Higher-Order Electroweak Contributions to Indirect CP Violation

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Based on 2108.00017 with J. Brod and S. Kvedaraitė
and 2207.07669 with J. Brod, S. Kvedaraitė, and A. Youssef

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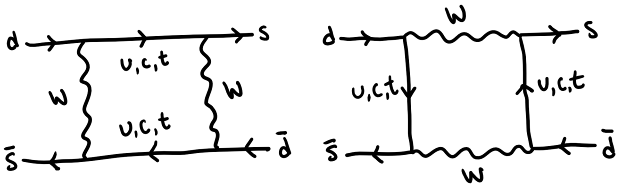
CP Violation in Neutral Kaons

- CP violation first discovered in decays of kaons (1964)
- $K^0 - \bar{K}^0$ mixing can lead to (indirect) CP-violation $\rightarrow$ parameterized by ϵ_K
- Sensitive probe of new physics, input for global CKM fit



Diagonalizing the Hamiltonian

- Time evolution of $K^0 - \bar{K}^0$ system described by

$$i\frac{d}{dt}\begin{pmatrix} |K^0\rangle \\ |\bar{K}^0\rangle \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} |K^0\rangle \\ |\bar{K}^0\rangle \end{pmatrix}$$

- Diagonalized by linear combinations

$$|K_L\rangle = p\,|K^0\rangle - q\,|\bar{K}^0\rangle\,, \qquad |K_S\rangle = p\,|K^0\rangle + q\,|\bar{K}^0\rangle$$

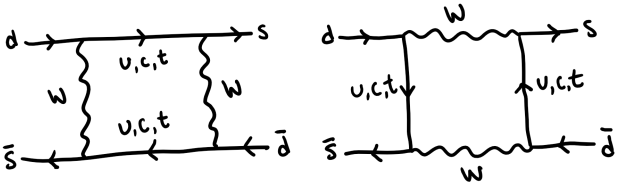
- If $|p/q| = 1$, K_L and K_S CP eigenstates $\Rightarrow$ K_L (CP odd) $\rightarrow \pi\pi$ (CP even) forbidden

Definition of ϵ_K

- Indirect *CP* violation suppressed by GIM $\rightarrow$ sensitive probe of high energies

$$\epsilon_K \equiv \frac{\langle (\pi\pi)_{I=0} | K_L \rangle}{\langle (\pi\pi)_{I=0} | K_S \rangle}$$

- Experimentally[1]: $|\epsilon_K|_{\text{ex}} = 2.228 \pm 0.011 \times 10^{-3}$



[1]**PDG 2022**.

Why Electroweak?

- Re-parameterize Hamiltonian using CKM unitarity

$$\mathcal{H}^{|\Delta S|=2}_{n_f=3} = \frac{G_F^2 M_W^2}{4\pi^2}\left[\lambda_c^2 C''^{cc}_{S2}(\mu) + \lambda_t^2 C''^{tt}_{S2}(\mu) + \lambda_c\lambda_t C''^{ct}_{S2}(\mu)\right] Q''_{S2} + h.c. + \dots$$

$$\mathcal{H}^{|\Delta S|=2}_{n_f=3} = \frac{G_F^2 M_W^2}{4\pi^2}\left[\lambda_u^2 C''^{uu}_{S2}(\mu) + \lambda_t^2 C''^{tt}_{S2}(\mu) + \lambda_u\lambda_t C''^{ut}_{S2}(\mu)\right] Q''_{S2} + h.c. + \dots$$

- Drastic reduction of perturbative theory errors[2][3]

$$|\epsilon_K|_{\text{th}} = 1.81(16)_{\text{pert}}(5)_{\text{non-pert}}(23)_{\text{param}} \times 10^{-3} \quad \rightarrow \quad |\epsilon_K|_{\text{th}} = 2.16(6)_{\text{pert}}(7)_{\text{non-pert}}(15)_{\text{param}} \times 10^{-3}$$

- Perturbative errors $\lesssim$ expected e/w effects $\rightarrow$ relevant!

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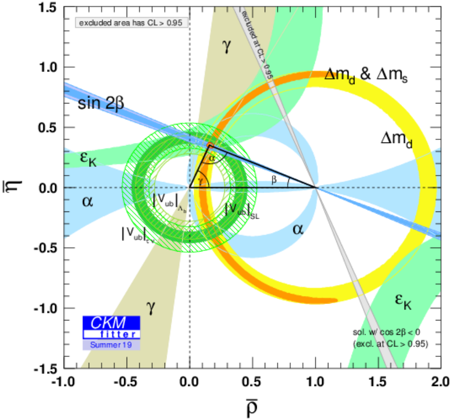
[2] **Brod, Gorbahn, Stamou, Phys.Rev.Lett. 125 (2020) 17, 171803, 1911.06822 [hep-ph].**

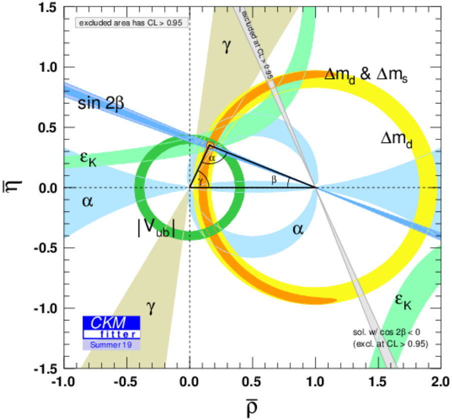
[3] **Brod, Gorbahn, Phys.Rev.Lett. 108 (2012) 121801, 1108.2036 [hep-th].**

Reduction of Perturbative Error

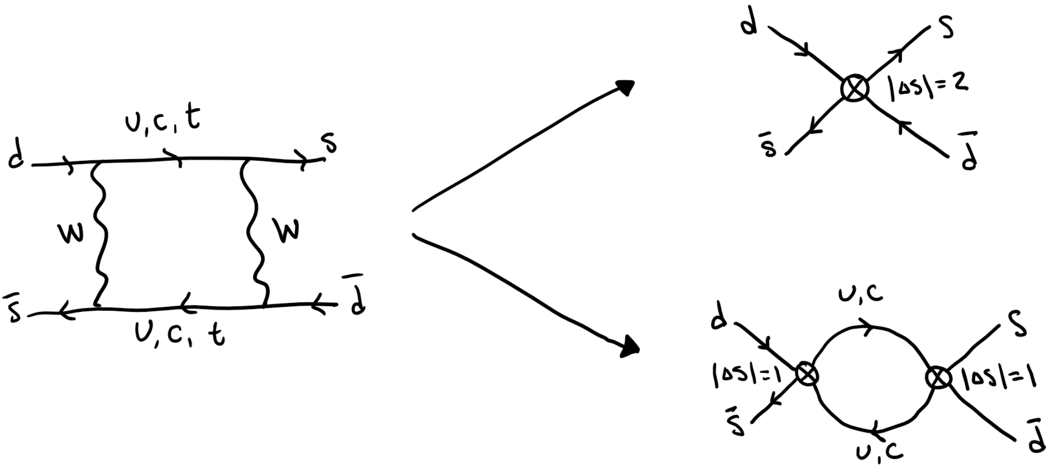
Before



After

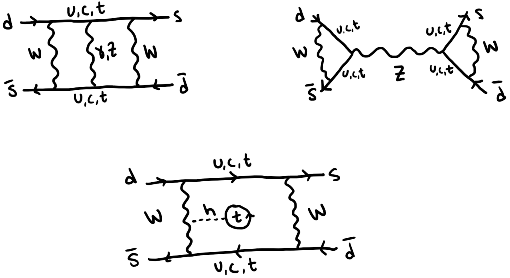


Different Contributions in EFT



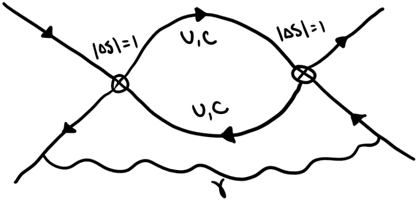
Top Quark Contribution: E/W Matching

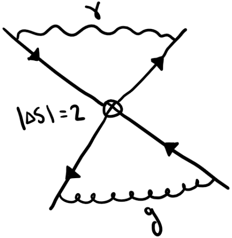
- Calculate all $O(30,000)$ two-loop Feynman diagrams ($p_{\text{ext}} = 0$)
- Diagrams generated by `qgraf` and calculated using self-written `FORM` routines
- Separately calculated and verified agreement



Charm-Top Contribution: Exercise in EFTs

- Generated via mixing of $2 \times |\Delta S| = 1 \to |\Delta S| = 2$ below E/W scale
- Threshold corrections when decoupling at quark mass scales, μ_b and μ_c





E/W Contribution to ϵ_K

- Previous value with QCD-only[4]

$$|\epsilon_K|_{\text{th}} = 2.16(6)_{\text{pert}}(7)_{\text{non-pert}}(15)_{\text{param}} \times 10^{-3}$$

[4] Brod, Gorbahn, Stamou, 1911.06822

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[4] Brod, Gorbahn, Stamou, 1911.06822
[5] Ciuchini et. al, 2111.05153

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- QCD + E/W Top-quark + m_c power corrections + E/W Charm-Top

$$|\epsilon_K|_{\text{th}} = 2.17(6)_{\text{pert}}(7)_{\text{non-pert}}(15)_{\text{param}} \times 10^{-3}$$

[4] Brod, Gorbahn, Stamou, 1911.06822
[5] Ciuchini et. al, 2111.05153

EFT Scheme Dependence

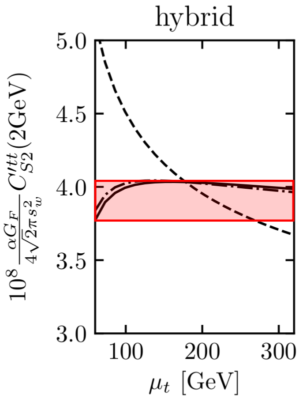
- **Any physical observable must be independent of renormalization scheme!!!**
- Both top and charm contributions are scheme-dependent $\rightarrow$ cancel with $\langle Q_{S2} \rangle$ (lattice)
- Scheme dependence is numerically tiny ($\lesssim$ order magnitude of E/W shifts) and effect neglected to approximate ϵ_K
- Fully consistent determination only possible with lattice QED determination

Conclusions

- Calculated NLO E/W corrections to ϵ_K
- Analogous top calculation: $B^0 - \bar{B}^0$ system[6] (First independent re-calculation, reproduced numerics)
- Seeing many $\mathcal{O}(1\%)$ shifts: important given reduced error
- Future three-loop QCD top contributions and possible updated lattice calculations will reduce theory uncertainty of ϵ_K

[6] Gambino, Kwiatkowski, Pott, 9810400

Perturbative Theory Error



- Higher order effects "leak in" (e.g. solving RGEs)
- Residual scale variation give estimation of size of these effects $\rightarrow$ Perturbative error