technische universität
dortmund

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

31.01.2023

Outline

1. Introduction
2. Model Setup
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

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

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]

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

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]

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

$\Rightarrow 3.8\,\sigma$ 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 $2.7\,\sigma$!
- 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! [2207.08539]

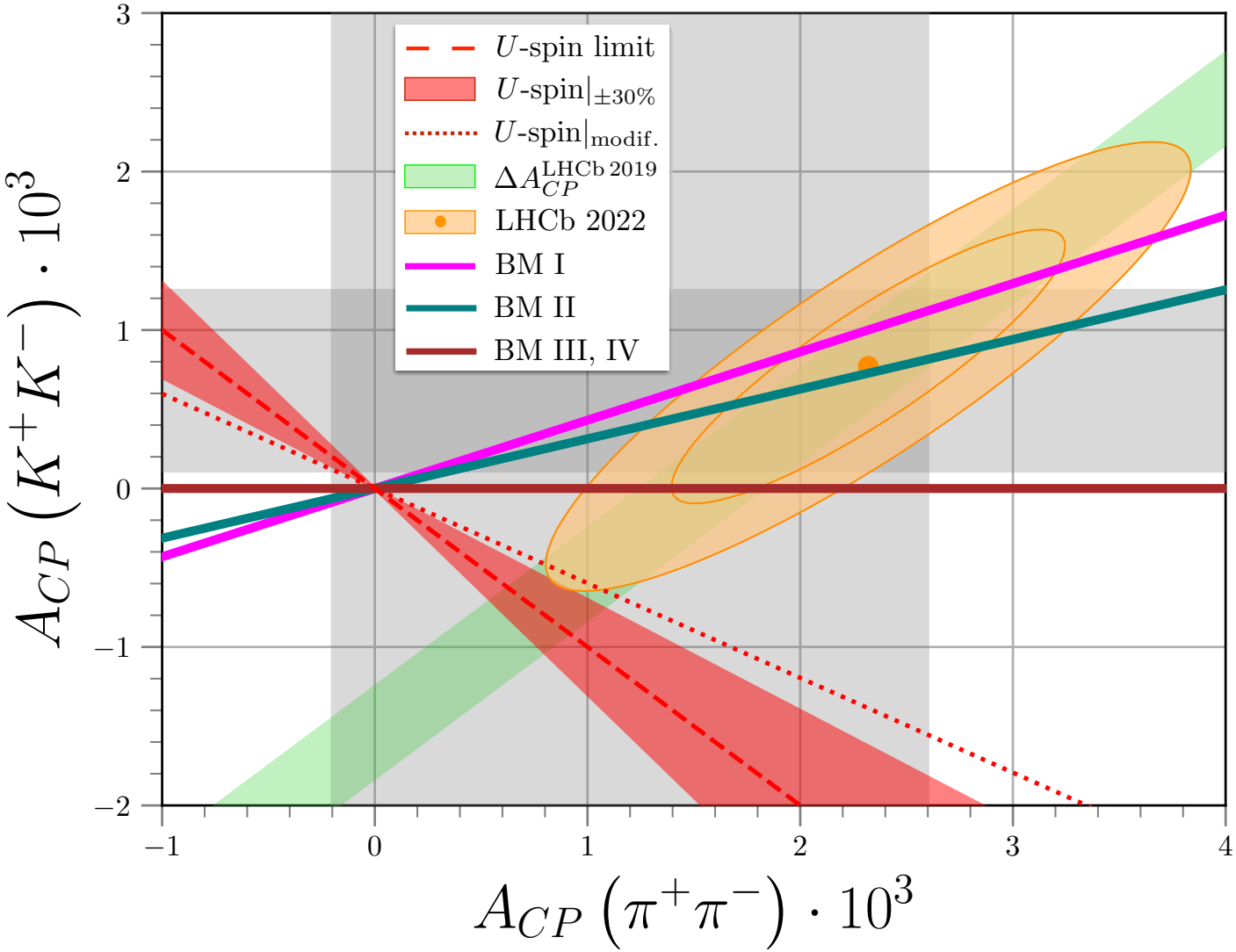
CP Violation in charm: Theoretical perspective

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 $2.7\,\sigma$!
- 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! [2207.08539]

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

The U-Spin-CP Anomaly

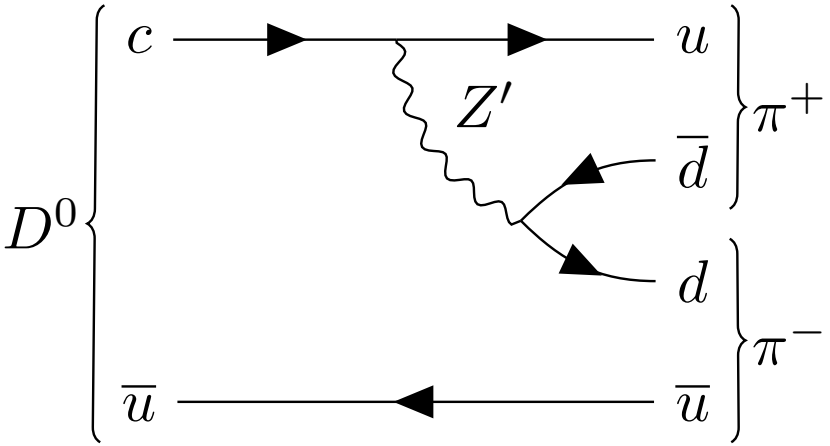


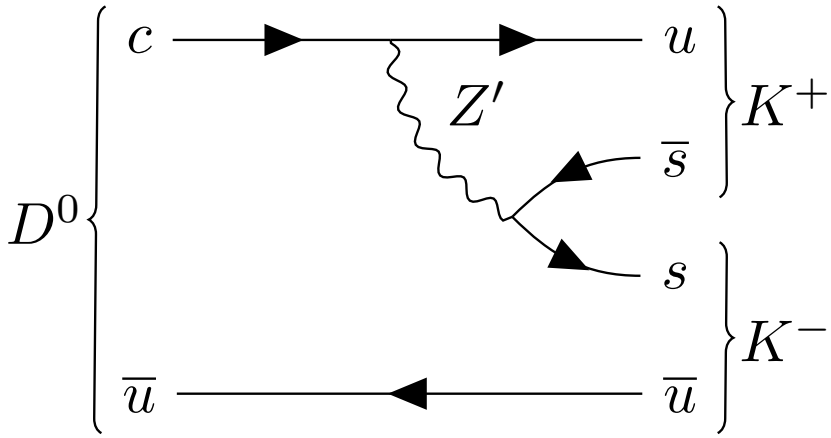
Model Setup

Model Setup

How to adress the anomaly?

Idea: Z' with generation dependent charges





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

- 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

Benchmarks & Ingredients

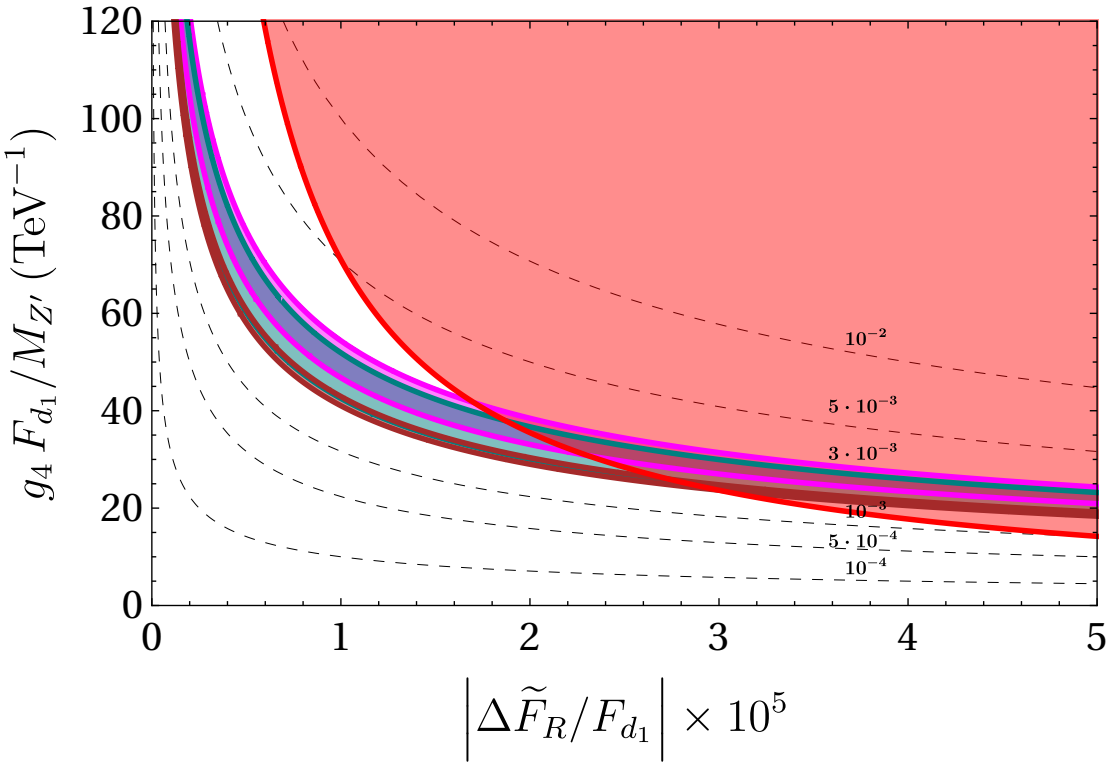
Model	F_{Q_i}			F_{u_i}			F_{d_i}			F_{L_i}			F_{e_i}			F_{ν_i}		
BM I	0	0	0	9	-16	7	20	-11	-9	15	-6	-9	-16	0	16	6	12	-18
BM II	0	0	0	-19	9	10	20	-8	-12	4	1	-5	15	2	-17	8	2	-10
BM III	0	0	0	G	$-F$	0	F	$-G$	0	0	0	0	0	$-G$	F	0	G	$-F$
BM IV	0	0	0	$-F_u$	F_u	0	F_d	0	$-F_d$	0	0	0	F_e	0	$-F_e$	F_ν	$-F_\nu$	0

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

Phenomenology & Constraints

Phenomenology & Constraints

D-Mixing



$\frac{g_4}{M_{Z'}}\Delta\widetilde{F}_R < 7.1\cdot10^{-4}\,\mathrm{TeV}^{-1}$ from D-mixing (e.g. LHCb'21 [2106.03744])

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

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

Charm dilepton & invisibles data

Lepton couplings of the Z' are constrained by various processes

- BR's (semi-)muonic D-decays (see LHCb talk @ ICHEP 2022)
  $\Rightarrow D^0 \to \mu^+\mu^-, \quad D^0 \to \pi^0\mu^+\mu^-, \quad D^+ \to \pi^+\mu^+\mu^-$
- Drell-Yann data for $\ell = e, \tau$ [2003.12421]

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

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

Z' could couple to RH neutrinos ν or SM singlet vector-like fermions χ

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

- $D^0 \to \pi^0 +$ inv. constrains $|F_{\nu,\chi}|$ (BESIII'21 [2112.14236])
- $D^0 \to$ inv. constrains $|F_{\nu}|$ (BELLE'16 [1611.09455])

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

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: $\frac{A_{\mathrm{CP}}(\pi^0\pi^0)}{A_{\mathrm{CP}}(\pi^+\pi^0)} = \frac{d_{\pi^0}}{d_{\pi'}} \simeq 1.08 \pm 0.10$ [2004.01206]
- For $F_{d_2} \ll F_{d_1}$ all CP asymmetries involving pions are correlated!
  $A_{\mathrm{CP}}(\pi^+\pi^0) \simeq \frac{d_{\pi'}}{d_{\pi^0}} A_{\mathrm{CP}}(\pi^0\pi^0) \simeq -\frac{d_{\pi'}}{d_{\pi}} \left(1 - \frac{F_{u_1}}{F_{d_1}}\right) \Delta A_{\mathrm{CP}}$
- $d_\pi \sim d_{\pi'} \sim d_{\pi^0}$ 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 $\Delta A_{\mathrm{CP}} \sim 10^{-3}$

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

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

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

Combine D-mixing & A_{CP} constraints

$\Rightarrow$light Z' of $\mathcal{O}(10\ \text{GeV})$

$\Rightarrow$Mass window severly constrained!

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

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

- Additional constraints from $\Upsilon(\bar{b}b) \to jj$ for $F_{d_3} \neq 0$, $M_{Z'} \simeq 10$ GeV
- Maybe also a $M_{Z'} < 10$ GeV window exists
  $\Rightarrow$WET breaks down (*not in this work*)

Kinetic Mixing

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

  $\Rightarrow$From ρ-parameter: $\boxed{\varepsilon(M_Z) \lesssim 3 \cdot 10^{-1}}$ where $\varepsilon = \frac{-\eta}{\sqrt{1-\eta^2}}$

  $\Rightarrow\varepsilon$ induces Z'-lepton-couplings via $\mathcal{L}_\varepsilon = -\varepsilon\, e J^\mu Z'_\mu$

- Limits from dark photon searches

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

  $\Rightarrow$kinetic mixing parameter has to be small $\boxed{\varepsilon(M_{Z'}) \lesssim 10^{-3}}$

Kinetic Mixing

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

  $\Rightarrow$From ρ-parameter: $\boxed{\varepsilon(M_Z) \lesssim 3 \cdot 10^{-1}}$ where $\varepsilon = \frac{-\eta}{\sqrt{1-\eta^2}}$

  $\Rightarrow\varepsilon$ induces Z'-lepton-couplings via $\mathcal{L}_\varepsilon = -\varepsilon\, e J^\mu Z'_\mu$

- Limits from dark photon searches

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

  $\Rightarrow$kinetic mixing parameter has to be small $\boxed{\varepsilon(M_{Z'}) \lesssim 10^{-3}}$

- Translate to bounds on lepton charges

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

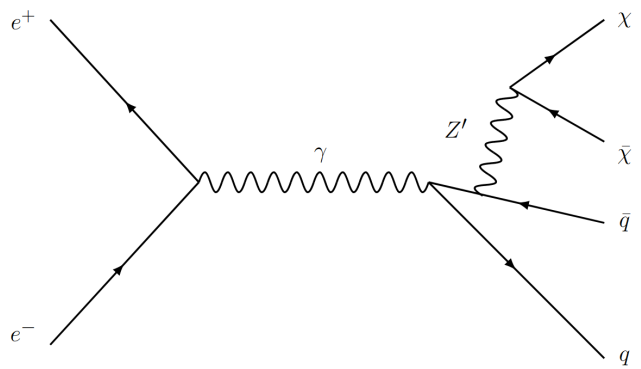
  $\Rightarrow$much stronger than constraints from (semi-)leptonic decays

  $\Rightarrow$BM I, II ruled out!

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 $\mid F_{\nu_i,\chi} \mid \gtrsim \mid F_{\psi_i} \mid$
  $\Rightarrow e^+e^- \rightarrow$ hadrons $+ \not{E}_T$
  $\Rightarrow \mid F_{\psi_i} \mid$ limited by Landau poles



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 flavorful Z' of 10-20 GeV (very predictive!)
  $\Rightarrow$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 flavorful Z' of 10-20 GeV (very predictive!)
  $\Rightarrow$Up to now the only available explanation for the anomaly!

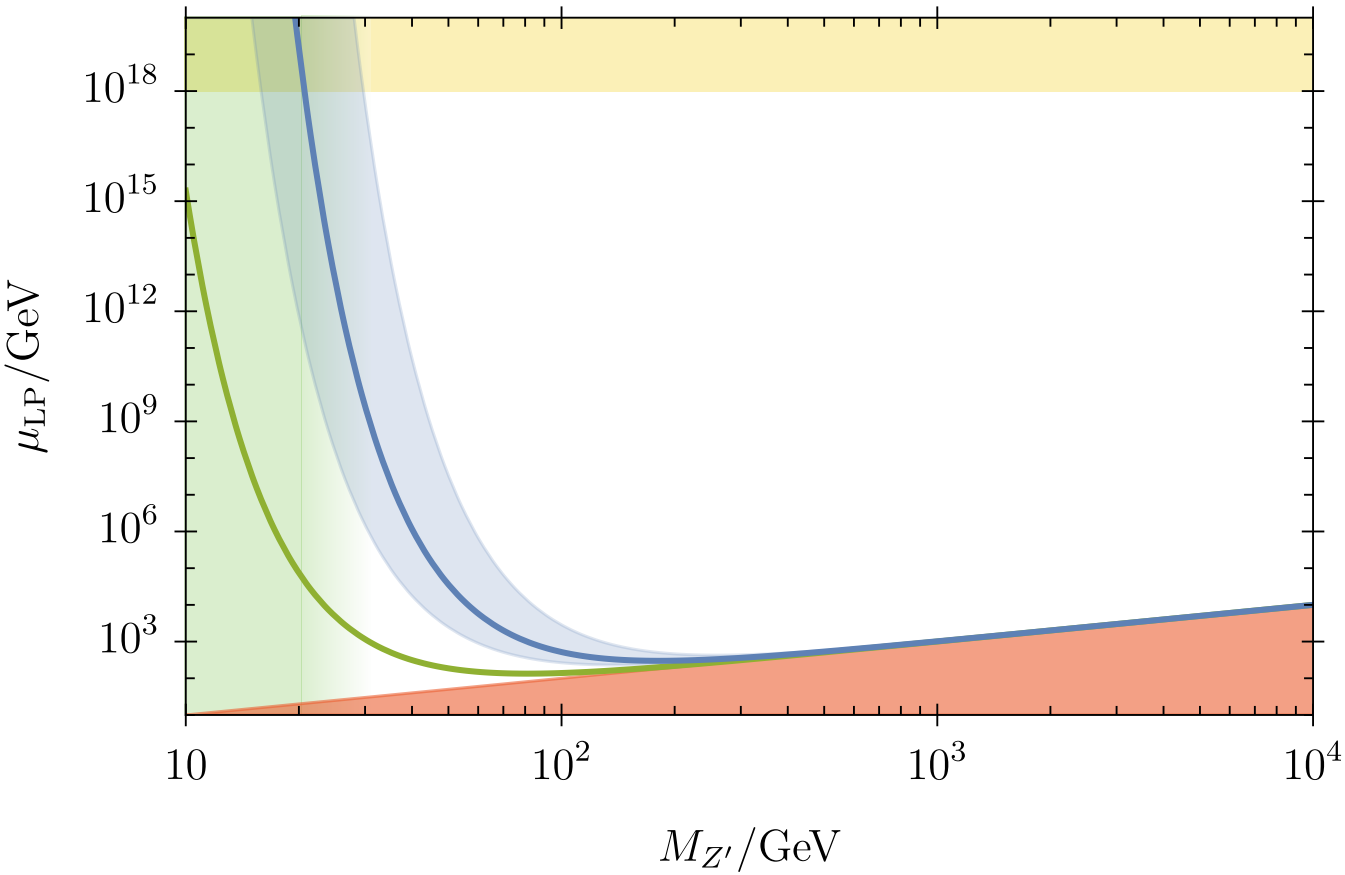
What to do next?

- Many search channels (also for LHCb)
  $\Rightarrow A_{CP}(\pi^0\pi^{0/+})$, dijets, invisible D-decays, ditaus, τ Drell-Yann
- Relation to U-Spin puzzle in B-Decays? [2211.06994]
- Reduce large uncertainties due to hadronic corrections
  $\Rightarrow$*talk by E. Solomonidi tomorrow*

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

BACKUP

High Energy Behaviour



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

Anomaly Cancellation Conditions

Chiral fermions contribute to gauge anomalies
$\Rightarrow$Contributions have to cancel in sum!

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

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

Constraints on lepton charges

Lepton couplings & charges are constrained by

- BR's of rare (semi-)leptonic charm decays [2011.09478]
- Drell-Yann searches [2003.12421]

$\Rightarrow$the most stringent bounds read:

$$\sqrt{F_{L_1}^2 + F_{e_1}^2} \lesssim 2.3|F_{d_1}| \quad \text{Drell-Yann } e$$

$$|F_{L_2} - F_{e_2}|,\ \sqrt{F_{L_2}^2 + F_{e_2}^2} \lesssim 0.8|F_{d_1}| \quad \text{(semi-)muonic } D^0 \text{decays}$$

$$\sqrt{F_{L_3}^2 + F_{e_3}^2} \lesssim 4.7|F_{d_1}| \quad \text{Drell-Yann } \tau$$

RG evolution Kinetic Mixing

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

$\Rightarrow$From ρ-parameter: $\boxed{\varepsilon(M_Z) \lesssim 3 \cdot 10^{-1}}$ where $\varepsilon = \frac{-\eta}{\sqrt{1-\eta^2}}$

$\Rightarrow\varepsilon$ induces Z'-lepton-couplings via $\mathcal{L}_\varepsilon = -\varepsilon\, e J^\mu Z'_\mu$ even if $F_{L_i,e_i} = 0$

$\Rightarrow$kinetic mixing parameter has to be small $\boxed{\varepsilon(M_{Z'}) \lesssim 10^{-3}}$

RG evolution Kinetic Mixing

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

$\Rightarrow$From ρ-parameter: $\boxed{\varepsilon(M_Z) \lesssim 3 \cdot 10^{-1}}$ where $\varepsilon = \frac{-\eta}{\sqrt{1-\eta^2}}$

$\Rightarrow\varepsilon$ induces Z'-lepton-couplings via $\mathcal{L}_\varepsilon = -\varepsilon e J^\mu Z'_\mu$ even if $F_{L_i,e_i} = 0$

$\Rightarrow$kinetic mixing parameter has to be small $\boxed{\varepsilon(M_{Z'}) \lesssim 10^{-3}}$

$\Rightarrow$*Problem*: $\varepsilon(M_Z)$ is in general RG induced even if $\varepsilon(M_{Z'}) = 0$

$\Rightarrow$Two solutions:

- BM IV: ε is natural, i.e. $\frac{\mathrm{d}\varepsilon}{\mathrm{d}\ln\mu} \propto \varepsilon$
  $\Rightarrow$controlled by small or vanishing $\varepsilon(M_{Z'})$
- BM III: RGEs induce $|\varepsilon(M_Z) - \varepsilon(M_{Z'})| \gtrsim 10^{-2}$
  $\Rightarrow$Dilepton bounds require moderate tuning of $\varepsilon(M_{Z'})$ order 10%

$\Rightarrow$kinetic mixing constraints can be avoided