Theory of CKM physics and CP violation

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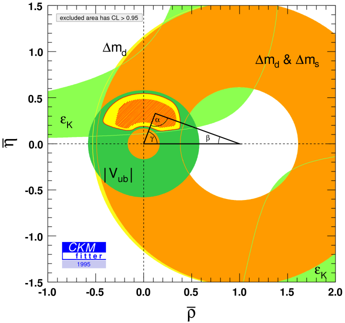
This is where we are. [CKMfitter, http://ckmfitter.in2p3.fr]



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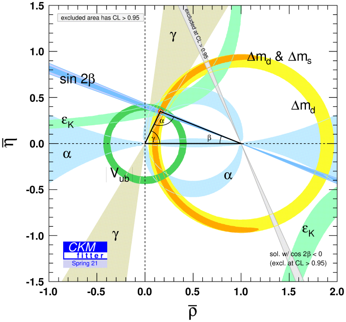


Moriond 2021

- Community effort due to both theoretical and experimental progress.

Please note:

This is my personal list, so the overview is biased towards my own work.

Signs of a new era? Anomalies in Flavor Physics

- There are several anomalies. We are not sure what is behind them.
- Semileptonic and rare B decay data: Lepton-flavor non-universality?
- CP is not a fundamental symmetry.
- Therefore, generically, BSM physics will also violate CP.
- If anomalies confirmed: Expect deviations from SM also in CPV.

Outline

- Charm CP Violation
- Beauty CP Violation
- CKM anomalies
- Meson Mixing

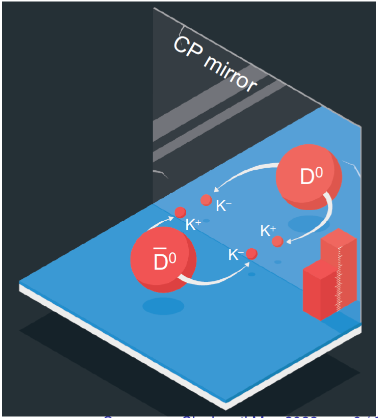
Charm CP Violation

Charm CP Violation:
New unique gate to flavor structure of up-type quarks.

$$\Delta A_{CP} \approx a_{CP}^{\text{dir}}(D^0 \to K^+K^-) - a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-) = (-0.164 \pm 0.028)\%$$

[LHCb 1903.08726, HFLAV 1909.12524]

- Expected unobservably tiny.
- But it is not.
- The jury is still out: SM or not?
- NP interpretations: Z', 2HDMs, ...
- $r_{QCD} \equiv$ Loop/Tree $= \mathcal{O}(1)$?



"$\Delta U = 0$ rule": $r_{\rm QCD} \sim 1$ [Grossman StS 1903.10952]

- We claim $\Delta U = 0$ follows similar pattern as generalized $\Delta I = 1/2$ rule.
- Both due to low energy QCD, rescattering.

"$\Delta I = 1/2$ rules" for isospin in $P^+ \to \pi^+\pi^0$, $P^0 \to \pi^+\pi^-$, $P^0 \to \pi^0\pi^0$

- Relevant ratio of strong isospin matrix elements:

$r_{QCD}^{\Delta I=1/2} \equiv A^{\Delta I=1/2}/A^{\Delta I=3/2}$	Kaon	Charm	Beauty
Data	22	2.5	1.5
"No QCD" limit	$\sqrt{2}$	$\sqrt{2}$	$\sqrt{2}$
Enhancement	$\mathcal{O}(10)$	$\mathcal{O}(1)$	$\mathcal{O}(\alpha_s)$

[D: Franco Mishima Silvestrini 2012, B: Grinstein Pirtskhalava Stone Uttayarat 2014]

- Rescattering most important in K decays, less important but still significant in D decays, and small in B decays.

Comparison of approaches: What is r_{QCD}?

Data

Assuming the SM, and $\delta_{\rm QCD} = \mathcal{O}(1)$, the data implies $r_{\rm QCD}^{\Delta U=0} \sim 1$.

Ref.	Theory Method/Assumptions	$r_{QCD}^{\Delta U=0}$	SM/NP
[Grossman StS 1903.10952]	Analogy to $\Delta I = 1/2$ rules Low energy QCD, rescattering is $\mathcal{O}(1)$	$\mathcal{O}(1)$	SM
[Brod Kagan Zupan 1111.5000]	Phenomenological analysis	$\mathcal{O}(1)$	SM
[Soni 1905.00907, StS Soni 2110.07619]	Resonance model	$\mathcal{O}(1)$	SM
[Petrov Khodjamirian 1706.07780] [Chala Lenz Rusov Scholtz 1903.10490]	Light Cone Sum Rules Resonances in principle incorporable.	$\mathcal{O}(\alpha_s/\pi)$	NP

What next? Apply methods to $\Delta I = 1/2$ rule in charm!

Reproduction of $\Delta I = 1/2$ crucial for NP case in $\Delta U = 0$.

Key Measurements for $D \to PP'$.

A_{CP} sum rules including breaking effects [Müller Nierste StS 1506.04121]

- SM sum rule 1: $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$.
- SM sum rule 2: $D^+ \to K_S K^+$, $D_s^+ \to K_S\pi^+$, $D_s^+ \to K^+\pi^0$.

Isospin Analysis [Grossman Kagan Zupan 1204.3557]

- Extract $\Delta I = 1/2$ and $\Delta I = 3/2$ MEs from

$$D^0 \to \pi^+\pi^-, D^+ \to \pi^+\pi^0, D^0 \to \pi^0\pi^0.$$

- $a_{CP}^{\mathrm{dir}}(D^+ \to \pi^+\pi^0) = 0.$ Higher orders < sensitivity.

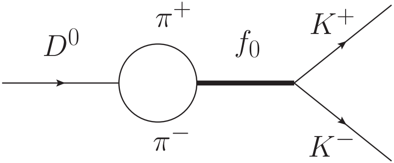
What next?

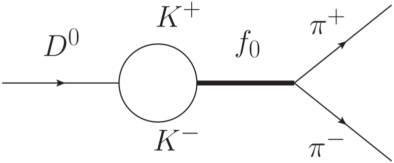
- Measurements of CP asymmetries in all SCS $D \to PP'$ decays.
- Need sum rules for multi-body decays at higher order in $SU(3)_F$.

What next? Check dynamical mechanism from data.

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^-$$

$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^- \xrightarrow{\text{QCD}} \pi^+\pi^-$$





Assumptions [StS and A. Soni, 2110.07619]

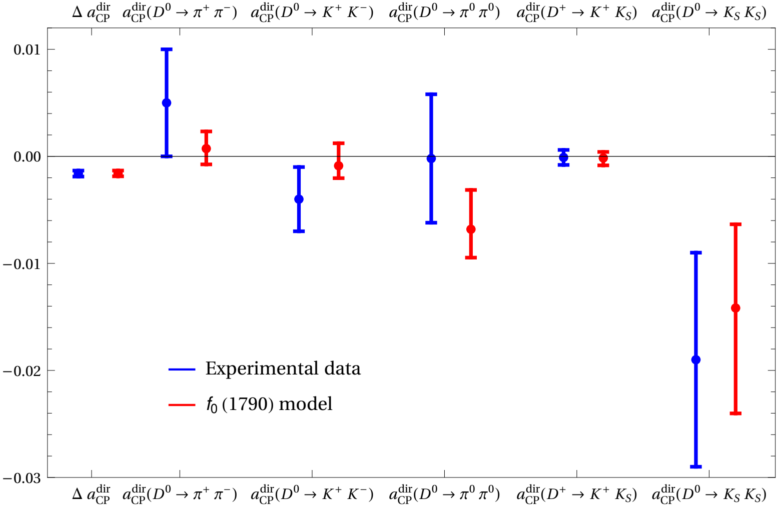
- Amplitudes to $I = 0$ states dominated by f_0 close to D^0 mass.
- Amplitudes into $I = 1$ states relatively suppressed.

Resonance structure can also be incorporated in future LCSR calculations.

[Khodjamirian Petrov 1706.07780]

Predictions in Scalar Resonance Model

[StS and A. Soni, 2110.07619]



What next? Study of $\Delta U = 0$ in three-body decays

[Dery Grossman StS Soffer 2101.02560]

$$\mathcal{A}(D^0 \to \pi^+\rho^-) = -\lambda\, T^{P_1V_2} - V_{cb}^* V_{ub}\, R^{P_1V_2}$$
$$\mathcal{A}(D^0 \to \pi^-\rho^+) = -\lambda\, T^{P_2V_1} - V_{cb}^* V_{ub}\, R^{P_2V_1}$$

- Time-integrated CP asym. of 2-body decays give only combinations

$$|\widetilde{R}^{P_1V_2}|\sin(\delta_{P_1V_2}) \qquad \text{and} \qquad |\widetilde{R}^{P_2V_1}|\sin(\delta_{P_2V_1}),$$

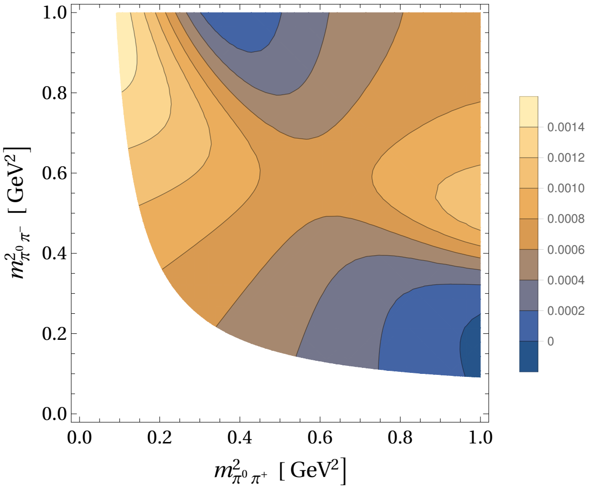
  but **not** magnitudes and phases separately.

- Three body decay changes 2 things:
  - We have additional kinematic dependences.
  - Only in a three-body decay we have interference between $D^0 \to \pi^+(\rho^- \to \pi^-\pi^0)$ and $D^0 \to \pi^-(\rho^+ \to \pi^+\pi^0)$.

↳Extraction of all parameters from time-integrated CP meas.

Local $a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-\pi^0)$ in overlap region of $\rho^\pm$

[Dery Grossman StS Soffer 2101.02560]



Numerical example: $\widetilde{R}^{P_1V_2} = \exp(i\pi/2)$, $\widetilde{R}^{P_2V_1} = \frac{1}{4}\exp(i\pi/3)$

SU(3)-flavor

- SU(3): Approximate symmetry for the light quarks u, d, s.
- Very useful, but $\mathcal{O}(30\%)$ breaking from corrections.
- Going to higher order: complicated.

$$(\mathbf{15}) \otimes (\mathbf{8}) = (\mathbf{42}) \oplus (\mathbf{24}) \oplus (\mathbf{15_1}) \oplus (\mathbf{15_2}) \oplus (\mathbf{15'}) \oplus (\bar{\mathbf{6}}) \oplus (\mathbf{3})$$

$$(\bar{\mathbf{6}}) \otimes (\mathbf{8}) = (\mathbf{24}) \oplus (\mathbf{15}) \oplus (\bar{\mathbf{6}}) \oplus (\mathbf{3})$$

Decay d	$B_1^{3_1}$	$B_1^{3_2}$	$B_8^{3_1}$	$B_8^{3_2}$	$B_8^{\bar{6}_1}$	$B_8^{\bar{6}_2}$	$B_8^{15_1}$	...
$D^0 \to K^+K^-$	$\frac{1}{4\sqrt{10}}$	$\frac{1}{8}$	$\frac{1}{10\sqrt{2}}$	$\frac{1}{4\sqrt{5}}$	$\frac{1}{10}$	$-\frac{1}{10\sqrt{2}}$	$-\frac{7}{10\sqrt{122}}$	...
$D^0 \to \pi^+\pi^-$	$\frac{1}{4\sqrt{10}}$	$\frac{1}{8}$	$\frac{1}{10\sqrt{2}}$	$\frac{1}{4\sqrt{5}}$	$-\frac{1}{10}$	$\frac{1}{10\sqrt{2}}$	$-\frac{11}{10\sqrt{122}}$	...
$D^0 \to \bar{K}^0K^0$	$-\frac{1}{4\sqrt{10}}$	$-\frac{1}{8}$	$\frac{1}{5\sqrt{2}}$	$\frac{1}{2\sqrt{5}}$	0	0	$-\frac{9}{5\sqrt{122}}$	...
$D^0 \to \pi^0\pi^0$	$-\frac{1}{8\sqrt{5}}$	$-\frac{1}{8\sqrt{2}}$	$-\frac{1}{20}$	$-\frac{1}{4\sqrt{10}}$	$\frac{1}{10\sqrt{2}}$	$-\frac{1}{20}$	$\frac{11}{20\sqrt{61}}$	...
...	...	...	...	...	...	...	...	...

Solving the Problem of Higher Order SU(3)

[Gavrilova Grossman StS, 2205.soon]

We proved several theorems enabling calculations to arbitrary order.

- We are able to determine a priori up to which order sum rules exist.
- We do not need explicit Clebsches. Big complexity reduction.
- Hope: Opens the door for precision in hadronic decays.
- Close a gap between theory and experiment.

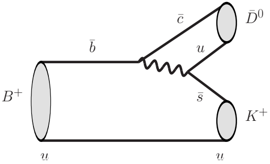
Take advantage of precision data on nonleptonic decays.

This is just the beginning of the exploration of charm CPV

- Crucial: CP asymmetries of all SCS two-body charm decays.
- Necessary to benefit from insights of flavor symmetry sum rules.
- Most promising for next observation: $D \to K_S K_S$ and $D \to K K^*$.
- Test picture of flavor symmetry breaking: at expected level (30%)?
- Important to search for optimized observables for multi-body decays.
  How can we maximize sensitivity to CP violation?
  What is the smartest binning for multi-body decays?
- How can we formally account for the phase space effects when comparing Dalitz plots that are related by flavor symmetries?

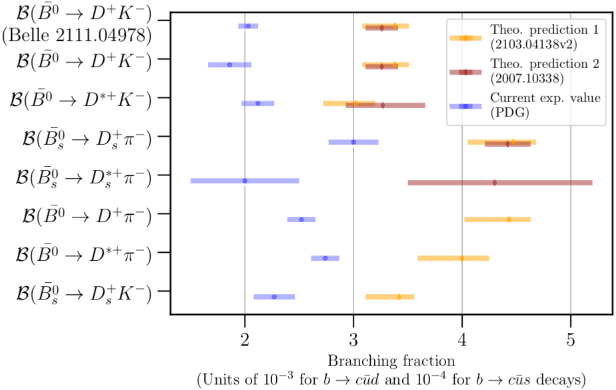
Beauty CP Violation

Extraction of γ from $B \to DK$



- Can be used to measure γ with almost no theory uncertainties.
- Recently: charm parameters and γ extracted in one framework.
- How can we make optimized use of the available data?
- Look for best binning. Currently: Model used to find best binning. Unclear if possible to find better binning/how to adjust based on available charm data.
- Other idea: Unbinned methods. Binning may loose some sensitivity.
- But: Trade-off which statistical method is used.
- More work needed to check how we optimize the methodology.

Nonleptonic $B \to DP$ decays



[Plot courtesy of Nicola Skidmore]

- Lesson for QCDF? E.g. hadronic uncertainties underestimated?
- BSM effect in tree-level decays? W' of extended electroweak sector?

Charmless b decays

$K\pi$ puzzle

- Tension with isospin sum rule for $B \to K\pi$ CP asymmetries $\sim 1.4\sigma$.
- More precise measurements of all involved CP asymmetries crucial: $B^0 \to K^0\pi^0$, $B^0 \to K^+\pi^-$, $B^+ \to K^0\pi^+$, $B^+ \to K^+\pi^0$.

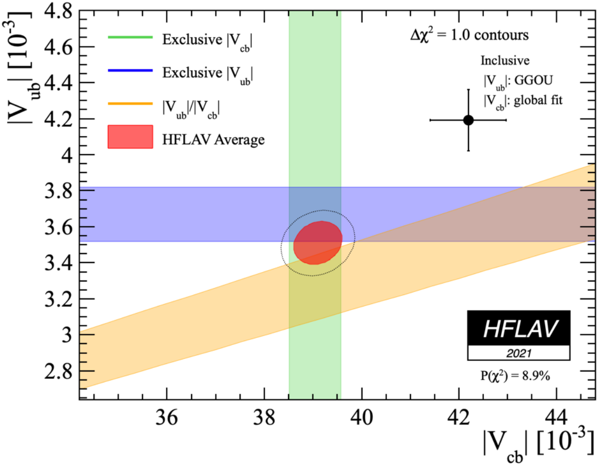
Baryonic decay modes

- Expect direct CPV from interference of $b \to u$ and $b \to d, s$.
- Rich underlying resonance structure: potentially large CPV effects.
- First evidence for baryonic CPV in $\Lambda_b \to p\pi^-\pi^+\pi^-$ (LHCb)
- Further searches ongoing.

CKM Anomalies

CKM anomalies: V_{cb}–V_{ub} puzzle

[HFLAV 2021]

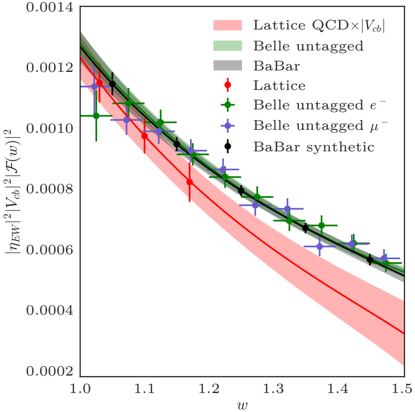


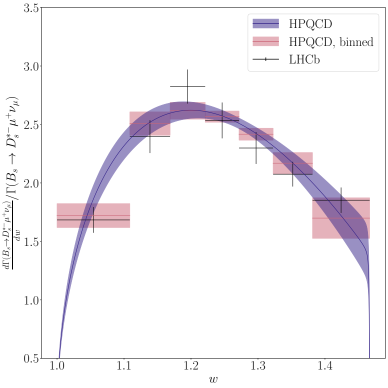
- V_{cb} important for many predictions, including ΔM_q, $B_q \to \mu^+\mu^-$, ε_K.
- $|V_{ub}/V_{cb}|$ directly constrains one side of the unitarity triangle.
- Future opportunity: V_{cb} from leptonic decay $B_c^+ \to \tau^+\nu$.

New results from Lattice QCD

$B \to D^*$: [FNAL/MILC 2105.14019]

$B_c \to J/\psi$: [HPQCD 2007.06956]
$B_s \to D_s^*$: [HPQCD 2105.11433]





$|V_{cb}| = 38.57(0.70)_{\text{th}}(0.34)_{\text{exp}} \cdot 10^{-3}$

$|V_{cb}| = 43.0(2.1)_{\text{latt}}(1.7)_{\text{exp}}(0.4)_{\text{EM}} \cdot 10^{-3}$

CKM unitarity: First row (Cabibbo Anomaly)

First row CKM unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \, .$$

Deviation between 2–4 σ.

- V_{ud}: nuclear beta decays, neutron decays, pion beta decays.
- V_{us}: kaon decays, hyperon decays, tau decays.
- $|V_{ub}|^2 \simeq 1.6 \cdot 10^{-5}$ negligible at current uncertainties:
  Up to $\mathcal{O}(\lambda^6) \simeq 0.0001$, we can write $V_{ud} = \cos\theta_C$, $V_{us} = \sin\theta_C$.
- Note that testing for equality of Cabibbo angle is not identical to unitarity test.

CKM unitarity: Second row

Second row unitarity

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.$$

Not yet conclusive because of large errors in V_{cd} and V_{cs}.

- V_{cd}: $D \to \pi l\nu$, $D^+ \to \mu\nu$.
- V_{cs}: $D \to K l\nu$, $D_s^+ \to \mu\nu$, $D_s^+ \to \tau\nu$.
- Semileptonic decays require form-factors.
- Leptonic decays require decay constants: very well-known.
- Continuing experimental progress will enable more precise test.

Meson Mixing

Comparison of Theory vs. Experiment

Mixing

- Mixing described by 2x2 matrix $M^q - i\Gamma^q/2$
- Diagonalizing ⇒ heavy B_H and light B_L mass eigenstates.
- Masses $M_{H,L}$ and widths $\Gamma_{H,L}$.

Theoretical quantities: $|M_{12}^q|, \quad |\Gamma_{12}^q|, \quad \arg\left(-M_{12}^q/\Gamma_{12}^q\right).$

Experimental quantities: $\Delta M_q = M_H^q - M_L^q, \qquad \Delta\Gamma_q = \Gamma_L^q - \Gamma_H^q$

$$a^q_{\text{flavor specific}} = \mathrm{Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) \approx a^q_{\text{semileptonic}} \equiv \frac{\Gamma(\overline{B}_q(t) \to X l^+ \nu_l) - \Gamma(B_q(t) \to \overline{X} l^- \overline{\nu}_l)}{\Gamma(\overline{B}_q(t) \to X l^+ \nu_l) + \Gamma(B_q(t) \to \overline{X} l^- \overline{\nu}_l)}$$

Plays important role in recent models of baryogenesis.
[Elor Escudero Nelson 1810.00880, Alonso-Alvarez Elor Escudero 2101.02706]

Status quo

Theory: NNLO completed!

[Gerlach Nierste Shtabovenko Steinhauser 2205.soon]

$$\Delta\Gamma_s^{\text{theory}} = (0.076 \pm 0.017) ps^{-1}$$

Experiment

[LHCb 2104.04421, 2011.12041, CMS 2007.02434, ATLAS 2001.07115, HFLAV]

$$\Delta M_s^{\exp} = (17.7656 \pm 0.0057)\, ps^{-1} \qquad \Delta\Gamma_s^{\exp} = (0.082 \pm 0.005) ps^{-1}$$

$$a_{fs}^{s,\exp} = (60 \pm 280) \cdot 10^{-5}$$

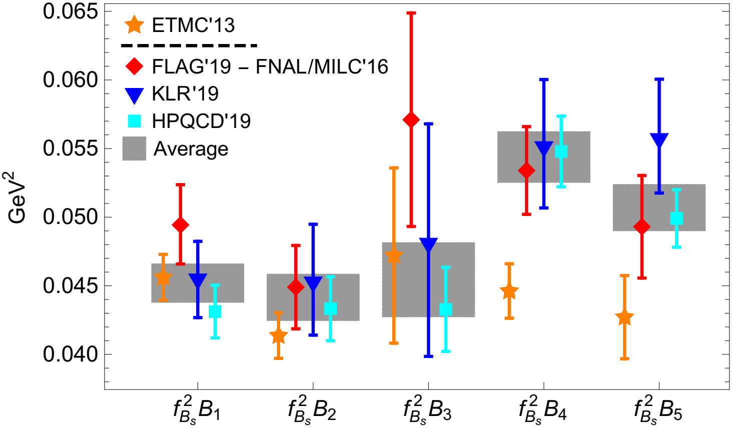
What next?

- NNLO also for a_{fs}^s.
- Current NLO result: $a_{fs}^s = (2.02^{+0.17}_{-0.19}) \cdot 10^{-5}$.

  [Gerlach Nierste Shtabovenko Steinhauser 2202.12305]
- Need more precise measurement of a_{fs}^s.

Non-perturbative Mixing Matrix elements

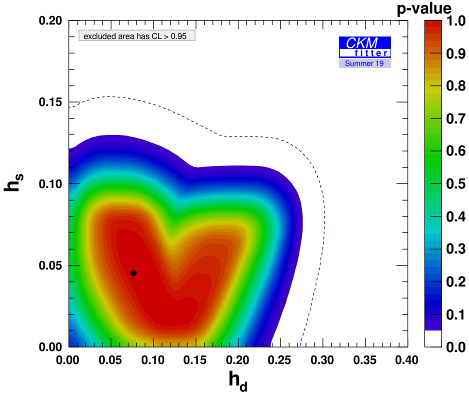
[Luzio Kirk Lenz Rauh 1909.11087]



- Good agreement between HQET sum rules (blue) and lattice.
- Further convergence of lattice necessary for envisioned 1% precision.

Constraints on New Physics in Mixing

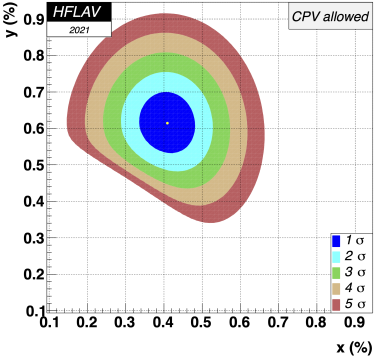
- Assumptions:
  1) NP enters at loop level.
  2) Conserve CKM unitarity.
- Then mixing parametrizable as:
  $M_{12}^q = \left(M_{12}^q\right)_{SM} (1 + h_q e^{2i\sigma_q})\,.$

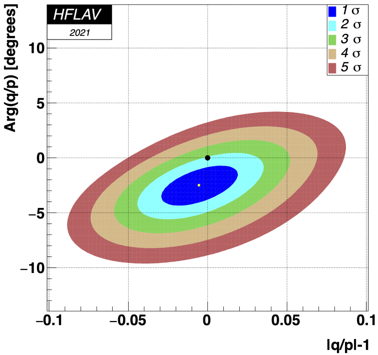


[Charles et al, 2006.04824]

There is a lot of parameter space to explore!

Charm Mixing





- Mixing parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/(2\Gamma)$.
- 2021: First observation of $x \neq 0$ with $> 7\sigma$. [LHCb 2106.03744].
- Uncertainty of y reduced by a factor two in [LHCb 2110.02350].
- $|q/p| \neq 1$ would indicate CPV in mixing.
- $\mathrm{Arg}(q/p) \neq 0$ would indicate CPV from interference mixing/decay.
- SM: hard to calculate. Qualitative agreement with SM.

Exclusive Approach: Hadron-Level

$$\Gamma_{12}^D = \sum_n \rho_n \left\langle \overline{D^0} \right| \mathcal{H}_{eff}^{\Delta C=1} |n\rangle \langle n| \mathcal{H}_{eff}^{\Delta C=1} \left| D^0 \right\rangle ,$$

$$M_{12}^D = \sum_n \left\langle \overline{D^0} \right| \mathcal{H}_{eff}^{\Delta C=2} \left| D^0 \right\rangle + \mathcal{P} \sum_n \frac{\left\langle \overline{D^0} \right| \mathcal{H}_{eff}^{\Delta C=1} |n\rangle \langle n| \mathcal{H}_{eff}^{\Delta C=1} \left| D^0 \right\rangle}{m_D^2 - E_n^2}$$

- n: all possible hadronic states. ρ_n: density of state. $\mathcal{P}$: principal value.
- Result: $y \sim 1\%$, agreeing with measurements.

What next?

- More experimental input needed (BRs and phases).
- Theory: Need to take into account more SU(3)$_F$ breaking effects.
- Long-term: Lattice predictions?

Inclusive Approach: Quark-Level

- Heavy-Quark Expansion (HQE), motivated by $\tau(D^+)/\tau(D^0)$.
- Needed non-perturbative matrix elements from sum rules or Lattice
- Severe GIM-cancellations may take place.

Recent Developments

[Lenz Piscopo Vlahos 2007.03022]

- GIM depends on scales entering different box contributions.
  These contain different amounts of strangeness.
- No need that these scales are the same ⇒ GIM cancellation broken.
- HQE uncertainty gets larger, including y^{exp}.

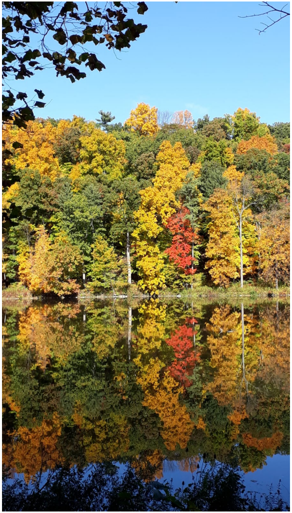
What next?

- Higher orders in HQE expansion.
- After Γ_{12} also M_{12}, e.g. with dispersion relations.

Conclusions

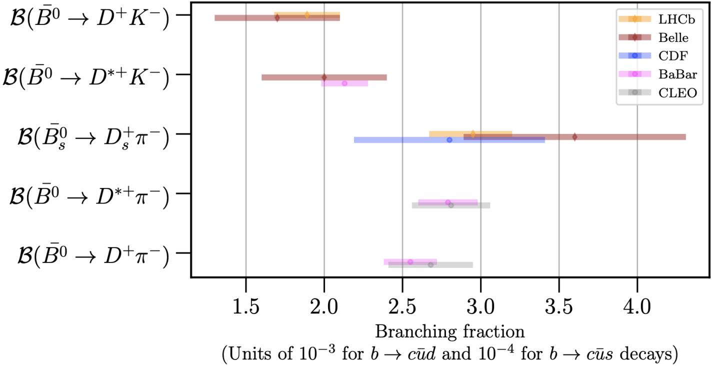
- So much more data and theory ideas: New era in flavor physics.
- We need to keep:

  Theory error < Experimental error .
- No matter what, we will learn sth new: QCD or New Physics.



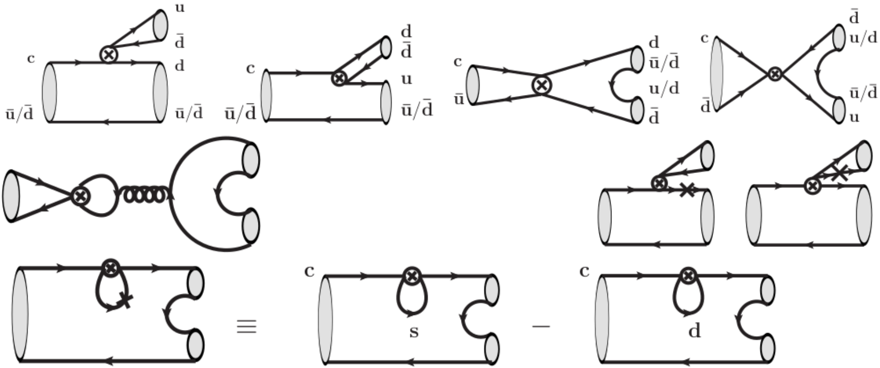
BACK-UP

Experimental Agreement for $B \to DP$ decays



[Plot courtesy of Nicola Skidmore]

Charm: Non-perturbative Diagrams



Direct CP Violation is an Interference Effect

$$a_{CP}^{\mathrm{dir}}(f) \equiv \frac{|\mathcal{A}(D^0 \to f)|^2 - |\mathcal{A}(\overline{D}^0 \to f)|^2}{|\mathcal{A}(D^0 \to f)|^2 + |\mathcal{A}(\overline{D}^0 \to f)|^2} \approx 2(r_{\mathrm{CKM}} \sin \varphi_{\mathrm{CKM}})\,(r_{\mathrm{QCD}} \sin \delta_{\mathrm{QCD}})\,.$$

f = CP-eigenstate.

The decay amplitude:

$$\mathcal{A} = 1 + r_{\mathrm{CKM}}\, r_{\mathrm{QCD}}\, e^{i(\varphi_{\mathrm{CKM}} + \delta_{\mathrm{QCD}})}$$

- r_{CKM} : real ratio of CKM matrix elements.
- φ_{CKM} : weak phase.
- r_{QCD} : real ratio of hadronic matrix elements.
- δ_{QCD} : strong phase.

Where does the interference come from?

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^-$$

$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^- \xrightarrow{\text{QCD}} \pi^+\pi^-$$

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^- \xrightarrow{\text{QCD}} K^+K^-$$

$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^-$$

$KK \leftrightarrow \pi\pi$ rescattering into same final state.

Weak and strong factors

$$\frac{\mathcal{A}(D \to \pi\pi \to KK)}{\mathcal{A}(D \to KK)} = \left(r_{\mathrm{CKM}} e^{i\varphi_{\mathrm{CKM}}}\right)\left(r_{\mathrm{QCD}} e^{i\delta_{\mathrm{QCD}}}\right)$$

- r_{QCD}: ratio of rescattering amplitudes.
- $\delta_{\mathrm{QCD}} = \mathcal{O}(1)$: strong phase.
- $r_{\mathrm{CKM}} = 1$: ratio of CKM factors, $\left|V_{cd}^* V_{ud} / (V_{cs}^* V_{us})\right|$
- $\varphi_{\mathrm{CKM}} \approx 6 \cdot 10^{-4}$: deviation from 2×2 unitarity.

Prediction

$$\Delta a_{CP}^{dir} \sim 10^{-3} \times r_{\mathrm{QCD}}$$

- U-spin decomposition: $r_{\mathrm{QCD}} = r_{\mathrm{QCD}}^{\Delta U=0} \equiv \mathcal{A}^{\Delta U=0} / \mathcal{A}^{\Delta U=1}$.