Flavor Physics Review

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Outline

- Theory:
  - QCD factorization
  - Flavor symmetry
  - heavy-quark expansion
  - QCD sum rules
  - ChPT
  - lattice results
  - Status of higher-order corrections
- B physics:
  - LFU (R_K, R_{K^*})
  - B "anomalies"
  - V_{ub}, V_{cb} inclusive / exclusive tension
  - R_D, R_{D^*}
  - Determination of ϕ_3/γ
  - $B \to hh$
- D physics:
  - mixing and indirect CPV
  - direct CPV, ΔA_{CP}
  - $D \to hh$
- K physics:
  - rare K decays ($K \to \pi\nu\bar{\nu}$)
  - other rare modes ($K_L \to \mu\mu$, $K_L \to \pi^0\ell\ell$)
  - direct and indirect CPV (ϵ_K, ϵ')
  - First-row unitarity
- Hadrons:
  - sum rules for hadrons
  - direct CPV
  - hadron spectroscopy
  - exotic hadrons

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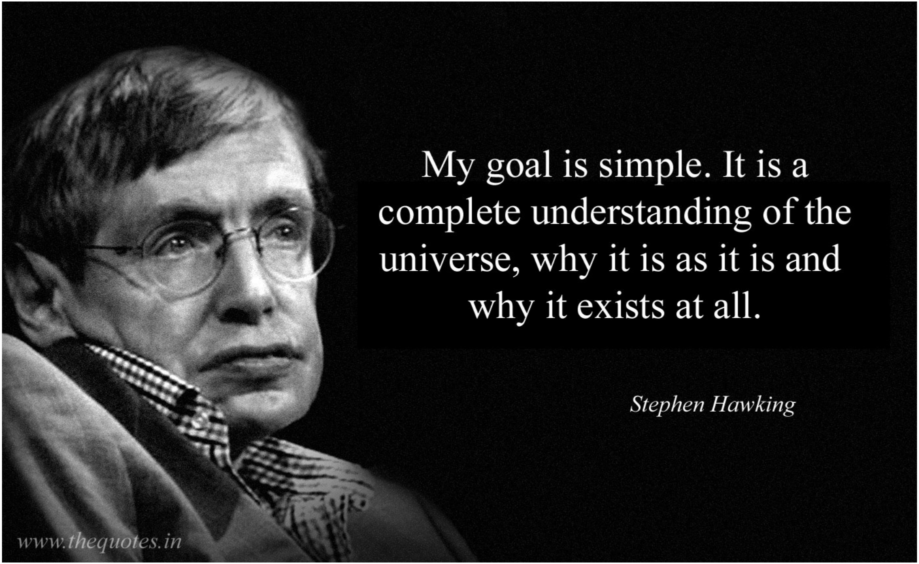
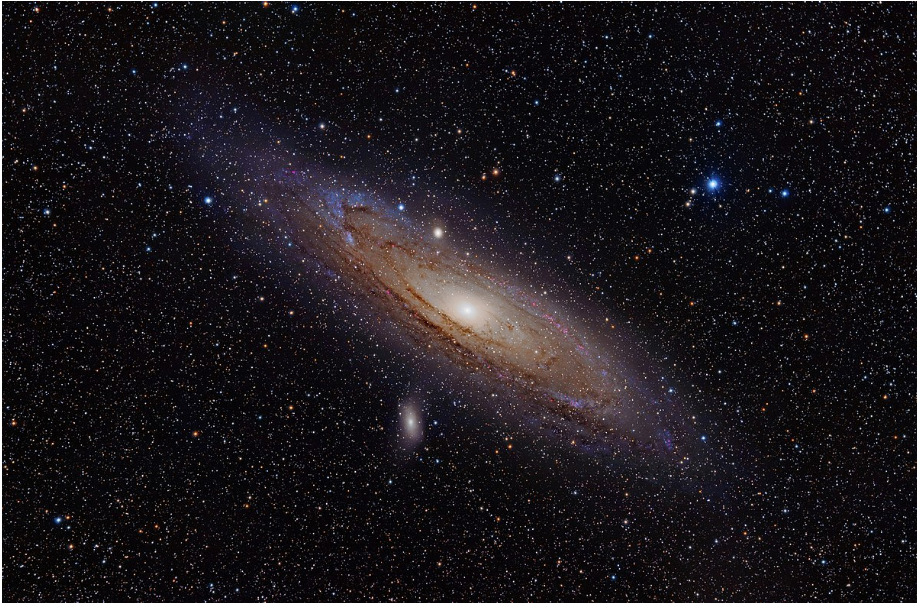
Motivation


My goal is simple. It is a complete understanding of the universe, why it is as it is and why it exists at all.
Stephen Hawking
www.thequotes.in

My Goal is even simpler:



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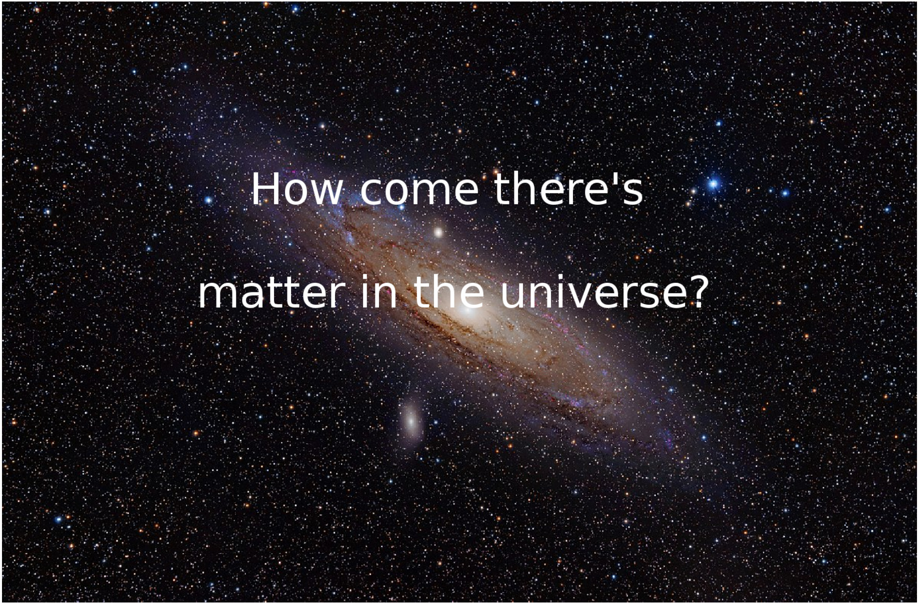


Baryogenesis – where does matter come from?

- $\eta \equiv \frac{\rho_B - \rho_{\bar{B}}}{\rho_\gamma} \sim 10^{-9}$
- Three conditions to generate baryons from a symmetric initial state: [Sakharov 1967]
  - C / CP violation
  - Baryon number violation
  - departure from thermal equilibrium
- The SM fails due to large Higgs mass
- In addition, $d_{CP} \sim J_{CP}/T_c^{12} \sim 10^{-19}$ [Bernreuther 2002]
  - Jarlskog invariant $J_{CP} \sim \prod_{\text{up, down}}(m_{q_i}^2 - m_{q_j}^2) \times \text{Im}(V_{\text{CKM}}^4)$

Wasn't this supposed to be a Flavor Review?

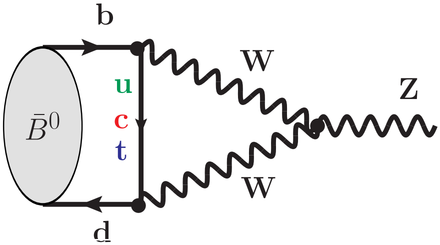
- Frequently, baryogenesis used as motivation for flavor physics
- Only models I'm aware of that use SM CP violation are Mesogenesis + variations
  [Elor et al. 2018, Nelson et al. 2019]
  - Departure from thermal equilibrium: Late decay of scalar field to SM mesons
  - C / CP violation: SM
  - Baryon number violation: SM meson decays to dark sector
- Already strongly constrained by Belle / BaBar data
  [2110.14086, 2302.00208 $\rightarrow$ Talk by S. Robertson]
- So, does flavor tell us anything about baryogenesis?

What is Flavor Physics?

What is flavor physics?

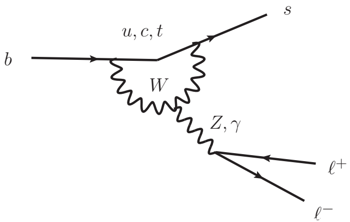
- Nothing distinguishes the three fermion generations but their masses
- Flavor is the physics of the Yukawa couplings
  - Yukawa: general complex 3×3 matrices
- SM:
  - Can simultaneously diagonalize all fermion mass terms and Yukawa interactions
  - *if we introduce flavor violation in the charged current (CKM matrix)*
  - No FCNCs ("Flavor-Changing Neutral Currents") at tree level
- BSM:
  - Can have tree-level FCNCs: "standard" flavor tests of the SM
  - CP violation also in flavor-conserving processes (electric dipole moments!)
  - Effective theory (EFT): all independent
  - Concrete models: correlations (e.g. CPV entails FV...)
- So I think the motivation is still valid

Flavor-Changing Neutral Currents

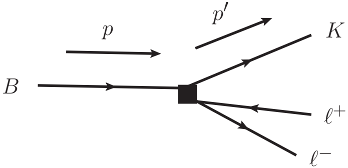


R_K, R_{K^*}

$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$



- In general, $d\Gamma(B \to K\ell\ell) \propto |\langle K\ell\ell|H_{\mathrm{eff}}|B\rangle|^2$ ... complicated function involving nonperturbative QCD
- For small $q^2 = (p - p')^2$, form factors simplify – "color transparency"



SM Expectation

$$R_K^{\text{SM}} \equiv \frac{\Gamma_\mu^{\text{SM}}}{\Gamma_e^{\text{SM}}}$$

- SM prediction is very clean: [Hiller et al. hep-ph/0310219, Bobeth et al. 0709.4174]
- Numerically, including QED effects [Bordone et al. 1605.07633] we have

$$R_K^{\text{SM}} = 1 + ‰ + \text{cut-dep. QED of } \mathcal{O}(\text{few } \%) \, .$$

New LHCb results for R_K, R_{K^*}

- Most systematics cancels in double ratio

$$R_{K,K^*}^{\text{LHCb}} \equiv \frac{\text{BR}(B^{+,0} \to K^{+,*0}\mu\mu)}{\text{BR}(B^{+,0} \to K^{+,*0}ee)} \Bigg/ \frac{\text{BR}(B^{+,0} \to K^{+,*0}J/\psi(\mu\mu))}{\text{BR}(B^{+,0} \to K^{+,*0}J/\psi(ee))}$$

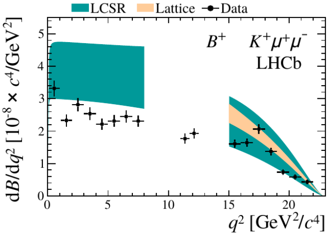
- New LHCb [2212.09152 → Talk by F. Volle]:

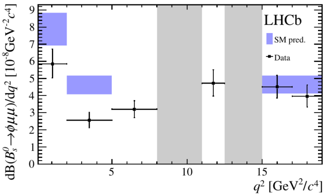
$$R_K^{\text{LHCb 2022}} = 0.949^{+0.042}_{-0.041}\ (\text{stat.})\ ^{+0.022}_{-0.022}\ (\text{syst.})$$

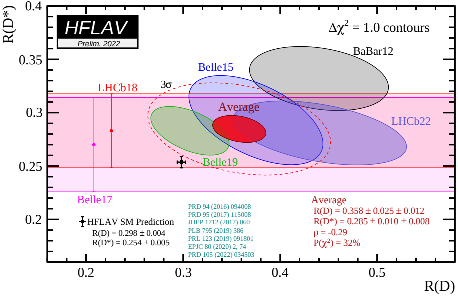
$$R_{K^*}^{\text{LHCb 2022}} = 1.027^{+0.072}_{-0.068}\ (\text{stat.})\ ^{+0.027}_{-0.026}\ (\text{syst.})$$

Other 3σ "anomalies" in $b \to s\mu^+\mu^-$

- $B^+ \to K^+\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ differential branching ratios
  [1403.8044, 1506.08777]
- Angular observables in $B^0 \to K^{0*}\mu^+\mu^-$ [LHCb 2003.04831]
- Theory much more challenging – charm loops

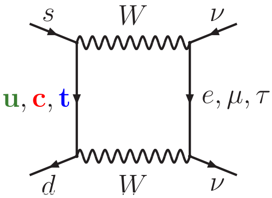




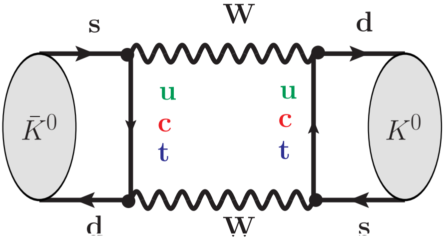


Kaons

$K \to \pi\nu\bar{\nu}$



Reminder: neutral kaons



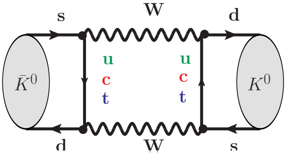
CP Violation in the Neutral Kaon System

- CP transformation $\left(|K^0\rangle \sim |\bar{s}d\rangle, \quad |\overline{K^0}\rangle \sim |\bar{d}s\rangle\right)$
  - $CP|K^0\rangle = -|\overline{K^0}\rangle$
  - $CP|\overline{K^0}\rangle = -|K^0\rangle$
- CP eigenstates
  - $|K_1\rangle \equiv \big(|K^0\rangle - |\overline{K^0}\rangle\big)/\sqrt{2}$ (CP even)
  - $|K_2\rangle \equiv \big(|K^0\rangle + |\overline{K^0}\rangle\big)/\sqrt{2}$ (CP odd)
- $K_2^0 \to \pi\pi$ is forbidden by CP

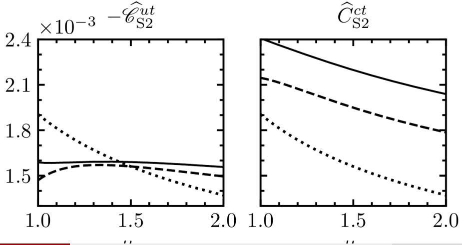
Progress in ϵ_K

Definition of ϵ_K

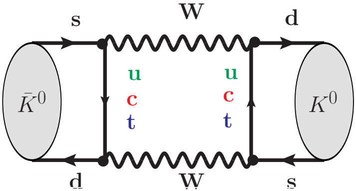
$$\epsilon_K \equiv \frac{\langle(\pi\pi)_{I=0}|K_L\rangle}{\langle(\pi\pi)_{I=0}|K_S\rangle} \stackrel{\text{exp}}{=} 2.228(11) \times 10^{-3}$$



- Calculation split into two parts:
  - "Short-distance" (perturbative)
  - "Long-distance" (lattice, ChPT)
- "Simple" rearrangement of effective Hamiltonian has reduced perturbative uncertainty from order 30% to order 1% [Brod et al. 1911.06822]



c-t vs. u-t Unitarity



$$\lambda_u = V_{us} V_{ud}^* \,, \quad \lambda_c = V_{cs} V_{cd}^* \,, \quad \lambda_t = V_{ts} V_{td}^* \,, \quad \lambda_u + \lambda_c + \lambda_t = 0$$

c-t unitarity

	Im	Re
λ_t^2	$\sim \lambda^{10}$	$\sim \lambda^{10}$
$\lambda_c \lambda_t$	$\sim \lambda^6$	$\sim \lambda^6$
λ_c^2	$\sim \lambda^6$	$\sim \lambda^2$

u-t unitarity

	Im	Re
λ_t^2	$\sim \lambda^{10}$	$\sim \lambda^{10}$
$\lambda_u \lambda_t$	$\sim \lambda^6$	$\sim \lambda^6$
λ_u^2	0	$\sim \lambda^2$

$$\mathrm{Im}(M_{12}) \to \epsilon_K \qquad \mathrm{Re}(M_{12}) \to \Delta M_K$$

$K \to \mu^+\mu^-$

A new golden mode?

- Assume that K_L and K_S are CP eigenstates:

	$(\mu^+\mu^-)_{\ell=0}$	$(\mu^+\mu^-)_{\ell=1}$
K_L	CP conserving	(CP violating)
K_S	CP violating	CP conserving

- However, experiment cannot distinguish $\ell = 0$ and $\ell = 1$
- Notation: write
  - ${A_\ell}^L = A[K_L \to (\mu^+\mu^-)_\ell]$
  - ${A_\ell}^S = A[K_S \to (\mu^+\mu^-)_\ell]$

Time-dependent decay rate of neutral kaons

$$\frac{d\Gamma(K(t) \to \mu^+\mu^-)}{dt} \propto C_L e^{-\Gamma_L t} + C_S e^{-\Gamma_S t} + 2\big[C_{\sin}\sin(\Delta M t) + C_{\cos}\cos(\Delta M t)\big] e^{-\Gamma t}$$

- C_i given in terms of amplitudes, e.g.
  - $C_L = |A^L_{\ell=0}|^2 + |A^L_{\ell=1}|^2$
  - $C_S = |A^S_{\ell=0}|^2 + |A^S_{\ell=1}|^2$
- Interference terms $C_{\text{int}}^2 = C_{\cos}^2 + C_{\sin}^2$ sensitive to short-distance component!
  [D'Ambrosio, Kitahara 1707.06999]

A useful relation

- *Single assumption*: $A^L_{\ell=1} = 0$
- It follows immediately ("in two lines!")

$$\mathrm{Br}(K_S \to \mu^+\mu^-)_{\ell=0} = \mathrm{Br}(K_L \to \mu^+\mu^-) \times \frac{\tau_S}{\tau_L} \times \left(\frac{C_{\mathrm{int}}}{C_L}\right)^2$$

[A. Dery et al. 2104.06427]

You don't believe it?

$$\frac{\mathrm{Br}(K_S \to (\mu\mu)_{\ell=0})}{\mathrm{Br}(K_L \to \mu\mu)}$$

You don't believe it?

$$\frac{\mathrm{Br}(K_S \to (\mu\mu)_{\ell=0})}{\mathrm{Br}(K_L \to \mu\mu)} = \frac{|A_0^S|^2}{|A_0^L|^2} \times \frac{\tau_L}{\tau_S}$$

You don't believe it?

$$\frac{\mathrm{Br}(K_S \to (\mu\mu)_{\ell=0})}{\mathrm{Br}(K_L \to \mu\mu)} = \frac{|A_0^S|^2}{|A_0^L|^2} \times \frac{\tau_L}{\tau_S} = \frac{|A_0^S|^2 |A_0^L|^2}{|A_0^L|^4} \times \frac{\tau_L}{\tau_S}$$

You don't believe it?

$$\frac{\mathrm{Br}(K_S \to (\mu\mu)_{\ell=0})}{\mathrm{Br}(K_L \to \mu\mu)} = \frac{|A_0^S|^2}{|A_0^L|^2} \times \frac{\tau_L}{\tau_S} = \frac{|A_0^S|^2 |A_0^L|^2}{|A_0^L|^4} \times \frac{\tau_L}{\tau_S}$$

$$C_{\mathrm{int}}^2 = \left| \left(A_0^S\right)^* A_0^L \right|^2 = |A_0^S|^2 |A_0^L|^2 \,,$$

You don't believe it?

$$\frac{\mathrm{Br}(K_S \to (\mu\mu)_{\ell=0})}{\mathrm{Br}(K_L \to \mu\mu)} = \frac{|A_0^S|^2}{|A_0^L|^2} \times \frac{\tau_L}{\tau_S} = \frac{|A_0^S|^2 |A_0^L|^2}{|A_0^L|^4} \times \frac{\tau_L}{\tau_S}$$

$$C_{\mathrm{int}}^2 = \left| \left(A_0^S\right)^* A_0^L \right|^2 = |A_0^S|^2 |A_0^L|^2 \,, \qquad C_L^2 = |A_0^L|^4$$

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$$C_{\mathrm{int}}^2 = \left|\left(A_0^S\right)^* A_0^L\right|^2 = |A_0^S|^2 |A_0^L|^2 \,, \qquad C_L^2 = |A_0^L|^4$$

$$\Rightarrow \mathrm{Br}(K_S \to \mu^+\mu^-)_{\ell=0} = \mathrm{Br}(K_L \to \mu^+\mu^-) \times \frac{\tau_S}{\tau_L} \times \left(\frac{C_{\mathrm{int}}}{C_L}\right)^2$$

A useful relation

- *Single assumption*: $A^L_{\ell=1} = 0$
- It follows immediately ("in two lines!")

$$\text{Br}(K_S \to \mu^+\mu^-)_{\ell=0} = \text{Br}(K_L \to \mu^+\mu^-) \times \frac{\tau_S}{\tau_L} \times \left(\frac{C_{\text{int}}}{C_L}\right)^2$$

[A. Dery et al. 2104.06427]

- Recall $K_S \to (\mu^+\mu^-)_{\ell=0}$ is CPV $\Rightarrow$ sensitive to UV physics!
- Corrections to $A^L_{\ell=1} = 0$ expected to be order $\epsilon_K \sim 10^{-3}$

Compare to SM

- Experiment will provide:

$$\text{Br}^{\text{exp}}(K_S \to \mu^+\mu^-)_{\ell=0} = \text{Br}(K_L \to \mu^+\mu^-) \times \frac{\tau_S}{\tau_L} \times \left(\frac{C_{\text{int}}}{C_L}\right)^2$$

- We want to compare to the SM prediction!
- Three parts:
  - Hadronic matrix element is just f_K – kaon decay constant
  - SD contribution – can calculate
  - Effect of indirect CP violation – estimate from data!

SM short-distance contribution

- CPV – imaginary part of weak Hamiltonian
  - $\Rightarrow$ Only top-quark contribution relevant
- Including three-loop QCD and two-loop electroweak: [Bobeth et al., 1311.0903]

$$\mathrm{Br}(K_S \to \mu^+\mu^-)^{\text{pert.}}_{\ell=0} = 1.70\,(02)_{\text{QCD/EW}}(01)_{f_K}(19)_{\text{param.}} \times 10^{-13}$$

Impact of indirect CP violation

- $K_S = K_1 + \epsilon_K K_2$ (mainly CP even)
- $K_L = K_2 + \epsilon_K K_1$ (mainly CP odd)

- Can then show: $A_0^S = A_0^S|_{\epsilon_K=0} + \epsilon_K A_0^L$
- Squaring to get decay rate [Brod, Stamou 2209.07445]

$$\begin{aligned}\mathrm{Br}(K_S \to \mu^+\mu^-)_{\ell=0} = &\,\mathrm{Br}(K_S \to \mu^+\mu^-)_{\ell=0}^{\text{pert.}} \\ &\times \left(1 + \sqrt{2}|\epsilon_K| \frac{|A_0^L|}{|A_0^S|}(\cos\phi_0 - \sin\phi_0)\right),\end{aligned}$$

- From branching ratios, we know $|A_0^L| \gg |A_0^S|$
- Obtain ϕ_0 from $K_L \to \mu^+\mu^-$ and $K_L \to \gamma\gamma$, up to four-(two-)fold ambiguity [A. Dery et al., 2211.03804]

- Additional $\pm 2\%$ or $\pm 3\%$ correction to $\mathrm{Br}(K_S \to \mu^+\mu^-)_{\ell=0}$

Flavor Symmetry

Example: Neutral D-meson decays

$$D^0(\bar{D}^0) \to K^+K^- , \quad \pi^+K^- , \quad K^+\pi^- , \quad \pi^+\pi^-$$

Example: Neutral D-meson decays

$$D^0(\bar{D}^0) \to K^+K^-\,, \quad \pi^+K^-\,, \quad K^+\pi^-\,, \quad \pi^+\pi^-$$

U-spin symmetry: $s \leftrightarrow d$

$$\pi \leftrightarrow K$$

Expected corrections $f_K/f_\pi - 1 \sim 20\,\%$

A few branching ratios

$$\mathrm{BR}(D^0 \to \pi^+ K^-) = 3.89(4) \times 10^{-2}$$

$$\mathrm{BR}(D^0 \to K^+ K^-) = 3.97(7) \times 10^{-3}$$

$$\mathrm{BR}(D^0 \to \pi^+ \pi^-) = 1.407(25) \times 10^{-3}$$

$$\mathrm{BR}(D^0 \to K^+ \pi^-) = 1.48(7) \times 10^{-4}$$

Normalized amplitudes

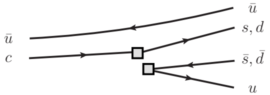
$$|A(D^0 \to \pi^+ K^-)| = 2.09\text{GeV}$$

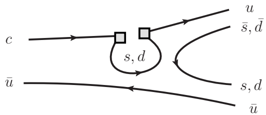
$$|A(D^0 \to K^+ K^-)| = 3.22\text{GeV}$$

$$|A(D^0 \to \pi^+ \pi^-)| = 1.73\text{GeV}$$

$$|A(D^0 \to K^+ \pi^-)| = 2.56\text{GeV}$$

Most general decomposition of amplitudes





$$A(K^+\pi^-) = A^T_{K^+\pi^-}$$

$$A(\pi^+\pi^-) = A^T_{\pi^+\pi^-}(1 + r_f e^{i(\delta_{\pi^+\pi^-} - \phi_{\pi^+\pi^-})})$$

$$A(K^+K^-) = A^T_{K^+K^-}(1 + r_f e^{i(\delta_{K^+K^-} - \phi_{K^+K^-})})$$

$$A(\pi^+K^-) = A^T_{\pi^+K^-}$$

- Total of 4+2 independent amplitudes

Three amplitude relations

$$\frac{|A(D^0 \to K^+ K^-)|}{|A(D^0 \to \pi^+ \pi^-)|} - 1 = (82 \pm 2)\%$$

$$\frac{|A(D^0 \to K^- \pi^+)|}{|A(D^0 \to K^+ \pi^-)|} - 1 = (15 \pm 3)\%$$

$$\frac{|A(D^0 \to K^+ K^-)| + |A(D^0 \to \pi^+ \pi^-)|}{|A(D^0 \to K^+ \pi^-)| + |A(D^0 \to K^- \pi^+)|} - 1 = (4.0 \pm 1.6)\%$$

U-spin decomposition for D decays

- Initial state: $D^0 \sim [c\bar{u}]$ is U-spin singlet

- Final states: singlet $(\langle K^+K^-| + \langle \pi^+\pi^-|)/\sqrt{2} \sim [\bar{s}u][\bar{u}s] + [\bar{d}u][\bar{u}d]$

$$\text{triplet} \begin{pmatrix} \langle K^+\pi^-| & \sim & [\bar{s}u][\bar{u}d] \\ \frac{1}{\sqrt{2}}(\langle K^+K^-| - \langle \pi^+\pi^-|) & \sim & [\bar{s}u][\bar{u}s] - [\bar{d}u][\bar{u}d] \\ \langle K^-\pi^+| & \sim & [\bar{u}s][\bar{d}u] \end{pmatrix}$$

- Hamiltonian: singlet $(Q_i^{\bar{s}s} + Q_i^{\bar{d}d})/\sqrt{2} \sim (\bar{c}s)(\bar{s}u) + (\bar{c}d)(\bar{d}u)$

$$\text{triplet} \begin{pmatrix} Q_i^{\bar{d}s} & \sim & (\bar{c}s)(\bar{d}u) \\ \frac{1}{\sqrt{2}}(Q_i^{\bar{s}s} - Q_i^{\bar{d}d}) & \sim & (\bar{c}s)(\bar{s}u) - (\bar{c}d)(\bar{d}u) \\ Q_i^{\bar{s}d} & \sim & (\bar{c}d)(\bar{s}u) \end{pmatrix}$$

Flavor symmetry breaking

- Two independent singlet amplitudes:

$$t_0 \propto \langle f_1|H_1|\bar{D}\rangle\,, \qquad p_0 \propto \langle f_0|H_0|\bar{D}\rangle\,.$$

- Flavor symmetry is not exact! $\epsilon \sim f_K/f_\pi - 1 \sim 20\,\%$
- Include U-spin breaking due to QED and quark-mass effects
  - We find three amplitudes linear in ϵ
  - We find three amplitudes quadratic in ϵ
  - Plus more at higher order in U-spin breaking

Fitting the pieces together

- $\epsilon \sim (f_K/f_\pi - 1) \sim 0.2, \qquad \xi_{\rm CKM} = |V_{cb}^* V_{ub}/V_{cs} V_{us}^*| \sim 6 \times 10^{-4}$

$$A(\bar{D}^0 \to K^+\pi^-) = t_0 - \epsilon t_1 + \epsilon^2 t_2' + \ldots$$

$$A(\bar{D}^0 \to \pi^+\pi^-) = t_0 + \epsilon s_1 + \epsilon^2 t_2 - \xi_{\rm CKM}(p_0 - \epsilon p_1 + \epsilon^2 p_2) + \ldots$$

$$A(\bar{D}^0 \to K^+K^-) = t_0 - \epsilon s_1 + \epsilon^2 t_2 - \xi_{\rm CKM}(p_0 + \epsilon p_1 + \epsilon^2 p_2) + \ldots$$

$$A(\bar{D}^0 \to \pi^+K^-) = t_0 + \epsilon t_1 + \epsilon^2 t_2' + \ldots$$

- Only six amplitudes are independent, two can be absorbed by redefinition
- Also all higher terms $\propto \epsilon^3, \epsilon^4, \ldots$ can be reabsorbed

Fitting the pieces together

$$A(\bar{D}^0 \to K^+\pi^-) = t_0 - \epsilon t_1$$

$$A(\bar{D}^0 \to \pi^+\pi^-) = t_0 + \epsilon s_1 + \epsilon^2 t_2 - \xi_{\mathrm{CKM}}(p_0 - \epsilon p_1)$$

$$A(\bar{D}^0 \to K^+K^-) = t_0 - \epsilon s_1 + \epsilon^2 t_2 - \xi_{\mathrm{CKM}}(p_0 + \epsilon p_1)$$

$$A(\bar{D}^0 \to \pi^+K^-) = t_0 + \epsilon t_1$$

U-spin limit

$$A(\bar{D}^0 \to K^+\pi^-) = t_0 - \epsilon t_1$$

$$A(\bar{D}^0 \to \pi^+\pi^-) = t_0 + \epsilon s_1 + \epsilon^2 t_2 - \xi_{\mathrm{CKM}}(p_0 - \epsilon p_1)$$

$$A(\bar{D}^0 \to K^+K^-) = t_0 - \epsilon s_1 + \epsilon^2 t_2 - \xi_{\mathrm{CKM}}(p_0 + \epsilon p_1)$$

$$A(\bar{D}^0 \to \pi^+K^-) = t_0 + \epsilon t_1$$

U-spin limit

$$A(\bar{D}^0 \to K^+\pi^-) = t_0$$

$$A(\bar{D}^0 \to \pi^+\pi^-) = t_0$$

$$A(\bar{D}^0 \to K^+K^-) = t_0$$

$$A(\bar{D}^0 \to \pi^+K^-) = t_0$$

- All amplitudes are equal in the U-spin limit
- Clearly not a good approximation to data

CF vs. DCS

$$A(\bar{D}^0 \to K^+\pi^-) = t_0 - \epsilon t_1$$

$$A(\bar{D}^0 \to \pi^+\pi^-) = t_0 + \epsilon s_1 + \epsilon^2 t_2 - \xi_{\mathrm{CKM}}(p_0 - \epsilon p_1)$$

$$A(\bar{D}^0 \to K^+K^-) = t_0 - \epsilon s_1 + \epsilon^2 t_2 - \xi_{\mathrm{CKM}}(p_0 + \epsilon p_1)$$

$$A(\bar{D}^0 \to \pi^+K^-) = t_0 + \epsilon t_1$$

- Keep terms linear in ϵ

CF vs. DCS

$$A(\bar{D}^0 \to K^+\pi^-) = t_0 - \epsilon t_1$$

$$A(\bar{D}^0 \to \pi^+K^-) = t_0 + \epsilon t_1$$

- Explains rate difference between CF and DCS decay modes with nominal U-spin breaking $\epsilon \sim 20\%$

$$\frac{|A(D^0 \to K^-\pi^+)|}{|A(D^0 \to K^+\pi^-)|} - 1 = (15 \pm 3)\%$$

Large penguins

$$A(\bar{D}^0 \to K^+\pi^-) = t_0 - \epsilon t_1$$

$$A(\bar{D}^0 \to \pi^+\pi^-) = t_0 + \epsilon s_1 + \epsilon^2 t_2 - \xi_{\text{CKM}}(p_0 - \epsilon p_1)$$

$$A(\bar{D}^0 \to K^+K^-) = t_0 - \epsilon s_1 + \epsilon^2 t_2 - \xi_{\text{CKM}}(p_0 + \epsilon p_1)$$

$$A(\bar{D}^0 \to \pi^+K^-) = t_0 + \epsilon t_1$$

- Keep terms linear in ϵ; neglect terms $\propto \xi_{\text{CKM}} \sim 10^{-4}$

Large penguins

$$A(\bar{D}^0 \to K^+\pi^-) = t_0 - \epsilon t_1$$

$$A(\bar{D}^0 \to \pi^+\pi^-) = t_0 + \epsilon s_1 + \epsilon^2 t_2 - \xi_{\mathrm{CKM}}(p_0 - \epsilon p_1)$$

$$A(\bar{D}^0 \to K^+K^-) = t_0 - \epsilon s_1 + \epsilon^2 t_2 - \xi_{\mathrm{CKM}}(p_0 + \epsilon p_1)$$

$$A(\bar{D}^0 \to \pi^+K^-) = t_0 + \epsilon t_1$$

$$\frac{|A(D^0 \to K^+K^-)|}{|A(D^0 \to \pi^+\pi^-)|} - 1 = (82 \pm 2)\%$$

- Data tells us that $s_1\epsilon \gg t_1\epsilon$
  - Unexplained hierarchy in U-spin breaking??
  - Large penguins: $s_1 \gg t_1$!
- Explains rate difference between SCS decay modes with nominal U-spin breaking $\epsilon \sim 20\%$

Quadratic U-spin sum rule

$$A(\bar{D}^0 \to K^+\pi^-) = t_0 - \epsilon t_1$$

$$A(\bar{D}^0 \to \pi^+\pi^-) = t_0 + \epsilon s_1 + \epsilon^2 t_2 - \xi_{\text{CKM}}(p_0 - \epsilon p_1)$$

$$A(\bar{D}^0 \to K^+K^-) = t_0 - \epsilon s_1 + \epsilon^2 t_2 - \xi_{\text{CKM}}(p_0 + \epsilon p_1)$$

$$A(\bar{D}^0 \to \pi^+K^-) = t_0 + \epsilon t_1$$

- Keep terms linear in ϵ; neglect terms $\propto \xi_{\text{CKM}} \sim 10^{-4}$

Quadratic U-spin sum rule

$$A(\bar{D}^0 \to K^+\pi^-) = t_0 - \epsilon t_1$$

$$A(\bar{D}^0 \to \pi^+\pi^-) = t_0 + \epsilon s_1$$

$$A(\bar{D}^0 \to K^+K^-) = t_0 - \epsilon s_1$$

$$A(\bar{D}^0 \to \pi^+K^-) = t_0 + \epsilon t_1$$

- The following relation ("sum rule") is valid to quadratic order in U-spin breaking:
- $A(\bar{D}^0 \to K^+\pi^-) + A(\bar{D}^0 \to \pi^+K^-) = A(\bar{D}^0 \to \pi^+\pi^-) + A(\bar{D}^0 \to K^+K^-)$
- This is borne out by the experimental relation

$$\frac{|A(D^0 \to K^+K^-)| + |A(D^0 \to \pi^+\pi^-)|}{|A(D^0 \to K^+\pi^-)| + |A(D^0 \to K^-\pi^+)|} - 1 = (4.0 \pm 1.6)\%$$

Three types of CP violation

I $|\bar{A}_{\bar{f}}/A_f| \neq 1$ (CP violation in decay)

$$a_f^d := \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

II $|q/p| \neq 1$ (CP violation in mixing)

$$a_{sl} := \frac{\Gamma(\bar{D}^0(t) \to \ell^+ X) - \Gamma(D^0(t) \to \ell^- X)}{\Gamma(\bar{D}^0(t) \to \ell^+ X) + \Gamma(D^0(t) \to \ell^- X)}$$

III $\mathrm{Im}(\lambda_f) \equiv \mathrm{Im}(\frac{q}{p}\frac{\bar{A}_f}{A_f}) \neq 0$ (interference-type CP violation)

$$a_{f_{CP}} := \frac{\Gamma(\bar{D}^0(t) \to f_{CP}) - \Gamma(D^0(t) \to f_{CP})}{\Gamma(\bar{D}^0(t) \to f_{CP}) + \Gamma(D^0(t) \to f_{CP})}$$

Example: ΔA_{CP}

- Experiments measure

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

- Theory "predicts"

$$\Delta A_{CP} = 2\mathrm{Im}\big(\xi_{\mathrm{CKM}}\big)\left|\frac{p_0}{t_0}\right| \sin\delta_{\mathrm{strong}}$$

- $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$ [LHCb combi 1903.08726]
  gives $|p_0/t_0| = -0.65$ [Grossman, Schacht 1903.10952]

- Consistent picture assuming nominal U-spin breaking $\epsilon_U \approx 20\%$
  [Brod et al. 1203.6659]

A consistent picture emerges. . .

$$\Delta A_{CP} \approx -0.15\%$$

$$\frac{|A(D^0 \to K^+K^-)|}{|A(D^0 \to \pi^+\pi^-)|} - 1 = (82 \pm 2)\%$$

$$\frac{|A(D^0 \to K^-\pi^+)|}{|A(D^0 \to K^+\pi^-)|} - 1 = (15 \pm 3)\%$$

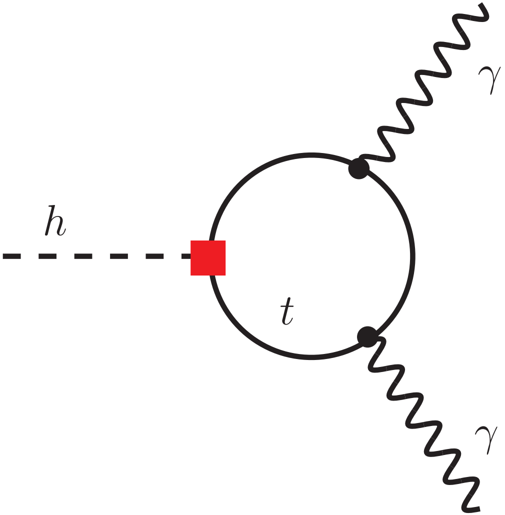
$$\frac{|A(D^0 \to K^+K^-)| + |A(D^0 \to \pi^+\pi^-)|}{|A(D^0 \to K^+\pi^-)| + |A(D^0 \to K^-\pi^+)|} - 1 = (4.0 \pm 1.6)\%$$

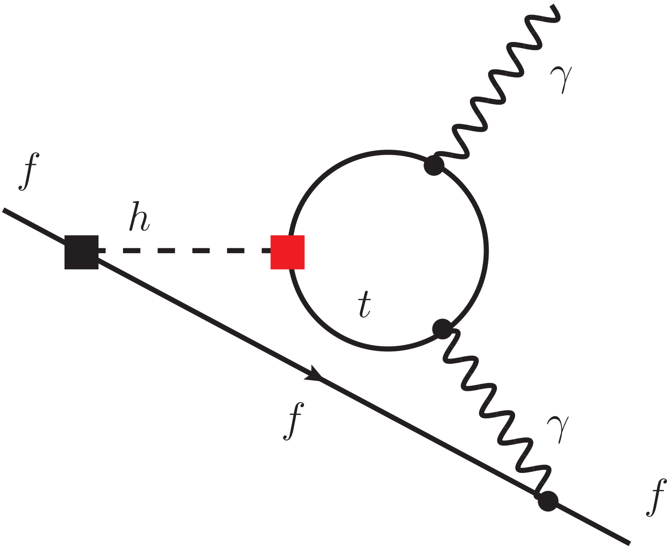
...but is it the SM?

An application in B decays

- $B_s \to K^0 \bar{K}^0$ is FCNC decay
- $\mathrm{Br}(B_s^0 \to K^0 \bar{K}^0) = (1.76 \pm 0.31) \times 10^{-5}$
  [LHCb 2002.08229, Belle 1512.02145]
- Related to $B_s \to K^+ \bar{K}^-$, $B^0 \to K^0 \bar{K}^0$, $B^0 \to K^+ \pi^-$ by flavor symmetry
- Three puzzles: [Amhis et al. 2212.03874]
  - $\frac{|V_{td}^2|}{|V_{ts}^2|} \frac{\Gamma(B_s \to K^0 \bar{K}^0)}{\Gamma(B^0 \to K^0 \bar{K}^0)} = 0.61(13) \ll 1$ (Rescattering?)
  - $\frac{\Gamma(B_s \to K^0 \bar{K}^0)}{\Gamma(B_s \to K^+ \bar{K}^-)} = 0.66(13) \ll 1.06(2)$ (Large e/w penguins?)
  - $\frac{\Gamma(B_s \to K^0 \bar{K}^0)}{\Gamma(B_s \to K^+ \bar{K}^-)} \frac{\Gamma(B^0 \to \pi^- \bar{K}^+)}{\Gamma(B^+ \to \pi^+ K^0)} = 0.59(12) \ll 1$ (Large U-spin breaking?)

Flavor Conserved – EDMs


h
t
γ
γ



f
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γ
t
f
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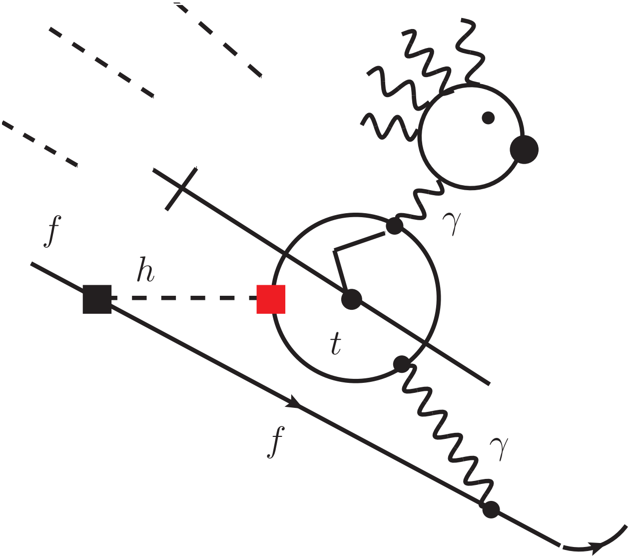
f


f
h
t
γ
f
γ

Modified Higgs Yukawas

- In SM, can always rotate fields such that $m_f = y_f v/\sqrt{2}$
- Flavor and CP violation only in charged currents (CKM matrix)
- BSM: no longer true (e.g. vector-like top quark, 2HDM, ...)
- Frequently parameterize as ("κ framework")

$$\mathcal{L} \supset -\frac{y_f^{\text{SM}}}{\sqrt{2}} \kappa_f \bar{f} \left(\cos\phi_f + i\gamma_5 \sin\phi_f\right) f\, h$$

- SM: $\kappa_f = 1$ and $\phi_f = 0$
- THIS IS NOT A CONSISTENT QUANTUM FIELD THEORY
- Calculations / results may be wrong (e.g. gauge dependent)
  [Brod et al. 1811.05480, Altmannshofer et al. 2009.01258]

Effective theory framework

- Better to use EFT
  - (Best, in my opinion, to commit to a model...)
- Closest to κ framework: HEFT (dim.4 in unitarity gauge)
- More popular: SMEFT

$$\begin{aligned}\mathcal{L}_{\text{Yukawa+SMEFT}} = & - \bar{Q}_L \tilde{H} Y_u u_R + \frac{1}{\Lambda^2}(H^\dagger H)\bar{Q}_L \tilde{H} C'_{uH} u_R \\ & - \bar{Q}_L H Y_d d_R + \frac{1}{\Lambda^2}(H^\dagger H)\bar{Q}_L H C'_{dH} d_R \\ & - \bar{L}_L H Y_\ell \ell_R + \frac{1}{\Lambda^2}(H^\dagger H)\bar{L}_L H C'_{\ell H} \ell_R + \text{h.c.}\,.\end{aligned}$$

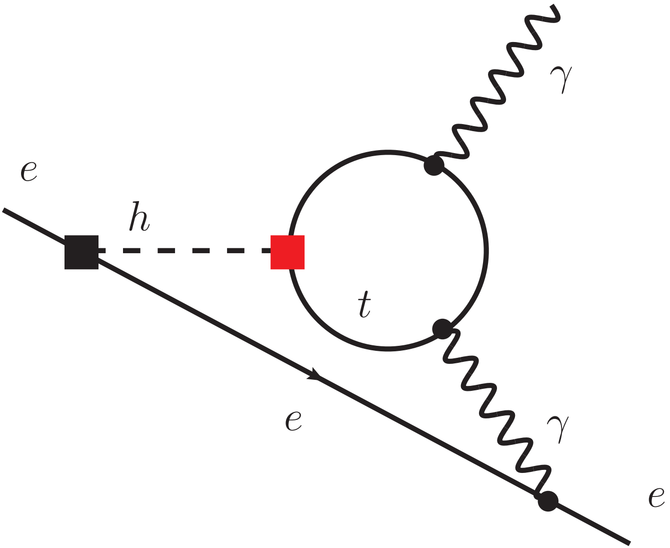
- Primes indicate that not all entries are physical

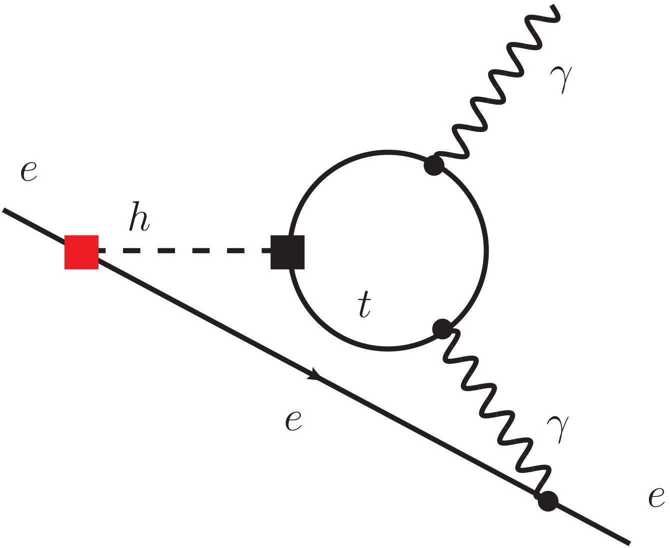
Effective theory framework

- Express as many parameters as possible in terms of observables:
  - fermion masses
  - CKM matrix elements
- Split rotated WC into real and imaginary, $C_{fH} \equiv C_{fH+} + iC_{fH-}$
- Connection to κ framework:

$$\kappa_f \cos\phi_f \mathrel{\hat{=}} 1 - \frac{v}{\sqrt{2}m_f}\frac{v^2}{\Lambda^2}C_{fH+}\,, \qquad \kappa_f \sin\phi_f \mathrel{\hat{=}} -\frac{v}{\sqrt{2}m_f}\frac{v^2}{\Lambda^2}C_{fH-}\,.$$

- Correlation CPV and FV [Alonso-Gonzáles et al. 2103.16569 , 2109.07490]


e
h
γ
t
e
γ
e


e
h
t
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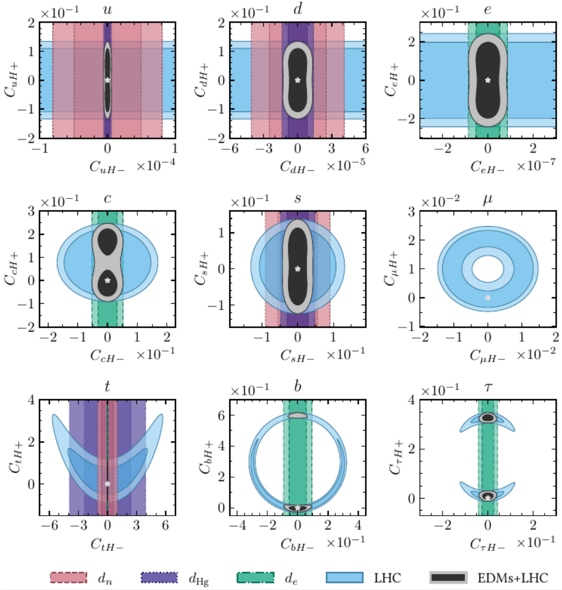
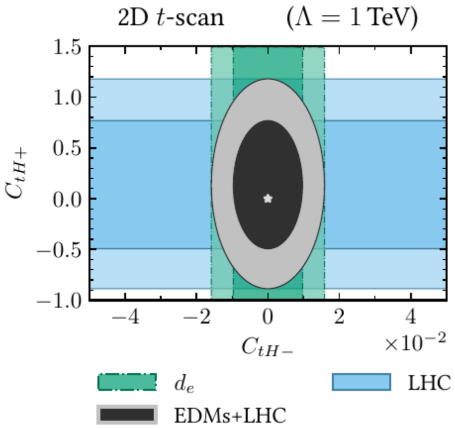
γ
e
e

A first global analysis

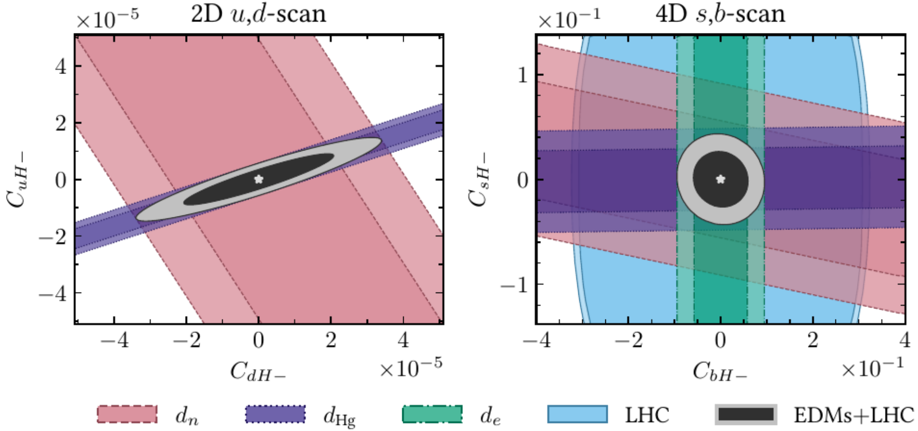
- Scanning up to six parameters (Wilson coefficients) [Brod et al. JHEP 08 (2022) 294]
  - Electron, neutron, mercury EDM (one- and two-loop; one-loop RG)
  - $gg \to h$, $h \to \gamma\gamma$ (one-loop); $h \to b\bar{b}, c\bar{c}, \tau^+\tau^-, \mu^+\mu^-$ decay rates
  - total Higgs decay width
  - $h \to \tau^+\tau^-$ angular analysis [CMS 2110.04836 → Talk by M. Sessini]
  - `HiggsSignals_2.5.0` [Bechtle et al. 2012.09197]
  - `HiggsBounds_5.8.0` [Bechtle et al. 2006.06007]
  - `GAMBIT` [1705.07908, 1705.07919]

2D single-flavour scans $(\Lambda = 1\,\text{TeV})$

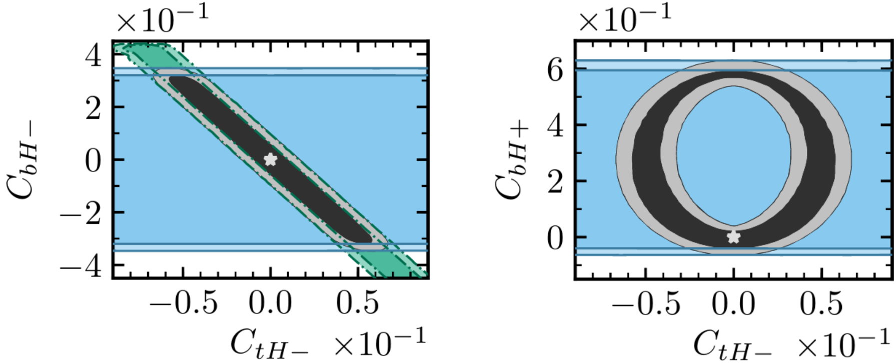



2D t-scan ($\Lambda = 1$ TeV)
C_{tH+}
1.5
1.0
0.5
0.0
−0.5
−1.0
−4
−2
0
2
4
C_{tH-}
$\times 10^{-2}$
d_e
LHC
EDMs+LHC

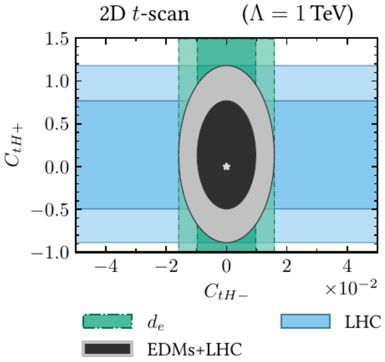
$\Lambda = 1\,\mathrm{TeV}$

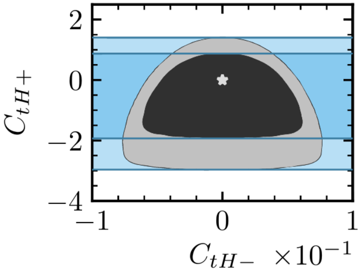


4D scans – C_{tH+}, C_{tH-}, C_{bH+}, C_{bH-}

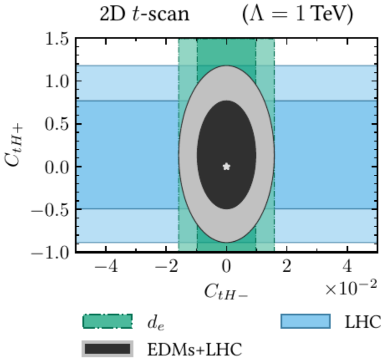


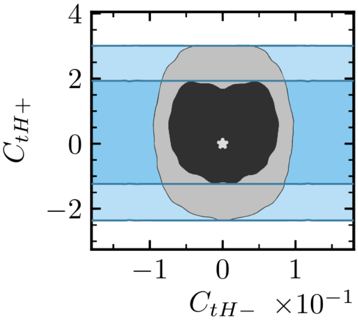
2D vs. 4D scans – top quark



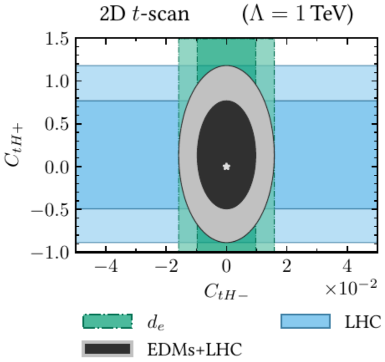


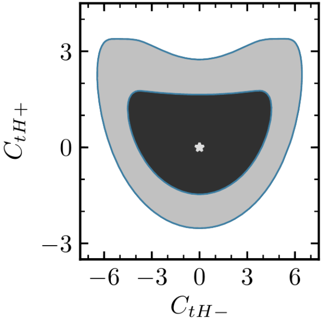
2D vs. 6D scans – top quark





Beyond 6 parameters – 2D vs. 4D top quark





Summary

- Status of B anomalies
- Two "new" precision observables in kaon physics:
  - Indirect CPV (ϵ_K)
  - $\text{Br}(K_S \to \mu^+\mu^-)_{\ell=0}$
- Flavor symmetries help understand flavor data
- EDMs constrain flavor-diagonal CPV

Appendix

In terms of explicit matrix elements

$$P \equiv \langle K^+K^-|C_i Q_i^{\bar{d}d}|\bar{D}^0\rangle = \langle \pi^+\pi^-|C_i Q_i^{\bar{s}s}|\bar{D}^0\rangle$$

$$T \equiv -\frac{1}{2}\Big(\langle K^+K^-|C_i\big(Q_i^{\bar{d}d} - Q_i^{\bar{s}s}\big)|\bar{D}^0\rangle - \langle \pi^+\pi^-|C_i\big(Q_i^{\bar{d}d} - Q_i^{\bar{s}s}\big)|\bar{D}^0\rangle\Big)$$

$$= \langle K^+\pi^-|C_i Q_i^{\bar{d}s}|\bar{D}^0\rangle = \langle \pi^+K^-|C_i Q_i^{\bar{s}d}|\bar{D}^0\rangle$$

$$P_{\text{break}} \equiv \frac{1}{2}\Big(\langle K^+K^-|C_i\big(Q_i^{\bar{d}d} - Q_i^{\bar{s}s}\big)|\bar{D}^0\rangle + \langle \pi^+\pi^-|C_i\big(Q_i^{\bar{d}d} - Q_i^{\bar{s}s}\big)|\bar{D}^0\rangle\Big)$$

- $p_0 = P + \frac{1}{2}T$
- $p_1 = P,\ t_0 = T,\ s_1 = P_{\text{break}} + \frac{1}{2}T$
- $t_1 = T,\ t_2 = -P_{\text{break}}$