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Old and new anomalies in charm

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The recent LHCb determination of the direct *CP* asymmetries in the decays $D^0 \to K^+K^-, \pi^+\pi^-$ hints at a sizeable breaking of two approximate symmetries of the SM: *CP* and U-spin. We aim at explaining the data with BSM physics and use the framework of flavorful Z' models. Interestingly, experimental and theoretical constraints very much narrow down the shape of viable models: Viable, anomaly-free models are electron- and muon-phobic and feature a light Z' of 10-20 GeV coupling only to right-handed fermions. The Z' can be searched for in low mass dijets or at the LHC as well as dark photon searches. A light Z' of ~ 3 GeV or ~ 5-7 GeV can moreover resolve the longstanding discrepancy in the $J/\psi, \psi'$ branching ratios with pion form factors from fits to $e^+e^- \to \pi^+\pi^-$ data, and simultaneously explain the charm *CP* asymmetries. Smoking gun signatures for this scenario are Υ and charmonium decays into pions, taus or invisbles.

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1. Introduction

Recently, LHCb determined the direct CP asymmetries in $D^0 \to \pi^+\pi^-, K^+K^-$ decays to [2]

$$a^d_{K^+K^-} = (7.7 \pm 5.7) \cdot 10^{-4}, \qquad a^d_{\pi^+\pi^-} = (23.2 \pm 6.1) \cdot 10^{-4}. \tag{1}$$

These results are puzzling for two reasons. Firstly, a SM explanation of $a^d_{\pi^+\pi^-}$ requires higher-order contributions h to be enhanced over the tree-level amplitude t by $\frac{h}{t} \sim 2$. This is significantly larger than the estimations from [3, 4]. Secondly, the fit implies a 2.7σ violation of the approximate SM U-spin symmetry [5], that is $a^d_{\pi^+\pi^-} = -a^d_{K^+K^-}$, which is a factor ~ 4 larger than the naively expected U-spin breaking in the SM of $\mathcal{O}\left(\frac{m_s - m_d}{\Lambda_{QCD}}\right) \sim 30\%$, see Fig. 1. This constitutes the U-spin-CP anomaly in charm, which we aim to explain with a flavorful Z' model [1].

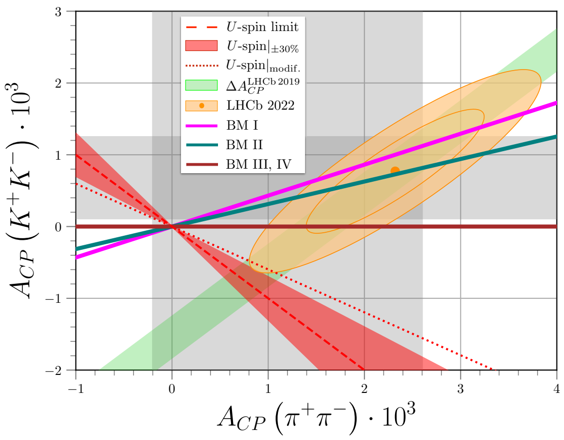

Figure 1: The U-spin-CP anomaly in charm, showing LHCb bounds (gray & green), the best fit region (orange) and the SM expectation including $\lesssim 30\%$ U-spin breaking (red cone). Coloured lines relate to benchmark models of [1].

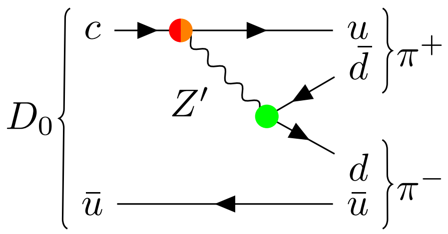

Figure 2: Z' contribution to the decay $D^0 \to \pi^+\pi^-$.

2. Explaining the anomaly with a flavorful Z'

The Z' contributes to the CP asymmetries in $D^0 \to \pi^+\pi^-, K^+K^-$ decays via Fig. 2 as

$$a^d_{\pi^+\pi^-,K^+K^-} = \frac{g_4^2}{M_{Z'}^2} \Delta\widetilde{F}_R \left[c_{\pi,K} F_{Q_{1,2}} + d_{\pi,K} F_{d_{1,2}}\right] \tag{2}$$

where g_4 and M'_Z are the $U(1)'$ gauge coupling and Z' mass, respectively, and $c_{\pi,K}, d_{\pi,K}$ are hadronic parameters. Moreover, $\Delta\widetilde{F}_R = \sin\theta_u \cos\theta_u (F_{u_2} - F_{u_1})$ contains the right-handed c-u mixing angle θ_u. Explaining the CP data (1) requires the $U(1)'$-quark charges to obey $F_{u_2} \neq F_{u_1}$ and $|F_{d_1}| \gg |F_{d_2}|$ due to the hierarchy $a^d_{\pi^+\pi^-} \gg a^d_{K^+K^-}$ (1), along with $\theta_u \neq 0$ and sizeable relative weak and strong phases.

The shape of viable benchmark models in Tab. 1 is further narrowed down by demanding anomaly cancellation which might require adding $U(1)'$ charged right-handed neutrinos ν_R. Additional constraints arise from Kaon FCNCs, (semi-)leptonic and (semi-)invisible $D \to (\pi)\ell^+\ell^-, \nu\nu$ decays as well as Drell-Yan searches. Viable models also predict $A_{CP}(\pi^0\pi^+) \simeq A_{CP}(\pi^0\pi^0) \simeq +10^{-3}$.

Moreover, strong constraints from D-mixing combined with CP data (1) surpisingly point to a sub-electroweak Z' mass of a few $\times 10$ GeV. The Z' coupling to d-quarks leads to collider signals in low mass dijets with initial state radiation, resulting in a mass bound of $M_{Z'} \lesssim 20$ GeV [6].

Model	F_{Q_i}			F_{u_i}			F_{d_i}			F_{L_i}			F_{e_i}			F_{ν_i}		
BM III	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	1	0	0	-1
BM IV	0	0	0	$-\frac{985}{1393}$	$\frac{985}{1393}$	0	1	0	-1	0	0	0	$\frac{1}{1393}$	0	$-\frac{1}{1393}$	F_ν	$-F_\nu$	0

Table 1: Benchmarks for viable, anomaly-free $U(1)'$ extensions of the SM+3ν_R explaining $a^d_{\pi^+\pi^-,K^+K^-}$ (1).

3. A hadrophilic Z' of $O(10\text{ GeV})$?

Light Z' models are also constrained by dark photon searches [7], which imply a strict bound on lepton charges of $|F_{L_{1,2},e_{1,2}}| \lesssim 10^{-3}|F_{d_1}|$. Hence, the Z' has to be leptophobic.

The Z' can also mediate quarkonia decays. In BM IV, mass bounds arise from $\Upsilon(1s)$ decays via the b_R-coupling. Moreover, the Z' contributes to charmonium decays $\psi_i \to Z'^* \to \pi^+\pi^-(,\tau^+\tau^-,\nu\nu)$ with $\psi_i = J/\psi, \psi'$, see Fig. 3. In particular, the electrophobic Z' enhances $\mathcal{B}(\psi_i \to \pi^+\pi^-)$ with respect to $\mathcal{B}(\psi_i \to e^+e^-)$, see Fig. 4. Thereby, for $M_{Z'} \simeq 3$ GeV (5-7 GeV) in BM III (BM IV) the model is able to resolve the longstanding discrepancy between the pion form factor $F_\pi(q^2)$ extracted from $J/\psi \to \pi^+\pi^-$ [8] and $e^+e^- \to \pi^+\pi^-$ [9]. In this case, in BM III the Z' mass range of $M_{Z'} \lesssim 2.2$ GeV allowed by $\mathcal{B}(\psi' \to \tau^+\tau^-) = (3.1 \pm 0.4)\cdot 10^{-3}$ [10] almost coincides with the pion form factor window, whereas $\mathcal{B}(J/\psi \to \text{nothing}) < 7\cdot 10^{-4}$ [10] implies that the decay to BSM neutrinos should be kinematically forbidden by $M_\nu > M_{J/\Psi}/2$ which can be achieved e.g. via the Dirac inverse see-saw mechanism.

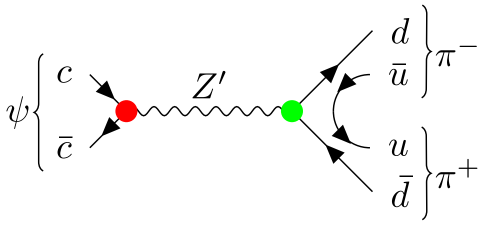

Figure 3: Z' contribution to the charmonia decays $J/\psi, \psi' \to \pi^+\pi^-$.

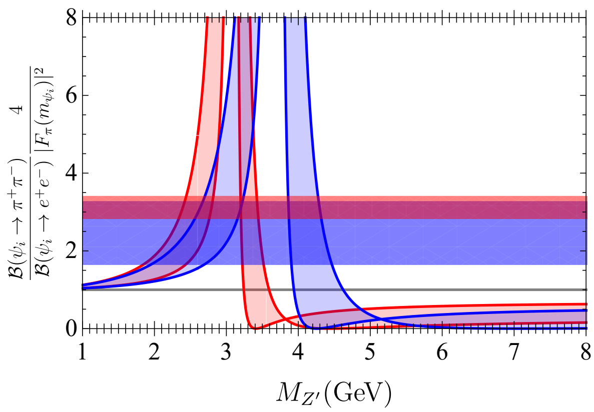

Figure 4: Constraints from charmonium decays. Horizontal red (blue) bands denote J/ψ (ψ') data [8] using $F_\pi(q^2)$ from [9]. Curves correspond to predictions in BM III including experimental uncertainties from (1). The SM prediction corresponds to the horizontal gray line.

4. Conclusion

Recent charm data (1) imply sizeable violation of CP and U-spin, possibly hinting new physics. We obtain a viable explanation from a flavorful Z' boson which is light of $O(10\text{ GeV})$, leptophobic and couples only to $SU(2)_L$ singlets. Moreover, a Z' of a few GeV can resolve the pion form factor discrepancy between $e^+e^- \to \pi^+\pi^-$ and $J/\psi \to \pi^+\pi^-$ extractions. In this scenario, hadronic, tauonic and invisible quarkonia decays are smoking gun signatures of the model. Longstanding anomalies such as the large isospin breaking between $\psi(3770) \to D^+D^-$ and $D_0\bar{D}_0$ [10] could potentially also be addressed.

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