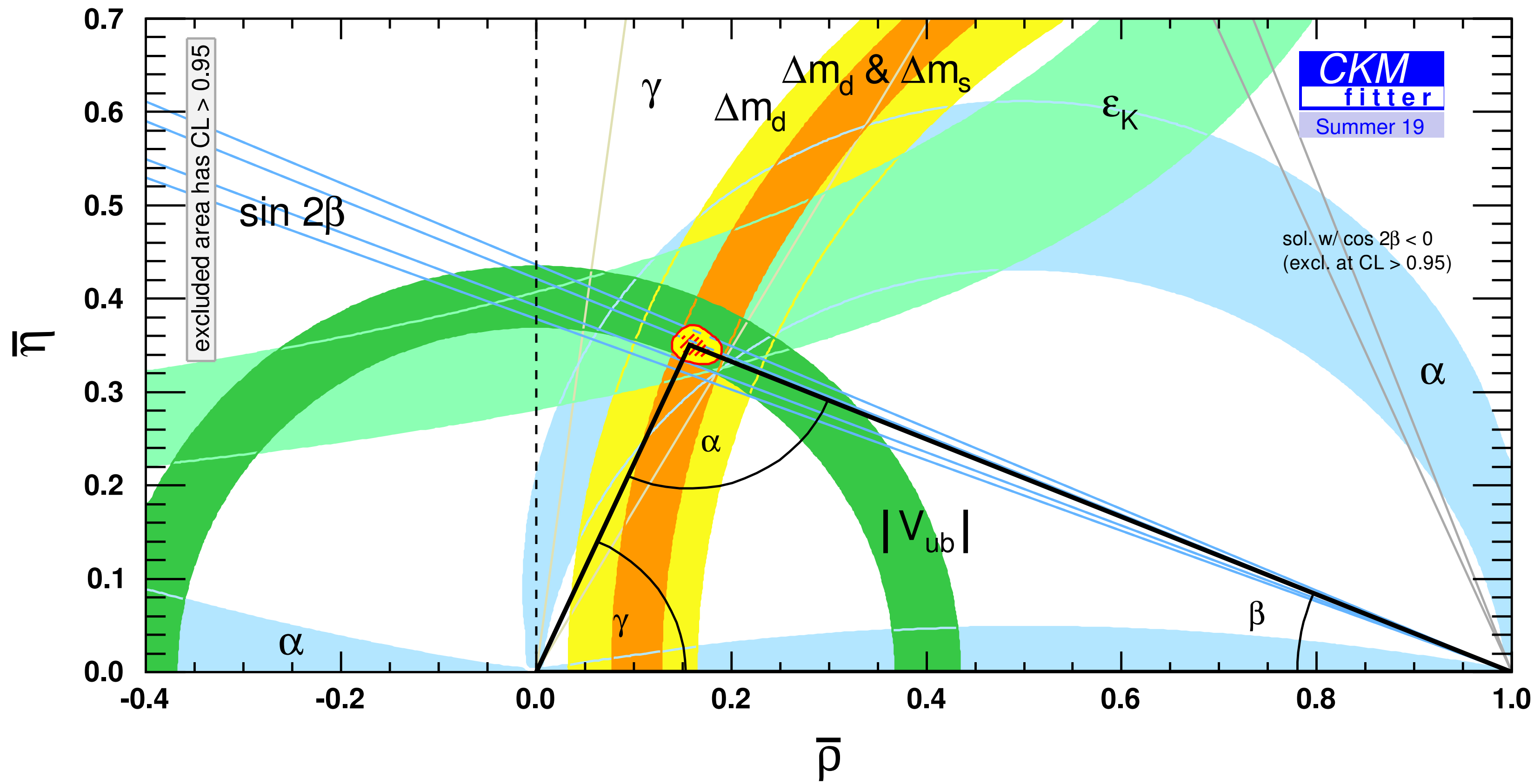
Flavor Physics

Yuval Grossman

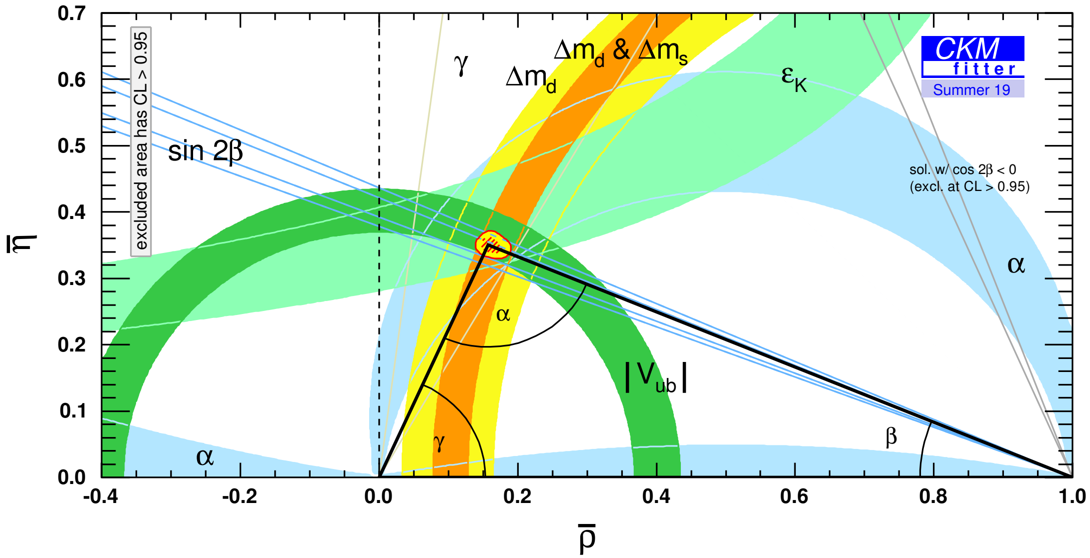
Cornell

Status of flavor physics



The goals of flavor physics (1)

Finding hints for BSM physics



Are we seeing the tail?

The goals of flavor physics (2)

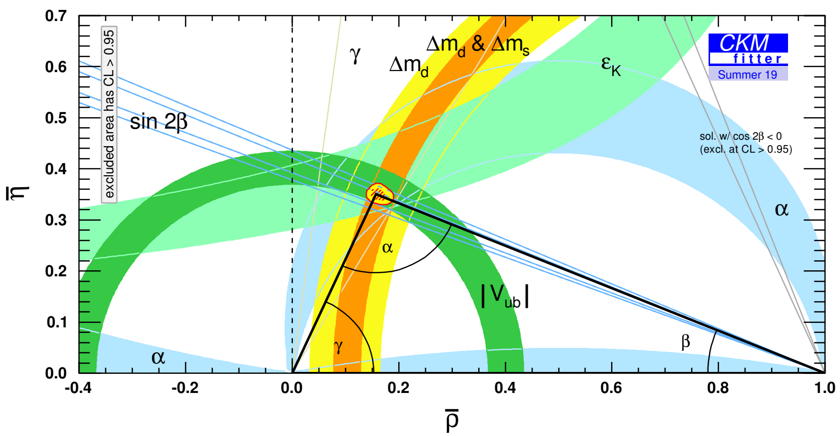
The weak/strong interplay

- Traditional: Overcome QCD to probe the weak interaction
  - Eliminate or calculate QCD parameters
- New: Use the weak interaction to probe QCD
  - Measure QCD parameters

In this talk

A biased sample of ideas on both directions

- B physics and flavor sum rules
- CPV in charm physics
- Clean information from $K \to \mu^+\mu^-$



B physics

B Physics

- B physics is not a teenager anymore
- What next?
  - Anomalies
  - The future is bright: more data with clean modes
  - Theory developments are keep coming

Higher order SU(3) sum rules

- Use the approximate symmetries of QCD
  - Isospin: $u - d$
  - SU(3): $u - d - s$
  - U-spin: $d - s$
- Isospin is very useful as the breaking is of $O(1\%)$
- SU(3), or just U-spin, is useful but it comes with large breaking of $O(20\%)$
- We can use SU(3) to
  - Estimate isospin breaking effects
  - Get rough predictions
  - Get precise predictions when we used relations that hold to higher order in SU(3) breaking

All order U-spin sum rules

M. Gavrilova, YG, S. Schacht, in preparation

- We show how to get U-spin sum rules in any system without the need to decompose the amplitudes
- The system is mapped into a multi-dimensional geometrical lattice
- Sum rules that are valid to order b correspond to b dimensional subspaces
  - point: leading order
  - line: first order
  - plane: second order
- It is not clear, however, how useful it is in practice

Charm physics

The birth of charm CPV

$$\Delta A_{CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-} = (-1.54 \pm 0.29) \times 10^{-3}$$

Born in 2019. What is next for charm CPV?

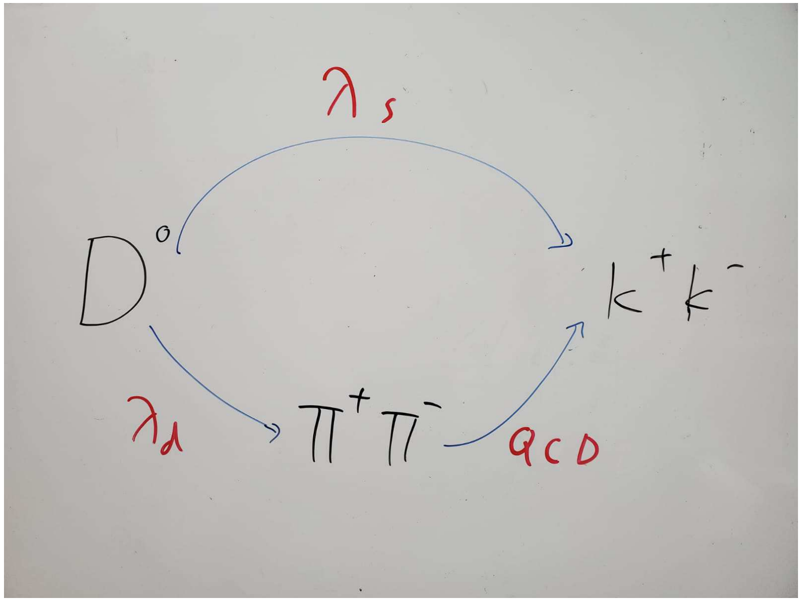
- We can learn about QCD from charm
- We have SU(3)-based rough SM predictions to test

The small parameters for charm

We can estimate all the parameters in charm in terms of the following small parameters

- Non-unitarity of the 2×2 CKM: $\varepsilon_{\rm NU} \sim 10^{-3}$
- SU(3) breaking: $\varepsilon_{\rm SU(3)} \sim 0.2$
- The Wolfenstein parameter of the CKM: $\lambda \sim 0.2$
- For example [$x \sim \Delta m$, $y \sim \Delta\Gamma$]
  - Theory: $x_{\rm th} \sim y_{\rm th} \sim \lambda^2 \varepsilon^2_{\rm SU(3)} \sim 0.2\%$
  - Experiment: $x_{\rm ex} \sim y_{\rm ex} \sim 0.5\%$

Interference via Rescattering



- We need two amplitude to interfere
- $\pi\pi$ represents many similar states like $\pi\rho$, $\rho\rho$
- Interference of trees with λ_s and λ_d
- We do not talk about penguins

Tree rescattering in Nature

The factors

$$\frac{\mathcal{A}(D \to \text{“}\pi\pi\text{''} \to KK)}{\mathcal{A}(D \to KK)} = \left(r_{\rm QCD} e^{i\delta}\right) \left(r_{\rm CKM} e^{i\varphi}\right)$$

$$a^d = 2(r_{\rm QCD} \sin\delta)(r_{\rm CKM} \sin\varphi)$$

- $r_{\rm QCD}$: ratio of rescattering amplitudes
- $\sin\delta = O(1)$: strong phase
- $r_{\rm CKM} = 1$: ratio of CKM factors, $|\lambda_d/\lambda_s|$
- $\sin\varphi \sim \varepsilon_{\rm NU} \sim 10^{-3}$: deviation from 2×2 unitarity

$$a^d \sim \varepsilon_{\rm NU} \times r_{\rm QCD} \sim 10^{-3} \times r_{\rm QCD}$$

What we learn from direct CPV

Within the SM the data implies $r_{\mathrm{QCD}} \sim 1$

- Theory: $a^d \sim 10^{-3} \times r_{\mathrm{QCD}}$
- Data: $a^d \sim 10^{-3}$

We conclude

- The assumption of large rescattering agrees with the data
- It is hard to argue that the LHCb result requires BSM
- we learn something about QCD

Future: testing the SM pattern

Kagan, Silvestrini, arXiv:2001.07207, YG et al. in preparation

$$a_f \equiv \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})} \approx a_f^d + a^m + a_f^i$$

1. a_f^d. For SCS $\qquad a_f^d \sim \varepsilon_{\rm NU} \times O(1)_f \sim 10^{-3}$

2. a^m. Universal

$$a^m \sim y\,\frac{\varepsilon_{\rm NU}}{\varepsilon_{\rm SU(3)}} \sim \varepsilon_{\rm NU} \times \varepsilon_{\rm SU(3)} \sim 10^{-4}$$

3. a_f^i. Approximate universality

$$a_f^i \sim x\,\frac{\varepsilon_{\rm NU}}{\varepsilon_{\rm SU(3)}} \times \left[1 + O(\varepsilon_{\rm SU(3)})_f\right] \sim 10^{-4} \pm 10^{-5}$$

Kaon physics

Kaon Physics

- Kaon CPV was “born” in 1964
- Mature, but clearly not retired yet
- NA62 and KOTO look for the clean $K \to \pi\nu\bar{\nu}$ modes
- What about $K \to \mu\mu$?

$K \to \mu\mu$

G. D'Ambrosio, T. Kitahara, 1707.06999

A. Dery, M. Ghosh, YG, S. Schacht, 2104.06427

- Rare FCNC decay
- It was very important in developing the SM: the GIM mechanism
- The K_L rate was measured, while LHCb is looking for the K_S rate

$$\mathcal{B}(K_L \to \mu\mu) \approx 7 \times 10^{-9} \qquad \mathcal{B}(K_S \to \mu\mu) \sim 5 \times 10^{-12}$$

- The problem is QCD, long distance physics
- $\ell = 0$ and $\ell = 1$
- Only $\mathcal{B}(K_S \to (\mu\mu)_{\ell=0})$ is theoretically clean

The prediction

The calculation gives

$$\mathcal{B}(K_S \to (\mu\mu)_{\ell=0}) = 1.8 \times 10^{-13} \times \left(\frac{A^2\lambda^5\eta}{1.3 \times 10^{-4}}\right)$$

- The numerical value is known from SD calculations
- Hadronic uncertainties are less than 1%
- Blue is theoretically clean
- We have a theoretically clean determination of η
- Can we measure it? How can we seperate the $\ell = 0$ from $\ell = 1$?

The time depidence

$$\left(\frac{d\Gamma}{dt}\right) \propto C_L e^{-\Gamma_L t} + C_S\, e^{-\Gamma_S t} + 2\left[C_{sin}\sin(\Delta m t) + C_{cos}\cos(\Delta m t)\right] e^{-\Gamma t}$$

$$C_L = |A(K_L)_{\ell=0}|^2$$
$$C_S = |A(K_S)_{\ell=0}|^2 + |A(K_S)_{\ell=1}|^2$$
$$C_{cos} = Re[A(K_S)_{\ell=0} \times A^*(K_L)_{\ell=0}]$$
$$C_{sin} = Im[A(K_S)_{\ell=0} \times A^*(K_L)_{\ell=0}]$$

Then, we can get the clean amplitude

$$|A(K_S)_{\ell=0}|^2 = \frac{C_{cos}^2 + C_{sin}^2}{C_L}$$

Conclusion

What next for flavor?