CORRELATING RARE SEMILEPTONIC DECAYS OF K AND D MESONS

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In collaboration with

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OUTLINE

- Introduction
- $\bar{Q}Q\,\bar{L}L$ effective operators in 1st and 2nd generation
- Alignment in K and D rare processes, universality of CPV
- Conclusions
- Prospects - 3 generations

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STANDARD MODEL
AND DIM-6 EFFECTIVE OPERATORS

$$\mathcal{L}_{\rm SM} + \frac{c}{\Lambda_L} LLHH + \frac{1}{\Lambda^2}\sum_i C_i Q_i$$

- Lots of recent experimental input for the first two generations of quarks (BESIII, LHCb, NA62, KOTO)
- Strong bounds on FCNCs for the light generation case.

$8 : (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

- Left-handed currents phenowise very interesting:

$$(\bar{Q}_i \gamma_\mu \sigma^a Q_j)(\bar{L}_\ell \gamma^\mu \sigma_a L_\ell) \qquad (\bar{Q}_i \gamma_\mu Q_j)(\bar{L}_\ell \gamma^\mu L_\ell)$$

D. Butazzo, A. Greljo, G. Isidori, D. Marzocca, 1706.07808;
Angelescu, Becirevic, Faroughy, Sumensari, 1808.08179

- Simultaneously generate effects in the light quarks
- Easy to describe and analyze
- Left-handed semileptonic effects in 1st and 2nd generation?

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LEFT-HANDED SEMILEPTONIC DECAYS OF K AND D

- Only two SMEFT operators: $$\mathcal{L}_{\rm SMEFT} = \frac{X^{(3)}_{ij}}{\Lambda^2}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}\gamma^\mu\sigma_a L) + \frac{X^{(1)}_{ij}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{L}\gamma^\mu L)\,.$$ $\Lambda = 1\,\text{TeV}$

$s \to d\nu\bar{\nu}$ and $c \to u\ell^-\ell^+$

$$\mathcal{L}^{(-)}_{\rm FCNC} = \frac{1}{\Lambda^2}X^{(-)}_{ij}\left[(\bar{u}'_i\gamma^\mu P_L u'_j)(\bar{\ell}\gamma_\mu P_L\ell) + (\bar{d}_i\gamma^\mu P_L d_j)(\bar{\nu}\gamma_\mu P_L\nu)\right]$$

$$X^{(-)} = X^{(1)} - X^{(3)}$$

$s \to d\ell^-\ell^+$ and $c \to u\nu\bar{\nu}$

$$\mathcal{L}^{(+)}_{\rm FCNC} = \frac{1}{\Lambda^2}X^{(+)}_{ij}\left[(\bar{u}'_i\gamma^\mu P_L u'_j)(\bar{\nu}\gamma_\mu P_L\nu) + (\bar{d}_i\gamma^\mu P_L d_j)(\bar{\ell}\gamma_\mu P_L\ell)\right]$$

$$X^{(+)} = X^{(1)} + X^{(3)}$$

- Mass basis for down quarks. Two generations framework.
- Couplings are lepton flavour specific and conserving - We turn on only one lepton-specific NP Wilson Coefficient at time

$$u'_i = (V_{\rm CKM})^*_{ji}\,u_j$$

$$V_{\rm CKM} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$$ valid to $\mathcal{O}(\sin\theta_c^4)$

- $X^{(\pm)}$ are Hermitian 2x2 matrices, contain 4 parameters each. Expand them through Pauli matrices
- λ irrelevant: enters only flavour-conserving neutral currents

$$X_{ij} = \lambda\delta_{ij} + c_a(\sigma^a)_{ij}\,.$$

- The two sectors talk through charged currents induced by $X^{(3)}$ and collider (LHC) experiments

GEOMETRIC INTERPRETATION

- Traceless 2x2 Hermitian matrices are equivalent to 3D rotations [think of SU(2) ~ SO(3)]

[Blum,Grossman,Nir, Perez, 0903.2118]
[Gedalia, Manelli, Perez, 1002.0778, 1005.3106]
[Gedalia, Kamenik, Ligeti, Perez, 1202.5038]

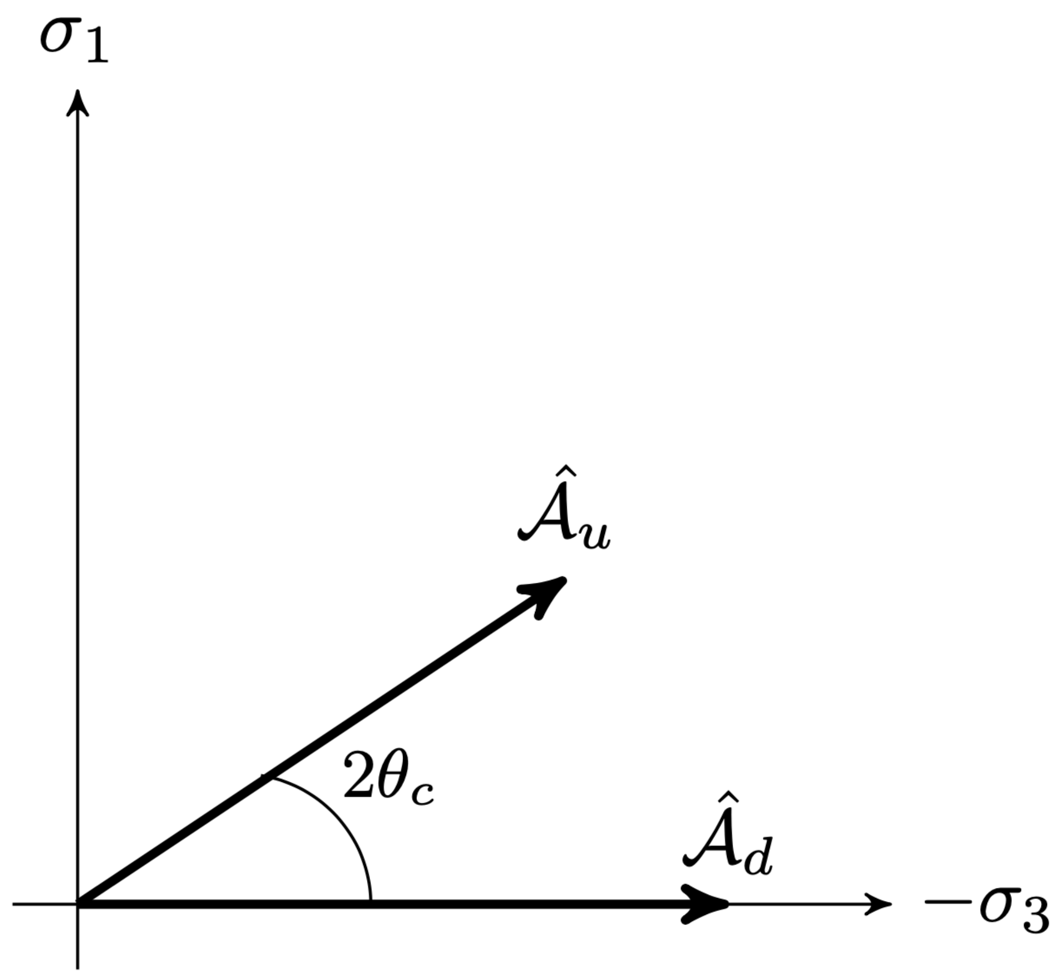
$$X = x_a \sigma_a = \boldsymbol{x} \cdot \boldsymbol{\sigma} \qquad \Leftrightarrow \qquad \boldsymbol{x}$$

$$\boldsymbol{x} \cdot \boldsymbol{y} \equiv \frac{1}{2} \mathrm{Tr}\,[XY]\,, \qquad \boldsymbol{x} \times \boldsymbol{y} \equiv -\frac{i}{2}\,[X, Y]$$

- Physical basis vectors (in down-quark mass basis):

$$\mathcal{A}_d = (Y_d Y_d^\dagger)_{\not{tr}} = -\frac{y_s^2 - y_d^2}{2} \sigma_3$$

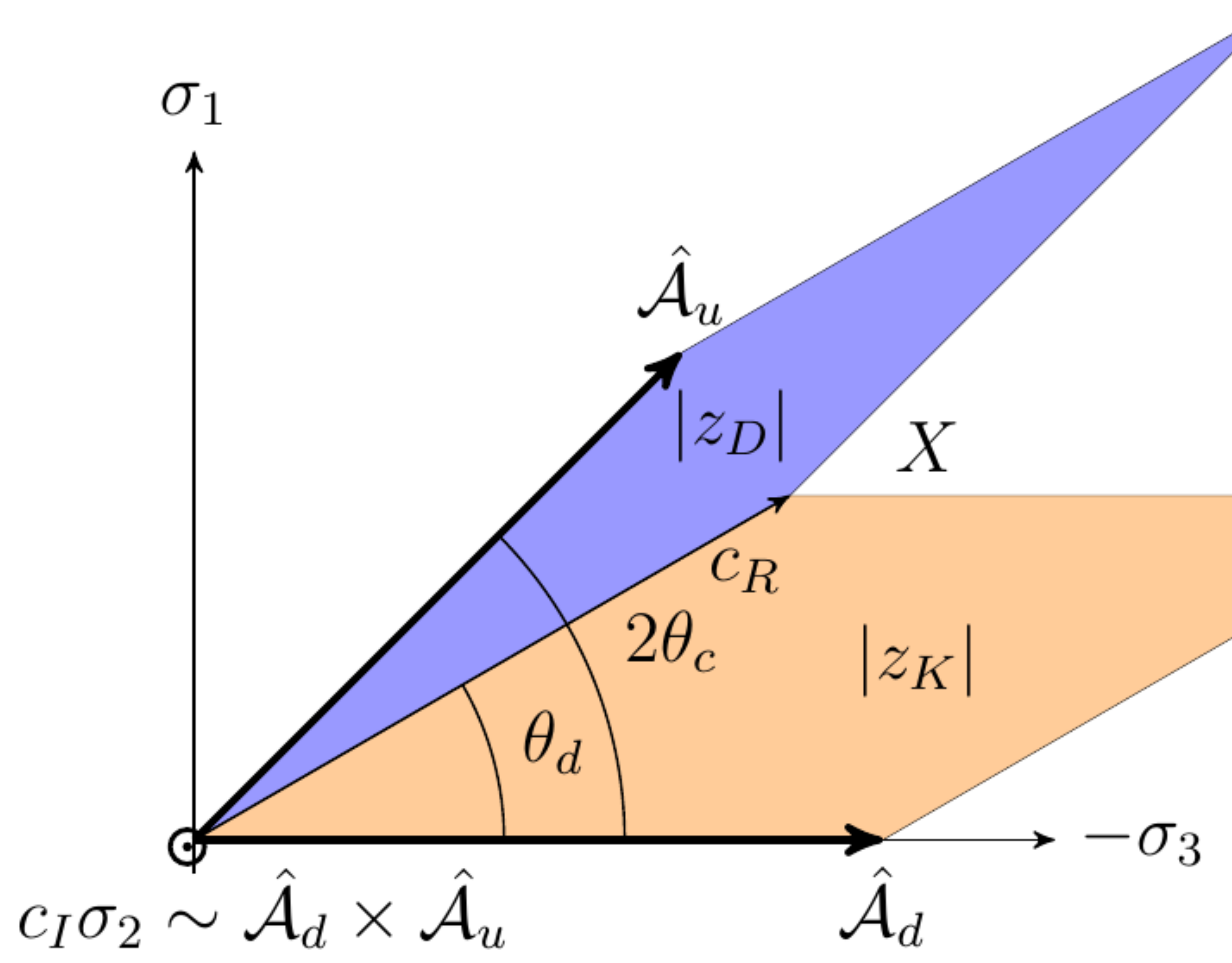
$$\mathcal{A}_u = (Y_u Y_u^\dagger)_{\not{tr}} = \frac{y_c^2 - y_u^2}{2} \Big(-\cos(2\theta_c)\sigma_3 + \sin(2\theta_c)\sigma_1 \Big)$$



- Manifestly CP-even (real) in down basis.

GEOMETRIC INTERPRETATION

- CP conserving part is in the 1-3 plane



$$X = \underbrace{c_R \cos\theta_d\,(-\sigma_3) + c_R \sin\theta_d\,\sigma_1}_{\text{spanned by } \mathcal{A}_{u,d}} + c_I\,\sigma_2$$

$$z_K \equiv X_{12} = c_R \sin\theta_d - ic_I$$
$$z_D \equiv (VXV^\dagger)_{12} = c_R \sin(2\theta_c - \theta_d) - ic_I$$

$$X_Q^{\text{down}} = \begin{pmatrix} \lambda - c_R\cos\theta_d & c_R\sin\theta_d - ic_I \\ c_R\sin\theta_d + ic_I & \lambda + c_R\cos\theta_d \end{pmatrix}$$

$$X_Q^{\text{up}} = \begin{pmatrix} \lambda - c_R\cos(\theta_d - 2\theta_c) & c_R\sin(\theta_d - 2\theta_c) - ic_I \\ c_R\sin(\theta_d - 2\theta_c) + ic_I & \lambda + c_R\cos(\theta_d - 2\theta_c) \end{pmatrix}$$

- CPV is universal, independent of alignment angle θ_d

$$\Im(z_K^{(\pm)}) = \Im(z_D^{(\pm)}) = \Im\left(-X^{(\pm)} \cdot \frac{\hat{\mathcal{A}}_d \times \hat{\mathcal{A}}_u}{|\hat{\mathcal{A}}_d \times \hat{\mathcal{A}}_u|}\right) = -c_I^{(\pm)}.$$

- True only for $\Delta F = 1$

- CP even magnitude depends on alignment angle θ_d

$$|z_K^{(\pm)}| = |X^{(\pm)} \times \hat{\mathcal{A}}_d| = \sqrt{\left(c_R^{(\pm)} \sin\theta_d^{(\pm)}\right)^2 + (c_I^{(\pm)})^2},$$

$$|z_D^{(\pm)}| = |X^{(\pm)} \times \hat{\mathcal{A}}_u| = \sqrt{\left(c_R^{(\pm)} \sin(2\theta_c - \theta_d^{(\pm)})\right)^2 + (c_I^{(\pm)})^2}$$

WHERE DO WE GET OUR BOUNDS FROM?

- Low-energy neutral-current experiments:
  - $K^{(+)} \to \pi^+ \nu\bar{\nu}, K_L \to \ell\ell, D \to \pi\ell\ell, D \to \ell\ell, D \to \pi\nu\bar{\nu}$
- Collider experiments
  - HighPT package - neutral and charged currents

[Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch, 2207.10756]

[HFLAV, 1909.12524]
[FLAG, 2111.09849]
[Hardy, Towner, 1411.5987]

- Low-energy charged-current experiments:
  - HFLAV (V_{cs}, V_{cd}), FLAG (V_{us}), superallowed β-decay, $\pi \to (e,\mu)\nu, \tau \to \pi\nu\ldots$
- Lattice input for form-factors [Lubicz et.al, 1706.03017]

HIGH-PT LIMITS

- Proton collisions give us simultaneously contributions from $X^{(-)}$ and $X^{(+)}$. For the neutral-currents $pp \to \ell^-\ell^+$, we have:

$$\sigma_{\text{high}-p_T} \supset 2\int_{\tau_{\min}}^{\tau_{\max}} d\tau \frac{\tau\, S_{\text{had}}}{144\pi} \times$$

$$\Big[\mathcal{L}_{u\bar{u}}\left(\lambda^{(-)} - c_R^{(-)}\cos(2\theta_c - \theta_d^{(-)}) + F_{\text{SM},u\bar{u}}\right)^2 + \mathcal{L}_{c\bar{c}}\left(\lambda^{(-)} + c_R^{(-)}\cos(2\theta_c - \theta_d^{(-)}) + F_{\text{SM},u\bar{u}}\right)^2$$

$$+\mathcal{L}_{d\bar{d}}\left(\lambda^{(+)} - c_R^{(+)}\cos\theta_d^{(+)} + F_{\text{SM},d\bar{d}}\right)^2 + \mathcal{L}_{s\bar{s}}\left(\lambda^{(+)} + c_R^{(+)}\cos\theta_d^{(+)} + F_{\text{SM},d\bar{d}}\right)^2$$

$$+(\mathcal{L}_{u\bar{c}} + \mathcal{L}_{c\bar{u}})\left((c_R^{(-)}\sin(2\theta_c - \theta_d^{(-)}))^2 + (c_I^{(-)})^2\right) + (\mathcal{L}_{d\bar{s}} + \mathcal{L}_{s\bar{d}})\left((c_R^{(+)}\sin\theta_d^{(+)})^2 + (c_I^{(+)})^2\right)\Big],$$

$$\mathcal{L}_{q\bar{q}} \equiv \mathcal{L}_{q\bar{q}}(\tau, \mu_F) = \int_\tau^1 \frac{dx}{x} f_q(x, \mu_F) f_{\bar{q}}(\tau/x, \mu_F)$$

- Weakest bounds for $X^{(-)}$ ($X^{(+)}$) occur when $c_R^{(+)} = c_I^{(+)} = 0$ ($c_R^{(-)} = c_I^{(-)} = 0$).
- Marginalisation over traces $\lambda^{(-)}, \lambda^{(+)}$.
- High-pT charged currents ($pp \to \ell\nu$) constrain only one direction of parameter space - not an over-constraining system

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$X^{(-)}$: RELATING $s \to d\nu\bar{\nu}$ AND $c \to u\ell^+\ell^-$ - MUONS

- Weak effective theory couplings

$$s \to d\nu\bar{\nu}: \qquad C_{L,\nu}^{\text{down, NP}} = \frac{2\pi}{\alpha_{em}}\frac{v^2}{\Lambda^2}\left\{c_R^{(-)}\sin\theta_d^{(-)} - ic_I^{(-)}\right\}$$

$$c \to u\ell_L^+\ell_L^-: \qquad C_9^{\text{up,NP}} = -C_{10}^{\text{up,NP}} = \frac{\pi}{\alpha_{em}}\frac{v^2}{\Lambda^2}\left\{c_R^{(-)}\sin(\theta_d^{(-)} - 2\theta_c) - ic_I^{(-)}\right\}$$

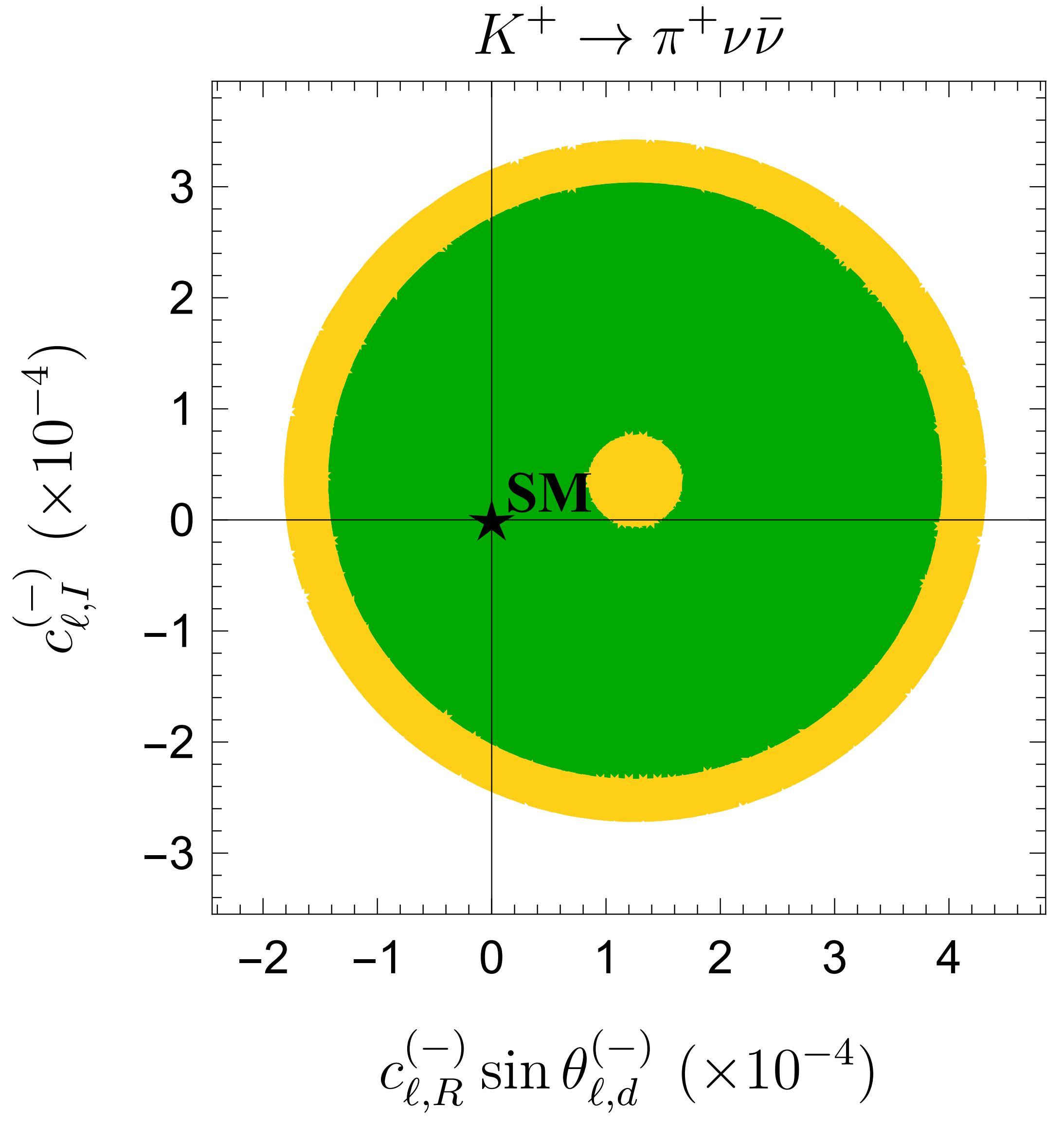
$$\frac{d\mathcal{B}}{dq^2}(K^\pm \to \pi^\pm\nu_\ell\bar{\nu}_\ell) \sim G_F^2\alpha^2 f_{+,K\to\pi}^2(q^2)|C_{L,\nu_\ell}^{\text{down,SM}} + C_{L,\nu_\ell}^{\text{down,NP}}|^2,$$

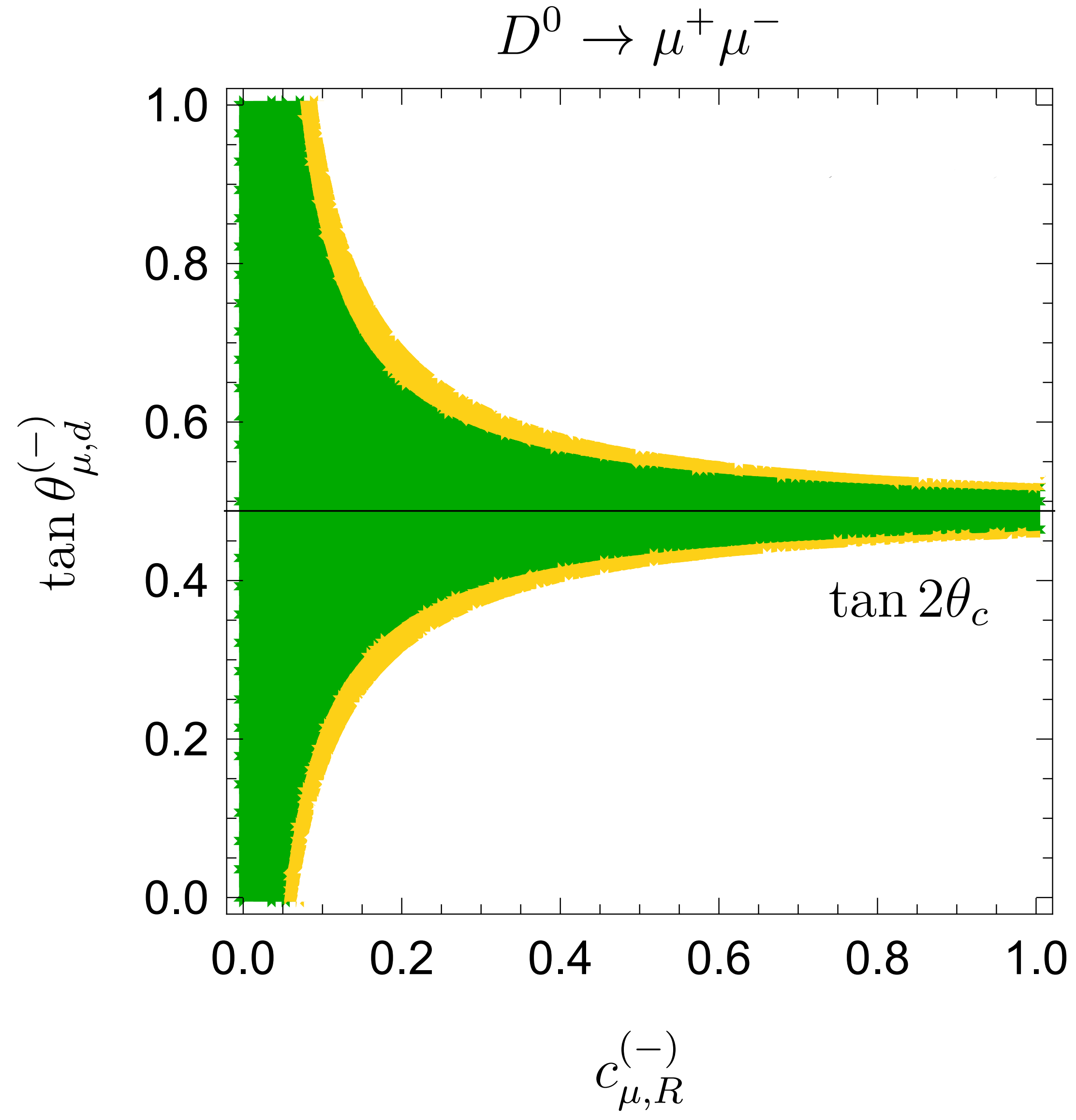
[KOTO, NA62]

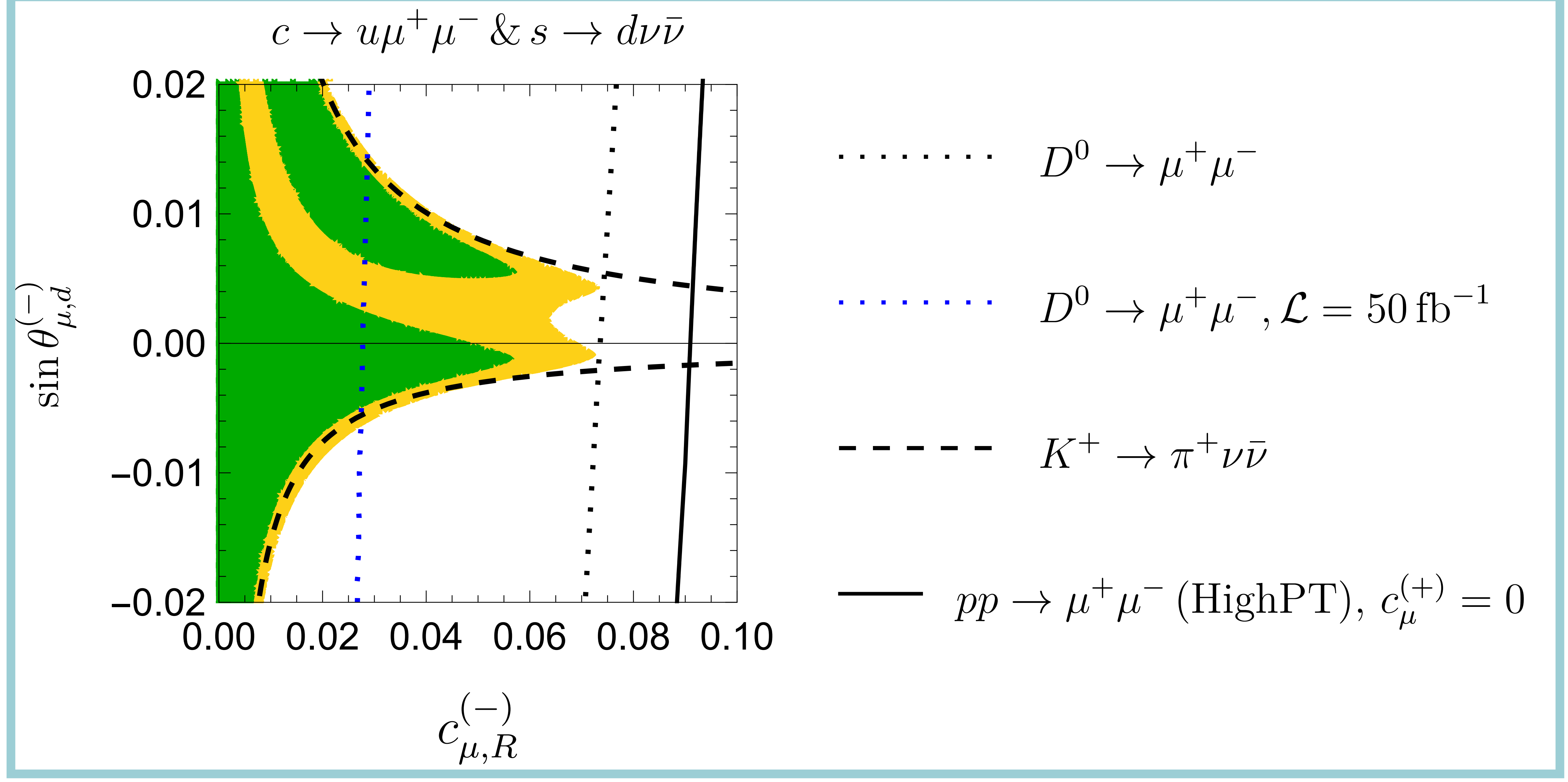
$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = 1.14^{+0.40}_{-0.33} \times 10^{-10}$$

[LHCb, 2212.11203]

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1 \times 10^{-9}$$







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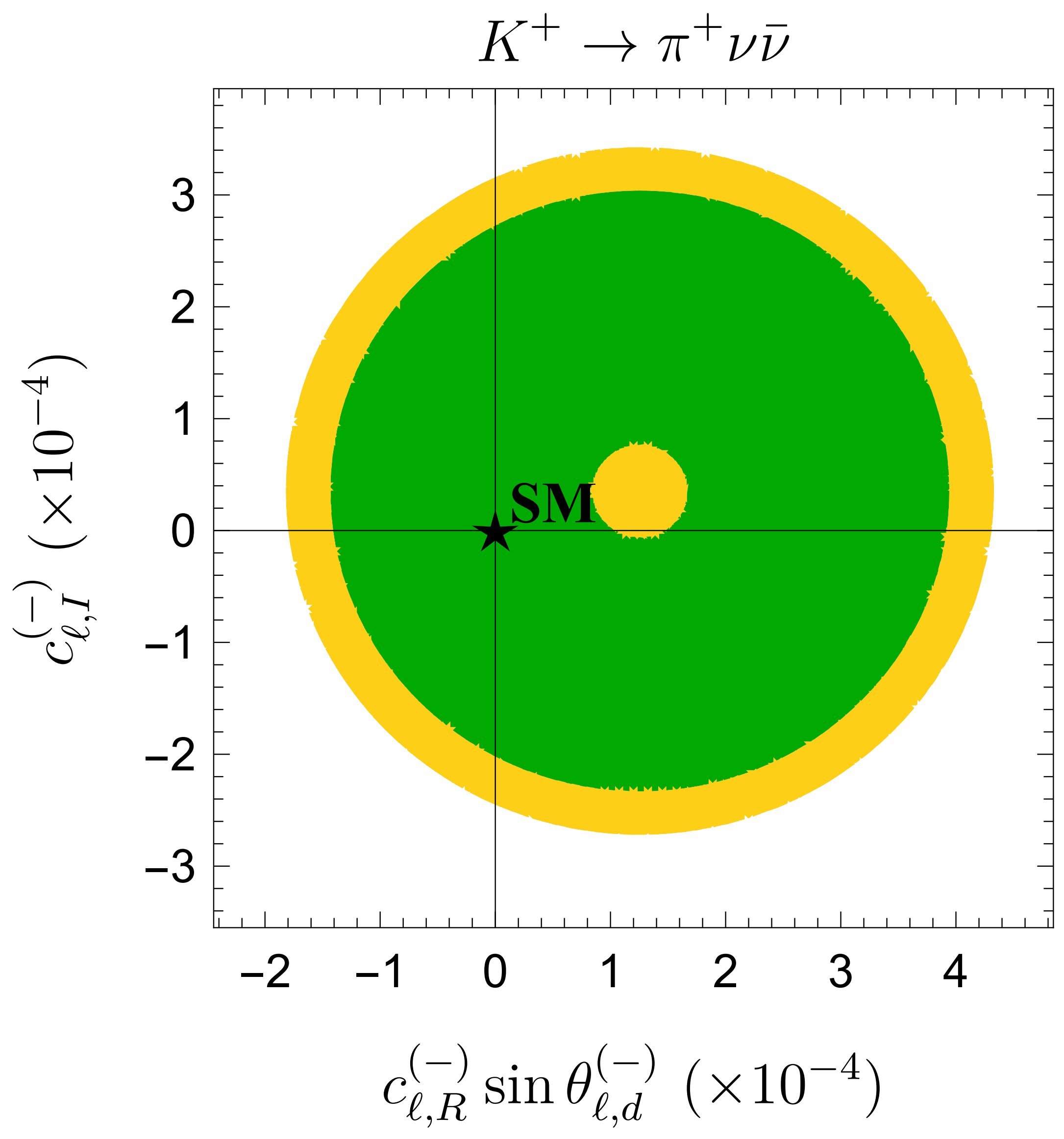
[Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, 2003.12421]

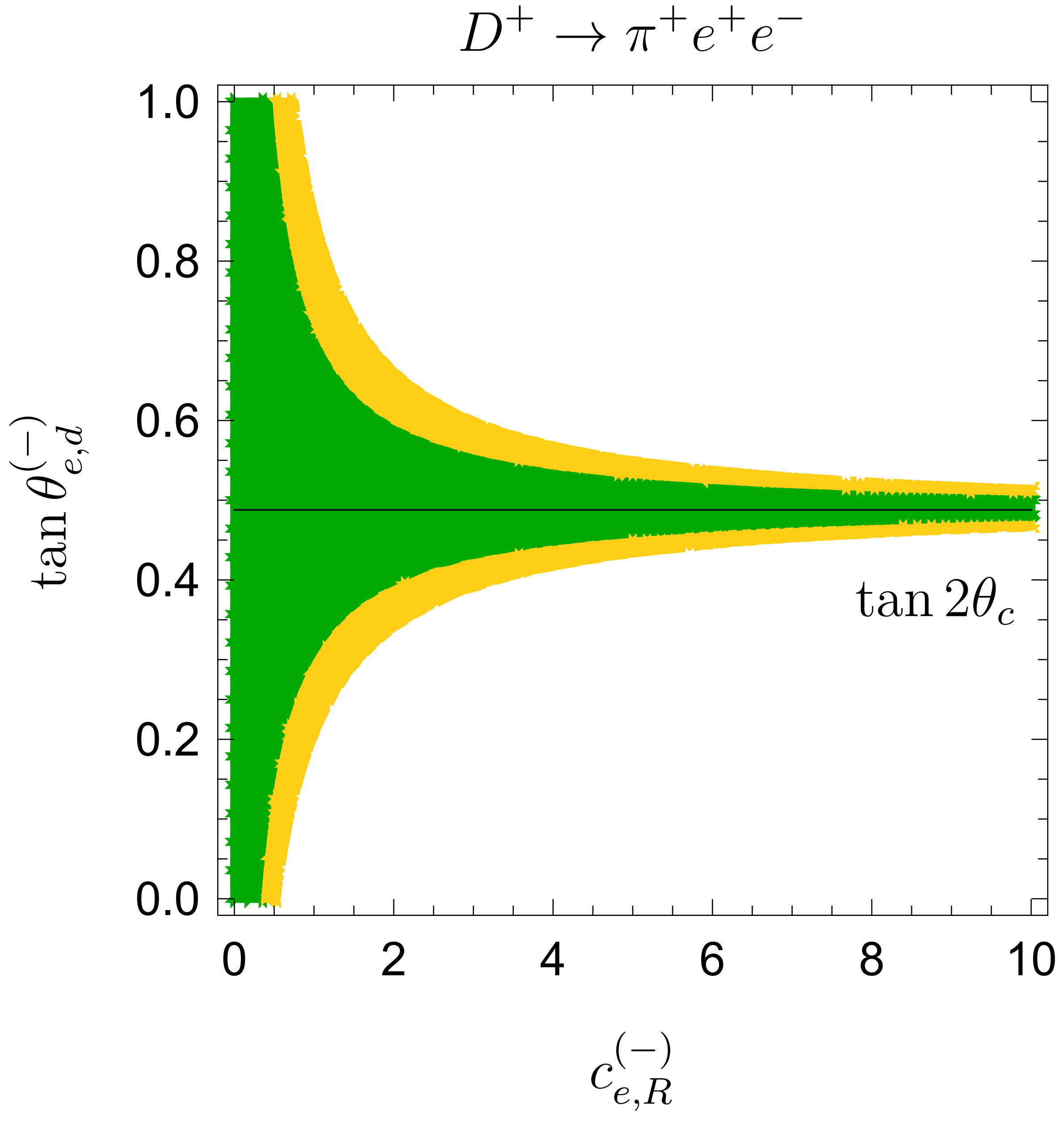
[KOTO, NA62]

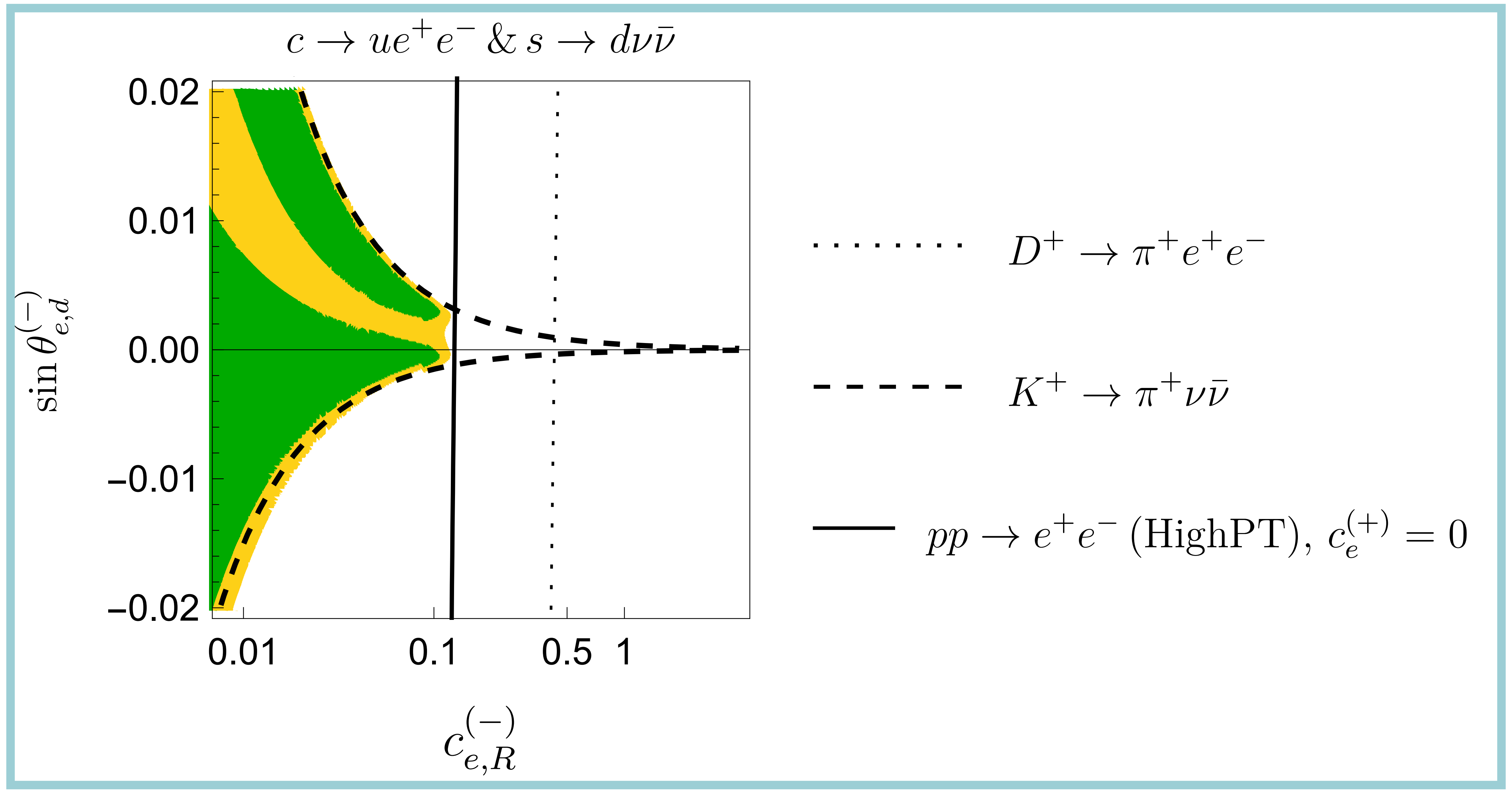
[BaBar, 1107.4465]

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = 1.14^{+0.40}_{-0.33} \times 10^{-10}$$

$$\mathcal{B}(D^+ \to \pi^+e^+e^-) < 1.1 \times 10^{-6}$$







$X^{(-)}$: RELATING $s \to d\nu\bar{\nu}$ AND $c \to u\ell^+\ell^-$ - TAUS

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$$\frac{d\mathcal{B}}{dq^2}(K^\pm \to \pi^\pm\nu_\ell\bar{\nu}_\ell) \sim G_F^2\alpha^2 f_{+,K\to\pi}^2(q^2)|C_{L,\nu_\ell}^{\text{down,SM}} + C_{L,\nu_\ell}^{\text{down,NP}}|^2,$$

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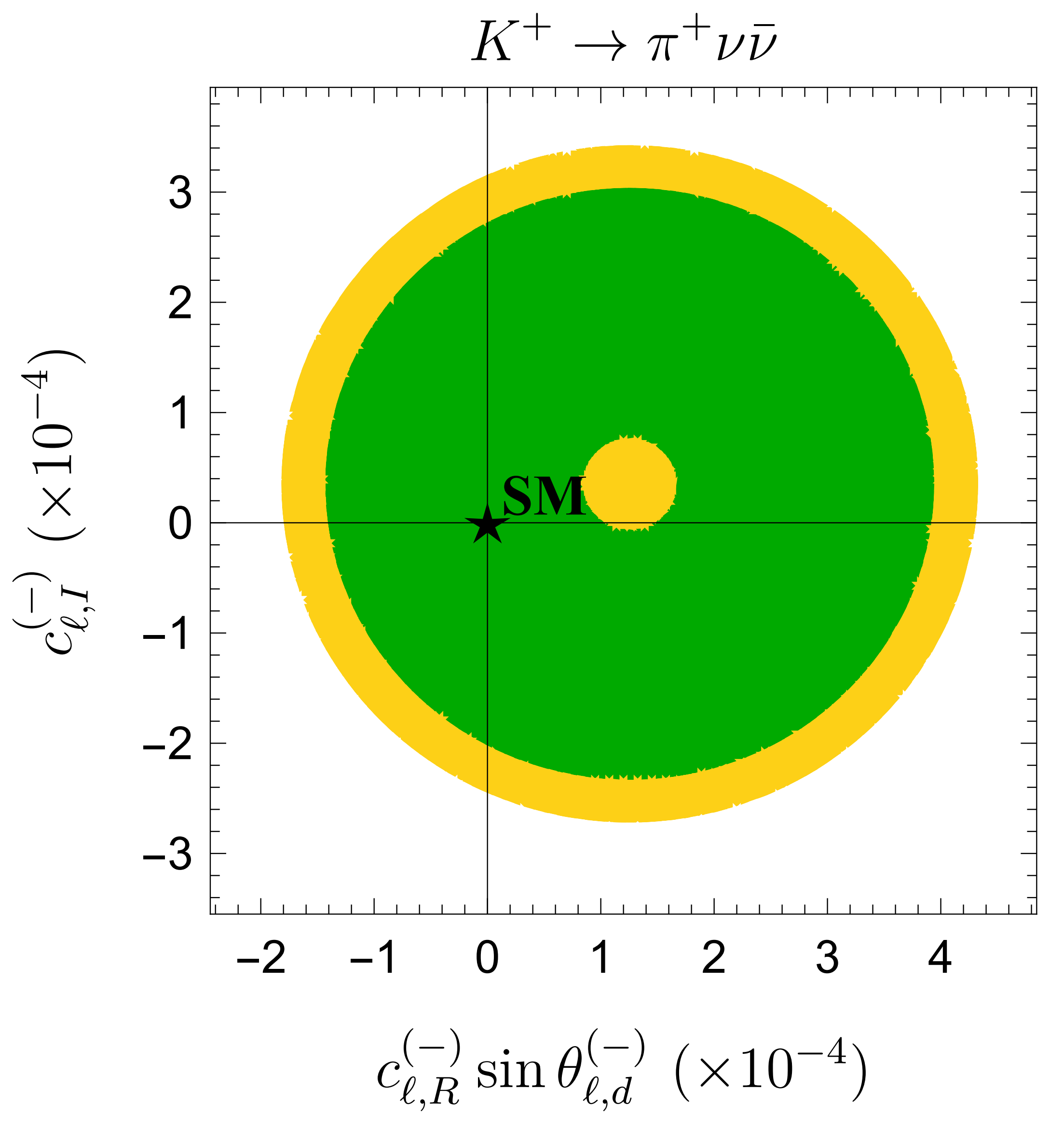
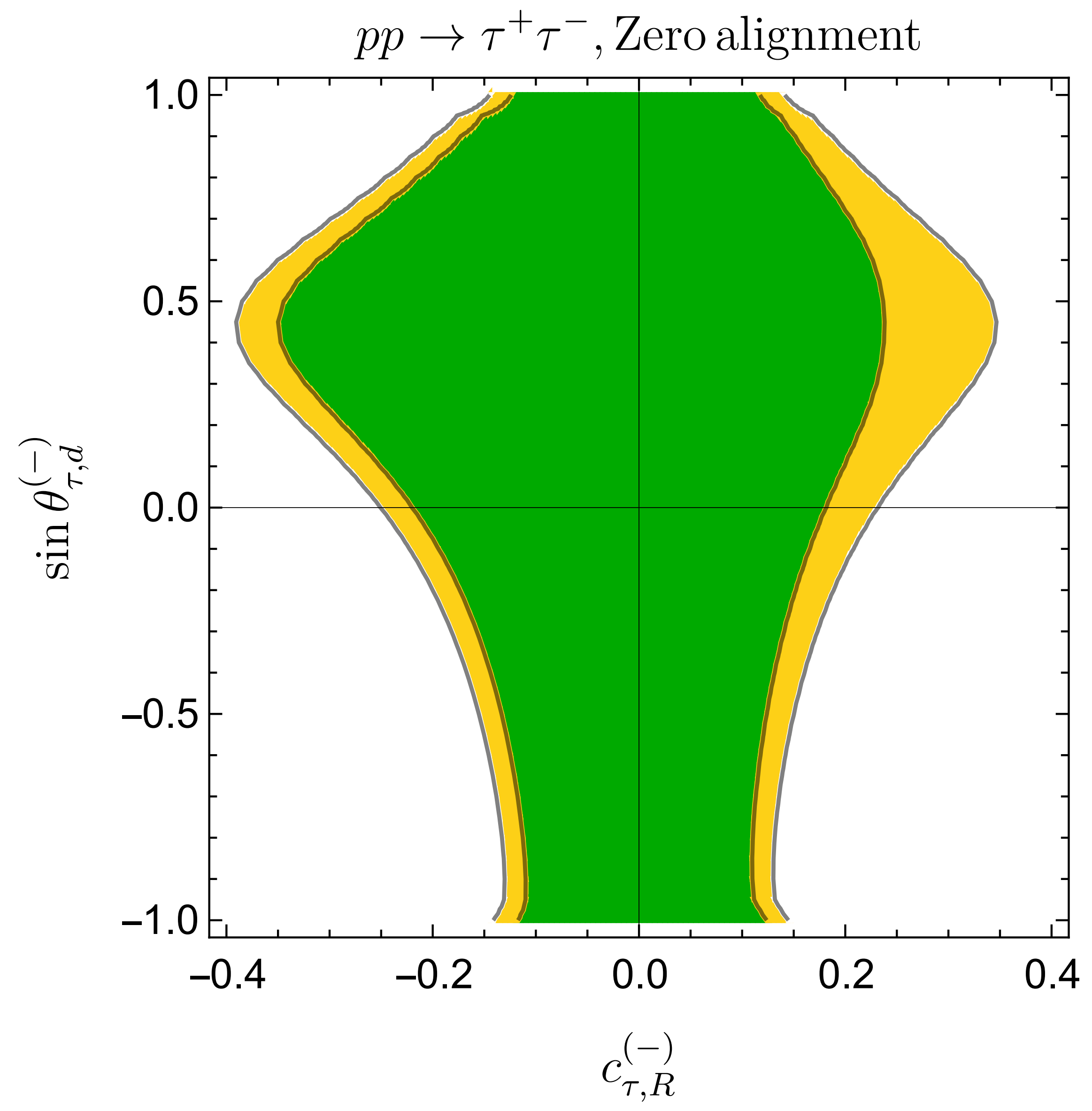
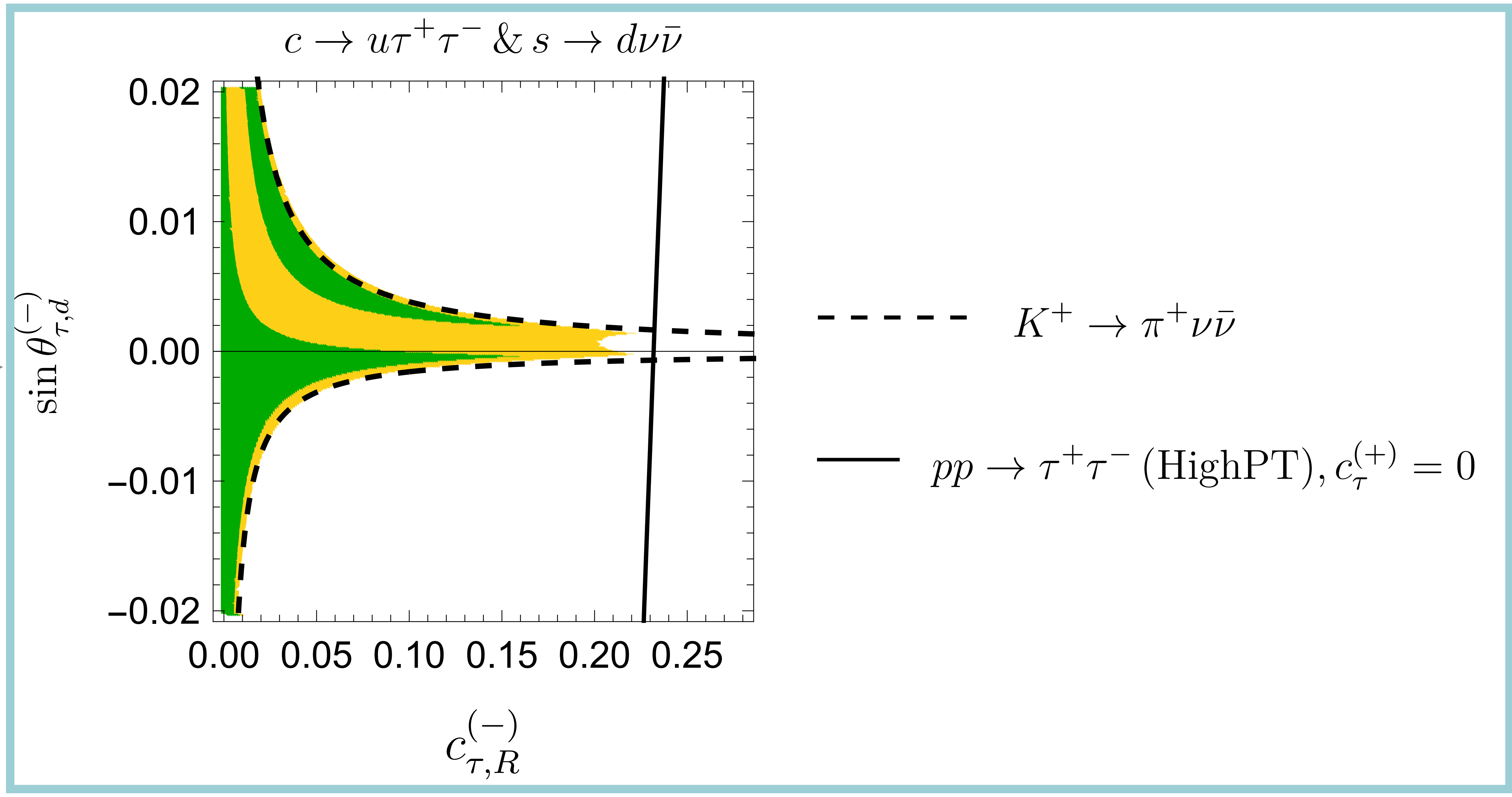
[Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch, 2207.10756, 2207.10714]

[ATLAS 2002.12223]







$X^{(-)}$: PREDICTIONS AND RESULTS

- CPV prediction

$$\mathcal{A}^{\rm CP}_{\rm tot} = \frac{\Gamma(D^+ \to \pi^+\ell^+\ell^-) - \Gamma(D^- \to \pi^-\ell^+\ell^-)}{\Gamma(D^+ \to \pi^+\ell^+\ell^-) + \Gamma(D^- \to \pi^-\ell^+\ell^-)}$$

$$|\mathcal{A}^{\rm CP}_{\rm tot}| = \frac{\int d\phi \, |{\rm Im}\,(\mathcal{A}_{\rm NP})\,|\,|\mathcal{A}_{\rm SM}|}{\int d\phi \, |\mathcal{A}_{\rm SM}|^2} \leq \sqrt{\frac{\int d\phi \, |{\rm Im}\,(\mathcal{A}_{\rm NP})\,|^2}{\int d\phi \, |\mathcal{A}_{\rm SM}|^2}}$$

Inequality based on Cauchy-Schwarz th.

[Gedalia, Kamenik, Ligeti, Perez, 1202.5038]

$$|\mathcal{A}^{\rm CP}_{\rm tot}(D^\pm \to \pi^\pm e^+ e^-)| \lesssim 6.0 \times 10^{-3}$$

$$|\mathcal{A}^{\rm CP}_{\rm tot}(D^\pm \to \pi^\pm \mu^+ \mu^-)| \lesssim 6.1 \times 10^{-3}$$

The SM part dominated by the ϕ pole

➡ CPV in rare charm semileptonic decays is small in left-handed scenario of NP.

$X^{(+)}$: RELATING $c \to u\nu\bar{\nu}$ AND $s \to d\ell^+\ell^-$ - MUONS

- Considerably weaker charm constraints, $c_I^{(+)}$ determined entirely by kaon processes.
- Since $K_L \to \mu^+\mu^-$ is sensitive only to the real part, use $K_L \to \pi^0\mu^+\mu^-$ to limit $c_{\mu,I}^{(+)}$

$$s \to d\ell^+\ell^- : \qquad C_9^{\mathrm{down,NP}} = -C_{10}^{\mathrm{down,NP}} = \frac{\pi}{\alpha_{\mathrm{em}}}\frac{v^2}{\Lambda^2}\left\{c_R^{(+)} \sin\theta_d^{(+)} - i c_I^{(+)}\right\}$$

$$c \to u\nu\bar{\nu} : \qquad C_{L,\nu}^{\mathrm{up,NP}} = \frac{2\pi}{\alpha_{\mathrm{em}}}\frac{v^2}{\Lambda^2}\left\{c_R^{(+)} \sin(\theta_d^{(+)} - 2\theta_c) - i c_I^{(+)}\right\}.$$

$$c_{\mu,I}^{(+)} \lesssim 2 \times 10^{-4}$$

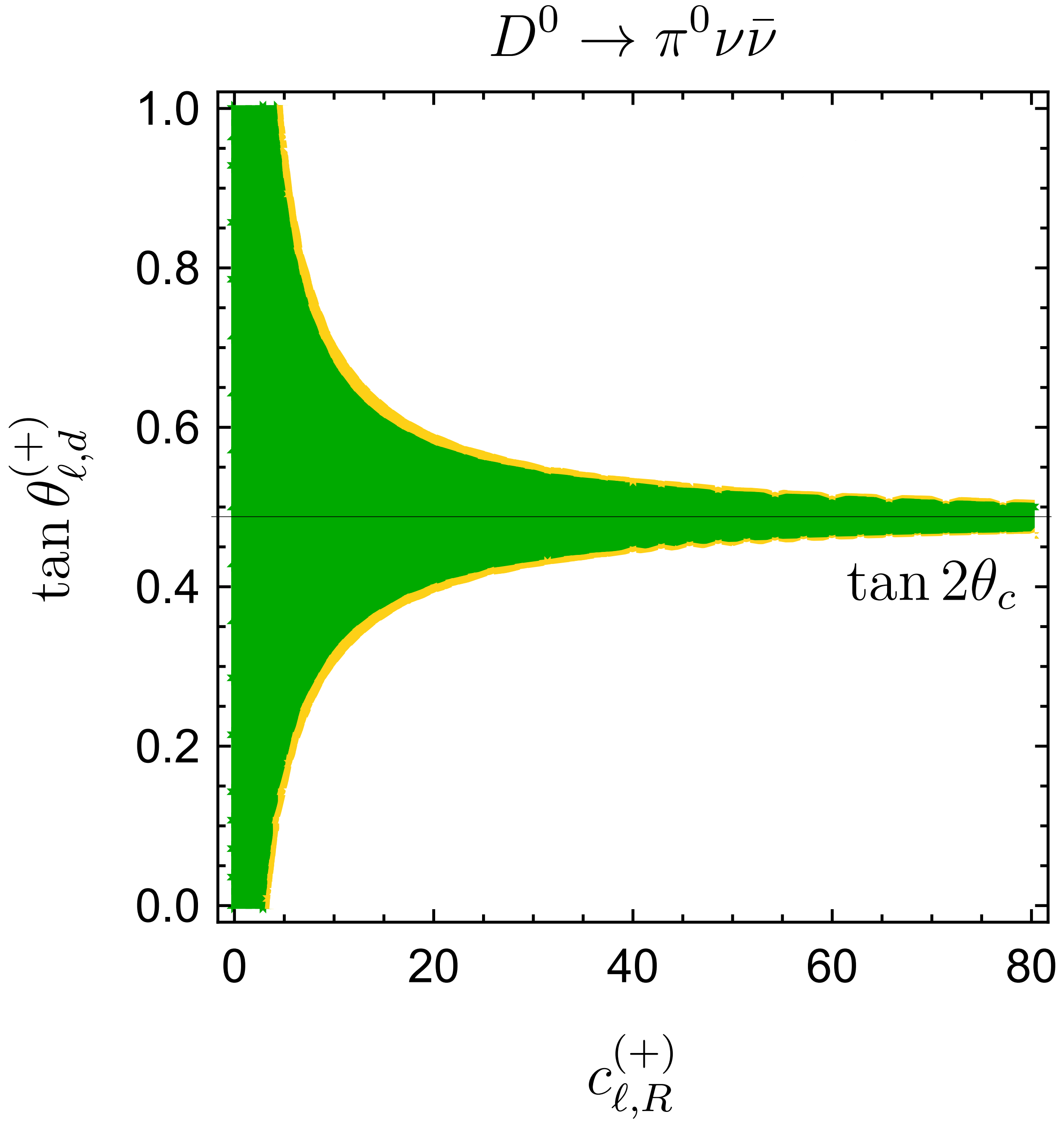
[KTeV, hep-ex/0309072]
[Mescia,Smith,Trine, hep-ph/0606081]

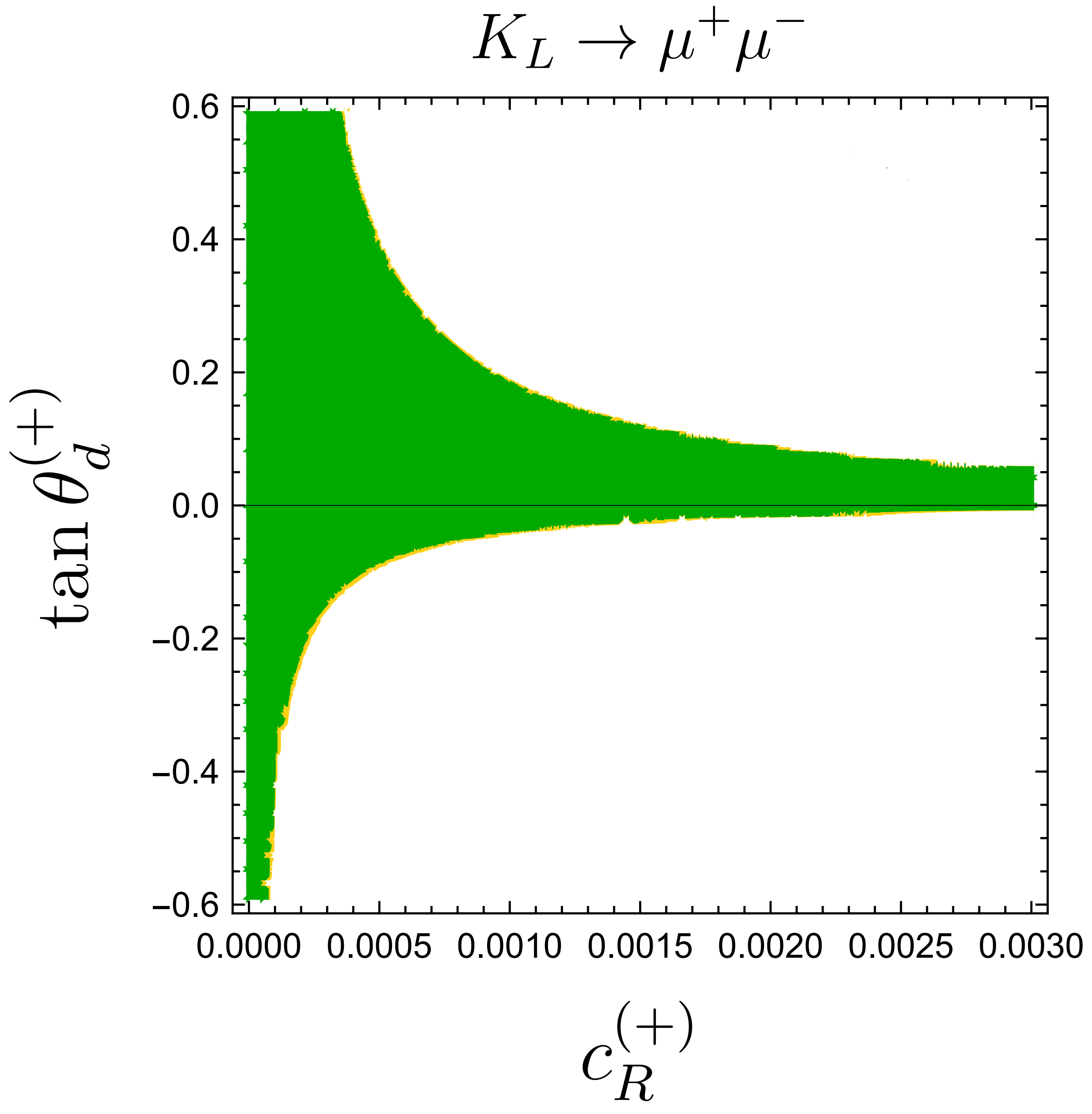
[BESSIII, hep-ex/2112.14236]

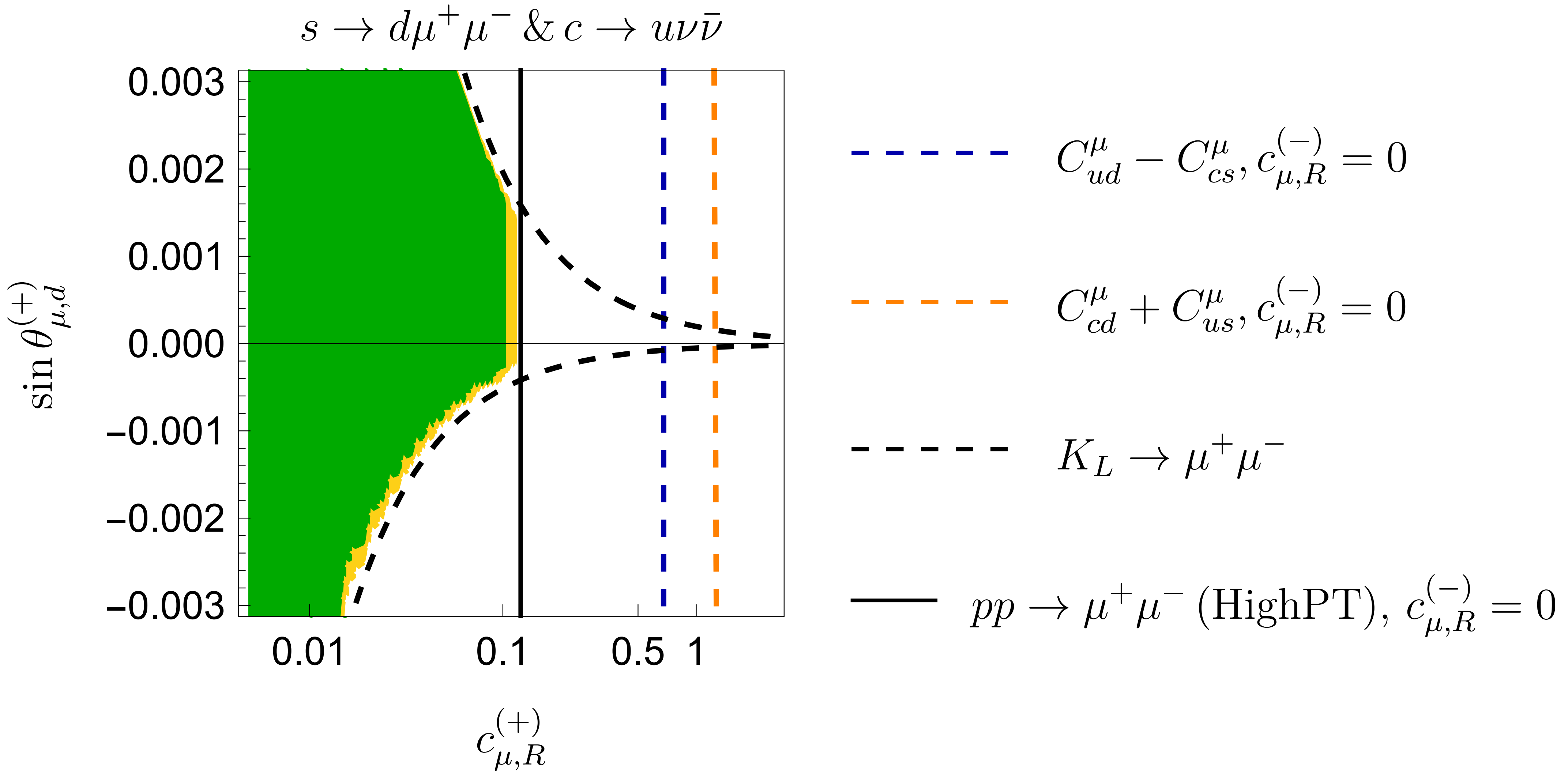
$$\mathcal{B}(D^0 \to \pi^0\nu\bar{\nu}) < 2.1 \times 10^{-4}$$

[PDG, Ambrose, 2000]

$$\mathcal{B}(K_L \to \mu^+\mu^-)^{\mathrm{exp}} = (6.84 \pm 0.11) \times 10^{-9}$$







$X^{(+)}$: RELATING $c \to u\nu\bar{\nu}$ AND $s \to d\ell^+\ell^-$ - ELECTRONS

- Considerably weaker charm constraints, $c_I^{(+)}$ determined entirely by kaon processes.
- Since $K_L \to e^+e^-$ is sensitive only to the real part, use $K_L \to \pi^0 e^+e^-$ to limit $c_I^{(+)}$

$$s \to d\ell^+\ell^- : \quad C_9^{\text{down,NP}} = -C_{10}^{\text{down,NP}} = \frac{\pi}{\alpha_{\text{em}}}\frac{v^2}{\Lambda^2}\left\{c_R^{(+)} \sin\theta_d^{(+)} - i c_I^{(+)}\right\}$$

$$c \to u\nu\bar{\nu} : \quad C_{L,\nu}^{\text{up,NP}} = \frac{2\pi}{\alpha_{\text{em}}}\frac{v^2}{\Lambda^2}\left\{c_R^{(+)} \sin(\theta_d^{(+)} - 2\theta_c) - i c_I^{(+)}\right\}.$$

$$c_{e,I}^{(+)} \lesssim 2 \times 10^{-4}$$

[KTeV, hep-ex/0309072]

[Mescia, Smith, Trine, hep-ph/0606081]

[BESSIII, hep-ex/2112.14236]

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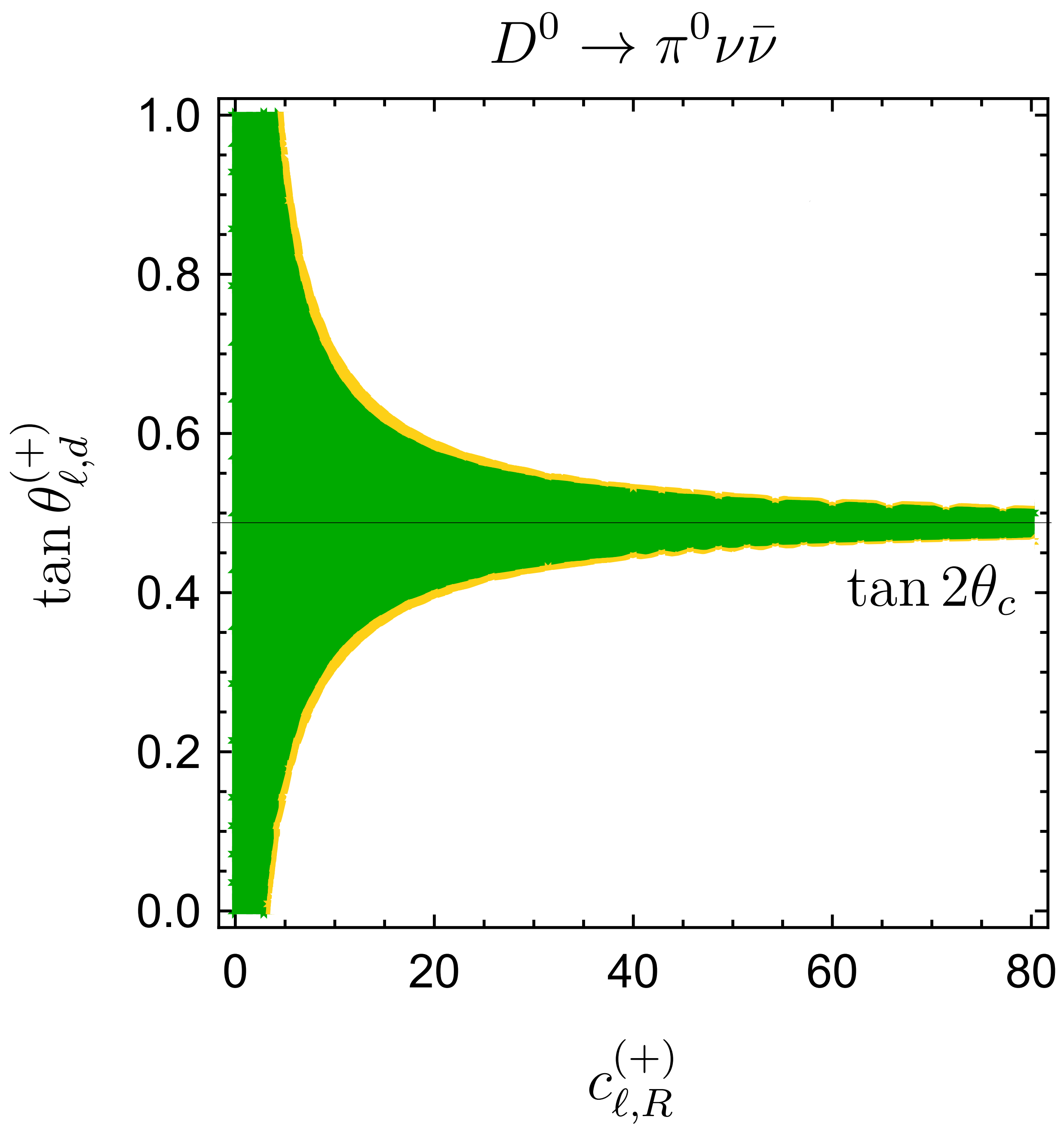
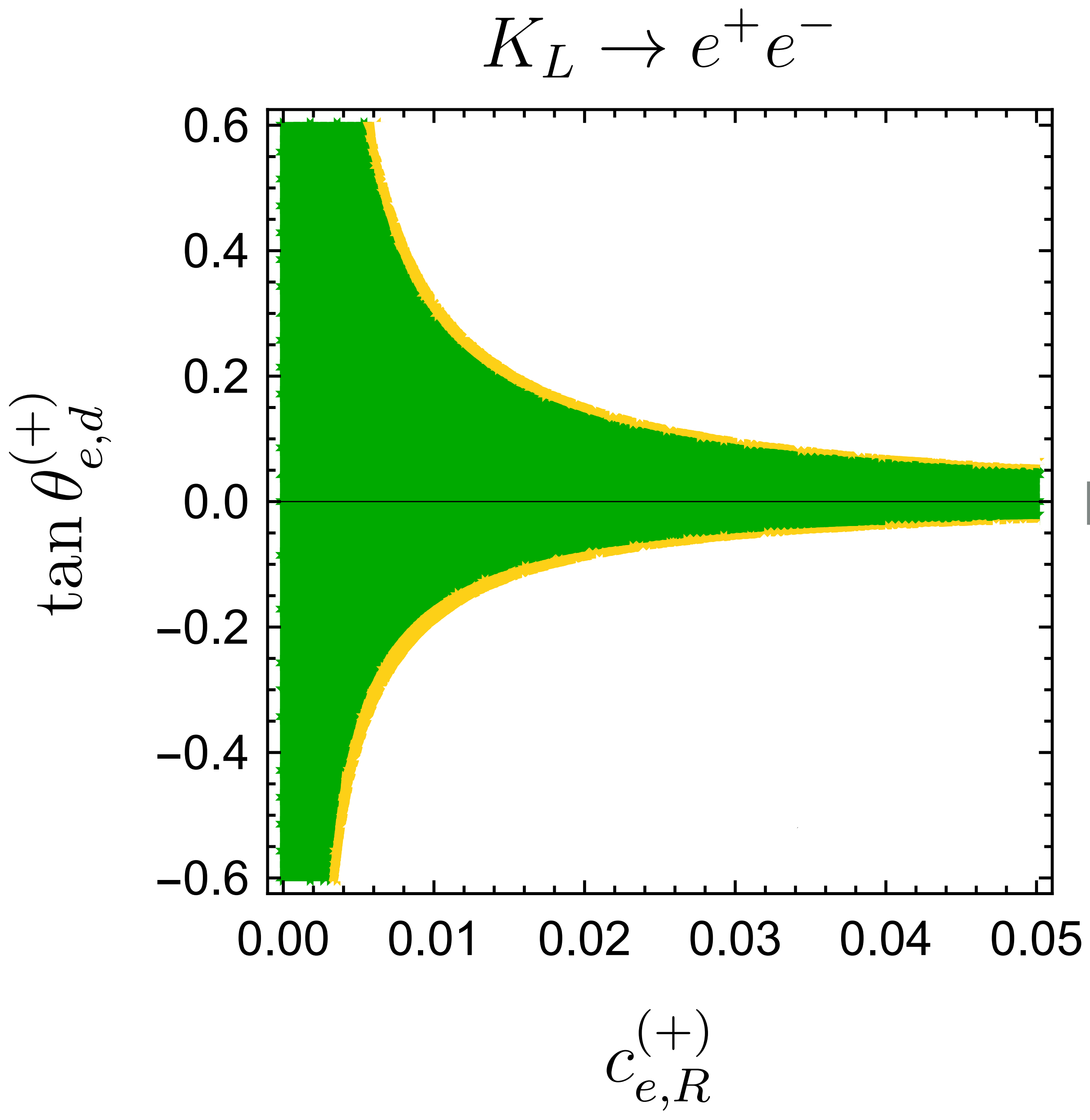
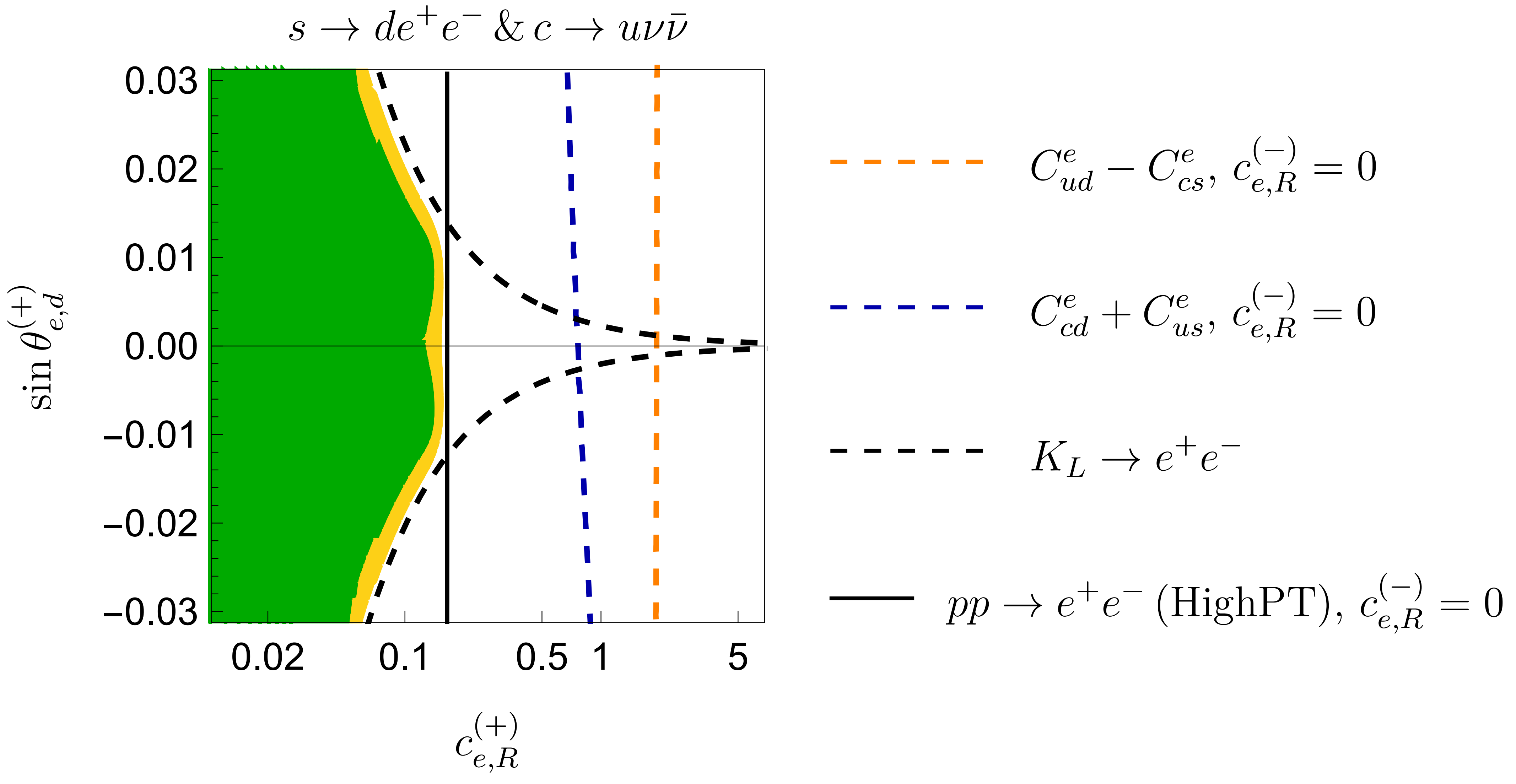


[PDG, Ambrose, 1998]

$$\mathcal{B}(K_L \to e^+e^-)^{\text{exp}} = 9^{+6}_{-4} \times 10^{-12}$$





$X^{(+)}$: RELATING $c \to u\nu\bar{\nu}$ AND $s \to d\ell^+\ell^-$ - TAUS

$$s \to d\ell^+\ell^- : \qquad C_9^{\rm down,NP} = -C_{10}^{\rm down,NP} = \frac{\pi}{\alpha_{\rm em}}\frac{v^2}{\Lambda^2}\left\{c_R^{(+)}\sin\theta_d^{(+)} - ic_I^{(+)}\right\}$$

$$c \to u\nu\bar{\nu} : \qquad C_{L,\nu}^{\rm up,NP} = \frac{2\pi}{\alpha_{\rm em}}\frac{v^2}{\Lambda^2}\left\{c_R^{(+)}\sin(\theta_d^{(+)} - 2\theta_c) - ic_I^{(+)}\right\}.$$

- Use HighPT to constrain the (+) parameter space
- Use HighPT again to obtain $|c_{\tau,I}^{(+)}| \lesssim 0.15$ - the weakest bound possible

[BESSIII, hep-ex/2112.14236]

[Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch, 2207.10756, 2207.10714]

[ATLAS 2002.12223]

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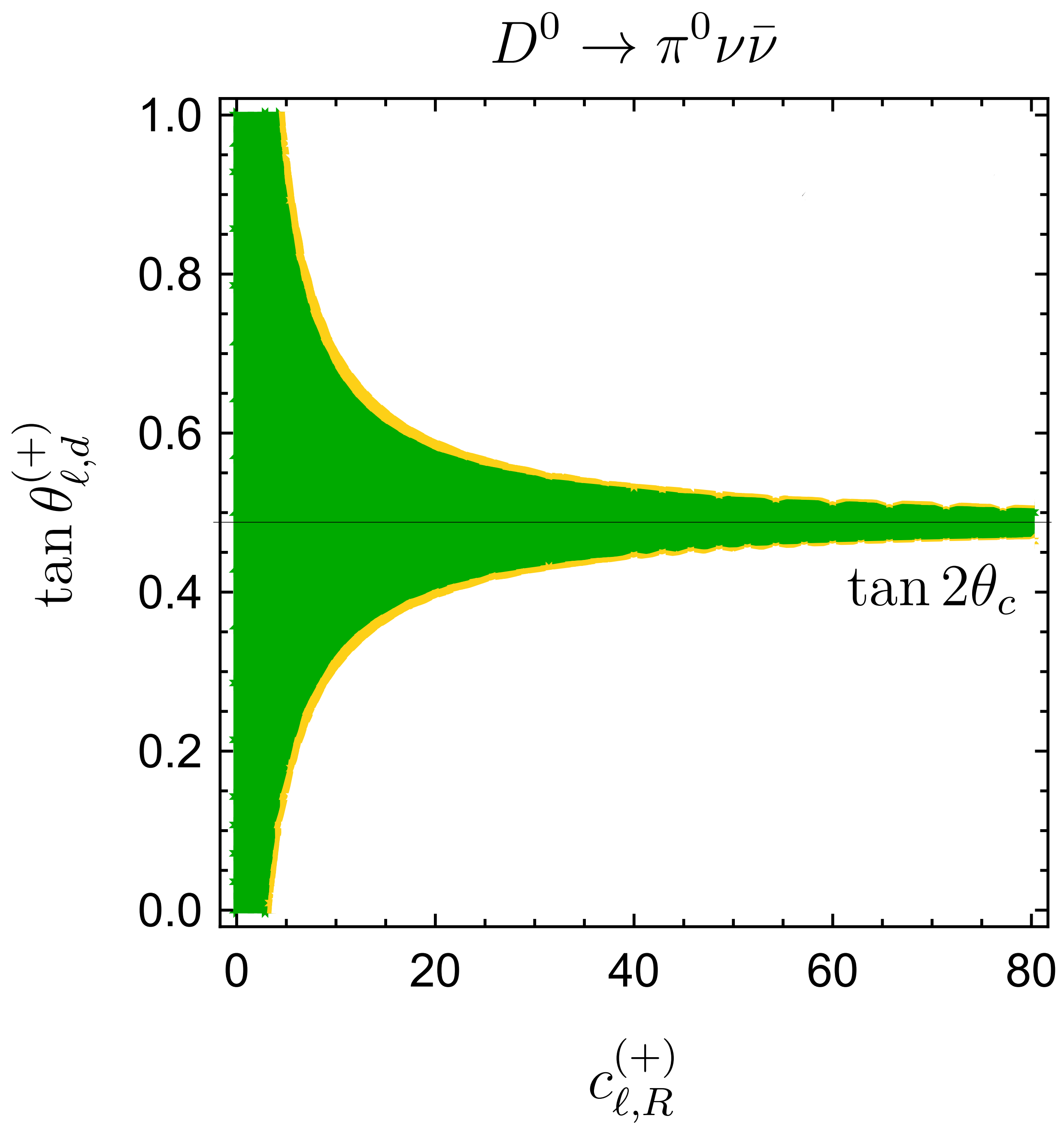
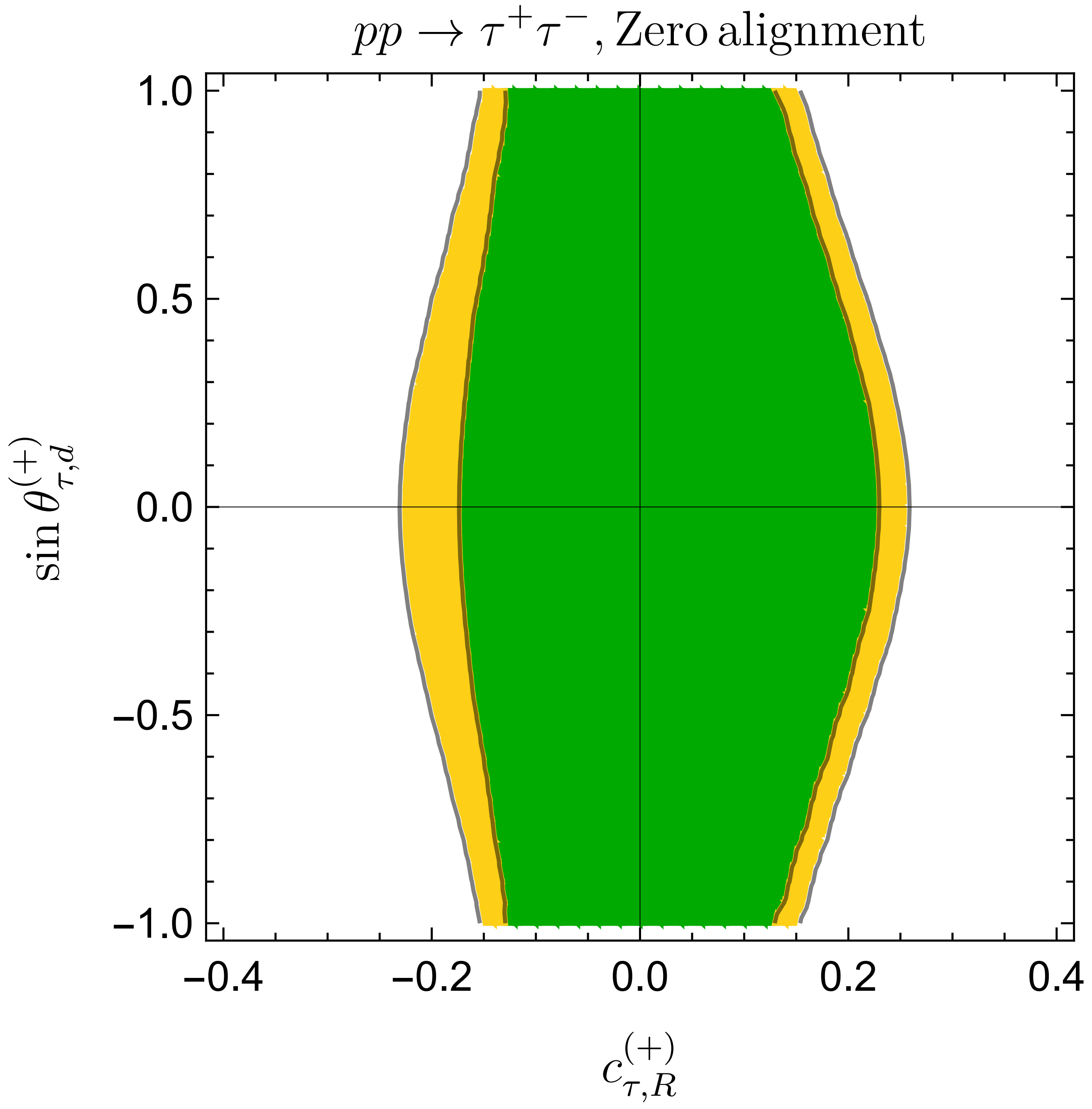
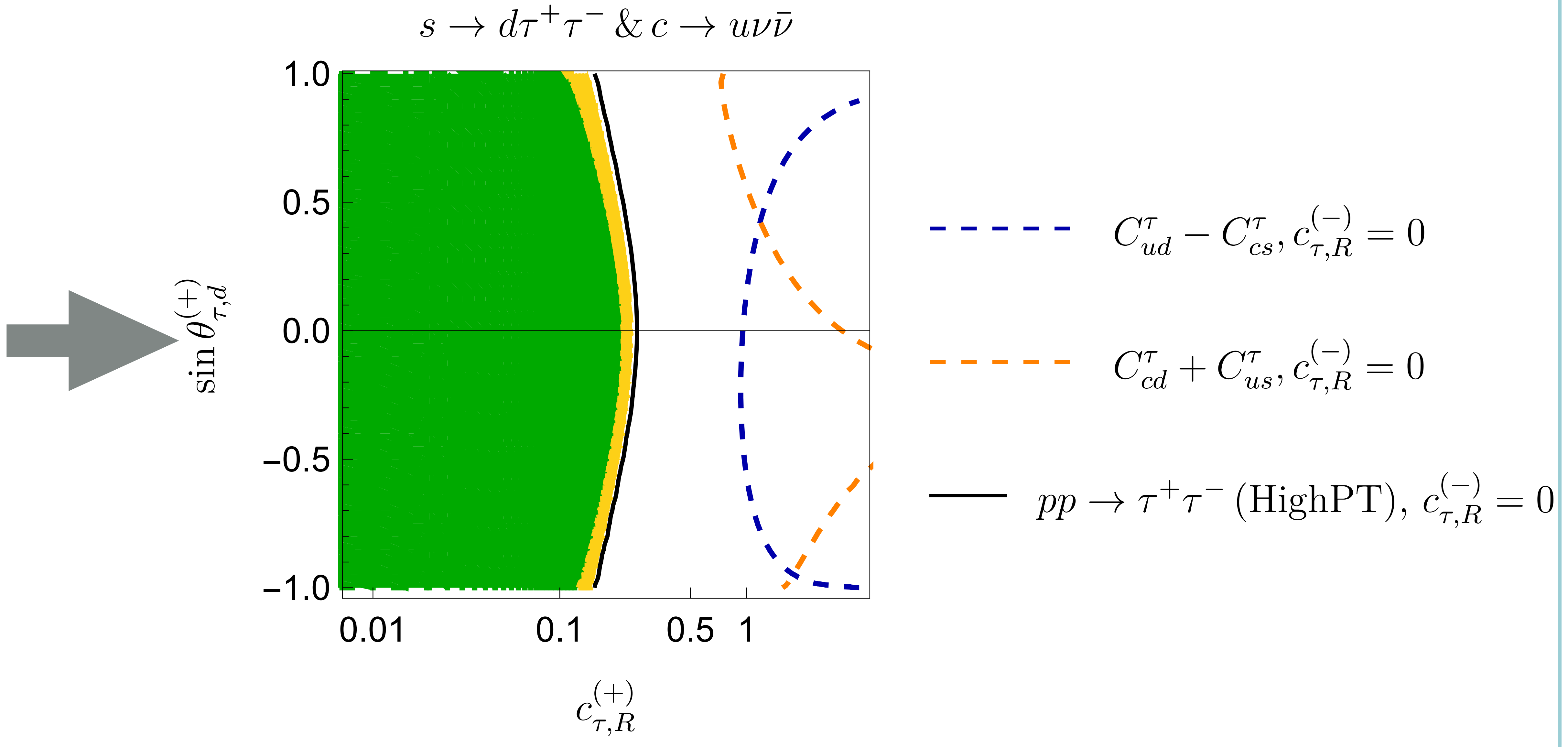
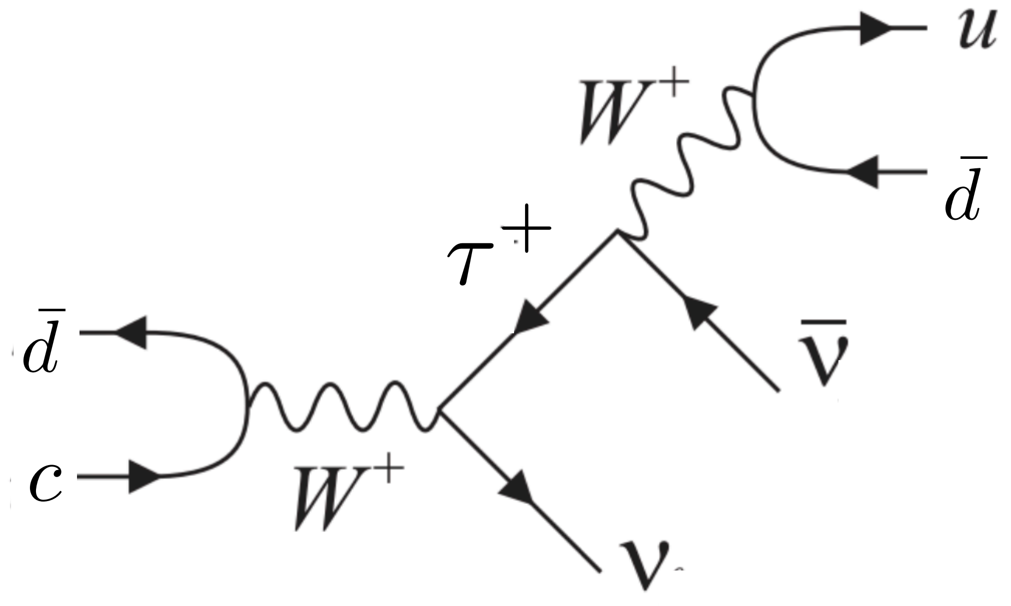


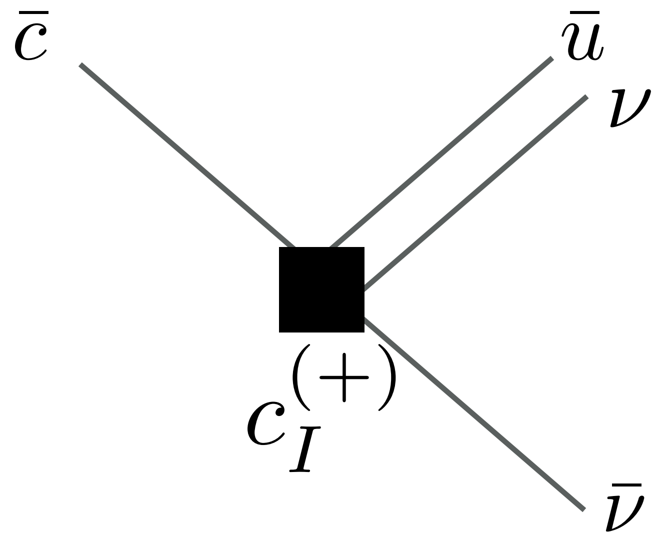




$X^{(+)}$: RELATING $c \to u\nu\bar{\nu}$ AND $s \to d\ell^+\ell^-$

- CPV prediction
  - CPV in charm should be invisible: $|c^{(+)}_{\tau,I}| \lesssim 0.15$ implies $|\mathcal{A}^{\rm CP}_{\rm tot}(D^\pm \to \pi^\pm \nu\bar{\nu})| < 5.8 \times 10^{-9}$





CONCLUSIONS

- Left-handed $\bar{Q}Q\,\bar{L}L$ operators are promising avenue of NP with large overlap with the SM structure

- K and D rare decays given in terms of 2 (x2) CP even and 1 (x2) CP odd parameter:

$$c_R \qquad \theta_d \qquad c_I$$

- Interplay of K and D rare decay constrain CP even operators - importance of alignment angle

- CP odd parameter c_I is universal, dominated by bounds from kaons

- Expected improvements by NA62, KOTO for kaons and LHCb, BESS III on the charm side

WHAT'S NEXT?

FLAVOR ALIGNMENT WITH 3 GENERATIONS

- Generic 3×3 Hermitian matrix can be decomposed with Gell-Mann matrices
  - No geometric interpretation now, since we have an 8-dimensional space

- Setting up a flavor symmetry can ease the decomposition

FLAVOR ALIGNMENT WITH 3 GENERATIONS - U(2) CASE

With e.g. a U(2) flavor theory at hand, the CKM has only 1 physical parameter:

$$V_{\mathrm{CKM},U(2)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

The singlet operator $X_Q(\bar{Q}\gamma_\mu Q)(\bar{L}\gamma^\mu L)$ will have the form:

$$X_Q^{\mathrm{up}} = \begin{pmatrix} X_{\mathrm{tr}} + X_{11} & X_{12}\cos\theta_{23} - X_{13}\sin\theta_{23} & X_{13}\cos\theta_{23} + X_{12}\sin\theta_{23} \\ X_{12}^*\cos\theta_{23} - X_{13}^*\sin\theta_{23} & X_{\mathrm{tr}} - c_R\cos(\theta_d - 2\theta_{23}) & c_R\sin(\theta_d - 2\theta_{23}) - ic_2 \\ X_{13}^*\cos\theta_{23} + X_{12}^*\sin\theta_{23} & c_R\sin(\theta_d - 2\theta_{23}) + ic_2 & X_{\mathrm{tr}} + c_R\cos(\theta_d - 2\theta_{23}) \end{pmatrix}$$

where we did the following substitution:

$$(X_Q)_{i\geq 2, j\geq 2} = c_R\cos\theta_d(-\sigma_3) + c_R\sin\theta_d\sigma_1 + c_I\sigma_2$$

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SU(2) substructure

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PROSPECTS

- Considering 3 families, we have 3 CPV phases - bound them through appropriate experiments
- Use the U(2) limit and repeat the procedure for c,s,t,b.
- Expecting better bounds from NA62, KOTO, BES III

THANK YOU!

BACKUP

$X^{(+)}$ AND $X^{(-)}$: CHARGED CURRENTS

- In general, both considered sectors induce modifications of CKM in the 1st and 2nd generation

$$\mathcal{L}_{\rm CC} = \frac{1}{\Lambda^2} 2X^{(3)}_{ij} (\bar{u}'_i \gamma^\mu P_L d_j)(\bar{\ell}\gamma_\mu P_L \nu)$$

$$2X^{(3)}_{ij} = (\lambda^{(+)} - \lambda^{(-)})\delta_{ij} + (c_a^{(+)} - c_a^{(-)})(\sigma^a)_{ij}.$$

1 trace parameter (specific to CC)

FCNCs parameters

- Modified CKM framework: $\mathcal{L}_{cc} = C_{ij} \frac{4G_F}{\sqrt{2}} (\bar{u}_L \gamma_\mu d_L)(\bar{\ell}_L \gamma^\mu \nu_\ell) + \text{h.c.}$

$$C_{ij} = V_{ij}(\theta_c) + \frac{v^2}{\Lambda^2}\left(c_R^{(3)} f_1(\theta_d^{(3)} - \theta_c) + i c_I^{(3)} f_2(\theta_c) + f_3(\theta_c)\lambda^{(3)}\right)$$

$$X^{(3)}_{ij} \left(\bar{Q}^i \gamma_\mu \sigma^a Q^j\right)\left(\bar{L}_k \gamma_\mu \sigma_a L_k\right) \supset$$

$$(\bar{s}_L\gamma_\mu u_L)(\bar{\nu}_\mu\gamma_\mu\mu)\left(2c_R^{(3)}\sin(\theta_d^{(3)} - \theta_c) + 2ic_{\theta_c}c_I^{(3)} - 2s_{\theta_c}\lambda^{(3)}\right)$$
$$+(\bar{d}_L\gamma_\mu c_L)(\bar{\nu}_\mu\gamma_\mu\mu)\left(2c_R^{(3)}\sin(\theta_d^{(3)} - \theta_c) - 2ic_{\theta_c}c_I^{(3)} + 2s_{\theta_c}\lambda^{(3)}\right)$$
$$+(\bar{s}_L\gamma_\mu c_L)(\bar{\nu}_\mu\gamma_\mu\mu)\left(2c_R^{(3)}\cos(\theta_d^{(3)} - \theta_c) + 2is_{\theta_c}c_I^{(3)} + 2c_{\theta_c}\lambda^{(3)}\right)$$
$$-(\bar{d}_L\gamma_\mu u_L)(\bar{\nu}_\mu\gamma_\mu\mu)\left(2c_R^{(3)}\cos(\theta_d^{(3)} - \theta_c) - 2is_{\theta_c}c_I^{(3)} - 2c_{\theta_c}\lambda^{(3)}\right)$$

- $c_I^{(3)}$ irrelevant - no interference with SM CKM
- Trace affects diagonal CKMs
- Impose constraints from superallowed β decay on V_{ud}
- V_{us} from FLAG, V_{cs} , V_{cd} from HFLAV (leptonic decays)

$X^{(+)}$AND $X^{(-)}$: CHARGED CURRENTS

- Use the following linear combinations to avoid trace marginalisation:

$$C^{\ell}_{us} + C^{\ell}_{cd} = \frac{v^2}{\Lambda^2}\left[c_R^{(+)} \sin\left(\theta_c + \theta_d^{(+)}\right) - c_R^{(-)} \sin\left(\theta_c + \theta_d^{(-)}\right)\right]$$

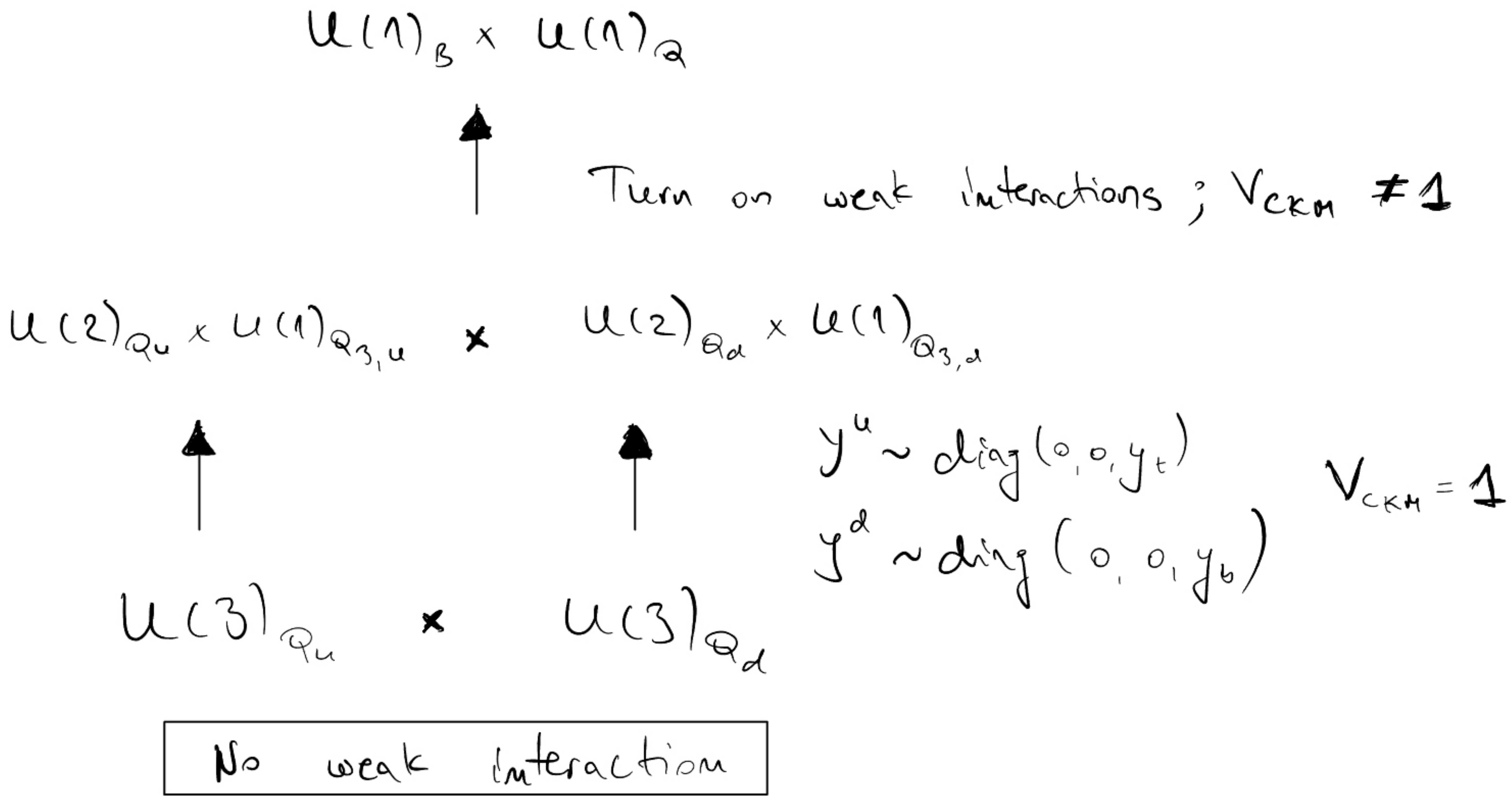
$$C^{\ell}_{ud} - C^{\ell}_{cs} = \frac{v^2}{\Lambda^2}\left[- c_R^{(+)} \cos\left(\theta_c + \theta_d^{(+)}\right) + c_R^{(-)} \cos\left(\theta_c + \theta_d^{(-)}\right)\right]$$

- Geometric interpretation:

$$\left(C^{\ell}_{us} + C^{\ell}_{cd}\right)^2 + \left(C^{\ell}_{cd} - C^{\ell}_{cs}\right)^2 = \left(\frac{v}{\Lambda}\right)^4 \left[\left(c_R^{(+)}\right)^2 + \left(c_R^{(-)}\right)^2 - 2c_R^{(+)}c_R^{(-)} \cos\left(\theta_d^{(+)} - \theta_d^{(-)}\right)\right]$$

- Due to large uncertainties in charged D decays, bounds irrelevant in the $X^{(-)}$ - don't contribute to the χ^2.
- Cabbibo angle should in principle also float - since sectors are effectively decoupled, keep it as constant, but leave $\theta_d^{(+)}$ (and $\theta_d^{(-)}$) floating.

FLAVOR ALIGNMENT WITH 3 GENERATIONS - U(2) CASE



$$V_{\rm CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

[Gedalia, Perez, Mannelli, 1003.3869]
[Kagan, Perez, Volansky, Zupan, 0903.1794]

FLAVOR ALIGNMENT WITH 3 GENERATIONS - U(2) CASE

$$V_{\text{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

- The SU(2) substructure was expected, as our CKM matrix is reducible.
- Also obvious if we start building a basis like in the two-generation case:

[Gedalia, Perez, Mannelli, 1003.3869]
[Kagan, Perez, Volansky, Zupan, 0903.1794]

$$\mathcal{A}_d = Y_d Y_d^\dagger - \frac{1}{3}\text{tr}(Y_d Y_d^\dagger)\mathbb{1} = \frac{y_b^2}{3}\begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 2 \end{pmatrix} = \frac{y_b^2}{3}\lambda_8$$

$$\mathcal{A}_u = Y_u Y_u^\dagger - \frac{1}{3}\text{tr}(Y_u Y_u^\dagger)\mathbb{1} = y_t^2\begin{pmatrix} -\frac{1}{3} & 0 & 0 \\ 0 & -\frac{1}{3} + \sin^2\theta_{23} & -\cos\theta_{23}\sin\theta_{23} \\ 0 & -\cos\theta_{23}\sin\theta_{23} & -\frac{1}{3} + \cos^2\theta_{23} \end{pmatrix} \propto a_1\lambda_3 + a_2\lambda_6 + a_3\lambda_8$$

$$J = \frac{y_b^2 y_t^2 \sin\theta_{23}\cos\theta_{23}}{2}\lambda_7$$

$$J_u = \frac{y_b^2 y_t^4 \sin\theta_{23}\cos\theta_{23}}{2}\left(\left(\frac{1}{2} - \sin^2\theta_{23}\right)\lambda_6 + \sin\theta_{23}\cos\theta_{23}\lambda_7\right)$$

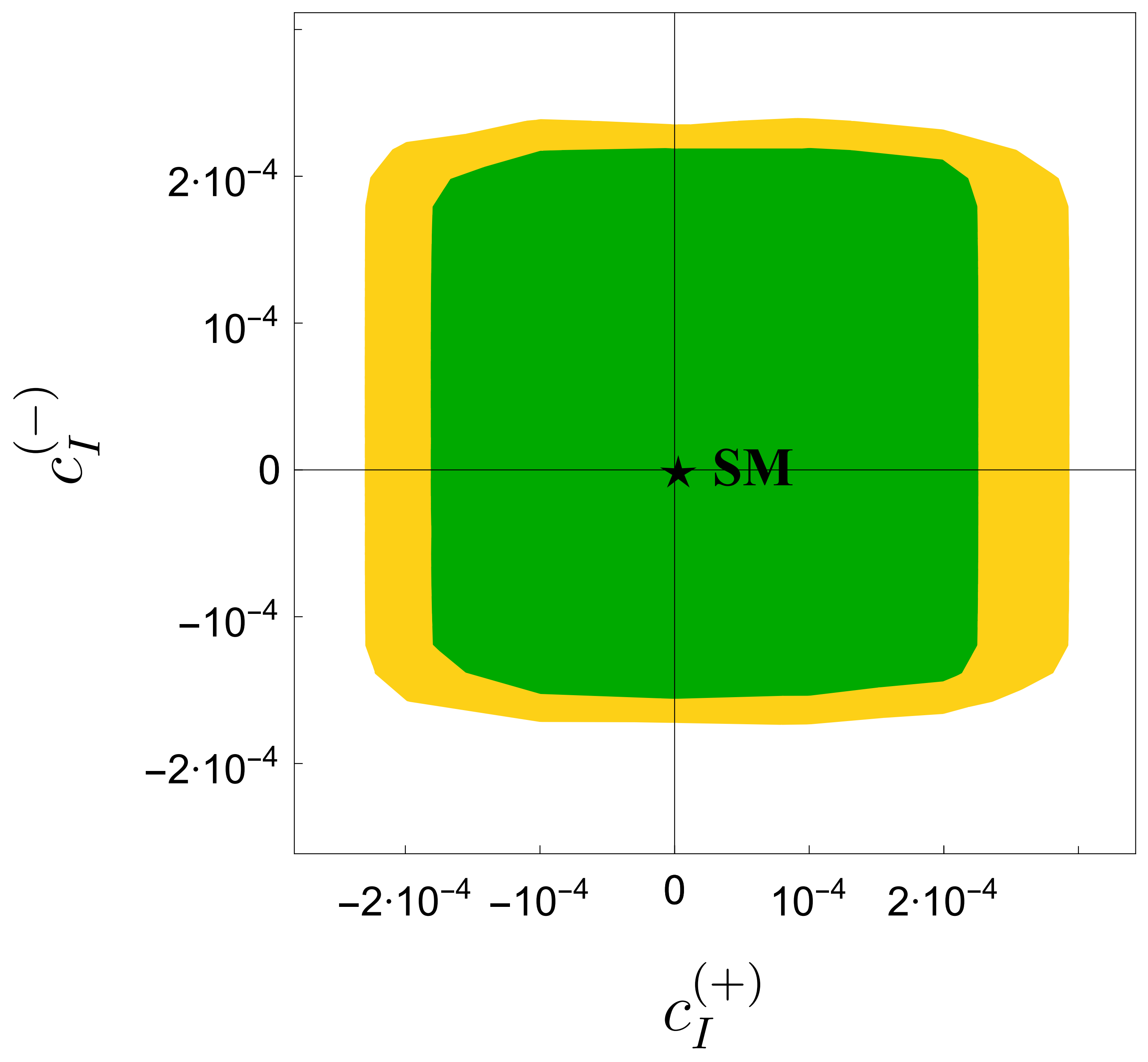
$$J_d = \frac{y_b^4 y_t^2 \sin\theta_{23}\cos\theta_{23}}{4}\lambda_6$$

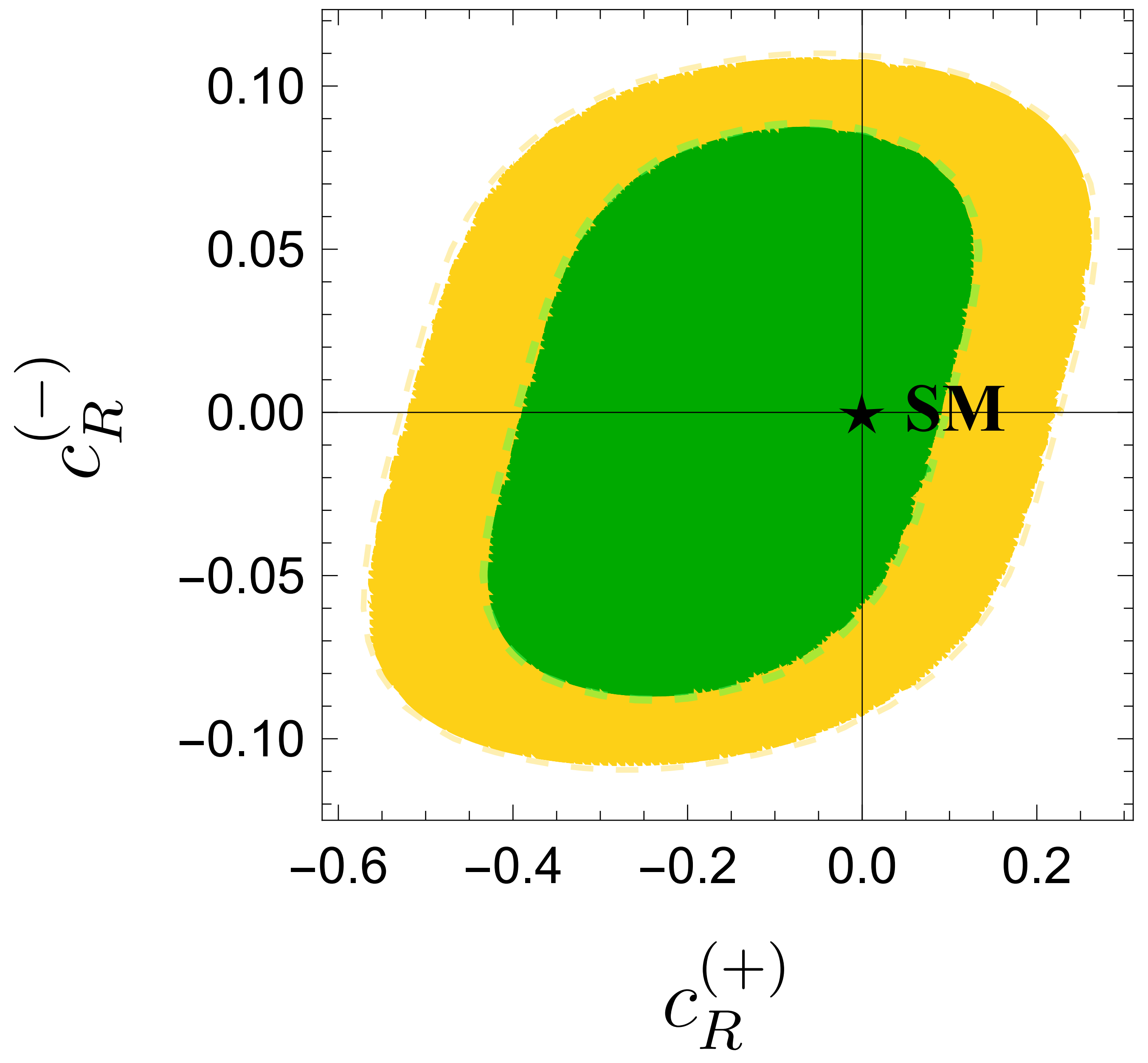
$$J_u \times J_d \propto \mathcal{A}_d$$

SU(2) subalgebra of SU(3)

$X^{(+)}$AND $X^{(-)}$: CHARGED CURRENTS & GLOBAL FITS

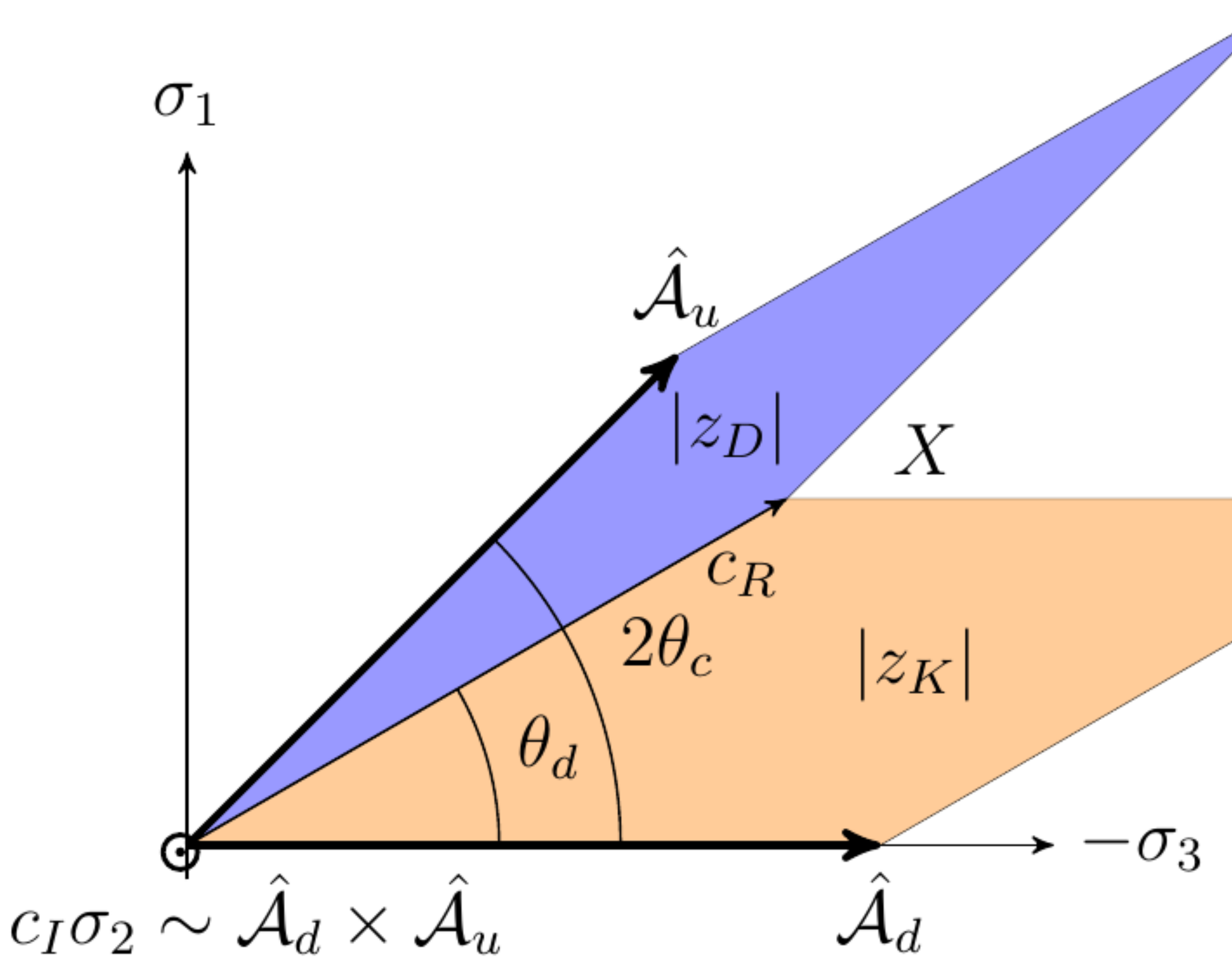
- No large correlation observed between $c_R^{(\pm)}$, none between $c_I^{(\pm)}$





OPTIMAL ALIGNMENT ANGLE

- Suppose we know experimental upper bounds on $|z_D|^{\exp}, |z_K|^{\exp}$



Bound on c_R from $|z_K|^{\exp}$ weakest at small angle θ_d

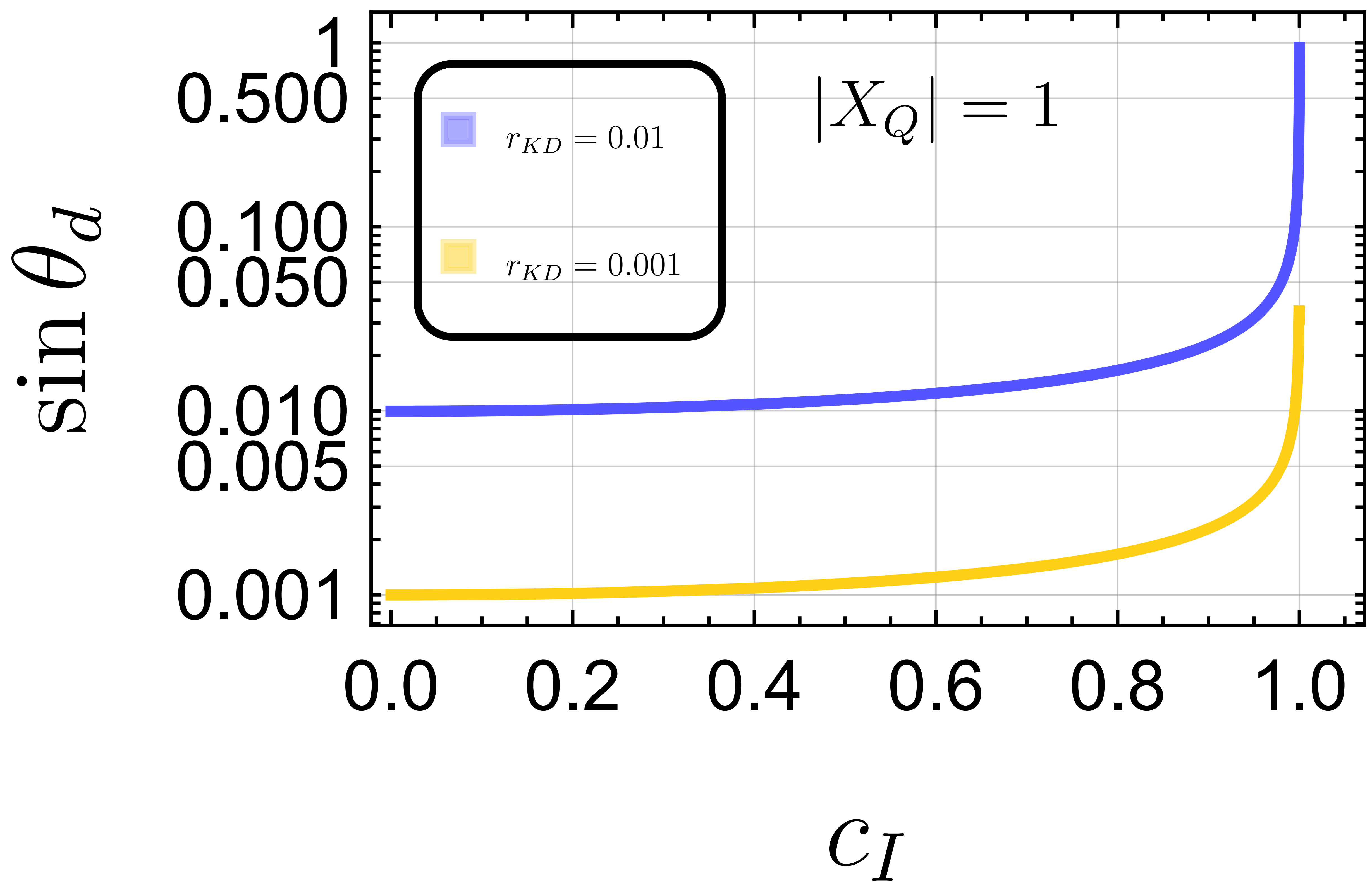
Bound on c_R from $|z_D|^{\exp}$ weakest at $\theta_d \sim 2\theta_c$

At optimal angle θ_d^*, $|z_D|^{\exp}, |z_K|^{\exp}$ bounds are equally strong

$$\left|\frac{z_K}{z_D}\right|_{\theta=\theta_d^*} = \frac{|z_K|^{\exp}}{|z_D|^{\exp}} = r_{KD}$$

$$\tan\theta_d^*\big|_{c_I=0} = \frac{r_{KD}\sin 2\theta_c}{1 + r_{KD}\cos 2\theta_c}$$

DEPENDENCE OF c_I AND θ_d



LARGE-DISTANCE CONTRIBUTION IN $K_L \to \mu\mu$

- LD dominated process

$$\mathcal{B}(K_L \to \mu^+\mu^-)^{\rm SM} = (7.64 \pm 0.73) \times 10^{-9}$$

[Isidori, Unterdorfer, hep-ph/0311084]
[Gerard, Smith, Trine, hep-ph/0508189]

$$\mathcal{B}(K_L \to \mu^+\mu^-) = \frac{1}{\Gamma_{K_L}} \frac{G_F^2 \alpha_{em}^2}{8\pi^3} f_K^2 m_K m_\ell^2 \sqrt{1 - 4m_\ell^2/m_K^2} |C_{10}^{\rm down}|^2$$

$$C_{10}^{\rm down} = -\left(2\pi \Re(\lambda_t y'_{7A}) + 2\pi \Re(\lambda_c y_c) - \frac{\pi v^2}{\alpha_{em}\Lambda^2} c_R^{(+)} \sin\theta_d^{(+)} \right) \pm \frac{A^\ell_{L\gamma\gamma}}{\sin^2\theta_w} \, .$$

- Large theoretical uncertainty on the $\gamma\gamma$ contribution

$$A^\ell_{L\gamma\gamma} = 1.98 \times 10^{-4} \big(0.71 \pm 0.15 \pm 1.0 - i5.21\big)$$

Experimental input and SM predictions

- $K^+ \to \pi^+ \nu\bar{\nu}$ gives stronger constraint on $c_I^{(-)}$ than $K_L \to \pi^0 \nu\bar{\nu}$
- $D^0 \to \mu^+\mu^-$ gives stronger constraints as $D^+ \to \pi^+\mu^+\mu^-$

Process	$\mathcal{B}$	SM Prediction
$K_L \to \mu^+\mu^-$	$= (6.84 \pm 0.11) \times 10^{-9}$	$(7.64 \pm 0.73) \times 10^{-9}$ [24, 42]
$K_S \to \mu^+\mu^-$	$< 2.1 \times 10^{-10}$	4×10^{-12} [24, 42]
$K_L \to \pi^0\nu\bar{\nu}$	$< 3.0 \times 10^{-9}$	$(3.4 \pm 0.6) \times 10^{-11}$ [41]
$K^+ \to \pi^+\nu\bar{\nu}$	$= 1.14^{+0.40}_{-0.33} \times 10^{-10}$	$(8.4 \pm 1.0) \times 10^{-11}$ [41]
$K_L \to \pi^0 e^+e^-$	$< 2.8 \times 10^{-10}$	$3.54^{+0.98}_{-0.85}\,(1.56^{+0.62}_{-0.49}) \times 10^{-11}$ [50, 24]
$K_L \to \pi^0\mu^+\mu^-$	$< 3.8 \times 10^{-10}$	$1.41^{+0.28}_{-0.26}\,(0.95^{+0.22}_{-0.21}) \times 10^{-11}$ [50, 24]
$K^+ \to \pi^+ e^+e^-$	$= (3.00 \pm 0.09) \times 10^{-7}$	$(2.75 \pm 0.23 \pm 0.13) \times 10^{-7}$ [51]
$K^+ \to \pi^+\mu^+\mu^-$	$= (9.4 \pm 0.6) \times 10^{-8}$	$(9.5 \pm 0.7) \times 10^{-8}$ [42]