3. Phenomenology & Constraints
4. Conclusion

Introduction

CP Violation in charm: Experimental Status

We are living in exciting times!

CP Violation in charm: Experimental Status

We are living in exciting times!

- LHCb'19: First observation of CP violation in charm sector [1903.08726]
  $\Rightarrow$Difference of CP asymmetries in $D^0 \to K^+K^-, \pi^+\pi^-$ decays

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \cdot 10^{-4}$$

- LHCb'22: Direct measurement of $A_{CP}(K^+K^-)$ [2209.03179]

$$A_{CP}(K^+K^-) = (6.8 \pm 5.4 \pm 1.6) \cdot 10^{-4}$$

- LHCb'22: Fit of both direct CP asymmetries [2209.03179]

$$\mathbf{a^d_{K^+K^-}} = (\mathbf{7.7} \pm \mathbf{5.7}) \cdot \mathbf{10^{-4}}$$
$$\mathbf{a^d_{\pi^+\pi^-}} = (\mathbf{23.2} \pm \mathbf{6.1}) \cdot \mathbf{10^{-4}}$$

$\Rightarrow$3.8 σ evidence for direct CP violation in $D^0 \to \pi^+\pi^-$!

CP Violation in charm: Theoretical perspective

Experimental results are puzzling!

CP Violation in charm: Theoretical perspective

Experimental results are puzzling!

- $a^{d}_{\pi^-\pi^+} > |\Delta A_{CP}|$ is quite large!
  $\Rightarrow$SM interpretation: $a^{d\,\mathrm{SM}}_{\pi^-\pi^+} \sim 2 \cdot \mathrm{Im}(V^*_{cb}V_{ub}/(V^*_{cd}V_{ud}))h/t$
  $\Rightarrow$Would require enhanced higher order contributions h over tree-level ones t by $h/t \sim 2$ to compensate CKM suppression!

CP Violation in charm: Theoretical perspective

Experimental results are puzzling!

- $a^d_{\pi^-\pi^+} > |\Delta A_{CP}|$ is quite large!
  $\Rightarrow$SM interpretation: $a^{d\,\mathrm{SM}}_{\pi^-\pi^+} \sim 2 \cdot \mathrm{Im}(V^*_{cb}V_{ub}/(V^*_{cd}V_{ud}))h/t$
  $\Rightarrow$Would require enhanced higher order contributions h over tree-level ones t by $h/t \sim 2$ to compensate CKM suppression!
- The SM has an approximate U-spin symmetry ($d \leftrightarrow s$)
  $\Rightarrow$U-Spin limit $a^d_{K^+K^-} = -a^d_{\pi^+\pi^-}$ broken by $2.7\,\sigma$! [2207.08539]
- U-spin breaking in SM: order $\frac{m_s - m_d}{\Lambda_{QCD}} \sim 30\%$
  $\Rightarrow$sufficient to explain $\frac{\mathcal{B}(D\to\pi^+\pi^-)}{\mathcal{B}(D\to K^+K^-)} \sim 2.8$
  $\Rightarrow$insufficient to explain $a^{d,\mathrm{exp}}_{\pi^-\pi^+}$, $a^{d,\mathrm{exp}}_{K^-K^+}$ by a factor 4-5!

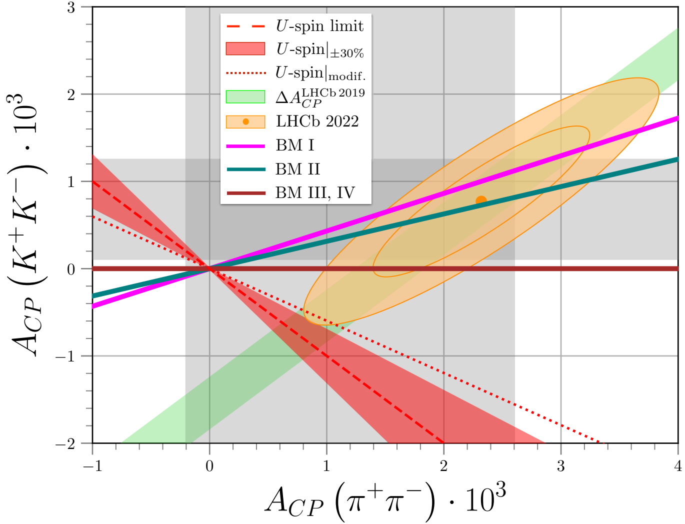
CP Violation in charm: Theoretical perspective

Experimental results are puzzling!

- $a^d_{\pi^-\pi^+} > |\Delta A_{CP}|$ is quite large!
  $\Rightarrow$SM interpretation: $a^{d\,\mathrm{SM}}_{\pi^-\pi^+} \sim 2 \cdot \mathrm{Im}(V^*_{cb} V_{ub}/(V^*_{cd} V_{ud}))h/t$
  $\Rightarrow$Would require enhanced higher order contributions h over tree-level ones t by $h/t \sim 2$ to compensate CKM suppression!
- The SM has an approximate U-spin symmetry ($d \leftrightarrow s$)
  $\Rightarrow$U-Spin limit $a^d_{K^+K^-} = -a^d_{\pi^+\pi^-}$ broken by $2.7\,\sigma$! [2207.08539]
- U-spin breaking in SM: order $\frac{m_s - m_d}{\Lambda_{QCD}} \sim 30\%$
  $\Rightarrow$sufficient to explain $\frac{\mathcal{B}(D\to\pi^+\pi^-)}{\mathcal{B}(D\to K^+K^-)} \sim 2.8$
  $\Rightarrow$insufficient to explain $a^{d,\exp}_{\pi^-\pi^+}$, $a^{d,\exp}_{K^-K^+}$ by a factor 4-5!

$\Rightarrow$**Hint for CP- and U-Spin violating NP!**

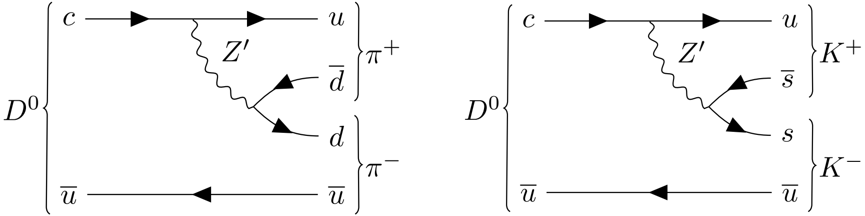
The U-Spin-CP Anomaly



Model

How to adress the anomaly?

Idea: Z' with generation dependent charges



$$a^d_{\pi^-\pi^+} = \frac{g_4^2}{M_{Z'}^2}\Delta\widetilde{F}_R[c_\pi\, F_{Q_1} + d_\pi\, F_{d_1}]\,,\quad a^d_{K^-K^+} = \frac{g_4^2}{M_{Z'}^2}\Delta\widetilde{F}_R[c_K\, F_{Q_2} + d_K\, F_{d_2}]$$

- g_4, $M_{Z'}$ are the $U(1)'$ coupling and Z'-mass
- F_{ψ_i} are SM fermion $U(1)'$ charges
- $c_{\pi,K}$, $d_{\pi,K}$ are hadronic parameters (contain HMEs & RG effects)

Benchmarks & Ingredients

- $\Delta\widetilde{F}_R = \sin\theta_u \cos\theta_u (F_{u_2} - F_{u_1}) \neq 0$ to induce ucZ'-vertex
  $\Rightarrow$Right-handed c-u-mixing by angle $\boxed{\theta_u \neq 0}$ (adjust)
  $\Rightarrow$different $U(1)'$ charges $\boxed{F_{u_2} \neq F_{u_1}}$
- $\boxed{F_{Q_{1,2}} = 0}$ to avoid Kaon constraints
- $\frac{F_{d_2}}{F_{d_1}} = \frac{d_\pi \; a^d_{K^-K^+}}{d_K \; a^d_{\pi^-\pi^+}}$ to generate $a^{d,\mathrm{exp}}_{K^+K^-,\,\pi^+\pi^-}$ $\Rightarrow$ $\boxed{\mid F_{d_2} \mid \ll \mid F_{d_1} \mid}$
- six anomaly cancellation conditions on F_{ψ_i}
  $\Rightarrow$add ν_R with $\boxed{F_{\nu_i} \neq 0}$

Model	F_{Q_i}			F_{u_i}			F_{d_i}			F_{L_i}			F_{e_i}			F_{ν_i}		
BM III	0	0	0	G	-F	0	F	-G	0	0	0	0	0	-G	F	0	G	-F
BM IV	0	0	0	-F_u	F_u	0	F_d	0	-F_d	0	0	0	F_e	0	-F_e	F_ν	-F_ν	0

Phenomenology & Constraints

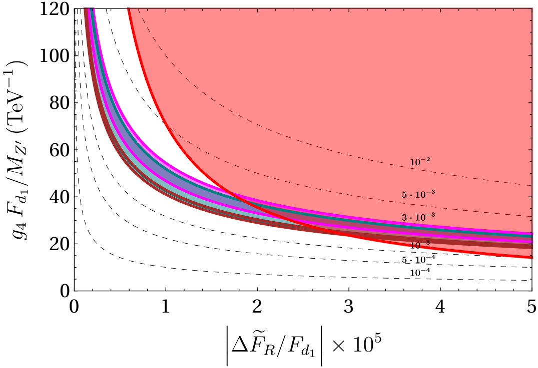
Predicting $A_{CP}(\pi^0\pi^0)$ and $A_{CP}(\pi^0\pi^+)$

- $F_{d_1} \neq F_{u_1}$ violates Isospin and induces $A_{CP}(\pi^0\pi^{0/+}) \neq 0$
- Similar size: $\frac{A_{\text{CP}}(\pi^0\pi^0)}{A_{\text{CP}}(\pi^+\pi^0)} = \frac{d_{\pi^0}}{d_{\pi'}} \simeq 1.08 \pm 0.10$ [2004.01206]
- For $|\, F_{d_2} \,| \ll |\, F_{d_1} \,|$ all CP asymmetries involving pions are correlated!
  $A_{\text{CP}}(\pi^+\pi^0) \simeq \frac{d_{\pi'}}{d_{\pi^0}} A_{\text{CP}}(\pi^0\pi^0) \simeq -\frac{d_{\pi'}}{d_\pi}\left(1 - \frac{F_{u_1}}{F_{d_1}}\right) \Delta A_{\text{CP}}$
- $d_\pi \sim d_{\pi'} \sim d_{\pi^0}$ and in our BMs $|\, F_{u_1} \,| < |\, F_{d_1} \,|$
  $\Rightarrow A_{CP}(\pi^0\pi^{0/+})$ are positive
  $\Rightarrow A_{CP}(\pi^0\pi^{0/+})$ are of similar magnitude as $\Delta A_{\text{CP}} \sim 10^{-3}$

$$A_{CP}^{\text{BM III}}(\pi^0\pi^{0/+}) \simeq -1 \cdot \Delta A_{\text{CP}}$$

$$A_{CP}^{\text{BM IV}}(\pi^0\pi^{0/+}) \simeq -\left(1 \pm \frac{1}{\sqrt{2}}\right) \cdot \Delta A_{\text{CP}}$$

D-Mixing



$\frac{g_4}{M_{Z'}}\Delta\widetilde{F}_R < 7.1\cdot 10^{-4}\,\mathrm{TeV}^{-1}$ from D-mixing (e.g. LHCb'21 [2106.03744])

$$\left|\frac{\Delta\widetilde{F}_R}{F_{d_1}}\right| \lesssim \mathcal{O}(10^{-5}) \qquad \Rightarrow \qquad \boxed{\theta_u \ll 1}$$

$$\frac{g_4 F_{d_1}}{M_{Z'}} \gtrsim \frac{1}{\mathbf{25\,GeV}}\cdot\frac{|a^d_{\pi^+\pi^-}|}{0.002} \qquad \Rightarrow \qquad \boxed{\textbf{light } \mathbf{Z'} \textbf{ (or large } \mathbf{g_4 F_{d_1}}\textbf{)!}}$$

Charm dilepton & invisibles data

Lepton couplings of the Z' are constrained by various processes

- BR's of (semi-)muonic D-decays (LHCb talk @ ICHEP'22)
  $\Rightarrow D^0 \to \mu^+\mu^-, \quad D^0 \to \pi^0\mu^+\mu^-, \quad D^+ \to \pi^+\mu^+\mu^-$
- Drell-Yan data for $\ell = e, \tau$ [2003.12421]

$\Rightarrow$Lepton charges should not be excessive compared to quarks

$\Rightarrow$very roughly $\boxed{|F_{L_i}, F_{e_i}| \lesssim |\, F_{d_1} \,|}$

Charm dilepton & invisibles data

Lepton couplings of the Z' are constrained by various processes

- BR's of (semi-)muonic D-decays (LHCb talk @ ICHEP'22) $\Rightarrow D^0 \to \mu^+\mu^-, \quad D^0 \to \pi^0\mu^+\mu^-, \quad D^+ \to \pi^+\mu^+\mu^-$
- Drell-Yan data for $\ell = e, \tau$ [2003.12421]

$\Rightarrow$Lepton charges should not be excessive compared to quarks

$$\Rightarrow \text{very roughly } \boxed{|F_{L_i}, F_{e_i}| \lesssim |F_{d_1}|}$$

Z' couples to ν_R (+ potentially SM singlet vector-like fermions χ)

$\Rightarrow$Couplings constrained by charm BR's with invisibles in final state!

- $\mathcal{B}(D^0 \to \pi^0 \text{ inv.}) < 2.1 \cdot 10^{-4}$ (BESIII'21 [2112.14236]) constrains $|F_{\nu,\chi}|$
- $\mathcal{B}(D^0 \to \text{inv.}) < 9.4 \cdot 10^{-5}$ (BELLE'16 [1611.09455]) constrains $|F_{\nu}|$

$$\Rightarrow \boxed{|F_{\nu,\chi}| \lesssim 110 |F_{d_1}|}$$

A flavorful Z' of $\mathcal{O}(10\text{ GeV})$?

Mass window severely constrained!

- Dijets + ISR (CMS'19 [1905.10331])

$\Rightarrow \boxed{g_4 F_{d_1} \lesssim 0.5}$ implying $\boxed{10\text{ GeV} \lesssim M_{Z'} \lesssim 20\text{ GeV}}$

A flavorful Z' of $\mathcal{O}(10\text{ GeV})$?

Mass window severely constrained!

- Dijets + ISR (CMS'19 [1905.10331])

  $\Rightarrow \boxed{g_4 F_{d_1} \lesssim 0.5}$ implying $\boxed{10\text{ GeV} \lesssim M_{Z'} \lesssim 20\text{ GeV}}$

Z'-γ kinetic mixing induces Z'-fermion-couplings via $\mathcal{L}_\varepsilon = -\,\varepsilon\, e J^\mu Z'_\mu$

- Limits from dark photon searches! $\Rightarrow \boxed{\varepsilon(M_{Z'}) \lesssim 10^{-3}}$

  $\Rightarrow Z' \to \mu^+\mu^-$ (LHCb'19 [1910.06926]), $Z' \to e^+e^-$ [1801.04847]

- Translate to bounds on lepton charges

  $\Rightarrow$**The Z' has to be (quasi-)leptophobic!** $\boxed{\dfrac{F_{L_{1,2},e_{1,2}}}{F_{d_1}} \lesssim \dfrac{1}{750}}$

  $\Rightarrow$much stronger than constraints from DY & semileptonic decays

Conclusion

Conclusion

U-Spin-CP-anomaly

- $a^d_{\pi^+\pi^-}$ factor ~ 2 enhanced over SM tree-level (LHCb'22)
- U-Spin breaking ($\sim 4-5$) times larger than in SM (LHCb'22)
- Explanation by light, flavorful Z' (very predictive!)
  $\Rightarrow M_{Z'} =$ 10-20 GeV, μ-,e-phobic, coupling only to RH fermions
  $\Rightarrow$Up to now the only available explanation for the anomaly!

Conclusion

U-Spin-CP-anomaly

- $a^d_{\pi^+\pi^-}$ factor ~ 2 enhanced over SM tree-level (LHCb'22)
- U-Spin breaking ($\sim 4-5$) times larger than in SM (LHCb'22)
- Explanation by light, flavorful Z' (very predictive!)
  $\Rightarrow M_{Z'} =$ 10-20 GeV, μ-,e-phobic, coupling only to RH fermions
  $\Rightarrow$Up to now the only available explanation for the anomaly!

What to do next?

- Many search channels & signatures (also for LHCb)
  $\Rightarrow A_{CP}(\pi^0\pi^{0/+})$, dijets, invisible D-decays, τ Drell-Yan
- Relation to U-Spin puzzle in B-Decays? [2211.06994]
- Reduce large hadronic uncertainties (rescattering) [2203.04056], [PVS@ICHEP'22]

$\Rightarrow$**Joint experimental & theoretical effort to disentangle SM & NP**

BACKUP

Anomaly Cancellation Conditions

Chiral fermion contributions to gauge anomalies have to cancel!

$$
\begin{aligned}
SU(3)_C^2 \times U(1)' &: 2\langle \mathcal{F}_Q \rangle - \langle \mathcal{F}_u \rangle - \langle \mathcal{F}_d \rangle = 0\,,\\
SU(2)_L^2 \times U(1)' &: 3\langle \mathcal{F}_Q \rangle + \langle \mathcal{F}_L \rangle = 0\,,\\
U(1)_Y^2 \times U(1)' &: \langle \mathcal{F}_Q \rangle + 3\langle \mathcal{F}_L \rangle - 8\langle \mathcal{F}_u \rangle - 2\langle \mathcal{F}_d \rangle - 6\langle \mathcal{F}_e \rangle = 0\,,\\
\text{gauge-gravity} &: 6\langle \mathcal{F}_Q \rangle + 2\langle \mathcal{F}_L \rangle - 3\langle \mathcal{F}_u \rangle - 3\langle \mathcal{F}_d \rangle - \langle \mathcal{F}_e \rangle - \langle \mathcal{F}_\nu \rangle = 0\,,\\
U(1)_Y \times U(1)'^2 &: \langle \mathcal{F}_Q^2 \rangle - \langle \mathcal{F}_L^2 \rangle - 2\langle \mathcal{F}_u^2 \rangle + \langle \mathcal{F}_d^2 \rangle + \langle \mathcal{F}_e^2 \rangle = 0\,,\\
U(1)'^3 &: 6\langle \mathcal{F}_Q^3 \rangle + 2\langle \mathcal{F}_L^3 \rangle - 3\langle \mathcal{F}_u^3 \rangle - 3\langle \mathcal{F}_d^3 \rangle - \langle \mathcal{F}_e^3 \rangle - \langle \mathcal{F}_\nu^3 \rangle = 0
\end{aligned}
$$

$$\text{where } \langle \mathcal{F}_\psi^{(n)} \rangle = \textstyle\sum_{i=1}^3 F_{\psi_i}^{(n)}$$

Additionally to avoid kinetic mixing at 1-loop:

$$\langle \mathcal{F}_Q \rangle - \langle \mathcal{F}_L \rangle + 2\langle \mathcal{F}_u \rangle - \langle \mathcal{F}_d \rangle - \langle \mathcal{F}_e \rangle = 0$$

Constraints on lepton charges

Lepton couplings & charges are constrained by

- BR's of rare (semi-)leptonic charm decays [2011.09478]
  $\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.9 \cdot 10^{-9}$ @90% c.l. (LHCb talk ICHEP'22)
- Drell-Yan searches [2003.12421]

$\Rightarrow$Combination with $a^d_{\pi^+\pi^-}$ yields as most stringent bounds:

$$\begin{aligned} \sqrt{F_{L_1}^2 + F_{e_1}^2} &\lesssim 2.3|F_{d_1}| \quad && \text{Drell-Yan } e \\ |F_{L_2} - F_{e_2}|, \sqrt{F_{L_2}^2 + F_{e_2}^2} &\lesssim 0.8|F_{d_1}| \quad && \text{(semi-)muonic } D^0 \text{decays} \\ \sqrt{F_{L_3}^2 + F_{e_3}^2} &\lesssim 4.7|F_{d_1}| \quad && \text{Drell-Yan } \tau \end{aligned}$$

Kinetic Mixing

Z'-γ kinetic mixing via $\mathcal{L}_\eta = -\frac{\eta}{2} F^{\mu\nu} Z'_{\mu\nu}$

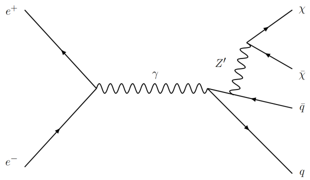
- From ρ-parameter: $\boxed{\varepsilon(M_Z) \lesssim 3 \cdot 10^{-1}}$ where $\varepsilon = \frac{-\eta}{\sqrt{1-\eta^2}}$
- From induced Z'-lepton-couplings via $\mathcal{L}_\varepsilon = -\,\varepsilon\, eJ^\mu Z'_\mu$:
  $\boxed{\varepsilon(M_{Z'}) \lesssim 10^{-3}}$ and $\boxed{F_{L_{1,2},e_{1,2}} \lesssim 10^{-3} \cdot F_{d_1}}$
  $\Rightarrow$BM III: $|G| \ll |F|$ & BM IV: $|F_e| \ll |F_{u,d}|$
- *Problem*: $\varepsilon(M_Z)$ is in general RG induced even if $\varepsilon(M_{Z'}) = 0$
  $\Rightarrow$BM IV: ε is natural $\frac{\mathrm{d}\varepsilon}{\mathrm{d}\ln\mu} \propto \varepsilon$ and controlled by small $\varepsilon(M_{Z'})$
  $\Rightarrow$BM III: RGEs induce $|\,\varepsilon\,(M_Z) - \varepsilon(M_{Z'})| \gtrsim 10^{-2}$
  $\Rightarrow$Require moderate tuning of $\varepsilon(M_{Z'})$ order 10%

$\Rightarrow$**kinetic mixing constraints can be avoided**

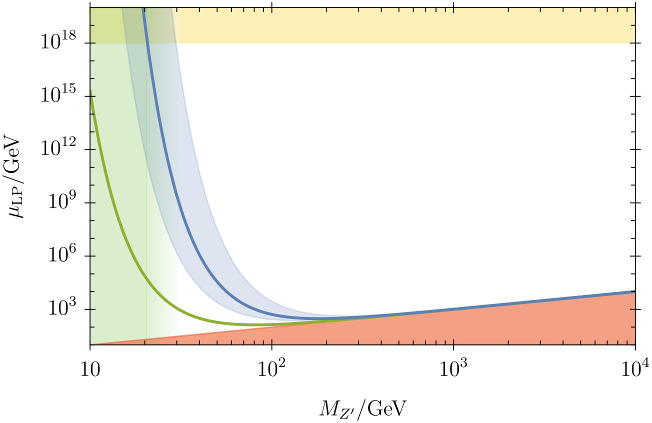
Z' Branching ratios

Model	jets	b	c	e	μ	τ	$\nu_{e,\mu,\tau}$
BM III	38%	0%	37%	0%	0%	12%	13%
BM IV$\vert_{M_{Z'}=10\,\mathrm{GeV}}$	59%	22%	18%	0%	0%	0%	0%
BM IV$\vert_{M_{Z'}=20\,\mathrm{GeV}}$	52%	31%	17%	0%	0%	0%	0%

- Decays via kinetic mixing suppressed by $\lesssim \mathcal{O}(10^{-7})$
  $\Rightarrow$negligible
- Branching ratios can be suppressed by adding $\mid F_{\nu_i,\chi} \mid \gtrsim \mid F_{\psi_i} \mid$
  $\Rightarrow e^+e^- \to$ hadrons $+ \not{E}_T$
  $\Rightarrow \mid F_{\nu_i,\chi} \mid$ limited by Landau poles



High Energy Behaviour



$M_{Z'} \lesssim$ few $\times$ 10 GeV to avoid sub-TeV-ish Landau pole