Flavor phenomenology with RK=1: quo vadis?

1. the glass is half full
2. go global and 'up'

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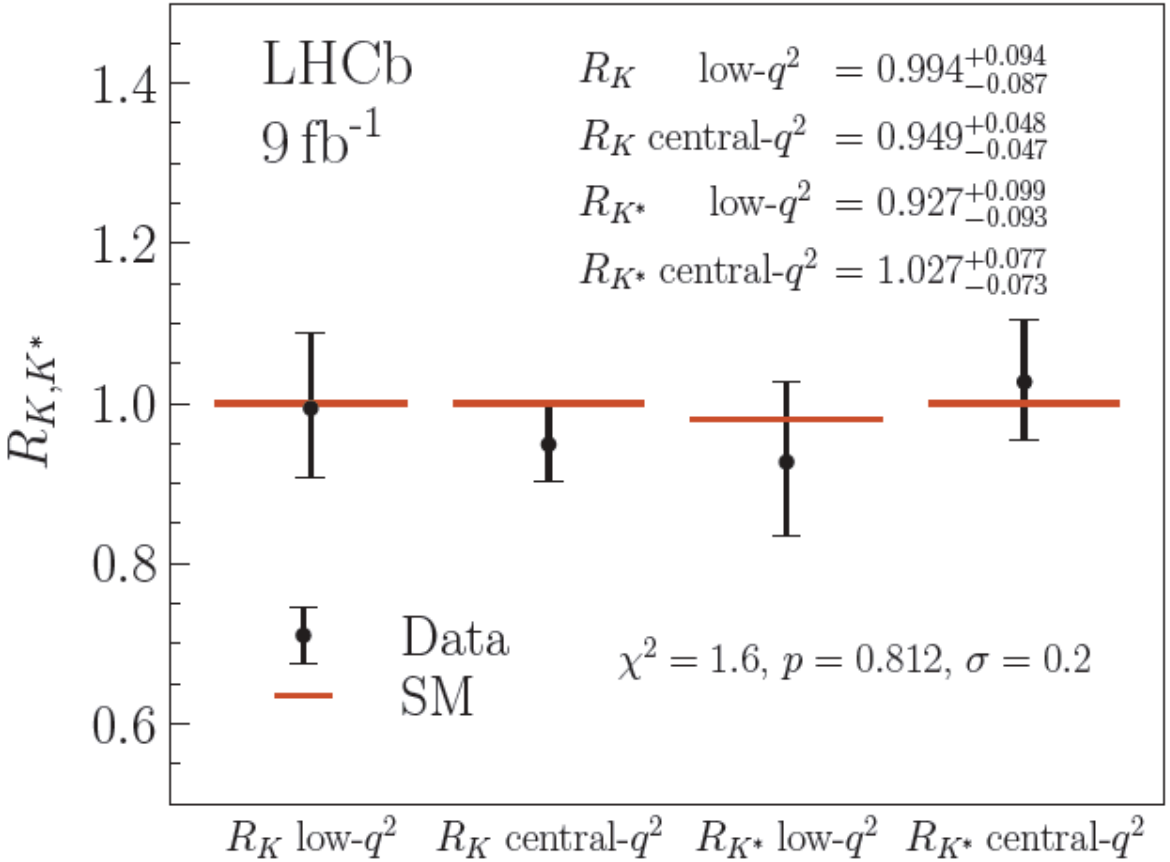
$R_{K,K^*} \simeq 1$ $R_H = \frac{B(B \to H\mu\mu)}{B(B \to Hee)}, \quad H = K, K^*, ..,$ hep-ph/0310219 [hep-ph]



LHCb 2212.09153

e's and mu's couple alike in $b \to s$ FCNCs, universality is back the b's are still anomalous: several $b \to s\mu\mu$ branching ratios below SM, angular observables off, global fit $> 4\sigma$

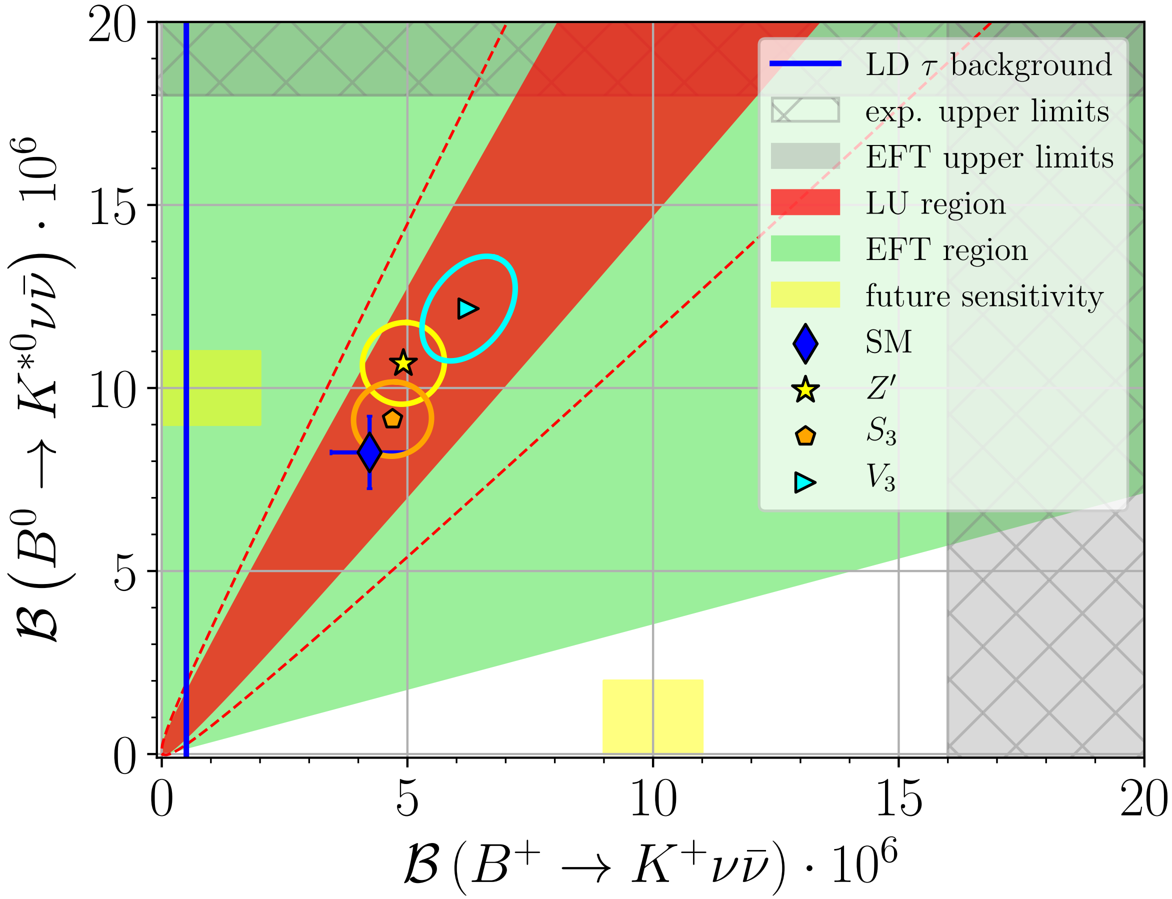
the glass is half full.

The other half were the cleaner observables, but this is were we are:

1. Since $R_{K,K^*} \simeq 1$ and the μ's are off expect similar shift in $b \to see$ observables.

2. Tau's could be different from e, μ, but $b \to s\tau\tau$ bounds are presently much weaker.

3. Dineutrinos $b \to s\nu\bar{\nu}$ give insights on lots: test SM, test lepton flavor, probe top-FCNCs.



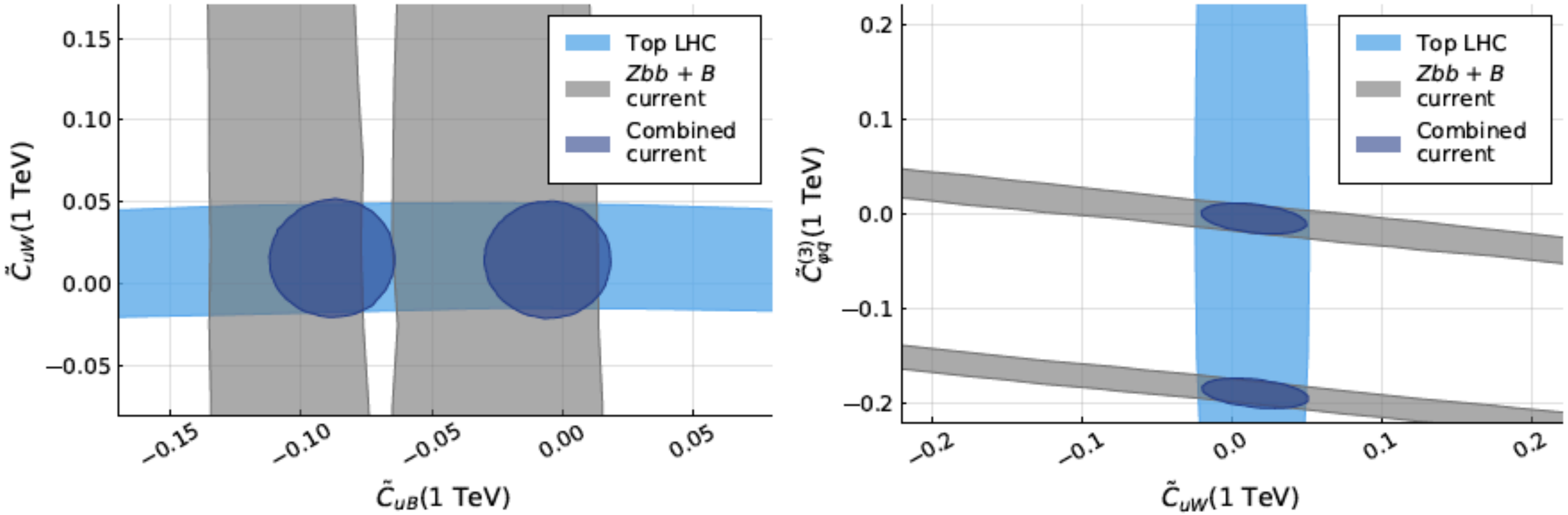
2109.01675

Belle II (KEK, Japan) is expected to measure the dineutrino BRs

Data	$\lvert\kappa_A^{q_1 q_2 \ell\ell'}\rvert$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
Rare B decays to Dineutrinos	$\lvert\kappa_R^{bd\ell\ell'}\rvert$	210	210	210	210	210	210
	$\kappa_L^{tu\ell\ell'}$	$[-197, 223]$	$[-197, 223]$	$[-197, 223]$	210	210	210
	$\lvert\kappa_R^{bs\ell\ell'}\rvert$	35	35	35	32	32	32
	$\kappa_L^{tc\ell\ell'}$	$[-22, 47]$	$[-22, 47]$	$[-22, 47]$	32	32	32
Rare B decays to Charged dileptons	$\kappa_R^{bd\ell\ell'}$	~ 10	$[-4, 4]$	~ 2500	~ 20	~ 280	~ 200
	$\kappa_L^{bd\ell\ell'}$	~ 10	$[-8, 2]$	~ 2500	~ 20	~ 280	~ 200
	$\kappa_R^{bs\ell\ell'}$	$\mathcal{O}(1)$	$[0.2, 0.8]$	~ 800	~ 2	~ 50	~ 60
	$\kappa_L^{bs\ell\ell'}$	$\mathcal{O}(1)$	$[-1.6, -1.1]$	~ 800	~ 2	~ 50	~ 60
Drell-Yan	$\lvert\kappa_{L,R}^{bd\ell\ell'}\rvert$	583	314	1122	260	800	866
	$\lvert\kappa_{L,R}^{bs\ell\ell'}\rvert$	331	178	637	142	486	529
$t + \ell$	$\kappa_L^{tt\ell\ell'}$	$[-196, 243]$	$[-196, 243]$	–	–	–	–

Table from 2109.01675, best bounds for τ's from dineutrinos, also limits for top -FCNC couplings.

Framework: NP $\gg$ EWK; $SU(2)$-link between left-handed t, b, and ν, ℓ (a la SMEFT)



2012.10456

SMEFT is a tool that allows to study flavor globally (multi-sectors, experiments, observables)

genuinely flavorful: 4-fermion operators $\bar{Q}_i \gamma_\mu Q_j \bar{L}_k \gamma^\mu L_l$

More flavor synergies in talk by Lara Nollen 2304.12837 from today

Cross checking: $B_{(s)} \to$ nothing

$B_q \to \nu\bar{\nu}$ constrains impact of operators with light right-handed neutrinos

$$Q^{ij}_{LR} = (\bar{q}_L \gamma_\mu b_L)(\bar{\nu}_{jR}\gamma^\mu \nu_{iR}), \quad Q^{ij}_{RR} = (\bar{q}_R \gamma_\mu b_R)(\bar{\nu}_{jR}\gamma^\mu \nu_{iR}),$$
$$Q^{ij}_{S(P)} = (\bar{q}_L b_R)(\bar{\nu}_j (\gamma_5) \nu_i), \quad Q^{ij}_{T(T5)} = \frac{1}{2}(\bar{q}\,\sigma_{\mu\nu}\, b)(\bar{\nu}_j\, \sigma^{\mu\nu}\,(\gamma_5)\,\nu_i),$$

Presently, $\mathcal{B}\,(B_d \to \nu\bar{\nu})_{\text{exp}} < 2.4 \cdot 10^{-5}$, no limit on $B_s \to nothing$.

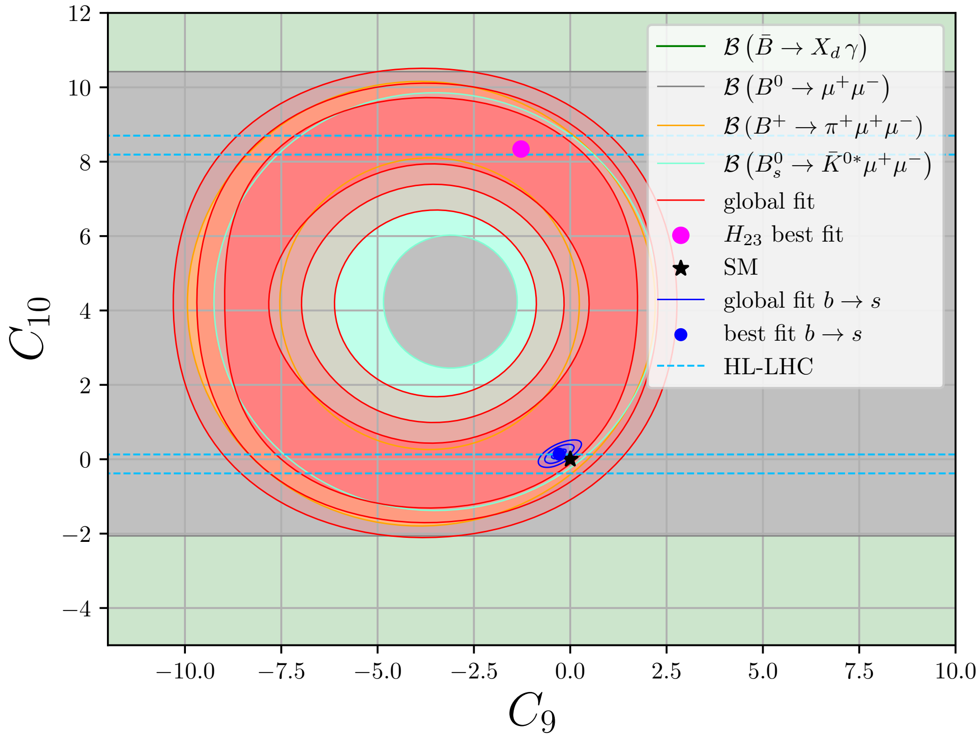
projections for Belle with $0.12\,\text{ab}^{-1}$ (Belle II with $0.5\,\text{ab}^{-1}$)

$$\mathcal{B}\left(B^0_s \to \nu\bar{\nu}\right)_{\text{proj}} < 9.7\,(1.1) \cdot 10^{-5}\ . \tag{1}$$

Quantitatively: $Q^{ij}_{S(P)}$ in $b \to d$ can reach $\mathcal{O}(100\%)$ on SM-Brs; improved limit of $\mathcal{B}(B^0 \to \nu\bar{\nu}) \sim 5 \cdot 10^{-7}$ would reduce to $\mathcal{O}(1\%)$.

The projected reach constrains $Q^{ij}_{S(P)}$ effects in $b \to s$ to less than $\mathcal{O}(30\%)$ (Belle with $0.12\,\text{ab}^{-1}$), and $\mathcal{O}(3\%)$ (Belle II with $0.5\,\text{ab}^{-1}$) on SM. Limits important. Also null test.

$b \to d$ ($\propto V_{tb}V_{td}^* \sim \lambda^3$) much less explored than $b \to s$ ($\propto V_{tb}V_{ts}^* \sim \lambda^2$)



2209.04457

lots of room for NP with or without MFV; angular info on $b \to d\mu\mu$ missing to break main ambiguity

$A_{FB} \propto C_9 C_{10} + ..$ in $B_s \to K^*\ell\ell$, of $B \to \rho\ell\ell$, or $\Xi_b \to \Sigma\,\ell^+\ell^-$, $\Omega_b^- \to \Xi^-\,\ell^+\ell^-$

Testing the Standard Model with $|\Delta c| = |\Delta u| = 1$ FCNCs of mesons and baryons:

- $c \to u\gamma$ Br $\sim 10^{-6} - 10^{-4}$
- $c \to u\mu\mu, uee$ Br $\sim 10^{-7} - 10^{-6}$
- $c \to u\nu\bar{\nu}, a, Z', ...$ Br $\lesssim 10^{-5}$

Probe different physics (dipole couplings, 4-fermion operators, light NP, ..)

Complementary to kaon and B-physics – charm is unique probe of flavor in the up-sector

0112235, 1510.00965, 1805.08516 , 2011.09478, ...

TH Progress: New BSM strategies for $|\Delta c| = |\Delta u| = 1$

SM tests in rare charm decays are null tests based on approximate symmetries of the SM: GIM, CP, cLFC, LFU, LNC, $SU(3)_F$

Advantages charm (vs beauty):

i) GIM-suppression very efficient: $C_\nu^{\rm SM} = C_{10}^{\rm SM} = 0$

ii) $SU(3)_F$ partner modes - SM-like and NP-sensitive ones related.

Useful as and well-known from state-of-the-art b-physics studies: angular distributions.

BSM-sensitive Charm decays

resonant and multi-bodies, mesons and baryons,.. $P_{1,2,3} = \pi, K$

radiative $c \to u\gamma$: $D \to V\gamma$, $V = \rho, ..$, $D \to P_1 P_2 \gamma$,
$D \to A\gamma$, $A = K_1, ..$, $D \to P_1 P_2 P_3 \gamma$,
$\Lambda_c \to p\gamma$, $\Xi_c^0 \to \Lambda(\to p\pi)\gamma$,....

semileptonic $c \to u\ell\ell^{(\prime)}$: $D \to \pi\mu\mu$, $D \to \mu\mu$, $D \to P_1 P_2 \ell\ell$,
$\Lambda_c \to p\ell\ell$, $\Xi_c^0 \to \Lambda(\to p\pi^-)\ell\ell$,...

dineutrinos/MET/ALPs $c \to u\nu\bar{\nu}$: $D \to \pi\nu\bar{\nu}$, $D \to \nu\bar{\nu}$, $D \to P_1 P_2 \nu\bar{\nu}$,
$\Lambda_c \to p\nu\bar{\nu}$, $\Xi_c^0 \to \Lambda(\to p\pi^-)\nu\bar{\nu}$,...

Very little probed so far

radiative $c \to u\gamma$: $D \to V\gamma$, $V = \rho, ..,$ $D \to P_1 P_2 \gamma$,
$D \to A\gamma$, $A = K_1, ..$ $D \to P_1 P_2 P_3 \gamma$, $\Lambda_c \to p\gamma$, $\Xi_c^0 \to \Lambda(\to p\pi)\gamma$,....
$B(D^0 \to \rho^0\gamma) = (1.77 \pm 0.31) \cdot 10^{-5}$ Belle'16, Cabibbo-favored modes:
$B(\Lambda_c \to \Sigma\gamma) < 2.6 \cdot 10^{-4}$, $B(\Xi_c^0 \to \Xi^0\gamma) < 1.8 \cdot 10^{-4}$ Belle 2206.12517
$B(\Lambda_c \to \Sigma\gamma) < 4.4 \cdot 10^{-4}$ BESIII 2212.07214

semileptonic $c \to u\ell\ell^{(\prime)}$: $D \to \pi\mu\mu$, $D \to \mu\mu$, $D \to P_1 P_2 \ell\ell$,
$\Lambda_c \to p\ell\ell$, $\Xi_c^0 \to \Lambda(\to p\pi^-)\ell\ell$,... $B(D \to \pi\pi\mu\mu) \simeq 9.6 \cdot 10^{-7}$ LHCb'18 ,
$B(\Lambda_c \to p\mu\mu) \lesssim 7.7 \cdot 10^{-8}$ LHCb'17, [$D \to \pi\mu\mu, D \to \mu\mu$ upper limits]

dineutrinos/MET/ALPs $c \to u\nu\bar{\nu}$: $D \to \pi\nu\bar{\nu}$, $D \to \nu\bar{\nu}$, $D \to P_1 P_2 \nu\bar{\nu}$,
$\Lambda_c \to p\nu\bar{\nu}$, $\Xi_c^0 \to \Lambda(\to p\pi^-)\nu\bar{\nu}$,... $B(D^0 \to nothing) < 9.4 \cdot 10^{-5}$
Belle'16, $B(D^0 \to \pi^0\nu\bar{\nu}) < 2.1 \cdot 10^{-4}$ BESIII 2112.14236

Can $\Delta A_{CP} = A_{CP}(D \to K^+K^-) - A_{CP}(D \to \pi^+\pi^-)$ come mainly from $A_{CP}(D \to \pi^+\pi^-)$?

CP and U-Spin puzzle 2207.08539, 2210.16330 - two approx symmetries challenged

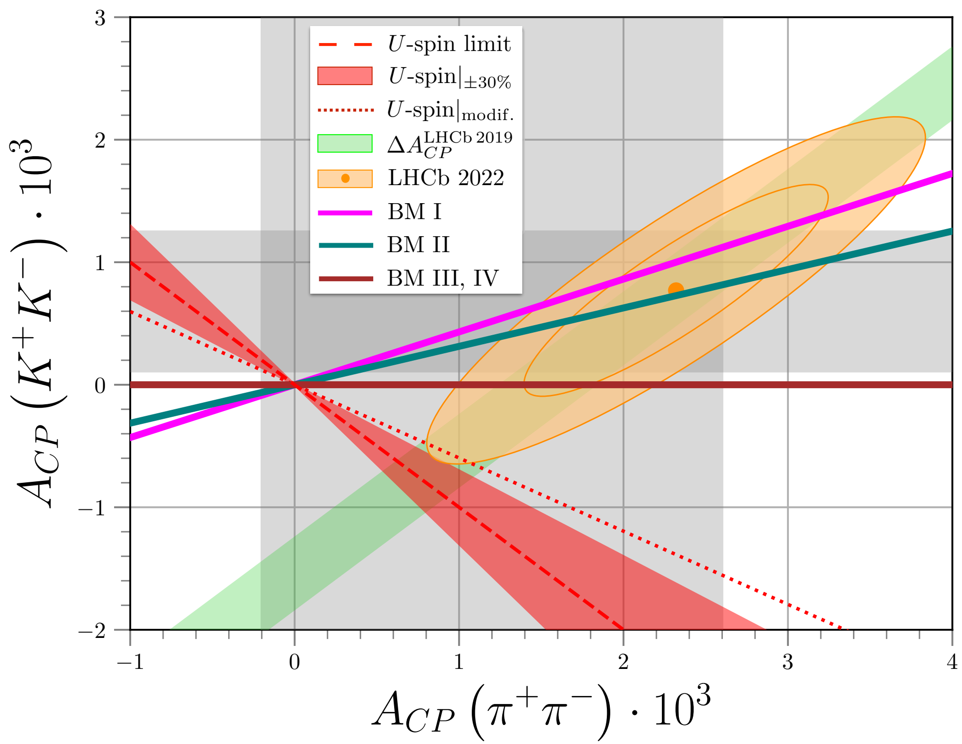


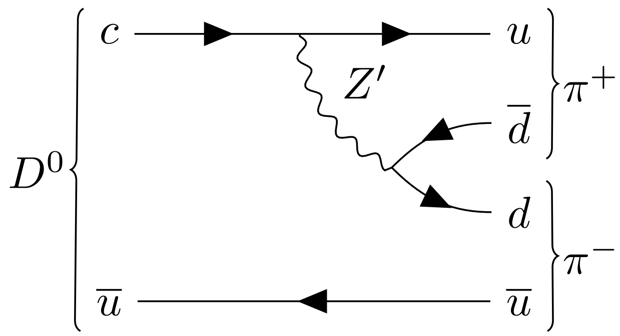
Fig from 2210.16330, LHCb result from 2209.03179;

A Puzzle in hadronic charm CPX

Is this even explainable?

Single solution known 2210.16330

BSM effects in semileptonic 4-fermion operators $\sim \bar{u}_R \gamma_\mu c_R \bar{d}_R \gamma^\mu d_R$. Very light Z', sub 20 GeV (CMS ISR constraints), leptophob (LHCb $A \to \mu\mu$ search)



Signatures in low mass dijets, $J/\Psi/\Psi'$ decays, $A_{CP}(D \to \pi^0\pi^0), A_{CP}(D \to \pi^+\pi^0) \sim A_{CP}(D \to \pi^+\pi^-)$.

Summary

- universality strikes back – $b \to s\mu\mu$ anomalies remain; imply $b \to see$ anomalies
- last unknowns in $b \to s$ system: $\tau\tau$ and $B \to K^{(*)}\nu\bar{\nu}$; Looking forward to Belle II
- $b \to d$ fit just at the beginning (MFV and beyond)
- correlations with up-sector: tops and charm for flavor picture -SMEFT application
- Very little experimentally explored in rare charm decays – lots of blanks in PDG
- BSM effects in $|\Delta c| = |\Delta u| = 1$ can be huge.
- Plenty of Terra Incognita in flavor phenomenology — explore synergies